FINAL REPORT

OF THE PROJECT

MORPHOLOGICAL STUDY OF KRISHNA AND TUNGABHADRA BASINS USING REMOTE SENSING TECHNIQUE

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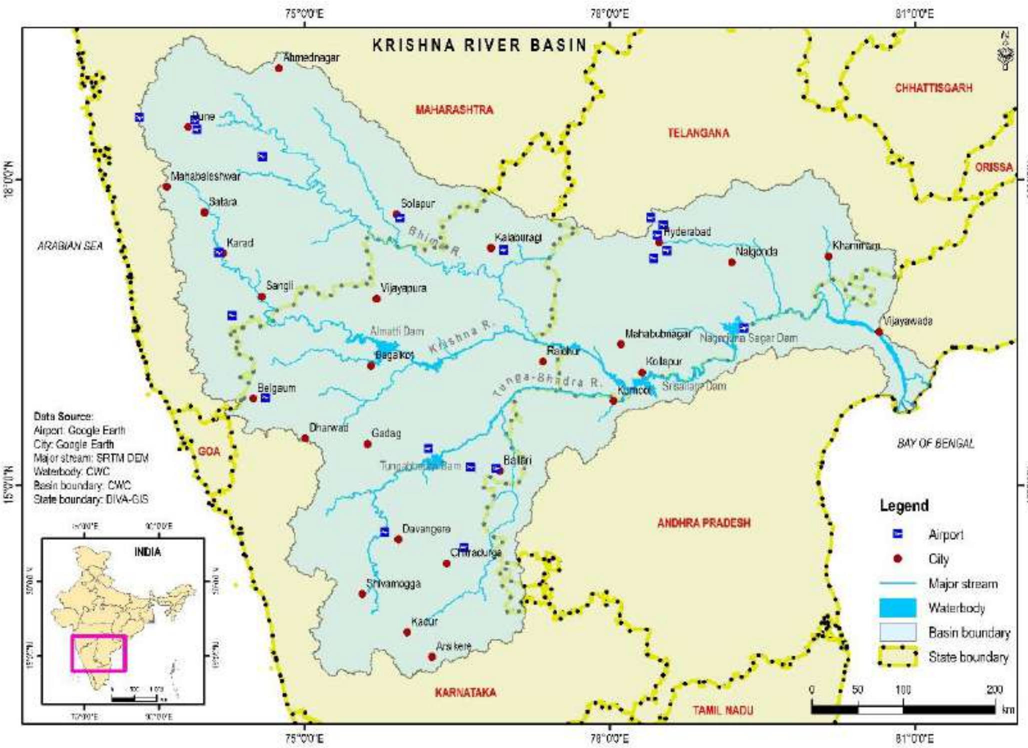
EXECUTIVE SUMMARY

The rivers modify their channels at various spatial and temporal scales through erosion of the channel boundary and the reworking and deposition of sediments in order to cope up with the changes in magnitudes of water and sediment discharges due to construction of hydraulic structures, modification of land use/land cover pattern of the catchment as well as changes in the climatic variables. The problems associated with river morphological changes are ubiquitous, but show regional variabilities with changes in magnitudes as well as the driving mechanisms. Hence, widespread efforts have been undertaken in diverse environments across the world to understand the changes in channel morphology and the environmental changes responsible for the changes of the river channels. Although numerous studies of this kind were carried out in the Indian context, the Himalayan Rivers were in the limelight, and the peninsular rivers are still at its infant stage. The present study addressed the changes in channel morphology, especially in the context of bank erosion and deposition processes occurred in Krishna and Tungabhadra rivers during 1973-2011 using remote sensing-based approach.

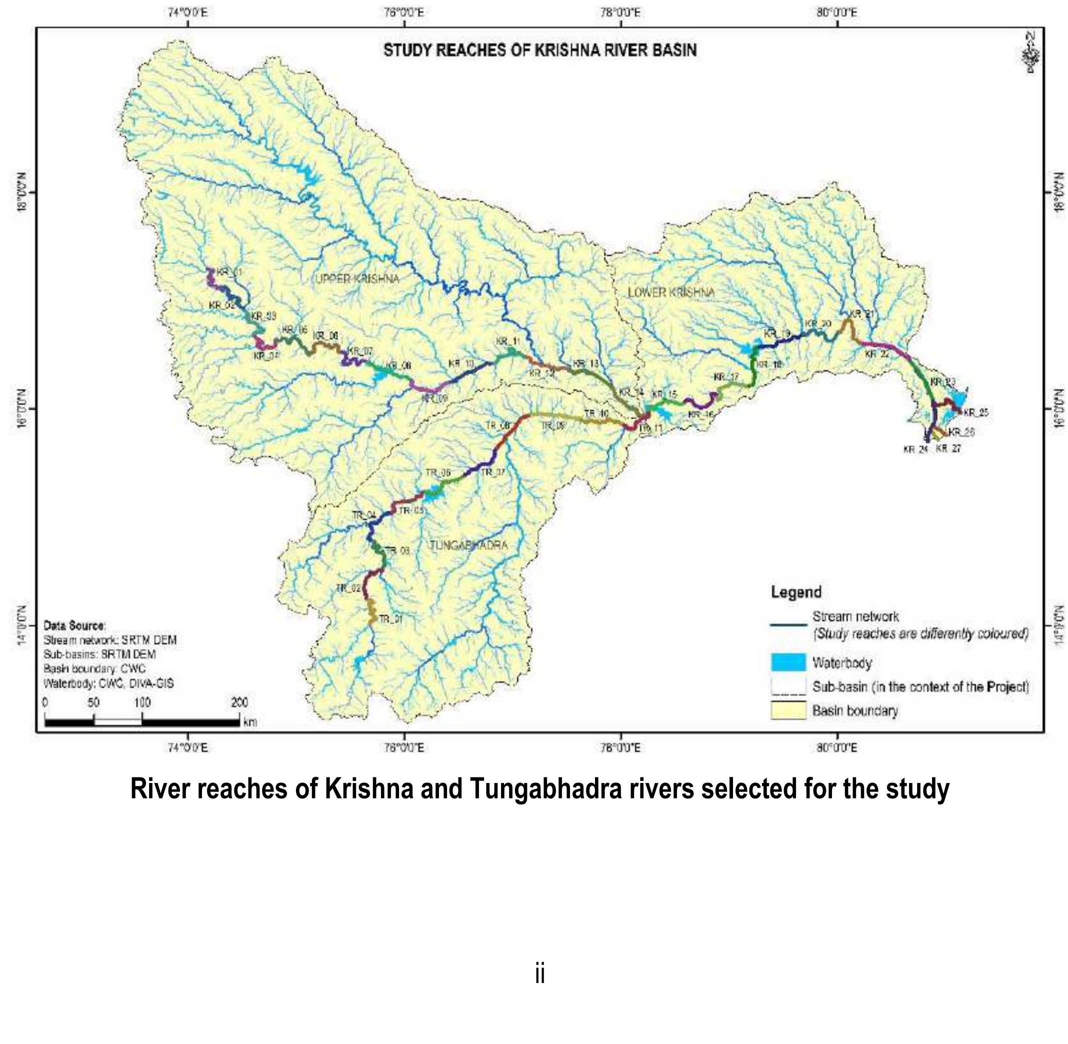
The Krishna River Basin (KRB) is the fourth largest drainage system of India, which has a catchment area of 2,58,948 km^2 (the figure given below). The mainstream of Krishna has a length of approximately 1,400 m, and the Bhima and the Tungabhadra are the principal tributaries of Krishna River.



Krishna River Basin, India

The basin elevation varies from MSL to 1908 m above MSL, and shows a clear altitudinal zonation from west to east, and majority of the basin area is relatively flat and gentle in slope and more than 90 percent lies below 750 m above MSL. The climate of the basin varies from humid to arid, where the majority of the basin (inland areas) falls under semi-arid climate. The cropland is the dominant land use/ land cover of the basin, which accounts for more than 80% of the basin area. The interactions among the lithology, structure/tectonics, and climate of the basin have led to the evolution of the diverse landforms, and irrespective of the physiographic setting and geology, the river reaches show wide range of morphological characteristics along the course. The basin accommodates around 855 water resources projects, including 660 dams, 12 barrages, 58 weirs, 6 anicuts, and 119 lifts, which qualifies Krishna to be categorized as "strongly affected" by flow fragmentation and regulation. Major lithological types of the basin are the Deccan Traps rocks as well as the peninsular gneisses.

The scope of the present study is restricted to the mainstream channels of the Krishna and Tungabhadra rivers. The mainstream of Krishna River is considered between the river segment where Koyna River meets with Krishna River, and the river meets with Bay of Bengal (1194 km) and the mainstream of Tungabhadra River is considered from the confluence between Tunga and Bhadra Rivers and the river confluences with Krishna River (537 km). The Krishna River is segmented into a total of 27 reaches (the figure given below) at 50 km intervals (KR_01 to KR_27), and the Tungabhadra into 11 reaches (TR_01 to TR_11).



River reaches of Krishna and Tungabhadra rivers selected for the study

The mean width of the river reaches shows considerable variability across Krishna as Tungabhadra rivers (i.e., from 167 to nearly 4000 m in Krishna River and 359 to 4312 m in Tungabhadra River). The study reaches belong to Upper Krishna (KR_01 to KR_14) are mostly underlain by basalts, Kaladgi Group rocks, potassic granodiorite to granite, granite as well as metavolcanics with metasediments and granitoid gneiss, whereas the study reaches of Lower Krishna are developed predominantly on potassic granodiorite to granite, Srisailam quartzite, Kurnool Group rocks and Cumbum Formation. However, the study reaches of Tungabhadra River are underlain by TTG, greywacke with volcanics and chemogenic precipitates, metavolcanics with metasediments and granitoid gneiss, granite as well as potassic granodiorite to granite.

The average annual rainfall in the Krishna basin is around 800 mm, while the mean daily maximum temperature of the basin varies from 27.7 to 40.4°C, and the mean daily minimum temperature ranges between 20.6 and 27.2°C. The headwater reaches as well as downstream portions of the basin receive a good amount of rainfall during southwest and northeast monsoon episodes respectively, while inland areas of the basin receive a significantly lower amount of rainfall annually, i.e., a decreasing rainfall gradient towards the central part from upstream as well as from downstream portions of the basin. The long-term mean annual surface flow of KRB is 78 km^3, of which 58 km^3 is considered to be utilizable, and a drastic reduction in streamflow during the past years is contributed by the hydraulic structures constructed across the river course. The results of the flood frequency analysis using the annual maximum daily discharge values for the H.O. sites, using the Gumbel's distribution method indicates that severe flood events (return period of more than 100 years) happened during the years 2005, 2006 and 2009. The flow duration curves of the many of the H.O. stations indicate that the curve is flat in both high flows as well as in low flows, implying sustenance of moderate flows throughout the year probably due to artificial streamflow regulation, or due to a large groundwater capacity which sustains the base flow to the stream.

In order to accomplish the objectives of the project, various spatial and non-spatial (historic as well as contemporary) data were used. The SoI topographic maps (of 1: 50,000 scale) were purchased, which were primarily used as a reference as well as for georeferencing of the satellite images. The SRTM DEM (1 arc second) was used for the physiographic analysis as well as for the delineation of lower order stream network of the KRB. The choice of the remote sensing images for the project (1973, 1977, 1991, 2001 and 2011) was based on the availability, season, cloud cover, spectral as well as radiometric quality and spatial resolution of the data. Satellite scenes, corresponding to the basin, from different LANDSAT missions and IRS for the dry season, mostly from January and April, (with less than 10% cloud cover) were collected to minimize the errors related to the delineation of channel bank lines. Even though the remote sensing images have different spatial resolutions, a common scale (1: 50,000 in this case) was fixed for the mapping purposes to reduce the uncertainty in vectorization of landforms contributed by the pixel size. The CWC provided the basic geospatial and attribute data of the KRB, and the project has updated the geodatabase from the inputs collected during the project. Hydrologic data (e.g., gauge, discharge, sediment load, bed material particle size, and cross section) recorded at different H.O. stations in KRB were collected from CWC, which was updated by comparing the data collected from WRIS-India portal. The cross-section and longitudinal profile data were collected from CWC. The cross-section data consist of cross-section profiles at 112 transects in Krishna and Tungabhadra rivers (74 and 38 cross section profiles respectively).

Although the study utilized various types of geospatial as well as hydro-climatic data for the analysis, the present investigation encountered a few critical issues, which are discussed in detail. The methodological framework of the study was to assess the variability of bank erosion and deposition on the decadal scale by collecting satellite images at 10-year intervals (1970, 1980, 1990, 2000 and 2010). The satellite data for 1970 are unavailable as the LANDSAT programme was initiated in 1972, and hence, data during 1973 was used instead of 1970. Similarly, satellite data (with reasonable spatial and radiometric quality) during the 1980s was not available, and the best available data was during 1977. However, remote sensing data for post-1990s have numerous choices, and the availability of data was not an issue for the period. Although the declassified images of the CORONA programme, occurred between 1959 and 1972 were available, the study did not consider the data as per the suggestions from the Consultancy Evaluation-Cum-Monitoring Committee (CEMC).

The scale of data capture is a major issue that seriously affects the delineation of channel boundary while using multi-temporal remote sensing data. The remote sensing data used in this study were of different spatial resolutions. Hence, the bank line from the images was digitized on a scale of 1:50,000 (without changing the zoom level) to reduce the inconsistency. However, positional inaccuracies could have contributed errors to the estimated values. Although the theoretical maximum precision of 1:50,000 scale topographic maps is 5 m, their actual precision is only 25 m (for the smallest measurement unit of 1 mm, with the possibility of interpolating to the nearest 0.5 mm). The spatial resolution of the Landsat 1 MSS images (1973) was 60 m, whereas the TM (1991) and OLI (2015) images had a spatial resolution of 30 m. Hence, the changes in bank lines with a magnitude less than 60 m could not be recognized during 1973-1991, and a change less than 30 m could not be detected during 1991-2015. Moreover, analysis of the polygons characterizing bank erosion and deposition evidently exhibits wide variability in their spatial extent, and the lower values than the aforementioned thresholds could mostly be the result of the errors during the delineation of bank lines.

Another issue encountered during the execution of the project was the lack of continuous hydrological data for the basin. Majority of the hydrological data (gauge-discharge, sediment concentration, particle size of bed materials) were provided by the Central Water Commission (CWC), and supplementary data were collected from WRIS-India. However, the data are heterogeneous (in the time period) across the H.O. stations of the basin. The recorded data length of river discharge varies from 8 years to 52 years, and about one-third of the H.O. stations have data for less than 30 years. Hence, the stations not having the required length of data were not used for the hydrological analysis. Although the gauge-discharge data are available for most of the stations, sediment concentration and bedload particle size data are limited to a few stations with varying data record length. In many H.O. stations of the basin, the discharge data were measured/calculated to the order of 10^{-1}, which is mediocre in data analysis. The cross-section and longitudinal profile data of the mainstream of Krishna and Tungabhadra were collected from CWC, but the surveyed data are available only after 2009, which prevents a fruitful comparison with the results of the bank erosion analysis (1973-2011).

In general, the mean width of the reaches of both Krishna and Tungabhadra rivers increases towards downstream as a result of the increasing discharges. However, exceptionally wide and narrow river segments are a result of the inundation of river valleys due to the construction of dams and incised nature of the river valleys to bedrock, respectively. The mean width of the reaches shows significant variability in a few reaches, such as KR_07 to KR_09, KR_13 to KR_18, TR_05, and TR_11, which is due to the submergence of the river valleys due to impoundment. The planform index (PFI) values of the downstream reaches estimated during different years. Among the different braided reaches, KR_22 and KR_23 show significantly lower PFI values in all the years, compared to other reaches. The temporal variability of the PFI values is very less, which suggests that irrespective of the time, these reaches show little changes in braiding intensity and pattern

In Krishna River, the total area of erosion of both the banks during 1973-1977 is 31.4 km^2, where erosion in left and right banks are 15.6 km^2 and 15.8 km^2 respectively. The total area of erosion of both the banks during 1977-1991 in the reaches of Krishna River is 31.5 km^2, where the area under erosion along the left and right bank is 13.6 and 17.9 km^2, respectively. During 1991-2001, the total area of erosion of both the banks in the reaches of Krishna River is 20.2 km^2, where the total area of erosion along the left bank is 10.8 km^2, and the total area of erosion along the right bank is 9.4 km^2. The changes in the bank lines of Krishna River during 2001-2011 indicates that the total area of erosion of both the banks during the period is 32.2 km^2, where the erosional area in both the banks is more or less similar (15.9 km^2 and 16.3 km^2 for left and right banks respectively). The total bank erosion of both the banks occurred in the study reaches of Krishna River during the entire period (i.e., 1973-2011) is 47.5 km^2, where the erosion area along the left bank is 21.9 km^2 and that of the right bank is 25.6 km^2. In other words, in the long term, the annual erosion of the total bank area is 1.30 km^2 in the reaches of Krishna River. During the different assessment periods, erosion along the left and right banks shows considerable spatial as well as temporal variability.

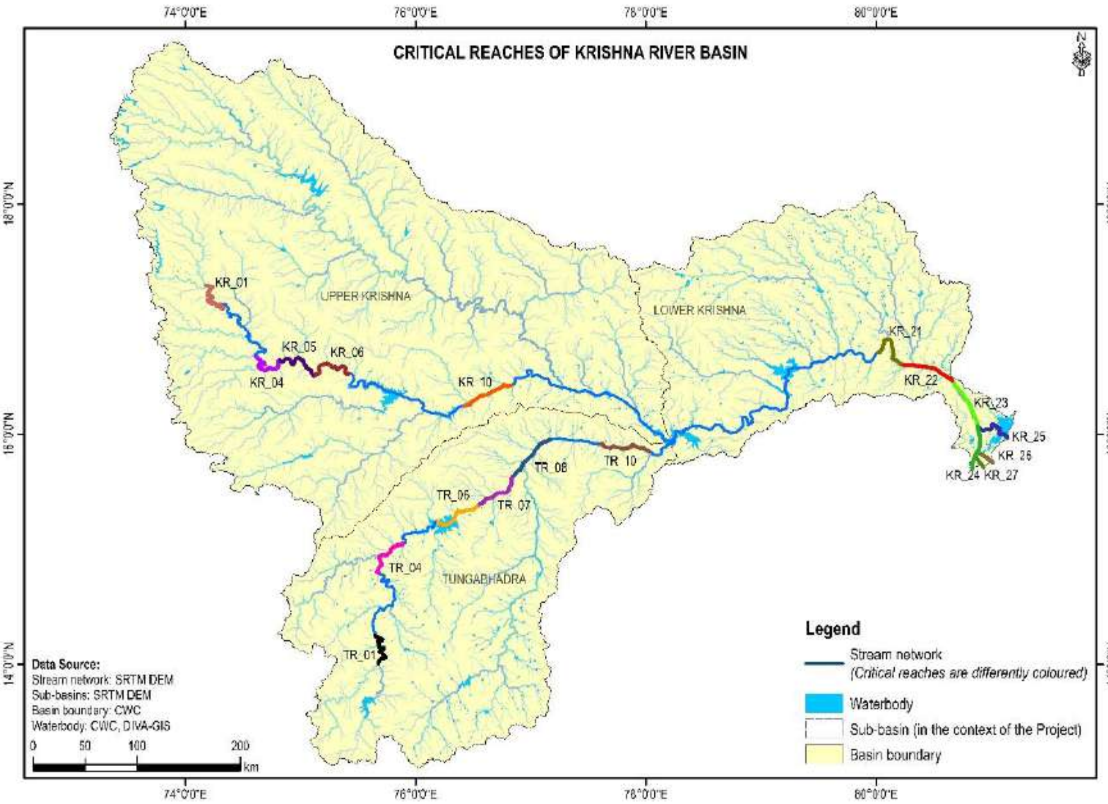
During 1973-1977, the total area of the depositional patches in both the banks of the reaches is 30.0 km^2, where the total area of deposition occurred along the left bank is 15.1 km^2, total area of deposition occurred along the right bank is 14.9 km^2. The total area of deposition in both the banks of the reaches during 1977-1991 is 40.2 km^2, where the areal extent of the depositional patches along the left and right banks is 19.6

km^2 and 20.6 km^2, respectively. The estimated area of total depositional patches in both the banks of the different reaches of Krishna River during 1991-2001 is 26.3 km^2, of which 12.5 km^2 is along the left bank and 13.8 km^2 along the right bank. During 2001-2011, the total area of deposition of both the banks of the entire reaches is 14.8 km^2, where the total area of deposition occurred along the left bank is 7.7 km^2, and the total area of deposition along the right bank is 7.1 km^2. The total area of deposition of both the banks of the entire reaches during the whole study period (1973-2011) is 42.2 km^2, of which 57% occurs along the left bank (24.2 km^2) and 43% along the right bank (18.0 km^2). The bank erosion/deposition pattern of the reaches of the Krishna River indicates that the downstream reaches exhibit a higher rate of erosion as well as deposition across the time periods.

The total area of erosion of both the banks of Tungabhadra River during 1973-1977 is 11.4 km^2, where the total area of erosion along the left bank is 4.8 km^2 and the total areal of erosion along the right bank of the entire study reaches sums up to 6.6 km^2. The total area of erosion of both the banks during 1977-1991 is 7.8 km^2, where 39% is contributed by the left bank (3.1 km^2) and 61% by the right bank (4.7 km^2). During 1991-2001, the total area of erosion of both the banks in the reaches is 8.4 km^2, where the total area of erosion along the left bank is 3.2 km^2, and the total area of erosion along the right bank is 5.2 km^2. The total erosion of both the banks of the study reaches is 13.6 km^2 during 2001-2011, where 55% of the same is contributed by the left bank (7.5 km^2) and rest by the right bank (6.1 km^2). The total area of erosion along both the banks of the study reaches of Tungabhadra River during the entire period (i.e., 1973-2011) is 14.7 km^2, the total area of erosion along the left bank is 5.0 km^2, total area of erosion along the right bank of the reaches sums up to 9.7 km^2. However, in the long term, the annual erosion of the total bank area is 0.4 km^2 across the reaches of the Tungabhadra River. The severity of erosion between left and right banks of the different reaches of Tungabhadra River indicates that the erosion is more severe in the right bank of the reaches, compared to the left bank during all the time periods, except during 2001-2011.

The total area of deposition in both the banks of the reaches of Tungabhadra River during 1973-1977 is 15.7 km^2, of which 9.9 km^2 area occurs along the left bank, and 5.7 km^2 area is along the right bank. During 1977-1991, the total area of deposition in both the banks of the reaches is 19.8 km^2, of which 12.6 km^2 area is along the left bank and 7.2 km^2 area is along the right bank. The total area of deposition of both the banks of the reaches during 1991-2001 sums up to 15.1 km^2. During the same period, the total depositional area along left and right banks is 9.0 km^2 and 6.1 km^2 respectively. During 2001-2011, the total area of deposition of both the banks of the reaches is 9.0 km^2, of which 4.2 km^2 is along left bank and 4.8 km^2 is along the right bank. The total area of deposition of the banks of the reaches during 1973-2011 is 33.0 km^2, the total area of deposition along left bank during the period is 22.7 km^2, and the total area of deposition along the right bank is 10.3 km^2.

Based on the temporal changes in the channel planform as well as the rate of erosion along the banks during the different short-term as well as long-term assessment periods, the critical reaches are identified based on the bank erosion vulnerability index (BEVI), which is a measure of mean width of erosion of the reaches as well as the percentage length of erosion along any given reach for the different time periods. The critical reaches of Krishna and Tungabhadra rivers, identified using BEVI are shown in the following figure.

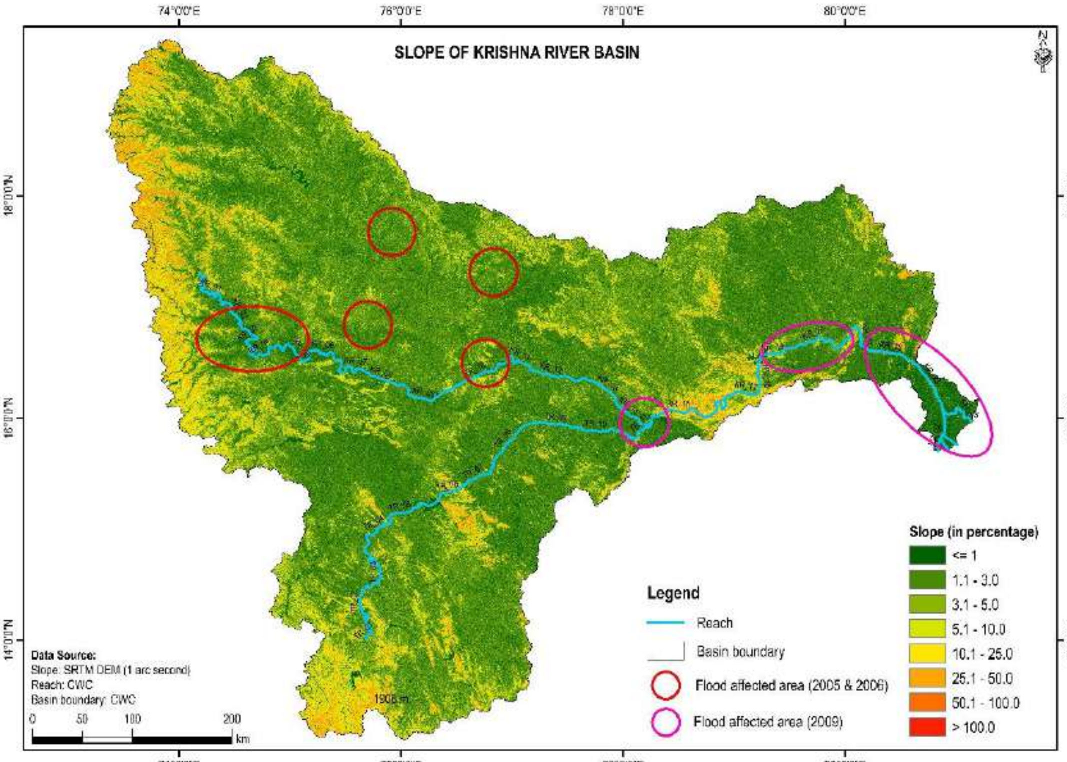


Spatial extent of the critical reaches of Krishna and Tungabhadra rivers

The trend analysis of the gridded rainfall data indicated that rainfall pattern in the majority of the basin area (> 90%) show hardly any significant trends at annual as well as southwest monsoon scales. However, a few grids in the Lower Krishna basin displayed significant positive trends in the annual as well as southwest monsoon rainfall during the study period. Although both the Krishna and Tungabhadra river segments are regulated, the peak flows show considerably higher variability in Krishna, compared to Tungabhadra. Similarly, the temporal variability of the area of bank erosion (during the period) in Krishna River exhibits relatively larger variation, compared to Tungabhadra River. However, the study does not provide any substantial pieces of evidence for a generalized relationship between peak flows and the rate of bank erosion. The absence of such a relationship could be a reflection of the controls exerted by other environmental factors (e.g., resistance of bank material, hydraulic structures etc.) on bank erosion.

The channel bankfull width, hydraulic mean depth as well as the cross-sectional area of the river segments of Krishna River exhibit an increasing trend towards downstream, whereas the bankfull width of the channel of Tungabhadra River shows a generally increasing trend towards downstream, and a decreasing trend for hydraulic mean depth. Despite any definite trend for cross-section area towards downstream in Tungabhadra River, the increasing spatial trend for wetted perimeter reflects the increasing irregularities along the channel bed possibly contributed by the channel bars. The longitudinal profile of Krishna is a typical convexo-concave, where different sections of the longitudinal profile show different concavities, and the knick points are correlated either with the NE-SW trending lineament/faults and/or with lithological margins.

A few reaches in Krishna and Tungabhadra rivers and nearby areas are highly prone to flooding (shown in the following figure) due to the characteristically lower slope and typical valley configuration as well as the hydraulic structures downstream. Among the different floods of high magnitude occurred in the KRB, only 2005, 2006 and 2009 floods are within the channel morphology assessment period, and the substantially high bank erosion rates during 2001-2011 can be correlated with the flood events. The changes in channel geometry due to the flood event occurred in 2009 are evident in many of the reaches, both in Krishna and Tungabhadra rivers, which were verified in the field also.



Flood affected areas of 2005, 2006 and 2009 flood events in KRB

The spatial pattern of the erosion patches along the regulated river reaches (e.g., KR_06, KR_08, KR_09, KR_13, KR_17, KR_19, and KR_21) suggests that the channel segment immediate downstream of the reservoirs show high erosion rates on both the banks. Hence, along with the critical reaches, the reaches that are characterized by localized erosion pockets (especially downstream of the hydraulic structures and along the channel bends), also need to be addressed for implementation of suitable conservation measures.

Based on the evidence of the study, reconnaissance survey and review of pertinent literature, the major river morphological problems in Krishna and Tungabhadra rivers were identified and listed as below:

- Erosion of river banks
- High magnitude, less frequent floods
- Flow regulation by vast numbers of water resources projects
- Modification of riparian vegetation
- Mining of fluvial sediments
- Farming along river bed as well as riparian zones and floodplains

The pressures related to the morphological alterations can be limited or can be overcome by implementing suitable river training works, and the major river training measures recommended for the restoration of critical river reaches include various structural (embankments, groynes or spurs, bed pitching and bank revetment, bank stabilization measures) as well as biological (e.g., vegetation development) measures. In the context of the findings of the present study, the following recommendations are recorded for sustainable management of the river resources of KRB.

- The major changes to the fluvial system (especially in the critical reaches) of Krishna and Tungabhadra rivers are caused by river regulations, water abstractions, modifications of river morphology as well as floodplain structure, creating different kinds of pressures, which needs to be restored using suitable river training works.
- Even though critical reaches have been identified on the basis of the total area of erosion occurring along the reach, many of the reaches have highly localized erosion pockets, which also need to be considered.
- River restoration protocols need to be developed on the basis of a holistic approach, which needs to cover the full range of physical conditions, morphological types, the degree of artificial alterations, and amount of channel adjustments. This also enables to understand cause-effect relationships between hydromorphological and biological indicators.

The present study recommends the following investigations, which are required to develop comprehensive river basin management plans for Krishna and Tungabhadra rivers.

- A detailed flood modeling study has to be carried out to understand the impacts of floods on the bank erosion as well as to understand the inundation in the downstream reaches, especially in the context of the changing climate.
- Since floods impacted the morphology of the rivers, detailed studies need to be conducted to assess the effects of integrated reservoir operations in flood management, and thereby river morphological stability.
- As the river segments support diverse aquatic fauna (e.g., Otter Conservation Reserve in Tungabhadra R.), detailed studies are required to understand the effects of morphological changes and hydrologic variability on the river biodiversity.

The present study has compiled/generated various types of spatial and attribute data for the Krishna and Tungabhadra rivers, and the details of the data inventory are given below:

Sl. No.	Data	Particulars
1.	Basin boundary	Boundary of the basin
2.	Major sub-basins	Boundary of the major sub-basins
3.	Drainage	Stream network
4.	Waterbody	Major reservoirs and river
5.	Major town	Location
6.	Airport	Location
7.	Transportation infrastructure	Road and rail network
8.	Hydraulic structure	Location and attributes of dam, barrage, anicut, and weir
9.	H.O. station	Location and attributes (e.g., gauge, discharge, sediment load, bed material size, and cross section)
10.	River cross section	Location and cross-section survey data
11.	River longitudinal profile	Location and survey data
12.	Land use/ land cover	Vegetation types
13.	Geology	Lithological types and major structures
14.	Digital elevation model	Elevation

Sl. No.	Data	Particulars
15.	Remote sensing data	Satellite images of Landsat 1 MSS, Landsat 2 MSS, Landsat 5 TM, Landsat 7 ETM^{+}, and IRS P6 LISS III
16.	Topographic maps	Survey of India maps (1:50,000 scale)
17.	Bank lines during different time periods (1973, 1977, 1991, 2001 and 2011)	Bank lines delineated from the multi-temporal remote sensing data
18.	Bank erosion and depositional areas during different time periods (1973, 1977, 1991, 2001 and 2011)	Bank erosion and deposition areas based on the analysis

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Acronym	Definition
APWRDC	Andhra Pradesh Water Resources Development Corporation
ASCE	American Society of Civil Engineers
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
B	Overall flow width
BEVI	Bank Erosion Vulnerability Index
bgl	below ground level
CCA	Cultivable Command Area
CEMC	Consultancy Evaluation-Cum-Monitoring Committee
CGWB	Central Ground Water Board
CV	Coefficient of Variation
CWC	Central Water Commission
D/s	Downstream
DEM	Digital Elevation Model
DMS	Degree Minute Second
DVP	Deccan Volcanic Province
EDC	Eastern Dharwar Craton
EGM96	Earth Gravitational Model 1996
EGMB	Eastern Ghats Mobile Belt
FRL	Full Reservoir Level
GCA	Gross Command Area
GCPs	Ground Control Points
GIS	Geographic Information System
GSC	Gross Storage Capacity
GSI	Geological Survey of India
H.O.	Hydrological Observation
IGBP	International Geosphere-Biosphere Programme
IMD	Indian Meteorological Department
InSAR	Interferometric Synthetic Aperture Radar
IRS	Indian Remote Sensing
KRB	Krishna River Basin
LCC	Lambert Conformal Conic
LSC	Live Storage Capacity
LUF	Local Uniform Flow

Acronym	**Definition**
MoU	Memorandum of Understanding
MoWR	Ministry of Water Resources
MSL	Mean Sea Level
MWL	Maximum Water Level
N	Number of braided channels
NGOs	Non-Governmental Organization
NRAA	National Rainfed Area Authority
NRSC	National Remote Sensing Centre
PFI	Plan Form Index
Qs	Sediment Discharge
Qw	Water Discharge
SoI	Survey of India
SSC	Suspended Sediment Concentration
T	Sum of flow top width of all the braided channels
TTG	Tonalite-Trondhjemite Gneiss
USGS	United States Geological Survey
WDC	Western Dharwar Craton
WGS84	World Geodetic System 1984
WHO	World Health Organization
WRIS	Water Resources Information System

H.O. Station Codes

K, T and B	Stations in the mainstream of Krishna, Tungabhadra and Bhima Rivers
KT, TT and BT	Stations in the tributaries of Krishna, Tungabhadra and Bhima Rivers

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SECTION 1
INTRODUCTION

1.1. Introduction

River systems are the most dynamic component of fluvial landscapes, which continuously interact with the atmosphere, lithosphere as well as the biosphere, thereby creating dynamic and diverse fluvial geomorphic forms and habitats, both in-stream and riparian and floodplain environments (Petts and Amoros, 1996). Although rivers are three-dimensional in shape, high spatial variability in channel morphology (e.g., cross-section shape, in-channel forms and channel slope) occurs along the river channels as the cross-sectional shape of the river channel at any given location depends on the flow, the quantity and character of the sediment in movement through the section, the character or composition of the materials making up the bed and banks of the channel and vegetation (Leopold et al., 1964). The river channels continuously shape and reform their channels at different time-scales also through erosion of the channel boundary and the reworking and deposition of sediments (Charlton, 2008). River morphology and morphodynamics are subject to governing conditions that include the volume and timing of water flows, the volume and calibre of sediment introduced into the river, in-channel wood debris, the nature of bed and bank materials and vegetation, and the geologic and topographic setting of the river, including landscape gradient, climate and human interference (Church, 2002; Buffington, 2012).

Since the channel morphology is sensitive to the water and sediment discharges, driving mechanisms promoting changes in magnitudes of water and sediment discharges, such as construction of hydraulic structures, modification of land use/land cover pattern of the catchment as well as climate change, play significant controls in the modification of the river channels (Leopold et al., 1964; Petts et al., 1989; Surian, 1999; Rinaldi, 2003; Gregory, 2006; Lane et al., 2007; Korhonen and Kuusisto, 2010; Comiti et al., 2011; Radoane et al., 2013; Abate et al., 2015; Morais et al., 2016; Joshi and Jun, 2017). Among the several external drivers affecting channel morphology, regional development activities (e.g., extraction of sand/gravel, infrastructure construction along the riverbank including river stabilization measures, artificial cutoffs, construction of bank revetments, regulation by dams and weirs, construction of artificial channels and alteration of land use/ land cover types) seriously affect the dynamic equilibrium of the river channels (Kesel, 2003; Surian and Rinaldi, 2003; Batalla et al., 2004; Wellmeyer et al., 2005). The magnitude of the changing inputs of water, sediment, and vegetation can bring forth a broad range of river responses over multiple time scales, where the channel response may range from the small-scale adjustment of channel characteristics (grain size, width, depth) to large-scale alteration of reach morphology and planform pattern.

The river reaches developed on alluvium adjust their boundaries by erosion, transfer, and deposition of sediment to approach a state of equilibrium, and hence remains stable in average dimensions (or the channel is in regime). The rivers achieve a regime condition by the adjustment of grain size of the sediments exposed on the bed surface (by size preferred erosion or deposition), or of the dimensions of labile primary bedforms (such as sand dunes), adjustment of channel width by bank erosion or sediment deposition in bars, adjustment of channel macro-form elements, that is, the development of pools, riffles, and bars, or assumption of a meandered habit, and adjustment of the mean gradient of the river by net degradation or aggradation, so that the excess energy is being consumed in overcoming resistance to flow. The adjustment of channel width by bank erosion and sediment deposition affects the aspect ratio of the channel which, in turn, affects the bed material transport because it affects the force imposed on the bed by the flow (Eaton et al. 2004; Church, 2015). Even though width may also change within the period of a flood, but more commonly changes through a sequence of floods. In general, bank erosion of river channels is being promoted by two different, but interrelated processes, such as mass wasting (including various types of slides and slab failures) and fluvial processes (Thorne 1982; ASCE, 1998). However, the extent and nature of bank erosion depend predominantly on the force exerted on the bank material by flood flow as well as the resistance of the bank material (Knighton, 1984). River channel systems exhibit enormous variability, arising mainly due to the spatial heterogeneity in the fluvial and mass wasting processes operating at a wide range of spatial and temporal scales, results in highly variable rates of bank erosion as well as deposition, and thereby complex patterns of planform evolution. Hence systematic and periodic assessment of changes in the channel morphology can help delineate the issues associated with channel instability caused by bank erosion and deposition processes. Understanding the nature, rates, and causes of the changes in channel geometry and morphology have thereof significant importance to river corridor management and hazard zoning (Gilvear et al., 1999). Further, the spatiotemporal assessment of channel morphology facilitates an understanding of the sensitivity of river channels to the changes in the natural as well as anthropogenic drivers, which serves as a guidance for the river engineers for the management and restoration of the critical river reaches (Surian and Rinaldi, 2003; Brierley et al., 2008; Downs et al., 2013).

Hence, an understanding of the changes in channel morphology across different timelines can help identify the environmental changes responsible for the changes of the river channels, which may be useful to develop sustainable river management plans and restoration measures. Over the past decades, considerable interest in this topic has grown exponentially mainly as a result of the increasing focus on the importance of the physical habitats created by the fluvial processes, the ecosystem services provided by river systems, the conservation values within them, the concerns raised by flooding and its socio-economic implications, as well as the environmental legislation that has spurred greater interdisciplinary collaboration amongst physical and biological scientists studying riverine ecosystems and watershed processes. Common approaches of monitoring of channel morphology document the changes in the channel planform and morphological units in two different ways, viz., broad-scale remote sensing (e.g., repeated aerial photography and satellite imagery) that typically provides fairly good resolution of channel features or (ii) small-scale, long-term monitoring that provides more detailed information, but only at individual cross-sections or reaches on the order of tens of channel widths in length. Hence, the approach for the morphological investigation strongly depends on the spatial as well as temporal scales of the study. However, most of the channel morphological investigations, nowadays, heavily depend on current and archival remote sensing data (of varying resolutions) for channel morphology data collection, and GIS platforms for integrating and analyzing the information collected (refer review of literature).

1.2. Background for the study

Post-independence period of Indian history witnessed rapid urbanization, development of industrial and power generation sectors, intensification of agriculture, which induced construction of several multi-purpose reservoirs, alteration of riparian belts and floodplains, changes in land use/land cover types and modification of topography, which all together detrimentally affected the catchments and their river channels (Smakhtin and Anputhas, 2009). As a result, large areas of the country are negatively affected by the fluvial processes causing severe damage to life and property, despite the countermeasures implemented both by Central and different State Governments. Hence, the Ministry of Water Resources, Government of India commenced comprehensive river morphological studies to understand the behavior of the major river systems of India and to evolve effective strategies to overcome the problems through the implementation of suitable river training works. During the 11th Plan period, morphological study of three rivers, viz., Ghaghra, Sutluj and Gandak using remote sensing technology was completed, and later during 12th Plan period, the study has been extended to fifteen more river basins, such as Ganga, Sharda, Rapti, Kosi, Bagmati, Yamuna, Brahmaputra, Subansiri, Pagladiya, Krishna, Tungabhadra, Mahananda, Mahanadi, Hoogli and Tapti (MoWR, 2016).

As part of the formulation of sustainable comprehensive river management plans, Central Water Commission (CWC) called for the morphological studies on various rivers of India using remote sensing techniques. In this connection, CWC approached the Indian Institute of Technology/National Institute of Technology (IIT/NITs) to carry out the above studies. In the first meeting of “Consultancy Evaluation-Cum-Monitoring Committee (CEMC)” with IIT/NITs, the objectives and detailed scope of works were finalized. Accordingly, IIT/NITs were requested to submit their consultancy proposals. In response, IIT Madras submitted the consultancy proposal for morphological studies of Krishna and Tungabhadra Rivers using remote sensing technique.

1.3. Objectives

The specific objectives of the present study are:

i. Compile complete river drainage map in Geographic Information System (GIS) by integrating available secondary maps in India Water Resources Information System (India WRIS) of CWC.

Collect additional required information on major flood protection structures, existing water resources projects, important cities/towns, CWC Hydrological Observation (H.O.) stations, airports, islands etc., and to be integrated with the final river drainage maps.

ii. Study shifting of river course and also changes in its plan form from the base year (say 1970) till 2010, by collecting four sets of satellite imageries at 10 years interval in addition to one set of Survey of India (SoI) toposheets for the base year on a scale of 1:50,000. In case toposheets are available for the older period, say 1950, the base year may be shifted accordingly.

iii. Compile changes in land use/land cover, and study of its impacts on river morphology.

iv. Channel evolution analysis to describe the status of the river channel. The analysis of the channel dimension, pattern and longitudinal profile identifying distinct river reaches i.e. channel in upper reaches, channel in flood plain with bank erosion etc. This segregation of the reaches is to be determined by using channel evolution analysis.

v. Work out the rate of bank erosion/deposition in term of erosion length and erosion area with respect to a base year at 50 km interval.

vi. Assess the present condition of critical reaches of the main channel of the river by conducting ground reconnaissance. Field reconnaissance trips may be taken, if required.

vii. Evaluate the impacts of major hydraulic structures on morphological behavior of the river course and its impacts on river morphology.

viii. Evaluate the braiding pattern of the river by using Plan Form Index (PFI) criteria along with its threshold classifications.

ix. Compile information (if any) on flood-affected areas in the vicinity of river course prepared by National Remote Sensing Centre (NRSC) using multi-temporal satellite data of IRS WiFS (188 m) & Radarsat Scan SAR Wide & Narrow (100 m & 50 m) for flood images.

x. Plot probability curve (exceedance probability vs. flow rate) and show flow rates corresponding to the return periods of 1.5 and 2 years for different CWC H.O. locations. The observed flows need to be normalized before using for analysis.

xi. Relate the morphological changes in the river on the basis of available peak discharges of different years in the time domain considered in this study. Study impact of changes in annual rainfall in the basin on river morphology.

xii. Identify critical and other vulnerable reaches, locations. Analysis of respective rate of river course shifting and based on it, future prediction of river course behaviors.

xiii. Suggest suitable river training works for restoration of critical reaches depending on site conditions.

1.4. Detailed scope of the study

i. The required inventory of one set of SoI toposheets in respect of reference time datum on a scale of 1:50,000 is to be procured from SoI by the consultant. The inventory of satellite imageries having a spatial resolution of 23.5 m, IRS LISS-I, LISS-II, LISS-III may be worked out covering the study area, and to be procured from NRSC.

ii. One set of SOI toposheets (say the year 1970) and digital satellite imageries of IRS LISS-I, LISS-II and LISS-III sensors, comprising scenes for the years 1980, 1990, 2000 and 2010 are to be used for the present study. In case of non-availability of the above data, the foreign satellite data of similar resolution may also be used. The maps and imagery are registered and geo-referenced with respect to SoI (1: 50,000 scale) toposheets with respect to base year by using standard techniques in GIS.

iii. Delineation of river bank line, river centre line along with generation of important GIS layers of river banks, major hydraulic structures, embankments/levees, railway bridge line, island, airport, cities/towns/villages and important monuments etc. located in the vicinity of river banks for the selected years of the studies are to be part of studies.

iv. Estimation of left and right bank shifting amount(s) with respect to the base year and appropriate graphical plotting of these shifting.

v. Evaluation of braiding of different river course reaches by using PFI criteria along with its threshold classification, wherever required.

vi. Estimation and comparison of each bank erosion for different reaches in term of erosion length & erosion area of the river with respect to base year by using appropriate GIS tool, accordingly vulnerability index for different reaches may be evolved & prioritized along with causative factors detail for this erosion may be worked out.

vii. Comparison of delineated different river courses on the same graphical plot on A0 size and all plots may be arranged in a separate volume.

viii. The most critical reaches may be shown separately with appropriate suitable stream reach(s) restoration with a recommendation of suitable bank stabilization technique(s) depending upon the channel planform and condition.

ix. The cross-section data available may be used for identifying riffle locations and measure topography changes. The cross-sectional data provided may be used to extract necessary information to analyze the channel, which ultimately led to identifying the channel stage or condition.

x. The plan view of various stream patterns may be used to define the geometric relationship that may be quantitatively defined through measurement of meander wavelength, radius of curvature, amplitude, and belt width. It may be done by separating river reaches based on the change in valley slopes into different RDs, estimation of sinuosity, numbers of bends for different RDs, average radius of curvature for each segment of the rivers defined. Based on this channel pattern analysis, proper interpretation may be given.

xi. River channel dimension: river channel width and the representative cross-section are a function of the channel hydrograph, suspended sediments, bed load, and bank materials, etc. The future river channel dimensions may be evaluated based on the available cross-section detail for vulnerable/critical reaches of the rivers.

xii. Maximum flow probability curves at CWC H.O. sites located on the river concerned may be developed to predict the channel discharge corresponding to 1.5 year and 2 year return interval (RI). These values i.e., 2 year RI is widely accepted as the "channel forming discharge" or "bankfull". These are the flows that contribute most to the channel dimension. These parameters may be used to determine the channel evolution stage based on the channel evolution analysis. Comparison of the channel forming discharge and the maximum channel capacity may be done, accordingly interpretation about the channel carrying capacity is to be presented.

xiii. Channel profile: channel profile is commonly referred to as channel slope or gradient. The channel profile may be developed for river reach under consideration. The proper interpretation with respect to bed formations, aggradation, degradation etc. may be made part of studies.

xiv. Impaired stream analysis: as part of the scope of work, part of impaired streams to be identified along with the causes and sources by the consultant. Based on the causes of stream impairment, stream restoration mechanism/methods to be recommended. While stream restoration and bank stabilization techniques do improve water quality, land use practices may also be discussed, which is typically the main culprit of chemical pollution.

xv. Results and recommendations are to be separate chapters. A proper discussion about results in respect of different reaches, i.e., upper reach, middle reach & lower reach of the river along with appropriate suggestions to be given.

xvi. Collection of additional information like topography, climate, soils, geology, and hydrology etc. required to be incorporated in the morphological report.

xvii. Analysis of shifting of left and right banks of the rivers at about 50 km interval as well as covering critical reaches of the river irrespective of river RDs interval.

xviii. Identification of flood-affected areas in the vicinity of river course which have experienced frequent flooding in the past and suggesting suitable remedial measures for flood proofing for the river reaches. It was informed by NRSC representatives that NRSC derived inundation from 10 years of multi-temporal satellite data (1998-2007). Based on the frequency and extent of inundation, the flood hazard is categorized into five classes - very high, high, moderate, low and very low. This helps the concerned authorities in planning developmental works in these areas. NRSC used multi-temporal satellite data of IRS WiFS (188 m) & Radarsat Scan SAR Wide & Narrow (100 m & 50 m) for flood images. It includes complete flood hazard statistics district wise. This published information can be utilized by IIT Madras to cover flood-affected aspects in the study.

xix. The entire satellite data used in the study by the IIT Madras, all analysis, results, maps, charts etc. and the subsequent report prepared shall be the exclusive property of CWC and the IIT Madras has no right whatsoever to divulge the information/data to others without the specific written permission of CWC.

xx. In order to ensure the desired quality of the generated outputs as well as to ensure that the GIS layers are hydrologically, hydraulically, and scientifically reasonable approximations. It was decided that the standards used for WRIS, as well as “standards for geomorphological mapping project” and “standards for land degradation mapping project” given in manuals of NRSC may be referred.

xxi. The compilation of changes in land use/land cover, and study of its impact on river morphology is to be incorporated in the study report. The NRSC’s published information about land use and land cover maps under NRSC Bhuvan thematic service on a scale of 1:50,000 as well as 1:2,50,000 for all states can be used for this purpose.

SECTION 2
REVIEW OF LITERATURE

2.1. General

Alluvial rivers are one of the most dynamic landforms subject to rapid morphological changes, which are predominantly sensitive to the fluctuations in water and sediment discharges. Short-term morphological changes mostly reflect the channel response to a specific extreme event, whilst long-term changes occur over a sequence of such events. Even though channel morphology is largely affected by the changes in hydrological balance, stream runoff and sediment load, which in turn reflect the changes in climate and/or land use, active tectonics also holds a significant control over the changes in channel morphology, which can easily be recognized (Gurnell and Petts, 1995; Schumm and Winkley, 1994; Rosgen, 1996).

Numerous techniques and methods have been applied for monitoring and document the changes in channel morphology. A detailed review of the various techniques, which have been used for the measurement of riverbank erosion and channel change is available in Lawler (1993), in which the techniques were classified according to the time scales involved (long, intermediate and short). Among the different approaches, use of sequential satellite imageries is being used to detect lateral channel change, especially for large systems, for detecting low-resolution channel change over long time periods (10-100 years). Despite the many shortcomings, such as the assumption of continuity and/or linearity in channel change over the time period, representativeness of temporal sampling, change of channel definition over time etc., recent channel morphological studies show heavy dependence on current and archival remote sensing data (of varying resolutions) for data collection. Interestingly, the lacuna in the availability of serial satellite images has been abridged by the advent of satellite data repositories and user interfaces for searching and downloading the data. What follows is a brief review on the relevant (selected) literature on the application of remote sensing and geoformation tools for the assessment of channel morphology of alluvial rivers in the global as well as regional context.

2.2. International scenario

Karwan et al (2001) analyzed the near stream land use changes and river channel morphology in the Venezuelan Andes, Jawra using aerial photographs and Landsat TM images. The results brought out the human impacts on river channels through a comparison of multiple watersheds over a 35-year time interval. Change in river channel morphology was observed to be greatest at the most deforested sites. Valley shape and channel constraint were also found to have a discernible effect on change in channel morphology.

Rinaldi (2003) investigated the channel adjustments in alluvial rivers of Tuscany, Central Italy using aerial photographs in the scale 1:30000 to 1:33000, orthophoto maps in the scale of 1:10000. He observed that a significant acceleration of channel incision occurred during the period 1945–80, in concomitance with the maximum sediment mining activity at a regional scale. Other human disturbances contributing to channel instability are discussed like reduction in sediment supply due to the construction of hydraulic structures and reforestation. Regional distribution of vertical adjustments does not show clear spatial trends since upstream migration has often been prevented by the presence of bedrock gorges. Channel narrowing represented a second major type of adjustment and occurred simultaneously or following bed-level lowering along most of the reaches analyzed.

Uribelarrea et al (2003) observed the changes in channel morphology of the Jarama and Tagus rivers (central Spain) over the past 500 years. The main mechanism of change observed for the Tagus has been meander cut-off during flood stages. In contrast, the Jarama, which flows through a steeper valley, has experienced not only cut-offs but also the growth and movement of bars, channel shifting, and even small avulsions. The river system was found to be severely altered by human intervention through flow regulation after 1956 and by gravel mining after the 1960s.

Chu et al (2006) discussed the changing pattern of erosion deposition patterns of the modern Yellow River subaerial delta, China, based multi-temporal remote sensing data of Landsat MSS and TM and sediment discharge data. The factors affecting the pattern of erosion and accretion over the Yellow River delta are found to be structural geology, sediment discharge, coastal processes, meteorological conditions, human activity, sea level rise, and land subsidence. The cumulative area of increase over the entire subaerial delta is closely correlated with the cumulative Yellow River sediment discharge. Wave-induced longshore current is the major driving force to transport sediment from eroded areas along the last two abandoned promontories, Diaokou and Shenxiangou promontories, are observed mostly westerly and partially easterly. Together with these coastal processes is the geographical shift of the Yellow River course associated with its discharge regime after 1976, leading to the accretion along the present Qingshuigou Promontory and then the Q8 Promontory.

Evans et al (2007) observed the upstream channel changes following dam construction and removal in Huron River, Ohio using a GIS and remote sensing approach. The pre-dam condition of the Huron River through the study area consisted of alternating sedimentation and erosion zones, similar to many natural rivers observed elsewhere. The downstream migration of these sedimentation and erosion zones over time was interpreted as the downstream translation of a sediment wave. The construction of the dam reduced the gradients and decreased the transport capacity upstream of the reservoir, resulting in no net downstream translation of the sediment wave. The sediment wave subsequently attenuated in situ by dispersion in response to the erosion of the upstream reaches and deposition into the new reservoir. Shifting of sediment downstream was marked by local episodes of bar growth, which increased the thalweg-path distance between the bedform centroids and a fixed point downstream. Removal of the dam in 2002 rejuvenated translation of sediment waves through the study reach. The downstream shift of sedimentation and erosion zones cut chutes and eroded the inner-bank margin of bars, resulting in a downstream shift in bedform centroids with respect to thalweg-path distance to a fixed point downstream

Hooke (2007) observed the spatial variability, mechanisms, and propagation of change in River Dane, New Zealand which is an active meandering one. The middle part of the River Dane showed high rates and frequencies of erosional and depositional activity and large lateral mobility in parts of the channel, particularly on the highly curved, free bends. There is no definite evidence of such effects that have been found to detect propagation of change into these reaches, particularly for the progressive movement of bars or sediment waves downstream. It is concluded that the within-channel changes are mostly localized and produce an overall movement of planform in the bend. This may eventually have a knock-on effect downstream by the alteration of the curvature, except where barrier reaches of various kinds exist. Investigation of the mechanisms at the conjunction of high mobility and stable reaches has shown that the active channels upstream of these barrier reaches tend to exhibit an oscillation of behavior, with sequences of widening and narrowing within a period of a few years that absorb the changes and produce net lateral movement.

Kummu et al (2008) used SPOT5 satellite images, aerial photographs and field survey data with a resolution of 2.5m in natural colors to assess the riverbank changes of the Mekong River in Thailand. Bank erosion and accretion rates were analyzed for two-time periods 1961-1992 and 1992-2005, which revealed the high erosion vulnerability of the river islands compared to the stream bank erosion. The quantified annual stream bank erosion rates were 0.8 and 1.0 m for the two-time periods respectively, while the global average for the rivers of similar size is of about 12.1 m. The dominant drivers of the river bank erosion were the construction interventions and possible sediment concentrations.

Ayalew (2009) analyzed the effects of historical and recent floods on channel pattern and the environment in the Lower Omo basin of Ethiopia using satellite images and GIS. SPOT4 images were used to delineate the river channel during the dry period when the volume of discharge was low, SPOT5 images were used to extract flood-affected areas and IKONOS to supplement the effort of defining the water–land boundary. A large flood occurred in 2006 which is found to have lasted long to incur environmental effects but, not initiated major changes in channel pattern. Hence, many of the adjustments were only in the form of minor increments in channel width and meander-bend amplitudes. However, the sediment load of the river had observed to be increased at the time of flooding because of the erosion of highly denude catchments. Images taken after the flood showed the accumulation of sediments in the lower part of the meander belt. It was also concluded that the inability of the Omo River to transport the sediments down to the delta area leaded to instability or channel pattern adjustment as excessive deposition causes the river bed to rise and in addition, as a sign of channel shortening, the river had breached its levees in the middle part of the meander belt, which has led to a change in meander geometry in the long feature.

Surian et al (2009) investigated the morphological effects of the different channel-forming discharges in Tagliamento River, Italy which is a gravel bed river by studying aerial photographs and conducting cross-section survey, grain-size analysis, and observation of painted sediments. Substantial morphological changes, e.g. bank erosion of several tens of meters up to more than 100 m, associated with flood events with recurrence interval between 1·1 year and 12 years have been found in the study. Discharges equal to 20– 50% of the bankfull discharge are found formative for the channels, whereas the bankfull discharge (1·1 year flood) is found formative for low bars in the case of the Tagliamento River. Larger floods, with a recurrence interval less than five years, are found required for full gravel transport on high bars and significant morphological changes of islands.

Ronco et al (2010) investigated the effects of dams on the morphology Zambezi River, Africa, with the aid of LANDSAT MSS, TM, ETM+ imageries. A simplified one-dimensional morphodynamic model, based on the LUF (Local Uniform Flow) hypothesis, was used for the study. It was observed that during the last and the next centuries the largest part of lower Zambezi in undisturbed conditions showed continuous and almost constant bottom aggradation and sediment fining. This trend is affected by the construction of the Kariba (1959) and Cahora Bassa (1975) dams, but only in a relatively minor way. The perturbations created by the impoundments, respectively in terms of water flow and sediment interception, appear to propagate along the river with different celebrities and with different consequences on the bottom profile and composition. The construction of dams has apparently produced an erosion of the delta area, which seems however somewhat recovering

Ahmed & Fawzi (2011) assessed the meandering and bank erosion of the River Nile and its environmental impact on the area between Sohag and El-Minia using field observations, Landsat MSS (Multi-Spectral Scanner), Landsat Thematic Mapper (TM), and Enhanced Thematic Mapper (ETM+) images. The processes of erosion and sedimentation are found to be in a dynamic state along the River Nile and its islands. Since completion of the High Aswan Dam, no sediment has been released downstream from the dam and the river discharge is also found very different from before. It was observed that The River Nile is moving towards a new equilibrium which may result in problems of degradation, bank stability, navigation, and erosion of urban areas and islands. The construction of the High Dam resulted in considerable changes to the flow characteristics of the Nile downstream of Aswan. Prior to the construction of the High Dam, the peak flow sometimes overtopped the river bank. The morphology of the channel began responding and is continuing to change. The present conditions of erosion and deposition of river meandering are being accelerated with human activities which proved its impact on the environment.

Segura-Beltran and Sanchis-Ibor (2013) analyzed the morphological changes during the last six decades for a 16.5 km reach of the Rambla de Cervera, a Mediterranean ephemeral stream located in Eastern Spain. Aerial photographs, orthophotos, and topographical surveys of different time periods were used to analyze the channel changes. The study indicated that the gravel channel underwent a general decline by losing the width and surface area due to the anthropogenic activities. The morphological changes in the channel exhibited temporal variability, with maximum decrease observed during 1946-1956 periods followed by 1977-1991 period. The other periods exhibited a mixed performance. The study concluded that the natural and human-induced factors producing contradictory effects are considered responsible for changes in the Ramble de Cervera channel.

Wang et al (2013) investigated the long-term morphological change and equilibrium state of the Changjiang (Yangtze) Estuary, China during the period 1842–2006 using river discharge and sediment flux data, nautical charts. Channel areas, which have lower aspect ratios and display minimum movement distance in their thalwegs, are found to be most stable. This is because narrow and deeper channels exert the least hydrodynamic resistance to the flow. The geomorphological changes are found to be strongly controlled by external conditions, including river and sediment discharges, which govern the localized erosion and accretion in the estuary, and tide and Coriolis force, which influence the direction of channel extension. Human influence within the estuary could have a significant impact on the overall estuarine geomorphology, especially when the activities are at particular locations in the estuary, which influence the sediment and river flow transportation.

Rozo et al (2014) analyzed the planform changes in the upper Amazon River over the period of 1986-2006 using remote sensing techniques. The study applied remote sensing image processing techniques applied to Landsat images acquired in 1986, 1994, 2001, and, 2006. The images were selected based on minimum daily water level variations while providing the widest temporal scan. The study reported that the river system had depositional tendencies between 1986 and 2006, with a period where erosion was more intense than deposition between 1994 and 2001. The analysis yielded a migration rate of 125 m/yr for the river system. The remote sensing analysis indicated that the depositions and erosion dynamics are more influenced by the temporal variations of the discharge.

Brunier et al (2014) studied the morphological changes in the Mekong and Bassac River, China and the marked impact of river-bed mining and implications for delta destabilization in the Mekong Delta using channel datasets. The channel beds of the Mekong and the Bassac showed significant and widespread deepening between 1998 and 2008, with a massive loss of bed material in both channels which is due to essentially large-scale river-bed sand mining. The numerous dykes and embankments constructed over the last two decades have also been found contributed to channel deepening.

Clerici et.al (2015) conducted a study on the morphological changes in the flood plain reach of the Taro River, Northern Italy in the last two centuries. The analysis revealed continuous reduction in channel width, at a variable rate, a reduction in braiding and an increase in sinuosity, at least until the end of the 20th century which is largely due to the recurrent subtraction of river areas to be used for agricultural and industrial purposes, and due to the construction of as many as 10 bridges, with their up and down-stream bank protections. Mining seems to have provoked a sharp incision and – only partially – a narrowing. It was also found that the morphological changes associated to the possible reduction in the flow regime shown by the sporadic and discontinuous hydrological data, can be considered negligible if compared with the significant changes due to human activity.

Petropoulos et al (2015) mapped the spatiotemporal changes of erosion and depositions in the two river deltas in Greece. The study used Landsat images over a 25 year period of 1984-2009 and direct photo-interpretation methodology is adopted. The study observed noticeable changes in both the rivers with erosion occurring mostly in earlier time periods (1999-2003) and deposition in more recent years (2003-2009). The degradation in the last 25 years is seen to primarily a result of decreased discharges and disrupted sediment dynamics due to extensive river regulation and irrigation.

Balaban et al (2015) developed a GIS-based method for evaluating sediment storage and transport in Pilcomayo River, Bolivia, which is a large mining-affected river system with the aid of Google earth, world imagery, and elevation data. The portion of the channel from Villamontes to D'Orbigny is found to account for more than half of the total c. 314 km^2 sedimentation area of the Pilcomayo in Bolivia, and also, the most environmentally problematic area is centered around Puente Sucre, where agriculture is practiced on the contaminated floodplain. The study brought out that, combined with supplementary bathymetric data on the depth of the river in various points around the channel, the method could offer further insight into the sediment fluxes and transport capacity of the Pilcomayo in various sectors and could thus be successfully used to assess other large mining-contaminated river channels around the world.

Abate et al (2015) studied the morphological changes in Gumara River channel over 50 years. The data used were SPOT images, aerial photographs (1:50000), Google maps, rainfall, streamflow, multiple river cross section etc. The overall analysis showed that the changes to Gumara River channel characteristics in the alluvial plain are linked to human-induced modifications in the upper catchment, in the river corridor, and on lake levels. Gumara River is a single thread meandering river and the study showed that its planform changes are very slow: minor channel narrowing and shifting of banks were observed. The overall sinuosity analysis showed that the considered reaches of the river have undergone little changes to the position of the meanders. The comparison of cross-sections through time illustrated that the vertical morphological changing process is very active: in-channel deposition (2.91 m) and streambank erosion. The observations at the sand mining sites also suggested that the river underwent bed aggradation and the anthropogenic activities along the banks of the river have facilitated bed deposition. Substantial deposition on the river banks is observed, in the floodplain as well as in the river bed.

Luan et al (2016) analyzed the morphological evolution of the Yangtze Estuary, China, in response to river input changes and estuarine engineering projects using annual water and suspended sediment discharge, the peak flood discharge, peak monthly flood, seasonal mean suspended sediment concentration (SSC) of the flood season, navigational charts and bathymetric maps (1958-2010). It was found that the river flood events played an important role in the decadal morphological evolution of the Yangtze Estuary. The sustained accretion rate in the mouth bar area was mainly attributed to engineering works, such as groins and breakwaters. The impact of estuarine engineering projects on morphological change was found to be extended beyond their given construction sites. Their findings suggested that the predominant control on the decadal morphological evolution of the Yangtze Estuary is currently shifting from natural processes to human interferences. The study also said that human activities in both the Yangtze River Basin and its estuary will most likely increase in the coming decades, and are expected to further complicate the morphological evolution of the estuary.

Yousefi et al (2016) investigated the changes in morphometric parameters of Karoon River, Iran using TM and ETM+ images, topography and geology map, active channel plan etc. It was observed that sand mining has a significant role in decreasing the flow length by increasing the probability of cutoff events. The study also brought out that dam building (discharge controlling) and land use change (removal of the riparian vegetation) have an important role in decreasing channel width in the study reach of the Karoon River.

Morais et al (2016) conducted a study on the spatial as well as temporal variations in the channel morphology induce by cumulative factors in the lower Peixe River, Brazil which is a meandering river. Aerial photographs (1:25000, 1:20000, 1:35000), aerial Maps (1:50000) and CBERS 2/HRC images (1:13500) are used for the study. A sharp decrease is observed in sinuosity between 1962 and 2008 in all reaches which implies that an adjustment of the channel and meander bend parameters leading to fewer, larger meanders and a simplified planform, accomplished by bend cutoff. Overall, evaluated parameters demonstrated that channel changes took place from downstream to upstream reaches. The fluvial dynamics of the alluvial segment in which the study reaches are located are subject to cumulative anthropogenic factors. Land use changes and an upstream reservoir are interpreted to be potential causes of the adjustment in the Peixe River observed during the study period. The creation of the downstream reservoir on the Paraná River resulted in the loss of a more mobile reach and consequently reduced the wetlands formed by fluvial dynamics.

Depret et al (2017) studied the causes of planform stability of Cher River, France, a low-energy meandering gravel-bed. The investigations have demonstrated the intrinsic capacity of the meanders to erode their alluvial deposits and the frequent mobilization of the entire particle-size distribution of the surface of the bed and highlighted a high density of engineering structures in the riverbed. For these reasons, the limited mobility of the meanders, confirmed by the diachronic analysis of planform of the river between 1830 and 2005, was explained primarily by the constraints exerted by these structures.

Spiekermann et al (2017) studied the stream bank erosion of 5 different river reaches, ranging from 3 to 14 km in length, in the Kaipara Catchment, Northland, New Zealand. Historic aerial survey photographs along with LiDAR images were used to collect data on the bank erosion rates from the 5 rivers. The changing river channel planform between the 1950s and 2015 was assessed using four to five well-spaced dates of the historical aerial photographs, and also the changes in the erosional activity over time and net change is estimated in the study. The results indicate that the migration rates in channel widths for large rivers (stream order 5-6) range between 0.4% and 0.8% of channel width per year. While the smaller streams are retreating more rapidly, with width averaged rates of 1.7% and 3.0%. The authors also concluded that the use of aerial photography and remote sensing is well suited for generating data on river bank erosion and analyzing the behavior of migrating streams and rivers over multi-decadal time scales.

Lauer et al (2017) studied the changes in the channel width in the Minnesota River basin. Aerial photograph-based measurements of the channel width were made for the 1938-2015 period at 16 multi-bend sub reaches by digitizing the area between vegetation lines and dividing by center line lengths. Results show considerable increases in width for the main stem and major tributaries but are inconclusive for smaller channels. Digital elevation model (DEM) analysis and regional hydraulic geometry show that the main stem and larger tributaries account for the majority of the bankfull channel volume. High-order channels are thus disproportionately responsible for sediment production through cross section enlargement, although floodplains or off-channel water bodies adjacent to these channels likely represent important sediment sinks.

Dewan et al (2017) used Landsat images to assess the changes in the channel morphology of the Ganges-Padma river system in Bangladesh. The study analyzed the changes in channel morphology over the period 1973 to 2011 using multi-temporal Landsat images and long-term flow data. The catchment area of the Ganga-Padma river basin is about 1.6 million km^2, with an average width of river 3.23 km and the analyzed reach had a length of 314 km. The analysis indicated that about 57 km^2 of land was lost on the right bank whereas 59 km^2 has been gained along the left bank during the assessment period. The study further concluded that the mean annual bank movement of the river was highly temporally variable and erratic.

2.3. Regional applications

In India, most of the studies related to fluvial geomorphology have been carried out on the Himalayan Rivers, where numerous research works are available on different aspects in river channel morphology as well as the controls exerted by various fluvial-hydrologic-processes, especially floods, and the geomorphic implications of regional tectonics. On the contrary, there exists a severe dearth of information on fluvial geomorphology of the rivers of Peninsular India.

Goswami (1999) investigated the bank line migration of the Subansiri River in Assam, for a period of 50 years (1920-1970) using topographic maps, aerial photographs, and satellite imageries. It was observed that the high discharge of sediment load has promoted the formation of mid-channel bars leading to obstruction of the flow resulting in bank erosion. In addition to this, the gradual increase in the channel slope has led to a change of channel pattern from meandering to braided over the time span of 50 years.

Among the various literature available on the fluvial geomorphology of the Indian Rivers, the attempt made by Kale (2002) is unequivocal, because the review not only demonstrated the rich fluvial diversity of the Indian region but has also shown a number of gaps in the fluvial research with unique features and process dynamics. Further, the study also urges to initiate in-depth studies for improving the understanding of the modes of meander development, channel migration, avulsion and mechanisms of bank erosion, with predictive capabilities as well as for developing deterministic equations for prediction of bed and bank erosion, and bedload transport. Later, in 2003, Kale also observed that the geomorphic effects of floods are most impressive only in the Himalaya, the Thar Desert, and the Indus-Ganga-Brahmaputra Plains, where flood-induced changes in the channel dimension, position and pattern are prominent. According to the observations of the study, the annual floods appear to be geomorphologically more effective than the occasional large floods in the Ganga-Brahmaputra Plains, whereas the geomorphic effects of floods on the rivers of the Indian Peninsula are modest.

Mani (2003) investigated the bank erosion and deposition pattern in Majuli island situated in the middle of river Brahmaputra in Assam, occurring by the erratic nature of the river using toposheets, IRS 1A LISS-II and LISS III images for a period of seven years (1991-1998). Erosion and deposition trends are analyzed by considering sections at 1 km interval in a north-south direction along the river reach flowing in an east-west direction. It was observed that both the river banks have eroded severely during the period 1991 to 1997. But, comparatively less erosion was observed during 1997-1998, though there had been a flood in 1998, which is interpreted as the result of bamboo protection provided at both the banks by the locals and NGOs.

Jain and Sinha (2004) studied channel morphology of an anabranching segment of the Baghmati River using hydrological data as well as the toposheets of 1924 (1:253,440), 1959–1975 (1:50,000) and 1986 (1:250,000) and remote sensing data (IRS LISS-II of the pre-monsoon period of 1989 and 2000). The observations suggest that the development of anabranches is related to rapid and frequent avulsions of the river channels with eight major avulsions observed in the 30-km-wide floodplain in the last 230 years, and the major causative factors for such channel instability are sedimentological readjustments and active regional tectonics.

Sarma (2005) conducted a comprehensive study on the fluvial processes and morphological aspects of the Brahmaputra River within Assam using the hydrological and hydro-meteorological data along with remote sensing data of different years. According to the study, the banks were migrated due to erosion and deposition processes, and hardly any definite trend of migration is observed of the banks of the braided reaches, whereas the migration of banks in the single channel nodes is unidirectional. Significant changes in the channel course have been reported in the past and observed during the study, mainly due to avulsion, and the rate of erosion of the banks was more during the period from 1912-1928 to 1963-1975, as compared to a later period from 1963-1975 to 1996. It was also observed that the unpredictable and frequent migration of the channel is predominantly due to a decrease in channel slope along with high sediment input into the river.

Sinha et al. (2005) characterized the rivers draining the Gangetic alluvial plains in terms of hydrological and sediment transport characteristics, which in turn reflected in the geomorphic diversity. The study made use of the Indian Remote Sensing satellite images (LISS III sensor with 23.5 m spatial resolution) and 1:50,000 scale topographic sheets coupled with field observations. The study characterized the Western Gangetic Plains (by a degradational topography with incised channels and extensive badland development in some parts) and the Eastern Gangetic Plains (by shallow, aggrading channels with frequent avulsions and extensive flooding) based on the stream power and sediment supply from the catchment areas, and the variability between them has arisen due to the differences in rainfall and rate of uplift in the hinterland.

Das (2007) analyzed the trend of morphological changes in the Barak River in North East India, by considering four different blocks along the river where changes have been detected prominently. For this study, data of six different years have been considered such as toposheets, Landsat MSS, TM, and IRS LISS-II images, and reported intense shift of the river towards northward direction due to the uplift of the southern part of the river valley.

Takagi et al. (2007) analyzed the spatiotemporal changes in channel (1967-2002) of the Brahmaputra River, Bangladesh, using satellite images and GIS and classified the study period into four different stages, viz., 1) the late 1960s to early 1970s, 2) the mid-1970s to early 1980s, 3) the mid-1980s to early 1990s, and 4) the mid-1990s to early 2000s, based on the river conditions. Among the different phases, 1 and 3 are transitional phases characterized by complex conditions, whereas 4 is characterized by much less complexity, which implies a state of dynamic equilibrium.

Hazarika et al. (2012) studied the temporal changes in the channel plan form, migration of the channel banks as well as land-use changes (in the floodplain) driven by river dynamics along two tributaries of Brahmaputra using SoI topographic maps (1:50,000 scale, 1969-70), Landsat MSS (spatial resolution = 60 m, 1973), Landsat TM (30 m, 1990, 2010) and Landsat ETM+ (30 m, 2000) images. The results suggest that shifting of the bank lines of the river segments under study shows considerable spatial (i.e., upstream vs. downstream) as well as temporal (i.e., over the decades) variability within the segments as well as between the segments. The study also observed that the agricultural lands as well as settlement areas, in the floodplains, were seriously affected by the migration of river courses during the study period.

Sarkar (2012) carried out a study on the nature and amount of bank erosion and deposition along the Brahmaputra River within India for a period of 18 years (1990-2008) using an integrated approach remote sensing and GIS. The data used in this study are IRS LISS-I, LISS-III images along with SoI toposheets and Landsat ETM+ images. It was observed that both banks have undergone severe erosion than deposition during the study period. Out of the 12 reaches, the critical reaches that had undergone maximum erosion were also identified.

Among the different rivers of the Indian Peninsula, most studies addressing fluvial geomorphology have been conducted on the Narmada and Tapti Rivers. However, none of the studies used remote sensing images for the analysis, except for cartographic purposes. For example, Kale et al. (1996) attributed the multi-channel pattern to the local effects of tectonic deformation and domal uplift, as well as the influence of structure and flood processes. According to the study, even though the response of Narmada is broadly analogous to that occurring in alluvial rivers, extreme conditions exerted by lithology as well as floods made a different timescale for the equilibrium adjustment of the river. Later Kale and Hire (2004) studied the geomorphic significance of infrequent, large-magnitude floods on channel morphology of Tapti River, and the results indicate that the morphological characteristics of the bedrock, as well as the alluvial channels, are maintained by large-magnitude, but low-frequency floods that occur at long intervals. Similarly, Kale (2005) studied the morphological and hydraulic characteristics of the sinuous bedrock channel of the Tapti River and reported that the bedrock channel is increasing the flow resistance and energy losses by developing and enhancing the meandering pattern. The channel morphology of Himalayan Rivers clearly shows their vulnerability to morphological adjustments as a result of various fluvial/hydrological processes. On the other hand, Kale (2003) reported that only the channel segments of the deltaic plains of Godavari, Krishna, Mahanadi and Cauvery rivers are subject to changes in the channel form and position due to floods.

The review of pertinent literature regarding the channel morphological investigations indicates that the changes in river morphology is a global issue, but shows variability in the intensity of changes as well as drivers of morphological changes. Further, the review also highlights the morphological problems of the Indian rivers and brought the dearth of channel morphological studies in the river basins of the peninsular region into the limelight. Hence, the present study, along with the other studies initiated by the Ministry of Water Resources, will be useful understanding the behavior of the major river systems of India as well as for evolving effective strategies to overcome the problems through the implementation of suitable river training works.

SECTION 3
KRISHNA RIVER BASIN

3.1. Description of the basin

Krishna River Basin (KRB), extending between N Lat. 13°10' and 19°22' and E. Long. 73°17' to 81°9' (Fig. 1), is the fourth largest drainage system of India (in terms of drainage area and discharge) after Ganges-Brahmaputra, Indus, and Godavari river basins. The KRB is the second largest peninsular river system draining to the Bay of Bengal, and rises in the Mahadev range of the Western Ghats at an altitude of 1,337 m above MSL near Mahabaleshwar in Maharashtra State, and is about 64 km from the Arabian Sea. The basin shape resembles a triangle with its base along the Western Ghats, the apex at Vijayawada and the Krishna itself forming the median (Jain et al., 2007). The basin has a maximum length and width of about 701 km and 672 km (MoWR, 2014).

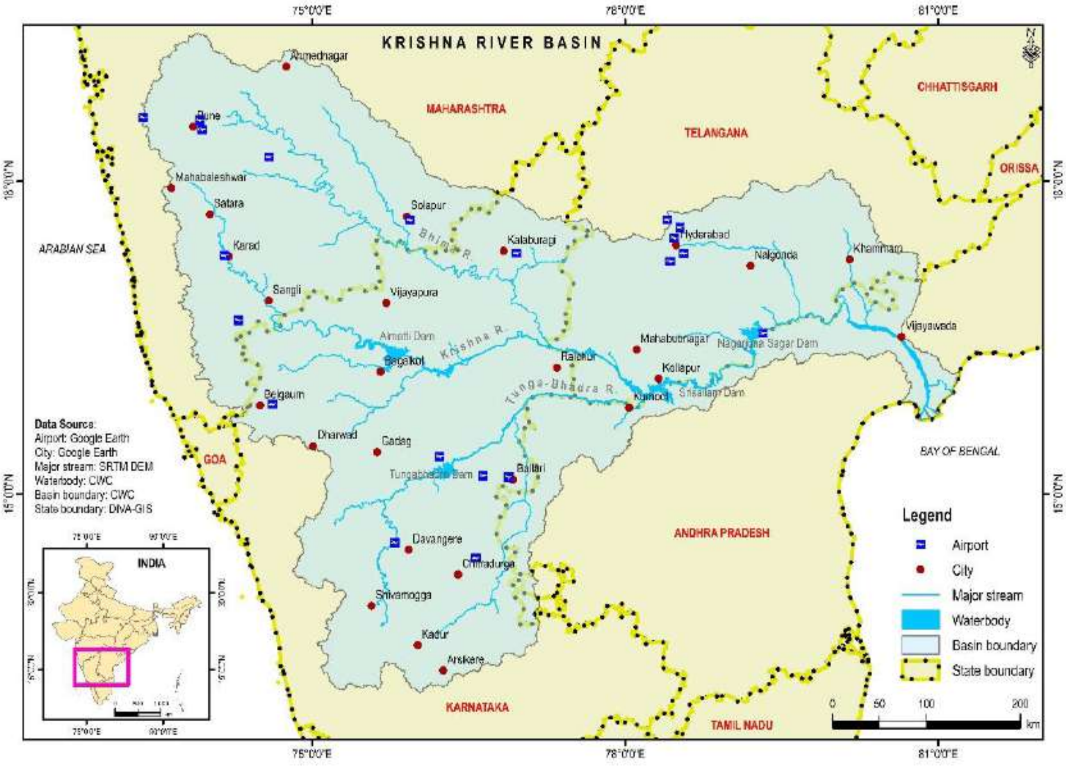

Fig. 1: Location map showing KRB, India.

The east-flowing Krishna River lies between the Godavari River Basin in the north and the Pennar and Cauvery River Basins in the south. The river originates in the Western Ghats and discharges into the Bay of Bengal. The NNW-SSE trending Western Ghats forms the drainage divide on the west of KRB, while the Bay of Bengal on the east. The Eastern Ghats dissects the KRB in the east, leaving broad flat tracts of land between the hill range and the sea. The northern boundary is constituted by the Balaghat, the

Harishchandragad and the Mahadeo ranges, which extend from the eastern flank of the Western Ghats. Moreover, the Anantagiri and associated hill ranges form the basin divide between the Krishna and the Godavari. The Uravakonda and the Mitta-Kondala ridges and the Erramalai hills outline the basin boundary (on the south) between KRB and the Pennar basin, while numerous ridges separate the KRB from the Cauvery river basin. The western divide of KRB is shared by numerous small West flowing basins of the Konkan strip. The basin has a total area of 2,58,948 km^2 (which is nearly 8% of the total geographical area of the country), of which roughly 44% area drains parts of Karnataka, 26% in Maharashtra, 20% in Telangana and 10% in Andhra Pradesh.

3.2. Drainage network

The Krishna River traverses across peninsular India from west to east and on its way, it is met by several major tributaries. The mainstream of KRB has a length of approximately 1,400 m, and it flows for a distance of 305 km in Maharashtra, 483 km in Karnataka and 612 km in Telangana and Andhra Pradesh before finally out debouching into the Bay of Bengal (Jain et al., 2007). Even though several tributaries (viz., Koyna, Yerla, Varna, Panchganga, Dhoodhganga, Ghataprabha, Malaprabha, Don, Bhima, Tungabhadra, Dindi, Halia, Musi, Paleru, Munneru and Wyra) feed the Krishna River, the Bhima River from the northwest and the Tungabhadra River from the west to southwest are the two major tributaries in KRB (Fig. 2).

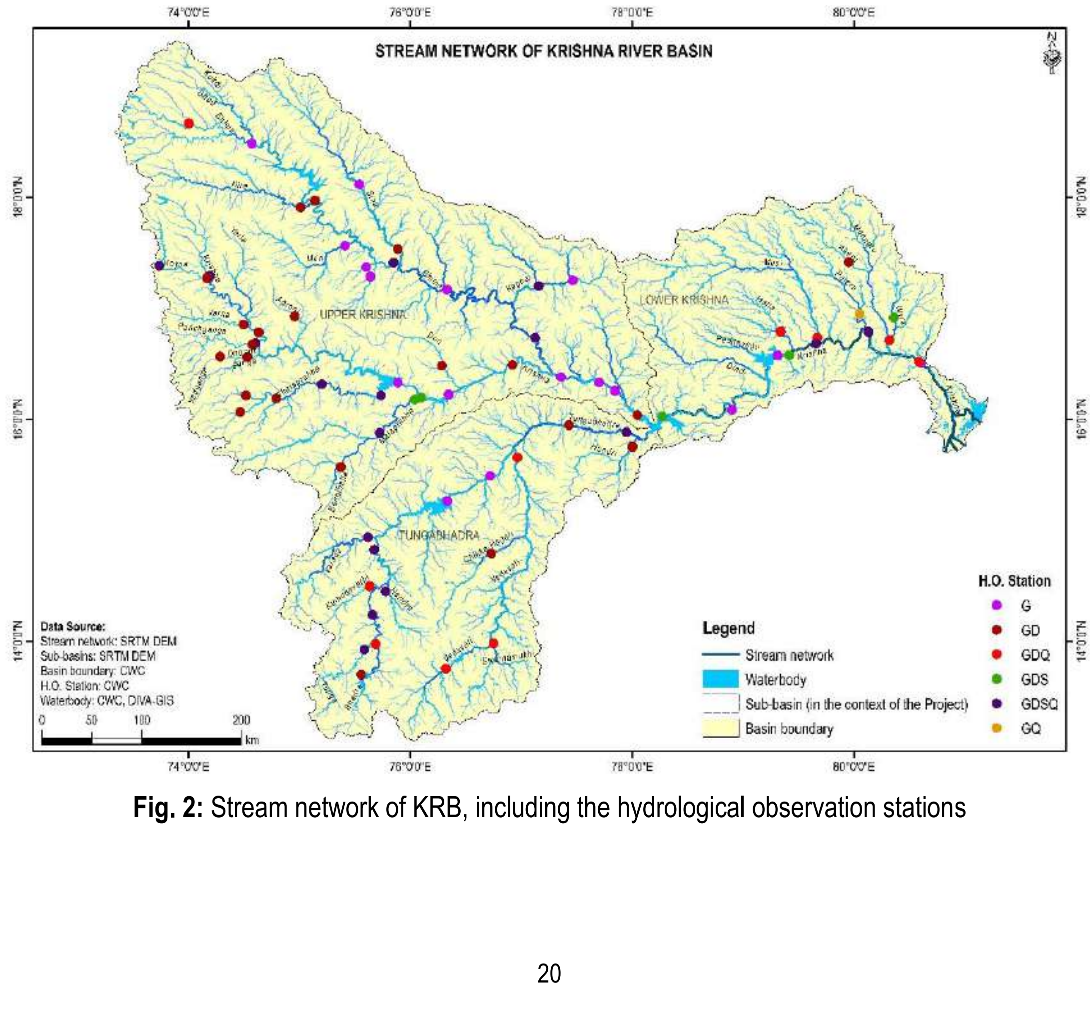

Fig. 2: Stream network of KRB, including the hydrological observation stations

Thirteen major tributaries join the Krishna River along its course, out of which six are right bank tributaries and seven are left bank tributaries (Table 1). Among these major tributaries, the Ghatprabha, the Malprabha and the Tungabhadra are the principal tributaries joining the right bank, which together account for 35.45% of the basin area, whereas the Bhima, the Musi, and the Munneru are the principal left bank tributaries, comprising of 35.62% of the basin area.

Table 1: Details of major tributaries of the Krishna River (modified after Jain et al., 2007)

No.	Tributary	Bank	Length (km)	Catchment area (km^2)	Maximum Elevation (m above MSL)*	Minimum Elevation (m above MSL)*
1.	Koyna	Right	118	1,890	1,448	562
2.	Panchganga	Right	74	2,575	1,029	537
3.	Dhoodhganga	Right	103	2,350	1,037	534
4.	Ghataprabha	Right	283	8,829	1,047	509
5.	Malaprabha	Right	304	11,549	1,027	492
6.	Bhima	Left	861	70,614	1,468	337
7.	Tungabhadra	Right	531	71,417	1,909	263
8.	Dindi	Left	178	3,490	881	160
9.	Peddavagu	Left	109	2,343	712	158
10.	Halia	Left	112	3,780	701	54
11.	Musi	Left	265	11,212	726	44
12.	Paleru	Left	152	3,263	487	26
13.	Munneru	Left	195	10,409	792	21

* Extracted from SRTM DEM (1 arc second)

The Koyna River is one of the major right bank tributaries of the Krishna River and originates at a height of 1337 m above MSL on the Western Ghats near Mahabaleshwar in Maharashtra State. Major tributaries of the river are the Kera, the Morna and the Wang (http://www.india-wris.nrsc.gov.in). The mainstream of the river has a length of 118 km, and the basin drains an area of 4,890 km^2 across the Western Ghats and the Deccan Plateau (Table 1; Fig. 2). The upstream segment of the river (i.e., about 65 km from the origin) follows roughly N-S direction and parallel to the trend of the Western Ghats, whereas the downstream orients nearly E-W.

The Panchganga River, one of the major tributary of KRB, in its upper catchment, is located in Maharashtra State and has a catchment area of 2,575 km^2 (Table 1; Fig. 2). The river joins the Krishna River at Narasoba Wadi, which is downstream of the confluence of the Varna River with the Krishna River. The mainstream has a length of 74 km and is oriented along a nearly E-W direction. The river is formed by four tributaries, viz., the Kasari, the Kumbhi, the Tulshi and the Bhogavati (http://www.india-wris.nrsc.gov.in). The Dhoodhganga is also a major right bank tributary of the Krishna River, which has a catchment area of 2,350 km^2 in both Karnataka and Maharashtra States (Table 1; Fig. 2). The Vedganga River is the major tributary of the Dhoodhganga River. The mainstream of the river has a length of 103 km and joins the Krishna River downstream of Narasoba Wadi.

The Ghataprabha is an important right bank tributary of KRB, which flows eastward for a distance of 283 km before its confluence with the Krishna River at Almatti (Table 1; Fig. 2). The river originates on the Western Ghats at an altitude of 884 m above MSL, and total catchment area of the river and its tributaries account for 8,829 km^2 in Maharashtra and Karnataka States. The principal tributaries of the Ghatprabha River are the Tampraparni, the Hiranyakeshi and the Markandeya (Jain et al., 2007). The Malprabha River is a right bank tributary of the Krishna River and joins downstream of Almatti. The river originates from the Chorla Ghats in the Western Ghats and flows towards east to the northeast (Fig. 2). The river traverses a length of 304 km before meeting the Krishna River (Table 1). The Bennihalla, the Hirehalla, and the Tuparihalla are the major tributaries to the Malaprabha River (Ramachandra, 2016). The Malaprabha river basin has a catchment area of 11,549 km^2, which entirely developed in the State of Karnataka.

The Bhima River is a major left bank tributary of the Krishna River, which also rises in the Western Ghats and flows south-eastwards (Fig. 2). The basin is trapezoidal in shape with its axis aligning northwest to southeast. The river joins the Krishna River at about 26 km north of Raichur (Jain et al., 2007). Major tributaries of the Bhima are the Mula, the Mutha, the Nira, the Ghod, the Man and the Sina. The river system is developed in Maharashtra, Karnataka, and Telangana States with the total catchment area of 70,614 km^2, and nearly 75% of the catchment area falls in Maharashtra State. The Bhima River is the longest tributary of the Krishna River, where the trunk stream has a length of 861 km (Table 1).

The Tungabhadra basin is the largest sub-basin of KRB. The river system drains a total area of 71,417 km^2 (Table 1; Fig. 2) in Karnataka, Telangana and Andhra Pradesh. The Tungabhadra River derives its name by joining the tributaries, viz., the Tunga (147 km) and the Bhadra (178 km) (Source: http://tbboard.gov.in). Both the tributaries originate at Varahagiri Hills of the Kudremukh range in the Western Ghats of Karnataka State, and confluences at Kudali village, near Shivamoga, Karnataka. After the confluence, the river flows for about 531 km roughly northeasterly and joins Krishna River near Kurnool. Tungabhadra river system is constituted by the tributaries, such as the Tunga, the Bhadra, the Kumudavathi, the Haridra, the Varada, the Vedavati and the Handri (http://www.india-wris.nrsc.gov.in).

The Dindi River is a left bank tributary of Krishna River and joins upstream of Nagarjuna Sagar Dam (Fig. 2). The mainstream of the river has a length of 178 km and has a total catchment area of 3,490 km^2 (Table 1). The river flows through Mahbubnagar and Nalgonda Districts and the basin is wholly developed in Telangana

State. In addition, Peddavagu River is also a left bank tributary of the Krishna River joining upstream of Nagarjuna Sagar Dam. The river has a catchment area of 2,343 km^2, and the mainstream has a length of 109 km. In fact, the protruding limbs of the Nagarjuna Sagar Reservoir pointing towards northwest reflect the confluence of these rivers to the Krishna River. The Halia River is another major left bank tributary, which joins the Krishna River downstream of the Nagarjuna Sagar Dam. The mainstream flows nearly 112 km before joining the Krishna River and has a total catchment area of 3,780 km^2.

The Musi River is a major left bank tributary of Krishna, having its origin in the hills of Anathagiri in Telangana State. Flowing southwards, the river meets the Krishna River near Wazirabad, roughly 40 km downstream of the Nagarjuna Sagar Dam (Fig. 2). The river flows through Hyderabad city, and the mainstream of the river has a length of 265 km (Table 1). The total catchment area of the basin is 11,212 km^2. In addition, the Paleru River is also an important left bank tributary joins the Krishna River, near Mukteswarapuram. The river basin has a catchment area of 3,263 km^2, with the mainstream length of 152 km. Similarly, the Munneru River is also another left bank tributary joining the Krishna River. Major tributaries of the river are the Akeru and the Wyra. The mainstream of the Munneru River is 195 km long, and the basin has a catchment area of 10,409 km^2. Downstream of the Krishna River, after the confluence of the Munneru River, is developed on a deltaic plain, viz., Krishna Delta, which is nearly 95 km wide and covers an area of about 4,800 km^2 (Jain et al., 2007). The downstream segment of the Krishna River splits in four distributaries (roughly 60 km downstream of Vijayawada), which debauch into the Bay of Bengal. Bifurcation of the first left bank distributary occurs upstream of Avanigadda Village, while the other two branches divert near Edurumondi Village.

In general, KRB is classified into 7 sub-basins, namely, Bhima upper (i.e., upstream catchment area of the confluence between Bhima and Sina), Bhima lower (catchment area excluding Bhima upper), Krishna upper (catchment area upstream of the confluence between Krishna and Bhima), Krishna middle (catchment area between Krishna upper and Nagarjuna Sagar dam), Krishna lower (downstream area of Nagarjuna Sagar dam), Tungabhadra upper (upstream of Tungabhadra dam) and Tungabhadra lower (catchment area excluding Tungabhadra upper) sub-basins (MoWR, 2014). The mainstreams of Krishna and Tungabhadra rivers join near Murvakonda (i.e., 30 km northeast of Kurnool), which is roughly 500 km upstream of the Krishna deltaic region. Almost 80% of the catchment area of KRB drains to the confluence point of Krishna and Tungabhadra rivers. After the construction of Srisailam dam (almost 100 km downstream of the confluence), the confluence point is inundated due to reservoir impoundment.

3.3. Physiography and geomorphology

The basin elevation of KRB varies from MSL to 1908 m above MSL and shows a clear altitudinal zonation from west to east (Fig. 3). The major sub-basins of KRB also show considerable variability in the maximum and minimum elevations of the sub-basins (Table 1). Even though maximum elevation in KRB reaches 1908 m above MSL, near Mangalore in the Western Ghats (in the WNW portion of the basin), the majority of the basin area is relatively flat and gentle in slope and more than 90 percent lies below 750 m above mean sea level (MSL). The areal extent of various elevation bands of KRB is shown in Table 2.

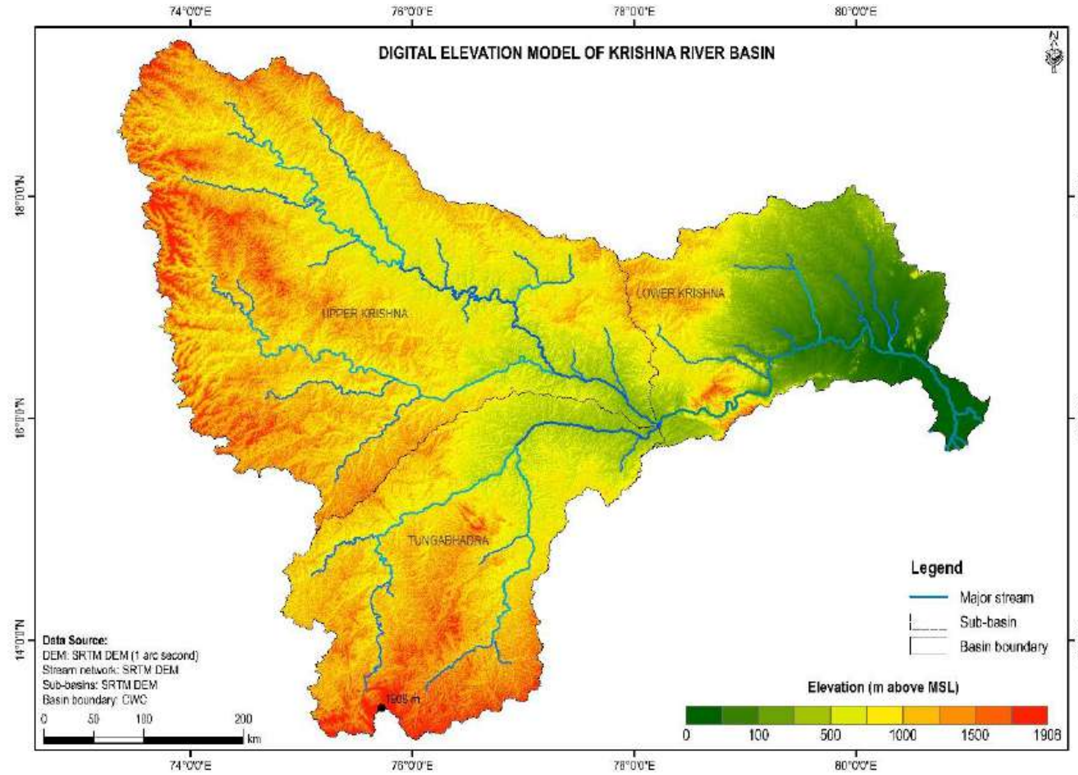

Fig. 3: DEM of KRB

Table 2: Areal extent of different elevation zones in the KRB

Sl. No.	Elevation zone (m above MSL)	Area (km^2)	Area (%)
1.	≤ 5	772	0.30
2.	6-10	1434	0.55
3.	10-25	1149	0.44
4.	26-50	1651	0.64
5.	51-100	5018	1.94
6.	101-250	16545	6.39
7.	251-500	70578	27.26
8.	501-750	141288	54.56
9.	751-1000	18368	7.09
10.	1001-1500	2090	0.81
11.	> 1500	54	0.02

MSL-mean sea level

The complex interactions among the lithology, structure/tectonics, and climate of KRB led to the evolution of the diverse landforms spanning across the basin. However, geomorphology of the basin can be broadly classified into three distinct segments, viz., fluvially-dissected hilly terrain, while plains in the downstream area and the plateau. The western parts of the basin (more precisely the eastern slopes of the Western Ghats) are highly dissected by fluvial processes, primarily because of the steepness of the terrain as well as the large quanta of annual rainfall experiencing over the region. However, the areal extent of this landform unit is significantly less compared to the rest of the geomorphologic types.

The hilly terrain of the Western Ghats is highly undulating and is characterized by V-shaped valleys. Further, the headwater region developed in the basaltic terrain resembles badland topography. However, the valleys in the headwater region are not as narrow as in the case of west-flowing Konkan Rivers. The rugged terrain is dominantly covered with dense and evergreen forests, while rest of the area is comparatively flatter and less undulating. The coalescence of the river systems originating from the Western Ghats has removed the interfluves leaving only occasional basalt mesas as the only topography (Widdowson, 1997). The Deccan laterites typically form distinctive cliffs around the margins of the basalt mesas. This physiographic region is characterized by heavy rainfall and falls under the humid climatic regime. However, the region roughly 50 to 60 km east of the Western Ghats (mostly the undulating plains of the Deccan Plateau) experience poor rainfall and hence dry climate.

A major portion of the basin is developed on the Deccan Plateau, which is bounded by the Western and Eastern Ghats and is the largest geomorphic sub-unit of the Indian Peninsula. The western and central India experienced the Deccan volcanic events mostly during late Cretaceous-Eocene, where the extensive outpourings of basalts not only buried the low-relief, pre-Trappean landscape but also created a youth-stage topography over which sub-aerial processes started operating and new drainage network was established. Erosion commenced on the newly formed rifted margin and operated to the then existing erosional base level, which gave rise to the present-day landforms including the Deccan Plateau and the Western Ghats (Kale, 2014).

Although the elevated inland plateau has little relief, it is further dissected into a series of valleys by drainage network of the tributaries, viz., Krishna and Bhima, which have slopes generally towards the east. The interior of the basin is predominantly developed in the Plateau and a major part of which is at an elevation between 300 and 600 m above MSL. The general slope of the region is towards the east, and the region consists of undulating plains and broad flat valleys interspersed with isolated ridges and residual mounds with rocky outcrops. The hill-sides are marked by conspicuous, wide, terraces except in the southern part where the hills are frequently crowned with great 'tors' or rounded hummocks of bare rock, the result of constant weathering (MoWR, 2014). The Eastern Ghats forms the southeastern boundary of the basin, where the Eastern Ghats comprise parallel ranges.

The drainage system of the basin is controlled by the tectonic fabric (NW-SE Dharwarian trend) and the eastward tilt of the Indian Plate as well as the regional domal uplift caused by the Deccan plume head (Cox 1989; Kale and Vaidhyanadhan, 2014). In general, the Peninsular Rivers are characterized by broad and shallow valleys with low gradients, and Krishna is no exception. In general, drainage network of KRB, especially in the middle and downstream reaches appears to be a misfit, as they are developed in broad valleys (3-5 km) covered with a thick cover of unconsolidated sediments. Bedrock reaches and erosional features are common in the river segments at multiple reaches, and river segments incised in rock have developed bedrock gorges (mostly of Holocene epoch), occasionally with waterfalls/cascades at the gorge head.

Irrespective of the physiographic segmentation and geology of KRB, the river channels in KRB manifest incised sections at several places, even across structural and topographic highs (e.g., reaches between Srisailam dam and Prakasam barrage), suggesting that either the rivers are antecedent or superimposed. Although the fluvial landscape of the Peninsular Rivers was laid in the middle Mesozoic, sufficient evidence is available to imply that the landscape of Peninsula was sculptured predominantly by fluvial systems throughout Cenozoic. It is believed that the major landscape elements of the basin very likely existed throughout the Cenozoic, although complete integration of younger Deccan Traps drainage with the older peninsular drainage must have taken some time. Apart from changes in the catchment hydrology, the long-term downward trend in the eustatic sea-level during mid to late Cenozoic not only lowered the erosional base level but also subaerially exposed previously submerged areas along the margins. The rivers most likely responded to the long-term base-level lowering by down cutting their channels, dissecting inland plateau and high-level surfaces, exposing the weathering fronts (giving rise to bornhardts and boulder inselbergs) and by increasing their sediment output (Kale, 2014).

The eastern coastal plain is a 100-130 km wide stretch of land lying between the Eastern Ghats Ranges and the Bay of Bengal. The width of the Krishna River shows a drastic increase when it enters the plains, and braided river channels are developed in the downstream reaches, where sand bars are composed of coarse to fine sands. The Krishna delta, occurring in the downstream of the river basin, comprises sediments of fluvial and marine action and has diverse continental and marine landforms such as levees, paleochannels, tidal islands, beach ridges, mangrove swamps, strandlines, spits and delta front sands. The delta is a gently rolling low lying plain with a general slope towards south and south-east. The Krishna River and its distributaries developed natural levees depositing coarse grain sediments, bordering their channels. The paleochannels are characterized by coarse sediments and flood plains with alternations of coarser and finer clastics. These channel deposits oriented approximately normal to the general shoreline trend constitute the most significant sand bodies. A few parallel ridges of sand, pebble and shells are situated at relatively higher elevations and the depressions between them are occupied by swamps, silts etc. These ridges are aligned behind the shoreline and the different ridges mark the position of a pre-existing shoreline (Babu, 1975).

Vast amounts of sediment material have been added at the mouths of the distributaries leading to the formation of river mouth bars and barrier islands with associated back island lagoons. The sand supplied by the river is built into delta front sands and spits enclosing lagoons on the delta margin. As the delta progressed, these lagoons were filled in with finer grained sediments (Jain et al., 2007). The Krishna delta has large tracts of mangrove swamps along the coast with maximum concentration surrounding the three main distributaries. The process of silt deposition at the mouth of the river helped the delta to extend gradually into the sea. However, recently, Gamage and Smakhtin (2009) observed a retreat of the delta at the average rate of 77.6 ha yr^{-1}, primarily a result of the reduced river inflow to the delta as well as the associated reduction of sediment load, which are invariably related to upstream reservoir storage development.

The deltaic region is highly vulnerable to flooding, especially during cyclonic storms of high intensity and short duration formed over the Bay of Bengal. The major causative factor for the flooding in the region is the elevated bed level (due to continuous sediment deposition) and the associated reduction in channel carrying capacity (MoWR, 2014). Although the delta area is prone to flooding, the extent of the damage due to flooding varies for different landforms (Ramana Murty et al., 1992). The deltaic region is chiefly covered by black clay of varying thickness underlain by fine to medium sand fractions (Nageswara Rao, 1982), which is the dominant reason for flooding, compared to the channel bar, point bar, natural levees, paleochannels, beach ridges and coastal dunes (Babu, 1975).

3.4. Soil

Owing to the spatial variability in the geology and climate in KRB, the soil types do also exhibit considerable variability across the basin. The important soil types found in the basin are black soils, red soils, lateritic soils, alluvium, mixed soils and saline and alkaline soils (MoWR, 2014). The soil types of the basin are characterized by clay or clay loam textures (Fig. 4). Soil erosion is moderate in more than 56% of the basin area (Fig. 5), whereas 2.5% of the basin area experiences very severe erosion (MoWR, 2014).

In general, the basaltic rocks of the Deccan traps, upon weathering, gives either laterite or bauxite and the soil derived from the weathering processes is the black soil (i.e., Vertisols). The black soil is mainly distributed across the northwestern and western portion of the basin (belonging mostly to Maharashtra, northern parts of Karnataka States, as well as western parts of Telangana States). The thickness of the soil shows significant spatial variability where the upstream areas of the basin have relatively higher soil thickness. The black soil is highly argillaceous with significantly higher clay contents (> 60%), with minimal amounts or even without coarser fractions. The soil color varies from deep black to grey, and the fertility levels of the soil vary from place to place. The soil fertility largely depends on the local topographical features, and on high elevations and sloping grounds, the soil column is thin, light colored and less fertile, while in the low lying lands and plains, they are thick, deep colored and highly fertile. The soil is rich in aluminum, calcium, magnesium, and poor in nitrogen, phosphorous and humus. The soil has high moisture retaining capacity, and hence, the Rabi crops are usually successful without irrigation. Although cotton is the major crop grown on the soil, other crops such as wheat, tobacco, linseed, millets, as well as large varieties of fruits and vegetables are also cultivated on the soil.

The red soil is developed over the igneous and metamorphic rocks (e.g., acid granites and gneisses) in the low rainfall regimes of the basin. The red soil is comparatively coarser than the black soil, and the moisture retaining capability is significantly low, compared to the black soil. The coarse-grained red soil in the dry upland areas is relatively less fertile, compared to the fine-textured red and yellow soils over the low-lying areas and plains. In their chemical composition, they are mainly siliceous and aluminous, with free quartz as sand. Red soil is also deficient in calcium, phosphorous, nitrogen as well as humus. Rice, wheat, sugarcane, cotton, and pulses are the major crops cultivated on the soil. The laterite soil of the basin is developed as a result of leaching, especially in the areas of high rainfall and high temperature. The soil is characterized by coarse texture and is poor in organic matter content, nitrogen, phosphorous and calcium. The soils of the downstream parts of the basin (e.g., lower Krishna basin) are mostly residual in origin and are mostly developed through decomposition of regional rock materials, except in the major river valleys where transported alluvium is encountered.

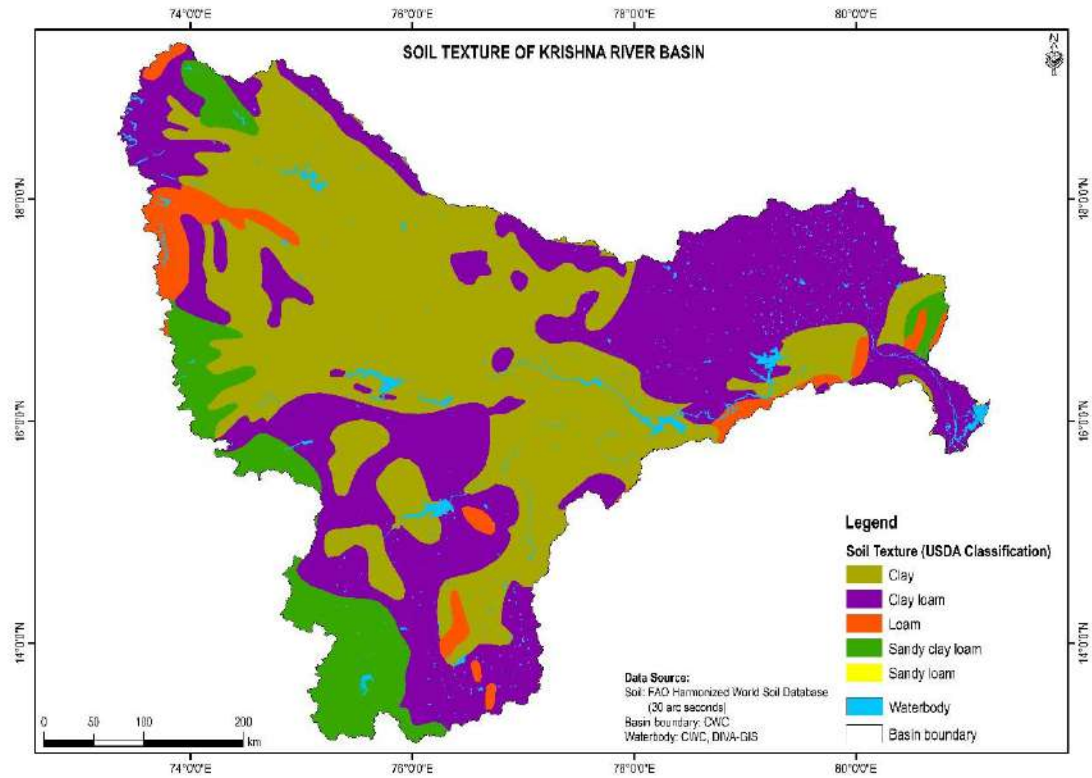

Fig. 4: Spatial variation of textural characteristics of the soils of KRB

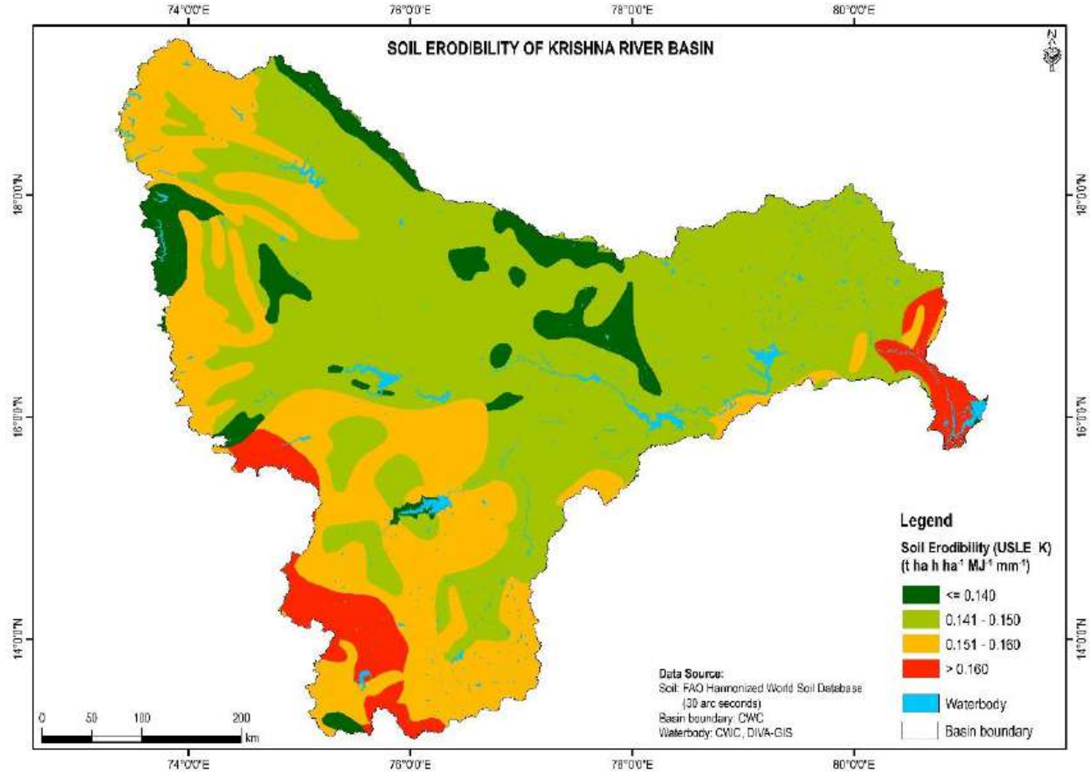

Fig. 5: Spatial variation of soil erodibility (i.e., USLE K factor) in KRB

3.5. Water resources structures

Among the different river basins selected for the river morphological assessment by the Ministry of Water Resources, Government of India, the KRB is unique due to various reasons. Unlike other river systems of India, KRB has already undergone severe modification of the hydrologic regime, during the pre-independence period itself, due to the agricultural development coupled with construction of major and minor irrigation schemes and water diversion structures (Venot et al., 2011), which gives an opportunity to evaluate the impacts of river regulation of channel morphology. Further, among the 30 river basins characterized as global level priorities for the protection of aquatic biodiversity, Krishna is one among the nine river basins from India and categorized as "strongly affected" by flow fragmentation and regulation (Groombridge and Jenkins, 1998; Nilsson et al., 2005; cited in Smakhtin and Anputhas, 2009).

The water resources structures of KRB were built to store the surface water to meet the needs from domestic, irrigation, agriculture, and hydropower sectors. A total number of water resources structures in the basin is around 855, which includes 660 dams, 12 barrages, 58 weirs, 6 anicuts and 119 lifts (Fig. 6). The details of the water resources projects are given as Appendices I to III. Sub-basin wise distribution of these structures has been given in Table 3. Majority of dams (81.36%) have storage capacity below 25 MCM, and nearly 90% of the total dams are used for irrigation purposes. Among the different projects, Nagarjuna Sagar, Srisailam (NSRSP), Tungabhadra, Almatti, Ujjani, and Hidkal are the major dams and reservoirs of KRB. Since the majority of the basin area is utilized for agricultural purposes, most of the water resources projects were developed to address the agricultural development of the basin (after MoWR, 2014).

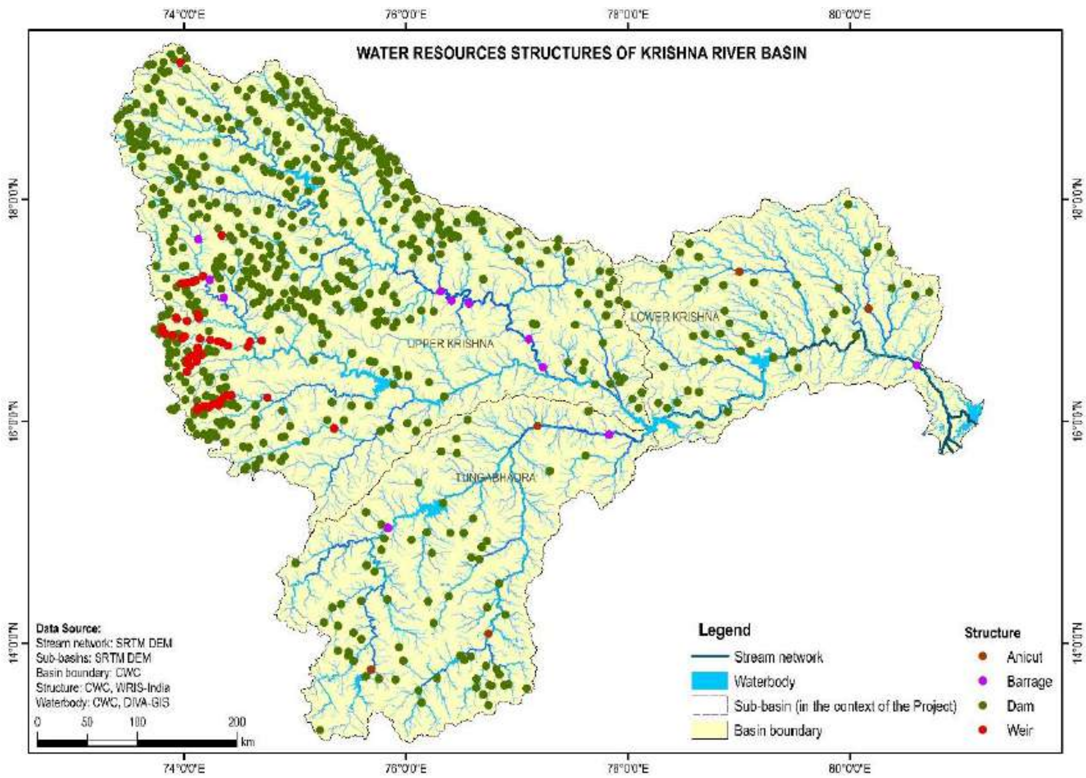

Fig. 6: Water resources structures in KRB

Table 3: Details of the water resources projects in the sub-basins of KRB

No.	Sub-basin	Dam	Weir	Barrage	Anicut	Total	Hydraulic structure density (per 1000 km^2)
1.	Koyna	4	7			11	6.0
2.	Panchganga	22	26			48	19.0
3.	Dhoodhganga	14				14	6.0
4.	Ghataprabha	41	13			54	6.0
5.	Malaprabha	17	1			18	2.0
6.	Bhima	341	1	5		347	5.0
7.	Tungabhadra	68		2	3	73	1.0
8.	Dindi	5				5	1.0
9.	Peddavagu	4				4	2.0
10.	Halia	6				6	2.0
11.	Musi	9			1	10	1.0
12.	Paleru	2				2	1.0
13.	Munneru	8			1	9	1.0

SECTION 4
GEOLOGY OF THE BASIN

4.1. Geological setting

The drainage network of KRB is developed on a wide spectrum of geological formations of peninsular India (Fig. 7; Table 4) ranging in age from the Precambrian to Recent, which include Deccan traps (Upper Cretaceous to Paleogene), granitoids and metasediments (Achaean to Proterozoic), sedimentaries (Mesoproterozoic to Neoproterozoic) and fluvial, fluvio-marine, aeolian and coastal sediments (Quaternary) (Source: Geological Survey of India). A major portion of the basin is developed on the Precambrian Dharwar Craton (or the Karnataka Craton), while north to northwestern portion of the basin is solely underlain by the Deccan Traps.

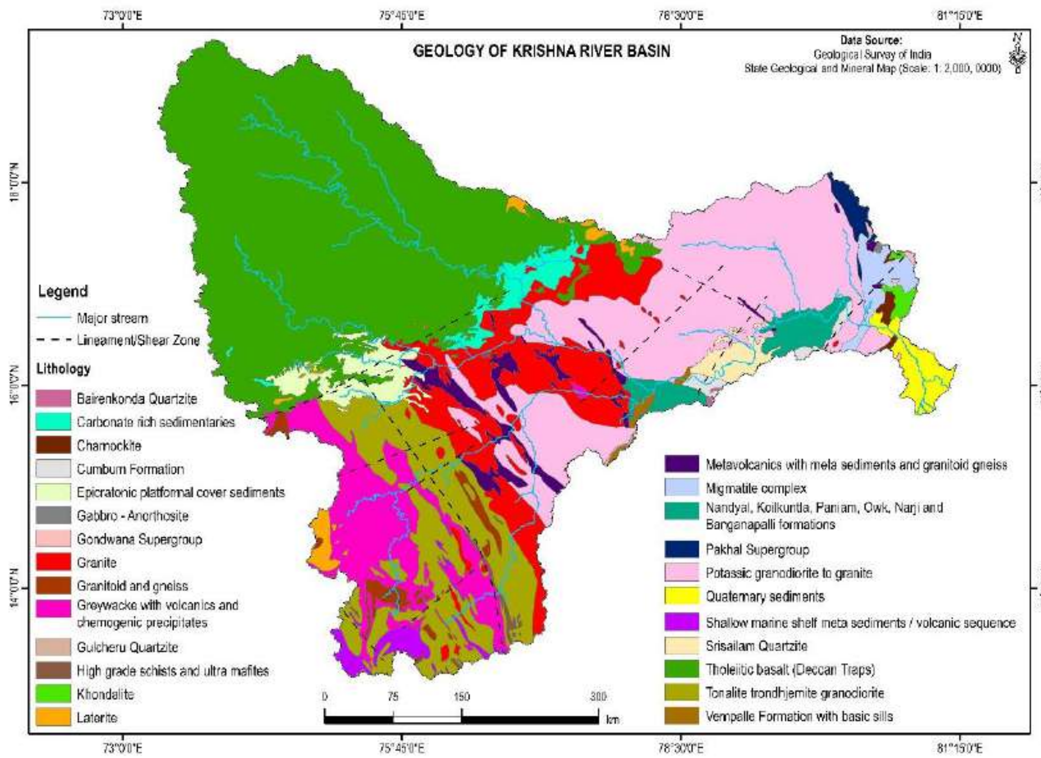

Fig. 7: Geology of KRB

The Deccan Traps or the Deccan Volcanic Province (DVP) are one of the Large Igneous Provinces in the world, which were emplaced during Cretaceous to Paleogene period (with the bulk of the volcanic activity being centered around the K-T boundary) along the western margin and the central part of continental India, a complex structure consisting of small basins, crossed rift systems and aborted rift zones (e.g., Pande 2002; Krishna et al. 2006; Chenet et al. 2008; Tandon et al., 2014).

Table 4: Geological characteristics of KRB

Lithology	Group	Super Group	Age
Undifferentiated fluvial/fluvio-marine/aeolian/coastal sediments			Quaternary
Laterite			Neogene
Tholeiitic basalt	Sahyadri	Deccan Trap	Upper Cretaceous to Paleogene
Undifferentiated Maleri, Kota, Chikiala, Golapalle, Raghavapuram, Tirupati, Vemavaram, Sriperumbudur and Satyavedu formations		Gondwana	Triassic to Cretaceous
Kamthi Formation			Permian to Triassic
Barakar Formation			Permian
Undifferentiated Talchir, Karharbari, Barakar formations and Barren Measures			Carboniferous to Triassic
Carbonate rich sedimentaries	Bhima		Neoproterozoic
Epicratonic platformal cover sediments	Kaladgi	Kaladgi	Neoproterozoic to Mesoproterozoic
Nandyal, Koilkuntla, Paniam, Owk, Narji and Banganapalli formations	Kurnool	Cuddapah	Neoproterozoic
Bairenkonda Quartzite	Nallamalai		Mesoproterozoic
Cumbum Formation			
Gulcheru Quartzite	Papaghni		
Vempalle Formation with basic sills			
Srisailam Quartzite			
Pakhal		Pakhal	
Granite	Closepet Granite and equivalents		Archaean to Proterozoic
Potassic granodiorite to granite	PGC - II	PGC	

Lithology	Group	Super Group	Age
Charnockite	Charnockite	Eastern Ghats	Archaean
Khondalite	Khondalite	Eastern Ghats	
Gabbro - Anorthosite			
Greywacke with volcanics and chemogenic precipitates	Chitradurga	Dharwar	
Shallow marine shelf metasediments/volcanic sequence	Bababudan	Dharwar	
Metavolcanics with metasediments and granitoid gneiss	Eastern Greenstone	Dharwar	
Granitoid and gneiss	Older Granites		
Migmatite Complex			
Tonalite trondhjemite granodiorite	PGC – I	PGC	
High-grade schists and ultramafites	Sagur Complex		

The Deccan Traps covers an area of about 500,000 km^2 of peninsular India, mostly in Maharashtra State and adjoining regions in Gujarat, Madhya Pradesh, Andhra Pradesh and Karnataka (Beane et al., 1986). The DVP is believed to have been originally almost three times as extensive as at present (i.e., about 1,500,000 km^2). The lava flows show wide variability in its thickness, where the thickest development (~2000 m) represents along the Western Ghats region and thins progressively eastward and southeastward to a thickness of 200 m (Tandon et al., 2014). The rocks of the DVP, in general, is fine-grained, non-porphyritic and predominantly tholeiitic in composition. However, alkali basalts (basanite and picrite), nephelinites, carbonatites, and rhyolite, occurring in minor amounts in the rifted western margin of the domain, and upon weathering, these rocks normally give either laterite or bauxite. The upstream sub-basin of KRB, such as Koyna, Panchganga, Dhoodhganga, and Bhima are predominantly covered (i.e., more than 80% of the basin area) by basalts (Table 5). Further, roughly 60% of the basin area of Ghataprabha is also dominated by basalt lithology.

The dominant lithology of the KRB is comprised of the rock suites of the Dharwar Craton (~400,000 km^2). Similar to the rest of the cratons of the Indian Shield, Dharwar Craton is also dominated by the Archean tonalite-trondhjemite gneiss (TTG), which is also known as Peninsular Gneiss. The TTG was originally plutonic, sometimes forming mappable diapiric domes, but was metamorphosed to orthogneiss during shallow-angle (Archean-type) subduction between microplates during the Precambrian. The TTG is interspersed with younger granitic intrusions of variable size, which plays a prominent part in the topographic relief of the Deccan Plateau. The TTG is also associated with the greenstones or schist belts with sedimentary associations.

The Dharwar Craton can be viewed as an assemblage of the high- and low-grade schist belts (greenschist to amphibolites facies) and the intrusive granites in the Peninsular Gneisses. However, the Dharwar Craton is broadly divided into Western and Eastern Cratons (WDC and EDC respectively), on the basis of differences in lithology, magmatism, grade of metamorphism and geochronological age, and is separated by a steeply dipping mylonite zone, the Chitradurga Shear Zone (Radhakrishna and Vaidyanadhan, 1997). Despite a few exceptions (mostly in the WDC), the dominant feature of the cratonic landscape is that all Late Archean syn-tectonic or younger granitoids underpin areas of topographic relief. The WDC is characterized by an older generation of TTG, which was emplaced ca. 3,300-3,100 Ma and granite plutons form small, neatly circumscribed outcrops (e.g. Chitradurga, Shivamoga), whereas granitic outcrops in the EDC are less distinctive, mainly due to the dominance of younger generation of TTG (2,900-2,700 Ma) in the EDC crust that underwent extensive syn- or late-orogenic melting (Gunnell, 2014). The tributaries, such as the NE-SW trending Thungabhadra and the nearly E-W trending Malaprabha originate in the Western Dharwar formations and later flows through the Eastern Dharwars before joining the mainstream of Krishna (Table 5; Fig. 7).

Table 5: Areal extent of different lithological formations in the sub-basins of KRB

Sl. No.	Sub-basin	Major lithology (areal coverage)
1.	Koyna	Basalt (100%)
2.	Panchganga	Basalt (100%)
3.	Dhoodhganga	Basalt (98%), Bhima Group (2%)
4.	Ghataprabha	Basalt (59%), Kaladgi Group (36%), TTG (2%), Bhima Group (1%), Laterite (1%)
5.	Malaprabha	TTG (38%), Greywacke with volcanics and chemogenic precipitates (25%), Kaladgi Group (19%), Basalt (6%), Granite (6%), Metavolcanics with metasediments and granitoid gneiss (3%), Granitoid and gneiss (3%)
6.	Bhima	Basalt (88%), Bhima Group (5%), Granite (4%), Potassic granodiorite to granite (2%), Laterite (1%)
7.	Tungabhadra	TTG (30%), Greywacke with volcanics and chemogenic precipitates (22%), Granite (18%), Potassic granodiorite to granite (14%), Metavolcanics with metasediments and granitoid gneiss (4%), Shallow marine shelf metasediments/volcanic sequence (4%), Granitoid and gneiss (3%), Laterite (2%), High grade schists and ultramafites (1%), Vempalle Formation with basic sills (1%)
8.	Dindi	Potassic granodiorite to granite (82%), Granite (14%), Srisailam Quartzite (4%)
9.	Peddavagu	Potassic granodiorite to granite (96%), Srisailam Quartzite (3%), Granite (1%)
10.	Halia	Potassic granodiorite to granite (97%), Metavolcanics with metasediments and granitoid gneiss (2%), Kurnool Group (1%)
11.	Musi	Potassic granodiorite to granite (87%), Basalt (7%), Granite (4%), Laterite (1%)
12.	Paleru	Potassic granodiorite to granite (98%), Kurnool Group (2%)
13.	Munneru	Potassic granodiorite to granite (53%), Migmatite Complex (26%), Pakhal Supergroup (13%), Khondalite (2%), Gondwana Supergroup (2%), Metavolcanics with metasediments and granitoid gneiss (2%), Charnockite (1%), Gabbro-Anorthosite (1%)

The roughly N-S trending Closepet Granite (a 400 km-long and 30 km-wide intrusion which runs parallel to the trend of the schist belts) dated at 2,520 Ma (Radhakrishna 1956; Moyen et al. 2003) is an excellent approximation of the boundary of the Eastern and Western Cratons (Ramakrishnan and Vaidyanadhan, 2008). The major schist belts trending NNW-SSE are volcanogenic and are known for their gold mineralization. The Dharwars are affected by various NNW-SSE to NW-SE trending transcrustal faults, which are intersected by major ENE-WSW to EW and NE-SW trending faults/lineaments (Rajaram and Anand, 2014).

The Chitradurga shear zone marks the boundary between EDC and WDC, apart from the Closepet Granite, and extends into the Moyar-Bhavani shear zones (Ramakrishnan, 2003). The Chitradurga shear system is a curved array of anastomosed shear zones. In the south, it consists in a northward-converging pattern of dextral and sinistral shear zones (i.e., the dextral Mysore shear lense, the Kollegal shear zone and the anastomosed shear system between Kollegal and Kabbaldurga) that merge around 13°30' N and diverges northward to form a duplex that ends NE of Ranibennur. North of that point, the Chitradurga shear system is confined to a single trace (i.e., the Dharwar shear zone) making the eastern boundary of the Shimoga greenstone belt (Chardon et al., 2008). The belt attains a maximum width near Chitradurga. It is interesting to note that the schist belts in both cratonic blocks show the same N-S trend with almost constancy of strike and dip of the foliation (Sharma, 2009).

The Purana basins are comprised of Precambrian-Early Palaeozoic sedimentary (or metasedimentary) sequences that form the basinal infrastructure of Peninsular India (Kale and Phansalkar, 1991). Several Meso-Neoproterozoic intracratonic basins with a large thickness of unmetamorphosed platformal sediments of mixed siliciclastic-carbonate lithology cover an extensive part of Peninsular India. The best-preserved sedimentary sequences include the areally extensive Cuddapah, Chhattisgarh and Vindhyan basins along with several smaller regional basins known as the Indravati, Khariar, Prahnita-Godavari, Kaladgi, Bhima, Kunigal, Kurnool and Marwar (Meert and Pandit, 2015). Among the various Purana basins, three (viz., Cuddapah, Kaladgi and Bhima) are occupied in the KRB. In addition, the rock suites of the Pakhal Supergroup of the Pranhita-Godavari basin are also exposed along the northeastern boundary of the KRB. The Proterozoic sedimentary basins of Bhima and Kaladgi are sandwiched between the Dharwar Craton and Deccan Traps, while the crescent-shaped Cuddapah basin occurs in the eastern fringes of Dharwar Craton. Despite their spatial differences, these basins share some common features such as their crystalline Archaean and Early Proterozoic basements with distinct angular and erosional unconformities, composition of shallow marine, platform sediments punctuated by mature orthoquartzites, absence of metamorphism as well as epicratonic nature (i.e., located along the fringes of the Archaean nuclei of the Indian Shield) (Kale and Phansalkar, 1991).

The crescent-shaped Cuddapah basin, exposed on the eastern margin of the EDC, is the second largest Proterozoic basin in India as far the outcrop extent is concerned (Ramakrishnan and Vaidyanadhan, 2008), where the Cuddapah formations are metasediments, chiefly composed of quartzites, limestones, and shales. It covers an area of approximately 44,500 km^2 and the westwardly convex margin spans nearly 440 km (Meert and Pandit, 2015). The sedimentary successions in the Cuddapah basin unconformably overlie granitoid basement including the Archean greenstone belts, traversed by the mafic dyke swarms (Saha et al., 2016). The formation contains extensive dolerite sills and dykes and basaltic flows and the volcano-sedimentary dominated, Nellore type schist belt forms a major thrust along the eastern margin of the Cuddapah basin (Rajaram and Anand, 2014). The eastern margin of the basin is demarcated by a thrust fault while all other boundaries are part of the 'Epi-Archaean Unconformity' (a non-conformity associated with undisturbed contact with older Archaean rocks) (Meert and Pandit, 2015). The basin is the thickest of the Purana sequences, estimated to be around 13,000 m aggregated stratigraphic thickness (Kale and Phansalkar, 1991).

The NNE-SSW strike in the northern parts of Cuddapah basin swings through an N-S trend in the central parts, to NNW-SSE orientation in the south. The Cuddapah basin has been divided into two broad structural sectors, divided by the Rudravaram Line. The region west of this line displays relatively gentle deformation, except in the vicinity of the cross-faults, and exposes the 'stratotypes' of the various stratigraphic units. This sector has been divided into the Papaghni, Srisailam, Kurnool and Palnad sub-basins. East of the Rudravaram Line, up to the eastern thrust margin of the Cuddapah basin, the sediments are severely deformed, which is recognized as the Nallamalai Fold Belt (Narayanaswami, 1966; Kale and Phansalkar, 1991). The close association of basic volcanic activity with the sedimentation in the Cuddapah Supergroup has significant implications in the tectonic evolution of this Cuddapah basin (Drury, 1984). Phansalkar et al. (1991) have inferred that the Papaghni Group was deposited in the 'synrift' phase of basin evolution, based on the association of evaporite, stromatolites and the interbedded spilitic (Reddy, 1988) basalt flows from the Vempalle Formation. The youngest igneous activity in the basin is the kimberlite and lamproite field located near the basin center (Chakrabarti et al., 2007).

Four sub-basins within the Cuddapah basin - the Papaghni sub-basin, the Kurnool sub-basin, the Srisailam sub-basin, and the Palnad sub-basin - have been recognized considering the spatial distribution and thickness variation of the constituent rock groups, and their sedimentation pattern (Nagaraja Rao et al., 1987; Dasgupta and Biswas, 2006). The Papaghni Group is divided into two formation rank units the Gulcheru Quartzite and the Vempalle Formation in ascending order. As the name implies the Gulcheru Quartzite is dominated by psammites with a thin basal interval of conglomerate, lying directly over the weathered granite gneisses of the Dharwar batholith. The Gulcheru Quartzite is overlain by the carbonate dominant Vempalle Formation with a gradational contact. The lower part of the Vempalle Formation consists of thin strata of splintery red mudstone alternating with cross-stratified siliciclastic and calc-arenite strata, often with herringbone structure. The folded, faulted and cleaved low-grade metasedimentary succession within the Nallamalai Group is divided into two formation rank units - the sandstone dominated Bairenkonda Quartzite and the dominantly argillaceous Cumbum Formation in ascending order. The Cumbum Formation consists of gray-green slate with thin, fine-grained sandstone and local dolomitic interbeds (Saha et al., 2016). The Srisailam Formation starts with a basal pebbly conglomerate horizon, followed sequentially upward by green gritty quartzite, dark-grey shale–quartzite intercalation and sub-feldspathic to feldspathic quartzite (Singh et al., 2017).

Sedimentation in the Cuddapah Basin was discontinuous and numerous unconformities exist within the Cuddapah Supergroup. A major unconformity separates the Cuddapah Supergroup from the overlying Kurnool Group, and the Kurnool Group was deposited unconformably over the Cuddapah rocks and is concentrated in the western portion of the basin (Meert and Pandit, 2015). The Kurnool Group is subdivided into five constituent formation rank units. Of these, the basal unit, the Banganapalli Quartzite (40-50 m), includes a massive, polymictic, matrix- to clast-supported basal conglomerate intercalated with trough cross-stratified, pebbly to gritty feldspathic sandstone or subarkose. The Narji Limestone, about 500 m thick, conformably overlies the Banganapalli Quartzite along a gradational contact in the Kurnool sub-basin and is the main repository of cement grade limestone in the Cuddapah basin. The Owk Shale, though having only 10-12 m of thickness is laterally extensive across the Kurnool district and often marked by clayey horizons near its lower and upper contacts. The Paniam Quartzite is also referred to as the “Plateau Quartzite” or “Pinnacled Quartzite”, because of the special geomorphic features in the Kurnool district, with which the formation is associated. Very well sorted medium-to-fine quartz arenite constitute the bulk of the Paniam Quartzite. The Koilkuntla Limestone overlies the Paniam Quartzite with a sharp transition. Thin-bedded gray micritic limestone with marly intercalations constitute the Koilkuntla Limestone with common development of cherty nodules. The Koilkuntla Limestone grades upward into a brown-gray, color-laminated shale-calcareous shale. The sand deficient, mud dominated Nandyal Shale (50-100 m thick) possibly represents deposition below storm wave base in a wide shelf, under tectonic quiescence (Saha et al., 2016). The Cuddapah basin litho units are mostly concentrated in Tungabhadra, Dindi, Peddavagu, Halia and Paleru sub-basins (Table 5).

The east-west-trending, ovoid-shaped Kaladgi basin is a significant Proterozoic intracratonic basin of the WDC. The total area of exposure and thickness of the basin are estimated to be about 8300 km^2 and 4500 m, respectively (Jayaprakash et al. 1987). This basin formed on TTG gneisses and greenstones of Archaean age. The Kaladgi Supergroup preserves the record of sedimentation in the basin and consists of sandstones, mudstones, and carbonates (Meert and Pandit, 2015). Part of the Kaladgi Supergroup is covered by basaltic volcanic rocks of the terminal Cretaceous Deccan Traps. The Kaladgi Group is separated, by a distinct angular unconformity, into the younger Badami Group and the older Bagalkot Group. The sediment package of the Bagalkot Group is dominated by arenite, shale and carbonate rocks with subordinate conglomerates and cherts. The basement of the Bagalkot Group comprises Neoarchaean Peninsular Gneiss, greenstone belts and Closepet Granite, which supplied detritus to the Kaladgi Basin. The Badami Group consists of undeformed, horizontal to subhorizontal beds mainly of arenites with subordinate shales and limestones. The group unconformably overlies the older Bagalkot Group as well as the basement Archaean granitoid-greenstone belts (Dey, 2015).

Broadly, three transgressive cycles of sedimentation, each floored by the clastic suite, and grading into cyclic argillite-carbonate (predominantly dolomite in the Bagalkot Group, but limestone in the Badami Group) suites can be recognized in the Kaladgi Supergroup. The clastics indicate beach and near-shore (partly estuarine) depositional environments at the base of each of these cycles, which have given way to tidal flat environments, both muddy and carbonate, with partly euxinic conditions. These repeated marine transgressions on an episodically sinking, epicratonic shelf are responsible for the accumulation of the thick pile of sediments in the Kaladgi basin. The Bagalkot Group is pervasively deformed by tight, isoclinal folds, which are recognized to be shear folds, developed predominantly in the quasi-plastic (to marginal elastofrictional) regime in high stress/low-temperature conditions. The relatively less deformed basin margins of the Bagalkot Group have suffered homogeneous strain-flattening (probably under the influence of gravity-related subsidence of the basin floor). In the axial sector of this basin, the Bagalkot Group has also suffered cross-folding and multiple co-axial deformations in different phases. However, the Badami Group has been very mildly deformed, with large amplitude open folds, and gentle dips (many of which are the rolling depositional dips) (Jadhav, 1987; Kale and Phansalkar, 1991). The Kaladgi basin rocks are exposed in the Ghataprabha and Malaprabha sub-basins (Table 5).

The Bhima basin (resembling as a sigmoidal array of en-echelon) is much smaller than the Cuddapah, and covers 5200 km^2, with the longest portion having an axis of 160 km (NE-SW). The southern portion of the basin is bounded by an unconformity with the underlying granitic gneisses while the east-west and NW–SE borders are fault-bounded (Meert and Pandit, 2015). The Bhima Group is predominantly composed of limestones; however, sandstone and conglomerate beds rest between the basement and the upper sequence limestones. The oldest age for the formation of the Bhima Basin is constrained by the underlying granitic gneisses to circa 2500 Ma (Sastry et al. 1999). The sediments of the Bhima Group display predominantly horizontal disposition, with moderate deformation in the vicinity of the faults which transect the basin. Most of these faults, with local drag-folding and subvertical dips in the Bhima sediments along their lengths, continue into the basement. They show evidence of syn-sedimentational, episodic activity, and have undoubtedly controlled the geometric outline of this basin (Peshwa and Chitrio 1983). Based on the recognition of predominant dextral strike-slip components of the relative movements along these faults, Kale and Peshwa (1989) have suggested that this shallow, epicratonic basin was evolved through an NW-SE directed shear couple along the Wadi Fault in the form of a 'pull-apart basin' (Mann et al., 1983). Bhima Group rocks are exposed in Dhoodhganga, Ghataprabha and Bhima sub-basins (Table 5).

The Pranhita-Godavari (P-G) basin is developed as a major rift system along the NW-SE trending Karimnagar granulite belt which delineates the Neoarchean suture between the Eastern Dharwar and Bastar cratonic nuclei (Meert and Pandit, 2015). Two NW-SE trending outcrop belts of the Proterozoic successions of the P-G valley basin are now separated by the axial outcrop of the Upper Paleozoic-Mesozoic Gondwana succession. There are numerous stratigraphic interpretations for the P-G sequence, and recently, the three major unconformity bound successions namely the Pakhal (Super)group with Mallampalli and Mulug Groups, Penganga and Sullavai groups in the western belt are clubbed together under the Godavari Supergroup

(Chaudhuri, 2003). Unconformably overlying the basement granites and gneisses including the Karimnagar granulite belt, the Pakhal Supergroup consists mainly of dolomitic limestone and minor conglomerate in the lower part and calcareous shales in the upper part constituting the Mallampalli Group (1400 m), and conglomerate, feldspathic sandstone, dolomitic limestone, calcareous shale, and minor chert constituting the Mulug Group (700 m) (Saha e al., 2016).

Several parts of the Indian peninsula (as in other continents) experienced tensions resulting in fracturing and faulting on the earth's crust leading to the deposition of fresh water or lacustrine sediments in grabens or basins. The Gondwana sediments are found at present in basins/grabens formed during this period (Verma, 1985). The NW-SE trending P-G Valley is unique as it preserves about 3000 m thick Gondwana sediments deposited in a time span of 200 Ma (from late Carboniferous/early Permian to Cretaceous) between the eastern and western portions of the P-G Basin. A generalized lithostratigraphic succession of the Gondwana sediments includes Talchir, Barakar, Barren Measures, Kamthi (Lower Gondwana Group), Maleri, Kota, Gangapur and Chikiala formations (Upper Gondwana Group) (Fig. 7; Table 4). Resting uncomformably over the Precambrian basement, Talchir Formation, 200-370 m thick, includes diamictite, rhythmite and light green sandstone in that sequence. The Barakar Formation is about 350 m thick and made of pebble beds and coarse feldspathic sandstone in the lower part and local-bearing finning-upward cyclothems in the upper part. A 60-800 m thick, middle to late Permian Barren Measures Formation overlies the Barakar Formation with a normal contact. Light yellow feldspathic sandstone, siltstone and grey shale are prominent litho-units. The Kamthi Formation is known to have widespread distribution and covers over two-thirds of the basinal area. The Kamthi Formation shows ‘overstep’ nature over the older Talchir, Barakar and Barren Measures Formations. The thickness of the Kamthi Formation ranges from 50-400 m and contains conglomerate, conglomeratic sandstone, and shale of early Triassic age. The Upper Gondwana Group begins with 250 m thick Maleri Formation comprising reddish brown to greenish grey clay, siltstone, argillaceous sandstone, and lime-pellet rock along with middle to late Triassic fauna. The succeeding Jurassic Kota Formation includes large-scale cross-bedded sandstone, limestone in the middle and upper sandstone and clay. White sandstone, buff siltstone, and light grey clay characterize the Gangapur Formation. Litho-assemblage of the Chikiala Formation includes unfossiliferous conglomerate sandstone and ferruginous sandstone (www.ndrdgh.gov.in).

The Eastern Ghats Mobile Belt (EGMB) is a Mesoproterozoic terrane that has a very long history of tectonothermal activities including migmatization and charnockitization of supracrustal rocks. The NE-SW-trending EGMB is defined along its western margin against the Archaean Bastar and Dharwar cratons by a prominent shear zone of the nature of a detachment thrust, which dips eastwards (Valdiya, 2016). In KRB, Minor inliers of the EGMB occur in the eastern part and local sedimentary outcrops of the Gondwana Supergroup. The EGMB is a highly-deformed granulite terrane, composed mainly of charnockites, khondalites, quartzite, calc-granulite, pyroxene granulite and quartzofeldspathic gneisses (or leptynites), having a predominant NE-SW trend. The EGMB supracrustal rocks are mainly seen in Munneru sub-basin (Table 5).

Isolated and massive lateritic patches are also exposed over the Deccan trap as well as the rocks of Chitradurga Group (Fig. 7). The formation of laterites over the youngest lava flows in the Deccan Traps Region is an indicator of intense and deep weathering immediately after the cessation of the Deccan volcanism. Laterites are found in three distinct belts in KRB, such as high-level laterites atop the Deccan Trap flows along the Western Ghats, laterites atop the Deccan Trap flows along the Solapur-Hyderabad highway and laterites developed on the Precambrian-Proterozoic Terrain in the basin (NRAA, 2011). The high level laterites were considered primary laterites while the others were considered secondary. Although the duricrusts can be found from close to sea level (i.e., western coastal regions) to roughly 2500 m above MSL (Nilgiri and Anaimalai hill complex), the high level laterites/bauxites over the Deccan Plateau are usually, but not exclusively, confined to areas above 900 m above MSL (Kale and Vaidyanadhan, 2014). Although the laterites developed over the Deccan Traps are certainly of the Cenozoic period, there is uncertainty about the age of laterites developed over the Precambrian rocks. The thick laterite duricrusts exposed outside the present humid areas, especially along the eastern margin of the Deccan Traps, have significant climatic implications as these denote inheritance from a former humid climate (Babechuk et al. 2014). Lateritic exposures are commonly seen in Ghataprabha, Bhima, Tungabhadra and Musi sub-basins (Table 5).

Quaternary alluvial deposits occur in the coastal segment of the Bay of Bengal and the Krishna Delta (Fig. 7). About 3417 km^2 area in the lower reaches of the basin constitutes the Quaternary sediments in the Krishna Delta. The Quaternary sedimentation in the basin Southeast of Vijayawada is controlled by the horst and graben structure of the Krishna-Godavari Basin (NRAA, 2011).

4.2. Hydrogeology

The diversity of geologic, physiographic, geomorphologic and climatic settings across KRB has resulted in varying hydrogeological types. The groundwater resources of the basin is an important resource not only for irrigated agriculture but also for meeting the water demands of the domestic, power as well as industrial sectors and overall development of the basin. As of March 2004, the net annual groundwater availability in KRB was 34,894 MCM (60% of the surface storage). The annual groundwater draft was 18,461 MCM and the overall stage of groundwater development was 53%. Static groundwater resources for the basin were estimated as 24,571 MCM (70 % of net groundwater availability) (CGWB, 2004).

Majority of the basin area (i.e., roughly two-thirds of the total area) is occupied by various hard rock formations. From the hydrogeological point of view, the consolidated formations of KRB are broadly classified into four lithological types - volcanic, igneous, metamorphic and carbonate rocks, and the most common rock types under this category are basalt, granite, gneiss, charnockite, quartzite, schist, phyllite etc. Although the primary porosities of these formations are negligible, these are rendered porous and permeable due to fracturing and weathering, and thereby the nature, occurrence, and movement of groundwater are controlled by secondary porosities. In the hard rock formations, the granite and the gneisses are better aquifers than charnockites. Further, the existence of lineaments, deeply weathered and fracture zones in the basin also form potential aquifers, irrespective of lithology.

In the area underlain by hard crystallines and meta-sedimentaries, the groundwater occurs in the fracture zone up to a depth of 100 m, while in certain favorable areas, groundwater potential is available even up to a depth of 200 m (NRAA, 2011). However, the groundwater yield of the crystalline and meta-sedimentary aquifers shows wide spatial variations. In most of these terrains, the weathered residue serves as an effective groundwater repository. The porous rock formations mainly include unconsolidated and semi-consolidated formations, where the former is dominantly confined to the Quaternary sediments, whereas the latter is mainly comprised of shale, sandstone, and limestone, belonging to Precambrian and Gondwana periods. Among these, the sandstone forms the highly potential aquifers. Similar to the spatial variability in the groundwater yield potential in hard rock aquifers, the water-yielding capability of the unconsolidated formations also varies considerably across space as a result of the variability in particle size, rounding and degree of the assertion of the aquifer matrix. The hydrogeological characteristics of the major aquifer systems of KRB are given in Table 6 and discussed in the following paragraphs (after NRAA, 2011).

The basaltic lava flows of the Deccan Traps are mostly horizontal, and hence, groundwater occurrence in the aquifer is controlled by the contrasting water-bearing properties of different lava flows. The topography and nature, as well as extent of vesicular basalts, are the important factors regulating the occurrence and the movement of groundwater in the aquifer system. The basaltic Deccan Traps behave as a multi-aquifer system, where potential water-bearing horizon (e.g., vesicular, amygdaloidal, fractured-jointed and weathered basalt) is sandwiched between comparatively massive basaltic flows. Basaltic flows have their distinctive hydrogeological characteristics in that primary porosity is due to the presence of vesicles, flow contacts, and lava tubes, while secondary porosity is developed as a result of jointing and weathering. Deccan Traps usually have medium to low permeability as the primary porosity in the rocks is relatively very less. Moreover, the vesicles are often filled with secondary minerals, which also reduces the porosity and permeability. Hence, the total available groundwater in these basaltic aquifers purely depends on the weathering characteristics and the fracture systems.

Table 6: Geo-hydrological characteristics of major geologic formations of KRB (after NRAA, 2011)

Sl. No.	Aquifer	Lithology	Hydrogeology	Groundwater potential
1.	Quaternary sediments	Recent alluvium, clays, silt, sand, conglomerates, calcareous concretions, etc.	Thick (up to 300 m) and regionally extensive confined/ unconfined aquifers	High yield (> 150 m^3 hr^{-1})
2.	Laterites	Primary and secondary laterites	Fairly thick (up to 20 m) unconfined, discontinuous aquifers	High yield (> 150 m^3 hr^{-1})
3.	Gondwana sediments	Clays, shale, siltstone, sandstone, conglomerate, limestone	Moderately thick (up to 150 m) and regionally extensive confined/unconfined aquifers	Moderate yield (50 - 150 m^3 hr^{-1})
4.	Deccan Traps	Basaltic lava flows and interflow material (bole, flow breccia, intertrappeans, etc.)	Moderately thick (up to 100 m) unconfined aquifers restricted to fractures and weathering zone. Minor confined aquifers	Moderate to low yield (up to 20 m^3 hr^{-1})
5.	Proterozoic sediments (Cuddapah, Bhima and Kaladgi Basins)	Limestone and dolomite sandstone, conglomerate, shale	Moderately thick (up to 100 m) but discontinuous confined/ unconfined aquifers	Moderate to low yield (up to 20 m^3 hr^{-1})
6.	Eastern Ghats Crystallines	Khondalites and charnockite with alkaline intrusives	Aquifers restricted to weathering zone and fractures	Low yield (~ 5 m^3 hr^{-1})
7.	Greenstone Belts	Phyllite, schist, quartzites, chert, metabasalts, etc.	Aquifers restricted to weathering zone and fractures, i.e., to secondary porosity. Thickness of aquifers variable.	Low yield (5 - 20 m^3 hr^{-1})
8.	Peninsular Gneissic Complex	Gneisses intruded by younger granites and pegmatites		Low yield (~ 5 m^3 hr^{-1})

The pink and purple colored basalts show a higher degree of weathering, and the pink zeolitic basalt is a better aquifer than the grey basalt as the latter is generally of massive character. Flow contacts (i.e., interflow spaces) in between two successive lava flows are often a better source of water supply in these aquifers, and groundwater flow through these intervening spaces represents flow through tortuous conduits. In general, the moderate to low porosity and permeability and the scanty rainfall experiencing over the region (mean annual rainfall = 750 mm) gives rise to a complex low-storage aquifer system.

In the basaltic aquifers, the dominant types of water abstraction structures are dug wells, dug-cum-bore wells and bore wells, and the depth of the dug wells varies from 5 to 15 m, with a diameter of 5 to 12 m. The transmissivity of different types of aquifers varies widely, where the transmissivity of weathered basalts, vesicular basalts, and fractured basalts ranges from 90-200 m^2 day^{-1}, 50-100 m^2 day^{-1} and 20-40 m^2 day^{-1}, respectively. Computed specific capacity of large diameter dug wells (average 5 to 10 m) is in the range of 80-200 lpm mdd^{-1}, 20-60 lpm mdd^{-1} and 100-300 lpm mdd^{-1} for weathered, fractured and vesicular basalts, respectively. Accordingly, the specific yield varies from 2-6%, 0.5-1.5% and 1-4% for the respective formations, with the porosity of 10-34%, 5-15% and 10-50%, respectively for the various formations (NRAA, 2011).

The lithotypes of the peninsular gneissic complex (mostly granite and gneisses) also have little primary porosity, but the secondary porosity is developed by fracturing and weathering, and the network of the interconnected fractures, planes, and joints permits the flow and storage of groundwater in the aquifer system. The storage capacity of these un-weathered hard rocks is restricted by the interconnected systems of fractures, joints, and fissures, which are mainly the result of tectonic activities. The coarse-grained granites develop closely spaced fractures tens to hundreds of meters long, which are often intruded by the residual acid magma resulting in pegmatite and quartz veins. At places, the granite occurs as cross-cutting intrusive bodies in several parts of the basin. The granite forms round shaped bodies and is affected by strong exfoliation. The weathering processes affect only the shallow upper parts of the rock. However, the occurrence of the weathered zone or tectonic fractures associated with granitic bodies as well as the contacts of granites with surrounding metamorphic rocks enhances the groundwater storage. Hence, the extent of weathering and fracture characteristics have a dominant role (compared to other properties) in deciding hydraulic conductivity in granitic rocks.

In granitic terrains, the major aquifer for dug wells and dug-cum-bore wells is the weathered and fractured granite, and the depth of the dug wells usually ranges from 5 to 25 m. The depth of weathered mantle ranges from about 8 to 15 m below ground level (bgl), and below this zone fractured rocks occur down up to 40 m bgl. The depth to water table ranges from less than a meter to 12 m bgl. Dug wells generally yield 10-80 and even up to 200 m^3 day^{-1} groundwater depending on their location. The transmissivity of the aquifers is in the range of 30-200 m^2 day^{-1} and storativity is about 2 to 4 %. The specific capacity of large diameter dug wells (average 5-10 m diameter) in these formations ranges from 100-230 lpm mdd^{-1}.

The groundwater in Gondwana sediments aquifers occurs under confined conditions, where the shale overlying the sandstone mostly acts as the confining medium. The groundwater is normally extracted by means of dug wells, dug-cum-bore wells and bore wells. The depth to water table ranges from 2.20 to 10.60 m bgl and the depth of dug wells varies between 5.00 and 18.50 m bgl. The tube wells in the area range in depth from 40.0 to 75.0 m bgl, with water yield ranging from 28 to 1300 lpm for a drawdown of 8.0-15.0 m.

In the Cuddapah and Kurnool group of rocks (e.g., slaty phyllites, quartzites, and limestone), the groundwater occurrence is mainly controlled by joints, bedding planes and weathered zones. However, the quartzites do not form good aquifers in the region because of their compactness and occurrence at a relatively higher elevation. The groundwater developed in slaty phyllites is extracted by dug wells, dug-cum-bore wells and bore wells, where the depth of wells varies from 3 to 25 m bgl. The depth to water table ranges from 0.4 to 7.0 m bgl, and the yield of wells ranges from 20 to 80 m^3 day^{-1}, with the exceptions in the highly fractured zones.

The semi-consolidated formations of KRB are mainly composed of shale, sandstone, and limestone of Precambrian, Gondwana and Tertiary periods. Among the different aquifer systems, the sandstone forms the highly potential aquifers. Although these formations possess moderate potential, terrain configuration restricts the development of groundwater. However, under favorable situations, at times these sedimentary formations give rise to artesian conditions. The rock types, viz., quartzites, limestones, and phyllites are connected to the upper unconsolidated colluviums via the fractures and vertical to sub-vertical joint systems, which facilitates the groundwater movement. The bedding planes in the formations are also a suitable avenue for groundwater movement. The groundwater is tapped both by dug wells as well as deeper bore wells/tube wells.

The sandstone aquifers possess moderate permeability and productivity, which is resultant of the limited shale intercalation, bedding planes, and deep vertical jointing as well as the varying grain sizes and degree of cementation. Further, the joints and bedding planes serve as a mechanism for infiltration and groundwater recharge. In general, intergranular permeability is low in sandstone, whereas but secondary porosity and permeability due to fracturing are significantly high. The permeability and the productivity of sandstone are moderate, where the aquifers have transmissivity values ranging from 100 to 2300 m^2 day^{-1}. The specific capacity of the large diameter dug wells varies from 100 to 250 lpm mdd^{-1}, with the specific yield ranging from 1% to 5%.

The limestone has substantial secondary porosity and permeability as a result of the fractures, solution cavities and openings along the bedding. Since limestone is susceptible to dissolution, groundwater occurrence and movement is also controlled by the nature of karst. The water yield potential of these rocks shows wide variations as solution cavities can lead to widely contrasting permeability over a short distance. The transmissivity of the aquifer is in the range of 50 to 250 m^2 day^{-1}, while the storativity ranges between 5% and 15%. The specific capacity of large diameter dug wells (average 5-10 m diameter) is in the range of 150-250 lpm mdd^{-1}.

Laterites, lateritic shingle and gravel occur in many parts of the basin and are potential aquifers with significantly high water yields. The unconsolidated sediments, constituted by younger alluvium, older alluvium, and coastal alluvium are one of the important repositories of groundwater in KRB, especially in the downstream parts of the basin. These formations are dominantly composed of clay, sand, gravel and boulders, ferruginous nodules and kankar deposits. The beds of sand, gravel and their admixtures form potential aquifers in the eastern plain region. The unconsolidated alluvium has inherent primary porosity and effective permeability, which helps in groundwater storage. The recent sediments in the lacustrine environment and alluvium serve as major storage for the water flowing from the adjoining relatively higher elevations. As these formations occur in the valleys as well as plains, the aquifer matrix is appreciably favorable for groundwater movement. Recharging of the groundwater reservoir in these aquifers mainly occurs through the vertical and lateral percolation of rainwater. The permeability and productivity of the aquifer vary from place to place depending on the grain size, sorting as well as the thickness of the matrix. The transmissivity of the aquifer varies from 250 to 4000 m^2 day^{-1}. The specific capacity of sandy alluvium, silty alluvium and clayey alluvium fluctuates from 12 to 20, 8 to 12, and 4 to 8%, respectively. The depth to water table in the alluvium, which is of fluviatile origin ranges from almost ground level to 5 m bgl. However, the wells located in the river terraces and alluvial ridges register relatively deeper water table conditions of 7 m to over 12 m bgl with poor to moderate discharges. The extensive deltaic alluvium occurring along the eastern and southeastern parts comprises of alluvium of over 100 m in thickness, yet the sandy-clay nature of the matrix is responsible for the poor permeability. The paleochannels and flood plains are potential aquifers. In the deltaic areas and coastal alluvium, the depth to groundwater table ranges from less than 1 m to about 5 m bgl.

SECTION 5
STUDY REACHES

5.1. Description of river reaches

The scope of the present study is restricted to the mainstream channels of the Krishna and Tungabhadra rivers. In this study, the mainstream of Krishna River is considered between the river segment where Koyna River meets with Krishna River (i.e., near Karad), and the river meets with Bay of Bengal (i.e., the Krishna delta). The total length of the aforementioned is 1194 km (based on calculations in ArcGIS), excluding the three distributaries in the Krishna delta, and the total length of the three tributaries is 74 km. Similarly, the mainstream of Tungabhadra River is considered from the confluence between Tunga and Bhadra Rivers (near Danayakpura) to the river confluences with Krishna River (near Kurnool). The total length of the mainstream of Tungabhadra is 537 km. In order to understand the variability in the changes in the channels, the mainstream channel of Krishna as well as Tungabhadra was segmented into different reaches, by constructing transects at 50 km intervals. Transects were defined perpendicular to the general trend of the reach. In river morphological studies, the basic spatial unit for the application of the assessment procedure coincides with the 'reach' (i.e., a section of the river along which present boundary conditions are sufficiently uniform, commonly a few kilometers in length), that is a geomorphologically meaningful spatial scale. However, in this study, the selection of the reach length (i.e., 50 km) is based on the MoU between CWC and IIT Madras. Accordingly, the Krishna River is segmented into a total of 27 reaches (Fig. 8; KR_01 to KR_27; i.e., upper 14 reaches in Upper Krishna and the rest 13 reaches in Lower Krishna sub-basins), and the Tungabhadra into 11 reaches (i.e., TR_01 to TR_11). A reach-wise description of the spatial extent, important tributaries, major water resources structures as well as the major towns are given in Table 7. The geometric details of the individual reaches, such as length, mean width, slope, upstream drainage area as well as lithology are tabulated in Tables 10 and 11.

The extreme downstream reaches of the Krishna and Tungabhadra rivers (44 and 37 km for KR_24 and TR_11 respectively) as well as the reaches developed in Krishna delta (43, 17 and 14 km for KR_25, KR_26 and KR_27 respectively) are relatively shorter, compared to the rest of the reaches (Table 10). The mean width of the river reaches of Krishna as Tungabhadra shows an order of magnitude variation (i.e., from 167 to nearly 4000 m in Krishna River and 359 to 4312 m in Tungabhadra River). In general, a downstream increase in river width is observed with a few exceptions such as KR_08, KR_09, KR_10, KR_15, KR_18, TR-05 and TR_06 (Table 10), which is mainly due to the inclusion of the water submerged area of Almatti, Narayanapura, Srisailam and Tungabhadra reservoirs. Similarly, the slope of the channel reaches also shows considerable variability among the reaches, with a general downstream decreasing trend. However, exceptions are also noticed, especially in the downstream reaches of Krishna River, which perhaps are a result of the controls exerted by regional geologic structures.

Table 7: Spatial extent of the reaches of Krishna and Tungabhadra rivers

Reach-ID	Longitude at origin (DMS)	Latitude at origin (DMS)	Longitude at end (DMS)	Latitude at end (DMS)	Important tributaries	Water resources projects	Major towns
Krishna River							
KR_01	74° 10' 35.45"E	17° 17' 41.64"N	74° 19' 43.70"E	17° 06' 25.28"N	Koyna	Tembhu Barrage	Karad, Vidyanagar, Karve, Kapil, Kodoli, Dushere, Shere, Gondi, Rethare Khurd, Tambave, Narsinghpur, Bahe
KR_02	74° 19' 43.70"E	17° 06' 25.28"N	74° 31' 40.43"E	16° 54' 11.62"N	Yerala	Satapewadi Barrage	Junekhed, Pundi, Walwa, Nagthane, Burli, Aamanapur, Dhangaon, Bhilawadi, Ankalkhop, Kasbe Digraj
KR_03	74° 31' 40.43"E	16° 54' 11.62"N	74° 36' 27.71"E	16° 40' 34.32"N	Varna, Panchaganga	Mhaisal K.T. Weir	Sangli, Arjunwad, Sangalwadi, Ghalwad, Kanwad, Ganeshwadi, Shirati, Gaurwad, Aurwad, Narasoba Wadi
KR_04	74° 36' 27.71"E	16° 40' 34.32"N	74° 49' 12.70"E	16° 38' 28.51"N	Dudhganga, Karka Nadi		Bubnal, Alas, Bastawad, Mangavati, Rajapur, Jugul, Bavan Soundatti, Manjari, Ugar Khurd
KR_05	74° 49' 12.70"E	16° 38' 28.51"N	75° 07' 37.46"E	16° 30' 43.52"N	Agrani		Kudchi, Ainapur, Siddapura, Krishna Kittur, Saptasagar, Nadi-Ingalgaon, Darur, Halyal, Khavatkoppa, Shegunasi, Satti
KR_06	75° 07' 37.46"E	16° 30' 43.52"N	75° 25' 04.74"E	16° 31' 36.69"N	Badachihalla, Hirehalla	Hipparagi Dam	Kulhalli, Hipparagi, Shirahatti, Zunjarwad, Shurpali, Jambagi, Algur, Hirepadasalagi, Chikkapadasalagi, Chingundi

Reach-ID	Longitude at origin (DMS)	Latitude at origin (DMS)	Longitude at end (DMS)	Latitude at end (DMS)	Important tributaries	Water resources projects	Major towns
KR_07	75° 25' 04.74"E	16° 31' 36.69"N	75° 39' 37.75"E	16° 25' 47.18"N	Hirehalla		Galagali, Jainapur, Araladinni, Wadawadagi, Yelaguru, Kalagi, Bidari, Kolur, Mundaganur
KR_08	75° 39' 37.75"E	16° 25' 47.18"N	76° 04' 04.81"E	16° 15' 30.84"N	Ghatprabha	Almatti Dam	Sitimani, Yelaguru, Wadawadagi, Kalagi, Chick Myageri
KR_09	76° 04' 04.81"E	16° 15' 30.84"N	76° 25' 29.55"E	16° 15' 07.03"N	Malaprabha	Narayanapura Dam	Tangadgi, Marola, Havargi, Koujaganur, Rakkasagi, Baladinni, Halkawatgi, Chittapur, Nalatvad
KR_10	76° 25' 29.55"E	16° 15' 07.03"N	76° 49' 35.24"E	16° 25' 25.19"N	Don, Devapur Nala, Hutti Nadi		Tintani, Devapur
KR_11	76° 49' 35.24"E	16° 25' 25.19"N	77° 07' 16.79"E	16° 28' 55.09"N			Markal Kollur, Hayyal B, Aneksugur, Kopper, Tumkur
KR_12	77° 07' 16.79"E	16° 28' 55.09"N	77° 31' 43.84"E	16° 21' 33.97"N	Yadgir Nala, Bhima		Bendbombli, Arshanagi, Deosugur, Ganjhalli, Mudumala
KR_13	77° 31' 43.84"E	16° 21' 33.97"N	77° 55' 15.36"E	16° 11' 41.74"N	Pedda Vagu	Priyadarshini Jurala / Jurala Dam	Atmakur, Garlapadu, Gadwal, Thoompally
KR_14	77° 55' 15.36"E	16° 11' 41.74"N	78° 14' 31.32"E	15° 57' 21.63"N	Ukacheti Vagu		Rangapur, Yaparla, Peddamaroor, Kaluru
KR_15	78° 14' 31.32"E	15° 57' 21.63"N	78° 35' 41.95"E	16° 04' 14.25"N	Yerragattu Vagu		Somasila, Kollapur
KR_16	78° 35' 41.95"E	16° 04' 14.25"N	78° 53' 05.28"E	16° 06' 27.79"N			Srisailam
KR_17	78° 53' 05.28"E	16° 06' 27.79"N	79° 10' 53.68"E	16° 12' 46.88"N		Srisailam Dam	Sundipenta

Reach-ID	Longitude at origin (DMS)	Latitude at origin (DMS)	Longitude at end (DMS)	Latitude at end (DMS)	Important tributaries	Water resources projects	Major towns
KR_18	79° 10' 53.68"E	16° 12' 46.88"N	79° 16' 42.17"E	16° 34' 29.36"N	Dinai, Peddavagu		Chintala Thanda, Kampalapally
KR_19	79° 16' 42.17"E	16° 34' 29.36"N	79° 41' 01.76"E	16° 41' 37.67"N	Halia, Musi	Nagarjuna Sagar Dam, Nagarjunasagar Tail Pond Dam	Nandikonda, Nagarjuna Sagar, Chintalapalem, Mallavaram, Gottimukkala, Mudhimanikyam, Irkigudem, Pondugala, Wazirabad
KR_20	79° 41' 01.76"E	16° 41' 37.67"N	80° 01' 20.26"E	16° 42' 37.50"N			Ramapuram, Mattampalli, Chintriyal, Tammavaram
KR_21	80° 01' 20.26"E	16° 42' 37.50"N	80° 14' 19.61"E	16° 36' 18.11"N	Paleru	Pulichintala Dam	Madipadu, Muktyala, Challagariga, Taduvayi, Ramanapeta, Chintapalli, Putlagudem, Pokkunuru, Achampet, Kodavatikallu, Nadukuru
KR_22	80° 14' 19.61"E	16° 36' 18.11"N	80° 39' 42.72"E	16° 27' 44.93"N	Budameru, Munneru	Prakasam Barrage	Eturu, Didugu, Amaravati, Kothapet, Tummalapalem, Guntupalli, Mandadam, Venkatapalem, Sitanagaram, Gollapudi, Chittinagar, Tarapet, Vijayawada, Ramalingeswara Nagar
KR_23	80° 39' 42.72"E	16° 27' 44.93"N	80° 52' 58.36"E	16° 04' 27.45"N			Chirravuru, Nuttakki, Chodavaram, Pedakonduru, Vallabhapuram, Munnangi, Kollipara, Srikakulam, Kokiligadda Kotha Palem

Reach-ID	Longitude at origin (DMS)	Latitude at origin (DMS)	Longitude at end (DMS)	Latitude at end (DMS)	Important tributaries	Water resources projects	Major towns
KR_24	80° 52' 58.36"E	16° 04' 27.45"N	80° 49' 59.29"E	15° 42' 04.33"N			Penumudi, Pulligada, Mineni Vari Palem, Vekanuru, Nagayalanka, Piratlanka, Lankevanidibba
KR_25	80° 54' 00.46"E	16° 03' 23.21"N	81° 08' 26.14"E	15° 57' 56.55"N			Avanigadda, Kothapeta, Kosuruvaripailem, Viswanadhapalli, Pittallanka, Pedakallepalli
KR_26	80° 53' 30.78"E	15° 50' 52.03"N	81° 00' 48.88"E	15° 45' 29.88"N			Edurumondi, Gullalamoda, Pedda Kamma Vari Palem, Gullalamoda
KR_27	80° 51' 57.90"E	15° 48' 56.41"N	80° 55' 58.59"E	15° 42' 52.26"N			Elachetladibba, Nachugunta
Tungabhadra River							
TR_01	75° 40' 30.23"E	14° 00' 24.47"N	75° 38' 48.22"E	14° 15' 13.16"N	Tunga, Bhadra		Sanyasi Kodamaggi, Nagasamudra, Anaveri, Chillur, Hosahalli, Sasvehalli, Govinakovi, Rampura, Haralahalli, Bidaragadde, Benakanahalli, Kammaragatte, Devanayakanahalli, Honnali
TR_02	75° 38' 48.22"E	14° 15' 13.16"N	75° 48' 08.32"E	14° 32' 40.15"N	Haridra, Kudumadvathi		Belimalluru, Holeharalahalli, Hiregonigere, Hallur, Konanathale, Govinahalu, Ukkadagathri, Vasana, Mudenur, Nandigavi, Bilasanur, Rajanahalli, Halasabalu, Anniger, Guttur
TR_03	75° 48' 08.32"E	14° 32' 40.15"N	75° 41' 04.30"E	14° 47' 26.72"N			Dheetur, Pamenahalli, Sarathi, Airani, Chikkabidre, Hirebidari, Kadathi, Nittur, Udagatti,

Reach-ID	Longitude at origin (DMS)	Latitude at origin (DMS)	Longitude at end (DMS)	Latitude at end (DMS)	Important tributaries	Water resources projects	Major towns
							Tavaragundi, Halvagalu, Belur, Haranagiri, Harivi, Kuruvatti
TR_04	75° 41' 04.30"E	14° 47' 26.72"N	75° 53' 07.43"E	15° 03' 09.03"N	Varada	Singatalur/Hammigi Barrage	Mylara, Kancharagatti, Havanur, Byalhunsi, Itagi, Magala, Bidarahalli, Hammigi
TR_05	75° 53' 07.43"E	15° 03' 09.03"N	76° 11' 25.12"E	15° 14' 08.54"N	Hiri Halla, Ayyanakeri Halla		Kombili, Korlahalli, Katarkigudlanur
TR_06	76° 11' 25.12"E	15° 14' 08.54"N	76° 33' 15.55"E	15° 23' 31.50"N	Rotti Halla, Shankarana Halla	Tungabhadra Dam	Hosapete, Hosa Halli, Huligi, Hampi, Anegudi
TR_07	76° 33' 15.55"E	15° 23' 31.50"N	76° 51' 20.64"E	15° 38' 27.34"N	Nari Halla		Kampli, Chikka Jantakal, Hebbal, Mustur, Nadivi
TR_08	76° 51' 20.64"E	15° 38' 27.34"N	77° 09' 57.11"E	15° 56' 58.53"N	Hagari, Anaikat Halla, Vedavathi		Dasanur, Kengal, Dadesagur, Madlapur
TR_09	77° 09' 57.11"E	15° 56' 58.53"N	77° 36' 30.87"E	15° 55' 00.52"N		Rajolibunda Anicut	Manthralayam, Bichale, Rampuram, Madhavaram, Talamari, Nagaladinne
TR_10	77° 36' 30.87"E	15° 55' 00.52"N	78° 01' 39.43"E	15° 51' 07.33"N	Pedda Vanka	Sunkesula Barrage	Keshvaaram, Peddadhanwada, Malasomapuram, Tummila, Kothakota, Rajoli, Panchalingala
TR_11	78° 01' 39.43"E	15° 51' 07.33"N	78° 15' 13.76"E	15° 58' 07.67"N	Hindri		Kurnool, Alampur

The chainage details of the major cities and hydraulic structures in the mainstream of Krishna and Tungabhadra rivers are given in Tables 8 and 9.

Table 8: Chainage details of major cities and landmarks in the mainstream of Krishna River

Sl. No.	Chainage (km)	Location details of Cross-section	Reach-ID
--	0	Origin at Mahabaleshwar	
1	10	Dhom Dam	
2	20	Wai Town	
3	30	Bhuinj	
4	40	Udtaare	
5	50	Limb	
6	60	Khsetra Mahuli	
7	70	Vandana Chinchner	
8	80	Angapur	
9	90	Nandgaon	
10	100	Perle	
11	110	Shivde (Umbraj)	
12	120	Shirwade	
13	130	Khodshi Weir	
14	140	Karad	KR_01
15	150	Kodoli	KR_01
16	160	Rethare	KR_01
17	170	Narsingpur	KR_01
18	180	Borgaon	KR_01
19	190	Takari	KR_02
20	200	Khed (Old)	KR_02
21	210	Nagthane	KR_02
22	220	Bhileade	KR_02
23	230	M.Digraj	KR_03
24	240	Ankli	KR_03
25	250	Kanwad	KR_03
26	260	Alas	KR_04
27	270	Jugal	KR_04
28	280	Yedur	KR_04
29	290	Ingali	KR_04

Sl. No.	Chainage (km)	Location details of Cross-section	Reach-ID
30	300	Molawad	KR_04
31	310	Kudchi Bridge (Ugar)	KR_05
32	320	Gundwad	KR_05
33	330	Saptsagar	KR_05
34	340	Darur	KR_05
35	350	Tamdoddi	KR_05
36	360	Asangi	KR_06
37	370	Shirguppi	KR_06
38	380	Mutthur	KR_06
39	390	Kadakol	KR_06
40	400	Chikpadsalgi	KR_06
41	410	Mundagnoor	KR_07
42	420	Galgali	KR_07
43	430	Girgavi	KR_07
44	440	Sonna	KR_07
45	450	Almatti reservoir	KR_08
46	460	Almatti dam	KR_08
47	470	Kalagi	KR_08
48	480	Hondargalia	KR_08
49	490	Gangur	KR_09
50	500	Dhannur	KR_09
51	510	Narayanpur reservoir	KR_09
52	520	Narayanpur Dam	KR_09
53	530	Chayadevi Temple	KR_09
54	540	Ammapur	KR_10
55	550	Geddalmuri	KR_10
56	560	Benchagaddi	KR_10
57	570	Tintani bridge	KR_10
58	580	Kampapur	KR_10
59	590	Anjala	KR_11
60	600	Joladahedgi	KR_11
61	610	Hayal Buzurg	KR_11
62	620	Koppur	KR_11
63	630	Gogal Barrage	KR_12

Sl. No.	Chainage (km)	Location details of Cross-section	Reach-ID
64	640	Arsangi	KR_12
65	650	Deosugar	KR_12
66	660	Backwater of Jurala Project	KR_12
67	670	Backwater of Jurala Project	KR_13
68	680	Backwater of Jurala Project	KR_13
69	690	2 km D/s of Jurala project	KR_13
70	700	12 km D/s of Jurala project	KR_13
71	710	1 km U/s of K.Agraharam	KR_13
72	720	Teluguvanipalli	KR_13
73	730	Beechpalli Highway bridge	KR_14
74	740	Backwater of Srisailam Dam	KR_14
75	750	Backwater of Srisailam Dam	KR_14
76	760	Backwater of Srisailam Dam	KR_14
77	770	Backwater of Srisailam Dam	KR_14
78	780	Backwater of Srisailam Dam	KR_15
79	790	Backwater of Srisailam Dam	KR_15
80	800	Backwater of Srisailam Dam	KR_15
81	810	Backwater of Srisailam Dam	KR_15
82	820	Backwater of Srisailam Dam	KR_15
83	830	Backwater of Srisailam Dam	KR_15
84	840	Backwater of Srisailam Dam	KR_16
85	850	Backwater of Srisailam Dam	KR_16
86	860	Backwater of Srisailam Dam	KR_16
87	870	Backwater of Srisailam Dam	KR_16
88	880	Backwater of Srisailam Dam	KR_16
89	890	10 km D/s of Srisailam dam	KR_17
90	900	Backwater of N.S.Dam	KR_17
91	910	Backwater of N.S.Dam	KR_17
92	920	Backwater of N.S.Dam	KR_17
93	930	Backwater of N.S.Dam	KR_18
94	940	Backwater of N.S.Dam	KR_18
95	950	Backwater of N.S.Dam	KR_18
96	960	Backwater of N.S.Dam	KR_18
97	970	Backwater of N.S.Dam	KR_18

Sl. No.	Chainage (km)	Location details of Cross-section	Reach-ID
98	980	Backwater of N.S.Dam	KR_19
99	990	D/s of N.S.Dam	KR_19
100	1000	Chityal	KR_19
101	1010	Adavidevulapalli	KR_19
102	1020	Pondugala	KR_19
103	1030	5 km D/s of Pondugala	KR_20
104	1040	Ramapuram	KR_20
105	1050	Gundeboinagudem	KR_20
106	1060	Mettapalli	KR_20
107	1070	Gundlapalli	KR_20
108	1080	Nemalipuri	KR_21
109	1090	Vedadri	KR_21
110	1100	Ramannapet (Gudimettlu)	KR_21
111	1110	Backwater of Barrage	KR_21
112	1120	Backwater of Barrage	KR_21
113	1130	Backwater of Barrage	KR_22
114	1140	Backwater of Barrage	KR_22
115	1150	Backwater of Barrage	KR_22
116	1160	Yanamalakuduru	KR_22
117	1170	Maddur (Kaasarlanka)	KR_22
118	1180	Badrirajpalem	KR_23
119	1190	Marshy Area near Sea	KR_23
120	1200	Marshy Area near Sea	KR_23
121	1210	Marshy Area near Sea	KR_23
122	1220	Marshy Area near Sea	KR_23
123	1230	Marshy Area near Sea	KR_24
124	1240	Marshy Area near Sea	KR_24
125	1250	Marshy Area near Sea	KR_24
126	1260	Marshy Area near Sea	KR_24
127	1270	Marshy Area near Sea	KR_24
128	1280	Marshy Area near Sea	KR_24
129	1290	Marshy Area near Sea	KR_24

Table 9: Chainage details of major cities and landmarks in the mainstream of Tungabhadra River

Sl. No.	Chainage (km)	Location details of Cross-section	Reach-ID
1	5	Holalur	TR_01
2	15	Chilur	TR_01
3	30	Govinkovi	TR_01
4	45	Honnalli	TR_01
5	60	Puttigeri	TR_02
6	68	Nandigudi	TR_02
7	83	Hulinghole	TR_02
8	98	Harihar	TR_02
9	113	Sarathi	TR_03
10	123	Nittur	TR_03
11	135	Garbagudi	TR_03
12	155	Kuruvathi	TR_03
13	163	Harlahalli	TR_04
14	175	Chikka Bennimath	TR_04
15	185	Anguru	TR_04
16	193	Magala	TR_04
17	203	Rajawali	TR_04
18	218	Medalkatti	TR_05
19	280	Munirabad	TR_06
20	295	Kamalapuram	TR_06
21	310	Kampli	TR_07
22	317	Avallhalli	TR_07
23	327	Oolenur	TR_07
24	337	Mukundi	TR_07
25	350	Virupapuram	TR_08
26	360	Upla	TR_08
27	370	Ayyanur	TR_08
28	385	Marali	TR_08
29	397	Kandukur	TR_09
30	408	Kataknur	TR_09
31	418	Madhavaram	TR_09
32	426	Mantralayam	TR_09
33	430	Talamari	TR_09

Sl. No.	Chainage (km)	Location details of Cross-section	Reach-ID
34	445	Nagaladenne	TR_09
35	455	Paddadanavada	TR_10
36	475	Dudyala	TR_10
37	490	Bawapuram	TR_10
38	500	Kurnool	TR_11

Table 10: Channel geometry of the reaches of Krishna and Tungabhadra rivers

Reach-ID	Length (km)	Width (m)	Slope (m m^{-1})	Drainage area (km^2)	Sinuosity	Sub-basin
Krishna River						
KR_01	50	217	0.040	5,933	1.87	Upper Krishna
KR_02	50	167	0.260	9,447	1.63	Upper Krishna
KR_03	50	168	0.140	14,867	1.90	Upper Krishna
KR_04	50	206	0.160	18,189	2.17	Upper Krishna
KR_05	50	244	0.080	20,980	1.39	Upper Krishna
KR_06	50	384	0.080	22,338	1.58	Upper Krishna
KR_07	50	713	0.160	23,452	1.78	Upper Krishna
KR_08	50	2527	0.340	33,512	1.05	Upper Krishna
KR_09	50	1976	1.320	46,747	1.33	Upper Krishna
KR_10	50	1366	1.460	52,299	1.06	Upper Krishna
KR_11	50	694	0.140	54,008	1.52	Upper Krishna
KR_12	50	1044	0.400	1,22,918	1.10	Upper Krishna
KR_13	50	1376	1.040	1,25,558	1.08	Upper Krishna
KR_14	50	1935	0.220	2,02,469	1.15	Upper Krishna
KR_15	50	2491	0.060	2,05,817	1.25	Lower Krishna
KR_16	50	729	0.100	2,06,640	1.60	Lower Krishna
KR_17	50	434	1.860	2,08,039	1.50	Lower Krishna
KR_18	50	3997	0.060	2,13,523	1.19	Lower Krishna
KR_19	50	1227	2.200	2,32,788	1.11	Lower Krishna
KR_20	50	542	0.420	2,35,878	1.43	Lower Krishna
KR_21	50	1111	0.040	2,38,967	1.92	Lower Krishna
KR_22	50	2953	0.360	2,51,219	1.04	Lower Krishna
KR_23	50	3124	0.120	2,56,500	1.03	Lower Krishna
KR_24	44	1567	0.050	2,58,948	1.03	Lower Krishna
KR_25	43	397	0.020	2,58,948	1.59	Lower Krishna

Reach-ID	Length (km)	Width (m)	Slope (m m^{-1})	Drainage area (km^2)	Sinuosity	Sub-basin
Krishna River						
KR_26	17	816	0.010	2,58,948	1.05	Lower Krishna
KR_27	14	671	0.010	2,58,948	1.05	Lower Krishna
Tungabhadra River						
TR_01	50	370	0.360	7,573	1.83	Tungabhadra
TR_02	50	384	0.360	13,005	1.44	Tungabhadra
TR_03	50	359	0.260	14,329	1.69	Tungabhadra
TR_04	50	442	0.280	22,045	1.40	Tungabhadra
TR_05	50	2046	0.100	23,766	1.28	Tungabhadra
TR_06	50	4312	1.980	29,921	1.19	Tungabhadra
TR_07	50	677	0.740	33,801	1.17	Tungabhadra
TR_08	50	788	0.420	62,978	1.05	Tungabhadra
TR_09	50	702	0.660	65,460	1.05	Tungabhadra
TR_10	50	831	0.560	67,290	1.10	Tungabhadra
TR_11	37	1061	0.300	71,417	1.35	Tungabhadra

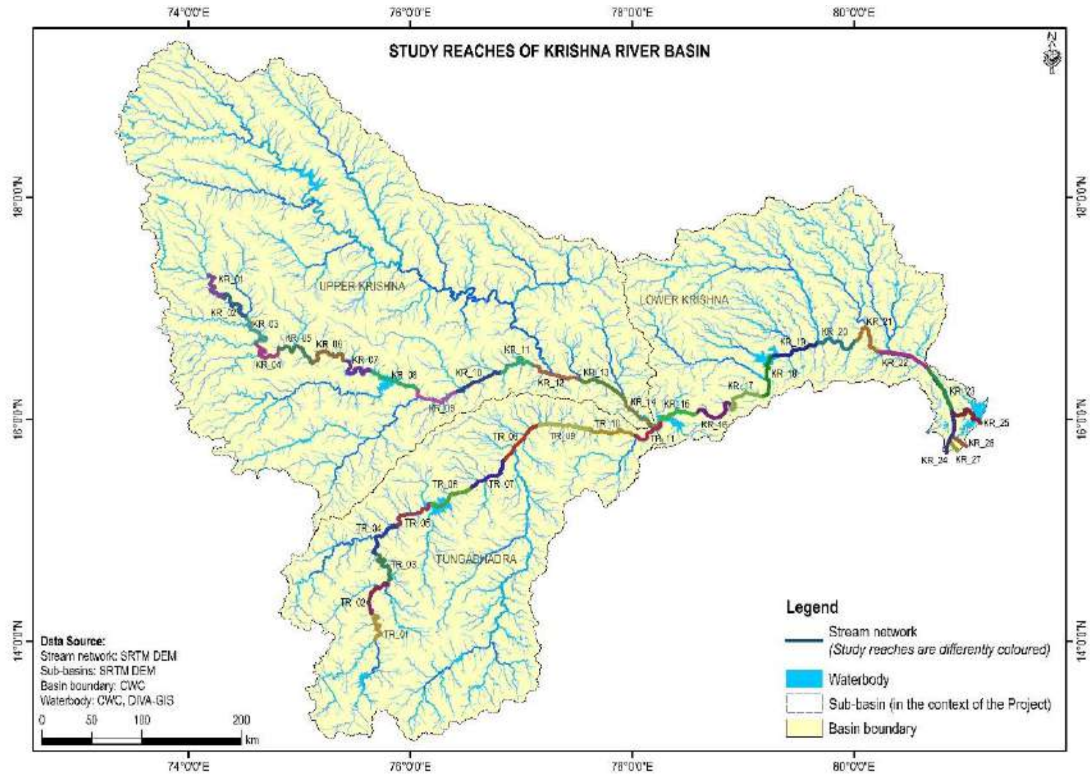

Fig. 8: Study reaches selected for morphological studies in Krishna and Tungabhadra Rivers

Sinuosity index of the river reaches indicates that eight reaches of Krishna River (i.e., KR_08, KR_10, KR_13, KR_22, KR_23, KR_24, KR_26, and KR_27; Table 10) and two reaches of Tungabhadra River (TR_08 and

TR_09) are classified as straight (i.e., sinuosity < 1.1), where six reaches of Krishna (KR_05, KR_09, KR_14, KR_15, KR_17, and KR_20) and Tungabhadra (TR_02, TR_04, TR_05, TR_06, TR_07 and TR_10) are characterized as sinuous (between 1.1 and 1.5). The highly sinuous (or meandered) reaches have sinuosity greater than 1.5 and are mostly developed in the upstream of the Krishna and Tungabhadra rivers. Further, the sinuosity of the reaches is controlled both by topography as well as channel hydraulics.

The study reaches belong to Upper Krishna (KR_01 to KR_14) are mostly underlain by basalts, Kaladgi Group rocks, potassic granodiorite to granite, granite as well as metavolcanics with metasediments and granitoid gneiss (Table 11), whereas the study reaches of Lower Krishna are developed predominantly on potassic granodiorite to granite, Srisailam quartzite, Kurnool Group rocks and Cumbum Formation. However, the study reaches of Tungabhadra River are underlain by TTG, greywacke with volcanics and chemogenic precipitates, metavolcanics with metasediments and granitoid gneiss, granite as well as potassic granodiorite to granite. All the reaches, except KR_01 to KR_04 and KR_23 to KR_27, are dominated by different rock types, where the KR_01 to KR_04 are purely developed on basalts and KR_22 to KR_27 are mainly formed on Quaternary sediments.

Table 11: Lithological types of the reaches of Krishna and Tungabhadra rivers

Reach-ID	Lithological type*
Krishna River	
KR_01	Basalt
KR_02	Basalt
KR_03	Basalt
KR_04	Basalt
KR_05	Basalt, Kaladgi Group
KR_06	Basalt, Kaladgi Group
KR_07	Kaladgi Group, Basalt, Granite
KR_08	Kaladgi Group, Granite, Basalt, Metavolcanics with metasediments and granitoid gneiss
KR_09	Granite, Potassic granodiorite to granite, Metavolcanics with metasediments and granitoid gneiss
KR_10	Granite, High-grade schists and ultramafites
KR_11	Potassic granodiorite to granite, Granite, Metavolcanics with metasediments and granitoid gneiss
KR_12	Granite, Potassic granodiorite to granite
KR_13	Potassic granodiorite to granite, Granite, Metavolcanics with metasediments and granitoid gneiss
KR_14	Kurnool Group, Potassic granodiorite to granite, Vempalle Formation with basic sills, Granite

Reach-ID	Lithological type*
Krishna River	
KR_15	Kurnool Group, Potassic granodiorite to granite, Vempalle Formation with basic sills, Cumbum Formation
KR_16	Cumbum Formation, Srisailam Quartzite
KR_17	Srisailam Quartzite
KR_18	Potassic granodiorite to granite, Srisailam Quartzite, Kurnool Group
KR_19	Potassic granodiorite to granite, Kurnool Group, Srisailam Quartzite
KR_20	Kurnool Group
KR_21	Potassic granodiorite to granite, Cumbum Formation, Kurnool Group
KR_22	Quaternary sediments, Migmatite Complex, Potassic granodiorite to granite, Charnockite
KR_23	Quaternary sediments
KR_24	Quaternary sediments
KR_25	Quaternary sediments
KR_26	Quaternary sediments
KR_27	Quaternary sediments
Tungabhadra River	
TR_01	TTG, Greywacke with volcanics and chemogenic precipitates, Granitoid, and gneiss
TR_02	Greywacke with volcanics and chemogenic precipitates, TTG
TR_03	Greywacke with volcanics and chemogenic precipitates
TR_04	Greywacke with volcanics and chemogenic precipitates, TTG
TR_05	TTG, Greywacke with volcanics and chemogenic precipitates
TR_06	TTG, Granite, Metavolcanics with metasediments and granitoid gneiss, Granitoid and gneiss
TR_07	Metavolcanics with metasediments and granitoid gneiss, Granite, Potassic granodiorite to granite
TR_08	Potassic granodiorite to granite, Granite
TR_09	Granite, Greywacke with volcanics and chemogenic precipitates
TR_10	Granite, Kurnool Group, Metavolcanics with metasediments and granitoid gneiss
TR_11	Vempalle Formation with basic sills, Kurnool Group

* Order of lithology depends on the descending order of their areal extent

SECTION 6
INPUT DATA AND METHODOLOGY

6.1. Description of data used

In order to accomplish the objectives of the project, various spatial and non-spatial (historic as well as contemporary) data were used. This section deals with the collection, processing, and analysis of the different datasets used in the present project.

6.1.1. Survey of India (SoI) topographic maps

The SoI topographic maps (of 1: 50,000 scale) were purchased (Table 12), which was primarily used as a reference as well as for georeferencing of the satellite images. The KRB is covered by 426 topographic sheets, among which 231 selected, where the mainstream channels of Krishna and Tungabhadra rivers have been mapped. However, only 173 sheets (among the 231 numbers) were purchased due to unavailability of the printed maps.

Table 12: Details of the SoI topographic maps procured from Survey of India

Scale	Year of Survey	Data Source	No. of sheets	Remarks
1: 50,000	1967	Survey of India	173	Purchased
Sheet Index				
47 F/07, 47 F/08, 47 F/11, 47 F/12, 47 F/15, 47 F/16, 47 G/05, 47 G/09, 47 G/10, 47 G/13, 47 G/14, 47 G/16, 47 J/04, 47 K/01, 47 K/02, 47 K/03, 47 K/04, 47 K/05, 47 K/06, 47 K/08, 47 K/15, 47 L/02, 47 L/11, 47 L/12, 47 L/14, 47 L/15, 47 L/16, 47 P/01, 47 P/02, 47 P/05, 47 P/06, 47 P/07, 47 P/08, 47 P/11, 47 P/13, 47 P/14, 48 M/07, 48 M/08, 48 M/09, 48 M/11, 48 M/12, 48 M/13, 48 M/14, 48 M/15, 48 M/16, 48 N/05, 48 N/06, 48 N/07, 48 N/08, 48 N/09, 48 N/10, 48 N/11, 48 N/12, 48 N/13, 48 N/14, 48 N/16, 48 O/01, 48 O/02, 48 O/03, 48 O/04, 48 O/05, 48 O/06, 48 O/07, 48 O/08, 48 O/09, 48 O/11, 48 O/12, 48 O/14, 48 O/16, 48 P/01, 48 P/05, 48 P/13, 56 D/01, 56 D/02, 56 D/03, 56 D/04, 56 D/06, 56 D/07, 56 D/09, 56 D/10, 56 D/11, 56 D/12, 56 D/13, 56 D/14, 56 D/16, 56 H/01, 56 H/02, 56 H/03, 56 H/04, 56 H/05, 56 H/06, 56 H/07, 56 H/08, 56 H/10, 56 H/11, 56 H/12, 56 H/14, 56 H/15, 56 H/16, 56 L/03, 56 L/04, 56 L/06, 56 L/07, 56 L/08, 56 L/10, 56 L/11, 56 L/12, 56 L/14, 56 L/15, 56 O/08, 56 O/12, 56 P/01, 56 P/03, 56 P/05, 56 P/07, 56 P/08, 56 P/10, 56 P/11, 56 P/12, 56 P/13, 56 P/15, 57 A/01, 57 A/02, 57 A/03, 57 A/04, 57 A/05, 57 A/06, 57 A/08, 57 A/11, 57 A/12, 57 A/14, 57 B/01, 57 B/02, 57 B/03, 57 B/04, 57 B/05, 57 B/09, 57 C/02, 57 C/03, 57 E/01, 57 E/02, 57 E/03, 57 E/04, 57 E/09, 57 E/10, 57 E/13, 57 E/14, 57 I/05, 57 I/06, 57 I/14, 57 M/01, 57 M/05, 65 C/04, 65 D/01, 65 D/03, 65 D/05, 65 D/06, 65 D/07, 65 D/08, 65 D/09, 65 D/10, 65 D/11, 65 D/12, 65 D/14, 65 D/15, 65 D/16, 65 H/02, 65 H/03, 65 H/04, 65 H/07, 66 A/09, 66 A/13&14, 66 E/01&02				

6.1.2. Digital elevation model (DEM)

Since DEMs of different spatial resolutions (e.g., SRTM, ASTER, and Cartosat) are freely available, it is highly critical to choose the appropriate DEM for the analysis. Hence, the different DEMs (1 arc-second) were downloaded from various repositories (i.e., https://earthexplorer.usgs.gov, http://bhuvan.nrsc.gov.in) and analyzed for their horizontal and vertical accuracy as well as the capability for the derivation of the accurate drainage network. As most of the voids in the DEMs have been filled using interpolation algorithms in conjunction with other sources of elevation data, the DEM data available in the repositories are mostly voidless. However, some of the tiles (especially the area covering coastal segments of the KRB) still contain voids, which were further filled using the delta surface fill method.

The voidless DEM is then processed to remove the sinks to create a seamless elevation grid for hydrologic analysis. Further, flow direction (using D8 flow algorithm) and flow accumulation rasters were generated, and cells with flow accumulation higher than a threshold value were identified as a stream. The basin boundary was delineated using the flow direction. All the analyses were done using the Spatial Analyst and Arc Hydro toolboxes for ArcGIS.

The analysis revealed that the SRTM DEM provides better accuracy in basin geometry as well as stream channel orientation than the other DEMs. Hence, the SRTM DEM (1 arc second) was used for the physiographic analysis as well as for the delineation of lower order stream network of the KRB. The SRTM global elevation data offer worldwide coverage of high-resolution elevation data at a resolution of 1 arc-second (Table 13). The mission collected radar interferometry (InSAR) data over 80% of Earth's landmass from 60°N to 56°S latitude in February of 2000. The C-band (λ = 5.6 cm) data acquired during the mission have horizontal and vertical accuracy near 20 m and 16 m (linear error at 90% confidence) respectively.

Table 13: Data characteristics of SRTM DEM

Product specification	
Projection	Geographic
Horizontal Datum	WGS84
Vertical Datum	EGM96
Vertical Units	Meters
Spatial Resolution	1 arc-second for global coverage (~30 meters)
Raster Size	1-degree tiles
C-band Wavelength	5.6 cm

6.1.3. Remote sensing images

The choice of the remote sensing images for the project (1973, 1977, 1991, 2001 and 2011) was based on the availability, season, cloud cover, spectral as well as radiometric quality and spatial resolution of the data (Table 14). The study period mentioned in the MoU is from the base year (say 1970) till 2010 (i.e., 4 sets of satellite imageries at 10 years interval). However, for KRB, the remote sensing images are available only from 1973 (i.e., Landsat 1), and hence the base period has been changed to 1973. Similarly, satellite data (i.e., Landsat 3) are not available during the 1980s, and the pre- and post-1980 time periods, where data available are 1977 (Landsat 2) and 1987 (SPOT 1). However, the SPOT1 data scenes were not available for the entire reaches, where the reaches of upstream of Tungabhadra (i.e., TR_01 to TR_07) and parts of Krishna (i.e., KR_08 to KR_11, KR_15 to KR_19 and KR_23 to KR_27) are not covered. Hence, the Landsat 2 data for the year 1977 were considered for the year 1980.

Satellite scenes, corresponding to the basin, from different LANDSAT missions and IRS for the dry season, mostly from January and April, (with less than 10% cloud cover) were collected to minimize the errors related to the delineation of channel bank lines. Even though the remote sensing images have different spatial resolutions, a common scale (1: 50,000 in this case) was fixed for the mapping purposes to reduce the uncertainty in vectorization of landforms contributed by the pixel size. The details of the satellite images used in each time period are given in Appendices IV to VIII.

Table 14: Details of the multispectral remote sensing data collected for the morphological studies

Sensor/Platform	Year	Data source	Spatial resolution (m)	Spectral resolution	No. of scenes**	Remarks
Landsat 1 MSS	1973	USGS	60*	4	28	Downloaded
Landsat 2 MSS	1977	USGS	60*	4	28	Downloaded
Landsat 5 TM	1991	USGS	30	7	26	Downloaded
Landsat 7 ETM+	2001	USGS	30	8	26	Downloaded
IRS P6 LISS III	2011	NRSC	24	4	43	Purchased

*original MSS pixel size was 79 x 57 meters, but resampled to 60 m; **spatial coverage of KRB

The downloaded/purchased remote sensing images were preprocessed to reduce the sensor as well as atmospheric noises using haze and noise reduction and histogram equalization algorithms. The remote sensing images used in the study are generated from different sensors of different missions. Hence, the image scenes were co-registered with the ground control points (GCPs), representing permanent man-made structures, mostly road intersections, dams, canals and bridges, taken from the topographic maps to reduce the geo-location errors and improve the horizontal accuracy. The GCPs were evenly distributed across the scenes. After the geometric corrections, the data were re-projected using Lambert Conformal Conic (LCC) projection and the WGS84 datum. A first-order polynomial fit was applied for resampling the images using the nearest neighbor method. After the geometric corrections, the individual scenes (during a given time period) were mosaicked, and the resulting mosaics were subject to radiometric correction to correct for varying sun angle and changes in surface reflectance (Jensen, 1996).

6.1.4. Geologic data

The geology of the KRB was prepared from the state geological and mineral maps of Maharashtra, Karnataka, Telangana and Andhra Pradesh States, which was mapped on a scale of 1: 2,000,000 published by the Geological Survey of India (GSI). The geological maps of the corresponding States were downloaded from the GSI portal, and were georeferenced and manually digitized the boundaries of different lithological units pertaining to the KRB.

6.1.5. Hydrologic data

The CWC provided the basic geospatial and attribute data of the KRB, and the project has updated the geodatabase from the inputs collected during the project (Table 15). The basic geospatial data, such as the boundary of KRB, the mainstream of Krishna and Tungabhadra rivers, waterbody along the riverine zone and major towns were collected from CWC. In addition, the spatial data of the major hydraulic structures (dam, barrage, weir, and anicut) were collected from CWC. However, the data were updated by appending the data from WRIS-India along with the attributes. The drainage network and major sub-basins of KRB are derived from the DEM.

Hydrologic data (e.g., gauge, discharge, sediment load, bed material particle size, and cross section) recorded at different H.O. stations in KRB were collected from CWC, which was updated by comparing the data collected from WRIS-India portal. A total of 72 H.O. stations exist in KRB (Fig. 9), among which 41 belong to the Upper Krishna, 17 belongs to Tungabhadra and 14 belongs to Lower Krishna sub-basins, and the data characteristics are given in Appendix IX. Among the 72 H.O. stations, 19 are closed, while the rest are functional. However, the data length is highly variable among the H.O. stations.

The rainfall data of KRB were gathered from the India Meteorological Department (IMD) in the form of 0.25° x 0.25° gridded data, which were derived from the daily rainfall records, from the archive of National Data Centre, IMD, Pune for 113 years (Data period = 1901-2013), collected from 6955 rain gauge stations across India with varying availability periods (Pai et al., 2014). The rainfall data were used for the analysis of spatial variation of annual rainfall in KRB as well as for rainfall-runoff analysis.

Table 15: Geospatial data profile of KRB

Data	Particulars	Remarks
Basin boundary	Spatial extent	Collected from CWC
Major sub-basins	Spatial extent	DEM-derived output
Drainage network	Spatial extent	DEM-derived output
Mainstream channel	Spatial extent	Collected from CWC
Waterbody	Spatial extent	Collected from CWC
Major town	Location	Collected from CWC
Airport	Location	Collected from Google Earth
Hydraulic structure	Location and attributes (see Appendices I and II)	Collected from CWC and WRIS-India
H.O. Station	Location and attributes (e.g., gauge, discharge, sediment load, bed material size, and cross section)	Collected from CWC
Rainfall	Gridded data (0.25° x 0.25°)	Collected from IMD
River cross section	Location and X-section survey data	Collected from CWC
River longitudinal profile	Location and survey data	Collected from CWC
Land use/ land cover	Vegetation types	Collected from Land Cover Institute (USGS)

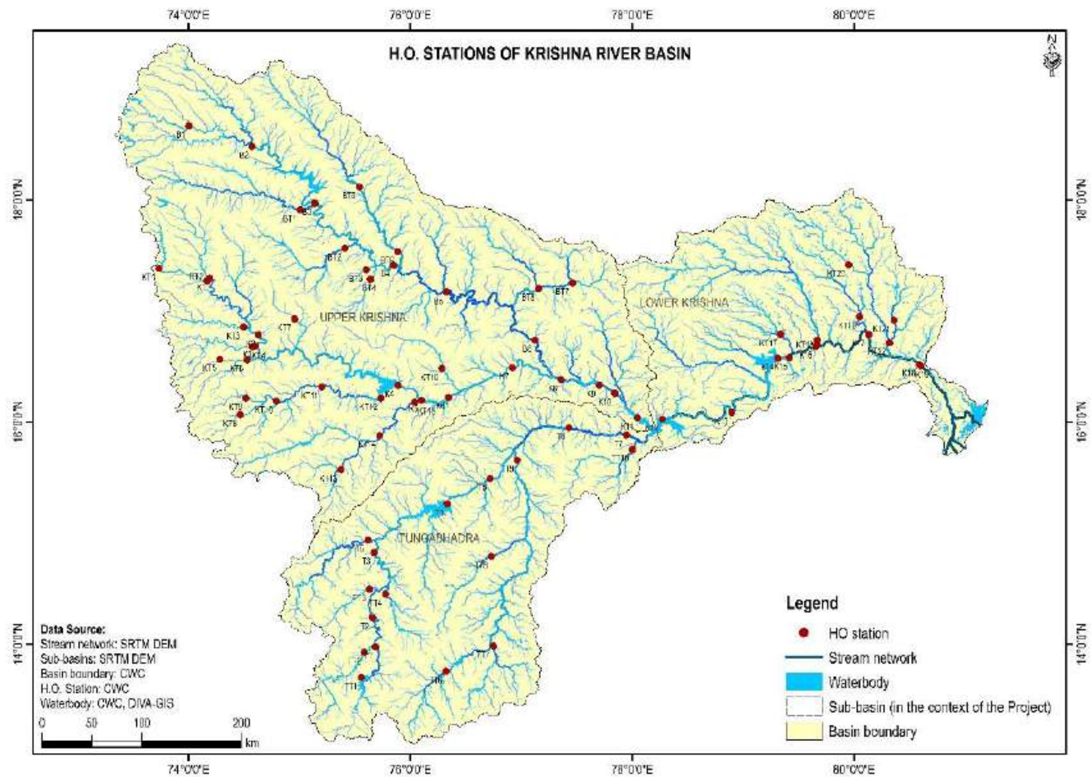

Fig. 9: H.O. stations of KRB

The cross-section and longitudinal profile data were collected from CWC. The cross-section data consist of cross-section profiles at 112 transects in Krishna and Tungabhadra rivers (74 and 38 cross section profiles respectively; Fig. 10). The data length is varying for Krishna (2009-2013) and Tungabhadra (2009-2015) Rivers. The cross-section profiles are not available along the inundated river segments due to reservoirs. The longitudinal profiles of Krishna River were also collected from CWC. Further, the H.O stations in KRB also have cross-section data, where the cross-section of the profile was recorded for multiple years. However, the data length is non-uniform for different H.O. stations.

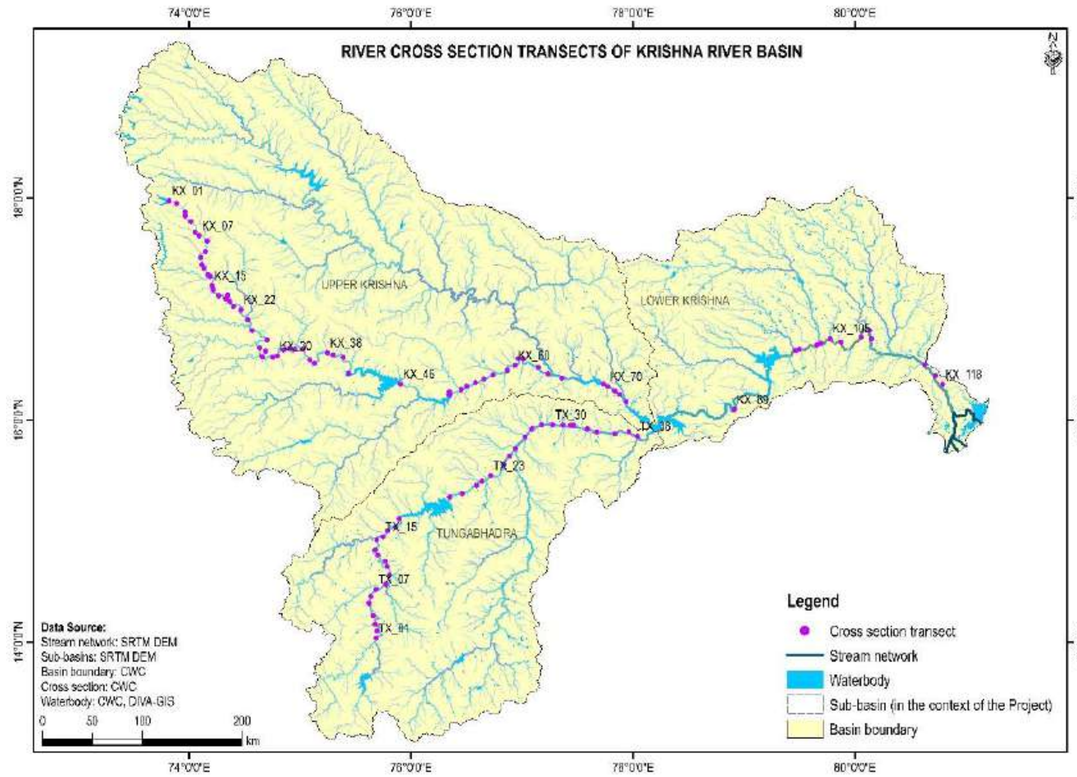

Fig. 10: River cross-section transects in Krishna and Tungabhadra rivers

6.1.6. Land use/ land cover

These land use/ land cover data (spatial resolution = ~500 m) describe the land cover type and are based on 10 years (2001-2010) of Collection 5.1 MCD12Q1 land cover type data of Moderate Resolution Imaging Spectroradiometer (MODIS). The value-added global land cover climatology was developed by weighting each land cover type by its corresponding confidence score for each year and using the highest-weighted land cover type in each pixel in the 2001-2010 MODIS data (Broxton et al., 2014). The classification of the land cover type is performed by the MODIS land cover type (MLCT) classification algorithm, which uses a supervised decision-tree algorithm (Quinlan 1993), which is distribution independent and contains robust procedures for handling missing data. More information regarding the data is available in Broxton et al. (2014).

6.2. Methodology

The methodological framework adopted to address the objectives of the study is given as Fig. 11 as a methodology flow chart:

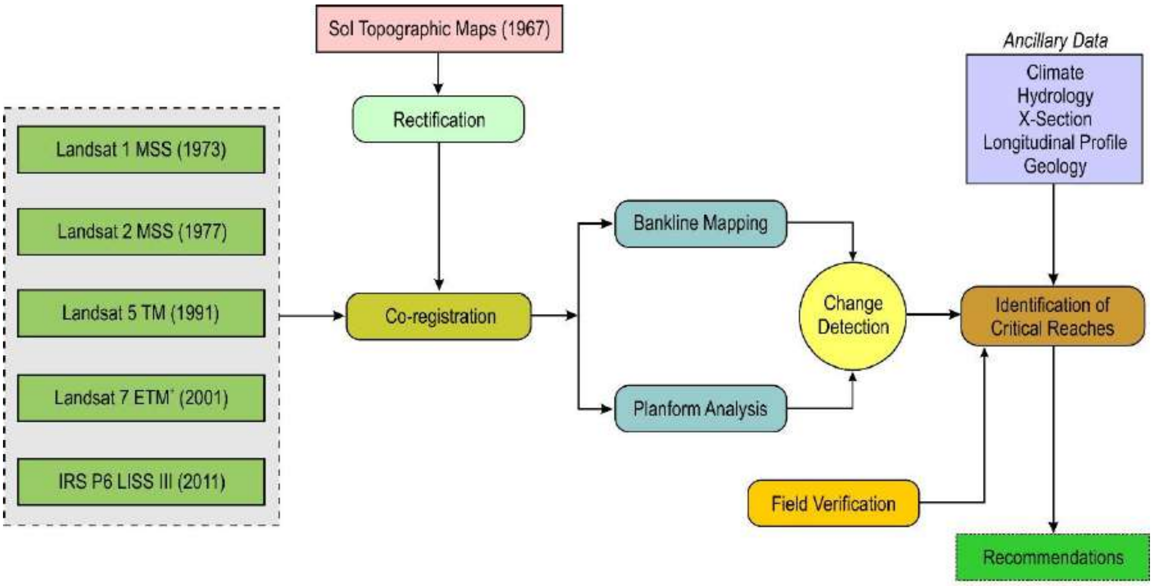

Fig. 11: Methodological framework adopted for the present study

SECTION 7
HYDROLOGICAL DATA PROCESSING & ANALYSIS

7.1. Introduction

Hydrological analysis mainly consists of rainfall-runoff modeling, flood frequency analysis, and sediment-discharge study using historical data. While rainfall-runoff modeling and flood frequency analysis are used for predicting the extreme events like floods and droughts, the quantity of sediments transported can be assessed from sediment discharge analysis. The results from the hydrologic analysis are generally used planning, design, and optimizing of water resources projects like reservoirs, hydropower plants, and many other hydraulic structures. The rainfall-runoff transformation process is highly nonlinear and varies in both space and time. The runoff generated from a catchment is also dependent on factors other than rainfall such as initial soil moisture conditions, land use, watershed geomorphology, evaporation, infiltration characteristics of soil etc. One of the commonly used parameters in the rainfall-runoff analysis is the runoff coefficient, which is a dimensionless parameter relating the runoff and rainfall characteristics of the basin. In this study, we estimated the runoff coefficients of different reaches using the historical observed records of rainfall and stream flow. A large value of runoff coefficient indicates areas with low infiltration and high runoff generation capacity such as urban areas, and lower values indicate permeable, well-vegetated areas like the forest. The identification of high runoff coefficient areas would aid in possible flood zone hazard delineation and flood channel control construction.

Flood frequency analysis aids in estimating flow values corresponding to specific return periods or probabilities at different reaches of the river. Flood frequency analysis is generally performed by considering annual maximum flows of the past years. The analysis yields frequency distribution and flow duration curves. Some of the commonly fitted distributions are Gumbel, Normal, Log-normal, exponential, Weibull, Pearson, and Log-Pearson, based on the best fitting appropriate distribution is selected. The flow duration and frequency distribution curves are used to estimate the design flow values corresponding to specific return periods, which are further used for planning and design of hydraulic structures such as dams, bridges, culverts, levees, highways, sewage disposal plants, waterworks, and, industrial buildings. In order to evaluate the optimum design specification for hydraulic structures, and to prevent over-designing or under designing, it is imperative to apply statistical tools to develop the flood frequency estimates. Along with hydraulic design, flood frequency estimates are also useful in flood insurance and flood zoning activities. Accurate estimation of flood frequency not only helps engineers in designing safe structures but also in protection against economic losses due to floods by proper maintenance of structures.

The magnitude of sediment transported by rivers has become a serious concern for water resources planning and management. The assessment of the volume of sediments being transported by a river is required in a wide spectrum of problems such as the design of reservoirs and dams, hydroelectric power generation and water supply, transport of sediment and pollutants in rivers, lakes and estuaries, determination of the effects of watershed management, and for environmental impact assessment. The sediment outflow the watershed is induced by processes of detachment, transportation, and deposition of soil materials by rainfall and runoff. The sediment discharge relationship would aid the water managers in estimating the amount of sediment accumulating in the reservoirs for their proper maintenance and also to take corrective measures for controlling bank erosion.

7.2. Climate

Krishna River basin (KRB) has a tropical climate and is dominated by the southwest monsoon, which provides most of the precipitation for the basin. The mean daily maximum temperature of the basin varies from 27.7 to 40.4 °C, and the mean daily minimum temperature ranges between 20.6 and 27.2 °C. Relative humidity in KRB shows large variability, i.e., between 17 and 92%, and mean relative humidity is significantly high during monsoon and post-monsoon periods compared to summer months. In KRB, wind direction varies from southwest during monsoon to north-west and north during post-monsoon to north-west and south-west during winter. The wind speed ranges from 4.0 to 21.7 km/h. Cloud cover of the basin varies between 0.8 to 8.0 oktas, and the sky is mostly clouded during monsoon and post-monsoon seasons (Jain et al., 2007).

The climate of the basin varies from humid to arid, where the majority of the basin (inland areas) falls under semi-arid climate. A narrow band (trending parallel) along the Western Ghats has a humid climate, while the foot slopes of the Western Ghats, the Eastern Ghats and the Krishna delta belong to the sub-humid climatic regime (Biggs, 2007). Jain et al. (2007) classified the climatic transition (from west to east) from per-humid through dry sub-humid through semi-arid. Further, the south-central part of the basin is characterized by the arid climate.

The average annual rainfall in the Krishna basin is 784 mm according to India-WRIS database. About 90% of annual rainfall is received during the Monsoon period, of which more than 70% occurs during July, August, and September. Being spread over the Indian Peninsula, monsoon (in two different spells) has dominant control over the climate of KRB. Although the rugged topography of the Western Ghats (in the upstream of the basin) comprises of nearly 10% of the basin area, it receives about 21% of annual rainfall of the basin and generates 57% of the basin's surface runoff (Biggs, 2007). The spatial distribution of mean annual rainfall over the basin is calculated using IMD gridded data for the period 1901-2013 as shown in Fig. 12. It can be observed that the headwater reaches as well as downstream portions of the basin receive good amount of rainfall during southwest and northeast monsoon episodes respectively, while inland areas of the basin receive significantly lower amount of rainfall annually, i.e., a decreasing rainfall gradient towards the central part from upstream as well as from downstream portions of the basin. Similarly, the coefficient of variation of the annual rainfall is also calculated and is depicted in Fig. 13.

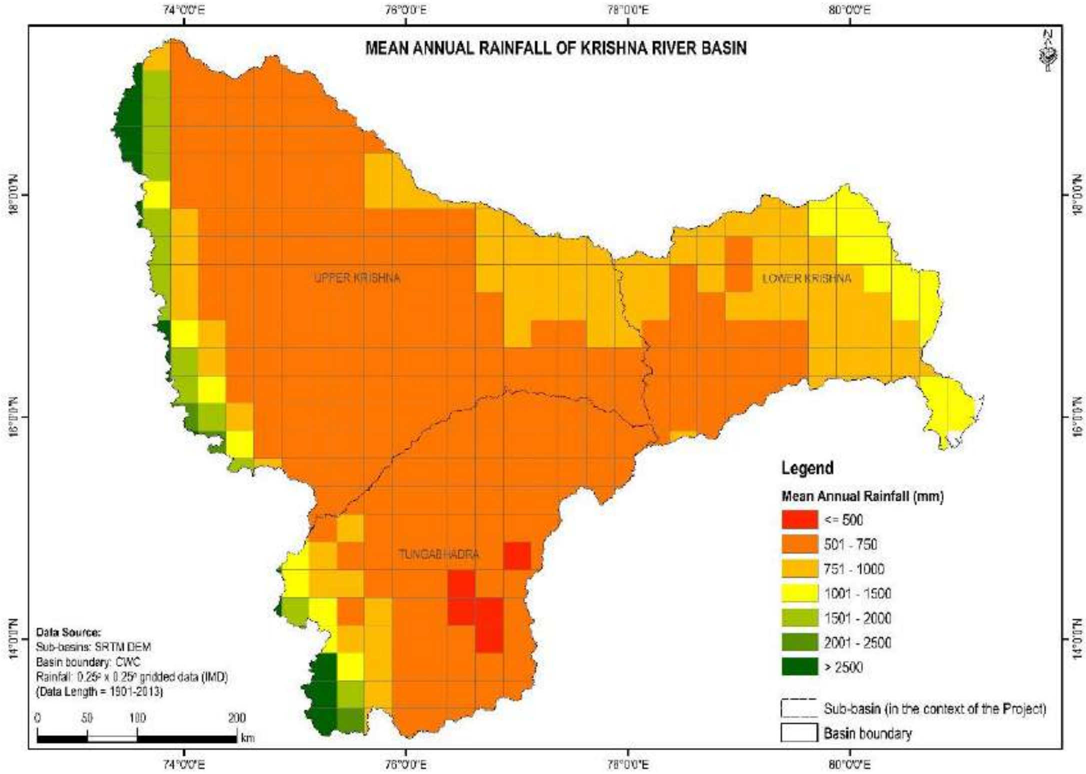

Fig. 12: Spatial variation of mean annual rainfall in KRB

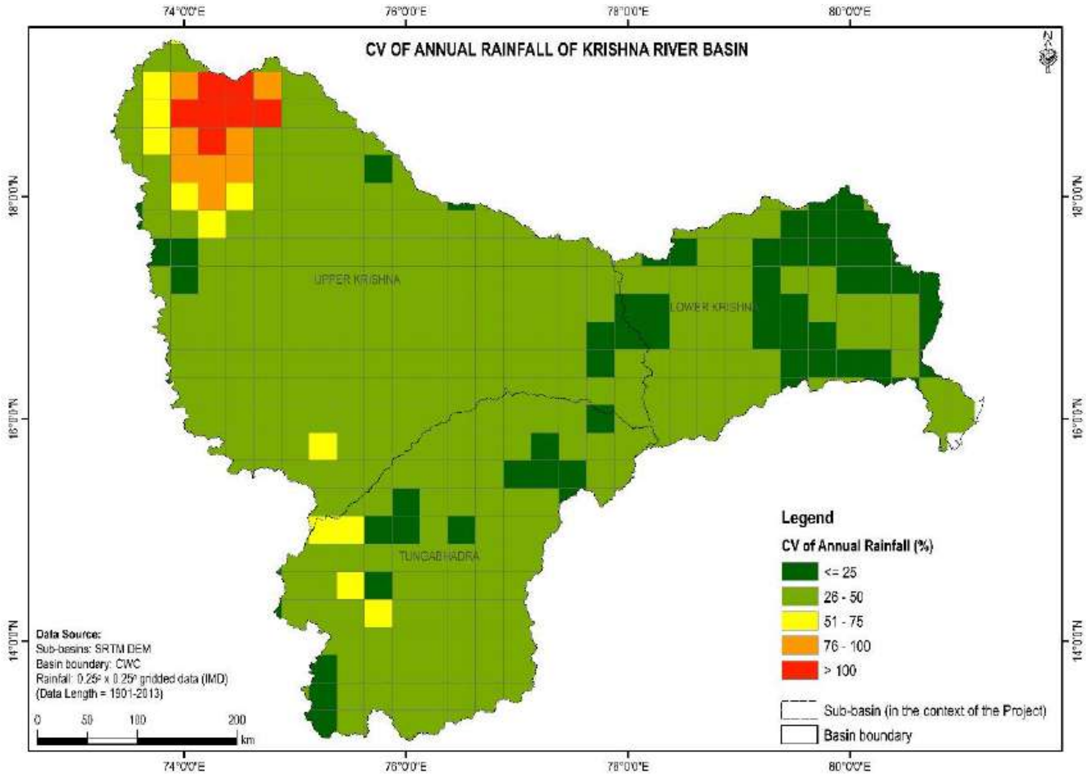

Fig. 13: Spatial variation of coefficient of variation of annual rainfall in KRB

A drastic decrease from more than 2500 mm (in the Western Ghats) to about 500 mm over a small distance to the eastern part of the Western Ghats is observed. Similarly, annual rainfall (gradually) decreases from about 1000 mm in the Krishna Delta in the east to roughly 500 mm in the north-western part of the basin. The same spatial pattern is reported by Gunnell (1997). Few regions in lower Tungabhadra basin receive less than 500 mm of annual rainfall.

7.3. Streamflow

The long-term mean annual surface flow of KRB is 78 km^3, of which 58 km^3 is considered to be utilizable (Amarasinghe et al. 2005). High flow in the river occurs during the months of August to December, while the lean flow season is from April to May (Jain et al., 2007). The basin has a long history of irrigation development projects (minor irrigation schemes as well as large-scale projects). Consequently, the discharge from KRB decreased rapidly during 1960-2003 due to expansion of irrigation projects (Biggs, 2007), dams, and, reservoirs along with other minor irrigation schemes to store about 54 billion cubic metres, which is 95% of the pre-1965 runoff when only a few dams were in existence (Venot, 2009). Annual runoff of KRB reduced from a pre-irrigation average of 57 km3 (1901-1960) or 29% of total rainfall to 13 km^3 (1994- 2003) or 7% of total rainfall, despite no significant change in rainfall. The measured runoff coefficients of Upper Krishna as well as Upper Bhima sub-basins shows a constant decrease, i.e., the coefficients fell from 0.68 in the 1960s, to 0.52 during 1971-1975, and to 0.45 during 1996-2001 in Upper Krishna, while in Upper Bhima, it decreased from 0.33 to 0.27 between 1971-1974 and 1996-2001 (Biggs, 2007).

The main reason behind the variation in the streamflow is the effect of hydraulic structures built in the river course. According to the purpose for which the dams are built, the releases also vary which in turn alters the normal stream flow. The releases from dams of different purposes vary according to the purpose of the dam. The releases at the hydropower dams have diurnal variations, where releases are curtailed for part of a day when the power demand is less, and relatively larger flows are released during peak demand periods. The releases from the dams built for irrigation vary monthly, where a large volume of water may be diverted during the cropping season to the command area, but in the non-cropping period most of the flows (and some sediment) are released to the downstream areas based on the operational policy of the dam. Irrespective of the purpose and release policy of dams, it is evident that the dams alter the natural stream flow of the river. In addition to changing the stream flow pattern, dams also act as sediment traps. The curtailment of sediment supply, along with the change in stream flow, have a significant impact on the downstream as well as upstream of the channel. The sediment load from various dams vary, for instance, the dams with the specific intent of sediment control would release little sediment to downstream while an irrigation or hydropower demand would release more sediment to maintain the storage levels of the reservoirs. The spatial and temporal variability of sediment flux in the KRB is discussed in 7.7.

The observed mean monthly streamflow data and sediment load data from the various H.O. stations in the KRB for the period 1965 - 2015 are plotted (Appendix X) to observe the variation of total sediment load and observed stream flow. Few of the observations are discussed herein. The sediment discharge and stream discharge downstream of the upper Tunga dam is observed to be uniform as is evident from TT2, plausibly due to the regulation of flows in the upstream by Upper Tunga dam which serves as hydropower as well as an irrigation dam. In another case for a station in Tungabhadra River (T3), uniform values can be observed for both water and sediment loads can be observed till 1995, after which the sediment loads diminish. A similar trend of diminishing of sediment load can be observed in B4 and BT6, this reduction in sediment discharge may be due to the construction and operations of dams upstream of these HO station sites. In BT1 and B6, the sediment load, as well as water discharge, are observed to be altered from 1990, which can be attributed to the construction of Girzani dam in Local Nallah and Yadgir barrage in Bhima River respectively. From the analysis, it is evident that there is a significant impact on the sediment and streamflow discharge due to the construction of dams and other hydraulic structures.

7.4. Flood frequency analysis

Flood frequency analysis involves the fitting of a probability distribution to the sample of annual maximum values recorded over a period of observation and obtaining the parameters of the distribution function. The model parameters estimated by this method can then be used to predict the extreme events of large recurrence interval. Reliable flood frequency estimates are vital for floodplain management; to protect the public, minimize flood-related costs to government and private enterprises; and for designing and locating hydraulic structures and assessing hazards related to the development of flood plains.

A flood frequency study was carried out using the annual maximum daily discharge values for the HO sites, using the Gumbel's distribution method which is one of the probability distribution methods used to model stream flows in Indian watersheds. Only those sites which are having a data length of more than twenty years are used for the analysis. In most of the sites, streamflow data is available from 1965 to 2015. Using Gumbel's probability distribution, the flood values corresponding to the return periods 1.5, 2, 5, 10, 25, 50, 100, 200 years are obtained and probability curves are plotted (Table 16; Appendix XI). An analysis was performed to identify the years in which the flood values pertaining to return periods (1.5, 2, 5, 10, 25, 50, 100, 200 years) were observed across the H.O. stations and same is presented in Appendix XII.

Table 16: Flood values ($m^3 s^{-1}$) corresponding to return periods

H.O. Code	Data Period	Return period in years							
		1.5	**2**	**5**	**10**	**25**	**50**	**100**	**200**
Krishna River									
B1	1992-2014	885	1208	2005	2532	3198	3692	4183	4672
B2	1967-2007	2246	3071	5100	6444	8142	9401	10651	11897
B3	1966-2015	2135	2957	4980	6320	8013	9268	10515	11756
B4	1965-2015	2376	3225	5315	6698	8446	9743	11030	12313
B6	1965-2015	3003	3951	6282	7826	9777	11224	12660	14091
BT1	1965-2015	831	1106	1784	2232	2798	3218	3636	4051
BT3	1979-2006	16	39	95	133	180	215	250	284
BT4	1979-2013	51	133	335	468	637	762	886	1010
BT6	1965-2015	474	749	1428	1877	2444	2865	3283	3700
BT7	1978-2006	223	374	745	991	1301	1531	1759	1987
BT8	1990-2015	627	863	1443	1827	2313	2673	3030	3386
K1	1965-2015	1970	2494	3786	4640	5721	6522	7317	8110
K10	1981-2007	6920	8659	12938	15771	19351	22006	24642	27269
K16	1975-2007	5874	8589	15271	19695	25284	29431	33547	37648
K17	1965-2015	6526	9122	15512	19743	25089	29054	32991	36913
K18	1965-2015	7325	9590	15163	18853	23515	26974	30407	33828
K2	1969-2014	2861	3450	4900	5861	7074	7974	8867	9757
K3	1972-2015	3919	4491	5899	6832	8010	8884	9752	10616
K7	1976-2015	5397	6314	8572	10067	11955	13356	14747	16133
KT1	1972-2007	529	868	1702	2255	2953	3471	3985	4498
KT10	1971-2014	859	1196	2023	2571	3263	3777	4287	4795
KT12	1966-2001	930	1182	1801	2211	2729	3114	3495	3875
KT14	1982-2014	525	744	1285	1642	2094	2430	2763	3094
KT17	1984-2015	25	291	946	1379	1926	2332	2736	3137
KT18	1968-2015	229	635	1634	2296	3133	3753	4369	4982
KT19	1965-2015	138	295	681	937	1260	1500	1738	1975
KT2	1966-2015	1172	1532	2419	3007	3749	4300	4846	5391
KT21	1984-2015	269	466	952	1274	1680	1982	2281	2580
KT22	1965-2015	1023	1719	3430	4563	5995	7057	8111	9162
KT3	1964-2014	1109	1321	1843	2188	2624	2948	3269	3590
KT4	1979-2014	1412	1644	2215	2593	3071	3425	3777	4128

KT5	1979-2007	310	362	490	575	682	761	840	919
KT6	1969-2014	981	1141	1535	1796	2125	2370	2612	2854
KT7	1979-2006	19	42	100	138	187	223	259	294
KT8	1978-2007	795	988	1462	1777	2174	2469	2761	3053
KT9	1980-2007	596	710	992	1179	1415	1591	1764	1938
Tungabhadra River									
T2	1980-2015	2191	2732	4061	4942	6054	6880	7699	8515
T3	1966-2015	2038	2503	3645	4401	5357	6066	6769	7470
T5	1972-2015	1660	2446	4379	5659	7277	8476	9667	10854
T6	1972-2015	2400	3680	6830	8915	11550	13505	15445	17378
T7	1965-2015	2440	3647	6617	8584	11068	12912	14741	16565
TT2	1972-2015	1986	2246	2886	3309	3845	4242	4636	5029
TT3	1990-2015	181	260	455	584	746	867	987	1106
TT4	1985-2015	101	157	295	386	502	587	672	757
TT5	1966-2015	600	731	1051	1263	1531	1730	1928	2124
TT6	1990-2015	45	96	224	308	415	494	573	651
TT8	1980-2004	18	33	71	96	128	151	174	198
TT9	1965-2014	492	697	1200	1533	1953	2266	2575	2884
TT10	1984-2005	117	216	458	619	822	973	1122	1271

The station having insufficient data length was excluded for the analysis

The longitudinal variability of the discharges of 1.5 year and 2 year return periods are shown in Figs. 14 and 15. It is noted that the discharge values increase drastically towards downstream, especially in the upstream section draining to the Jurala Dam, perhaps due to the contribution of flows from the major tributaries (other than Bhima River) of the Upper Krishna Basin. However, the variability in the discharges is substantially less in the downstream sections, where the major dams, such as Srisailam and Nagarjuna Sagar are located. Further, the gradual increase (although minor) downstream of the Nagarjuna Sagar dam could be the result of the flows contributed by the tributaries, viz., Musi, Paleru, Munneru, and Wyra Rivers. However, in Tungabhadra River, the downstream variability is remarkably lesser, compared to the Krishna River. Moreover, a rise in the discharge is observed only in the downstream of the Tungabhadra Dam.

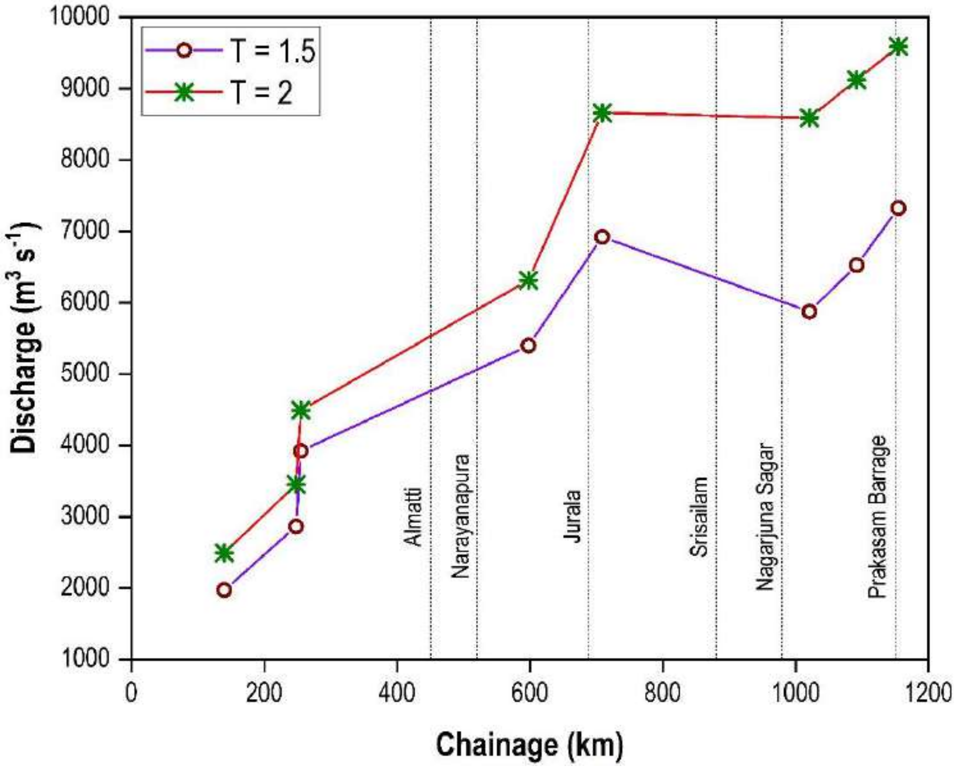

Fig. 14: Spatial variation of the discharges of 1.5 year and 2 year return periods, Krishna River

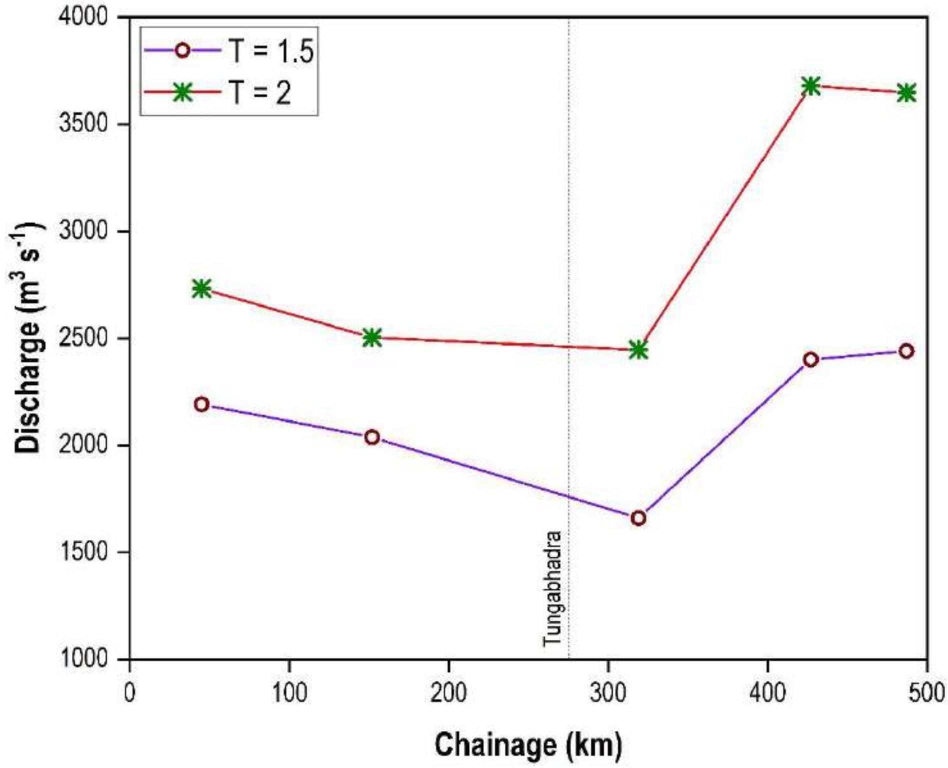

Fig. 15: Spatial variation of the discharges of 1.5 year and 2 year return periods, Tungabhadra River

7.5. Flow duration curve

The flow duration curves at different H.O. stations are also prepared using the historical observed data (Appendix XIII). A flow duration curve is a plot of discharge against the percentage of time that the discharge was equaled or exceeded. The area under the flow duration curve gives the average stream flow at the location. Information concerning the relative amount of time that flows past a site are likely to equal or exceed a specified value of interest is extremely useful for the design of structures on a stream. In addition, the shape of a flow-duration curve in its upper and lower regions is particularly significant in evaluating the stream and basin characteristics. The shape of the curve in the high-flow region indicates the type of flood regime the basin is likely to have, whereas, the shape of the low-flow region characterizes the ability of the basin to sustain low flows during dry seasons. A very steep curve (high flows for short periods) would be expected for rain-caused floods as seen in TT3 and K2. Snowmelt floods, which last for several days, or regulation of floods with reservoir storage, will generally result in a much flatter curve near the upper limit. In the low-flow region, an intermittent stream would exhibit periods of no flow as seen in T5, TT2, and TT3. A very flat curve indicates that moderate flows are sustained throughout the year due to natural or artificial streamflow regulation, or due to a large groundwater capacity which sustains the base flow to the stream. In B3, K6, KT15, T1, and TT9 the curve is flat in both high flows as well as in low flows which indicates moderate flow in the stream throughout the period of observation.

7.6. Particle size distribution

The bed material sizes are measured between the two stream banks to characterize the stream bed material variation along a cross-section. It can vary along the cross-section which is at a local scale as well as longitudinally along a reach. Fining of the bed sediment to the downstream is a process resulting in large-scale spatial variability of bed-material sizes. Usually, downstream fining occurs over a stream section several reaches long, but it might also occur over shorter distances as well. Downstream fining may be attributed to a number of mechanisms including local control of stream gradient, coarse tributary sediment supply, or particle abrasion and breakdown (Surian, 2000). Local grade control may be caused by geological uplift, blockage of the valley by mass movement, or man-made dams. A decrease in stream gradient leads to a decrease in the amount and particle size of bedload transport (Sambrook Smith and Ferguson 1995; Ferguson et al., 1998). Log jams can also trigger fining of bed particles by creating a local grade control. The following tables (Tables 17 to 25) show the average particle mean diameters measured at some particular sites in KRB and the silt factors which are calculated using the average diameter values.

The usual objective for sampling a stream section in which particle sizes become finer downstream is to demonstrate the degree of downstream fining and link it to a potential cause. Tables 17 to 25 suggests that K1, which is the most upstream site in the Krishna River have higher values for mean particle diameters, compared to other sites. Similarly, higher values of mean diameter can be observed in case of the site B4, which is also located in the Upper Krishna Basin. The mean diameter of the bed material particles in K1 indicates fine to medium pebbles, whereas the bed material at K17 is characterized by very coarse to coarse sand particle fractions, implying downstream fining of particles. Similarly, bed materials at B4 are primarily composed of very fine granules, while KT14, T7, B6, and BT8 are dominated by very fine granules to very coarse sand. The bed materials at TT5 consist of coarse to very coarse sand fractions. Although the bed material size exhibits substantial variability across space, the particle sizes showed hardly any significant differences between the years as well as between various seasons (except minor variabilities).

Table 17: Results of bed material analysis of selected reaches in Krishna and Tungabhadra rivers (2006-07)

H. O. Code	Pre-monsoon		Monsoon		Post-monsoon	
	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor
Krishna River						
B4	2.37	2.71			4.04	3.54
B6	1.02	1.78	0.21	0.81	1.95	2.45
BT8	2.02	2.5	2.26	2.65	0.71	1.48
K1	6.93	4.63	10.37	5.56		
K17					0.64	1.4
KT14	1.59	2.22	1.22	1.94		
Tungabhadra River						
T7	1.76	2.34	1.44	2.11	1.01	1.77

Table 18: Results of bed material analysis of selected reaches in Krishna and Tungabhadra rivers (2007-08)

H. O. Code	Pre-monsoon		Monsoon		Post-monsoon	
	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor
Krishna River						
B4	2.03	2.51			3.17	3.13
B6	1.17	1.9	0.23	0.85	0.24	0.87
BT8	3.08	3.09	1.83	2.38	0.84	1.62
K1	7.23	4.73	6.57	4.51	5.61	4.17
K17	0.88	1.65	0.15	0.69	0.15	0.68
KT14	1.21	1.94	1.05	1.8	0.59	1.36
Tungabhadra River						
T7	2.39	2.72	1.26	1.97	2.3	2.67

Table 19: Results of bed material analysis of selected reaches in Krishna and Tungabhadra rivers (2008-09)

H. O. Code	Pre-monsoon		Monsoon		Post-monsoon	
	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor
Krishna River						
B4	2.27	2.65			2.05	2.52
B6	1.81	2.37	0.71	1.49	0.66	1.43
BT8	1.66	2.27			1.15	1.88
K1	10.92	5.82	9.54	5.44	9.41	5.4
K17	0.82	1.59	0.94	1.71	1.28	1.99
KT14	2.8	2.94	1.19	1.92	2.2	2.61
Tungabhadra River						
T7	1.71	2.3	2.3	2.67	2.43	2.74
TT5	0.99	1.75	0.96	1.73	0.9	1.67

Table 20: Results of bed material analysis of selected reaches in Krishna and Tungabhadra rivers (2009-10)

H. O. Code	Pre-monsoon		Monsoon		Post-monsoon	
	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor
Krishna River						
B4	2.9	3			2.31	2.67
B6	1.61	2.23	1.19	1.92	1.61	2.23
BT8	2.01	2.49	1.27	1.99	1.47	2.13
K1	8.03	4.99	9.79	5.51	10.07	5.58
K17	0.9	1.67			0.19	0.77
KT14	1.51	2.16	1.2	1.93	0.88	1.65
Tungabhadra River						
T7	1.71	2.3	0.78	1.56	0.11	0.59
TT5	0.67	1.44	0.92	1.69	0.92	1.69

Table 21: Results of bed material analysis of selected reaches in Krishna and Tungabhadra rivers (2010-11)

H. O. Code	Pre-monsoon		Monsoon		Post-monsoon	
	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor
Krishna River						
B4	3.14	3.12			3	3.05
B6	1.08	1.83	0.75	1.53	0.88	1.66
BT8	1.33	2.03	1.74	2.32	1.37	2.06
K1					12.13	6.13
K17	0.9	1.67	0.71	1.49	0.94	1.71
KT14	1.23	1.95	1.11	1.86	2.11	2.55
Tungabhadra River						
T7	0.99	1.75	0.72	1.5	1.55	2.19
TT5	0.73	1.5	0.82	1.59	0.85	1.63

Table 22: Results of bed material analysis of selected reaches in Krishna and Tungabhadra rivers (2011-12)

H. O. Code	Pre-monsoon		Monsoon		Post-monsoon	
	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor
Krishna River						
BT8	1.69	2.29	1.87	2.41	1.53	2.17
Tungabhadra River						
T7	0.99	1.75			2.08	2.54
TT5	1.04	1.79	1.24	1.96	1.3	2.01

Table 23: Results of bed material analysis of selected reaches in Krishna and Tungabhadra rivers (2012-13)

H. O. Code	Pre-monsoon		Monsoon		Post-monsoon	
	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor
Krishna River						
B4	2.11	2.56			3.21	3.15
B6	1.15	1.89	1.13	1.87	1.02	1.78
BT8	2.08	2.54	1.77	2.34	2.25	2.64
K1	11.27	5.91	16.08	7.06	11.97	6.09
K17	1.01	1.77	0.93	1.69	0.96	1.72
KT14	1.36	2.05			2.06	2.53
Tungabhadra River						
T7	1.31	2.01	1.04	1.8	1.75	2.33

Table 24: Results of bed material analysis of selected reaches in Krishna and Tungabhadra rivers (2013-14)

H. O. Code	Pre-monsoon		Monsoon		Post-monsoon	
	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor
Krishna River						
B4	3.01	3.05			2.74	2.91
B6	0.82	1.6	0.88	1.65	0.93	1.69
BT8	2.27	2.65	0.61	1.37		1.34
K17	1.05	1.81	1.07	1.82	1.5	2.16
KT14	2.52	2.8	1.16	1.89	1.82	2.38
Tungabhadra River						
T7	2.13	2.57	1.13	1.87	1.28	1.99
TT5	1.51	2.16	1.62	2.24	1.49	2.15

Table 25: Results of bed material analysis of selected reaches in Krishna and Tungabhadra rivers (2014-15)

H. O. Code	Pre-monsoon		Monsoon		Post-monsoon	
	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor	Av. mean dia. (mm)	Silt factor
Krishna River						
B4	3.11	3.1	1.86	2.4	3.03	3.06
B6	1.21	1.93	1.21	1.94	1.06	1.81
BT8	1.81	2.37	2.02	2.5	1.41	2.09
K1	14.54	6.71	18.74	7.62	18.61	7.59
K17	1.55	2.19	1.14	1.88	1.22	1.94
KT14	2.6	2.84	2.54	2.8	1.33	2.03
Tungabhadra River						
T7	1.03	1.79	1.46	2.13	1.2	1.92

7.7. Sediment flux

The magnitude of the sediment flux from the tropical river basins is dominantly governed by the lithological characteristics as well as the gradient of the channel. Sediment load in the Indian rivers show significant dichotomy between the rivers draining the highly erodible Himalayan range (2390 t km^{-2}) and the tropical (Peninsular) river system (216 t km^{-2}) (Milliman and Meade, 1983). It is observed that KRB, the largest regulated river basin in term of dams and reservoirs in India, experienced coastal erosion due to the drastic reduction in streamflow and sediment flux (Bouwer et al., 2006; Biggs et al., 2007; Gamage and Smakhtin, 2009). Hence, in this study, sediment discharge (Qs) has been computed using the sediment concentration measured at different HO stations in KRB. Although suspended sediment concentration has been measured at several HO stations in KRB (Appendix IX), only those stations having reasonable lengthy data record have been selected for computations. Table 26 summarizes the details of the available sediment concentration data of the selected HO stations.

Table 26: Details of sediment concentration data recorded st selected HO stations in KRB

Sl. No.	Code	Name	Reach	Period	Time Scale
1.	K1	Karad	KR_01	1965-2015	Daily
2.	K3	Kurandwad	KR_03	2003-2014	Daily
3.	K7	Huvinhedgi	KR_11	1976-2014	Daily
4.	K10	K Agraharam	KR_13		Daily
5.	K16	Ponudugala	KR_19	1975-2006	Daily
6.	K17	Wadenpalli	KR_21	1966-2015	Daily

Sl. No.	Code	Name	Reach	Period	Time Scale
7.	K18	Vijayawada	KR_22	1965-2014	Daily
8.	KT2	Warunji	Tributary to KR_01	1974-2015	Daily
9.	KT14	Cholachiguda	Tributary to KR_09	1982-2014	Daily
10.	KT22	Keesara	Tributary to KR_22	1965-2015	Daily
11.	T2	Honnali	TR_01	1995-2015	Daily
12.	T3	Haralahalli	TR_04	1972-2014	Daily
13.	T5	Oollenur	TR_07	1973-2002	Daily
14.	T6	Mantralayam	TR_09	1977-2014	Daily
15.	T7	Bawapuram	TR_10	1965-2015	Daily
16.	TT2	Shimoga	Tributary to TR_01	1972-2015	Daily
17.	TT4	Byaladahalli	Tributary to TR_03	1997-2015	Daily
18.	B4	Talki	Tributary to KR_12	1966-2015	Daily
19.	B6	Yadgir	Tributary to KR_12	1965-2015	Daily
20.	BT1	Sarati	Tributary to KR_12	1966-2014	Daily
21.	BT6	Wadakbal	Tributary to KR_12	1965-2009	Daily
22.	BT8	Malkhed	Tributary to KR_12	1992-2015	Daily

Spatial variation of the Qs in the basin is shown in Fig. 16, where the mean annual Qs along with the temporal annual variability (as coefficient of variation) are given. It is noted that that the Qs in the mainstream of Krishna shows a gradual downstream increase in the Qs till the confluence of Tungabhadra River, followed by a significant reduction in the sediment yield. Such a drastic reduction can be explained by the trapping of the sediments in the two major reservoirs of the system, viz., Srisailam and Nagarjuna Sagar reservoirs. Reduction in Qs is noted in the downstream of Tungabhadra reservoir also. It is estimated that reservoirs reduced sediment transport globally by 30% (Vorosmarty et al., 2003) and in India by more than 70% (Gupta et al., 2012). Significant reduction in sediment load in Krishna River has been reported by Subramanian (1996), where construction of Srisailam dam reduced the sediment transport in the river with an annual load of 68 million tonnes upstream of the impoundment, while only 4 million tonnes in the downstream. Moreover, Higgins et al. (2018) forecasted 60-97% reductions in annual suspended sediment transport to Krishna delta due to full implementation of the National River Linking Project. Among the two major tributaries of KRB, Bhima River provides a major share of the sediment load to Krishna, compared to Tungabhadra River.

Temporal variability in Qs measured at different HO stations along the mainstream of Krishna and Tungabhadra Rivers is given in Figs. 17 and 18. Among the different locations, K10 and K7 recorded remarkable fluctuations across the years, while other stations exhibited hardly any significant temporal variability. Similarly, in Tungabhadra River, temporal variation of Qs at T6 and T7 locations also is considerably higher than the rest of the locations. In general, the stations showed a decreasing trend in Qs, which is apparent in those stations having high temporal variability (Figs. 17 and 18). Further, the decreasing trend in Qs can be correlated with the decreasing trend in water discharge, as there exists a strong decreasing trend in discharge over the last 50 years (Higgins et al., 2018).

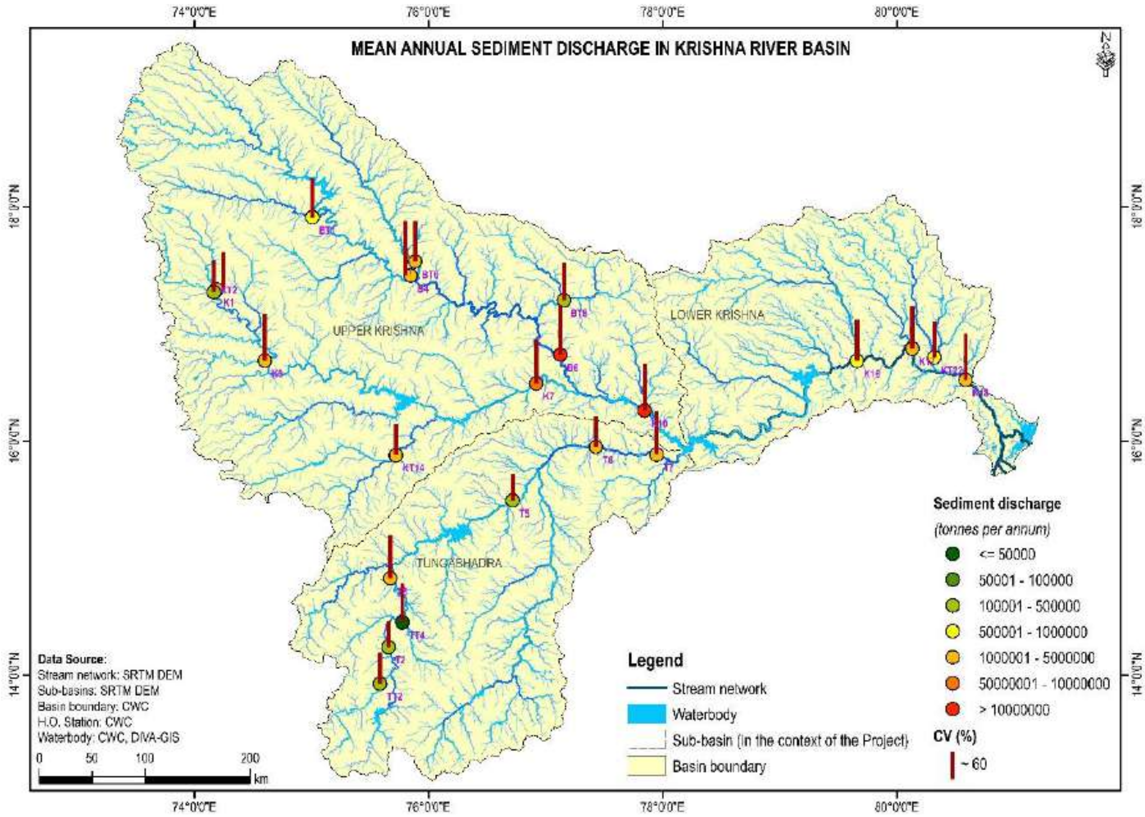

Fig. 16: Spatial variability in Qs in the KRB. The coefficient of variation (%) represents the variability across the period.

Using the sediment concentration and discharge data available at the HO stations, the sediment rating curves were fitted to the data with the form:

$$Q_s = aQ_w{}^b$$

which is a widely-applied form for the relation between water discharge (Qw) in m^3 s^{-1} and suspended sediment discharge (Qs) in kg s^{-1}. The sediment rating curves were developed for all the HO stations, where suspended sediment concentration and discharge data are available at daily time scale (Fig. 19). In addition, the 95% prediction intervals were also calculated and shown in the corresponding figures.

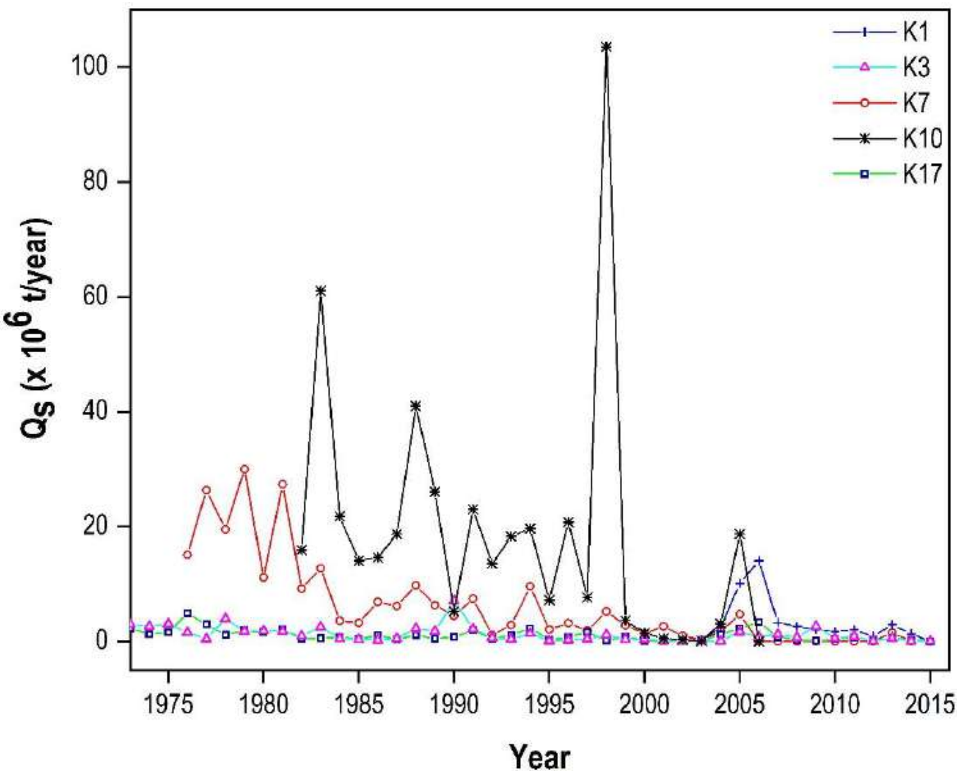

Fig. 17: Temporal variability of Qs at different HO stations along the mainstream of Krishna River

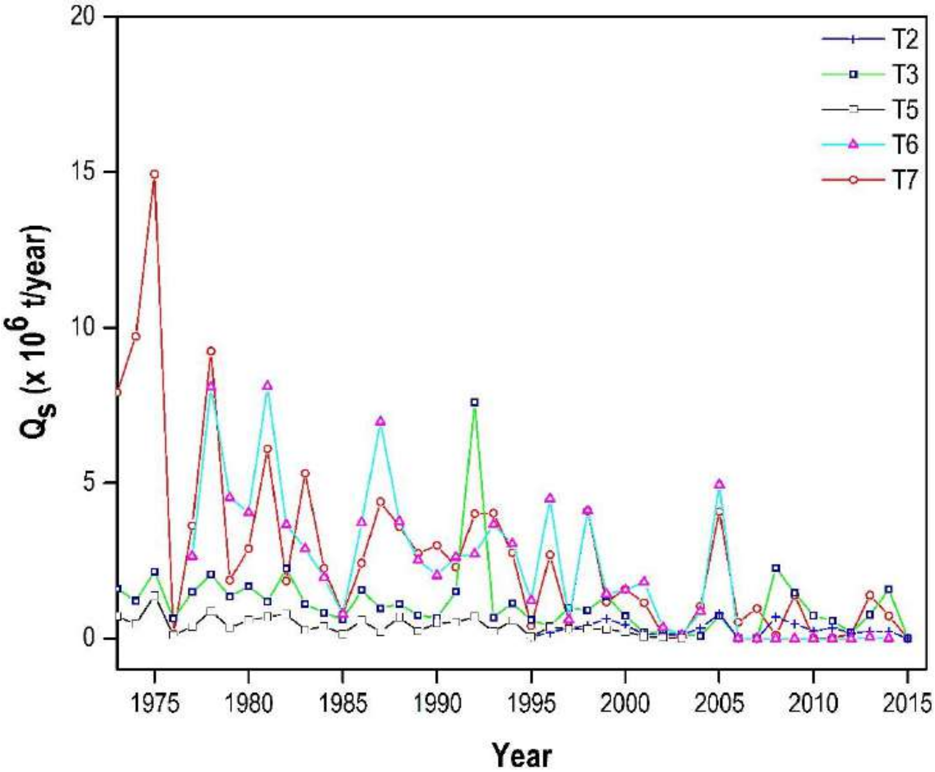

Fig. 18: Temporal variability of Qs at different HO stations along the mainstream of Tungabhadra River

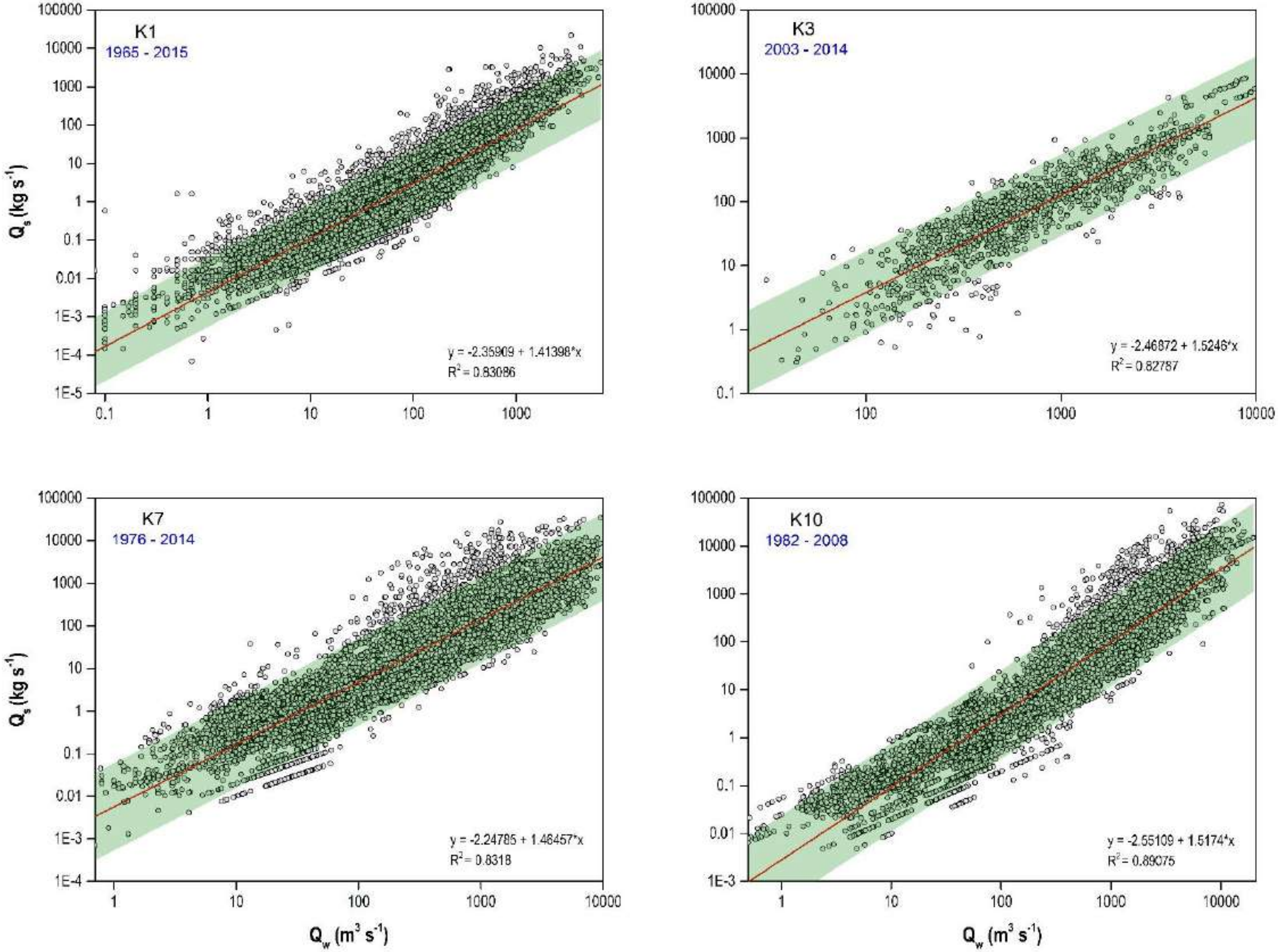

Fig. 19: Sediment rating curves for various HO stations in KRB

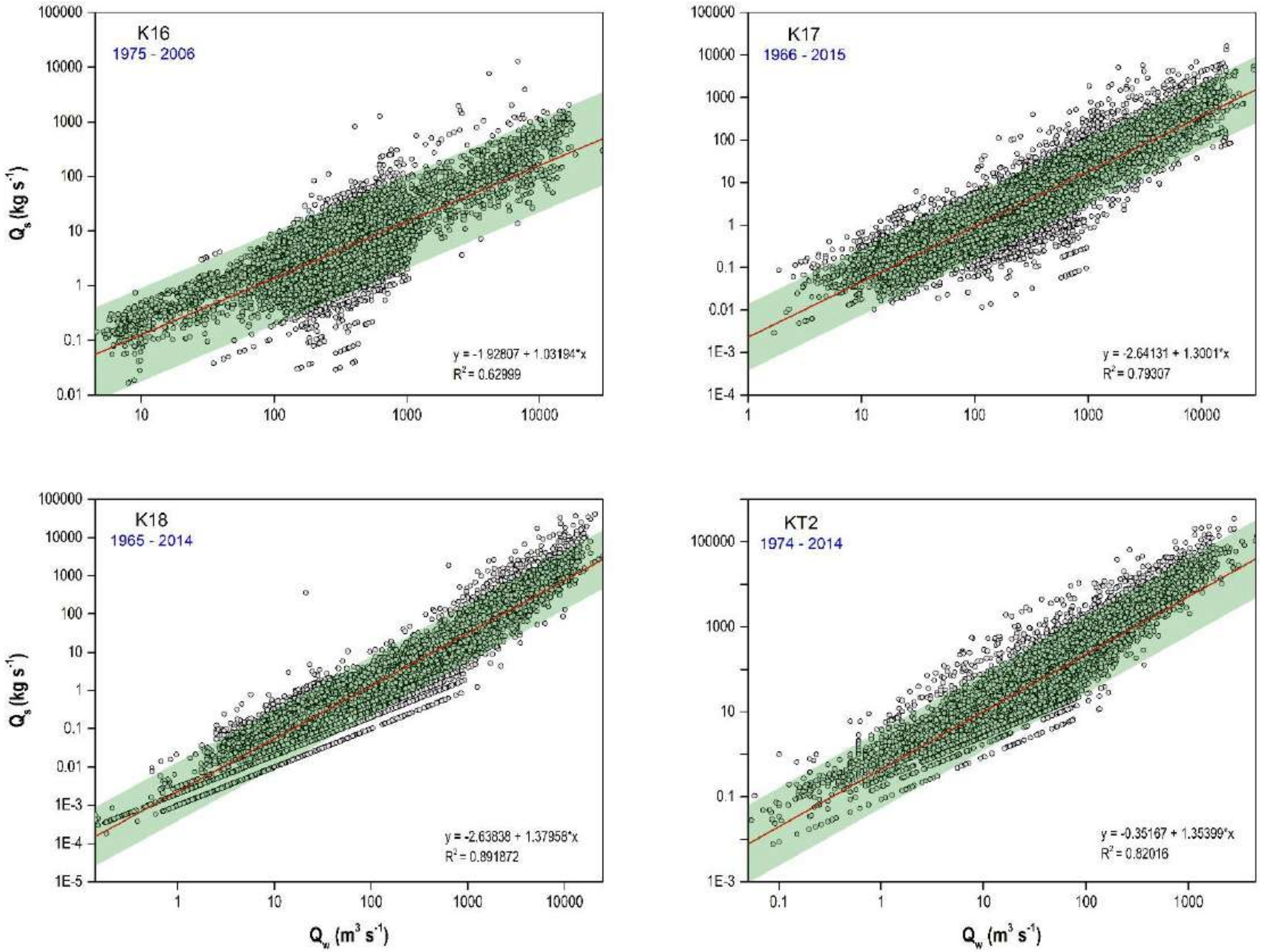

Fig. 19 (Contd'): Sediment rating curves for various HO stations in KRB

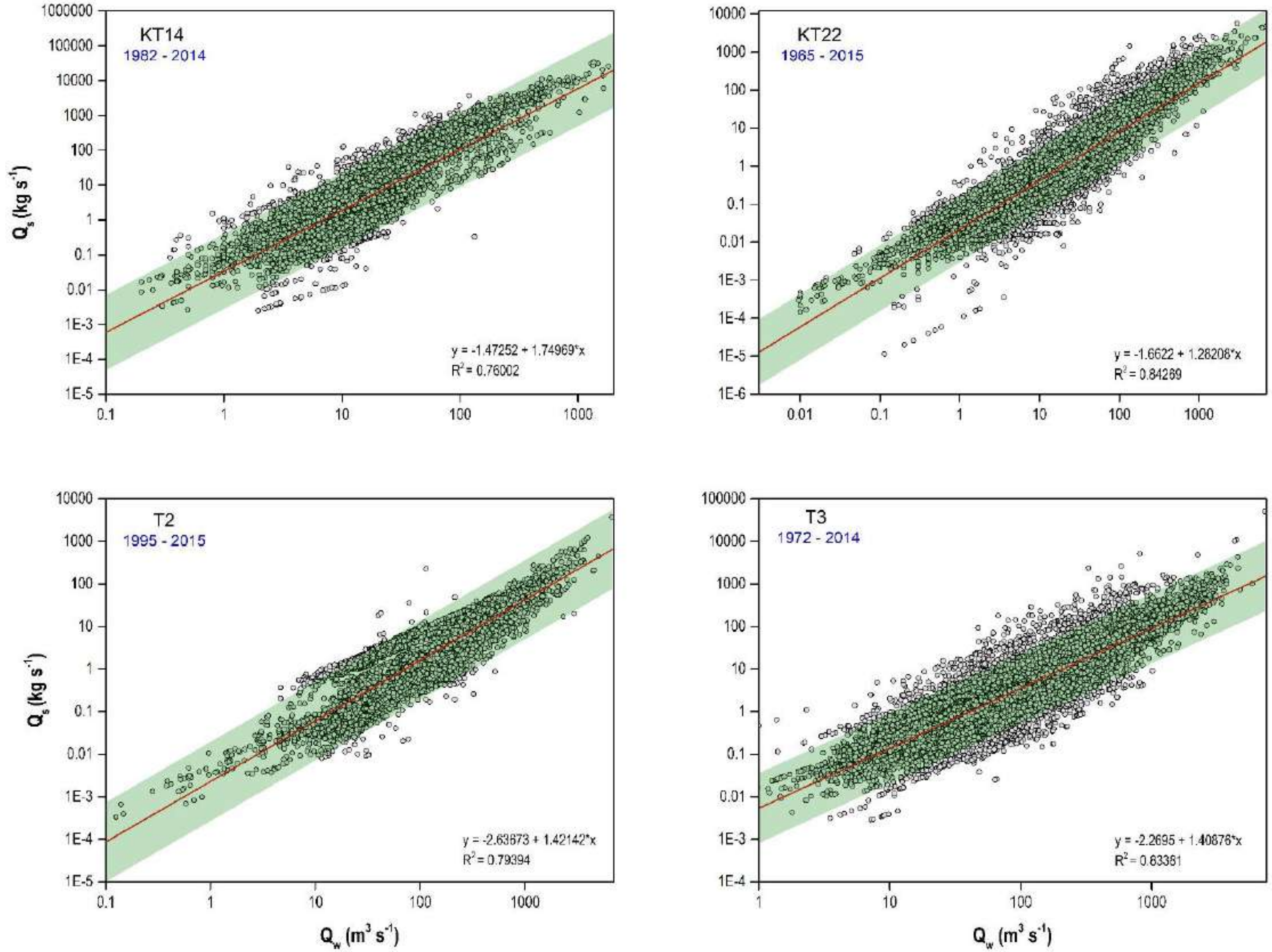

Fig. 19 (Contd'): Sediment rating curves for various HO stations in KRB

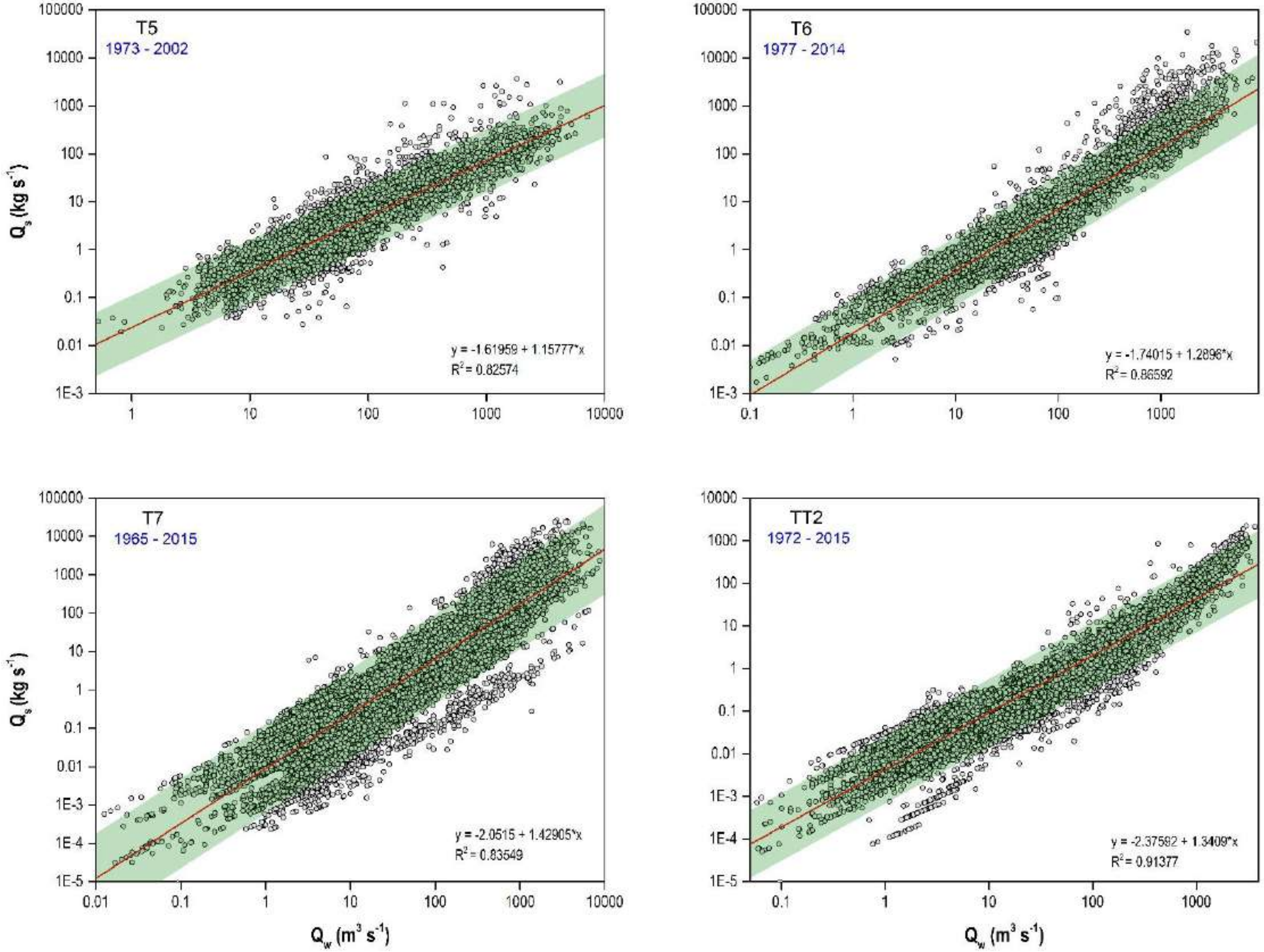

Fig. 19 (Contd'): Sediment rating curves for various HO stations in KRB

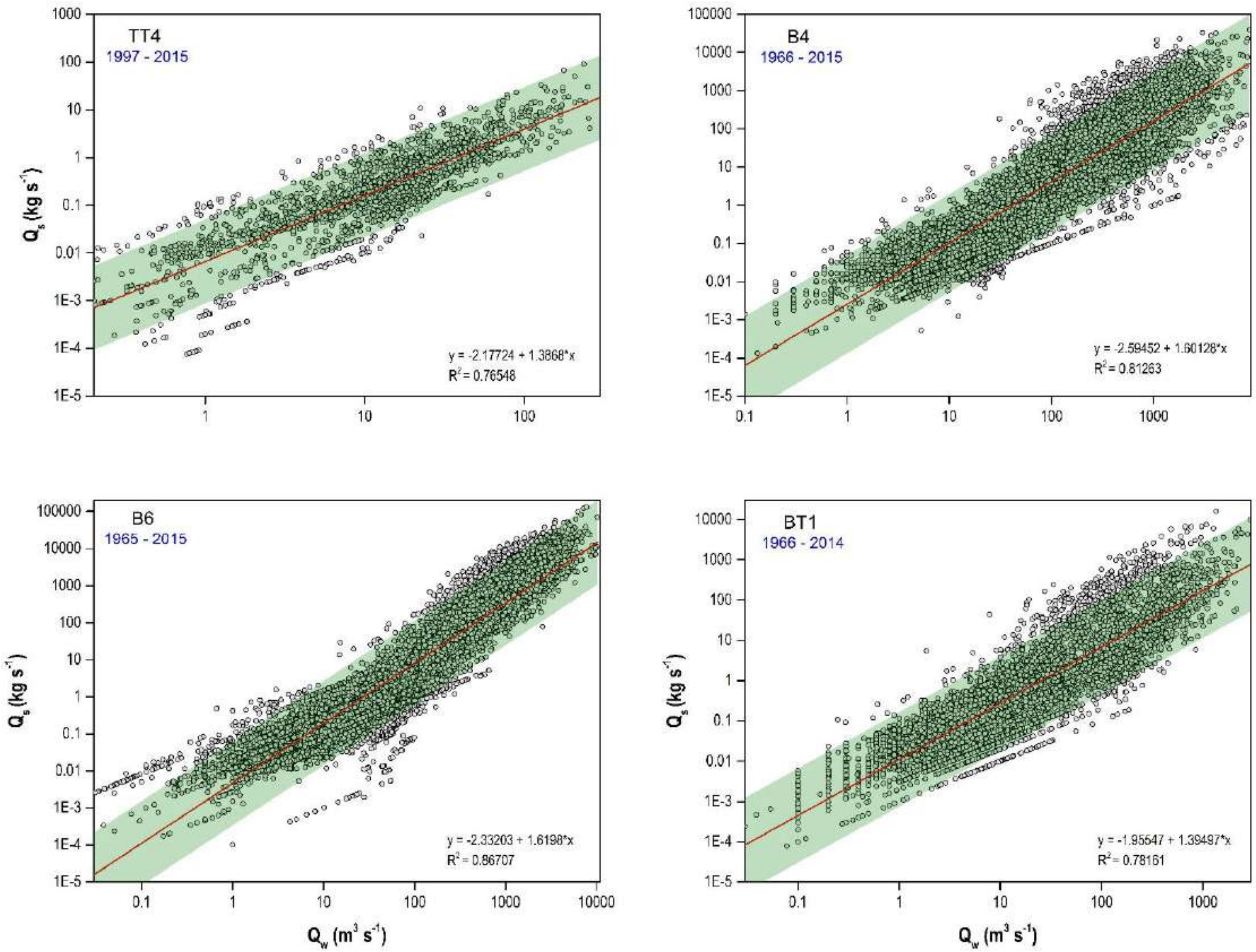

Fig. 19 (Contd'): Sediment rating curves for various HO stations in KRB

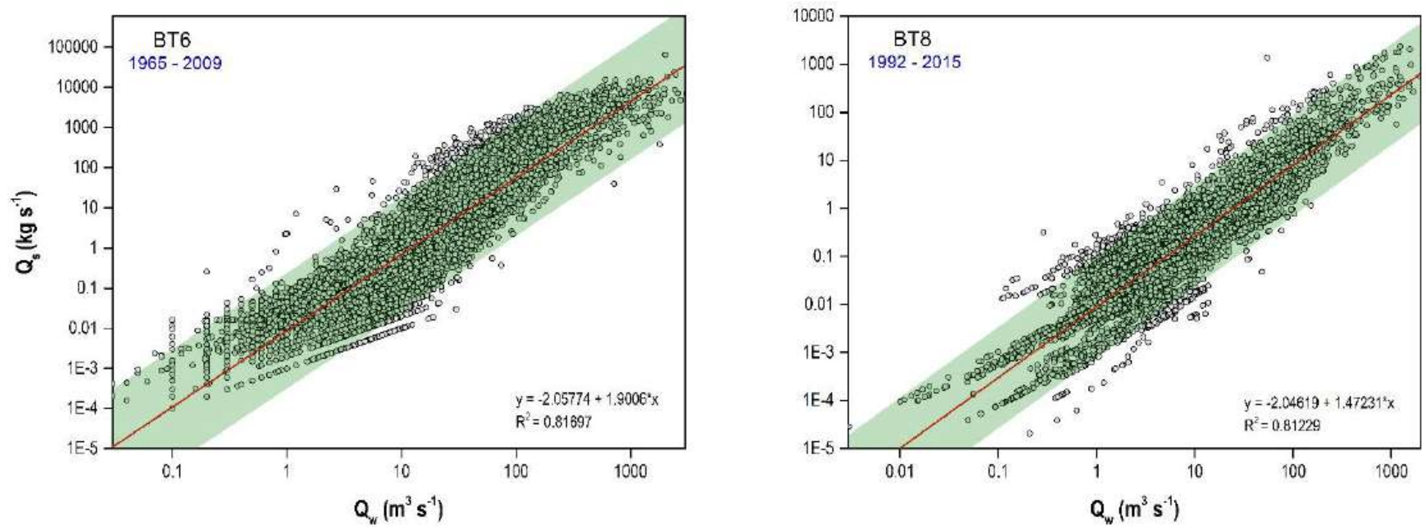

Fig. 19 (Contd'): Sediment rating curves for various HO stations in KRB

SECTION 8
LAND USE/ LAND COVER ANALYSIS

8.1. Land use/ land cover types of KRB

The land use/land cover types in KRB were extracted from the global land cover data (~500 m spatial resolution). Although KRB supports 16 types of land use/ land cover, the cropland is the dominant land use/ land cover of the basin, which account for more than 80% of the basin area (Fig. 20; Table 27). In addition, cropland and natural vegetation mosaic also form roughly 10% of the basin area.

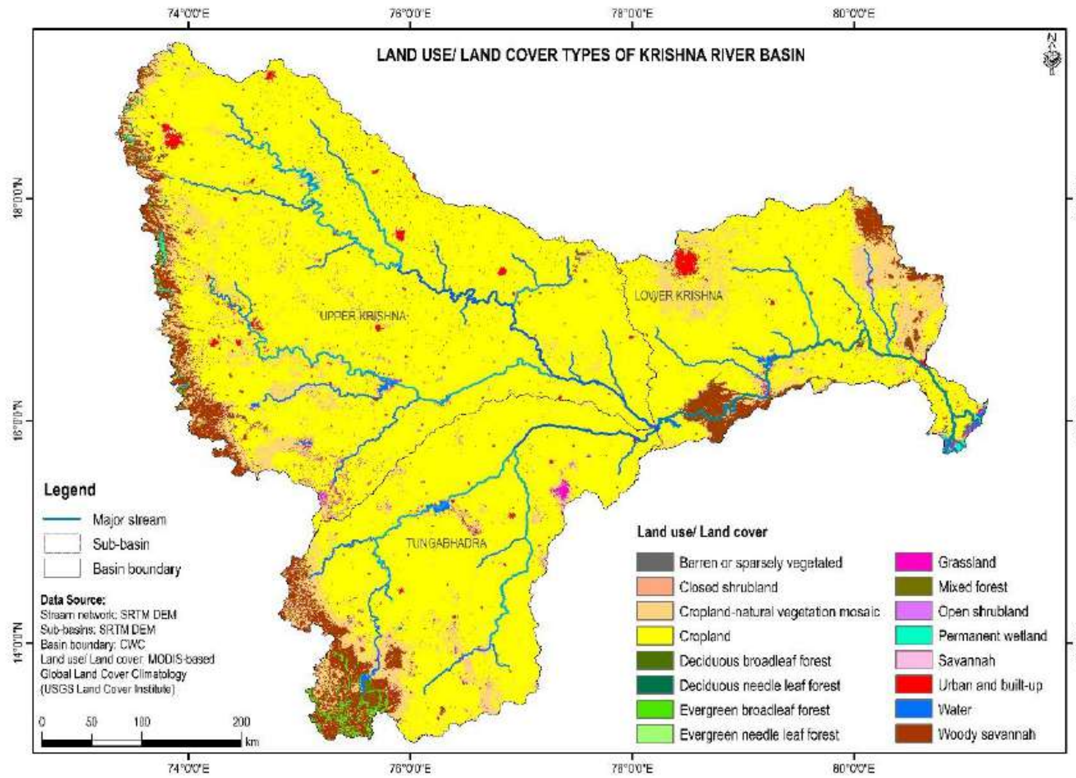

Fig. 20: Land use/ land cover types of KRB

The basin has a wide spectrum of cropping patterns, which include rice, sorghum, corn, sugarcane, millet, groundnut, grass fodder and a variety of horticultural crops. Summarizing the Agricultural census data, Biggs et al. (2007) classified the croplands of KRB into five cropping regions, viz., (i) rice-grains and cash crops, chiefly distributed in the downstream of KRB, which include the Krishna Delta, Nagarjuna Sagar command area, (ii) grains-rice-sugar, dominates across the plateau (in the northwest), and most rice-sugarcane irrigation occurs at the foot slopes and base of the Western Ghats, (iii) grains-rice-oilseeds in the center and central-south segments, (iv) oilseeds grains in the southwest and (v) rainfed rice and cash crops in the Western Ghats. Three cropping seasons characterize the annual cropping cycle in KRB, such as the Kharif (June to October), the Rabi (November to March), and the dry season (April to May).

About 6% of the basin area is covered by scrublands, grasslands, and savannas with sparse vegetation cover, while another 1% area is under different types of forest vegetation. The forested vegetation is mostly concentrated along the slopes of the Western Ghats and small patches are randomly distributed within the basin. Different types of forests exist in the basin, where species composition ranges from evergreen to dry deciduous. The evergreen patches are concentrated along the Western Ghats, where annual rainfall is more than 2000 mm, while deciduous forests show hardly any spatial patterns. About 1.5% of the basin area is classified as urban and built-up land use and is spatially evenly distributed across the basin (Fig. 20). Even though the areal extent of waterbodies in KRB is smaller compared to other land use types, the basin supports numerous dams and reservoirs, e.g., KRB has 660 dams and reservoirs (both completed and under construction), most of which are intended for irrigation purposes.

The spatial distribution of different land use/ land cover types of the major sub-basins of KRB is also tabulated in Table 27. All the sub-basins except Koyna are dominated by cropland land use/ land cover type, where Koyna and Panchganga basins have relatively lower areal extent for croplands (< 50%). In addition, more than 90% area of the sub-basins, namely, Bhima, Dindi, Peddavagu, and Paleru is covered by croplands. The study reaches of Krishna (KR-01 to KR_27) as well as Tungabhadra (TR_01 to TR_11), except KR-15, KR_16, and KR_17, are entirely located in the agricultural areas of the basin.

The different types of forests (i.e., evergreen needle leaf forest, evergreen broadleaf forest, deciduous needle leaf forest, deciduous broadleaf forest, and mixed forest) were mostly confined to the upstream parts of the basin, and are spatially distributed along the Western Ghats (Fig. 20). The areal extent of the woody savannahs is also relatively high in the upstream sub-basins of KRB, compared to downstream counterparts. However, woody savannahs are also concentrated in the Lower Krishna, especially between Kurnool (near confluence between Krishna and Tungabhadra rivers) and Nagarjuna Sagar dam.

The land use/ land cover statistics of the basin shows a general agreement with the land use statistics reported by NRSC (in MoWR, 2014), where the latter estimated the agricultural area as roughly 76% of the total basin area. However, the considerable deviation is noticed in the forest area as well as areal coverage by waterbody. The difference in the forested area between the NRSC and present statistics might be because of the differences in the classification scheme adopted by the agencies. In the present study, the land use/ land cover class are labeled on the basis of the most likely International Geosphere-Biosphere Programme (IGBP) class, which is different from the classification scheme used by NRSC.

Table 27: Areal extent of various land use/ land cover types in Krishna and its major sub-basins

Basin	Land use/ land cover type (areal coverage in %)															
	ENF	**EBF**	**DNF**	**DBF**	**MF**	**CS**	**OS**	**WS**	**S**	**G**	**PW**	**C**	**U**	**CNV**	**B**	**W**
Krishna	< 0.01	0.41	< 0.01	0.10	0.34	0.02	0.60	5.14	0.15	0.54	0.24	80.78	1.27	9.83	1.02	0.48
Sub-basin																
Koyna	-	2.58	-	0.25	2.46	0.11	0.15	38.62	0.41	0.19	4.83	21.37	0.41	28.05	0.05	0.50
Panchganga	-	1.34	0.01	-	0.11	0.02	0.05	24.83	0.57	0.07	0.66	40.25	4.29	27.77	-	0.03
Dhoodhganga	-	1.17	-	0.03	0.12	0.02	0.03	18.67	0.58	0.12	0.78	58.99	0.77	18.27	0.01	0.46
Ghataprabha	-	0.03	-	-	0.02	0.03	1.11	12.27	0.89	0.72	0.09	66.29	0.82	16.40	0.06	1.29
Malaprabha	-	0.03	-	-	< 0.01	0.01	3.42	3.07	0.15	3.01	0.02	78.58	0.56	10.85	0.04	0.24
Bhima	< 0.01	< 0.01	-	0.04	0.34	0.01	0.60	1.36	0.07	0.07	0.20	92.28	1.85	2.81	0.09	0.28
Tungabhadra	-	1.30	< 0.01	0.02	0.42	0.01	0.39	7.23	0.25	0.79	0.08	78.41	0.42	10.29	0.04	0.35
Dindi	-	-	-	0.17	0.35	0.03	0.05	1.83	< 0.01	0.18	-	92.00	0.32	5.04	0.02	-
Peddavagu	-	-	-	0.03	0.06	0.05	0.24	0.02	-	0.21	0.21	90.54	0.26	6.72	0.14	1.52
Halia	-	-	-	-	-	-	-	-	-	0.03	-	87.67	0.28	12.01	0.02	-
Musi	-	-	-	0.01	-	0.04	0.27	0.09	0.01	0.42	0.02	73.96	4.84	20.16	0.07	0.12
Paleru	-	-	-	-	-	-	-	-	-	-	0.02	95.63	0.91	3.25	0.10	0.10
Munneru	-	-	-	0.10	0.07	< 0.01	0.01	11.07	0.03	0.02	0.02	50.55	1.26	36.78	0.03	0.06

ENF- Evergreen needle leaf forest; EBF-Evergreen broadleaf forest; DNF-Deciduous needle leaf forest; DBF-Deciduous broadleaf forest; MF-Mixed forest; CS-Closed shrubland; OS-Open shrubland; WS-Woody savannah, S-Savannah; G-Grassland; PW-Permanent wetland; C-Cropland; U-Urban and built-up; CNV-Cropland-natural vegetation mosaic; B-Barren or sparsely vegetated; W-Water

SECTION 9
RIVER MORPHOLOGY AND STREAM BANK EROSION ANALYSIS

9.1. River morphology

In general, the data on river morphology includes information that defines the planform, cross-section and the longitudinal profile of the river channel. In the present project, the temporal variation of channel morphology of Krishna and Tungabhadra rivers was assessed on the basis of the changes in channel bank lines, cross-section, and longitudinal profiles as well as using planform index (PFI).

9.2. Delineation of river bank lines

The delineation of the river channel banks is a challenging task as numerous methods exist to extract river boundaries, which ranges from automated classification to manual digitization. The major drawback for the automated classification procedure is the inconsistencies aroused as a result of the similarities in spectral reflectance of riverine and associated features. Hence, most of the channel morphologic studies (e.g., Yang et al., 1999; Yao et al., 2011; Gupta et al., 2013; Dewan et al., 2017) recommended manual digitization for riverbank delineation from multispectral remote sensing data. Considering this, the channel banks of Krishna and Tungabhadra rivers were manually digitized from the satellite images of different time periods using multi-band combinations.

Even though the land-water boundary is evident in most of the river segments of the images, varying water levels in the river channels as well as masking of the waterbody by canopy of the riparian vegetation. Hence, we adopted a soil-vegetation limit approach (Gurnell, 1997) to identify the bankfull channel boundary, and the river channel is defined as the area in which vegetation cover is below 10% (Lawler, 1993; Tiegs and Pohl, 2005) so that 90% of the area is either bare soil or water. Further, the vegetation-based approach for delineating channel boundary was also tested successfully by several researchers (Gurnell, 1997; Winterbottom, 2000; Richard et al., 2005; Yao et al., 2011; Hossain et al., 2013). In addition, the breaks in the slope of the transverse (i.e., across the valley) elevation profiles were also considered for improving the accuracy of delineation of channel boundary.

The scale of data capture is another issue that can seriously affect the delineation of channel boundary while using multi-temporal remote sensing data (Tiegs and Pohl, 2005; Rozo et al., 2014). The remote sensing data used in this study have been procured by different sensors of different remote sensing missions, and differ in the spatial resolution (Table 14). Hence, the channel banks from all the images were digitized on a scale of 1:50,000 to eliminate the inconsistency owing to the scale of data capture.

9.3. Changes in channel planform

Mean width of the different river reaches of Krishna and Tungabhadra rivers was estimated the dividing the area of river polygon by the corresponding length of the reach. The mean width of the reaches of Krishna and Tungabhadra rivers in 1973, 1977, 1991, 2001 and 2011 is given in Tables 28 and 29 and Figs. 21 and 22.

Table 28: Mean width of the study reaches of Krishna River during different years

Reach-ID	Year					Coefficient of Variation (%)
	1973	1977	1991	2001	2011	
KR_01	208	214	223	220	221	2.9
KR_02	170	174	165	159	166	3.4
KR_03	169	170	170	164	166	1.6
KR_04	206	212	192	203	216	4.6
KR_05	232	241	225	228	294	11.7
KR_06	409	397	367	345	398	6.9
KR_07	374	390	371	368	2063	105.8
KR_08	1266	1256	1257	2924	5932	80.6
KR_09	1129	1134	2250	2661	2705	40.0
KR_10	1368	1367	1358	1363	1376	0.5
KR_11	707	686	680	703	695	1.6
KR_12	1071	1051	1037	1032	1026	1.7
KR_13	1170	1170	1178	1509	1853	22.1
KR_14	912	895	2011	2319	3538	56.9
KR_15	540	515	2858	3642	4902	77.7
KR_16	296	301	906	1010	1132	55.0
KR_17	363	371	457	444	533	16.1
KR_18	3496	3653	3969	4187	4678	11.7
KR_19	1134	1182	1242	1234	1342	6.3
KR_20	577	564	531	507	531	5.2
KR_21	1125	1120	1111	1077	1118	1.7
KR_22	2988	2981	2951	2904	2939	1.1
KR_23	3124	3179	3124	3084	3111	1.1
KR_24	1547	1560	1569	1577	1580	0.8
KR_25	395	407	402	385	397	2.1
KR_26	801	798	817	821	843	2.2
KR_27	624	634	691	709	700	5.9

Table 29: Mean width of the study reaches of Tungabhadra River during different years

Reach-ID	Year					Coefficient of Variation (%)
	1973	1977	1991	2001	2011	
TR_01	395	373	367	354	358	4.3
TR_02	410	397	383	364	368	5.0
TR_03	390	386	351	333	334	7.7
TR_04	464	457	438	422	427	4.1
TR_05	1641	1799	2140	2095	2552	17.2
TR_06	3985	4058	4503	4338	4676	6.8
TR_07	697	681	666	670	671	1.8
TR_08	820	818	770	759	771	3.7
TR_09	793	728	682	651	654	8.5
TR_10	839	859	819	793	846	3.1
TR_11	804	805	1244	1544	907	30.6

In general, the mean width of the reaches of both Krishna and Tungabhadra rivers increases towards downstream as a result of the increasing discharges. However, a few exceptions are observed in both rivers. The changes in the order of magnitude prominently reflect inundation of river valleys due to the construction of dams. For example, the sudden increase in the mean width of KR_08 (1266 m), KR_09 (1129 m) and KR_10 (1368 m) compared to their upstream and downstream reaches such as KR_07 (374 m) and KR_11 (707 m), respectively (Table 28) is due to the submergence of land area due to Almatti and Narayanpura dams and reservoirs (Fig. 8). Such an increase is also evident in KR_17 and KR_18 (Nagarjuna Sagar reservoir) as well as TR_05 and TR_06 (Tungabhadra reservoir). On the other hand, a drastic reduction of mean width is also occurred in KR_16 and KR_17, compared to upstream reaches, which is due to the incised nature of the river valley between Kurnool and Nagarjuna Sagar dam (Fig. 23). In such segments, the channel changes in the horizontal dimension are restricted due to the confined valley nature and bedrock channel walls.

The variation of the width of most of the study reaches of both Krishna and Tungabhadra rivers across the years (i.e., 1973-2011) shows hardly any significant differences, except in a few reaches (e.g., KR_07 to KR_09, KR_13 to KR_18, TR_05 and TR_11; Tables 28 and 29). This variability is also correlated with the areal extent of reservoir impoundment in the upstream of the aforementioned dams. For example, Almatti dam was completed in 2000, and Srisailam in 1984 (Appendix I), and the same is reflected in KR_07 and KR_08 and KR_14 and KR_15.

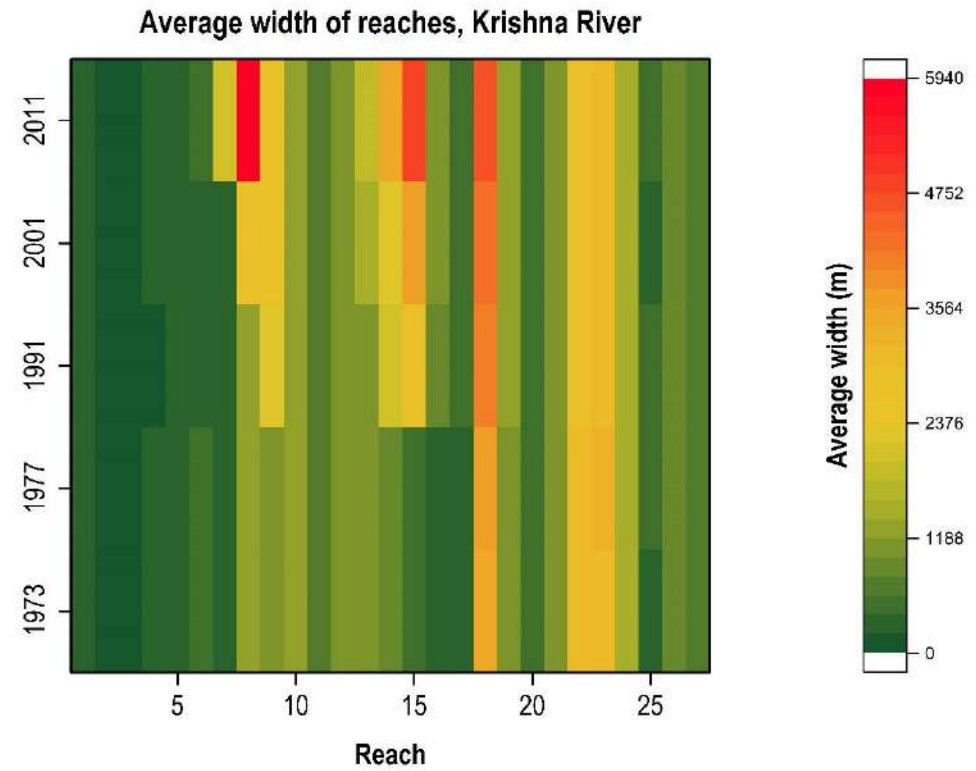

Fig. 21: Spatio-temporal variation of mean width of river reaches (KR_01 to KR_27) of Krishna River during 1973 and 2011. Red color indicates an increase in width due to reservoir impoundment.

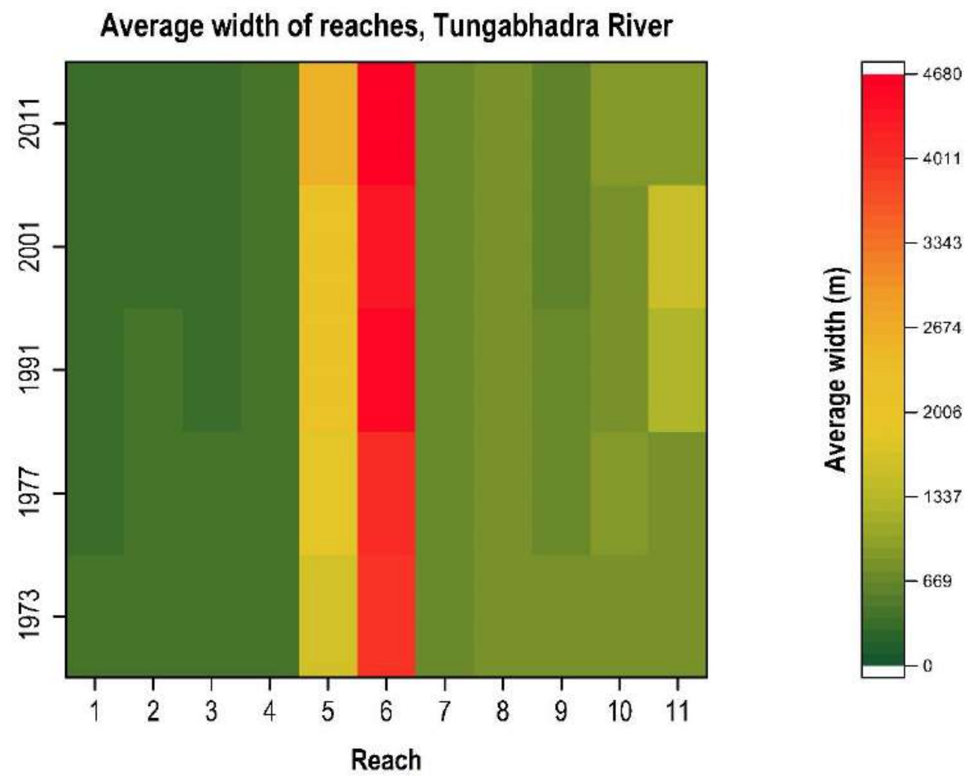

Fig. 22: Spatio-temporal variation of mean width of river reaches (TR_01 to TR_11) of Tungabhadra River during 1973 and 2011. Red color indicates an increase in width due to reservoir impoundment.

Even though KR_15 is also located in the upstream of the Srisailam dam, the variability in width across the years is not reflected, which is due to the incised nature of the river valley. In addition, the centerline of the river reaches in Krishna as well as Tungabhadra rivers also show insignificant shifts, except in the reaches that are influenced by reservoirs. Such geomorphic expressions are usually interpreted as a sign of channel stability.

Fig. 23: Downstream view of the incised river reach (KR_17) from Srisailam dam. The river segment (seen in the background) is incised into bedrock with an elevation drop of roughly 250 m

In general, the planform of the study reaches of Krishna and Tungabhadra rivers is classified as straight to sinuous channels, while the downstream reaches of Krishna River (KR_21 to KR_24), except the distributaries, are braided. The braiding phenomenon is developed only in the river reaches developed in the Quaternary sediments of the eastern coastal plain. In order to understand the braiding phenomena of these reaches, the planform index (PFI; Sharma, 1995) was calculated using Eq. X:

$$PFI = \frac{\frac{T}{B}\times 100}{N} \qquad \text{(X)}$$

where, T is the sum of the flow top widths of all the braided channels, B is the overall flow width and N is the number of braided channels. The PFI reflects the fluvial landform disposition with respect to a given water level and a lower PFI value is indicative of a higher degree of braiding.

Five transects at defined intervals (10 km) were drawn in each of the braided reaches of Krishna River to estimate the PFI of each transect, the PFI value of the reach was calculated as the mean value of the PFI values of different transects of any given reach. The PFI values of the downstream reaches estimated during different years are given in Table 30 and Fig. 24. Among the different braided reaches, KR_22 and KR_23 show significantly lower PFI values in all the years, compared to other reaches.

Sharma (2004) classified the PFI values to provide a broad range of classification of the braiding phenomenon, and the scheme classifies channels into highly braided (PFI ≤ 4), moderately braided (19 ≥ PFI > 4) and low braided (PFI > 19). Following the classification, KR_22 and KR_23 are moderately braided, whereas the other two reaches belong to the low braided class.

Table 30: Mean PFI of downstream reaches of Krishna River during different years

Reach-ID	KR_21	KR_22	KR_23	KR_24
1973	66.2 (9.8 - 100)	15.8 (8.3 - 30.5)	8.8 (6.3 - 13.9)	68.7 (7.7 - 100)
1977	68.4 (15.5 - 100)	13.7 (7.8 - 23.3)	7.1 (4.7 - 11.4)	68.2 (9.7 - 100)
1991	72.4 (21.1 - 100)	18.9 (9.1 - 26.3)	9.5 (6.5 - 12.6)	58.2 (7.8 - 100)
2001	67.9 (13.0 - 100)	14.2 (8.3 - 23.8)	9.7 (6.2 - 14.7)	58.0 (7.8 - 100)
2011	67.6 (13.0 - 100)	12.4 (6.3 - 24.5)	10.6 (4.3 - 16.0)	58.2 (8.3 - 100)

The values in parentheses denote the range of PFI values of transects

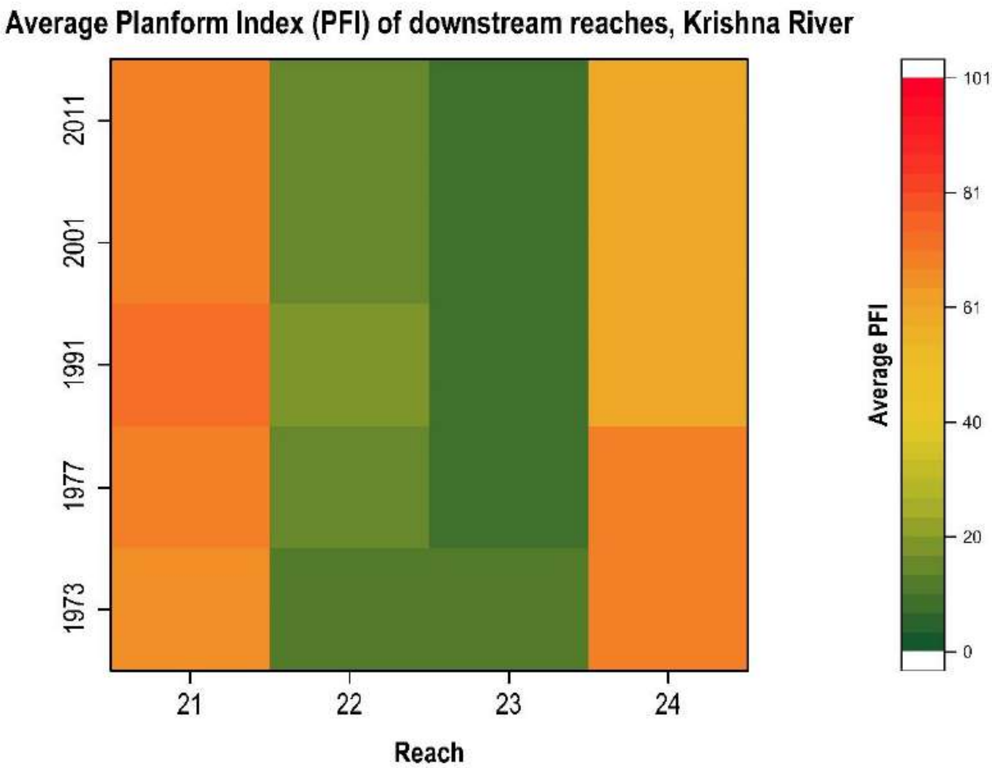

Fig. 24: Temporal variation of mean PFI of the downstream reaches (KR_21 to KR_24) of Krishna River during 1973 and 2011

The temporal variability of the PFI values is also comparably less in KR_22 and KR_23, compared to rest of the reaches (Table 30; Fig. 24), which suggests that irrespective of the time, the aforementioned reaches show little changes in braiding intensity and pattern. It is also evident that higher PFI values of all the reaches are predominant in the year 1991, except in KR_23.

The upper reaches of Krishna River (KR_01 to KR_07) developed minor meandering sections at a few locations, which is exemplified by the relatively higher sinuosity ratios of the reaches (refer Table 10). Hence, various characteristics of the meandered sections were estimated from the planform of the reaches. Since the planform of the reaches showed hardly any significant differences among the assessment period, the measurements were carried out for the channel planform in the year 2011. The meander properties, such as radius of curvature, meander amplitude and wavelength of the meandered bends were estimated (Table 31).

Table 31: Meander characteristics of upper reaches of Krishna River, 2011

Reach-ID	Number of bends	Mean		
		Radius of curvature (km)	Amplitude (km)	Meander wavelength (km)
KR_01	2	1.26	3.58	5.68
KR_02	1	0.70	1.41	3.35
KR_03	1	0.77	2.54	3.76
KR_05	1	2.10	4.3	10.70
KR_06	1	2.19	4.7	8.92
KR_07	1	3.14	5.4	9.80

The mean radius of curvature of the reaches varies between 0.70 km (KR_02) and 3.14 km (KR_07), whereas the mean amplitude of the meanders ranges from 1.41 km (KR_02) to 5.4 km (KR_07). Mean wavelength of the meanders is from 3.35 km (KR_02) to 10.70 km (KR_05). Although numerous relationships were developed to relate between meander properties and channel characteristics (e.g., Leopold and Wolman, 1960; Williams, 1986), the data from upper reaches of Krishna River are not valid for the established generalized relationships, which perhaps is the result of the development of meandering sections in the river courses due to topographic controls rather than hydraulic controls.

9.4. Bank erosion and deposition pattern

In the analysis of stream bank erosion and deposition, the river banks of Krishna and Tungabhadra Rivers were delineated during 1973, 1977, 1991, 2001 and 2011 were compared, and estimated the changes in the river bank position for five periods, such as 1973-1977 (4 years), 1977-1991 (14 years), 1991-2001 (10 years), 2001-2011 (10 years) as well as 1973-2011 (38 years). The delineated left and right bank lines of different years were merged into a single feature class in ArcGIS and created the polygons that represent the difference between the two bank lines. While comparing the changes in the bank lines between 1973 and 1977, 1973 was taken as the reference bank line, and the polygons (created by merging 1973 and 1977 bank lines) were classified into erosion and deposition, depending on the location of the polygons with respect to the reference year. For example, for left bank, the polygons left to 1973 bank line represent erosion and the polygons that located on the right of the bank line denote deposition polygon. The same process was used to characterize the erosion and deposition polygons on the right bank, but with the flowing change: polygons to the left and right of 1973 bank line represent deposition and erosion, respectively. Area of the polygons was estimated and summation of the areas of these polygons provided the total area under erosion and deposition during the analysis period.

The areas under erosion and deposition along the banks of the different reaches during different time periods are shown in Appendices XIV and XV. The analytical results are presented in a way to address the short-term (1973-1977, 1977-1991, 1991-2001, 2001-2011) as well as long term (1973-2011) changes in the channel bank lines and corresponding erosion and depositional patterns of Krishna and Tungabhadra rivers (Tables 32 to 41).

9.4.1. Bank erosion

9.4.1.1. Krishna River

The analysis of channel shifts in the reaches of Krishna River during 1973-1977 suggests that total area of erosion of both the banks is 31.4 km^2, where erosion in left and right banks are almost similar in areal extent (i.e., 15.6 and 15.8 km^2 respectively; Table 32). The total area of erosion of both the banks shows considerable variation across the reaches (Fig. 25), where the total area of erosion ranges from 0.6 km^2 (KR_12) to 3.2 km^2 (KR_23). Since KR_18 is entirely submerged due to reservoir impoundment of Nagarjuna Sagar dam, the erosion is not estimated. In general, the downstream reaches (i.e., KR_21 to KR_27) have a relatively higher area of erosion during the time period. Similarly, the total eroded area in the reaches KR_05 to KR_10 is also large, compared to the rest of the reaches.

The total area of erosion occurred along the left bank during 1973-1977 is 15.6 km^2 (Table 32). The area under erosion in the left bank of the reaches varies from 0.1 km^2 (KR_27) to 1.4 km^2 (KR_23), where majority of the reaches have area under erosion less than 1.0 km^2, and only three reaches have area of erosion greater than 1.0 km^2 (i.e., KR_07, KR_09, and KR_23) (Fig. 26). Similarly, the total area of erosion along the right bank is 15.8 km^2 (Table 32), and that of the reaches ranges between 0.1 km^2 (KR_08) to 1.8 km^2 (KR_23) (Fig. 27). Three reaches, viz., KR_22, KR_23, and KR_25 have an area under erosion greater than 1.0 km^2 along the right bank. The area of erosion between the left and right banks show contrasting patterns in that most of the high values of the area of left bank erosion are spatially concentrated in the upstream as well as midstream reaches, whereas the high values of the area of right bank erosion mostly occur in the downstream reaches. Although the area under erosion along the left and right banks of the various reaches shows hardly any remarkable differences, the mean width of erosion of the reaches between the banks show significant spatial variability, i.e., the mean width of erosion along left bank of the reaches varies between 5.5 m (KR_22) to 27.8 m (KR_23), whereas the range of mean width of erosion along right bank is from 2.4 m (KR_08) to 63.0 m (KR_27) (Figs. 28 and 29). The high erosion rates along the left bank are observed in KR_07, KR_08, KR_09, KR_23, KR_25, and KR_26, while the erosion rates along the right bank are remarkably high in the extreme downstream reaches (i.e., KR_22 to KR_27). The relatively higher values of erosion width of the distributary reaches (despite their lower eroded area) are due to the shorter reach length.

The total area of erosion of both the banks during 1977-1991 in the reaches of Krishna River is 31.5 km^2, where the area under erosion along the left and right bank is 13.6 and 17.9 km^2, respectively (Table 33). The total area of erosion of the different reaches (except KR_15, KR_16, and KR_18) is in the range of 0.2 km^2 (KR_09) to 3.0 km^2 (KR_22) (Fig. 25). The reaches KR_15, KR_16 and KR_18 are completely submerged, and hence, bank erosion was not assessed. Among the different reaches, the downstream reaches (KR_19 to KR_27) show comparatively higher area of erosion during 1977-1991 than the rest of the reaches. However, KR_08 also has a higher area of erosion, which is comparable to the range of the downstream reaches.

The total area of erosion along the left bank during 1977-1991 sums up to 13.6 km^2, which roughly 43% of the total erosion of both the banks (Table 33). The area of erosion along the left bank of the different reaches shows a range between nearly zero (KR_22) to 1.6 km^2 (KR_27), and 13 reaches have an area of erosion less than 0.5 km^2. Among the different reaches, high erosion along the left bank occurred in KR_25, KR_26, and KR_27 as well as in KR_06 (Fig. 26). The total area of erosion along the right bank is 17.9 km^2 (Table 33), and the same of the reaches varies from 0.1 km^2 (KR_09 and KR_27) to 3.0 km^2 (KR_22; Fig. 27). It is also evident that the erosion in KR_22 during the period occurred only along the right bank. The area of erosion along the right bank is relatively higher in KR_19, KR_21, KR_22, KR_23, and KR_24, most of which are located between downstream of Nagarjuna Sagar dam and Krishna delta. However, KR_13 and KR_08 also have a comparatively high area of erosion along the right bank. Similar to the area of erosion, the mean width of erosion along both left and right banks also shows considerable variability across the reaches of Krishna River (Figs. 28 and 29). The mean width of erosion along left and right banks are in the range from < 1.0 m (KR_22) to 116.3 m (KR_27) and 2.2 m (KR_09) to 59.2 m (KR_22), respectively.

During 1991-2001, the total area of erosion of both the banks in the reaches of Krishna River is 20.2 km^2 (Table 34), where the total area of erosion across the reaches shows variation between 0.2 km^2 (KR_14 and KR_17) and 1.9 km^2 (KR_11 and KR_24) (Fig. 25). The low areal extent of erosion along the banks of KR_14 and KR_17 is because of their characteristic positioning as both the reaches are upstream of Srisailam and Nagarjuna Sagar reservoirs, and the majority of the area of the reaches are submerged due to reservoir impoundment. Contrary to the previous assessment periods, during 1991-2001, the high values of the total area of erosion attribute to upstream reaches such as KR_08, KR_10, KR_11, and KR_04. However, in the downstream reaches, KR_24 and KR_25 have the relatively larger areal extent of bank erosion.

The total area of erosion along left bank during 1991-2001 is 10.8 km^2 (i.e., 54% of the total erosion), and in the reaches, it varies between 0.1 km^2 (KR_17) to 1.0 km^2 (KR_11) (Table 34). Most of the reaches are characterized by a relatively lower area of erosion (< 0.5 km^2) along the left bank. However, the relatively larger areal extent of left bank erosion is observed in KR_11, KR_24, KR_26, and KR_27 (Fig. 26). The total area of erosion along the right bank is 9.4 km^2, and that of the individual reaches ranges from nearly zero (KR_14) to 1.2 km^2 (KR_08) (Fig. 27). However, mean width of erosion of the reaches along left and right banks varies between 1.2 m (KR_17) to 53.6 m (KR_27) and 0.7 m (KR_14) to 24.5 m (KR_08), respectively (Figs. 28 and 29). The mean width of erosion of left bank is relatively high in the reaches of the deltaic region, whereas the mean width of erosion along right bank shows hardly any significant differences between the upstream and downstream reaches.

The changes in the bank lines of Krishna River during 2001-2011 indicates that the total area of erosion of both the banks during the period is 32.2 km^2, where the erosional area in both the banks is more or less similar (Table 35). The total area of bank erosion across the reaches ranges between 0.2 km^2 (KR_09) and 3.5 km^2 (KR_05), and the high erosion patches exist in KR_05 and KR_06 (> 3.0 km^2) as well as KR_20 to KR_23 (2.0-2.6 km^2) (Fig. 25). The downstream reaches of the Krishna River are characterized by their relatively larger areal extent of erosion. Even though these reaches have experienced high erosion during 2001-2011, the inclusion of the upstream reaches, viz., KR_05 and KR_06 are interesting to note. Further, these two reaches show only moderate to low erosion in the previous assessment periods.

During the period 2001-2011, the total area of erosion along the left bank is 15.9 km^2 (Table 35). The area of erosion along the left bank of the reaches shows a range between nearly zero (KR_08) to 2.0 km^2 (KR_05), and the reaches, such as KR_05, KR_06, KR_21, KR_22, and KR_23 have a comparably high area of erosion (> 1.0 km^2; Fig. 26). The total area of erosion along the right bank of the reaches is 16.3 km^2, and that of the individual reaches varies between nearly zero (KR_09) to 1.6 km^2 (KR_06) (Fig. 27). Along the right bank of the reaches, the high erosional area is observed in KR_05, KR_06, as well as KR_19 to KR_22 (> 1.0 km^2). The mean width of erosion along the left bank across the reaches varies from 0.6 m (KR_08) to 40.0 m (KR_05), whereas the same along the right bank is between 1.0 m (KR_09) to 32.7 m (KR_06) (Figs. 28 and 29).

The total bank erosion of both the banks occurred in the study reaches of Krishna River during the entire period (i.e., 1973-2011) is 47.5 km^2, where the erosion area along the left bank is 21.9 km^2 and that of the right bank is 25.6 km^2 (Table 36). The total erosion area of the different reaches varies from 0.2 km^2 (KR_07) to 3.7 km^2 (KR_05 and KR_24), and the reaches with higher areal extent of bank erosion (say > 2.0 km^2) are located in the downstream reaches (e.g., KR_19, KR_21 to KR_25), except a few in the upstream (KR_04 to KR_06, KR_10).

The area of erosion along the left bank of the reaches varies between nearly zero (KR_14 and KR_22) and 2.1 km^2 (KR_05) (Fig. 30), and the reaches with a high areal extent of erosion are KR_04 to KR_06 and the extreme downstream reaches (i.e., KR_24 to KR_27). The total area of erosion along the right bank of the study reaches is in the range of 0.1 km^2 (KR_09) to 3.2 km^2 (KR_22) (Fig. 30). The reaches, viz., KR_21 to KR_25 and KR_19 show the relatively higher areal extent of erosion along the right bank. The mean width of erosion along the left bank of the different reaches is in the range of 0.4 m (KR_22) to 98.6 m (KR_26), and that of the right bank varies between 1.0 m (KR_07) and 63.4 m (KR_22) (Fig. 31)

The temporal pattern of the areal extent and mean width of bank erosion of the different reaches of Krishna River (Figs. 25 to 31) indicates that the variability of bank erosion is relatively large across the downstream reaches (KR_21 to KR_27) as well as the upstream reaches KR_04 and KR_05. Further, the comparison of the bank erosion (both in quantitative terms of areal extent and mean width of erosion) during the short term and long term assessment periods also suggests that the downstream reaches, especially KR_22, KR_23, KR_24, KR-25, KR_26 and KR_27 as well as the upstream reaches, such as KR_04 to KR_06 are the most vulnerable reaches to bank erosion among the different study reaches of Krishna River. However, some of the upstream (KR_01 to KR_03), as well as downstream reaches (KR_19 to KR_21), have localized erosion areas, which are prominent in some of the time periods (Appendix XIV). On a mean basis, the annual total bank erosion during 1973-1977 was 7.8 km^2, whereas it was 2.2 km^2 during 1977-1991, 2.0 km^2 during 1991-2001 and 3.2 km^2 during 2001-2011. However, on the long term, the annual erosion of the total bank area is 1.30 km^2 in the reaches of Krishna River.

Table 32: Areal extent of banks under erosion and deposition in the reaches of Krishna River during 1973-1977

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_01	0.6	0.3	0.0	12.8	6.4	0.4	0.4	0.0	7.8	8.4	1.0	0.7
KR_02	0.5	0.3	0.0	9.2	6.5	0.4	0.3	0.0	8.0	6.6	0.9	0.7
KR_03	0.4	0.4	0.0	8.4	7.0	0.3	0.3	0.0	6.9	6.7	0.8	0.7
KR_04	0.6	0.3	0.0	11.8	5.7	0.4	0.4	0.0	8.0	8.0	1.0	0.7
KR_05	0.5	0.6	0.0	10.5	11.6	0.8	0.3	0.0	16.3	6.5	1.3	0.9
KR_06	0.5	0.9	0.0	10.0	17.3	0.5	0.8	0.0	10.9	15.6	1.0	1.6
KR_07	1.3	0.2	0.0	26.9	4.1	0.3	0.6	0.0	6.3	12.7	1.7	0.8
KR_08	1.0	0.5	0.0	20.5	9.0	0.1	1.2	0.0	2.4	24.4	1.1	1.7
KR_09	1.1	0.3	0.0	22.0	5.2	0.2	0.8	0.0	4.7	16.3	1.3	1.1
KR_10	0.8	0.3	0.0	17.0	7.0	0.5	1.0	0.0	9.3	20.2	1.3	1.4
KR_11	0.5	0.7	0.0	10.9	13.3	0.3	1.2	0.0	5.5	23.2	0.8	1.8
KR_12	0.4	0.7	0.0	7.5	13.9	0.2	0.9	0.0	4.2	17.5	0.6	1.6
KR_13	0.4	0.4	0.0	8.6	8.8	0.6	0.6	0.0	11.3	11.5	1.0	1.0
KR_14	0.6	0.8	0.0	12.3	16.1	0.3	0.9	0.0	6.3	18.6	0.9	1.7
KR_15	0.5	1.0	0.0	9.9	19.8	0.2	1.0	0.0	4.4	19.4	0.7	2.0
KR_16	0.7	0.2	0.0	14.5	5.0	0.3	0.5	0.0	5.5	9.6	1.0	0.7
KR_17	0.5	0.1	0.4	9.6	1.5	0.5	0.3	0.9	10.1	5.9	1.0	0.4
KR_18	0.0	0.0	13.6	0.0	0.0	0.0	0.0	4.2	0.0	0.0	0.0	0.0

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_19	0.4	0.3	3.1	7.0	6.9	0.8	0.2	0.1	15.2	4.7	1.1	0.6
KR_20	0.3	1.2	0.0	5.8	24.8	0.6	0.3	0.0	11.6	5.8	0.9	1.5
KR_21	0.3	1.1	0.0	6.9	21.6	0.9	0.4	0.0	18.1	8.4	1.3	1.5
KR_22	0.3	1.6	0.0	5.5	32.8	1.5	0.5	0.0	29.8	9.6	1.8	2.1
KR_23	1.4	0.2	0.0	27.8	4.4	1.8	0.2	0.0	36.6	4.7	3.2	0.5
KR_24	0.6	0.7	0.0	13.4	15.7	0.9	0.2	0.0	20.9	4.8	1.5	0.9
KR_25	0.8	0.6	0.0	19.0	13.4	1.1	0.8	0.0	26.1	18.8	1.9	1.4
KR_26	0.3	0.6	0.0	19.1	38.2	0.9	0.6	0.0	53.0	35.8	1.2	1.3
KR_27	0.1	0.7	0.0	7.4	51.4	0.9	0.0	0.0	63.0	2.3	1.0	0.8
Total	**15.6**	**15.1**	**17.0**			**15.8**	**14.9**	**5.2**			**31.4**	**30.0**

Table 33: Areal extent of banks under erosion and deposition in the reaches of Krishna River during 1977-1991

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_01	0.7	0.3	0.0	13.0	6.6	0.6	0.4	0.0	11.2	8.3	1.2	0.7
KR_02	0.3	0.4	0.0	7.0	8.8	0.3	0.6	0.0	5.6	12.7	0.6	1.1
KR_03	0.3	0.5	0.0	6.2	9.6	0.5	0.4	0.0	10.6	7.8	0.8	0.9
KR_04	0.6	0.3	0.0	12.7	6.1	0.2	1.5	0.0	3.1	30.2	0.8	1.8
KR_05	0.5	0.3	0.0	9.5	6.6	0.2	1.1	0.0	3.3	21.7	0.6	1.4
KR_06	1.1	0.4	0.0	21.0	8.5	0.3	2.4	0.0	5.6	48.3	1.3	2.8
KR_07	0.9	0.4	0.0	17.5	7.8	0.2	1.6	0.0	4.0	32.5	1.1	2.0
KR_08	0.9	0.5	0.0	17.6	10.0	1.0	1.3	0.0	20.3	26.7	1.9	1.8
KR_09	0.1	0.3	20.4	2.6	5.2	0.1	0.2	35.9	2.2	4.0	0.2	0.5
KR_10	0.5	0.7	0.0	9.3	14.9	0.6	0.7	0.0	11.9	14.3	1.1	1.5
KR_11	0.2	0.8	0.0	4.2	16.7	0.9	0.6	0.0	18.6	12.9	1.1	1.5
KR_12	0.1	1.2	0.0	2.5	24.6	0.9	0.5	0.0	18.5	10.5	1.1	1.8
KR_13	0.3	1.0	0.0	5.4	20.4	1.5	0.3	0.0	29.4	6.8	1.7	1.4
KR_14	0.1	0.1	27.2	2.8	2.3	0.3	0.0	28.5	6.2	0.1	0.4	0.1
KR_15	0.0	0.0	30.7	0.0	0.0	0.0	0.0	86.6	0.0	0.0	0.0	0.0
KR_16	0.0	0.0	15.1	0.0	0.0	0.0	0.0	15.2	0.0	0.0	0.0	0.0
KR_17	0.5	0.2	1.4	10.6	4.7	0.3	0.2	4.0	5.9	4.0	0.8	0.4
KR_18	0.0	0.0	13.5	0.0	0.0	0.0	0.0	7.2	0.0	0.0	0.0	0.0

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_19	0.3	0.6	3.2	6.7	12.3	1.1	0.9	0.4	22.1	18.7	1.4	1.5
KR_20	0.7	1.4	0.0	14.1	28.5	0.8	1.7	0.0	15.7	33.9	1.5	3.1
KR_21	0.4	2.3	0.0	8.3	46.3	1.9	0.5	0.0	38.4	9.2	2.3	2.8
KR_22	0.0	3.9	0.0	0.2	77.9	3.0	0.6	0.0	59.2	12.1	3.0	4.5
KR_23	0.4	2.4	0.0	7.1	47.0	1.1	1.8	0.0	22.8	37.0	1.5	4.2
KR_24	0.9	0.7	0.0	19.9	16.7	1.2	0.5	0.0	27.4	11.9	2.1	1.3
KR_25	1.1	0.5	0.0	24.5	12.7	0.7	1.3	0.0	15.3	29.4	1.7	1.8
KR_26	1.1	0.1	0.0	63.6	3.1	0.2	0.7	0.0	12.5	40.6	1.3	0.7
KR_27	1.6	0.0	0.0	116.3	0.1	0.1	0.5	0.0	9.1	38.4	1.8	0.5
Total	**13.6**	**19.6**	**111.4**			**17.9**	**20.6**	**177.8**			**31.5**	**40.2**

Table 34: Areal extent of banks under erosion and deposition in the reaches of Krishna River during 1991-2001

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_01	0.4	0.3	0.0	7.5	5.1	0.2	0.5	0.0	4.0	9.6	0.6	0.7
KR_02	0.4	0.4	0.0	8.4	7.0	0.2	0.5	0.0	3.5	11.0	0.6	0.9
KR_03	0.4	0.3	0.0	7.2	6.1	0.3	0.6	0.0	5.7	12.7	0.6	0.9
KR_04	0.6	0.2	0.0	12.1	4.6	0.5	0.3	0.0	10.2	5.9	1.1	0.5
KR_05	0.3	0.4	0.0	6.0	8.2	0.5	0.3	0.0	10.6	5.6	0.8	0.7
KR_06	0.4	0.9	0.0	7.6	18.3	0.3	0.8	0.0	5.6	16.6	0.7	1.7
KR_07	0.4	0.4	0.0	8.2	8.2	0.4	0.6	0.0	7.5	11.5	0.8	1.0
KR_08	0.4	0.1	20.6	8.6	2.0	1.2	0.0	61.2	24.5	0.3	1.7	0.1
KR_09	0.2	0.2	14.6	3.9	3.9	0.3	0.1	7.8	6.2	1.1	0.5	0.2
KR_10	0.6	0.7	0.0	11.1	13.5	0.7	0.4	0.0	14.9	8.2	1.3	1.1
KR_11	1.0	0.4	0.0	19.8	7.5	0.9	0.3	0.0	17.8	6.3	1.9	0.7
KR_12	0.5	0.4	0.0	10.7	8.8	0.3	0.7	0.0	6.1	13.3	0.8	1.1
KR_13	0.6	0.3	9.4	11.8	5.7	0.3	0.5	7.1	5.4	9.5	0.9	0.8
KR_14	0.2	0.0	11.0	3.4	0.3	0.0	0.1	9.2	0.7	2.8	0.2	0.2
KR_15	0.0	0.0	12.1	0.0	0.0	0.0	0.0	32.1	0.0	0.0	0.0	0.0
KR_16	0.0	0.0	4.0	0.0	0.0	0.0	0.0	5.1	0.0	0.0	0.0	0.0
KR_17	0.1	0.3	0.8	1.2	6.8	0.2	0.2	2.5	3.5	4.1	0.2	0.5
KR_18	0.0	0.0	16.4	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_19	0.2	1.0	2.3	4.3	19.1	0.3	0.7	0.2	5.4	14.6	0.5	1.7
KR_20	0.3	1.0	0.0	6.5	19.7	0.3	0.8	0.0	5.3	16.7	0.6	1.8
KR_21	0.3	1.3	0.0	5.7	26.3	0.2	0.9	0.0	4.9	18.2	0.5	2.2
KR_22	0.4	1.3	0.0	8.9	25.8	0.3	1.7	0.0	5.3	34.5	0.7	3.0
KR_23	0.4	1.4	0.0	7.3	27.8	0.2	1.2	0.0	4.5	23.9	0.6	2.6
KR_24	0.9	0.6	0.0	19.7	13.4	1.0	0.8	0.0	23.3	18.4	1.9	1.4
KR_25	0.4	0.7	0.0	9.6	16.3	0.6	0.8	0.0	12.8	19.3	1.0	1.5
KR_26	0.8	0.0	0.0	46.1	0.0	0.1	0.4	0.0	6.2	24.9	0.9	0.4
KR_27	0.8	0.0	0.0	53.6	0.0	0.1	0.4	0.0	6.8	27.8	0.8	0.4
Total	**10.8**	**12.5**	**91.3**			**9.4**	**13.8**	**128.1**			**20.2**	**26.3**

Table 35: Areal extent of banks under erosion and deposition in the reaches of Krishna River during 2001-2011

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_01	0.4	0.5	0.0	8.3	9.0	0.5	0.4	0.0	10.8	8.9	1.0	0.9
KR_02	0.3	0.3	0.0	6.6	5.6	0.5	0.2	0.0	10.0	3.8	0.8	0.5
KR_03	0.4	0.3	0.0	7.5	5.1	0.3	0.3	0.0	6.3	6.7	0.7	0.6
KR_04	0.7	0.3	0.0	14.7	5.1	0.5	0.4	0.0	10.7	7.5	1.3	0.6
KR_05	2.0	0.1	0.0	40.0	2.8	1.5	0.1	0.0	30.6	2.1	3.5	0.2
KR_06	1.5	0.4	0.0	30.4	7.5	1.6	0.1	0.0	32.7	2.7	3.2	0.5
KR_07	0.2	0.1	33.7	4.9	1.1	0.2	0.0	50.7	4.0	0.0	0.4	0.1
KR_08	0.0	0.5	44.6	0.6	10.3	0.5	0.0	108.0	9.0	0.1	0.5	0.5
KR_09	0.2	0.2	2.5	3.3	4.5	0.0	0.2	3.6	1.0	3.4	0.2	0.4
KR_10	0.5	0.4	0.0	9.6	8.8	0.9	0.2	0.0	17.1	4.4	1.3	0.7
KR_11	0.6	0.6	0.0	11.2	11.1	0.5	0.9	0.0	10.4	18.8	1.1	1.5
KR_12	0.4	0.4	0.0	8.7	7.7	0.3	0.6	0.0	5.5	12.6	0.7	1.0
KR_13	0.8	0.1	10.7	15.5	1.3	0.7	0.3	5.4	13.4	5.1	1.4	0.3
KR_14	0.1	0.1	20.3	2.6	1.3	0.1	0.0	42.5	2.7	0.9	0.3	0.1
KR_15	0.0	0.0	19.9	0.0	0.0	0.0	0.0	49.2	0.0	0.0	0.0	0.0
KR_16	0.0	0.0	6.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	0.0
KR_17	0.4	0.0	2.9	8.9	0.7	0.3	0.1	2.1	6.4	1.7	0.8	0.1
KR_18	0.0	0.0	23.4	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0	0.0

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_19	0.6	0.4	5.0	11.6	7.4	1.1	0.3	0.1	22.0	5.8	1.7	0.7
KR_20	0.9	0.5	0.0	17.2	9.2	1.1	0.3	0.0	22.5	6.0	2.0	0.8
KR_21	1.4	0.3	0.0	27.0	5.6	1.2	0.3	0.0	24.9	5.6	2.6	0.6
KR_22	1.1	0.5	0.0	22.4	10.3	1.5	0.3	0.0	29.2	6.4	2.6	0.8
KR_23	1.3	0.5	0.0	26.7	10.6	1.0	0.5	0.0	20.7	10.5	2.4	1.1
KR_24	0.8	0.5	0.0	18.4	11.0	0.7	0.6	0.0	14.8	13.8	1.5	1.1
KR_25	1.0	0.5	0.0	22.2	12.6	0.7	0.6	0.0	17.3	13.2	1.7	1.1
KR_26	0.2	0.2	0.0	9.7	11.5	0.2	0.2	0.0	12.4	10.4	0.4	0.4
KR_27	0.1	0.2	0.0	4.3	17.5	0.2	0.1	0.0	16.3	6.7	0.3	0.3
Total	**15.9**	**7.7**	**169.0**			**16.3**	**7.1**	**270.8**			**32.2**	**14.8**

Table 36: Areal extent of banks under erosion and deposition in the reaches of Krishna River during 1973-2011

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_01	1.3	0.6	0.0	25.8	11.2	0.7	0.8	0.0	15.0	16.5	2.0	1.4
KR_02	0.7	0.5	0.0	13.0	9.7	0.5	0.9	0.0	9.9	17.0	1.1	1.3
KR_03	0.7	0.7	0.0	14.9	13.5	0.6	0.9	0.0	12.7	17.0	1.4	1.5
KR_04	1.7	0.2	0.0	33.5	3.5	0.6	1.6	0.0	11.6	31.3	2.3	1.7
KR_05	2.1	0.3	0.0	42.4	5.6	1.6	0.4	0.0	32.1	7.2	3.7	0.6
KR_06	1.7	0.9	0.0	34.8	17.3	1.1	2.5	0.0	22.0	50.6	2.8	3.4
KR_07	0.2	0.1	35.9	3.1	1.1	0.1	0.1	49.2	1.0	1.8	0.2	0.1
KR_08	0.4	0.3	65.1	8.9	5.2	1.5	0.0	166.1	30.3	0.0	2.0	0.3
KR_09	0.3	0.3	36.1	5.3	5.8	0.1	0.3	42.9	2.5	6.1	0.4	0.6
KR_10	1.0	0.9	0.0	21.0	18.2	1.1	0.8	0.0	21.8	15.8	2.1	1.7
KR_11	1.1	1.2	0.0	21.4	23.9	0.7	1.2	0.0	14.3	23.1	1.8	2.4
KR_12	0.4	1.7	0.0	8.1	33.7	0.5	1.5	0.0	9.0	29.3	0.9	3.1
KR_13	0.6	0.6	20.5	12.5	12.2	1.3	0.3	13.1	25.1	5.7	1.9	0.9
KR_14	0.0	0.2	55.8	0.6	4.5	0.3	0.0	57.2	6.7	0.3	0.4	0.2
KR_15	0.0	0.0	59.4	0.0	0.0	0.0	0.0	158.7	0.0	0.0	0.0	0.0
KR_16	0.0	0.0	22.0	0.0	0.0	0.0	0.0	19.8	0.0	0.0	0.0	0.0
KR_17	0.8	0.0	4.0	15.5	0.5	0.6	0.0	4.8	12.5	0.8	1.4	0.1
KR_18	0.0	0.0	52.4	0.0	0.0	0.0	0.0	8.9	0.0	0.0	0.0	0.0

Reach-ID	Left bank					Right bank					Total erosion area (km^2)	Total deposition area (km^2)
	Area (km^2)			Mean width (m)		Area (km^2)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
KR_19	0.6	1.4	9.9	11.3	27.4	1.9	0.9	0.3	38.4	17.6	2.5	2.2
KR_20	0.6	2.6	0.0	12.8	51.4	0.9	1.2	0.0	17.7	24.9	1.5	3.8
KR_21	0.2	2.8	0.0	4.5	56.2	2.6	0.3	0.0	51.4	6.4	2.8	3.1
KR_22	0.0	5.5	0.0	0.4	110.2	3.2	0.1	0.0	63.4	2.7	3.2	5.6
KR_23	1.2	2.3	0.0	24.6	45.7	1.8	1.4	0.0	36.2	27.8	3.0	3.7
KR_24	1.6	0.6	0.0	37.4	13.5	2.0	0.7	0.0	46.4	16.8	3.7	1.3
KR_25	1.5	0.7	0.0	35.7	16.7	1.0	1.3	0.0	22.8	29.6	2.5	2.0
KR_26	1.7	0.0	0.0	98.6	1.2	0.4	0.7	0.0	21.1	41.2	2.0	0.7
KR_27	1.4	0.0	0.0	97.4	0.0	0.5	0.2	0.0	37.4	11.9	1.9	0.2
Total	**21.9**	**24.2**	**361.2**			**25.6**	**18.0**	**521.0**			**47.5**	**42.2**

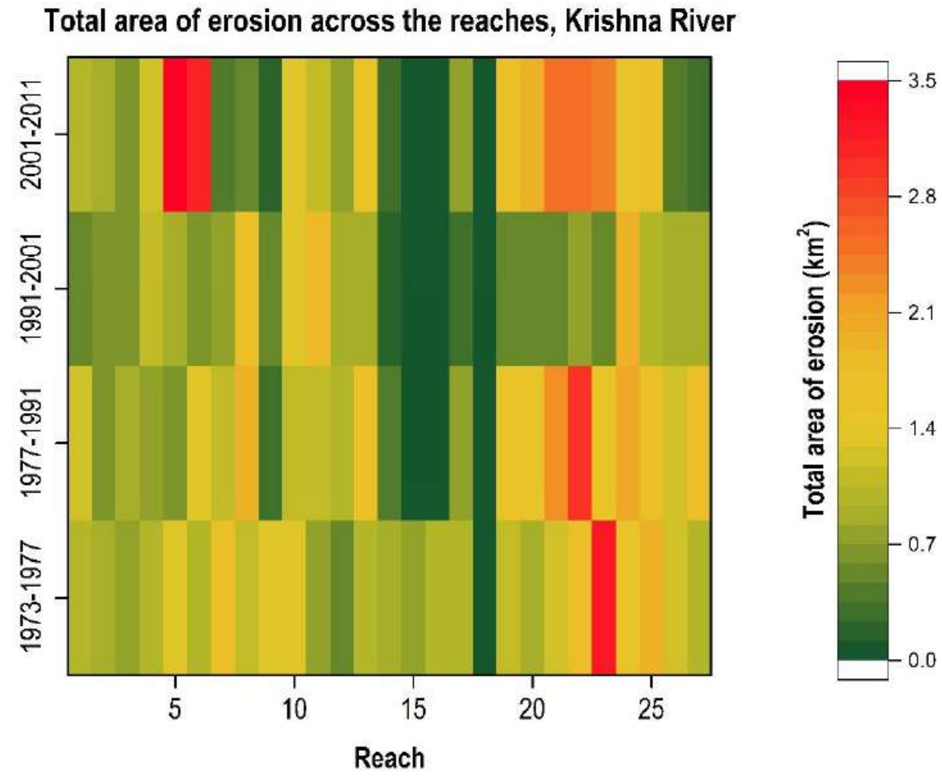

Fig. 25: Variability of the total area of bank erosion across different reaches of Krishna River during different periods

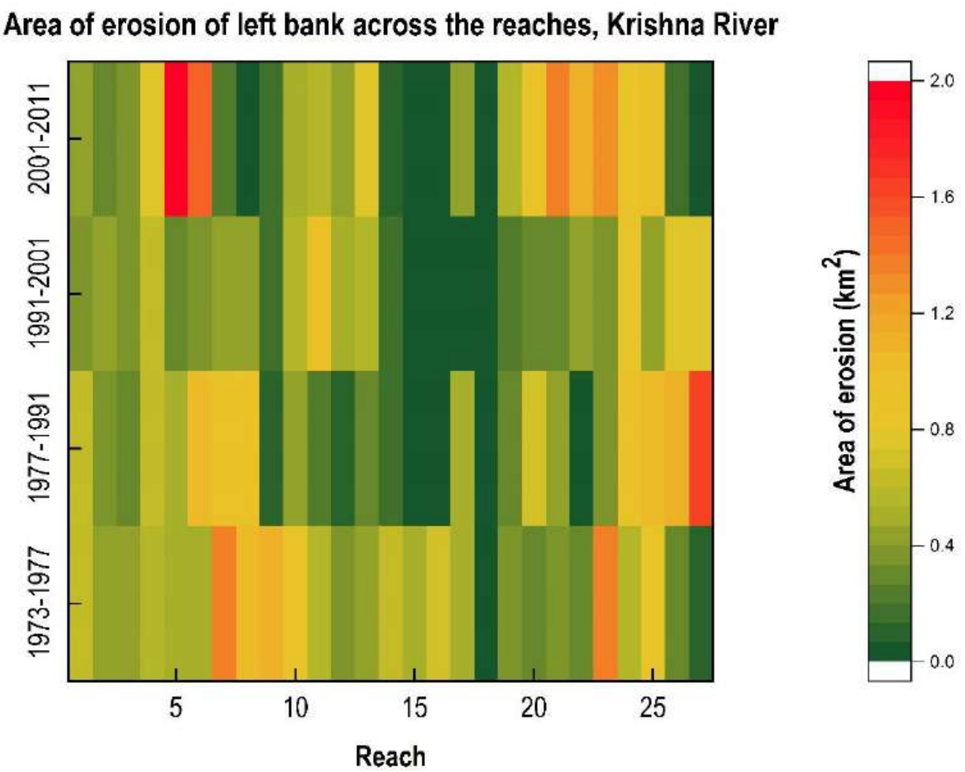

Fig. 26: Variability of the area of erosion along left bank across different reaches of Krishna River during different periods

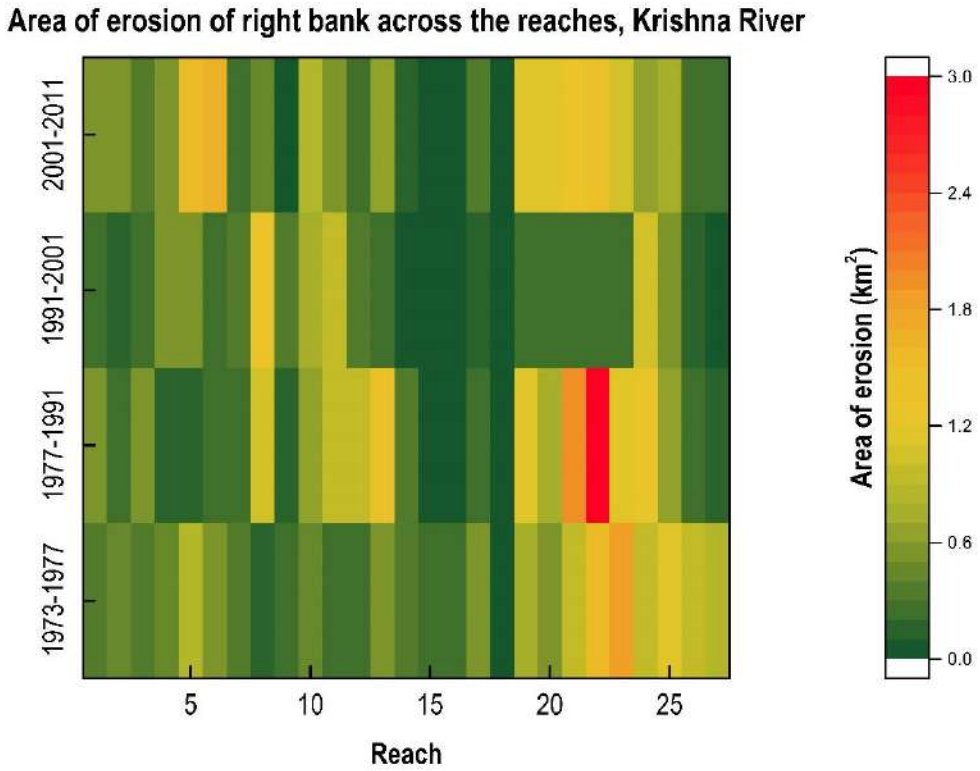

Fig. 27: Variability of the area of erosion along the right bank across different reaches of Krishna River during different periods

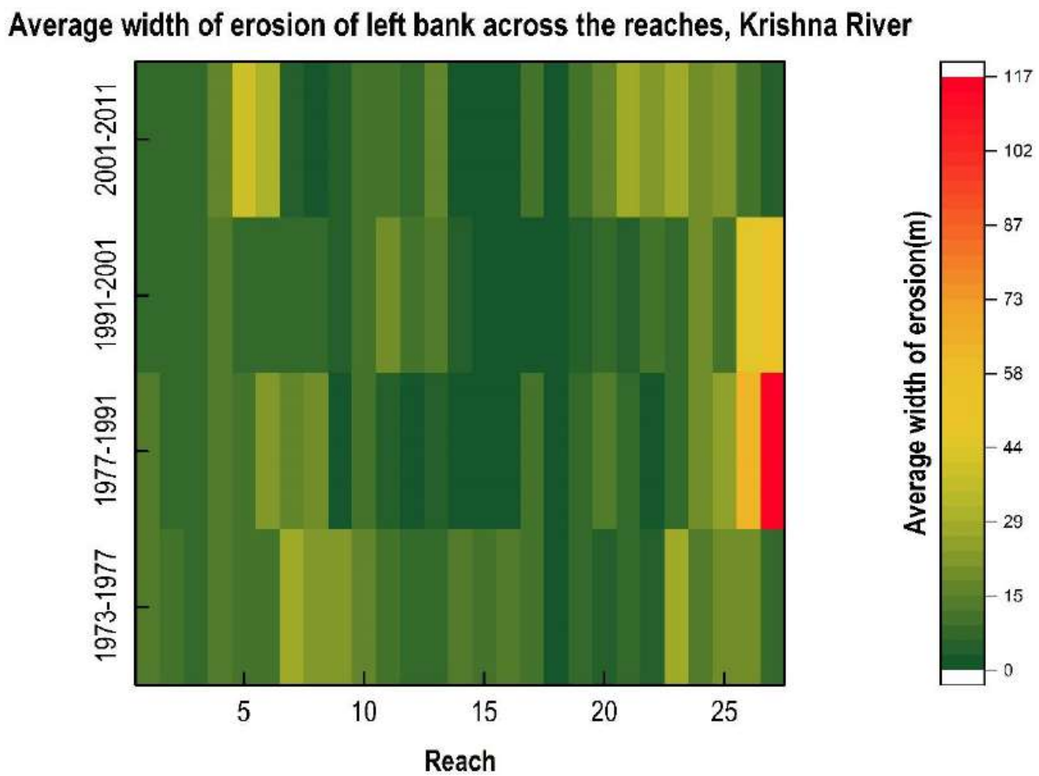

Fig. 28: Variability of the mean width of erosion along the left bank across different reaches of Krishna River during different periods

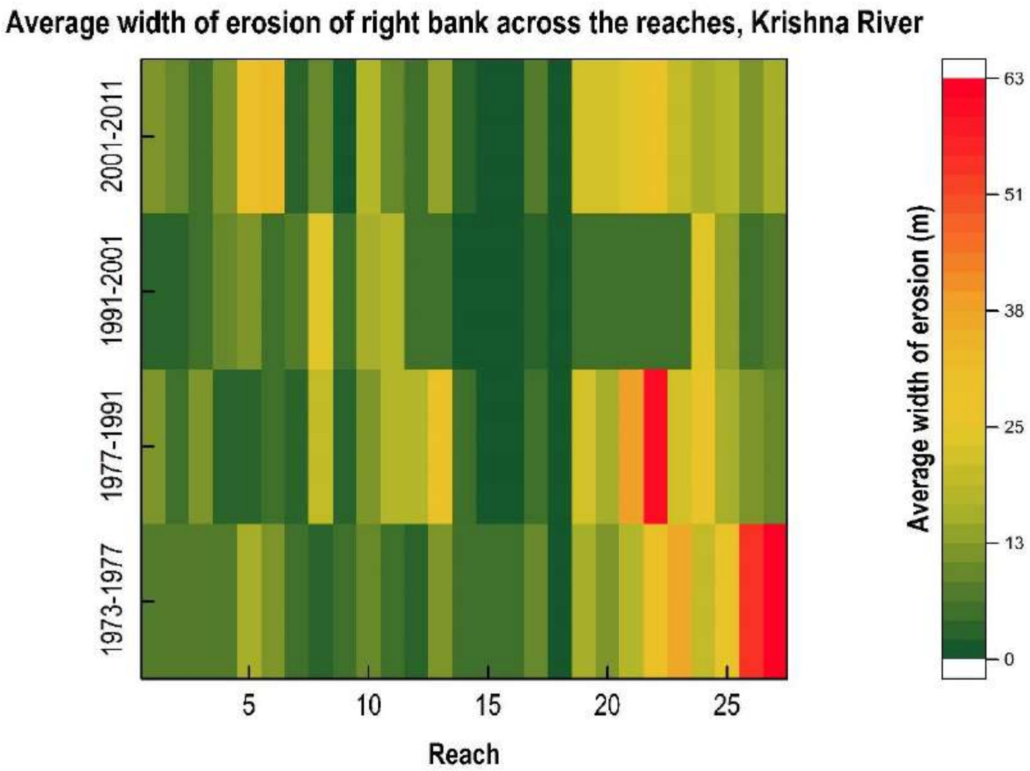

Fig. 29: Variability of the mean width of erosion along the right bank across different reaches of Krishna River during different periods

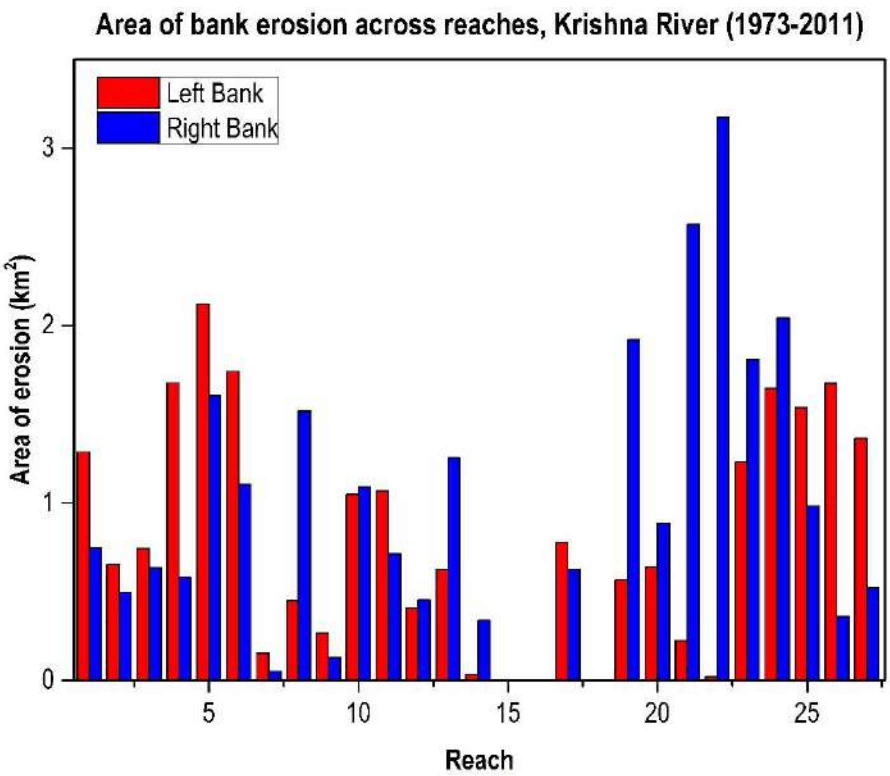

Fig. 30: Area of erosion along the left and right banks across different reaches of Krishna River during 1973-2011

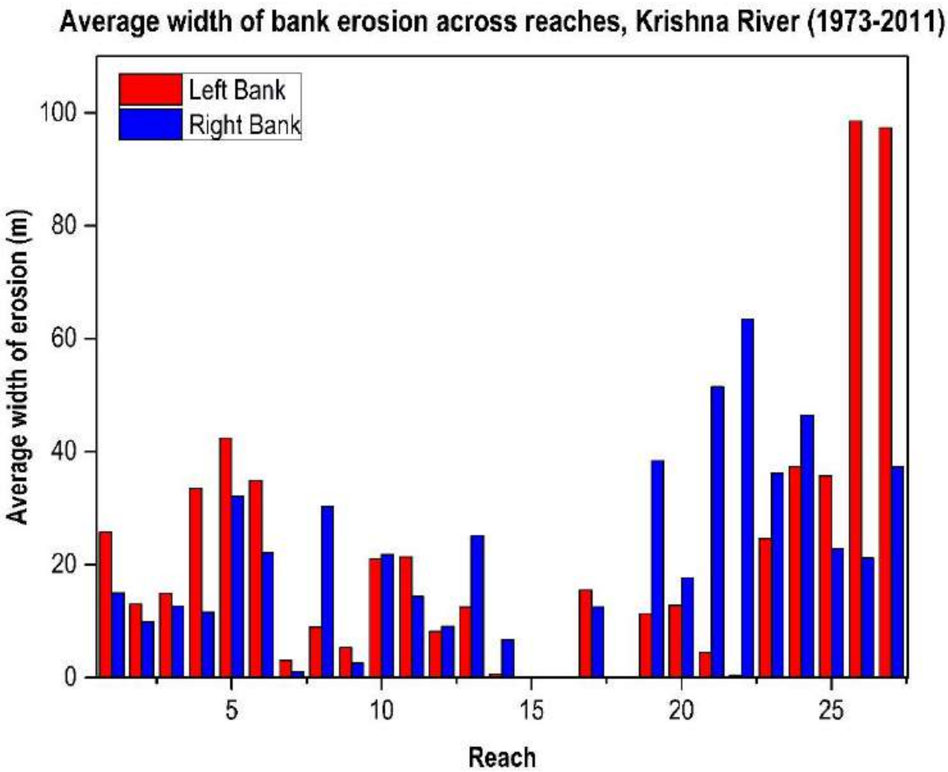

Fig. 31: Mean width of erosion along left and right banks across different reaches of Krishna River during 1973-2011

The severity of erosion between left and right banks of the different reaches of the Krishna River was compared (Figs. 31 to 35). During 1973-1977, it is evident that erosion along the left bank is more severe along the upstream reaches (except KR_05, KR_06, and KR_13), whereas downstream reaches are characterized by high erosion along right banks. However, erosion along the right bank is evident during 1977-1991, except in the extreme upstream (KR_01, KR_02, KR_04 to KR_07 and KR_09) and extreme downstream reaches (KR_25 to KR_27). However, during 1991-2001, erosion along the left bank is dominant in the downstream reaches (except KR_24 and KR_25) as well as the upstream reaches (except KR_05 and KR_08 to KR_10). Hardly any definite pattern between upstream and downstream reaches is observed during 2001-2011, where most of the downstream reaches (KR_21, KR_23 to KR_25) are more vulnerable to erosion along the left bank. However, during 1973-2011, erosion along the left bank is more in the upstream reaches and in the distributary reaches (Fig. 31). While comparing the bank erosion assessment periods, the number of reaches having erosion dominance between left and right banks are almost same, whereas, during 1991-2001, the number of reaches having erosion dominance along the left bank is significantly higher, compared to the number of reaches having erosion dominance along the right bank.

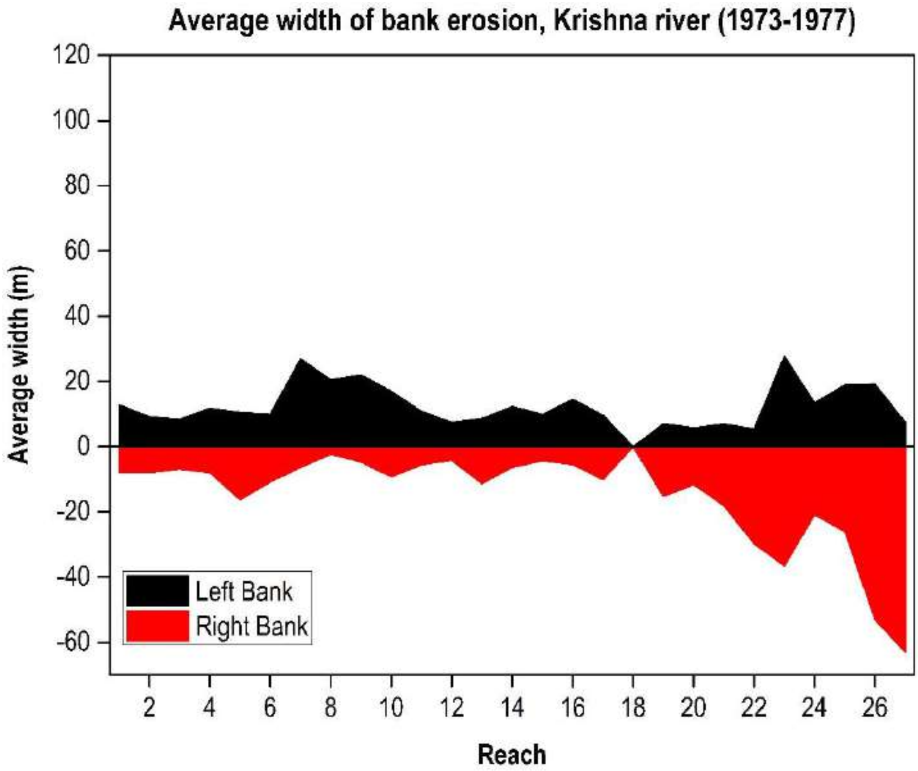

Fig. 32: Mean width of erosion along left and right banks across different reaches of Krishna River during 1973-1977

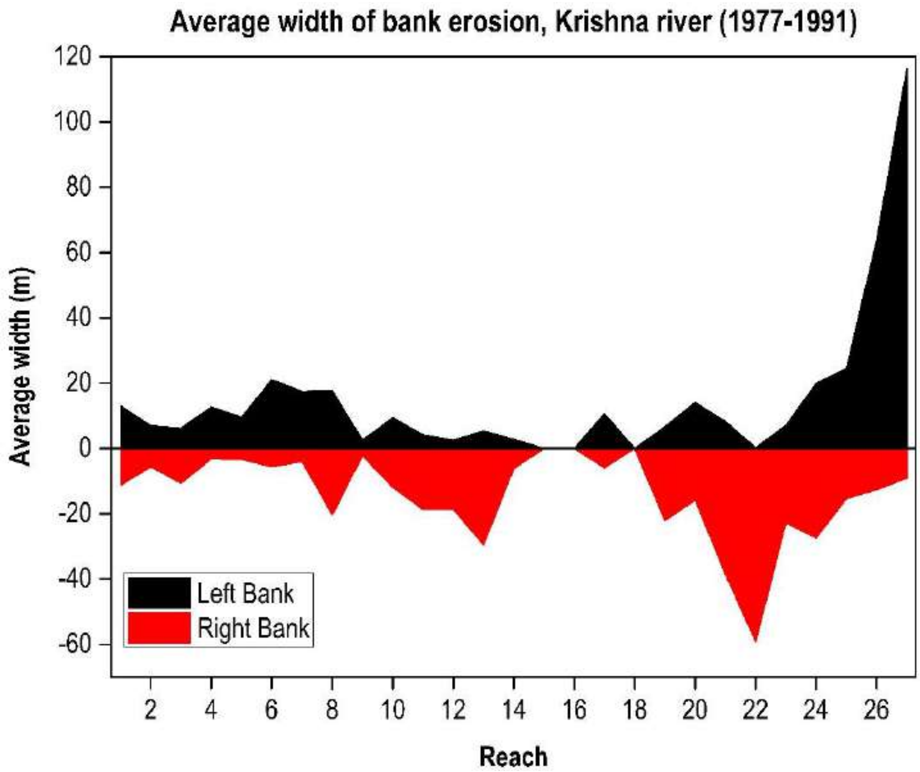

Fig. 33: Mean width of erosion along left and right banks across different reaches of Krishna River during 1977-1991

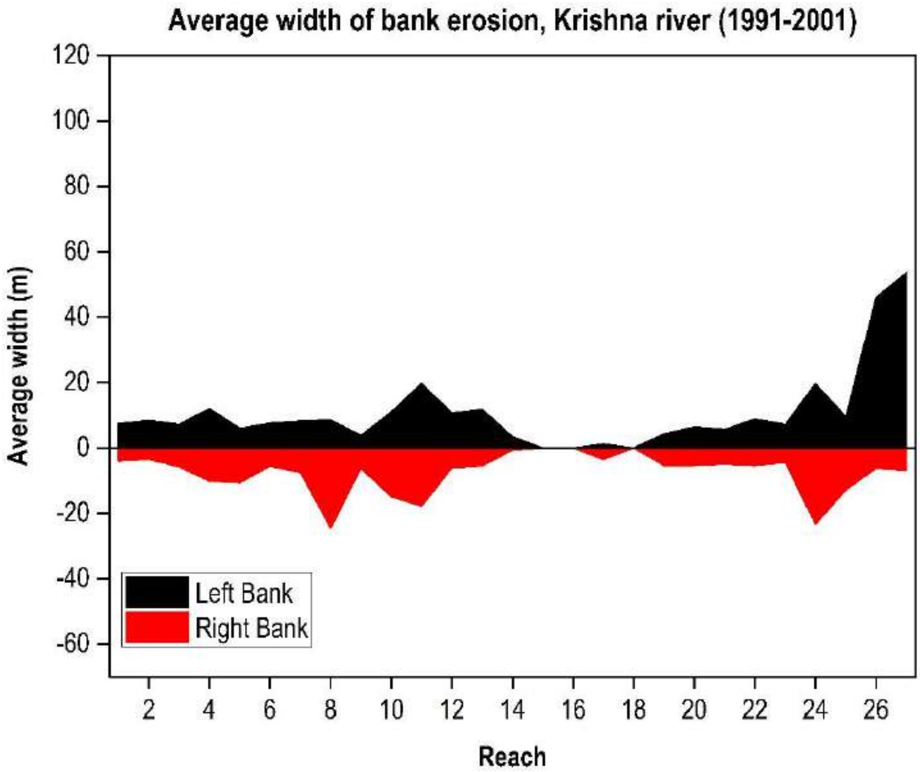

Fig. 34: Mean width of erosion along left and right banks across different reaches of Krishna River during 1991-2001

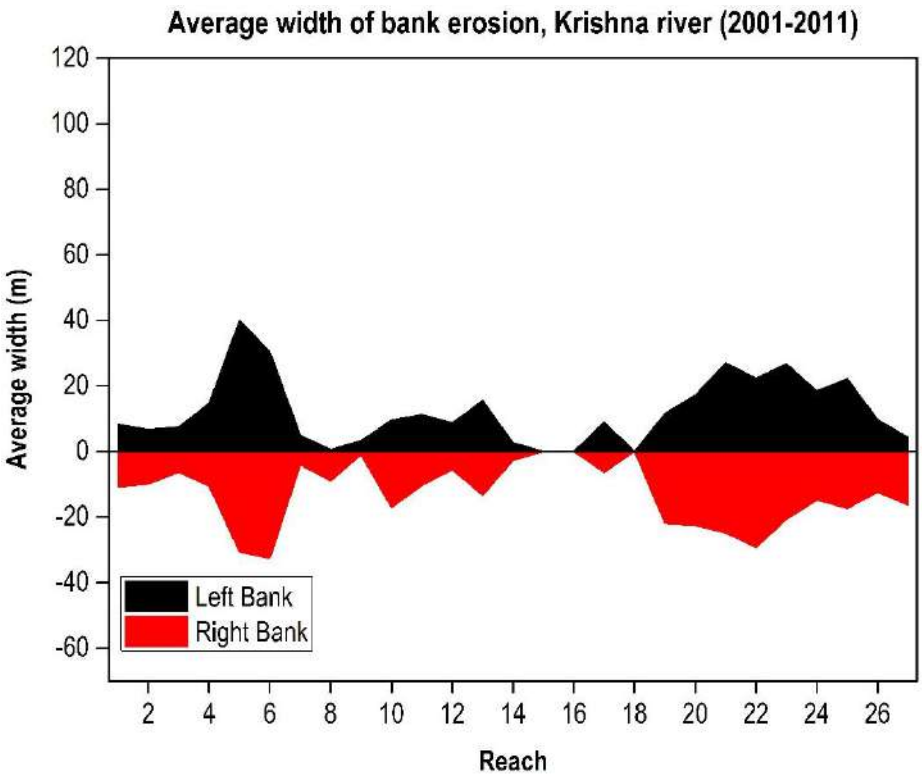

Fig. 35: Mean width of erosion along the left and right banks across different reaches of Krishna River during 2001-2011

9.4.1.2. Tungabhadra River

The analysis of the changes in the bank lines of the study reaches of Tungabhadra River during 1973-1977 reveals that the total area of erosion of both the banks is 11.4 km^2 (Table 37), where that of the individual reaches varies from 0.6 km^2 (TR_05) to 1.9 km^2 (TR_10). Among the reaches, TR_01, TR_02, TR_05, and TR_07 are reaches having the relatively lower areal extent of bank erosion (< 1.0 km^2) (Fig. 36). However, TR_06 and TR_10 are the reaches having a comparably larger areal extent of bank erosion in the study reaches of Tungabhadra River.

Among the different reaches, the total area of erosion along the left bank during 1973-1977 is 4.8 km^2 (roughly 42% of the total bank erosion) (Table 37). However, the range of the area under erosion along the left bank of the individual reaches is between 0.2 km^2 (TR_04) and 0.7 km^2 (TR_03 and TR_10) (Fig. 37). Except for the reaches, TR_04, TR_03, and TR_10, all the reaches have the areal extent of erosion along the left bank is between 0.3 km^2 and 0.5 km^2. The total area of erosion along the right bank of the reaches varies from 0.2 km^2 (TR_05) to 1.3 km^2 (TR_10) (Fig. 38), and the total areal of erosion along the right bank of the entire study reaches sums up to 6.6 km^2 (Table 37), which is nearly 58% of the total area of bank erosion. In addition to TR_10, TR_06 also has a comparatively higher area of erosion along the right bank. The mean width of erosion along the left bank of the reaches varies between 4.1 m (TR_04) to 14.6 m (TR_03), whereas the range of mean width of erosion along the right bank is from 4.4 m (TR_05) to 25.3 m (TR_10) (Figs. 39 and 40). The high erosion rates along the left bank are noticed in TR_03 as well as the downstream reaches (TR_09 to TR_11), whereas TR_04, TR_06, TR_08, TR-10, and TR_11 have considerably high erosion rates along the right bank.

The total area of erosion of both the banks during 1977-1991 is 7.8 km^2, where 39% is contributed by the left bank (3.1 km^2) and 61% by the right bank (4.7 km^2) (Table 38). The total erosion of both the banks of the reaches varies between 0.4 km^2 (TR_05) and 1.0 km^2 (TR_01 and TR_04). Among the different reaches, the areal extent of total erosion along the banks is mostly in the range of 0.5 km^2 to 0.7 km^2 (Fig. 36). The range of the area of erosion along the left bank of the individual reaches is between nearly zero (TR_05) and 0.5 km^2 (TR_01), and most of the reaches have areal extent between 0.2 km^2 and 0.4 km^2 (Fig. 37). The total area of erosion along the right bank of the reaches ranges from 0.2 km^2 (TR_11) to 0.6 km^2 (TR_03 and TR_04) (Fig. 38). The mean width of erosion along the left and right banks of the reaches is in the range between 0.5 m (TR_05) and 10.1 m (TR_01) and 5.4 m (TR_06) and 11.5 m (TR_03), respectively (Figs. 39 and 40).

During 1991-2001, the total area of erosion of both the banks in the reaches is 8.4 km^2 (Table 39), and the individual reaches show the total area of erosion between 0.2 km^2 (TR_05) and 1.4 km^2 (TR_07). In addition to TR_07, TR_06 and TR_08 are also characterized by relatively higher areal extent of total erosion (Fig. 36).

The total area of erosion along the left bank is 3.2 km^2, which is only 38% of the total erosion of both the banks (Table 39). Among the reaches, it varies from nearly zero (TR_05) to 0.7 km^2 (TR_07) (Fig. 37). However, most of the reaches have an area of erosion along the left bank between 0.1 km^2 and 0.3 km^2. In addition to TR_07, TR_06 also has a comparably larger areal extent of erosion along the left bank of the reaches of Tungabhadra River. The total area of erosion along the right bank is 5.2 km^2, and that of the reaches ranges between 0.2 km^2 (TR_05 and TR_11) to 0.7 km^2 (TR_06 and TR_07) (Fig. 38). The mean width of erosion of the reaches along left and right banks varies between 0.7 m (TR_05) and 14.4 m (TR_07) and 3.7 m (TR_05) and 14.1 m (TR_06), respectively (Figs. 39 and 40). The mean width of erosion of left bank is relatively more in TR_07 and TR_08, whereas that in the right bank is considerably high in TR_02, TR_06, TR_07, TR_08, and TR_10.

The total erosion of both the banks of the study reaches is 13.6 km^2 during 2001-2011 (Table 40), where 55% of the same is contributed by the left bank (7.5 km^2) and rest by the right bank (6.1 km^2). Among the different reaches, the variation of the total erosion of both the banks is between 0.2 km^2 (TR_05) and 3.8 km^2 (TR_10) (Fig. 36), while most of the values fall within a range of 1.0 km^2 to 1.5 km^2. The total area of erosion along the left bank of the reaches show a variability between 0.1 km^2 (TR_11) and 2.2 km^2 (TR_10), whereas the total area of erosion along the right bank of the reaches is in the range of nearly zero (TR_05) to 1.6 km^2 (TR_10) (Figs. 37 and 38). Except for TR_10, all the reaches have the areal extent of erosion along left as well as right banks less than 1.0 km^2. The mean width of erosion along the left bank of the reaches varies between 3.4 m (TR_11) and 44.6 m (TR-10), whereas the range of mean width of erosion along the right bank is from 0.9 m (TR_05) to 32.4 m (TR_10) (Figs. 39 and 40).

The total area of erosion along both the banks of the study reaches of Tungabhadra River during the entire period (i.e., 1973-2011) is 14.7 km^2 (Table 41), and that of the individual reaches varies between 0.6 km^2 (TR_05) to 3.8 km^2 (TR_10). Among the reaches, the larger areal extent of bank erosion occurs in TR_10, TR_06, and TR_07, compared to the rest. The area of erosion along the left bank of the reaches ranges from 0.1 km^2 (TR_05) to 1.7 km^2 (TR_10) (Fig. 41), and the total area of erosion along the left bank is 5.0 km^2 (Table 41). Most of the reaches show the areal extent of erosion along the left bank less than 0.5 km^2 during the period. The total area of erosion along the right bank of the reaches ranges from 0.5 km^2 (TR_01, TR_03, and TR_05) to 2.1 km^2 (TR_10) (Fig. 41), which sums up to 9.7 km^2. The mean width of erosion along the left and right banks of the reaches is in the range between 2.7 m (TR_11) and 33.2 m (TR_10) and 9.0 m (TR_05) and 42.9 m (TR_10), respectively (Fig. 42).

Table 37: Areal extent of banks under erosion and deposition in the reaches of Tungabhadra River during 1973-1977

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
TR_01	0.3	1.1	0.0	6.6	21.4	0.4	0.7	0.0	8.0	14.7	0.7	1.8
TR_02	0.3	0.6	0.0	6.8	11.8	0.3	0.7	0.0	6.5	13.8	0.7	1.3
TR_03	0.7	0.3	0.0	14.6	5.5	0.3	1.0	0.0	5.7	19.1	1.0	1.2
TR_04	0.2	1.1	0.0	4.1	22.5	0.9	0.4	0.0	18.8	7.4	1.1	1.5
TR_05	0.3	0.1	7.6	7.0	1.8	0.2	0.1	4.5	4.4	2.9	0.6	0.2
TR_06	0.4	0.5	3.5	8.2	9.4	1.0	0.2	7.7	20.5	3.4	1.4	0.6
TR_07	0.4	1.1	0.0	7.3	21.0	0.4	0.5	0.0	7.5	9.3	0.7	1.5
TR_08	0.4	0.8	0.0	8.9	16.6	0.8	0.5	0.0	16.0	10.6	1.2	1.4
TR_09	0.5	3.4	0.0	10.1	68.3	0.5	0.8	0.0	9.2	16.3	1.0	4.2
TR_10	0.7	0.5	0.0	13.1	10.1	1.3	0.4	0.0	25.3	8.0	1.9	0.9
TR_11	0.4	0.5	0.0	11.5	14.1	0.5	0.5	0.0	14.8	12.5	1.0	1.0
Total	**4.8**	**9.9**	**11.2**			**6.6**	**5.7**	**12.1**			**11.4**	**15.7**

Table 38: Areal extent of banks under erosion and deposition in the reaches of Tungabhadra River during 1977-1991

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
TR_01	0.5	0.4	0.0	10.1	8.3	0.5	0.9	0.0	9.7	17.6	1.0	1.3
TR_02	0.2	0.9	0.0	3.5	17.6	0.5	0.5	0.0	9.7	10.1	0.7	1.4
TR_03	0.2	1.7	0.0	3.4	34.0	0.6	0.8	0.0	11.5	15.8	0.7	2.5
TR_04	0.4	1.2	0.0	8.5	23.9	0.6	0.7	0.0	11.1	14.9	1.0	1.9
TR_05	0.0	0.4	15.6	0.5	7.6	0.3	0.1	9.6	6.8	2.4	0.4	0.5
TR_06	0.4	1.1	8.8	7.2	21.3	0.3	0.3	20.1	5.4	6.1	0.6	1.4
TR_07	0.4	1.0	0.0	8.2	19.4	0.5	0.7	0.0	10.3	14.2	0.9	1.7
TR_08	0.3	2.2	0.0	5.4	43.1	0.4	0.9	0.0	8.3	18.0	0.7	3.1
TR_09	0.2	2.0	0.0	3.5	40.6	0.4	0.9	0.0	8.8	18.1	0.6	2.9
TR_10	0.2	1.6	0.0	4.2	32.8	0.4	1.0	0.0	8.7	20.4	0.6	2.7
TR_11	0.3	0.2	9.1	8.8	5.3	0.2	0.3	7.6	5.9	7.6	0.5	0.5
Total	**3.1**	**12.6**	**33.5**			**4.7**	**7.2**	**37.2**			**7.8**	**19.8**

Table 39: Areal extent of banks under erosion and deposition in the reaches of Tungabhadra River during 1991-2001

Reach-ID	Left bank					Right bank					Total erosion area (km^2)	Total deposition area (km^2)
	Area (km^2)			Mean width (m)		Area (km^2)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
TR_01	0.2	0.6	0.0	3.0	12.6	0.4	0.6	0.0	8.0	11.3	0.6	1.2
TR_02	0.2	1.3	0.0	4.0	25.4	0.6	0.5	0.0	12.0	9.7	0.8	1.8
TR_03	0.1	0.9	0.0	2.3	18.9	0.4	0.5	0.0	9.0	9.8	0.6	1.4
TR_04	0.3	0.6	0.0	6.0	12.4	0.4	0.8	0.0	7.1	16.3	0.7	1.4
TR_05	0.0	0.1	10.7	0.7	2.6	0.2	0.1	6.3	3.7	1.5	0.2	0.2
TR_06	0.3	0.9	5.5	5.8	17.7	0.7	0.4	11.0	14.1	8.6	1.0	1.3
TR_07	0.7	0.6	0.0	14.4	12.3	0.7	0.6	0.0	13.7	11.4	1.4	1.2
TR_08	0.6	0.9	0.0	12.8	18.3	0.5	0.8	0.0	10.0	15.6	1.1	1.7
TR_09	0.3	1.2	0.0	6.0	24.6	0.5	1.1	0.0	9.2	21.4	0.8	2.3
TR_10	0.3	1.5	0.0	5.0	29.8	0.7	0.7	0.0	13.1	13.8	0.9	2.2
TR_11	0.2	0.3	3.1	4.7	7.2	0.2	0.2	10.0	5.9	4.3	0.4	0.4
Total	**3.2**	**9.0**	**19.3**			**5.2**	**6.1**	**27.3**			**8.4**	**15.1**

Table 40: Areal extent of banks under erosion and deposition in the reaches of Tungabhadra River during 2001-2011

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
TR_01	0.3	0.3	0.0	6.8	5.2	0.4	0.4	0.0	9.0	7.2	0.8	0.6
TR_02	0.4	0.4	0.0	8.0	7.9	0.6	0.4	0.0	12.2	8.2	1.0	0.8
TR_03	0.4	0.5	0.0	8.8	11.0	0.5	0.4	0.0	9.8	7.4	0.9	0.9
TR_04	0.7	0.5	0.0	13.1	9.3	0.5	0.5	0.0	10.9	9.9	1.2	1.0
TR_05	0.2	0.1	14.8	3.5	1.7	0.0	0.2	11.7	0.9	4.4	0.2	0.3
TR_06	0.7	0.2	9.6	13.2	4.4	0.3	0.4	14.7	6.3	7.8	1.0	0.6
TR_07	0.7	0.4	0.0	13.3	7.2	0.4	0.6	0.0	7.1	12.8	1.0	1.0
TR_08	1.0	0.4	0.0	20.8	8.5	0.5	0.5	0.0	9.4	10.1	1.5	0.9
TR_09	0.7	0.6	0.0	14.9	11.3	0.7	0.7	0.0	13.4	13.8	1.4	1.3
TR_10	2.2	0.6	0.0	44.6	12.9	1.6	0.6	0.0	32.4	11.7	3.8	1.2
TR_11	0.1	0.2	1.6	3.4	6.8	0.5	0.2	1.0	14.8	4.1	0.7	0.4
Total	**7.5**	**4.2**	**26.0**			**6.1**	**4.8**	**27.4**			**13.6**	**9.0**

Table 41: Areal extent of banks under erosion and deposition in the reaches of Tungabhadra River during 1973-2011

Reach-ID	Left bank					Right bank					Total erosion area (km²)	Total deposition area (km²)
	Area (km²)			Mean width (m)		Area (km²)			Mean width (m)			
	Erosion	Deposition	Inundation	Erosion	Deposition	Erosion	Deposition	Inundation	Erosion	Deposition		
TR_01	0.3	1.4	0.0	6.9	27.9	0.5	1.3	0.0	9.5	25.6	0.8	2.7
TR_02	0.2	2.2	0.0	3.2	43.5	0.8	0.8	0.0	15.5	16.9	0.9	3.0
TR_03	0.3	2.3	0.0	5.6	45.9	0.5	1.3	0.0	9.9	26.0	0.8	3.6
TR_04	0.3	2.2	0.0	6.9	43.3	0.8	0.8	0.0	15.4	16.0	1.1	3.0
TR_05	0.1	0.3	28.0	2.9	6.2	0.5	0.1	17.6	9.0	2.2	0.6	0.4
TR_06	0.6	1.5	11.0	12.2	30.6	1.4	0.4	24.4	28.9	8.4	2.1	2.0
TR_07	0.7	1.6	0.0	14.8	31.3	0.7	1.2	0.0	14.2	23.3	1.5	2.7
TR_08	0.5	2.4	0.0	9.5	48.2	0.8	1.3	0.0	15.0	25.8	1.2	3.7
TR_09	0.2	5.7	0.0	3.6	113.8	0.7	2.1	0.0	13.8	42.8	0.9	7.8
TR_10	1.7	2.6	0.0	33.2	51.7	2.1	0.9	0.0	42.9	17.3	3.8	3.5
TR_11	0.1	0.6	5.6	2.7	15.5	0.9	0.1	24.5	25.6	3.3	1.0	0.7
Total	**5.0**	**22.7**	**44.7**			**9.7**	**10.3**	**66.5**			**14.7**	**33.0**

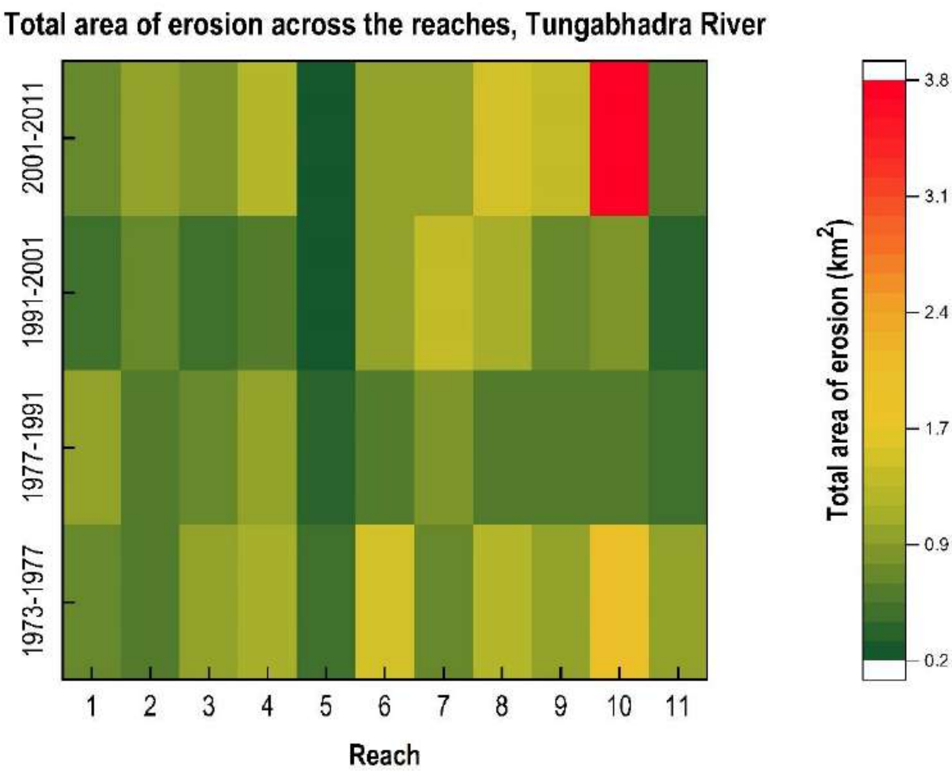

Fig. 36: Variability of the total area of bank erosion across different reaches of Tungabhadra River during different periods

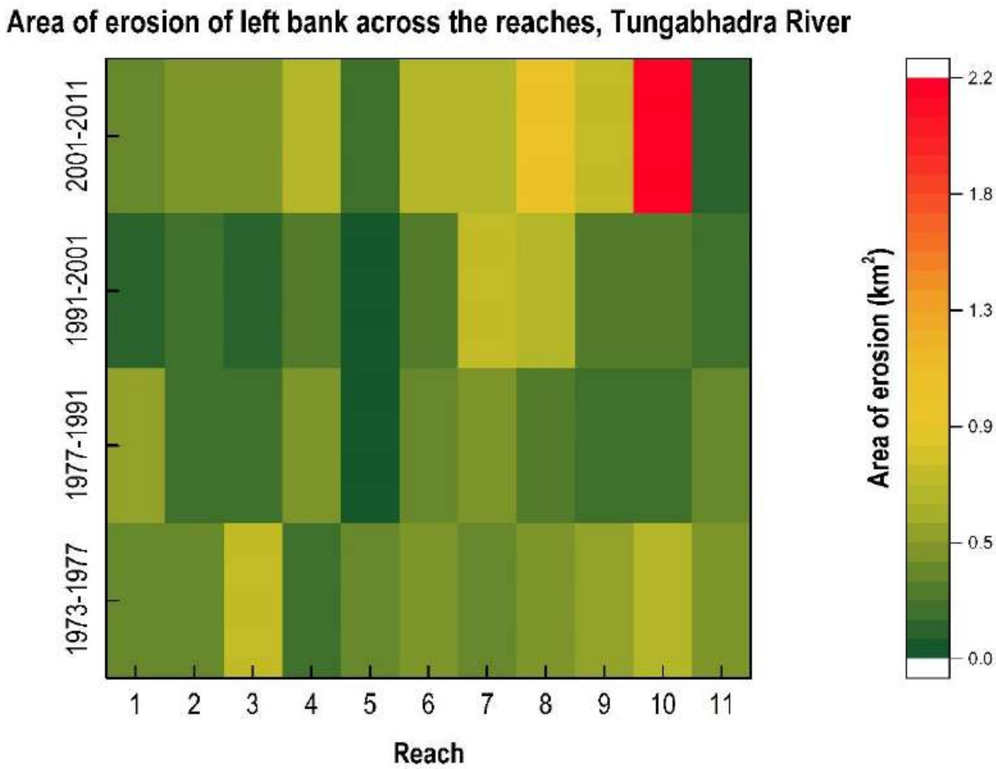

Fig. 37: Variability of the area of erosion along left bank across different reaches of Tungabhadra River during different periods

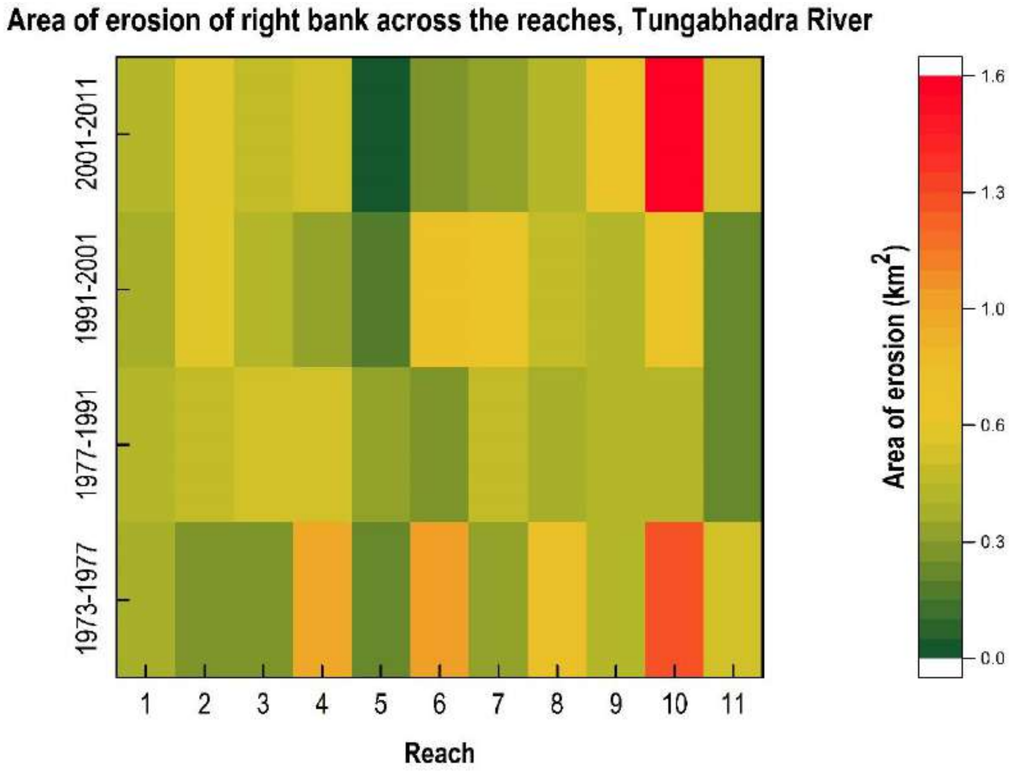

Fig. 38: Variability of the area of erosion along the right bank across different reaches of Tungabhadra River during different periods

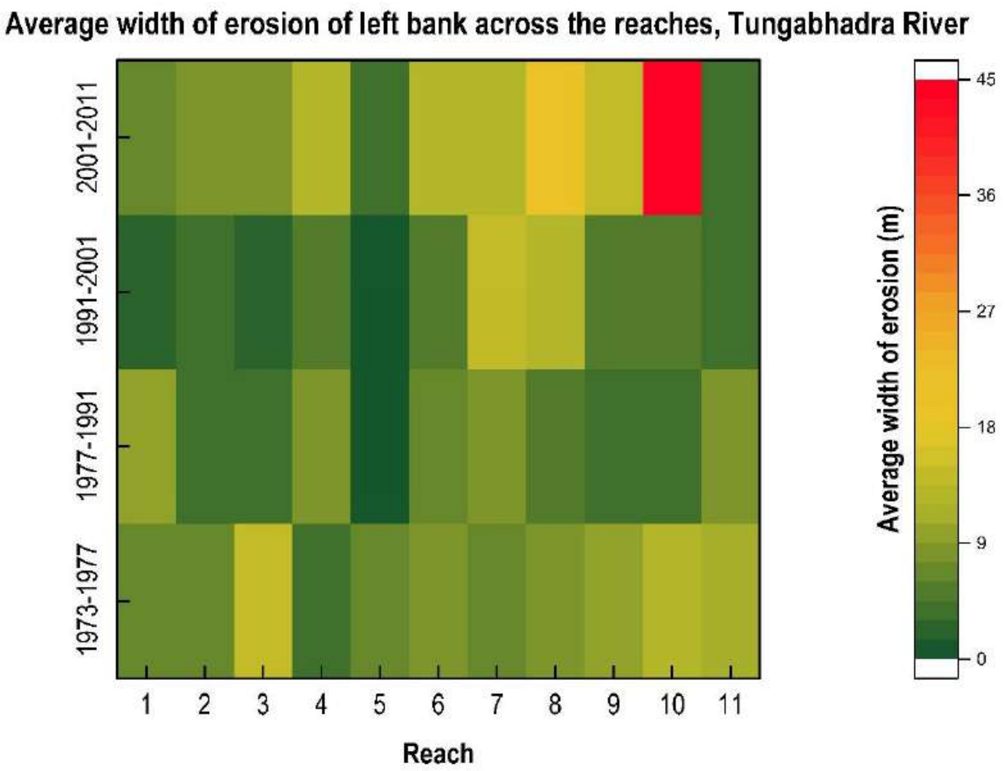

Fig. 39: Variability of the mean width of erosion along the left bank across different reaches of Tungabhadra River during different periods

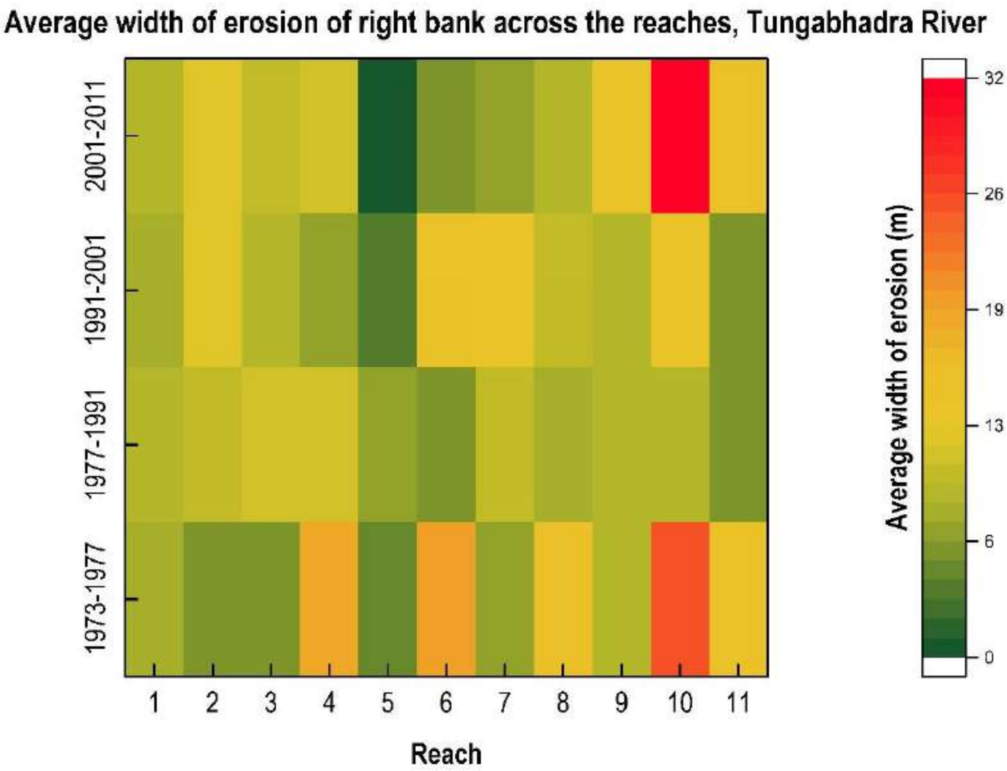

Fig. 40: Variability of the mean width of erosion along the right bank across different reaches of Tungabhadra River during different periods

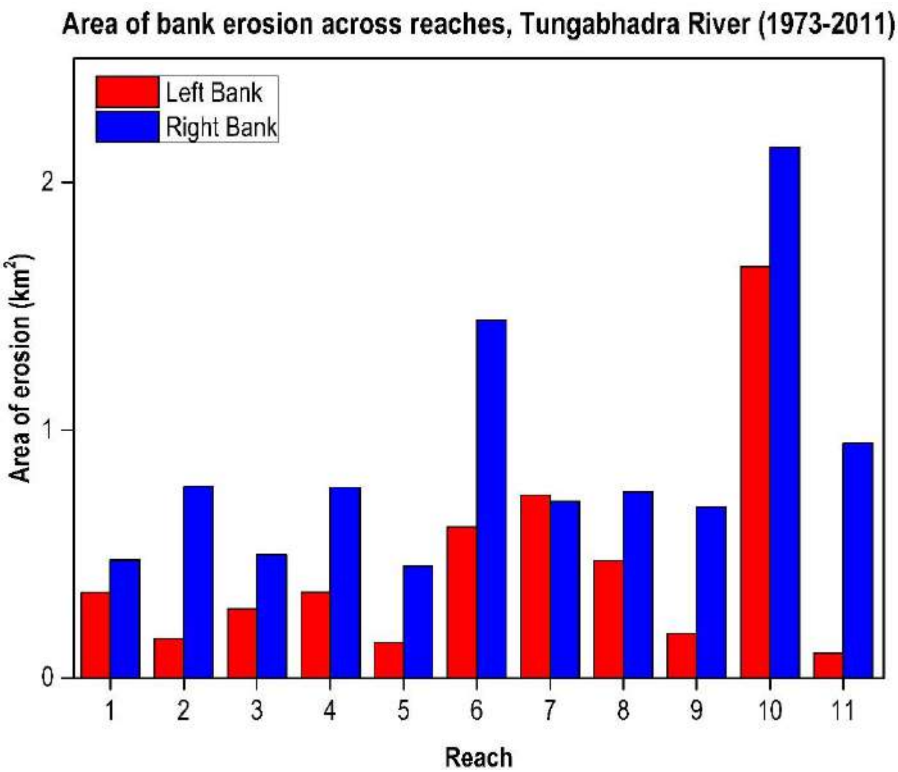

Fig. 41: Area of erosion along the left and right banks across different reaches of Tungabhadra River during 1973-2011

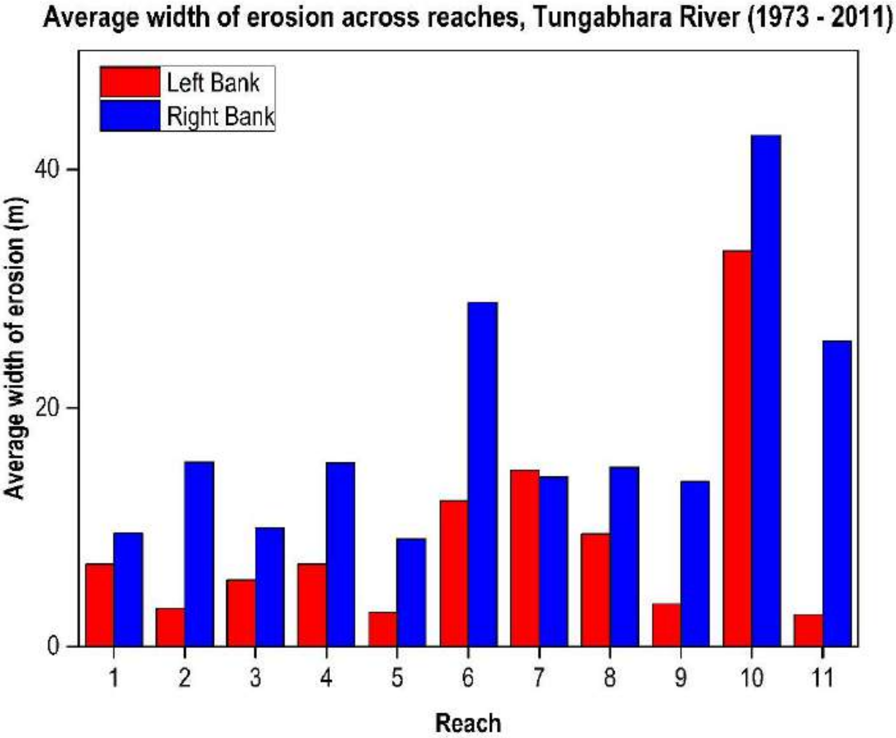

Fig. 42: Mean width of erosion along left and right banks across different reaches of Tungabhadra River during 1973-2011

The variability of the areal extent and mean width of bank erosion of the different reaches of Tungabhadra River across the time periods suggests that TR_10 shows large fluctuations in the bank erosion (Figs. 36 to 42). In addition, the comparison of the bank erosion (both areal extent as well as mean width of erosion) during the short term and long term assessment periods also suggests that TR_10 and TR_08 are the most vulnerable reaches to bank erosion among the different study reaches of Tungabhadra River. However, TR_06, TR_07, and TR_04 also have a comparatively higher vulnerability, compared to the rest of the reaches. Similar to the occurrence of the localized bank erosion patches in a few reaches of Krishna River, the reaches of the Tungabhadra River also show localized erosion zones in some of the reaches, but not consistent throughout the time period. On a mean basis, the annual total bank erosion during 1973-1977 was 2.8 km^2, whereas it was 0.6 km^2 during 1977-1991, 0.8 km^2 during 1991-2001 and 1.4 km^2 during 2001-2011. However, on the long term, the annual erosion of the total bank area is 0.4 km^2 across the reaches of Tungabhadra River.

The severity of erosion between left and right banks of the different reaches of Tungabhadra River was compared (Figs. 42 to 46), and the results suggest that the erosion more severe in the right bank of the reaches, compared to the left bank during all the time periods, except during 2001-2011. Except during 2011-2011, most of the reaches in the upstream as well as downstream show higher rates of erosion along the right bank.

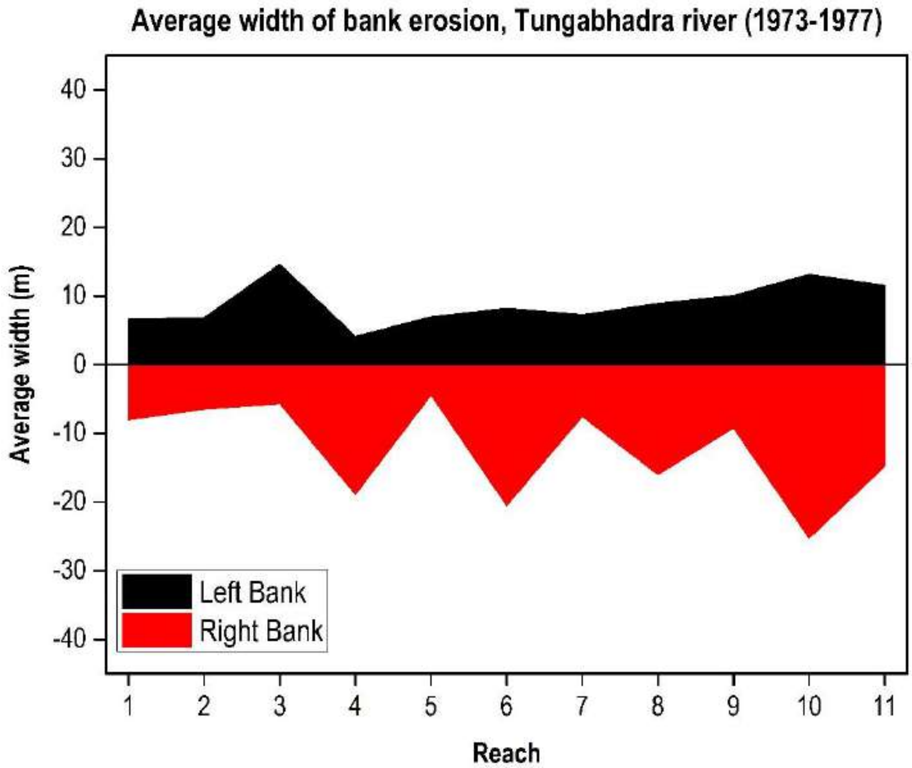

Fig. 43: Mean width of erosion along left and right banks across different reaches of Tungabhadra River during 1973-1977

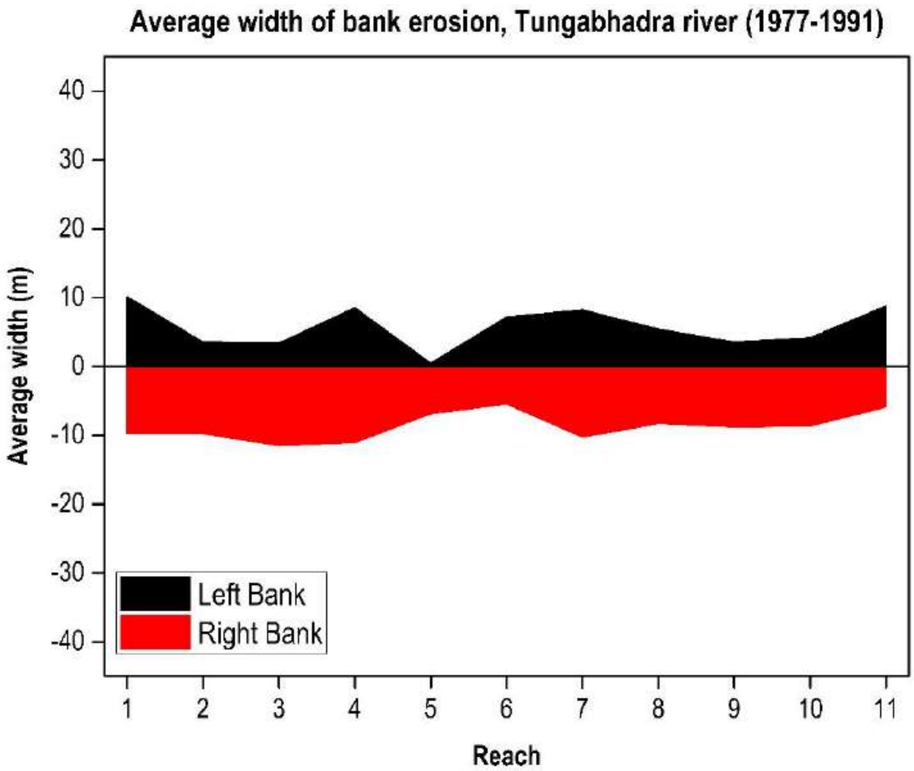

Fig. 44: Mean width of erosion along left and right banks across different reaches of Tungabhadra River during 1977-1991

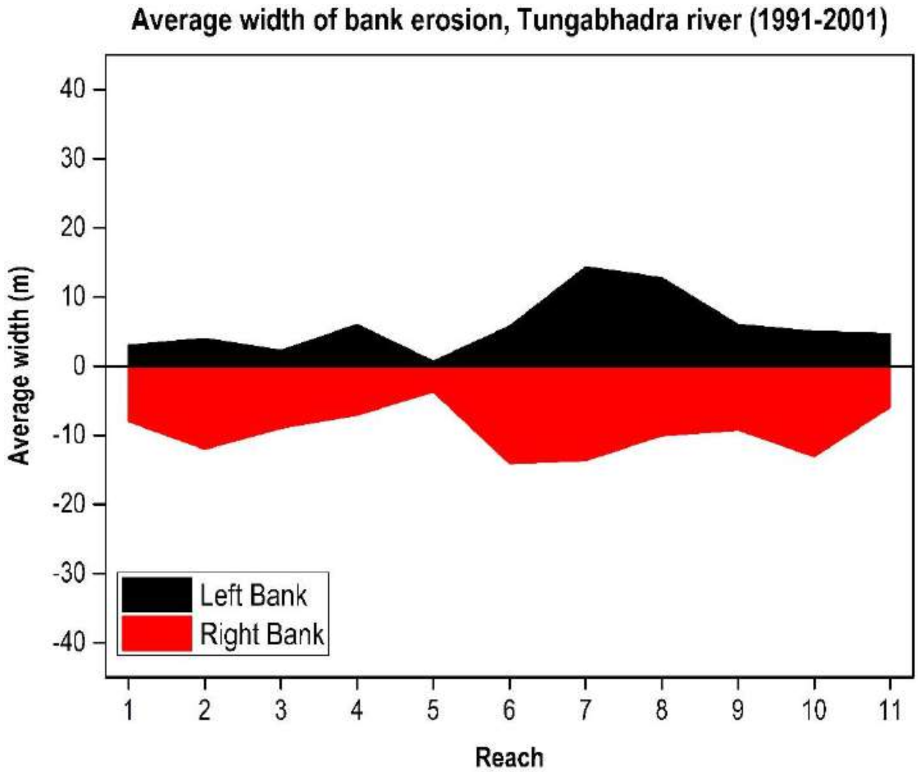

Fig. 45: Mean width of erosion along left and right banks across different reaches of Tungabhadra River during 1991-2001

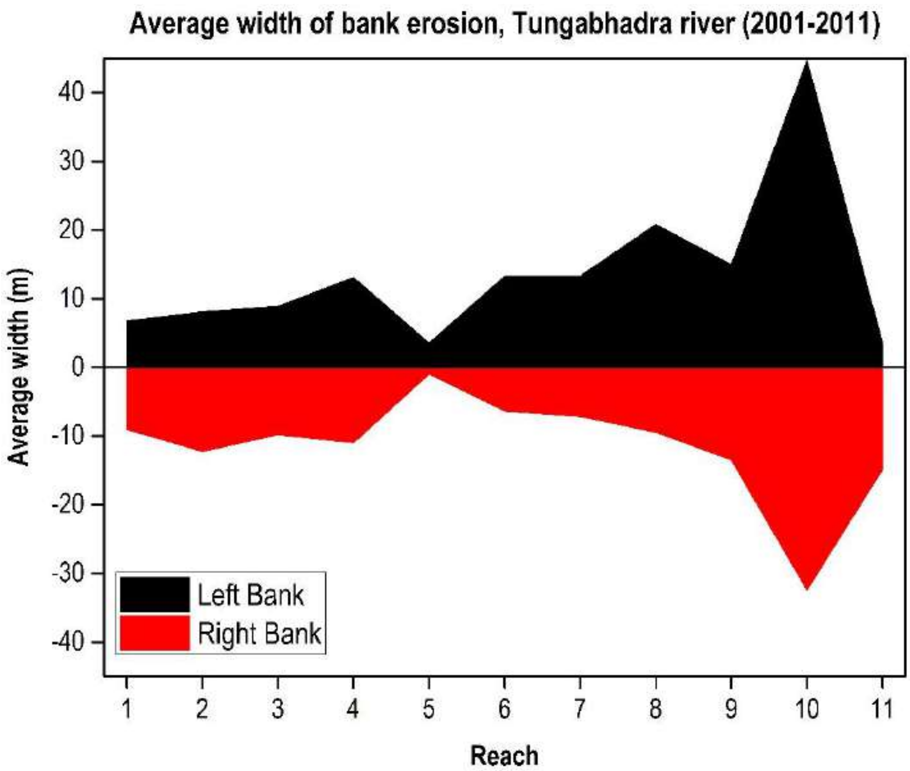

Fig. 46: Mean width of erosion along the left and right banks across different reaches of Tungabhadra River during 2001-2011

9.4.2. Bank deposition

9.4.2.1. Krishna River

Similar to the erosion estimates, the areal extent and mean width of the deposition patches along the reaches of the Krishna River during different periods were assessed (Tables 32 to 36). During 1973-1977, the total area of the depositional patches in both the banks of the reaches is 30.0 km^2 (Table 32), and that of the individual reaches varies between 0.4 km^2 (KR_17) and 2.1 km^2 (KR_22) (Fig. 47). The total area of deposition occurred along the left bank during 1973-1977 is 15.1 km^2, where that of the induvial reaches varies between 0.1 km^2 (KR_17) and 1.6 km^2 (KR_22) (Fig. 48). However, the mean width of deposition of the reaches shows a range from 1.5 m (KR_17) to 51.4 m (KR_27) (Fig. 49). Likewise, the total area of deposition occurred along the right bank is 14.9 km^2, and the total area of deposition of the reaches varies from nearly zero (KR_27) to 1.2 km^2 (KR_08 and KR_11) (Fig. 50). The mean width of deposition along the right bank of the reaches shows a range between 2.3 m (KR_27) and 35.8 m (KR_26) (Fig. 51).

The total area of deposition in both the banks of the reaches during 1977-1991 is 40.2 km^2, where the areal extent of the depositional patches along the left and right banks is 19.6 km^2 and 20.6 km^2, respectively (Table 33). The total area of deposition of both the banks across the reaches varies between 0.1 km^2 (KR_14) and 4.5 km^2 (KR_22) (Fig. 47), whereas the same along left and right banks shows a range from nearly zero (KR_27) to 3.9 km^2 (KR_22) and nearly zero (KR_14) to 2.4 km^2 (KR_06), respectively (Figs. 48 and 50). The mean width of deposition along the left bank of the reaches shows a range from 0.1 m (KR_27) to 77.9 m (KR_22) (Fig. 49), whereas the same along the right bank varies between 0.1 m (KR_14) and 48.3 m (KR_06) (Fig. 51).

The estimated area of total depositional patches in both the banks of the different reaches of Krishna River during 1991-2001 is 26.3 km^2, of which 12.5 km^2 is along the left bank and 13.8 km^2 along the right bank (Table 34). The total area of deposition of both the banks of the individual reaches varies from 0.1 km^2 (KR_08) to 3.0 km^2 (KR_22) (Fig. 47). Across the reaches, the total area of deposition along left bank shows variability between nearly zero (KR_26 and KR_27) and 1.4 km^2 (KR_23) (Fig. 48), and the mean width of deposition is in the range of less than 1.0 m (KR_26 and KR_27) to 27.8 m (KR_23) (Fig. 49). Similarly, the total area of deposition along right bank varies from nearly zero (KR_08) to 1.7 km^2 (KR_22) (Fig. 50), and mean width of deposition ranges from 0.3 m (KR_08) to 34.5 m (KR_22) (Fig. 51).

During 2001-2011, the total area of deposition of both the banks of the entire reaches is 14.8 km^2 (Table 35), and that of the individual reaches is in the range between 0.1 km^2 (KR_14) and 1.5 km^2 (KR_11) (Fig. 47). The total area of deposition occurred along the left bank is 7.7 km^2, and that of the reaches varies from nearly zero (KR_17) to a maximum of 0.6 km^2 (KR_11) (Fig. 48). The total area of deposition along the right bank is 7.1 km^2, and the reaches shows total depositional area between nearly zero (KR_07, KR_08, and KR_14) and 0.9 km^2 (KR_11) (Fig. 50). The mean width of deposition along the left bank of the reaches shows a range from 0.7 m (KR_17) to 17.5 m (KR_27) (Fig. 49), whereas the same along the right bank varies between < 1.0 m (KR_07) and 18.8 m (KR_11) (Fig. 51).

The total area of deposition of both the banks of the entire reaches during the whole study period (1973-2011) is 42.2 km^2 (Table 36), of which 57% occurs along the left bank (24.2 km^2) and 43% along the right bank (18.0 km^2). Among the different reaches, the total area of deposition of both the banks varies between 0.1 km2 (KR_17) and 5.6 km2 (KR_22). However, the total area of deposition along the left bank of the reaches varies from nearly zero (KR_17) to 5.5 km2 (KR_22), and that along the right bank is in the range of nearly zero (KR_17) to 2.5 km2 (KR_06) (Fig. 52). The mean width of deposition along left and right banks of the reaches is in the range of < 1.0 m (KR_27) to 110.2 m (KR_22) and < 1.0 m (KR_08) to 50.6 m (KR_06), respectively (Fig. 53).

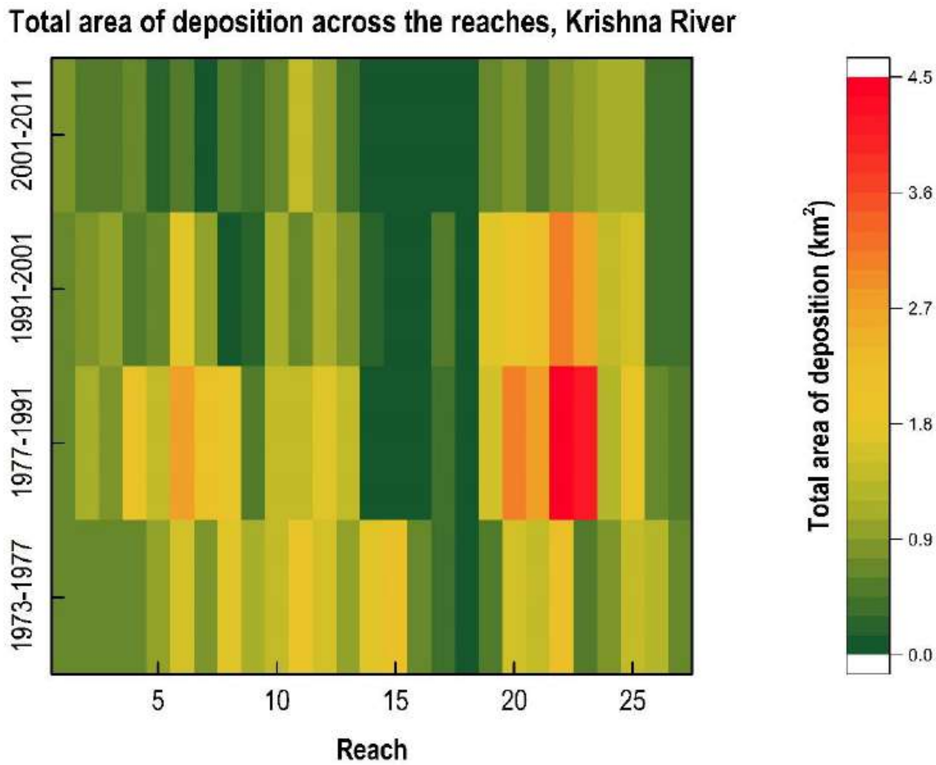

Fig. 47: Variability of the total area of bank deposition across different reaches of Krishna River during different periods

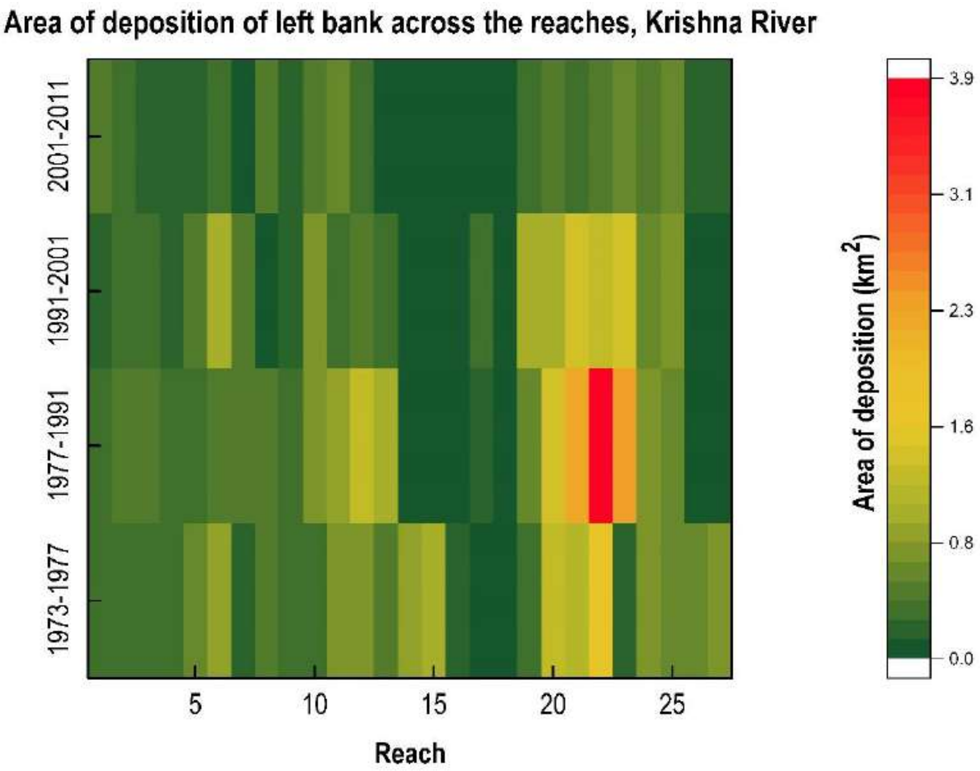

Fig. 48: Variability of the area of deposition along left bank across different reaches of Krishna River during different periods

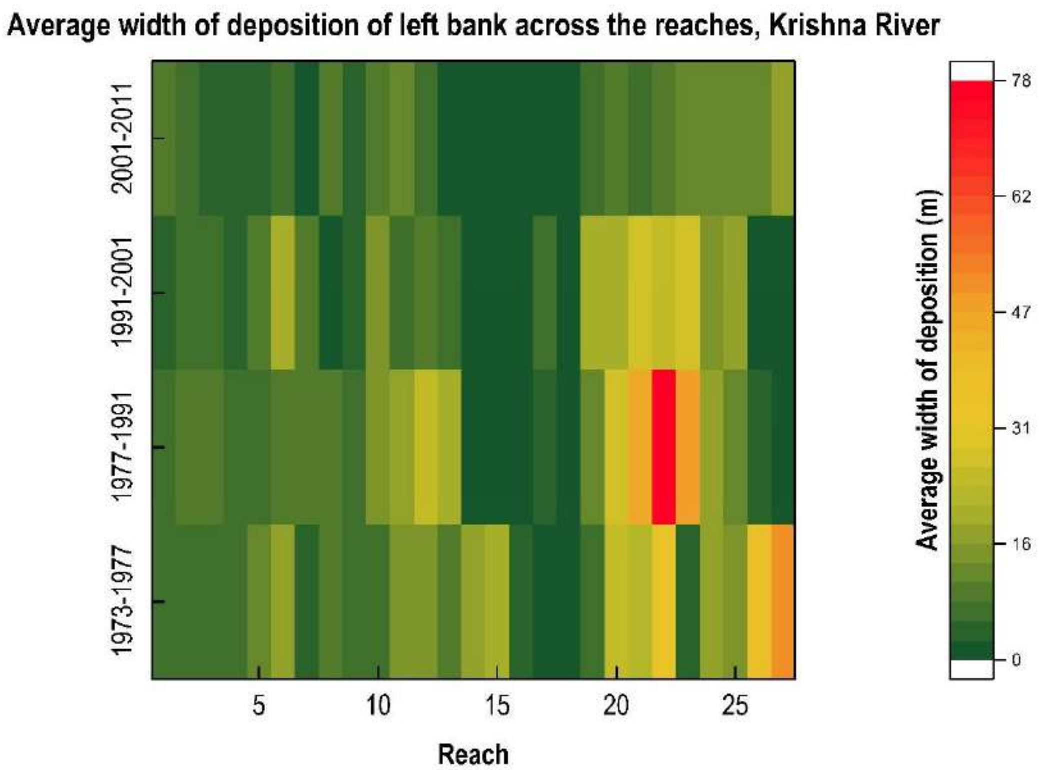

Fig. 49: Variability of the mean width of deposition along left bank across different reaches of Krishna River during different periods

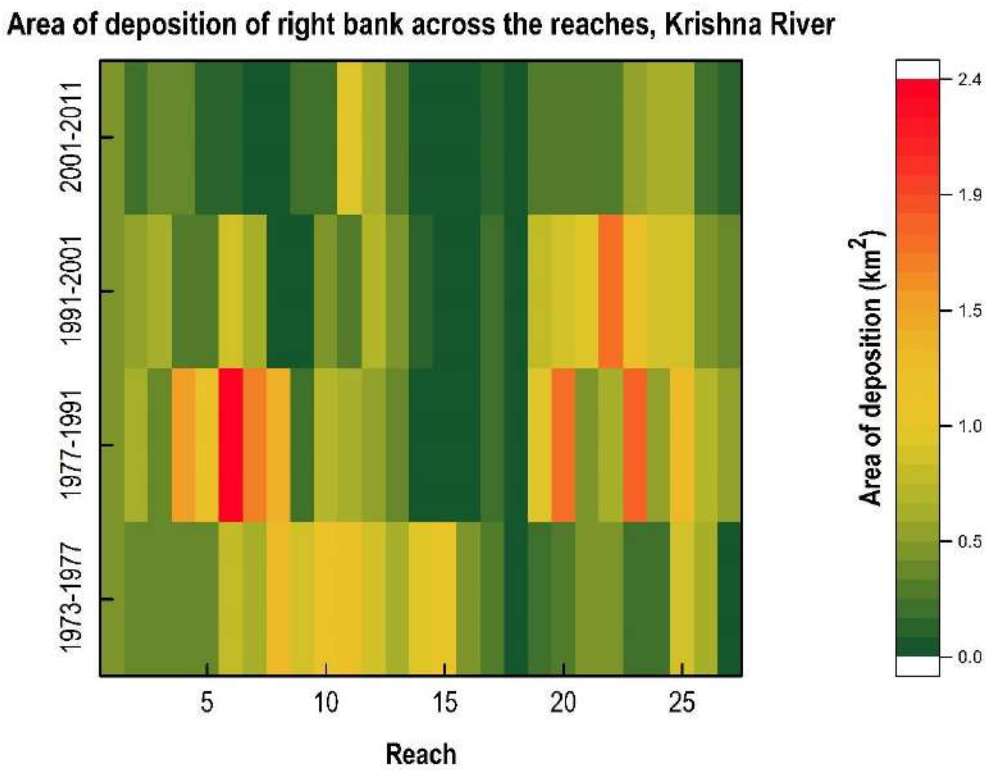

Fig. 50: Variability of the area of deposition along right bank across different reaches of Krishna River during different periods

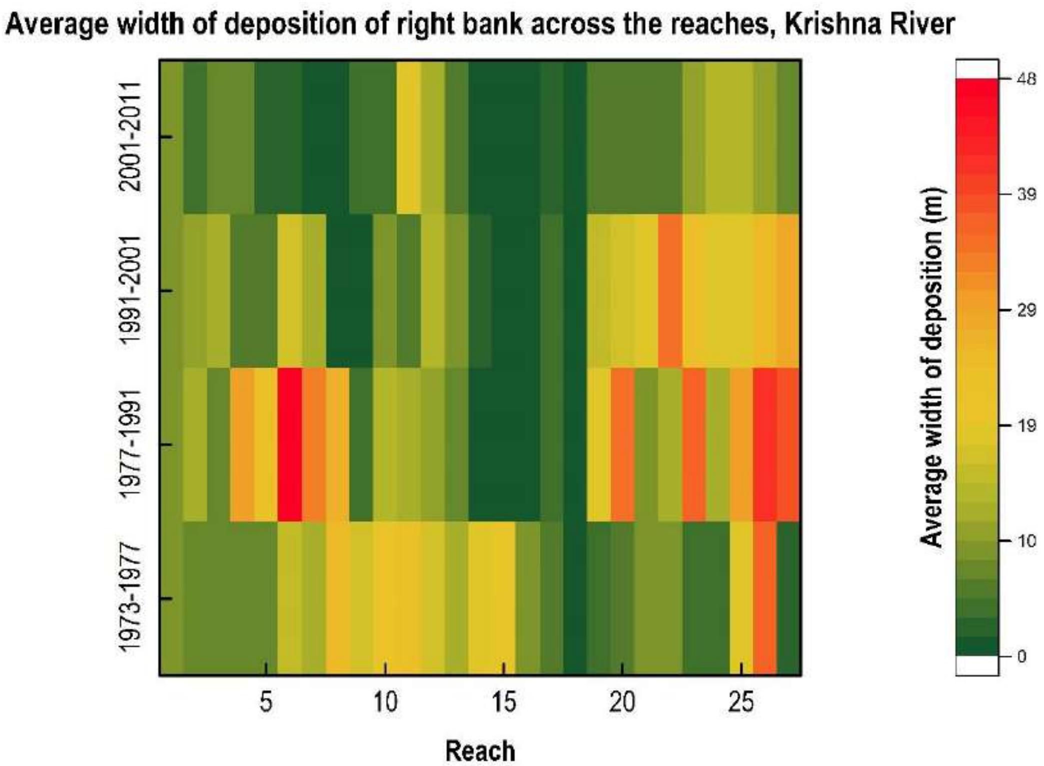

Fig. 51: Variability of the mean width of deposition along the right bank across different reaches of Krishna River during different periods

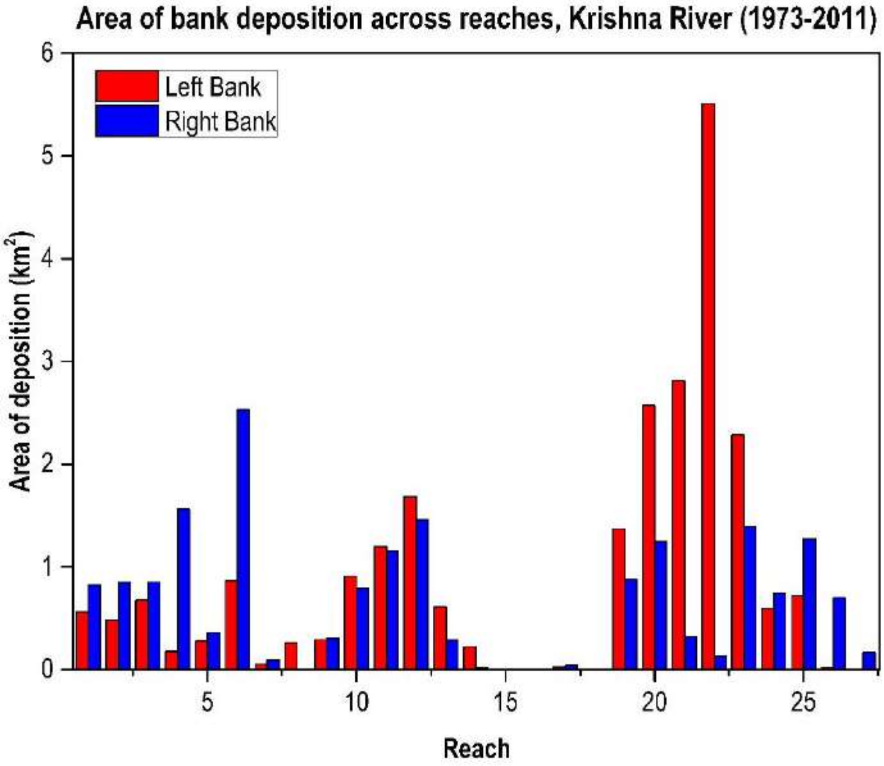

Fig. 52: Area of deposition along left and right banks across different reaches of Krishna River during 1973-2011

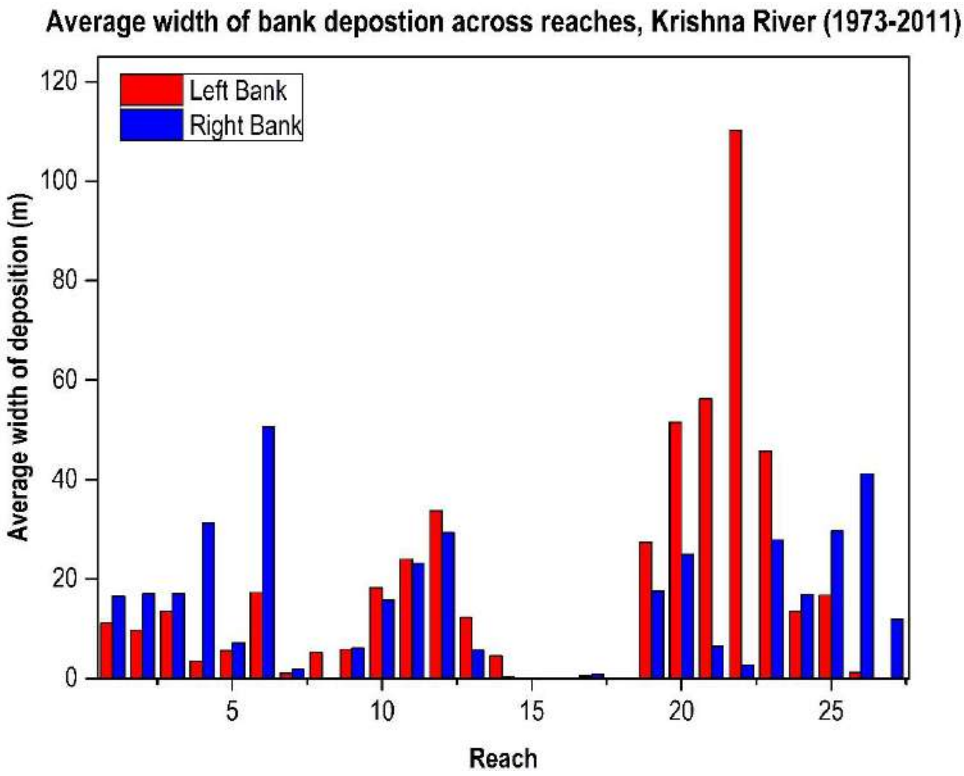

Fig. 53: Mean width of deposition along left and right banks across different reaches of Krishna River during 1973-2011

In general, the variability of the areal extent and mean width of bank deposition is relatively larger in the downstream reaches, mostly between KR_20 and KR_23 as well as upstream reaches such as KR_06 and KR_07 (Figs. 47 to 53). On a mean basis, the annual total bank deposition during 1973-1977 was 7.5 km^2, whereas it was 2.9 km^2 during 1977-1991, 2.6 km^2 during 1991-2001 and 1.5 km^2 during 2001-2011. However, on the long term, the annual erosion of the total bank area is 1.1 km^2 across the reaches of Krishna River.

The depositional pattern between left and right banks of the different reaches of the Krishna River was compared (Tables 32 to 36). The results suggest that deposition during 1973-1977 is generally more on the right banks, compared to left banks, and shows a dichotomy between the upstream and downstream reaches, i.e., deposition in the upstream reaches (KR_01 and KR_14, except KR_03, KR_05, and KR_06) is more along the right banks, while deposition in the downstream reaches is more along the left banks. However, during 1977-1991, deposition along the right bank more in the upstream (KR_01 to KR_08, except KR_03) as well as extreme downstream reaches (KR_25 to KR_27). During 1991-2001 also, a similar pattern as during 1977-1991 is observed. Most of the reaches show more deposition along the left bank during 2001-2011, which is a different pattern from the previous assessment periods. However, during 1973-2011, deposition is more along the right bank, compared to the left bank. Further, the upstream, as well as the extreme downstream reaches, are characterized by the high deposition rates along the right bank.

9.4.2.2. Tungabhadra River

The total area of deposition in both the banks of the reaches of Tungabhadra River during 1973-1977 is 15.7 km^2 (Table 37), while the same for induvial reaches varies between 0.2 km^2 (TR_05) to 4.2 km^2 (TR_09) (Fig. 54). Out of the 15.7 km^2 area of depositional patches, 9.9 km^2 area occurs along the left bank, and 5.7 km^2 area is along the right bank. The total depositional area along the left bank of the reaches ranges from 0.1 km^2 (TR_05) to 3.4 km^2 (TR_09) (Fig. 55), while the mean width of deposition varies between 1.8 m (TR_05) and 68.3 m (TR_09) (Fig. 56). Similarly, the total area of deposition along the right bank of the reaches is in the range of 0.1 km^2 (TR_05) to 1.0 km^2 (TR_03) (Fig. 57), and the mean width of deposition shows a variability between 2.9 m (TR_05) and 19.1 m (TR_03) (Fig. 58).

During 1977-1991, the total area of deposition in both the banks of the reaches is 19.8 km^2, of which 12.6 km^2 area is along the left bank and 7.2 km^2 area is along right bank (Table 38). The total area of deposition of the individual reaches varies from 0.5 km^2 (TR_11) to 3.1 km^2 (TR_08) (Fig. 54). The total depositional area along the left bank of the reaches ranges from 0.2 km^2 (TR_11) to 2.2 km^2 (TR_08) (Fig. 55), and the same along the right bank is between 0.1 km^2 (TR_05) and 1.0 km^2 (TR_10) (Fig. 57). The mean width of deposition along the left and right banks of the reaches is in the range of 5.3 m (TR_11) and 43.1 m (TR_08) and 2.4 m (TR_05) and 20.4 m (TR_10) respectively (Figs. 56 and 58).

The total area of deposition of both the banks of the reaches during 1991-2001 sums up to 15.1 km^2 (Table 39), and that of the reaches varies between 0.2 km^2 (TR_05) and 2.3 km^2 (TR_09) (Fig. 54). The total depositional area along left and right banks is 9.0 km^2 and 6.1 km^2 respectively. The total area of deposition along the left bank of the reaches varies from 0.1 km^2 (TR_05) to 1.5 km^2 (TR_10) (Fig. 55), and the mean width of deposition is between 2.6 m (TR_05) and 29.8 m (TR-10) (Fig. 56). Similarly, the total area of deposition along the right bank of the reaches is in the range of 0.1 km^2 (TR_05) to 1.1 km^2 (TR_09) (Fig. 57), and the mean width of deposition shows variability between 1.5 m (TR_05) and 21.4 m (TR_09) (Fig. 58).

During 2001-2011, the total area of deposition of both the banks of the reaches is 9.0 km^2, of which 4.2 km^2 is along left bank and 4.8 km^2 is along the right bank (Table 40). The total area of deposition of both the banks of the reaches varies between 0.3 km2 (TR_05) and 1.3 km^2 (TR_09) (Fig. 54). The total depositional area along the left and right banks is in the range of 0.1 km^2 (TR_05) to 0.6 km^2 (TR_09 and TR_10) and 0.2 km^2 (TR_05) to 0.7 km^2 (TR_09), respectively (Figs. 55 and 57). Similarly, the mean width of deposition along the left and right banks of the reaches is in the range of 1.7 m (TR_05) to 12.9 m (TR_10) and 4.1 m (TR_11) to 13.8 m (TR_09) (Figs. 56 and 58).

The total area of deposition of the banks of the reaches during 1973-2011 is 33.0 km^2 (Table 41), and that of the individual reaches varies between 0.4 km^2 (TR_05) and 7.8 km^2 (TR_09). The bank-wise area of deposition suggests that the total area of deposition along left bank during the period is 22.7 km^2, where the reaches shows a range of values between 0.3 km^2 (TR_05) and 5.7 km^2 (TR_09) (Fig. 59). Similarly, the total area of deposition along the right bank is 10.3 km^2, and that of the individual reaches ranges from 0.1 km^2 (TR_11) to 2.1 km^2 (TR_09) (Fig. 59). However, the mean width of deposition along the left and right banks of the reaches is in the range of 6.2 m (TR_05) to 113.8 m (TR_09) and 2.2 m (TR_05) to 42.8 m (TR_09), respectively (Fig. 60).

In general, the variability of the areal extent and mean width of bank deposition is relatively larger in the downstream reaches, mostly between TR_09 and TR_10 as well as upstream reaches such as TR_02 to TR_04 (Figs. 54 to 60). In addition, the comparison of the bank erosion (both areal extent as well as mean width of erosion) during the short term and long term assessment periods also suggests that the reaches between TR_09 and TR_10 as well as TR_02 to TR_04. On a mean basis, the annual total bank deposition during 1973-1977 was 3.9 km^2, whereas it was 1.4 km^2 during 1977-1991, 1.5 km^2 during 1991-2001 and 0.9 km^2 during 2001-2011. However, on the long term, the annual erosion of the total bank area is 0.9 km^2 across the reaches of Tungabhadra River.

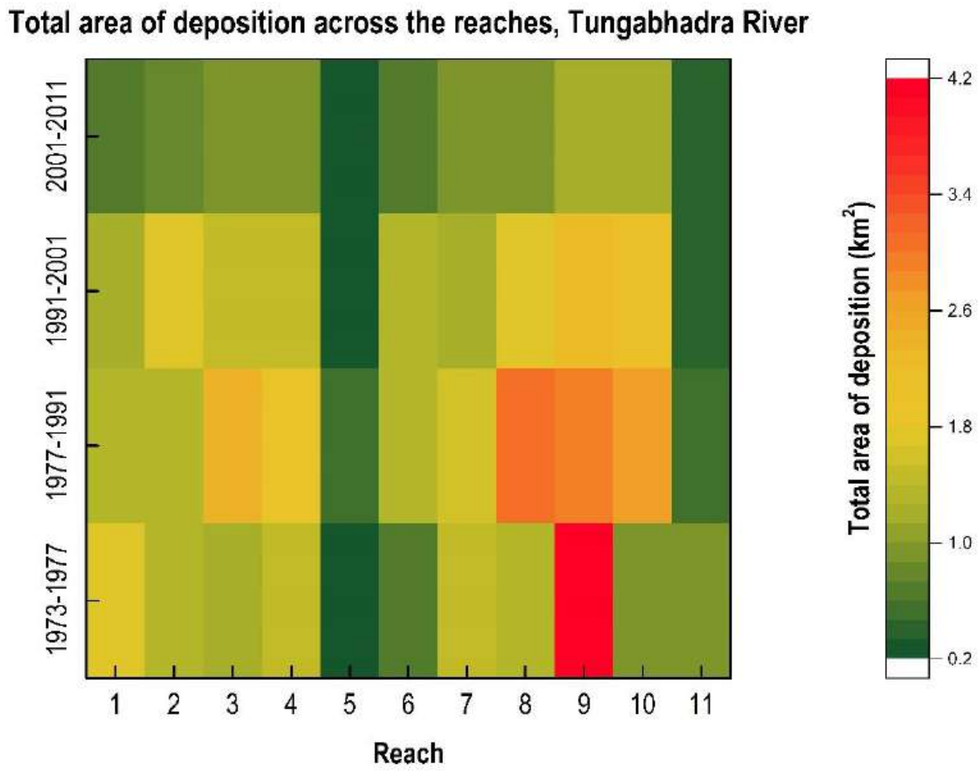

Fig. 54: Variability of the total area of bank deposition across different reaches of Tungabhadra River during different periods

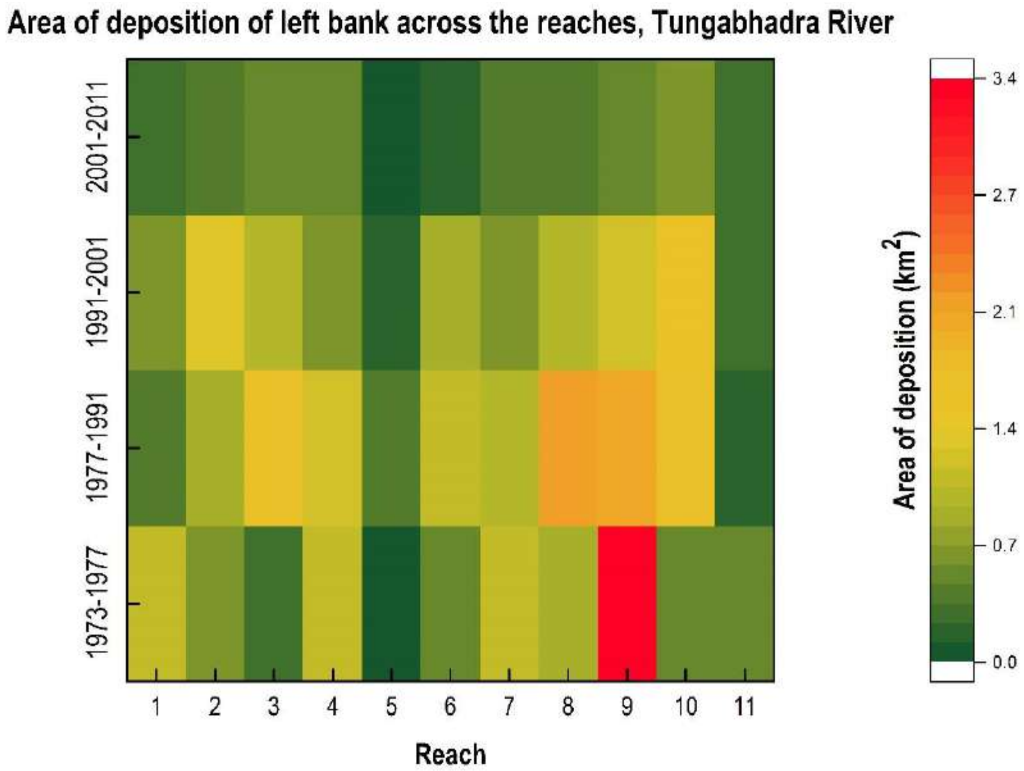

Fig. 55: Variability of the area of deposition along left bank across different reaches of Tungabhadra River during different periods

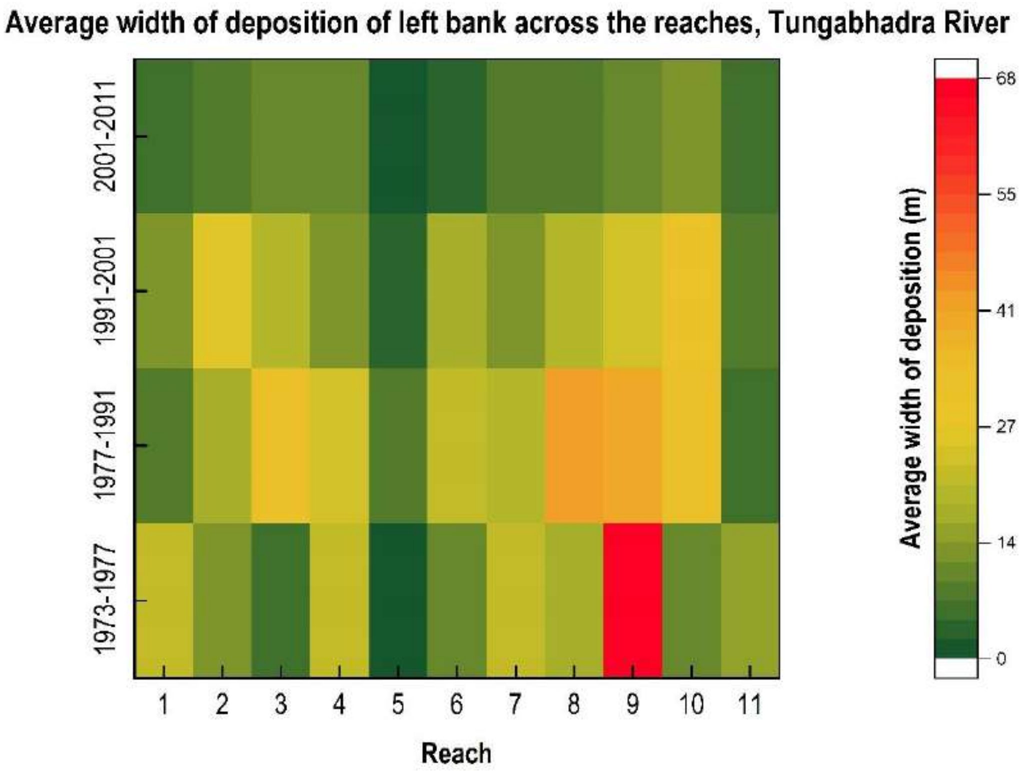

Fig. 56: Variability of the mean width of deposition along left bank across different reaches of Tungabhadra River during different periods

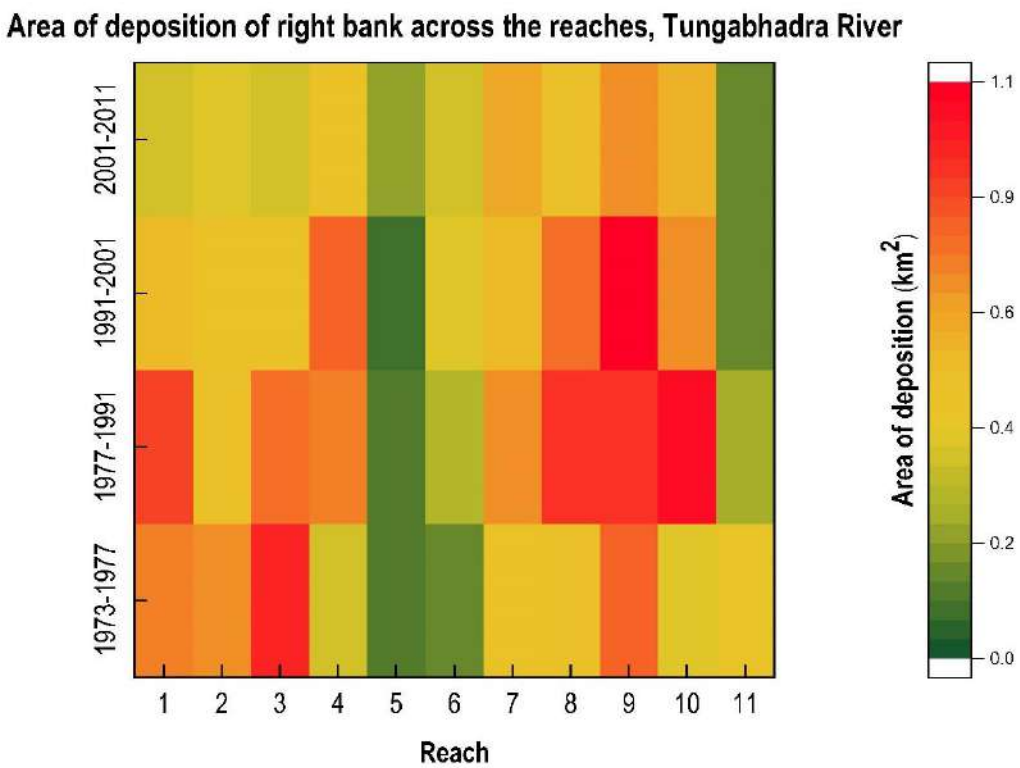

Fig. 57: Variability of the area of deposition along right bank across different reaches of Tungabhadra River during different periods

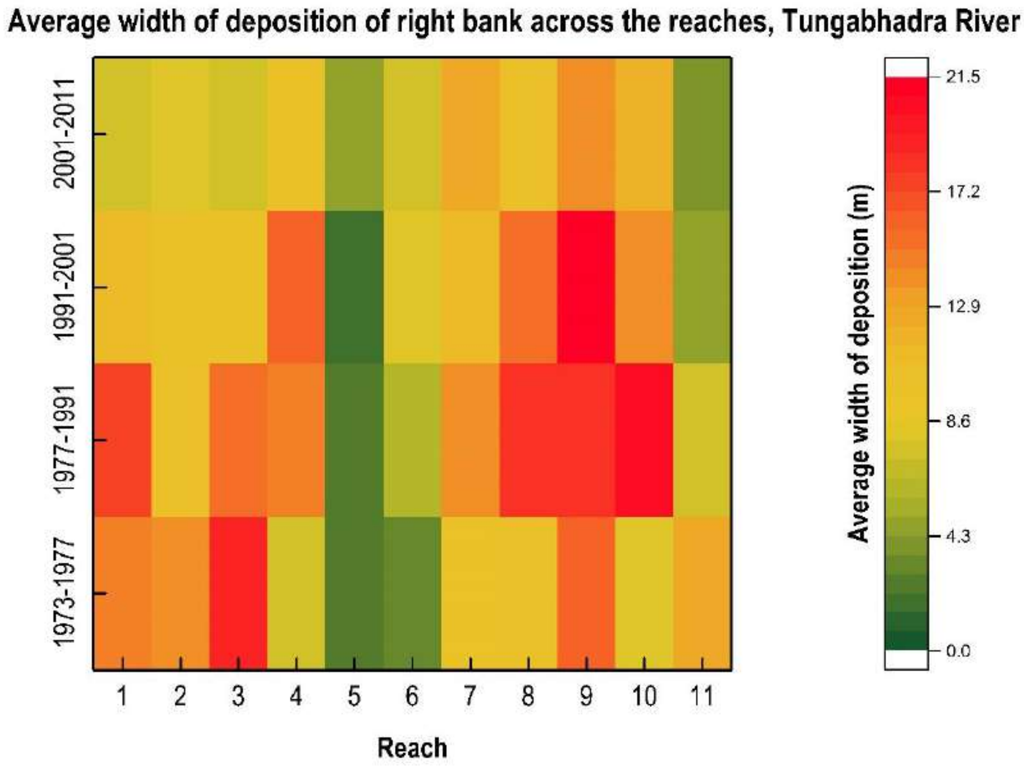

Fig. 58: Variability of the mean width of deposition along the right bank across different reaches of Tungabhadra River during different periods

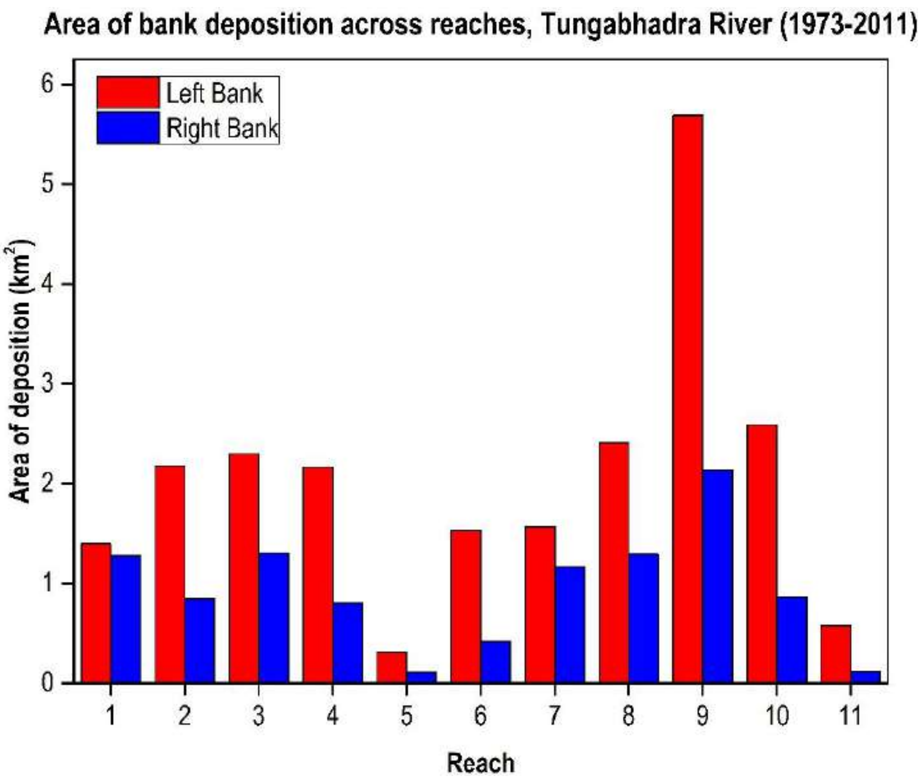

Fig. 59: Area of deposition along left and right banks across different reaches of Tungabhadra River during 1973-2011

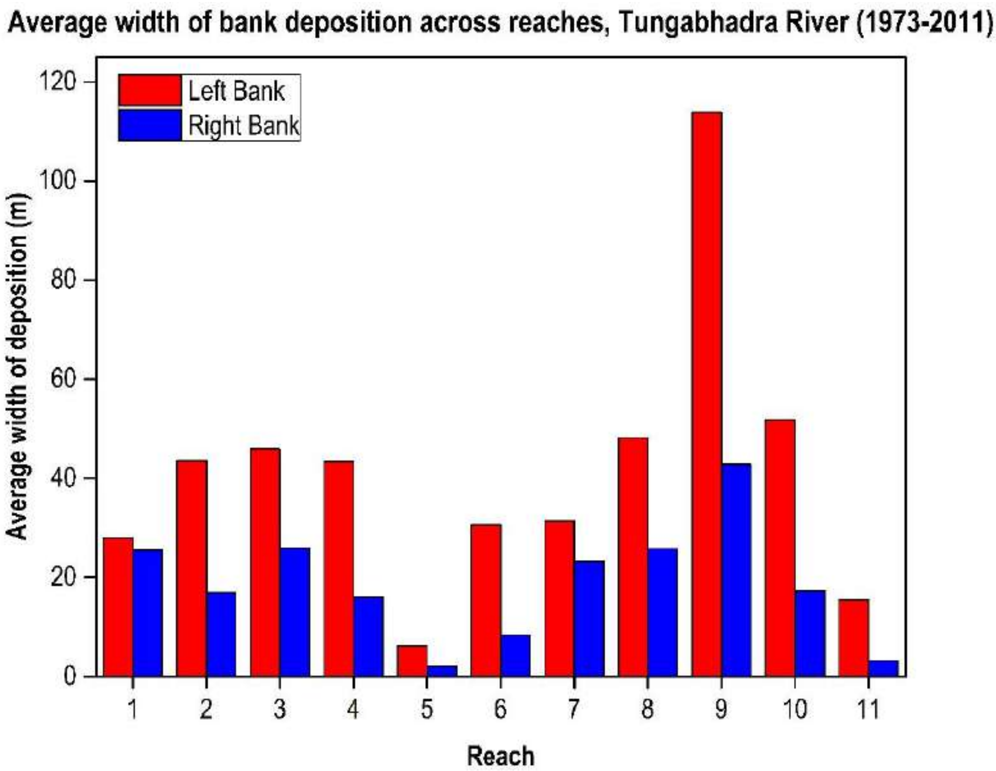

Fig. 60: Mean width of deposition along left and right banks across different reaches of Tungabhadra River during 1973-2011

The depositional pattern of the left and right banks of the different reaches of the Tungabhadra River during the assessment periods exhibits a dominance of deposition along the left banks. All the assessment periods, except 2001-2011 show a dominance of deposition along the left bank, whereas, during 2001-2011, deposition is more along the right bank of the reaches, except in TR_03, TR_10, and TR_11.

9.4.3. Bank erosion vs. deposition: Krishna and Tungabhadra Rivers

In order to understand the behavior of the study reaches of Krishna and Tungabhadra rivers, total erosion and deposition along both the banks are compared (Figs. 61 to 70). The bank erosion/deposition pattern of the reaches of Krishna River (Figs. 61 to 65) indicates that the downstream reaches exhibit a higher rate of erosion as well as deposition across the time periods. One of the reaches is KR_22, where high erosion and deposition are evident during most of the assessment periods. This is mainly because of the contrasting nature of the river banks, i.e., either of the banks is vulnerable to erosion, whereas the other promotes deposition. The net erosion (i.e., erosion - deposition) of the reaches during the study period indicates that KR_24 experiences high erosion compared to deposition during all the assessment periods, where KR_26 and KR_27 have high net erosion during most of the assessment periods. In addition, reaches, such as KR_01, KR_04, KR_05, KR_13, KR_14, and KR_17 also exhibit relatively high erosion compared to deposition along the banks.

The high rate of bank erosion and deposition in the downstream reaches of Krishna River may be correlated with the braided nature of the study reaches, as the deflection of the channel flows around the developed sand bars could be a primary cause of bank erosion and associated channel widening. In the Brahmaputra River, Akthar et al. (2011) observed that bank erosion along the braided reaches was induced by the flow concentrations due to the temporal evolution of multiple channels. Thorne et al. (1993) also identified bank migration processes, which are driven by bar development and migration in braided reaches operating at smaller spatial (3-6 km) and over shorter temporal scales (2-5 years). However, Ta et al. (2013) reported that the braided channel in the sand banked reach of upstream of the Yellow River was characterized by an increasing trend in both channel deposition and lateral channel erosion in response to decreased flows. It is further explained that erosion from toes of the channel bank causes bank failure, delivering excess volumes of sediment into the central portion of the channel, and thereby developing a bank-to-channel sediment transfer. This could have been a potential mechanism for the relatively higher rates of bank erosion as well as deposition along the braided reaches of the Krishna River.

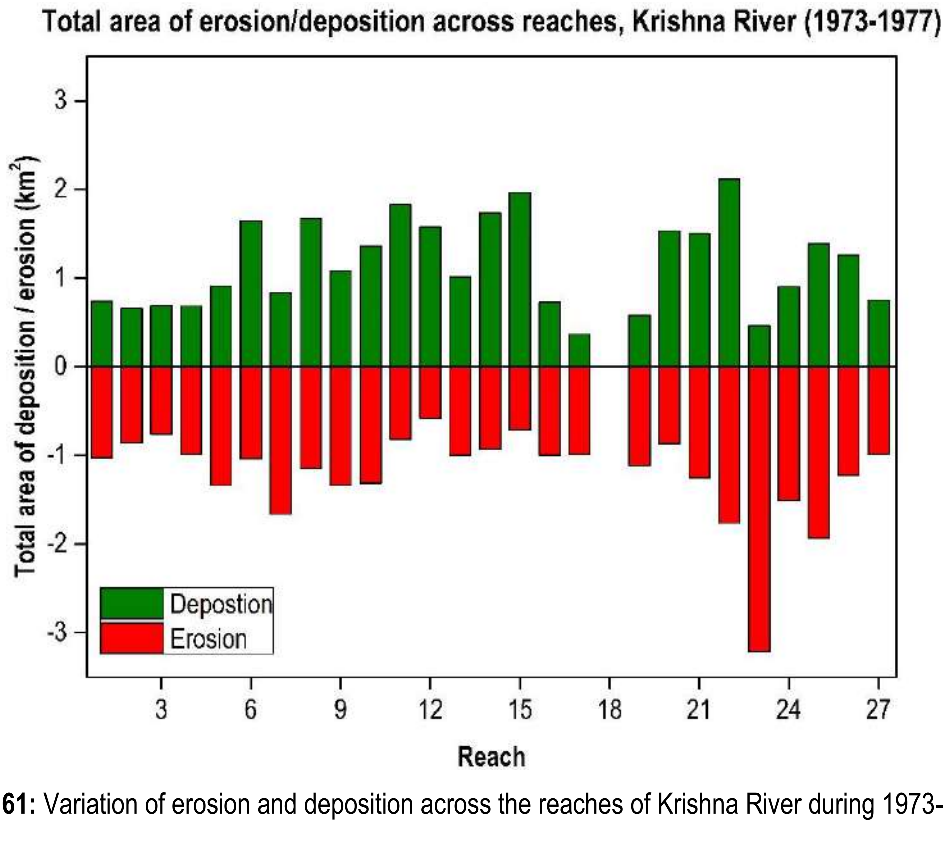

Fig. 61: Variation of erosion and deposition across the reaches of Krishna River during 1973-1977

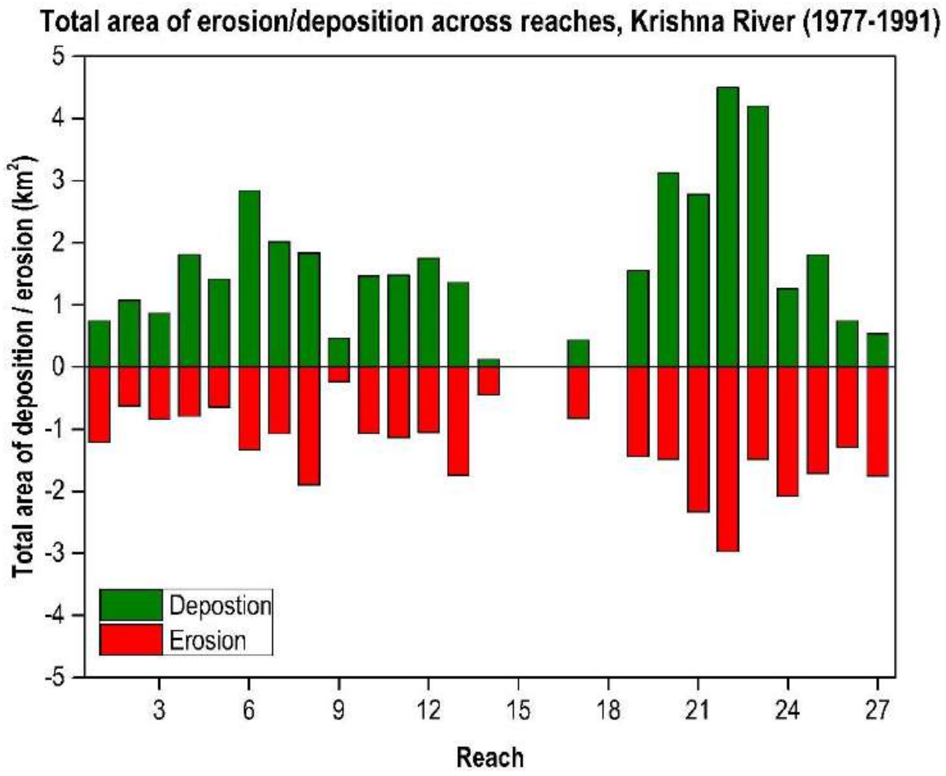

Fig. 62: Variation of erosion and deposition across the reaches of Krishna River during 1977-1991

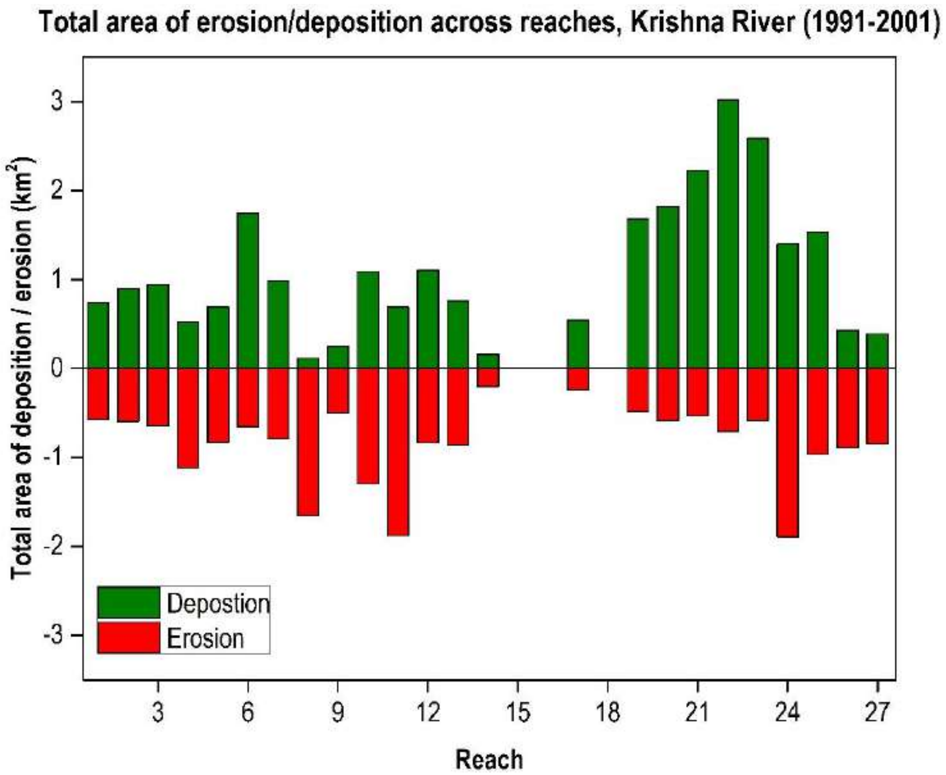

Fig. 63: Variation of erosion and deposition across the reaches of Krishna River during 1991-2001

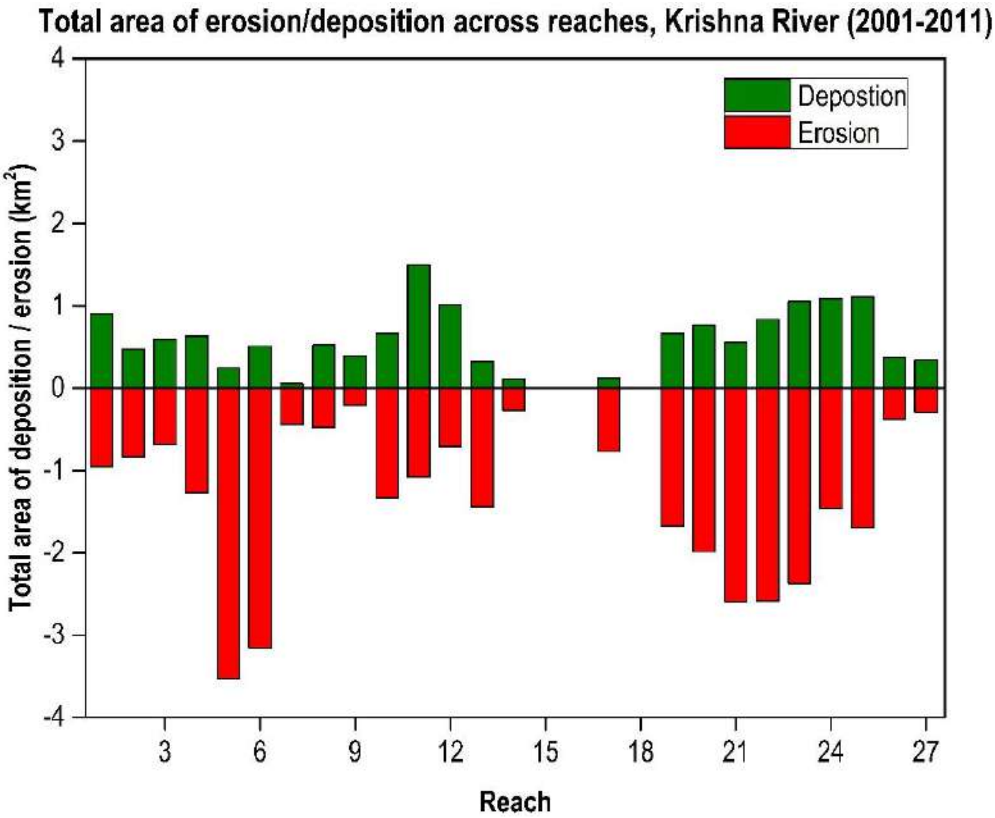

Fig. 64: Variation of erosion and deposition across the reaches of Krishna River during 2001-2011

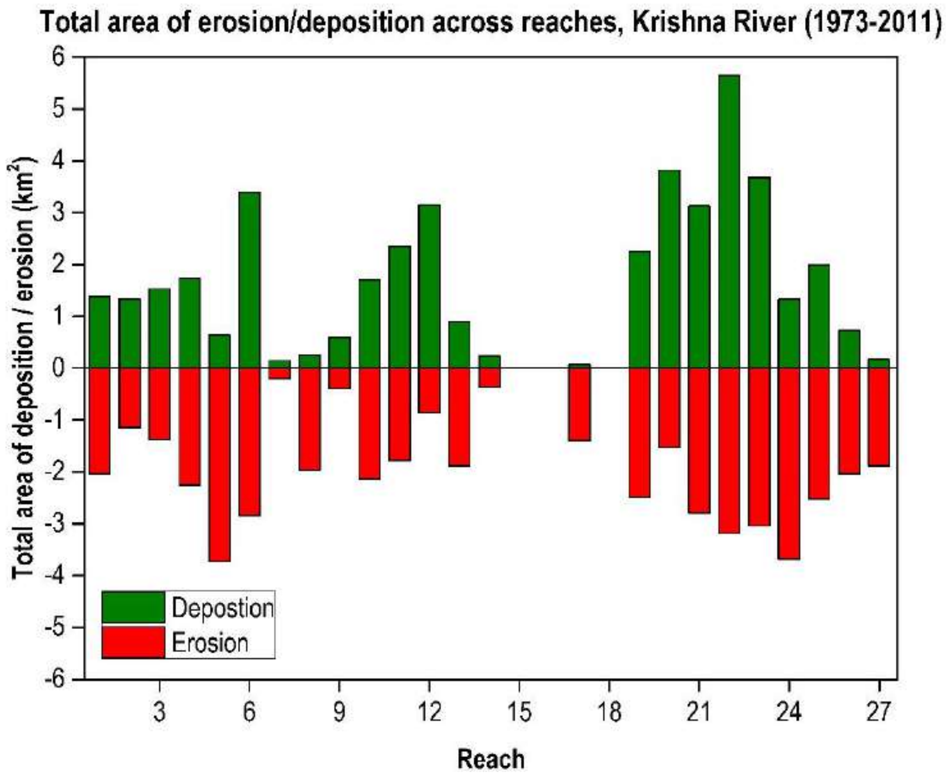

Fig. 65: Variation of erosion and deposition across the reaches of Krishna River during 1973-2011

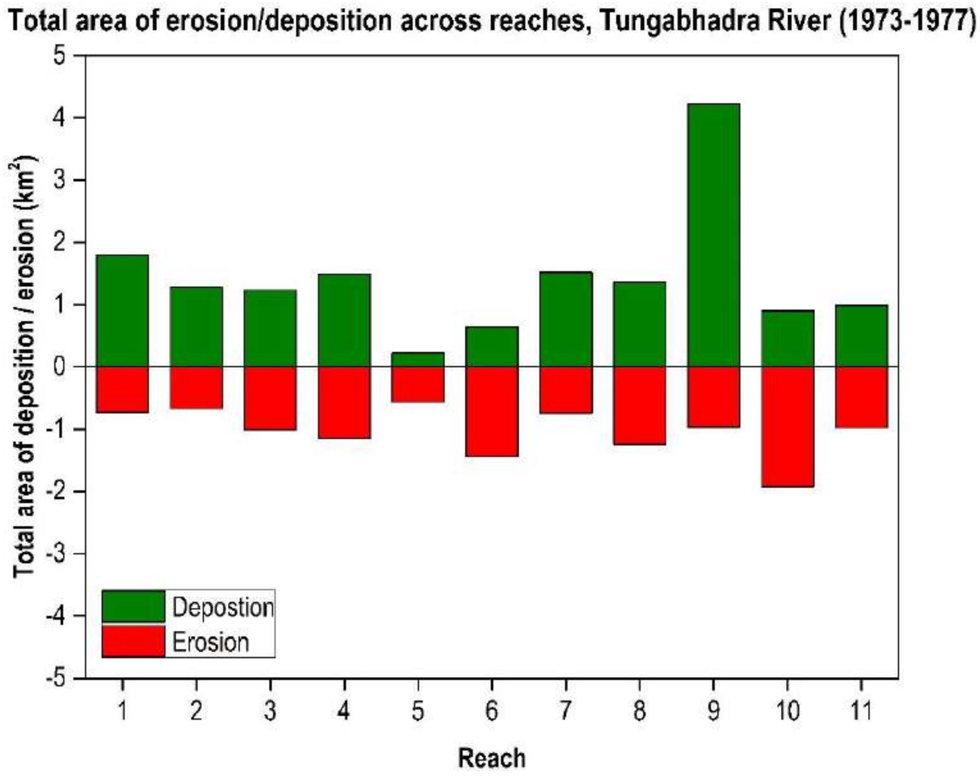

Fig. 66: Variation of erosion and deposition across the reaches of Tungabhadra River during 1973-1977

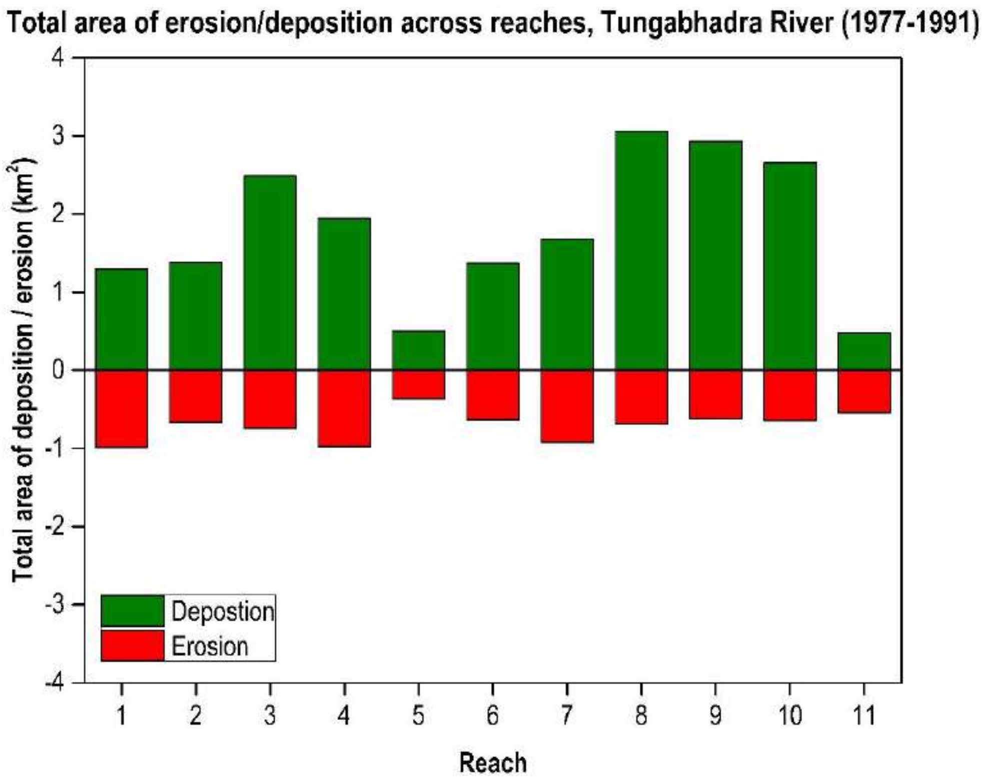

Fig. 67: Variation of erosion and deposition across the reaches of Tungabhadra River during 1977-1991

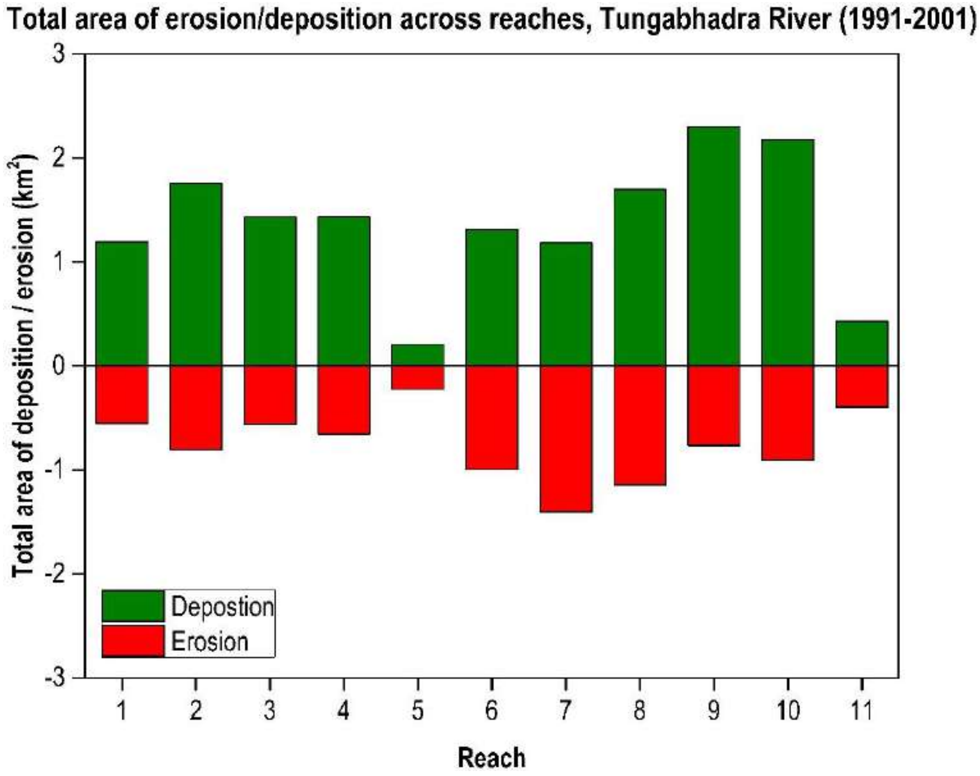

Fig. 68: Variation of erosion and deposition across the reaches of Tungabhadra River during 1991-2001

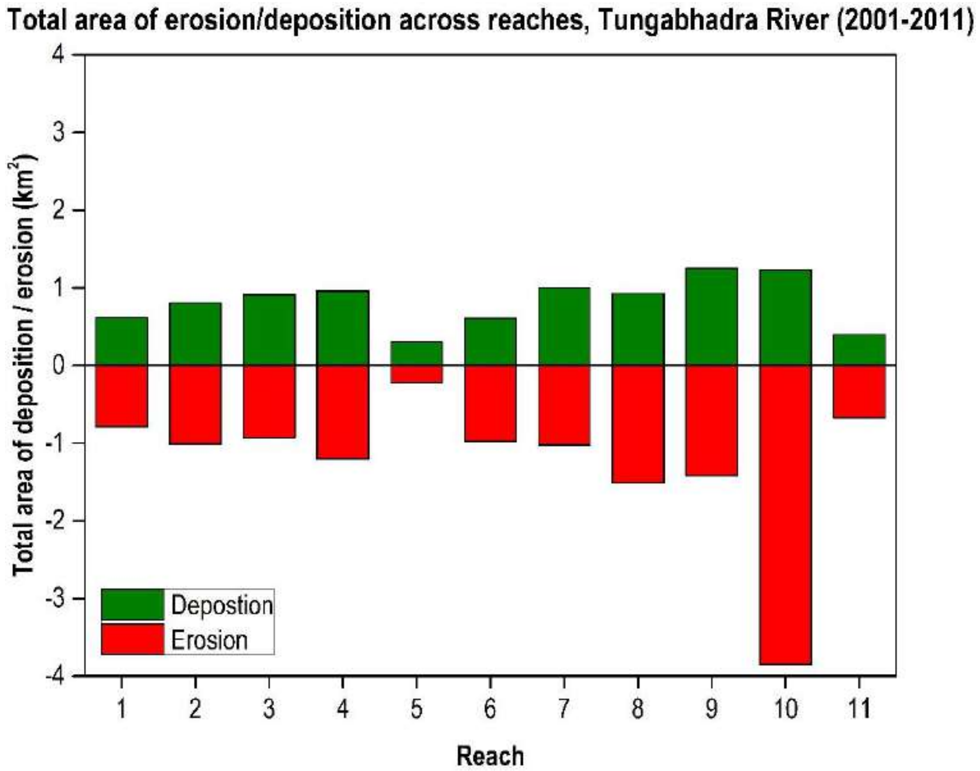

Fig. 69: Variation of erosion and deposition across the reaches of Tungabhadra River during 2001-2011

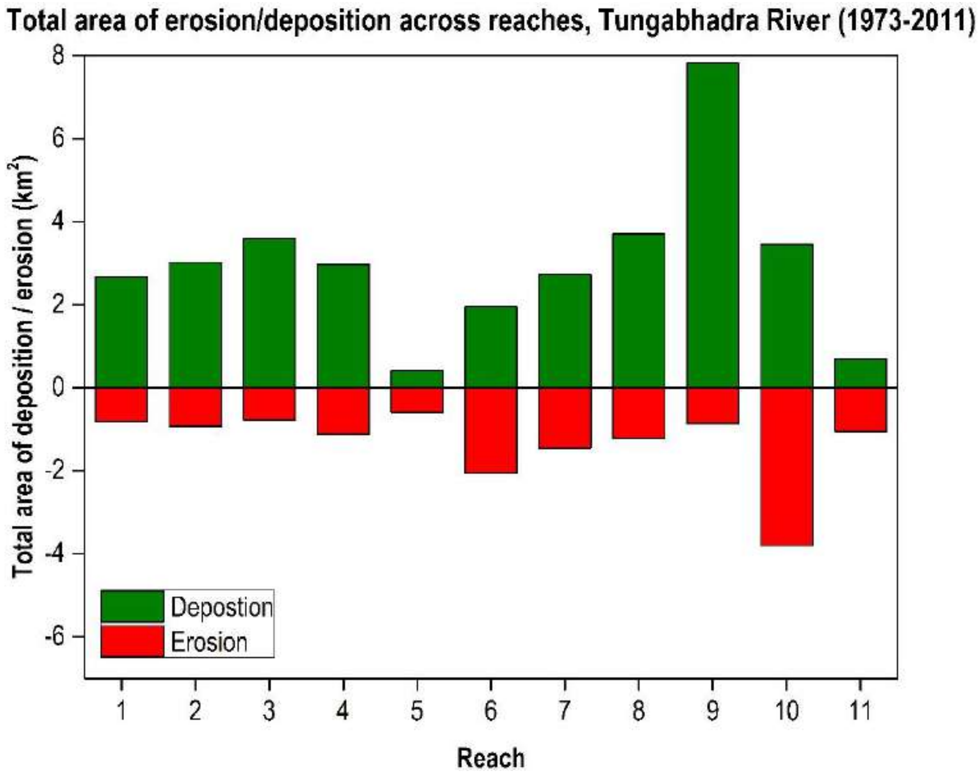

Fig. 70: Variation of erosion and deposition across the reaches of Tungabhadra River during 1973-2011

The study reaches of Tungabhadra River shows relatively high rates of deposition, compared to the erosion rates, during all the assessment periods, except 2001-2011 (Figs. 66 to 70). It is evident that the erosion along the banks are relatively high in the reaches downstream of TR_06, whereas the occurrence of depositional patches is more or less similar n the upstream as well as downstream reaches of TR-06.

9.4.4. Inundation of river reaches: Krishna and Tungabhadra Rivers

Krishna River Basin (KRB) is characterized by significantly high density of hydraulic structures, and the study reaches of Krishna River are regulated by 12 structures including dams, weirs, and barrages and the reaches of Tungabhadra River is regulated by 4 structures (Table 7). Among the different hydraulic structures of the river reaches, Almatti, Narayanpura, Srisailam (NSRSP), Nagarjuna Sagar and Tungabhadra are the major dams and reservoirs of the reaches, and consequently reservoir impoundment and inundation of the river reaches occur in a few reaches. In Krishna River, during 1973-1977, the inundation occurred in the reaches KR_17 to KR_19 (inundation area = 22.2 km^2) is mainly due to reservoir impoundment of the Nagarjuna Sagar dam (Table 32). However, the inundation area has been increased drastically during 1977-1991 (289.2 km^2; Table 33) due to the construction of Narayanpura and Srisailam dams, and the inundation is prominent along KR_09 (Narayanpura dam) as well as KR_14 to KR_19 (Srisailam and Nagarjuna Sagar dams). Further, the number of reaches under inundation has been increased during 1991-2001 (Table 34) due to the completion of Priyadarshini Jurala and Almatti dams, where the inundation effects are manifested in KR_13 and KR_07 and KR_08, respectively. During 2001-2011, the inundated area of the reaches of the Krishna River is 439.8 km^2 (Table 35). Further, the total area of the banks under inundation during the whole period (i.e., 1973-2011) is 882.3 km^2 (Table 36). A comparison of the total inundation area of the reaches across the different assessment periods indicates that the right bank of the reaches is more inundated, compared to the left bank, with the exception during 1973-1977.

In Tungabhadra River, the major dam is Tungabhadra dam, and the inundation is evident along the banks of TR_05 and TR_06 during all the periods (Tables 37 to 41). However, due to the reservoir impoundment of Srisailam dam, parts of TR_11 also get inundated, and the areal extent varies according to reservoir level. Although the dam is operation well prior to the assessment period, the area of inundation show variability because of the variation of the reservoir level during the capture of the satellite image.

9.5. Identification of critical river reaches

Based on the temporal changes in the channel planform as well as the rate of erosion along the banks during the different short-term as well as long-term assessment periods, the critical reaches are identified. The classification of the reaches was done on the basis of (1) mean width of erosion of the reaches as well as (2) the percentage length of erosion. Mean width and percentage length of erosion of the reaches were estimated during different periods (1973-1977, 1977-1991, 1991-2001 and 2001-2011) as well as for the entire period (1973-2011). Further, a ranking scheme was adopted to estimate the relativity of width as well as percentage length of erosion among the different reaches. Since Krishna and Tungabhadra experienced different intensities of bank erosion, different thresholds have been used for classification (Table 42).

Table 42: Ranking scheme used for prioritization of critical reaches of Krishna and Tungabhadra rivers

Krishna				Tungabhadra			
Mean width of erosion	Rank	% length of erosion	Rank	Mean width of erosion	Rank	% length of erosion	Rank
< 20.0	1	< 25.0	1	< 15.0	1	< 15.0	1
20.1-40.0	2	25.1-50.0	2	15.1-25.0	2	15.1-30.0	2
40.1-60.0	3	50.1-75.0	3	25.1-35.0	3	30.1-45.0	3
> 60.0	4	> 75.0	4	> 35.0	4	> 45.0	4

The ranking scheme was applied to the short term periods (1973-1977, 1977-1991, 1991-2001 and 2001-2011) as well as the entire period (1973-2011). Further, 60% weightage was given to the entire period (1973-2011) as remaining for the mean of the ranks of the short term periods. The weighted ranks for mean width of erosion and percentage length of erosion were aggregated to calculate the bank erosion vulnerability index

(BEVI), and a threshold was used to identify the critical reaches (Tables 43 and 44). The critical reaches of the Krishna and Tungabhadra rivers are shown in Fig. 71.

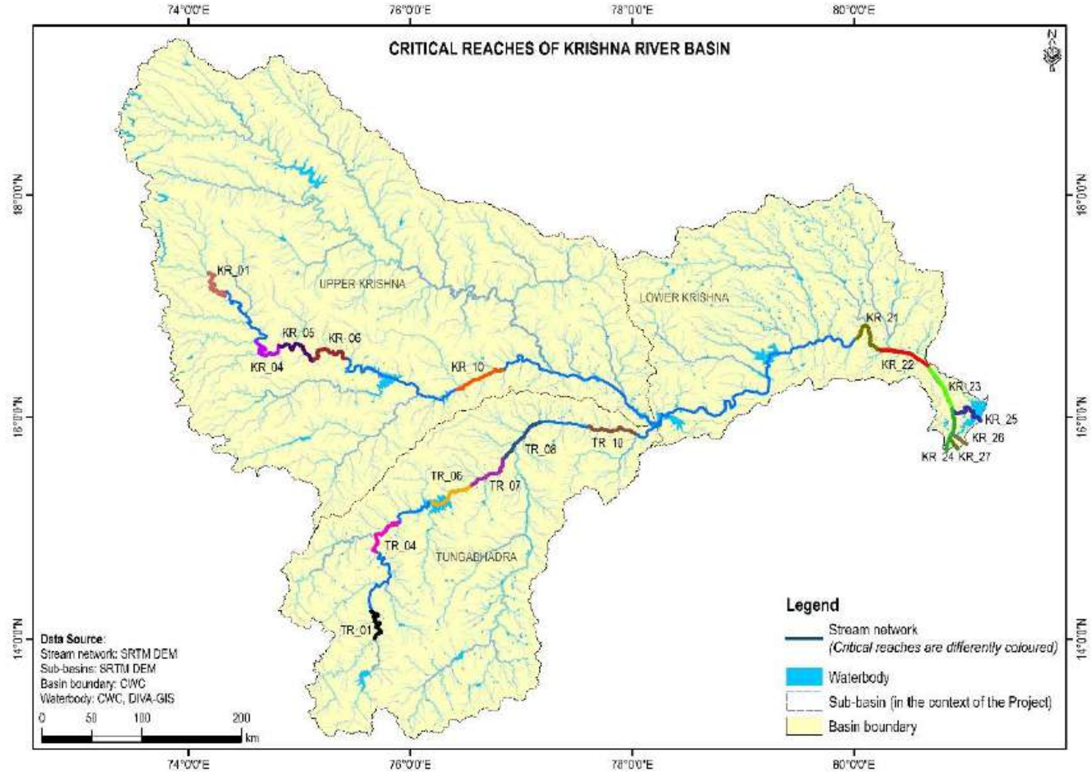

Fig. 71: Critical reaches of Krishna and Tungabhadra Rivers, KRB

Table 43: Critical reaches of the Krishna River based on the bank erosion vulnerability index (BEVI)

Reach	Percentage length of erosion						Mean width of erosion						BEVI
	1973-1977	1977-1991	1991-2001	2001-2011	Mean	1973-2011	1973-1977	1977-1991	1991-2001	2001-2011	Mean	1973-2011	
KR26	3	3	3	3	3	4	4	4	3	2	3.25	4	7.3
KR27	3	3	3	2	2.75	4	4	4	4	2	3.5	4	7.3
KR24	3	3	3	3	3	4	2	3	3	2	2.5	4	7.0
KR23	4	2	2	3	2.75	3	4	2	1	3	2.5	4	6.3
KR05	3	2	2	4	2.75	3	2	1	1	4	2	4	6.1
KR10	3	2	3	3	2.75	3	2	2	2	2	2	3	5.5
KR25	3	2	2	3	2.5	3	3	2	2	2	2.25	3	5.5
KR22	2	2	2	3	2.25	2	2	3	1	3	2.25	4	5.4
KR21	2	2	2	3	2.25	3	2	3	1	3	2.25	3	5.4
KR04	3	2	3	3	2.75	3	1	1	2	2	1.5	3	5.3
KR01	3	3	2	2	2.5	3	2	2	1	1	1.5	3	5.2
KR06	2	2	2	4	2.5	2	2	2	1	4	2.25	3	5.0
KR19	3	2	2	3	2.5	2	2	2	1	2	1.75	3	4.7
KR11	2	2	3	2	2.25	2	1	2	2	2	1.75	2	4
KR13	3	2	2	2	2.25	2	1	2	1	2	1.5	2	3.9
KR20	2	2	2	3	2.25	2	1	2	1	2	1.5	2	3.9
KR02	3	2	2	3	2.5	2	1	1	1	1	1	2	3.8
KR03	3	2	2	3	2.5	2	1	1	1	1	1	2	3.8
KR08	2	3	2	1	2	1	2	2	2	1	1.75	2	3.3

KR12	2	2	2	2	2	2	1	2	1	1	1.25	1	3.1
KR17	2	2	1	1	1.5	1	1	1	1	1	1	2	2.8
KR07	3	2	2	1	2	1	2	2	1	1	1.5	1	2.6
KR09	2	1	1	1	1.25	1	2	1	1	1	1.25	1	2.2
KR14	2	1	1	1	1.25	1	1	1	1	1	1	1	2.1
KR15	Completely submerged reaches												
KR16													
KR18													

Table 44: Critical reaches of Tungabhadra River based on the bank erosion vulnerability index (BEVI)

Reach	Percentage length of erosion						Mean width of erosion						BEVI
	1973-1977	1977-1991	1991-2001	2001-2011	Mean	1973-2011	1973-1977	1977-1991	1991-2001	2001-2011	Mean	1973-2011	
TR10	4	3	3	4	3.5	3	4	1	2	4	2.75	4	6.7
TR06	3	2	2	3	2.5	3	3	1	2	2	2	4	6.0
TR07	3	3	4	4	3.5	3	1	2	3	2	2	3	5.8
TR08	4	2	3	4	3.25	3	2	1	2	3	2	2	5.1
TR01	3	4	3	4	3.5	3	1	2	1	2	1.5	2	5.0
TR04	3	3	3	4	3.25	3	2	2	1	2	1.75	2	5.0
TR11	4	2	2	2	2.5	2	3	1	1	2	1.75	3	4.7
TR09	3	2	3	4	3	2	2	1	2	3	2	2	4.4
TR02	3	3	3	4	3.25	2	1	1	2	2	1.5	2	4.3
TR03	4	2	3	4	3.25	2	2	1	1	2	1.5	2	4.3
TR05	2	1	1	1	1.25	1	1	1	1	1	1	1	2.1

Although the critical reaches are identified based on the gross area of erosion along the given reaches, some of the reaches are characterized by localized erosion pockets, which also need to be addressed for implementation of suitable conservation measures.

9.6. Effects of rainfall variations and peak discharge on river morphological changes

Annual and southwest monsoon rainfall (0.25° x 0.25° gridded data) of the basin for the period 1971-2013 were analyzed for the presence of trends using Mann-Kendall test (Figs. 72 and 73). In this study, Mann-Kendall test was applied to the original values of the time series, if there is hardly any significant autocorrelation at the 5% level, and to the pre-whitened series when there is a significant serial correlation. The analysis indicated that rainfall pattern in the majority of the basin area (> 90%) show hardly any significant trends at annual as well as southwest monsoon scales. However, a few grids in the Lower Krishna basin displayed significant positive trends in the annual as well as southwest monsoon rainfall during the study period.

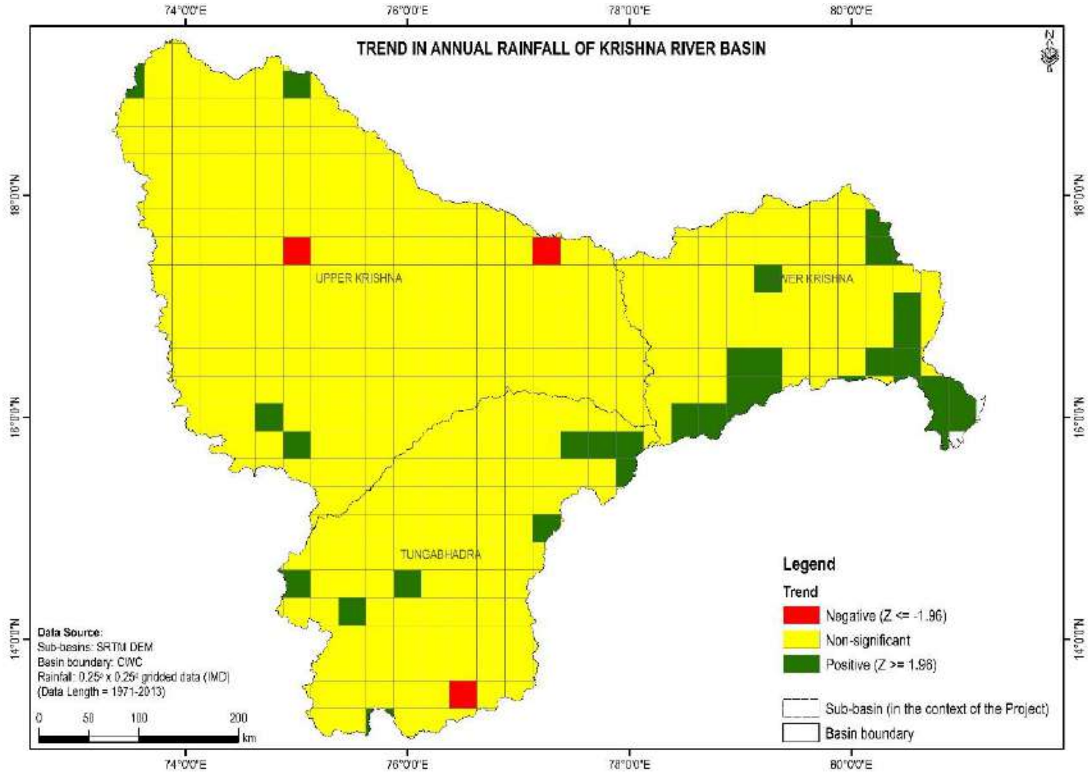

Fig. 72: Trend in annual rainfall of KRB

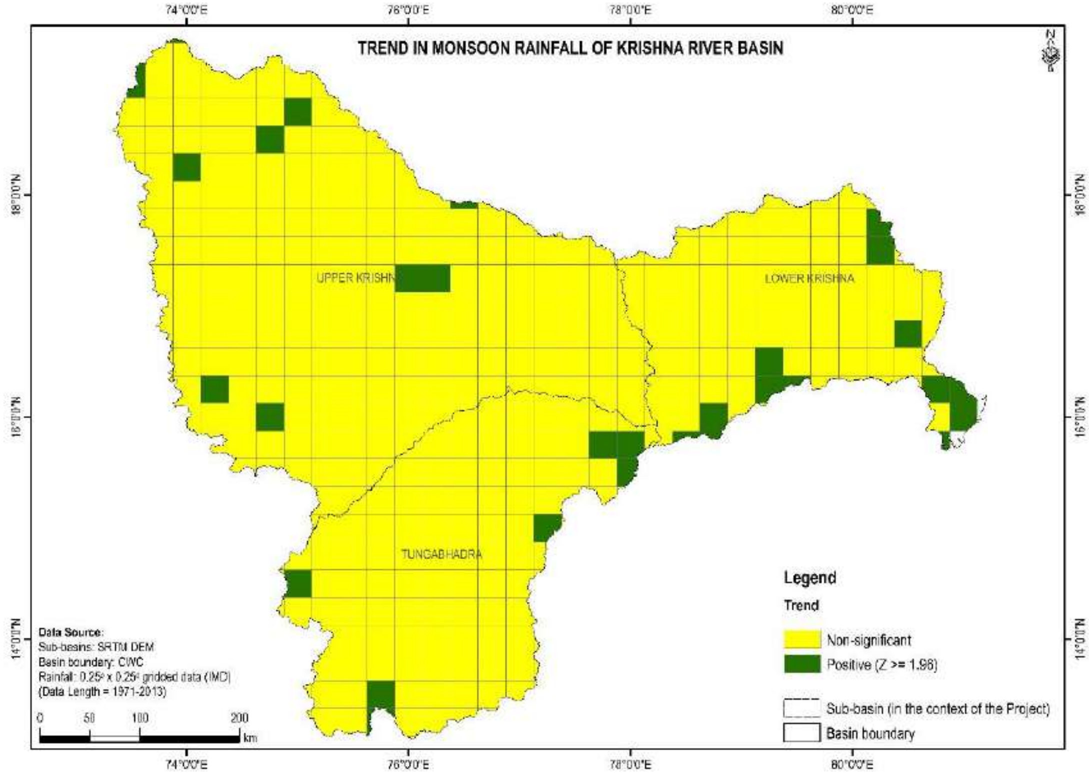

Fig. 73: Trend in southwest monsoon rainfall of KRB

Although the annual rainfall showed hardly any significant trends in annual rainfall across the basin, the variability in the peak flows during the study period and corresponding bank erosion rates of the study reaches were analyzed. Four segments (two segments from Krishna and Tungabhadra rivers each) were identified to assess the erosion of the banks to the variability of peak flows. In Krishna River, KR_03 and KR_04 in the upstream segment, and KR_21 and KR_22 in the downstream segment were considered. Similarly, in Tungabhadra, TR_04 and TR_05 in the upstream and TR_10 and TR_11 in the downstream section were included for the analysis. The HO stations (having data period similar to the duration of bank erosion assessment) associated with the river reaches were identified and extracted the flows with the non-exceedance probability of 95% during the different periods of bank erosion assessment (i.e., 1973-1977, 1977-1991, 1991-2001 and 2001-2011).

In Krishna River, variability in the peak flows is relatively high between 2001 and 2011, compared to other periods (Figs. 74 and 75), and the total area of bank erosion along the reaches also closely follows the pattern of peak flow variability, suggesting the interrelationship between the peak flows and intensity of bank erosion. However, a generalized relationship cannot be drawn from the observations as some of the reaches in a few bank erosion assessment periods deviates from the relationship. For example, in Fig. 74, KR_03 follows similar to the variability of peak flows, whereas KR_04 showed a different pattern. Such anomalies can be observed in the downstream sections also (Fig. 75). The downstream reaches of the Krishna River experienced a significantly higher rate of bank erosion, compared to other periods. Such an extent of erosion could be a result of the flood events occurred in Krishna River in 2005, 2006 and 2009. The outliers in the peak flow in Fig. 75 reflects the peak flows during the 2009 flood event.

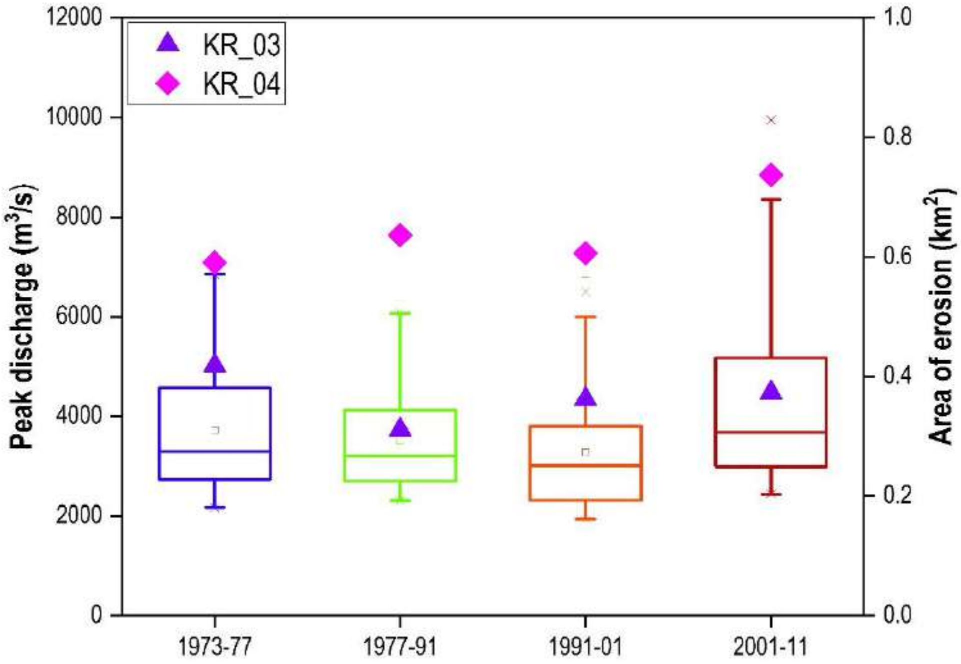

Fig. 74: Peak flows and area of erosion in the upstream reaches of Krishna River, 1973-2011

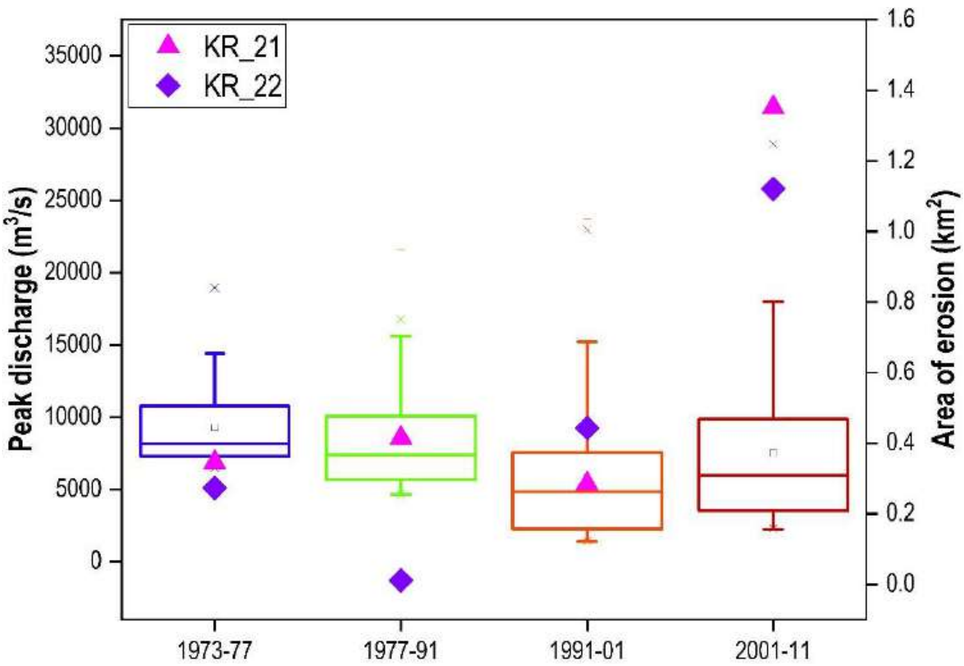

Fig. 75: Peak flows and area of erosion in the downstream reaches of Krishna River, 1973-2011

Variability in the peak flows in Tungabhadra River during different periods is given as Figs. 76 and 77. In the upstream as well as downstream reaches of Tungabhadra, the relationship between the variability in peak flows and bank erosion is not definite. Further, peak flow variability of the downstream reaches is significantly less, compared to the upstream reaches, which could be due to the flow regulation by the Tungabhadra dam. However, during 2011-2011, the erosion rates are comparatively high in these reaches, mostly due to the 2009 flood flows. However, TR_05 and TR_11 are exceptions, which is mainly due to the submergence of most parts of the reach by the Tungabhadra and Srisailam reservoirs.

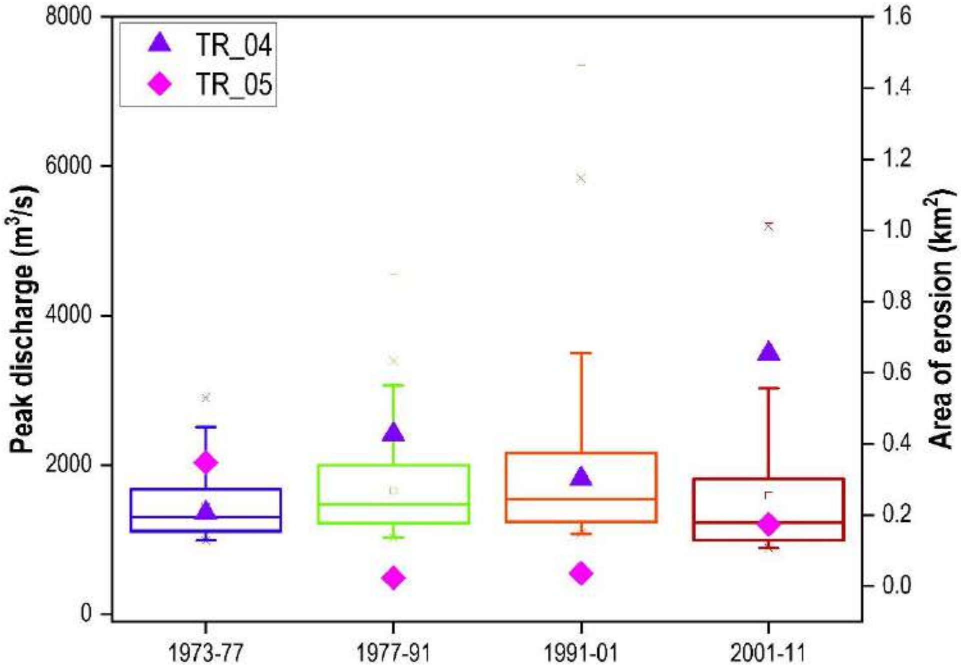

Fig. 76: Peak flows and area of erosion in the upstream reaches of the Tungabhadra River, 1973-2011

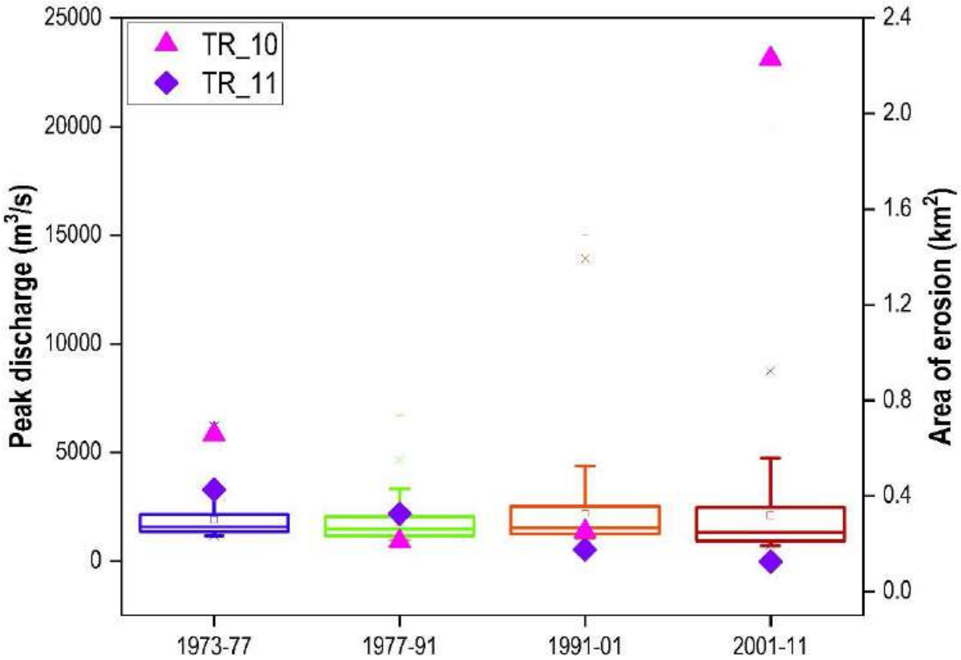

Fig. 77: Peak flows and area of erosion in the downstream reaches of the Tungabhadra River, 1973-2011

Although both the Krishna and Tungabhadra river segments are regulated, the peak flows show considerably higher variability in Krishna, compared to Tungabhadra. Similarly, the temporal variability of the area of bank erosion (during the period) in Krishna River exhibits relatively larger variation, compared to Tungabhadra River. However, the study does not provide any substantial pieces of evidence for a generalized relationship between peak flows and the rate of bank erosion. The absence of such a relationship could be a reflection of the controls exerted by other environmental factors (e.g., the resistance of bank material, hydraulic structures etc.) on bank erosion.

9.7. Impacts of floods on changes in channel morphology

Floods affect the channel morphology by erosion of river banks, development of bars and destabilization of the channel materials. Among the various flood effects, channel widening, erosion of banks and bars, scouring of the floodplain, deposition of coarse gravel within the channel and floodplain, and formation of channel-in-channel topography are the commonly observed impacts observed for the Indian rivers (Gupta, 1988). However, the impacts of a flood event on the fluvial landscape depend on the magnitude of the event. The changes in channel morphology due to large flood events (T > 50 years) are very often the cause of damages to buildings and infrastructures along the river banks as well as in the floodplains. Hence, the significance of the flood events happened in the river basin during the study period with respect to the changes in channel morphology is documented in the following paragraphs as linking them thus bear an enormous value for both the scientific community and river management agencies.

Owing to the highly regulated nature of the river, channel morphology of the Krishna as well as the Tungabhadra rivers might be relatively less disturbed due to flood events. The major flood events recorded in KRB was in 1903, 1913, 2005, 2006 and 2009 (NRAA, 2011). The flood frequency analysis of the data provided by CWC also confirms the same. Among the different floods of high magnitude, only 2005, 2006 and 2009 floods are within the channel assessment period (i.e., 1973-2011). Among the different time periods, 2001-2011 shows the relatively higher total areal extent of erosion of both the banks of Krishna and Tungabhadra rivers (Figs. 64 and 69). However, for individual reaches of the rivers, such a differentiation is not possible in that some of the reaches have the highest magnitude of bank erosion during 2001-2011, whereas for some others, the time period showing the high magnitude of bank erosion is different.

The reaches having relatively high bank erosion during 2001-2011 in Krishna and Tungabhadra rivers are KR_05, KR_06, KR_10 and KR_19 to KR_21 and TR_02, TR_04 and TR_08 to TR_10, respectively. The mean width of erosion of the banks in KR_05 and KR_06 during 2001-2011 are more than 30 m, which is higher than the mean width of erosion in the critical reaches of eastern coastal plains and deltaic region (Table 35). Further, no such high erosion rate has been reported from these reaches in any of the previous assessment periods, and the erosion rates of these reaches in the previous time periods are substantially lower than that during the 2001-2011 period. The spatial pattern of the erosion patches along KR_05 and KR_06 is also significantly different in 2001-2011, compared to the previous periods. Hence, it is logical to relate the bank erosion and large magnitude flood events happened during the time period.

The 2005 and 2006 flood events were a result of the high rainfall events across southern Maharashtra and northern Karnataka. The flood events were recorded in the H.O. stations K2 and K3, and according to the results of the flood frequency analysis of discharge data recorded at these stations, the flood occurred in 2005 is more than 100-year return flood. During the 2005 and 2006 floods, the regions belong to upstream parts of Krishna (e.g., Koyna, Varna, Kasari, Kumbhi, Bhogavati, Panchaganga and Dhoodhganga) were seriously affected. The KR_04 to KR_06 reaches are located downstream of joining Koyna, Panchaganga and Dhoodhganga rivers to Krishna, and hence, the floods occurred in the upper Krishna are reflected in the erosion of the banks as well as changes in the channel geometry. The flooding effect might be reduced to further downstream reaches because of the Almatti (in KR_08) and Narayanapura dams (in KR_09), which is perhaps the reason for not reflecting such high erosion intensity downstream of the dams. However, the 2009 flood event was severe in most of the reaches of the Krishna and Tungabhadra rivers, and the effects were more visible along the midstream and downstream reaches of Krishna and Tungabhadra rivers. During October 2009, heavy floods exceeding the record of once in 100 years were witnessed, which apparently made changes in the channel morphology (Fig. 78).

The changes in channel geometry due to the flood event occurred in 2009 are evident in the reaches, both in Krishna and Tungabhadra rivers. In addition to the extensive bank erosion and channel widening, redistribution and deposition of coarse sediments within the channel as well as along the banks are observed (Fig. 78). The changes in channel morphology have also been verified during the field visit in the downstream of Tungabhadra (TR_11) as well as downstream of Srisailam and Nagarjuna Sagar dams (KR_17 and KR_19). In KR_17, despite its incised nature and rocky exposure on the channel walls, the reach has been subjected to severe changes in the channel morphological perspective.

The removal of the unconsolidated materials deposited along the banks of KR_17 and redistribution and deposition further downstream is observed in the downstream of Srisailam dam. Similar erosion patches have been developed along the downstream of Nagarjuna Sagar dam. The coarser bed material (of boulder size) deposited in the tailwater section of the dam has been transported to further downstream during the 2009 flood (pers. comm.). In addition, large scour was also formed on the rocky channel wall of left bank immediate downstream of the Srisailam dam (Fig. 79), whereas the severe bank erosion occurred downstream of the Nagarjuna Sagar dam during the flood event (Fig. 80). However, the effect of the 2009 flood is not evident along the entire reaches as the downstream portion of KR_17 is inundated (Appendix XIV) due to the reservoir impoundment of the Nagarjuna Sagar dam.

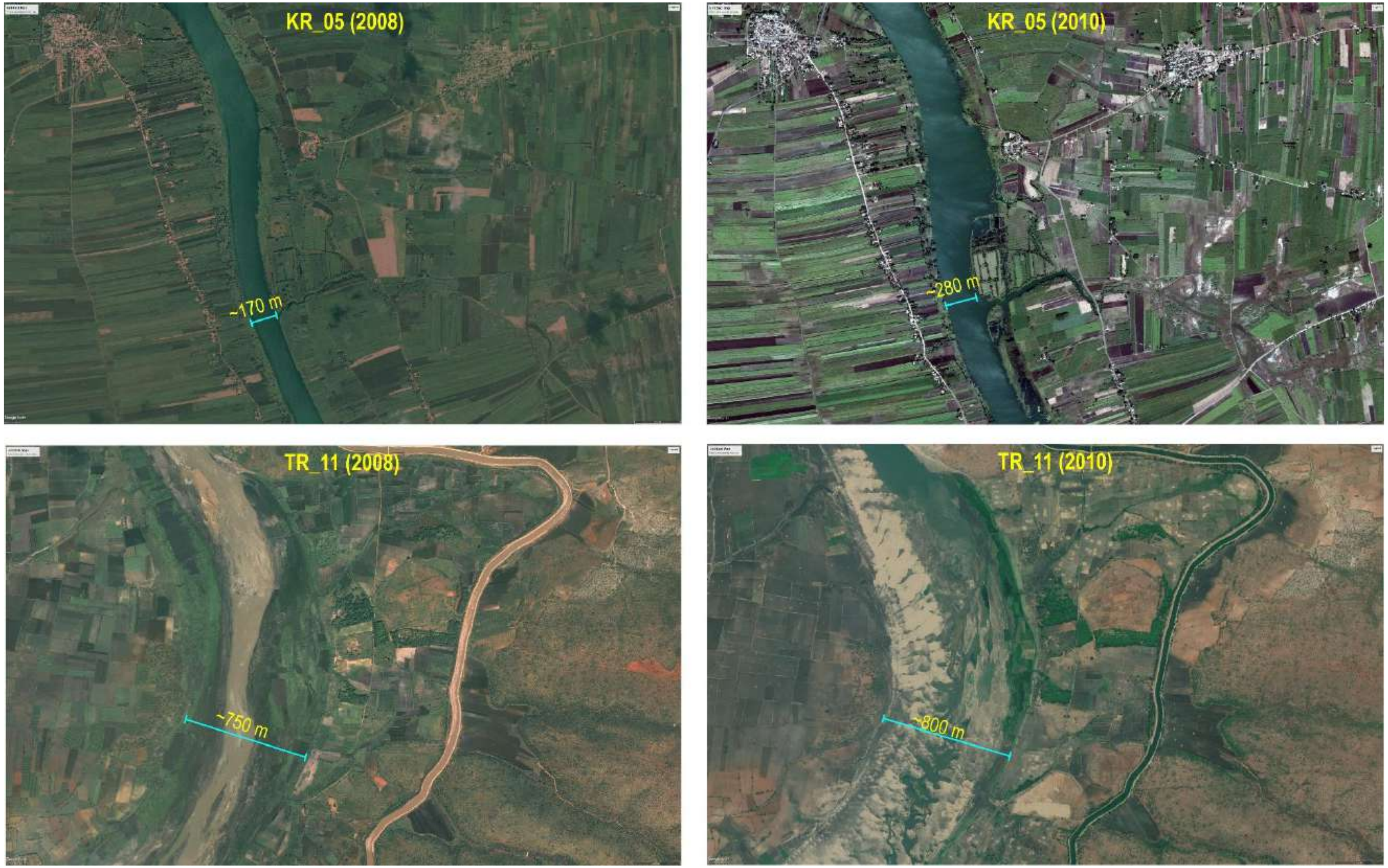

Fig. 78: Comparison of the channel bank lines: Pre- and post- 2009 flood scenarios (Source: Google Earth)

Fig. 79: Scouring occurred on the left bank channel wall in KR_17 during the 2009 flood; view towards NNE

Fig. 80: Bank protection measures along the right bank of KR_19 implemented after the 2009 flood; downstream view from Nagarjuna Sagar Dam

The main difference in the reaches between downstream of Srisailam and Nagarjuna Sagar dams (KR_17 vs. KR_19, KR_20, and KR_21) is the valley topography, where the former is developed in an incised valley, while the latter is formed in a more or less unconfined valley setup. Hence, the effects of the 2009 flood were more severe (both in terms of bank erosion) in the downstream reaches of Nagarjuna Sagar dam. The mean width of erosion also attests the same (Table 35), i.e., the mean width of erosion of KR_17 during 2001-2011 is 8.9 m and 6.4 m for left and right banks, respectively. However, the mean width of erosion along the left bank of KR_19, KR_20 and KR_21 is 11.6, 17.2, and 27.0, respectively, and that in right bank is between 22.0 m and 25.0 m. The flood severity was significantly high in the eastern coastal plains as well as in the deltaic region, but in the form of floodplain inundation than bank erosion, compared to the aforementioned reaches.

9.8. Channel cross-section and longitudinal profile analysis

River channel cross-section data were collected for Krishna (74 transects) and Tungabhadra (38 transects) rivers from CWC, which were used for the analysis of spatial variability of channel geometry as well as longitudinal profile. The data length is varying for Krishna (2009-2013) and Tungabhadra (2009-2015) Rivers. Since the cross-section survey period is after 2009, the data cannot be compared with the bank erosion estimates, which are derived from the changes in the bank lines of the river based on the remote sensing approach.

The variability in the channel cross-section across the different years for the 112 transects in Krishna and Tungabhadra rivers is given in Appendix XVI. Further, the bankfull width, hydraulic mean depth, cross-sectional area, wetted perimeter and hydraulic mean radius of the surveyed transects of both the rivers are also estimated. Downstream variation of bankfull width of the Krishna River suggests an increasing trend, with less temporal variability across the time period (Fig. 81). However, a sharp decline in bankfull width at KX_53 and KX_54 (downstream of the Narayanapura dam), compared to upstream sections is observed, which perhaps is a result of the narrowing of the channel downstream of the dam. Further, the river segment bifurcates downstream of the dam, where both the channel segments (the main channel as well as the other) have a width of 360 m. Moreover, the bifurcation of the river channel segment (of KR_10) cannot be attributed to the effect of the dam. A similar reduction of bankfull width is observed at KX_89 (in KR_17) also, which is downstream of the Srisailam dam, and the incised nature of the river channel might be the reason for the sudden decrease.

Similar to the bankfull width, hydraulic mean depth of the cross sections also shows an increasing trend (Fig. 82), implying that widening and deepening of the mainstream channel of Krishna River happen simultaneously. However, similar to the fluctuations in bankfull width, the hydraulic mean depth also shows variations across the transects (e.g., KX_53), and the variations in bankfull depth and mean hydraulic depth are reflected in the downstream variability of the cross section area, wetted perimeter, and hydraulic mean radius of the channel (Figs. 83 to 85).

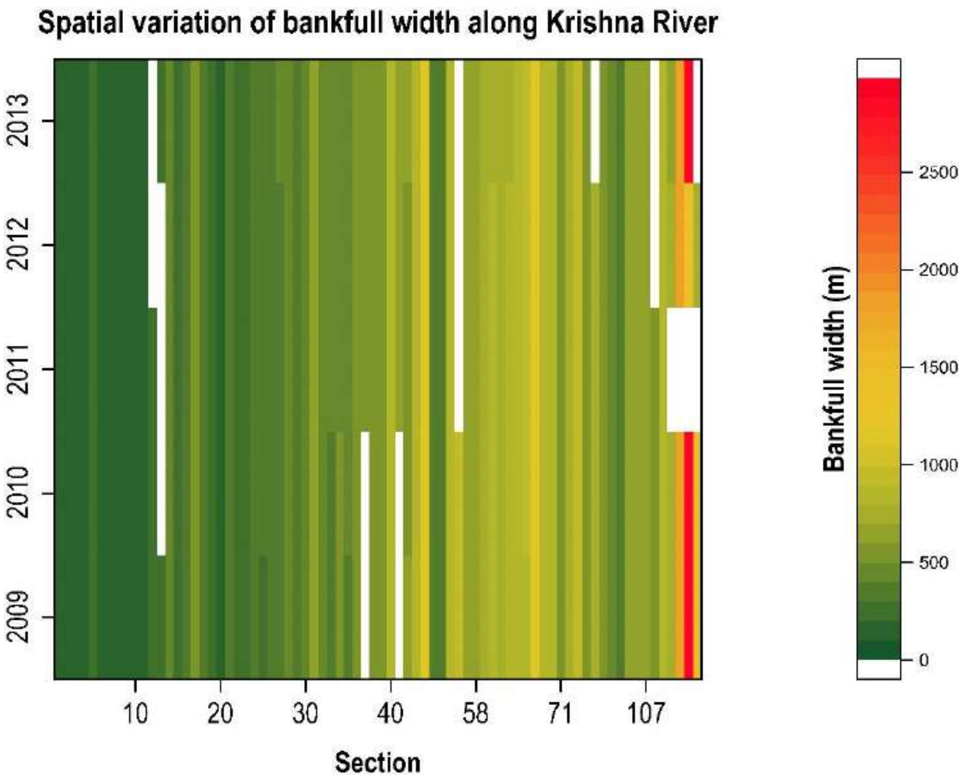

Fig. 81: Temporal variation of bankfull width across the measured cross-sections along Krishna River. White patches denote data gaps.

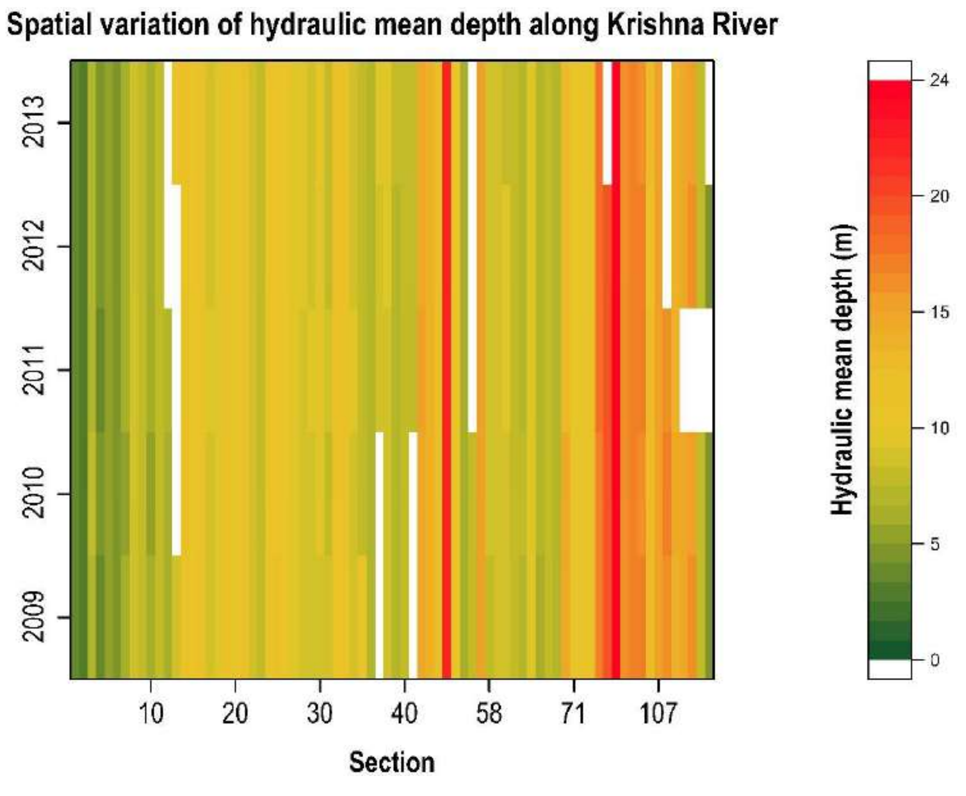

Fig. 82: Temporal variation of hydraulic mean depth across the measured cross-sections along Krishna River. White patches denote data gaps.

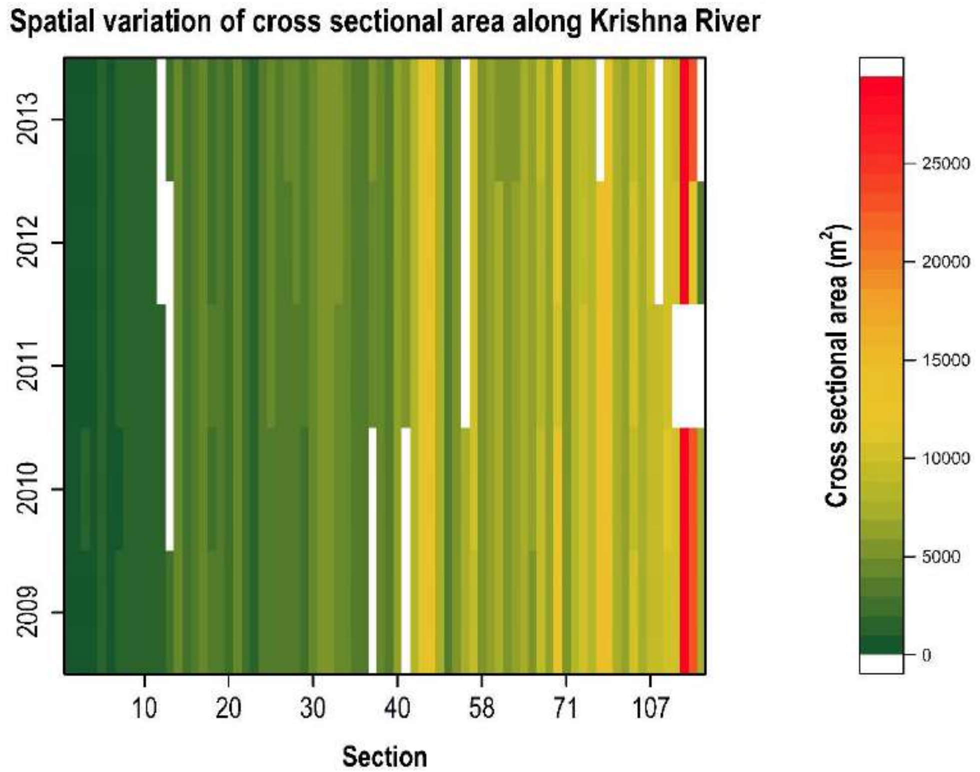

Fig. 83: Temporal variation of cross-sectional area across the measured cross-sections along Krishna River. White patches denote data gaps.

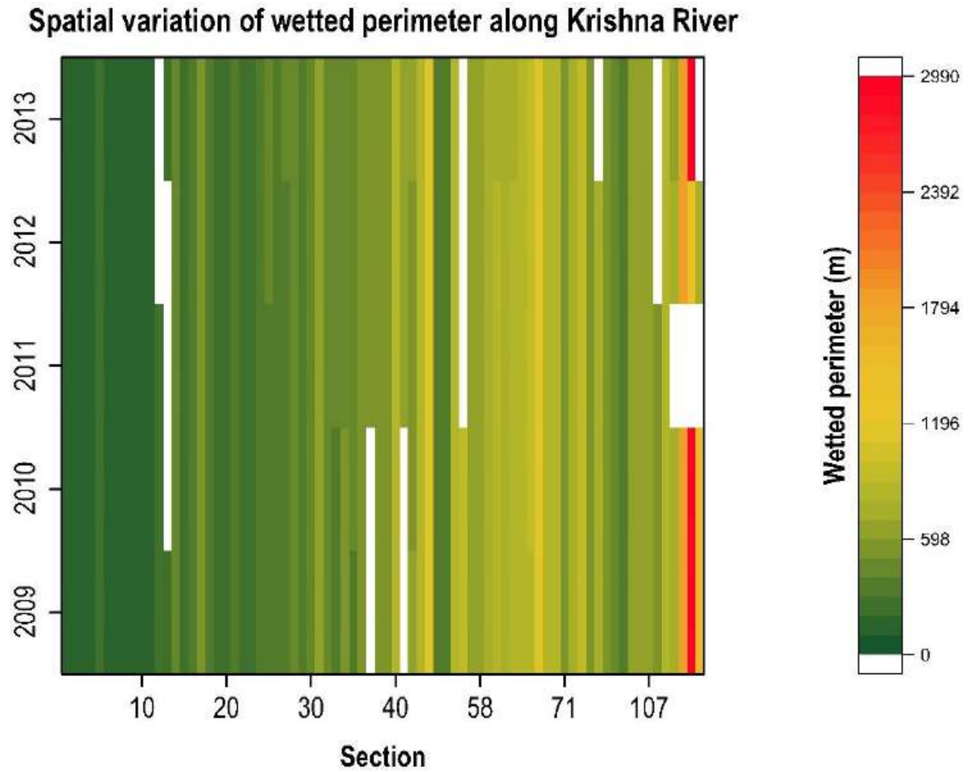

Fig. 84: Temporal variation of wetted perimeter across the measured cross-sections along Krishna River. White patches denote data gaps.

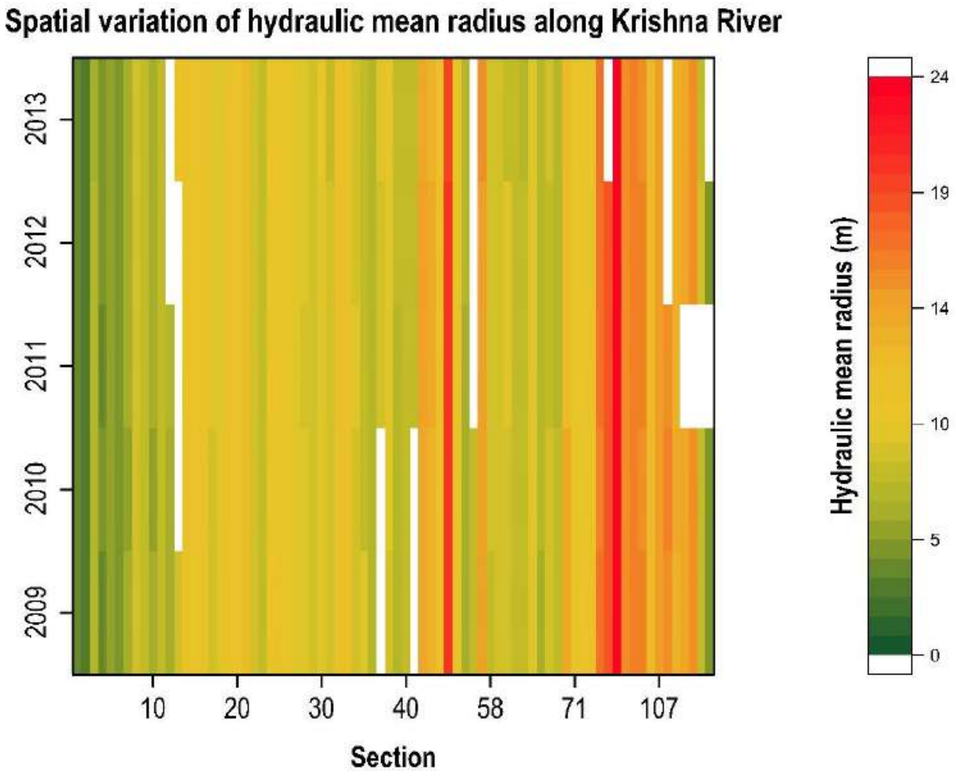

Fig. 85: Temporal variation of hydraulic mean radius across the measured cross-sections along Krishna River. White patches denote data gaps.

The data from 38 cross-section transects (Appendix XVI) along the Tungabhadra River indicate that the bankfull width of the river channel shows a generally increasing trend towards downstream (Fig. 86), whereas a decreasing trend for hydraulic mean depth (Fig. 87), which implies that the river channel widens and becomes shallow towards downstream. The cross-section area shows hardly any definite downstream trend (Fig. 88), which may be the result of the contrasting downstream behavior of the downstream variation of bankfull width and mean hydraulic depth. However, the wetted perimeter exhibits an increasing trend (Fig. 89), and obviously hydraulic mean radius a decreasing trend (Fig. 90). Despite any definite trend for cross-section area towards downstream, the increasing spatial trend for wetted perimeter reflects the increasing irregularities along the channel bed possibly contributed by the channel bars.

Further, the temporal variability is also relatively less in the majority of the reaches, except TX_07, TX_11, TX_29, and TX_36 (Appendix XVI). Among these transects, TX_36 shows a significant difference in the cross section, especially in hydraulic mean depth between 2009 and the rest of the years. The cross-section survey measurements in Tungabhadra River were recorded during the pre-monsoon season of 2009 (i.e., pre-2009 flood), while that in Krishna River during post-monsoon (i.e., post-2009 flood). Hence the changes in the channel cross-section can be correlated with the 2009 flood event, where the bed elevation was lowered as a result of the flood. Further, the transect is immediately downstream of the Sunkesula Barrage, and hence, the overtopping of the barrage structure of flood flows might have a significant role in the removal of bed materials from the channel downstream of the barrage.

The width-to-depth ratio of the river reaches of both Krishna and Tungabhadra show an increasing trend towards downstream (Figs. 91 and 92), implying that the stress placed within the near bank region is also increasing downstream. In general, it is expected to have accelerated bank erosion in the channels having high width-to-depth ratios as a result of high-velocity gradients and high boundary stress. However, hardly any correlation is observed in the Krishna River, but a linear relationship in the Tungabhadra River (Fig. 93). The exceptions are TR_06 and TR_10, which have a relatively higher rate of bank erosion during 1973-2011, compared to other reaches of Tungabhadra the River (Table 41). On comparison with Krishna, river flow of Tungabhadra River is less regulated, and hence, the non-linear relationship in the Krishna River might be the result of the influence of bank erosion by localized factors, such as hydraulic structures, the strength of the bank materials and so on.

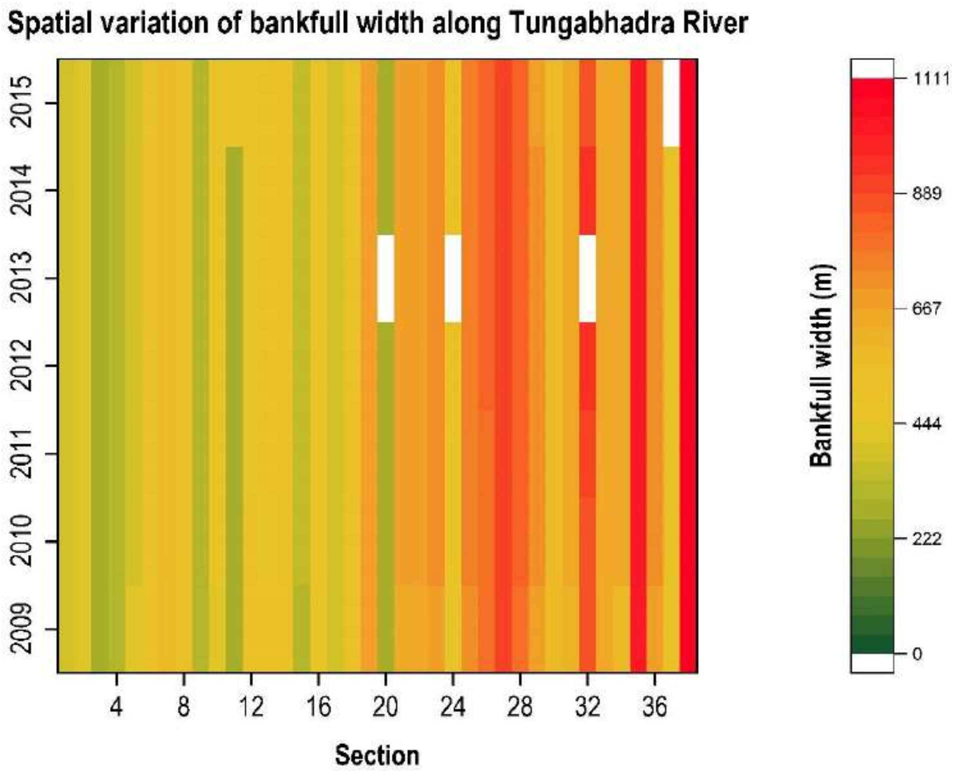

Fig. 86: Temporal variation of bankfull width across the measured cross-sections along Tungabhadra River. White patches denote data gaps.

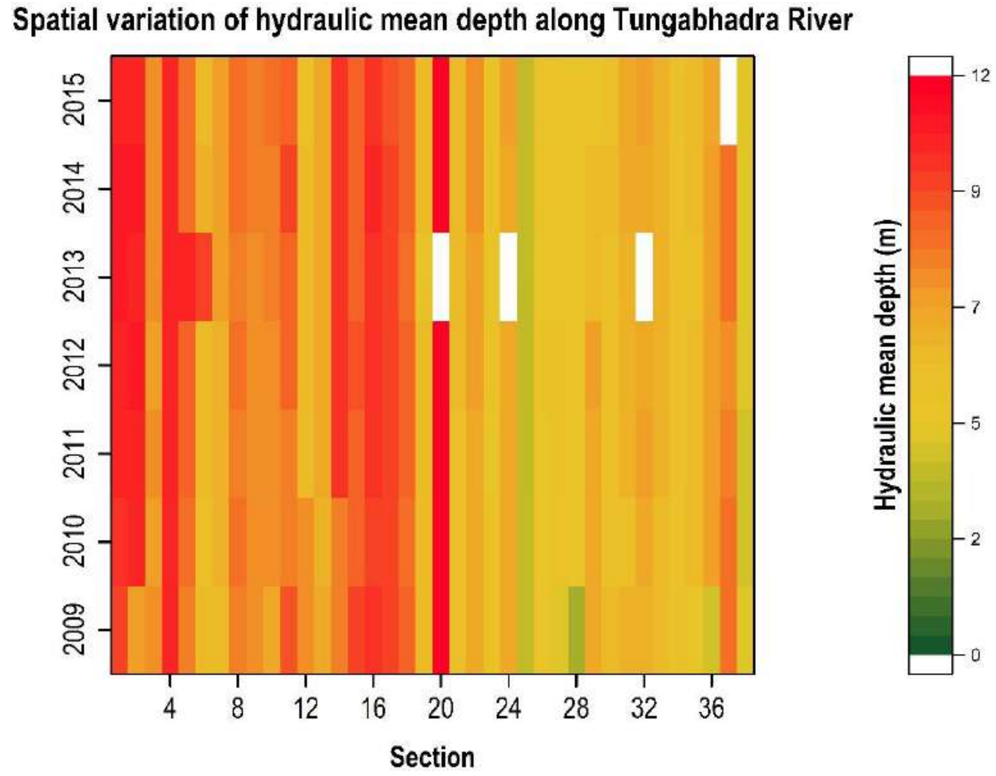

Fig. 87: Temporal variation of hydraulic mean depth across the measured cross-sections along Tungabhadra River. White patches denote data gaps.

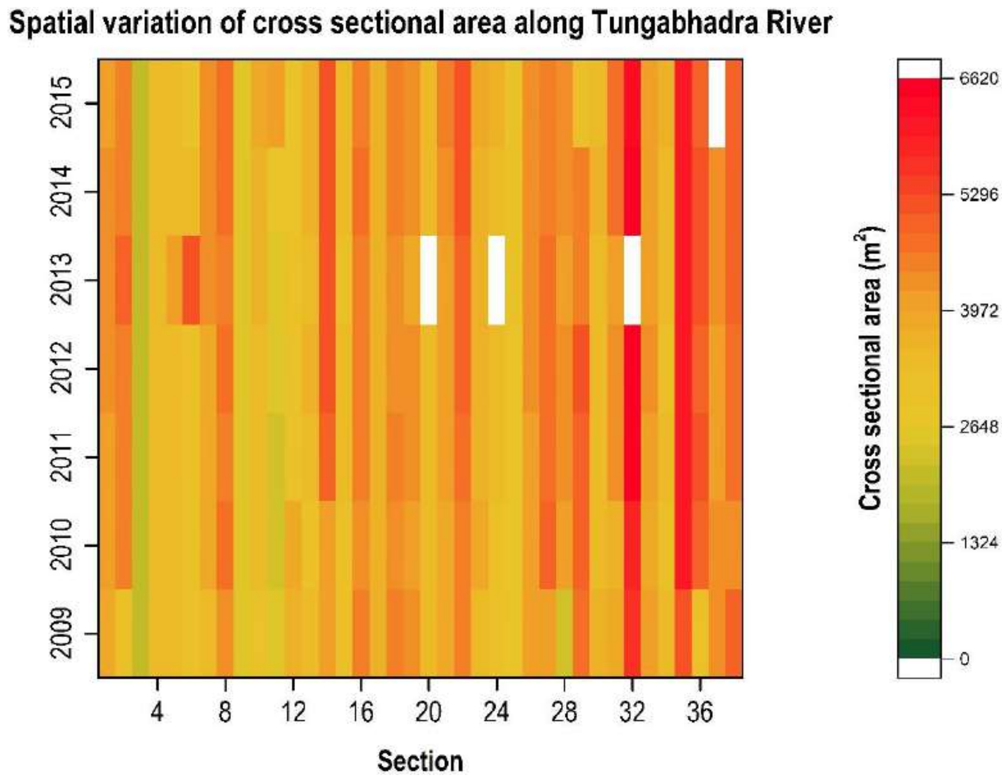

Fig. 88: Temporal variation of the cross-sectional area across the measured cross-sections along Tungabhadra River. White patches denote data gaps.

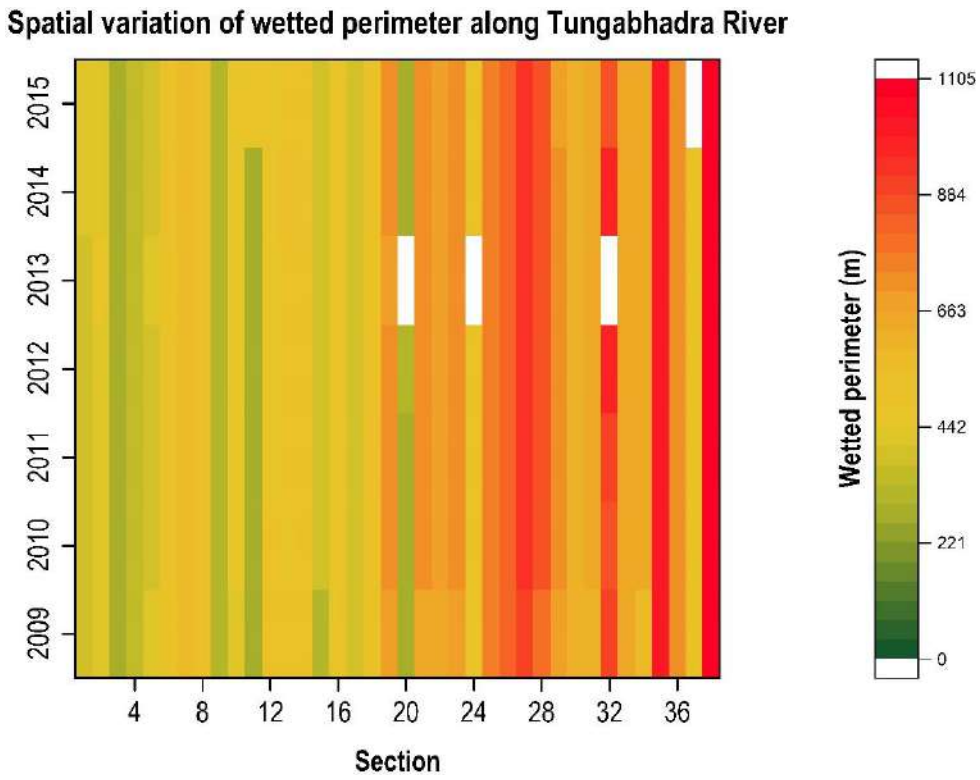

Fig. 89: Temporal variation of wetted perimeter across the measured cross-sections along Tungabhadra River. White patches denote data gaps.

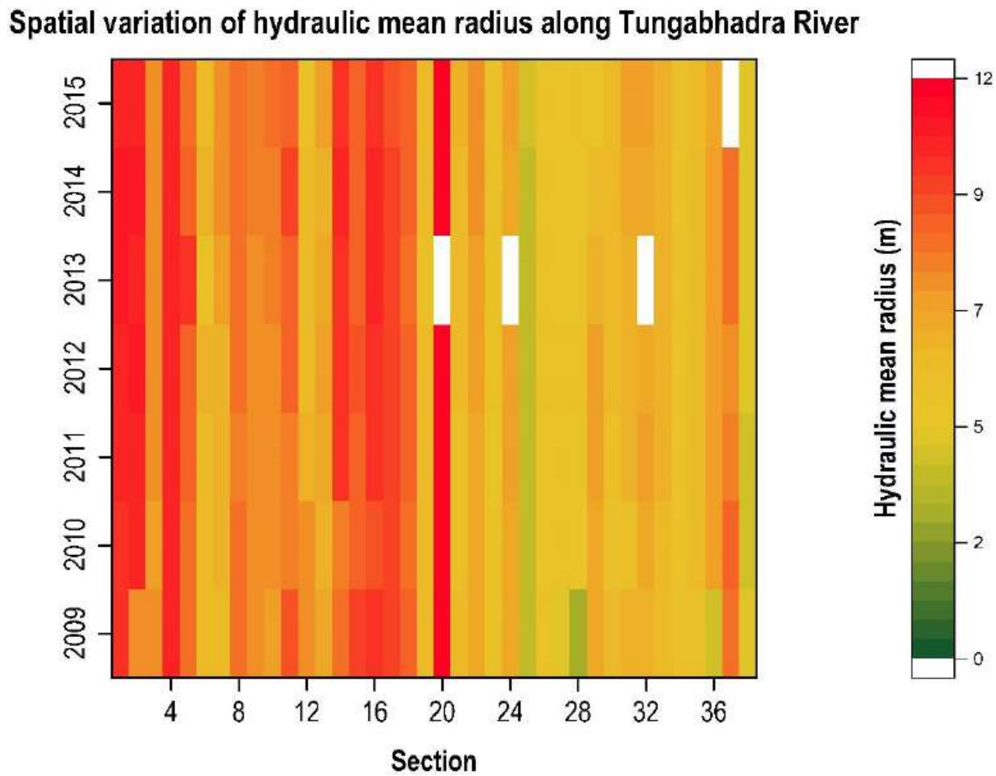

Fig. 90: Temporal variation of hydraulic mean radius across the measured cross-sections along Tungabhadra River. White patches denote data gaps.

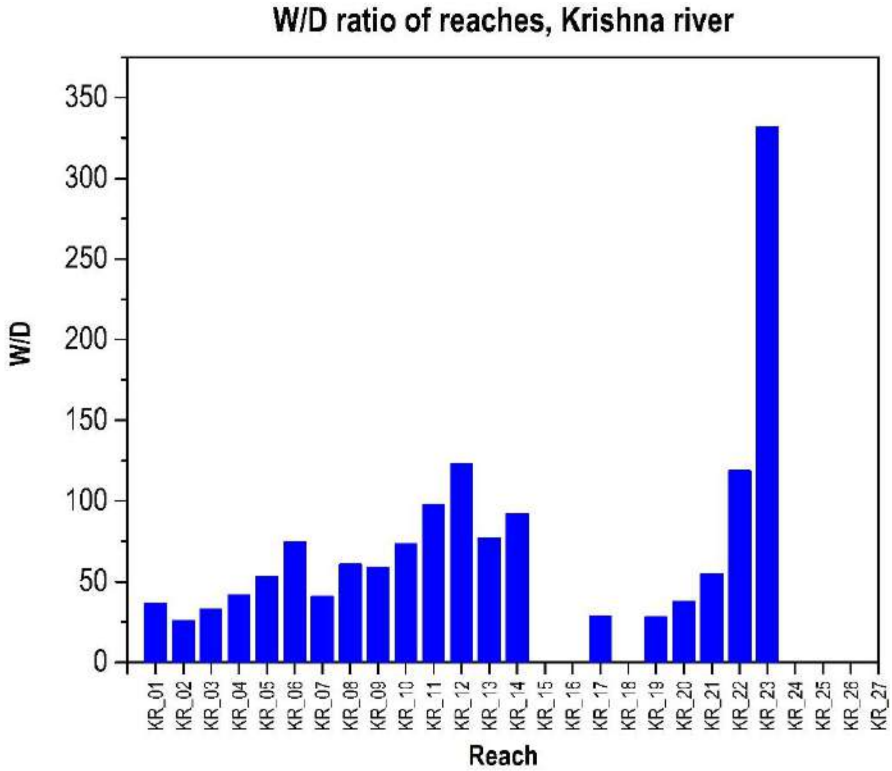

Fig. 91: Width/depth ratio of the reaches of Krishna River

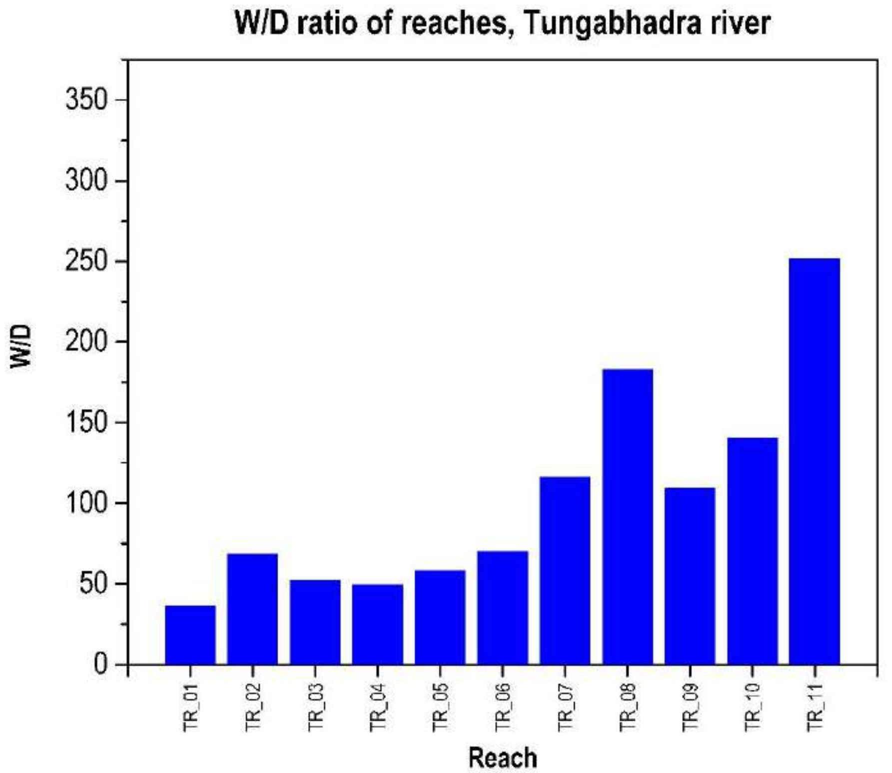

Fig. 92: Width/depth ratio of the reaches of Tungabhadra River

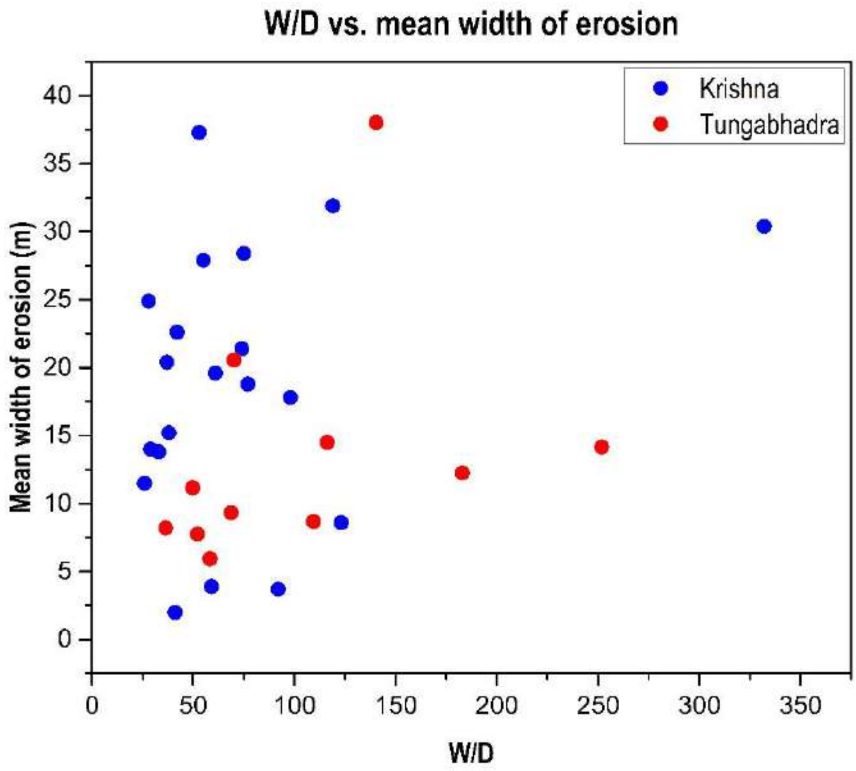

Fig. 93: Width/depth ratio vs. mean width of erosion of the reaches of Krishna and Tungabhadra rivers

The longitudinal profiles of rivers reflect the diverse effects of sediment-source rocks, sediment types, watershed evolution, and geologic structure of the river basin (Sinha and Parker, 1996). Hence, the longitudinal profile of Krishna (period = 2009-2012) and Tungabhadra rivers (period = 2009-2015) has been derived from the data provided by CWC and given in Appendices XVII and XVIII. The longitudinal profile of Krishna is a typical convexo-concave, where different sections of the longitudinal profile show different concavities. For example, the upstream part of the longitudinal profile is typically concave or quasi-equilibrium profile, which characterizes the river segment developed along the slopes of the Western Ghats. Owing to the knick point between KR_08 and KR_09, the profile has been changed into a convex, and further downstream, it continues to follow a concave profile. Three knick points on the longitudinal profile, such as between KR_08 and KR_09, KR_12 and KR_13 and between KR_21 and KR_22 are evident, and are correlated with the NE-SW trending lineament/faults as well as lithological margins (Fig. 7). The upper part of the longitudinal profile of Tungabhadra River also displays a convex profile, with an inflection point at TR_06. The temporal longitudinal profile data of both the rivers show hardly any significant changes in the bed elevation across the river.

Knick point migration is an important process of river channels in response to a base-level fall, which is a resultant of active tectonics, climate change, sea-level fall, river capture, resistant cap rock and differential incision in tributary junction and so on (Seidl and Dietrich, 1992; Whipple, 2004; Frankel et al., 2007). Since processes of knick point evolution are controlled by two primary factors, viz., the actual shear stress and the critical shear stress of the channel bed, the same can also be correlated with the active channel and bank erosion. However, the current longitudinal profile data is not sufficient to establish any relationships between the knick point migration and corresponding channel and bank erosion.

9.9. Impacts of major hydraulic structures on river morphology

In spite of the numerous values of hydraulic structures in river regulation for water resources management, these structures create artificial flow regimes downstream and interrupt the transfer of sediments from headwater source areas. Further, hydraulic structures, such as dams induce changes of the primary fluvial processes downstream of dams causing adjustments of channel form (Petts and Gurnell, 2005).

Since river flow of the study reaches of the Krishna and Tungabhadra is controlled by several hydraulic structures, their impact on the erosion and deposition along the banks is also addressed. Among the 27 reaches of Krishna River, eleven are regulated by various types of water resources structures (see Table 7; i.e., dams - KR_06, KR_08, KR_09, KR_13, KR_17, KR_19 and KR_21; barrage - KR_01, KR_02, and KR_22; weir - KR_03). Two barrages (TR_04 and TR_10), and one anicut (TR_09) were constructed in the study reaches of Tungabhadra River, whereas the major dam in the basin is the Tungabhadra dam (TR_06). The inundation of the banks as a result of reservoir impoundment is discussed in section 9.4.4.

The spatial pattern of the erosion patches along the regulated river reaches (e.g., KR_06, KR_08, KR_09, KR_13, KR_17, KR_19, and KR_21) suggests that the channel segment immediate downstream of the reservoirs show high erosion rates on both the banks (see Appendix XIV). Channel erosion immediately below dams, and immediately subsequent to dam closure has been reported by various researchers (e.g., Petts, 1979; Shields et al., 2000; Phillips et al., 2004; Yang et al., 2007). According to Wolman (1967), erosion is initiated in an upstream section close to the dam and maximum degradation usually occurs between the tail-water of the dam and a point 69 channel widths downstream.

However, several depositional patches have also been identified in the downstream reaches of the above-mentioned reaches even after the downstream of the hydraulic structures. For example, patches of sediment deposition (and aggradation of bed) were observed in the downstream channel segment of Srisailam dam (KR_17), which is contrary to the previous studies, which all observed degradation of the bed. It is also interesting to note that the sediment size ranges from very fine sand to boulder (Fig. 94). There are two reasons for the development of the depositional patch downstream of the Srisailam dam. The first one is the flood happened during 2009, which has overtopped the dam and displaced the sediments accumulated in the tailwater plunge pool to further downstream (pers. comm). In addition, there are significant contributions from one of the downstream tributary, joining the mainstream. A huge amount of sediments were deposited on the tributary channel (mainly during the construction of the powerhouse), which also moved downstream during exceptionally high flows. Development of depositional patches downstream of dams was also supported by the observations of Philips et al. (2005). In the study, Philips et al. (2005) reported that channel scour and erosion is prominent for about 60 km downstream, but beyond 60 km downstream, the river is characterized by extensive sediment storage and reduced conveyance capacity.

Fig. 94: Aggradation of channel bed in KR_17 (downstream of Srisailam dam) after 2009 flood

9.10. Identification of major river morphological problems

Understanding the behavior of the rivers is an important aspect of river engineering, where the impacts of the river morphological problems, which may be either short term or long term, localized or far-reaching, need to be addressed through sustainable river management strategies. The major river morphological problems in Krishna and Tungabhadra rivers are identified based on a review of previous literature, analysis of the results of the study as well as field visit, and are briefed below:

9.10.1. Erosion of river banks

Although the river course of Krishna and Tungabhadra is considered to be stable, erosion of the river banks, especially along the critical reaches is a major concern for sustainable river management. Erosion of the banks is relatively severe in the downstream reaches of Krishna and Tungabhadra as well as a few upstream reaches. In general, major drivers of bank erosion are floods, hydraulic structures as well as bar formation in braided channels. The erosion is also observed downstream of the man-made structures such as bridges. In addition, the outer bends of the river channel are also an erosion hotspot in the Krishna and Tungabhadra rivers. The impacts of floods and hydraulic structures on bank erosion are discussed in previous sections (9.6 and 9.8 respectively). However, the channel reaches (KR_21 to KR_24) are moderate to low braided, and the braiding pattern has been developed after local deposition of coarse material, which cannot be transported under local conditions of flow existing within the reach. This can also be correlated with the basin closure (Biggs et al, 2007). The deposition of the coarse materials facilitates bar formation by serving as a nucleus and subsequently grows into an island made up of coarse as well as fine material. As a result, the bar formation deflects the mainstream towards the banks and may cause bank erosion. The complex of islands is stabilized by vegetation in natural streams and experiences further high stage sedimentation (Akhtar, 2011). However, severe erosion along the banks of the islands in the downstream braided reaches of Krishna (especially downstream of Prakasam barrage) is evident (pers. comm.).

9.10.2. Floods

The importance of geomorphological consequences of floods has been recognized since the past century. Although Krishna and Tungabhadra rivers are not susceptible to frequent, large-magnitude flood events as in the Himalayan Rivers, due to the peculiarities of the spatiotemporal rainfall pattern as well as the regulation of the rivers. The history of the floods occurred in these rivers also underscores the same. Floods in the basin are related to high-intensity rainfall and/or releases of water from reservoirs in the upstream reaches, and the flooding occurs as a result of the inadequate capacity of the river channels as well as obstructions to flow and aggradation of river beds (NRAA, 2011). The present study brings forth evidence for the river morphological changes due to the large-magnitude floods occurred during 2005, 2006 and 2009. The impacts of the floods not only relevant to river morphology but also have significant socio-economic relevance. For example, the 2009 flood event occurred in the KRB affected 18.16 lakh population and damaged 2.14 lakh houses. Roughly 2.82 lakh hectares of croplands are damaged, and the total estimated damage is in Rs.12, 825 crores (Source: APWRDC).

9.10.3. Hydraulic structures

The KRB hosts roughly 855 water resources projects within an area of 2,58,948 km^2, which are constructed and operated mainly for agricultural, residential and industrial water supply, flood control and hydropower generation. Regardless of the purpose, these structures trap sediment to some degree and most alter the flood peaks and seasonal distribution of flows, thereby profoundly changing the character and functioning of rivers. The changes in the flow regime and sediment load lead to adjustments in alluvial channels, the nature of which depends upon the characteristics of the original and altered flow regimes and sediment loads (Kondolf, 1997). The morphological changes, such as enhanced river bank erosion, bar formation in the braided reaches, degradation of channel bed downstream of the dams as well as constriction active channel width are a few of the problems associated with river morphology of Krishna and Tungabhadra rivers.

9.10.4. Modification of riparian vegetation

The major land use/ land cover of KRB is agriculture (~82% area), and the river banks are subjected to modification of the riparian vegetation cover. Vegetation exerts significant control over fluvial processes and morphology through five mechanisms: flow resistance, bank strength, bar sedimentation, the formation of log-jams and concave-bank bench deposition (Hickin, 1984). The riparian vegetation binds sediment and increases the strength of the banks and raises the flow drag. Since the morphology and lateral stability of river channels strongly depend on the strength of the bank materials, binding properties of vegetation growing on the riparian zone might have crucial roles in maintaining the health of the fluvial systems. The role of vegetation as an influence on channel form and process in larger rivers is less important, compared to the mountain streams and watersheds, though it may still be quite significant in the Krishna as well as the Tungabhadra rivers.

9.10.5. Mining of fluvial sediments

Unscientific extraction of sand and gravel from the banks and channel is a major problem in several reaches of Krishna and Tungabhadra rivers (Fig. 95). In fact, the mining of the channel bed and in-channel bars results in channel instability through the direct disruption of pre-existing channel geometry or through the effects of the incision and related undercutting of banks (Collins and Dunne, 1989). Further, the discontinuity in the sediment supply-transport balance tends to migrate upstream as the river bed is eroded to make up for the supply deficiency (Knighton, I984). The in-channel mining is sometimes promoted in alluvial rivers to increase channel flood capacity and prevent flooding (Rinaldi et al. 2005; Russell et al. 2016). However, the changes induced by gravel mining have direct and serious effects on human stakes, such as depletion of groundwater.

Fig. 95: Extraction of sand from the channel bed in TR_11, Tungabhadra River

9.10.6. Land use/ land cover changes

Since the majority of the basin area of the KRB is utilized for agricultural purposes, the areal extent of the natural vegetation belt is comparably low. However, the changes in the land use/ land cover pattern might also have a crucial role as land use changes alter the water and sediment supplied to rivers, which, in response, alter their geometry and composition toward a condition capable of passing the supplied sediment with the available water (Clark and Wilcock, 2000). Since the study did not conduct a detailed analysis on the land use/ land cover changes occurred in the basin during the channel morphology assessment period (1973-2011), it is difficult to establish the links between land use/ land cover changes and the modification of the channel morphology in Krishna and Tungabhadra rivers.

9.10.7. Climate change

The spatial variability of the climatic variables across KRB is highly variable, and there are sufficient evidence to show that the climate over peninsular India is highly variable, and vary considerably over a relatively short time span. The impacts of climate change on fluvial systems are obvious in various river basins of India, including the large peninsular rivers (Shukla, 2003). In fact, the impacts on river morphology are sensitive to climate change through a series of cascades, first on amount and pattern of precipitation and evaporation, secondly on the catchment systems and thirdly on the morphology of the fluvial environment. The frequent occurrence of extreme events has a decisive role in redefining the morphology of the channels, which was already exemplified during the flood events during the 2001-2011 period.

9.10.8. Farming along river bed as well as riparian zones and floodplains

Riverbed vegetable farming is a pro-poor program intended to contribute on the livelihoods of people. Farming of the river bed and adjacent areas is observed in a few reaches of the Krishna and Tungabhadra rivers. In KR_14, such large scale farming practices are observed (Fig. 96). The reach is characterized by seasonal flooding due to the inundated backwater of the Srisailam dam. After the river water recedes, short duration cover crops are planted into the fertile alluvium deposited along the banks, and the crops are harvested before the next inundation episode. However, disturbing the deposited sediments by plowing and other activities increase the sediment load into the channel.

Fig. 96: Farming on the channel bed and floodplain in KR_14, Krishna River

9.10.9. Retreat of delta

The retreat of the Krishna delta is observed during the analysis, and the delta front has been retrograded approximately 500-1000 m towards the land area. The high erosion severity of the deltaic reaches observed in this study can also be correlated with the delta retreat. In 2009, Gamage and Samkhtin carried out a study to identify, locate and quantify coastal erosion and deposition processes in coastal segments of Krishna basin using a time series of Landsat 2 MSS, Landsat 5 TM and Landsat 7 ETM^+ images for 1977, 1990 and 2001, and observed that coastal erosion in the Krishna Delta progressed over the last 25 years at the average rate of 77.6 ha yr^{-1}, mainly due to the reduced river inflow to the delta and the associated reduction of sediment load. Similar attempt has also been made by Rao et al. (2010) in the Krishna and Godavari deltas using SoI topographic maps from the 1930s; Corona satellite photographs from 1965; Landsat TM images from 1990; Landsat ETM images from 2000; and IRS P6-LISS-III images from 2008, and reported a net erosion of 76 km^2 area along the entire 336-km-long twin delta coast during the past 43 years (1965-2008) with a progressively increasing rate from 1·39 km^2 yr^{-1} between 1965 and 1990, to 2·32 km^2 yr^{-1} during 1990-2000 and more or less sustained at 2·25 km^2 yr^{-1} during 2000-2008.

SECTION 10
BANK EROSION / DEPOSITION IN DELTAIC PLAINS

The results of the bank erosion/deposition analysis in KRB evidently suggest that the reaches downstream of the Nagarjuna Sagar dam, and particularly the reaches developed in the deltaic plains of the Krishna River are highly vulnerable to bank erosion as well as bank deposition. The reaches developed in the deltaic plains include KR_24, KR_25, KR_26, and KR_27, where KR_24 is the reach representing the mainstream of Krishna River, whereas KR_25, KR_26 and KR_27 are the distributaries. The details of the extent of erosion and deposition in these reaches are given in Tables 32 to 36. The areal estimates of bank erosion and deposition along the study reaches during 1973-1977 indicate that KR_25 experienced a relatively higher rate of bank erosion as well as deposition, compared to other reaches of the region (Fig. 97). It is noted that the erosion in the reaches was more along the right bank during the period. However, deposition was more along left bank in KR_24 and KR_27, while along right bank in KR_25. Moreover, the total area under bank erosion was comparably higher than the area under deposition in the river reaches, except KR_26. During 1977-1991, KR_24 showed a maximum rate of erosion along both the banks, while deposition was comparatively higher in KR_25. Among the banks, erosion was more along the left bank in the reaches with an exemption of KR_24. However, deposition showed the complementary pattern to bank erosion, i.e., deposition was more along the right bank of the reaches except for KR_24. The total area of bank erosion was relatively higher, compared to bank deposition in the reaches, except KR_25. It is observed that the total erosion along the banks of KR_27 was more than three times the bank deposition (Fig. 97).

The total area of bank erosion between 1991 and 2001 was also high in KR_24, whereas deposition was comparatively higher in KR_25 (Fig. 97). KR_24 and KR_25 showed maximum erosion along the right bank, whereas KR_26 and KR_27 exhibited high erosion along the left bank. But, deposition in all the reaches was high along the right bank. Except in KR_25, all the reaches experienced a relatively higher rate of erosion, compared to deposition. During 2001-2011, bank erosion and deposition was relatively higher in KR_25. All the reaches, except KR_27, showed comparatively higher erosion along the left bank and deposition along the right bank. During the period, KR_24 and KR_25 experienced pronounced erosion along their banks, compared to deposition, whereas other reaches had a more or less equal area under erosion and deposition. The bank erosion/deposition during the entire period of assessment, i.e., 1973-2011 also indicate that KR_24 experienced severe erosion during the period, whereas deposition was maximum at KR_25. Further, erosion was dominant along the left bank (except KR_24), and deposition dominated along the right bank (Table 36). Although the distributaries other than KR_25 also experienced the remarkable extent of erosion, the same is not highlighted in the areal estimates of bank erosion, which is mainly due to the lower length of the KR_26 (17 km) and KR_27 (14 km). The mean width of erosion as well as deposition along the reaches (Tables 32 to 36), clearly suggests that erosion/deposition width is considerably high in these distributaries.

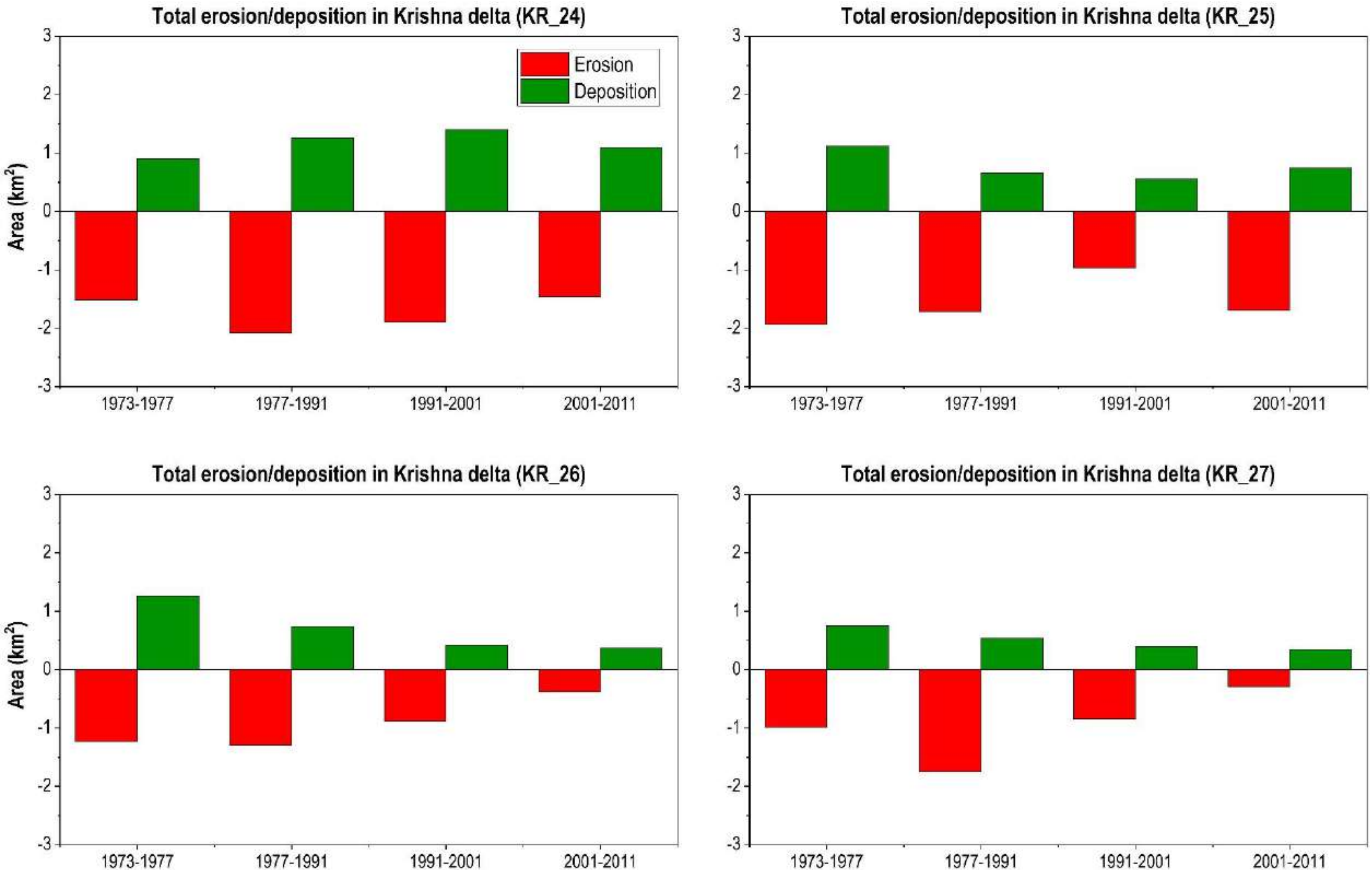

Fig. 97: Bank erosion and deposition in the river reaches of Krishna Delta

Considering the dominance of bank erosion and deposition along the reaches, the direction of the shifting of the channel bank lines were assessed (Table 45).

Table 45: Schematic diagram of shifting of the bank line of the reaches in deltaic plain across the time periods

Reach-ID	Left Bank						Right Bank				
	1973-1977	1977-1991	1991-2001	2001-2011	1973-2011		1973-1977	1977-1991	1991-2001	2001-2011	1973-2011
KR_24	→	←	←	←	←		→	→	→	→	→
KR_25	←	←	→	←	←		→	←	←	→	←
KR_26	→	←	←	→	←		→	←	←	→	←
KR_27	→	←	←	→	←		→	←	←	→	→

For left bank, ← indicates shifting away from channel centerline and → indicates shifting towards center line; for right bank vice versa

Table 45 suggests that the reaches in the deltaic plains showed different directions of movement of the bank line during different periods. However, considering the long term change in the bank lines (i.e., 1973-2011), it is evident that KR_24 and KR_27 were shifted both the bank lines from the centerline, whereas KR_25 and KR_26 shifted their bank lines unidirectional.

The relatively high rates of bank erosion in the deltaic plains are mostly related to the topographical and geological settings of the channels, as the nature of the geologic substrate strongly affects the susceptibility of the channel to change. It may be noted that the channels in the deltaic plain are developed in the Quaternary sediments, which are susceptible to bank erosion, compared to the crystalline rocks of the basin. It is also observed that the reaches developed in the Quaternary sediments, other than KR_24, KR_25, KR_26 and KR_27 (e.g., KR_23 and part of KR_22) also experienced relatively higher rates of erosion. In the downstream parts of KRB, it is evident that bank erosion is considerably higher in the Quaternary sediments, compared to other lithological types. For example, the river segments downstream of the Nagarjuna Sagar dam is developed in the Kurnool Group of rocks. Field observations indicated that the rocks of the Kurnool Group (consisting mainly of limestone, slate, and quartzite) are stratified and highly jointed, where erosion occurs primarily along the lines of weakness, such as joints or fractures. Hence, in such reaches, vertical erosion may be dominated over lateral erosion leading to confined valleys. On the other hand, erosion in the Quaternary sediments is primarily a function of the erodibility and shear strength of the bank matrix, and the high erosion intensity is the result of the weak bank resistance of the unconsolidated substrate.

SECTION 11
RECONNAISSANCE

11.1. Scope and purpose

Following prioritization of the river reaches based on the severity of bank erosion, two reconnaissance field visits were conducted to verify the findings of the study as well as to assess the present condition of the reaches. The reconnaissance survey employed different means of investigation, which included a review of previous reports, bank line and channel observations and interviews with engineers of the water resources department (both State and Central Government) and dam operations and with local farmers and other stakeholders. The reconnaissance surveys were completed in two phases and a total of 35 man days was utilized for the completion of the survey. The manpower for the survey included the principal investigators and staffs of the project, researchers from the IIT Madras, experts from National Institute of Hydrology, Kakinada as well as local engineers from the water resources department of Andhra Pradesh and Telangana States.

11.2. River reaches

The reconnaissance survey was conducted in four reaches of Krishna River and two reaches of Tungabhadra River during March and October 2017. The details of the river reaches are given in Table 46. However, the reconnaissance survey was conducted on the sub-reach scale, and sub-reaches were selected on the pattern of the erosion and deposition along the whole reach.

Table 46: Details of the river reaches considered for reconnaissance survey

Reach-ID	Longitude at origin (DMS)	Latitude at origin (DMS)	Longitude at end (DMS)	Latitude at end (DMS)	Criticality Status
Krishna River					
KR_14	77° 55' 15.36"E	16° 11' 41.74"N	78° 14' 31.32"E	15° 57' 21.63"N	Low to moderate
KR_17	78° 53' 05.28"E	16° 06' 27.79"N	79° 10' 53.68"E	16° 12' 46.88"N	Low to moderate
KR_22	80° 14' 19.61"E	16° 36' 18.11"N	80° 39' 42.72"E	16° 27' 44.93"N	High
KR_23	80° 39' 42.72"E	16° 27' 44.93"N	80° 52' 58.36"E	16° 04' 27.45"N	High
Tungabhadra River					
TR_10	77° 36' 30.87"E	15° 55' 00.52"N	78° 01' 39.43"E	15° 51' 07.33"N	High
TR_11	78° 01' 39.43"E	15° 51' 07.33"N	78° 15' 13.76"E	15° 58' 07.67"N	Low to moderate

11.3. Field verification and observations

The erosion and deposition patches identified during the 1973-2011 period were considered to verify in the field. Even though the assessment period is only up to 2011, it is assumed that the erosion and deposition pattern during the period is preserved. Among the 30 patches (including both erosion and deposition) selected to verify in the field, more than 90% of the patches confirmed the results of the present analysis. However, the study has identified three deposition patches (in TR_10 and TR_11), where the reconnaissance survey failed to identify the patches in the field.

The inundated areas due to reservoir impoundment, while on lean period, are utilized for agricultural purposes, and a wide variety of short term crops are being cultivated in those areas. Since the inundated areas are characterized by the presence of a thick column of fertile alluvium, most of the areas are being under cultivation. In addition, the survey also witnessed the effects on the channel as well as on the banks during the 2009 flood, especially in TR_11, KR_14, KR_17, KR_22, and KR_23. Even though the imprints of the flood event is preserved along the channel bed of these reaches, its effects on the banks are not evident in all the reaches due to the bank restoration as well as flood protection measures such as berms, cantilever retaining walls etc. (Figs. 98 and 99). Relicts of sand mining activities are visible in the channel bed as well as on the banks of KR_22, where the mining pits go deep to roughly 2.5 - 3.0 m below the sediment deposition patches (Fig. 100). The total depth of sand column in the river channel reaches up to 30 m, especially in the reaches downstream of Prakasam barrage and deltaic regions, and has drawn attention for mechanical sand mining. Further, dumping of municipal wastes in the river bed (and burning) is also observed in the reaches, which are close to the urban centers (KR_22 and KR_23).

Fig. 98: Berms constructed on the right bank of KR_22, upstream of Prakasam barrage

Fig. 99: Cantilever retaining walls constructed on the right bank downstream of Prakasam barrage; upstream view

Fig. 100: Sand mining in the depositional patches of KR_22; water level is nearly 2.5 m below the surface; downstream view

In order to understand the depositional characteristics in the areas of deposition, sediment samples were collected from the active channel, banks as well as overland area, and analyzed for the textural parameters by performing sieve analysis. A total of 9 sediment samples were collected both KR_14 and TR_11 were analyzed for the size frequency distribution. The results of the particle size analysis indicated that the samples collected from the active channel as well as depositional areas show hardly any significant differences in the statistical parameters of the sediment texture. Such results can be inferred as the deposited areas were once dominated by fluvial processes.

SECTION 12
RESTORATION OF CRITICAL & IMPORTANT RIVER REACHES

12.1. Introduction

The impacts of various natural, as well as anthropogenic drivers, threaten the resilience and sustainability of the fluvial systems and their ability to deliver the goods and services that benefit people (WHO, 2005). In KRB, major changes to the fluvial system are caused by river regulations, water abstractions, modifications of river morphology as well as floodplain structure, which create different kinds of pressures, such as hydrological regime pressures, river fragmentation pressures, morphological alteration pressures and other elements and process affected pressures (i.e., physicochemical). Further, these pressures result in changes to the natural structure and functioning of running waters by disrupting the natural flow regime (e.g., timing and magnitude of discharge) and the supply, transport, and deposition of inorganic and organic substrate, sediment, and detritus that shape and maintain a dynamic patchwork of river habitat (Garcia de Jalon et al., 2013).

The pressures related to the morphological alterations can be limited or can be overcome by implementing suitable river training works. Generally, river training works are essential in the rivers which faces the morphology issues such as frequent changes in the river courses, avulsion of one river into another river, heavy shoal formation leading to diversion of main current towards banks, development of natural cut-off, landslides in the catchment leading to rise in the silt load in the river, aggradation of river bed resulting in high flood levels during the flooding, heavy erosion in banks by hill streams due to flash floods, river instability due to changes in bed slopes, changes in the river base level, changes in river channels due to changes in rainfall pattern, erratic behavior of rivers in deltaic areas, erratic behavior of braided rivers, and formation of sand bars at river outfalls in to the sea. However, the nature of the river training works to be implemented depends on the characteristics of the reaches (e.g., mountain and sub-montane, quasi-alluvial, alluvial and tidal).

12.2. River training measures

The river training works include various structural, non-structural as well as biological measures, which are adopted with the aim to guide the river flow by protecting the banks of the river from erosion along with protection of downstream hydraulic structures (Schnick et al., 1982; CWC, 2012). The commonly adopted structural measures to address the problems associated with river morphology are discussed below:

12.1.1. Structural measures

Structural mitigation involves the process of constructing structures along the rivers to prevent or reduce the impacts of the causative factors of river morphological alteration. The structural measures can be either transversal protection measures, which are installed perpendicular to the river course or longitudinal protection measures that are implemented along the river banks parallel to the river course. However, this section discusses the structural measures in general.

12.1.1.1. Embankments

Embankments are constructed parallel to the river channel. The design and construction of these structures are similar to that of earth dams and the height of these structures may go up to 12 m. Based on the position of these structures, embankments can be classified into marginal embankments, retired embankments and approach embankments. Embankments are widely used in river training works, due to their ability to protect large areas by a comparatively small investment. These structures are mostly constructed with the locally available material and maintenance of these structures does not involve intricate methods. Construction of these structures also involves a few risk elements. Restricting the waterway leads to the chance of raising the flood levels. In the case of flash floods, the chances of failure of embankments are quite high. Since the construction involves a large area in the river banks it reduces the cultivable area.

Marginal embankments (also known as levees) are constructed as close to the banks as possible for preventing the possibility of submergence of areas behind the embankments. These structures are designed to withhold the water level up to a maximum anticipated high flood level without overtopping but as the height increases it is necessary to provide additional protections such as a key trench, zoned section etc. to make the structure more stable.

Retired embankments are built at a distance away from the river ridge as an additional defense behind the existing embankments and are constructed on lower ground. These type of embankments are also used as a replacement for a damaged flood embankment. In such cases, these structures are constructed around the breach connecting the retired embankment with the original one at locations sufficiently away from the breach so that by the time construction of retired embankment is over, the breach doesn’t propagate to the connecting points.

Approach embankments are provided if the width of the river is wide in the alluvial plain where the diversion structure is constructed with a restricted waterway considering the economy as well as better flow conditions. In places where river forms loops in the alluvial plain, the positioning of these structures has to be done carefully.

12.1.1.2. Groynes or spurs

These structures are constructed transverse to the river flow, extending from the bank into the river. These structures are mainly constructed to reduce the concentration of the flow near to the banks which are prone to erosion. These structures can be classified into different groups based on the materials used, the height of the spur with respect to the water level, and, the function to be performed by them. Groynes are much more effective when constructed in series as they create a pool of nearly still water between them which resists the current and gradually accumulates silt forming a permanent bank line in course of time.

The length of groynes depends upon the position of the original bank line and the designed normal line of the trained river channel. Each groyne can protect only a certain length and so the primary factor governing the spacing between adjacent groynes is their lengths. The top level of the spur is to be worked out by giving a freeboard of 1 to 1.5 m above the highest flood level for 1 in 500 year flood or the anticipated highest flood level upstream of the spur, whichever is more. In general, these structures protect the river bank by keeping the flow away from it. As the time spans, these structures form a silt deposition which reduces the width of the river also improving the navigation depth.

12.1.1.3. Bed pitching and bank revetment

These measures are done to counteract the general tendency of the water to notch away from the river banks. These kinds of protection come under direct methods which can be applied to the river banks, such as providing vegetal cover, pavement, revetment, grading of slope etc. Providing vegetal cover with long rooted grass having high tensile strength can also be used for bank protection. Bank riveting is applied to protect the banks against the action of water by laying closely packed stone blocks or boulders or even concrete blocks. The pitching of banks is also done in a mortar using stones, bricks or concrete blocks. Pitching in mortar are done with joints at the suitable interval to avoid cracks in the structure. Pitching is also done using geo-textile bags where geo-synthetic bags filled with sand are used.

12.1.1.4. Bank stabilization measures

The direct methods available for bank stabilization include self-adjusting armor made of stone or other materials, rigid armor as well as the flexible mattress. The self-adjusting armor structures are constructed using graded stones which include a mixture of a wide range of stone sizes where the larger ones resist hydraulic forces and smaller ones act as interlocking support. These structures can be used in a different manner and based on their configurations these armors are grouped into riprap blanket, trench fill, windrow, and longitudinal stone toe. The materials used for these structures involves concrete blocks, sacks, soil-cement blocks etc. The rigid armor is erosion resistant structures made of different materials such as asphalt, concrete, grouted riprap, and soil cement. These structures have little or no flexibility and are placed directly on the bank slope. Rigid armors withstand high velocities, have low hydraulic roughness, and prevent infiltration of water into the channel bank. They are practically immune to vandalism, damage from debris, corrosion, and many other destructive agents. The most common rigid armors are easily traversed by pedestrians. The flexible mattress structures are made of materials like concrete blocks, fabric, and gabions. These materials if used alone cannot resist the erosive forces can be fastened together or placed in a flexible container to provide adequate resistance to erosion. These structures have the flexibility to adjust to scour and settlement and still stay intact.

All these structures if designed precisely for a given situation are proven as sustainable river restoration measures and give immediate and effective protection against erosion. However, these structures demand bank slope preparation for geotechnical stability and to provide a smooth surface for proper placement which may result in high cost, environmental damage, and disturbance to adjacent structures.

12.1.2. Biological measures

In addition to the structural measures, the biological measures are also effective in controlling the problems associated with alteration of river morphology. Among the various biological measures, the establishment of a vegetative cover of strongly rooting plants is considered to be the most effective means of controlling river bank erosion and bank stabilization. Vegetation contributes to bank stability by retarding water speeds and tractive forces near the soil surface and buffering transported materials such as logs away from banks. Moreover, the reinforcing and soil-binding action of the roots provide a considerable degree of cohesion to soils. In addition to the direct benefits, the biological measures have numerous indirect benefits of hydrogeomorphological value, which include a reduction in nutrient and fine sediment enrichment, shade, shelter and filtering qualities for the aquatic ecosystem as well as aesthetic and recreational value. However, the choice of the vegetation types should be based on the nature of the bank material as well as other environmental aspects. For example, mangroves are highly efficient in controlling river bank erosion, especially in the downstream areas, but require a muddy river bank to proliferate, and hence not suitable for the bank substrate with coarse fraction sediments. In addition, wooden piling or posts, as well as geo-textiles, are also effective against riverbank erosion through the systematic installation to stabilize eroding banks.

In the context of the issues associated with river morphology, implementation of river training works as well as flood protection measures (Figs. 98 and 99), which are mostly structural measures, have already been initiated. However, implementation of the training works based on the prioritization of the river reaches will be beneficial for managing the morphological issues in a sustainable way. The proposed protection measures in the critical reaches of Krishna and Tungabhadra rivers are shown in Figs. 101 to 118.

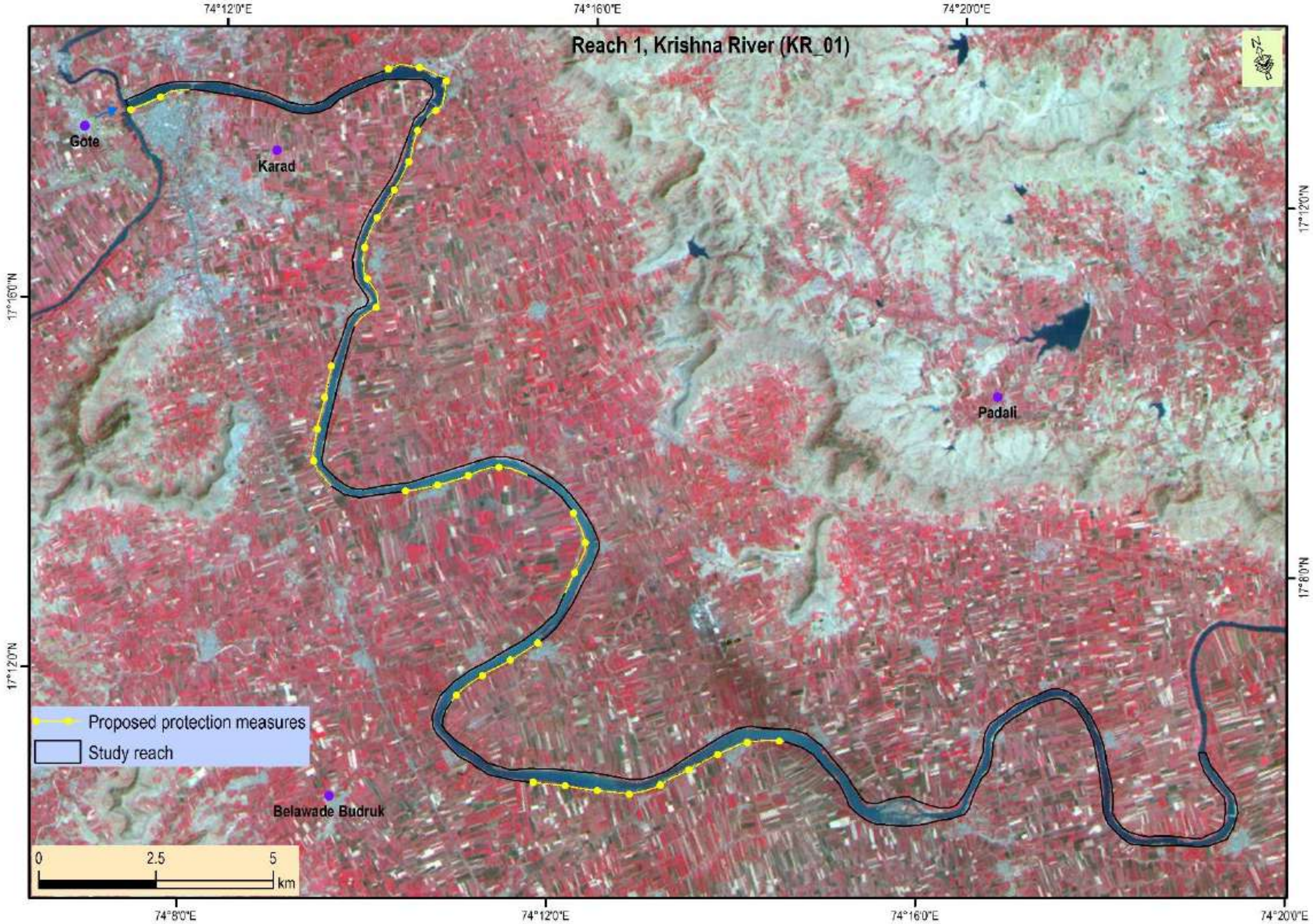

Fig. 101: Sections in the reach to be protected by various protection measures, KR_01, Krishna River

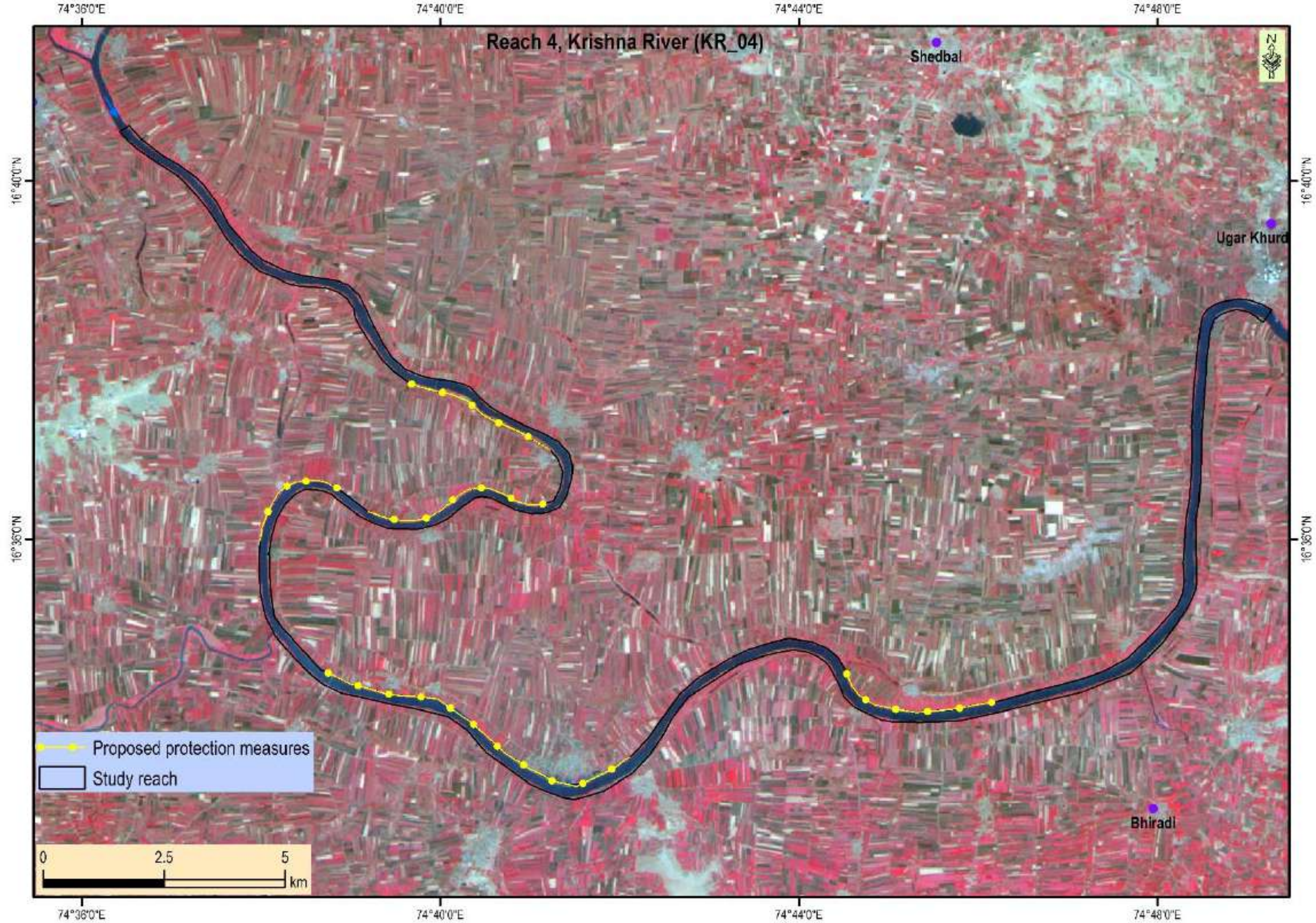

Fig. 102: Sections in the reach to be protected by various protection measures, KR_04, Krishna River

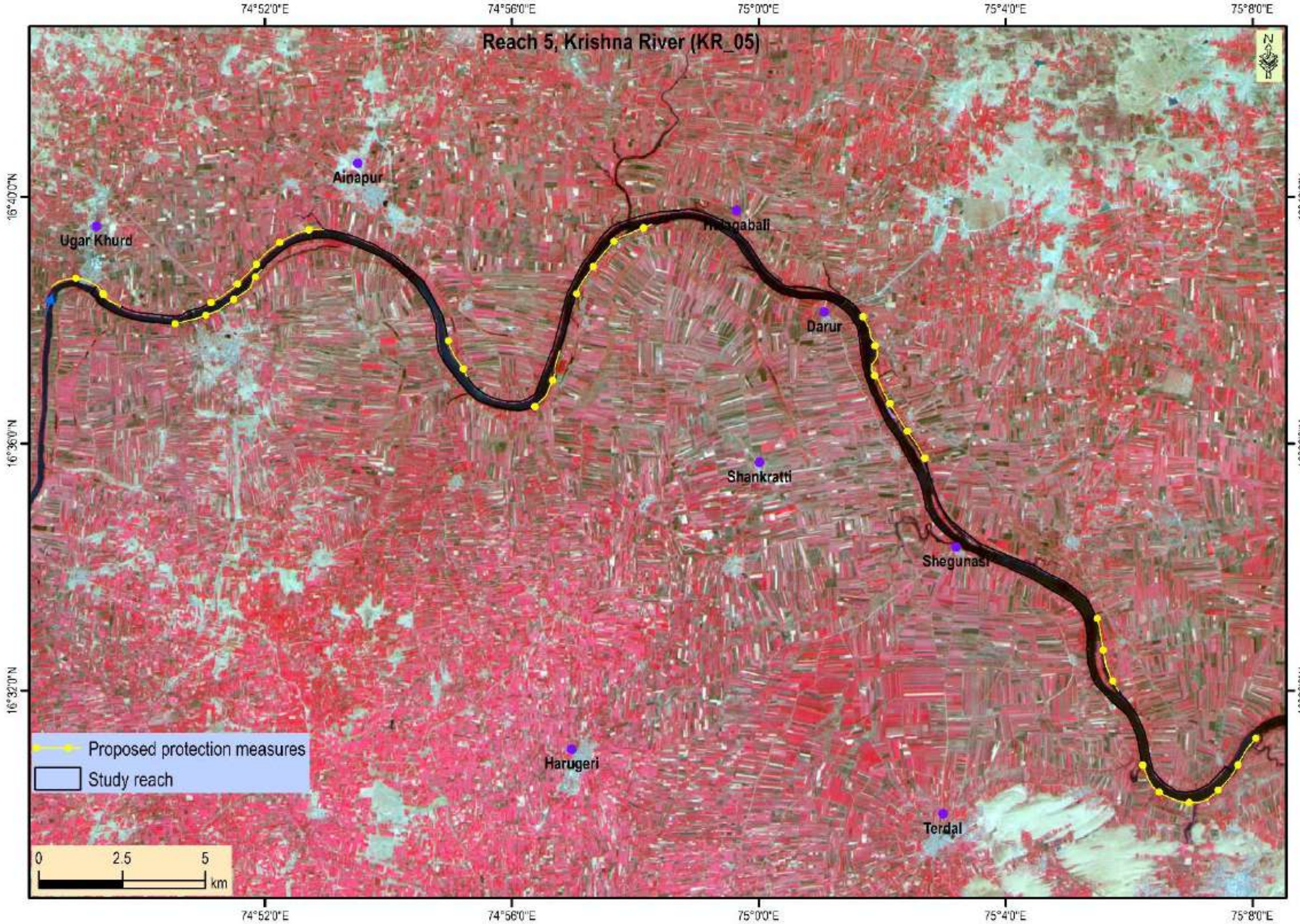

Fig. 103: Sections in the reach to be protected by various protection measures, KR_05, Krishna River

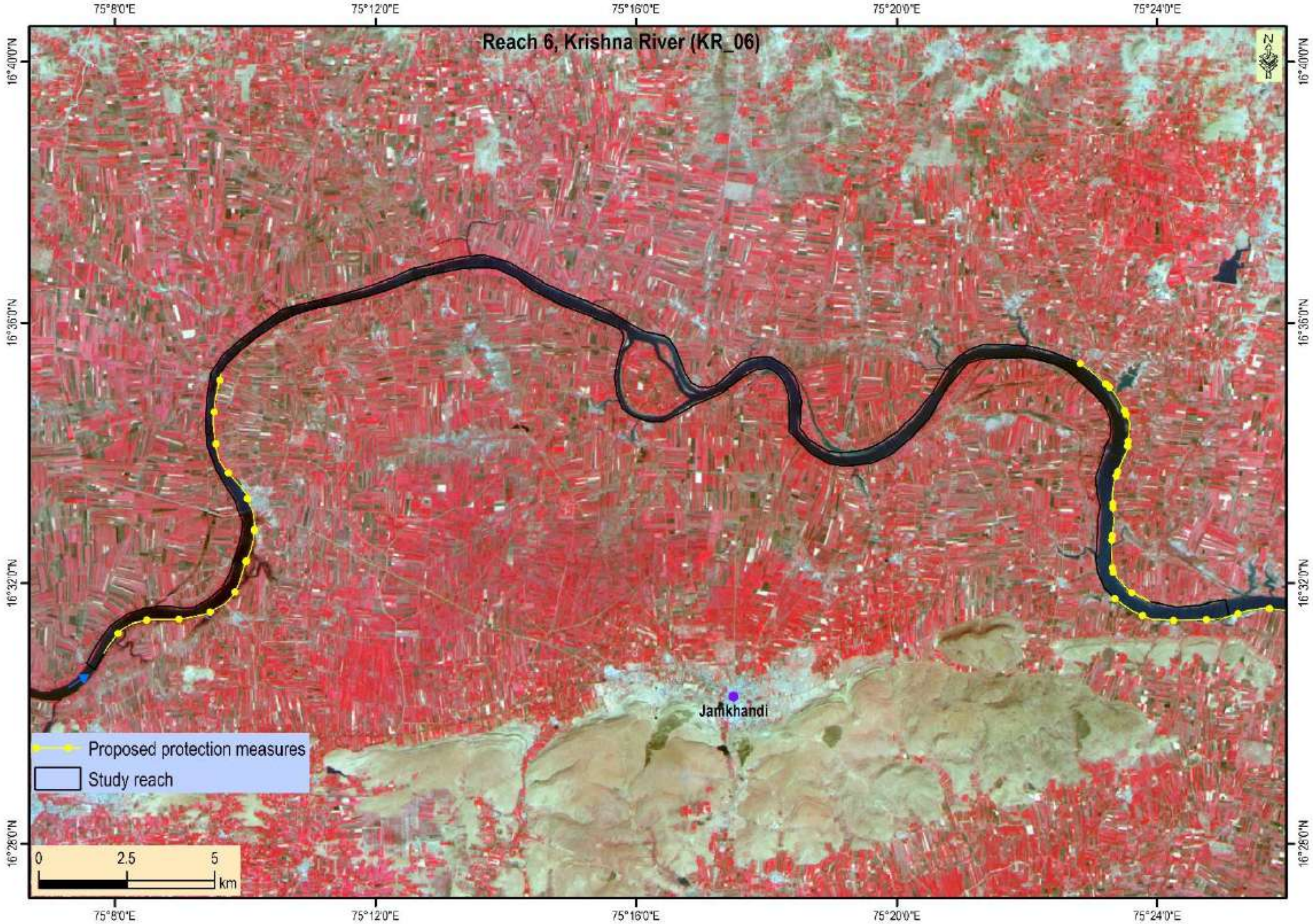

Fig. 104: Sections in the reach to be protected by various protection measures, KR_06, Krishna River

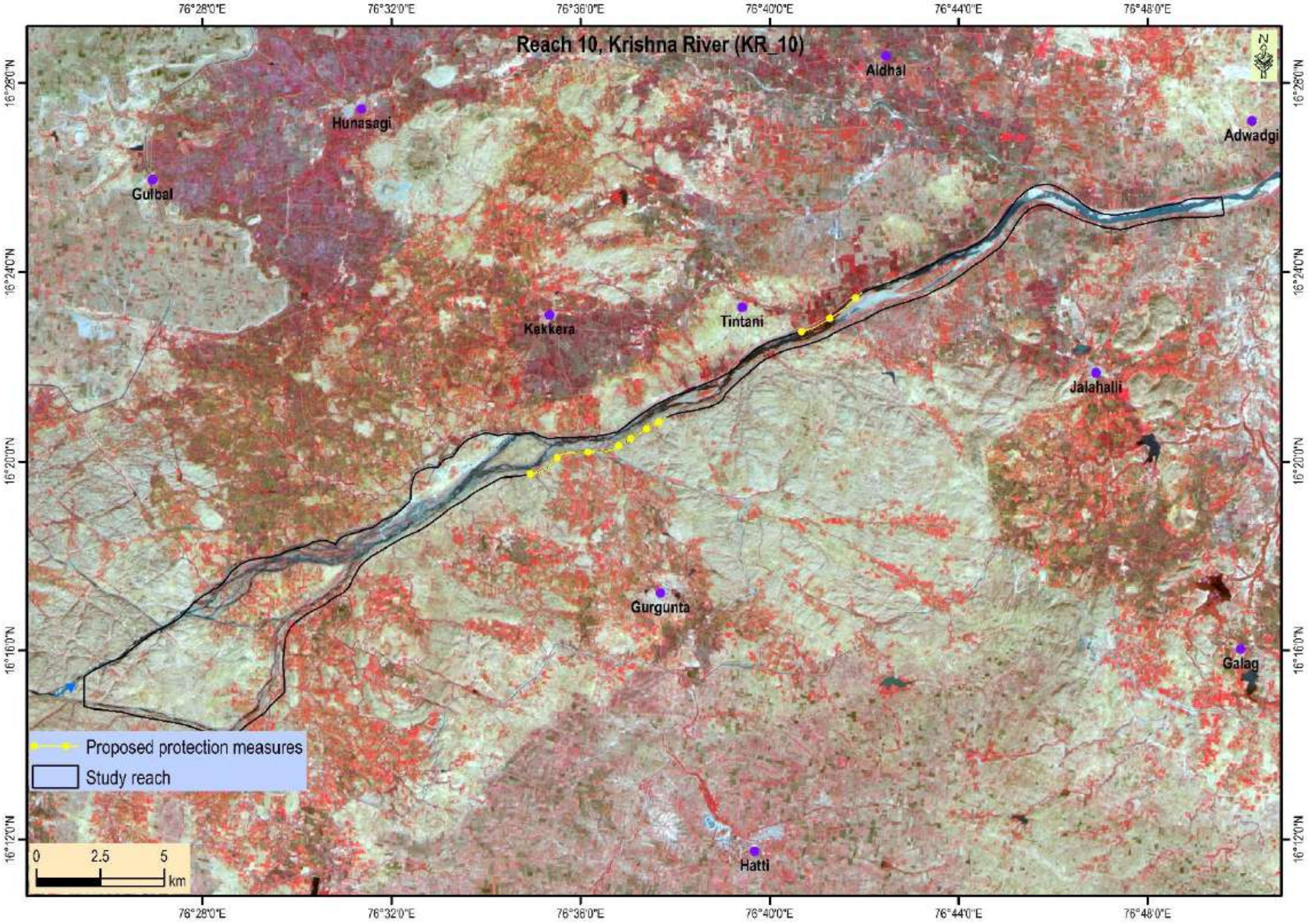

Fig. 105: Sections in the reach to be protected by various protection measures, KR_10, Krishna River

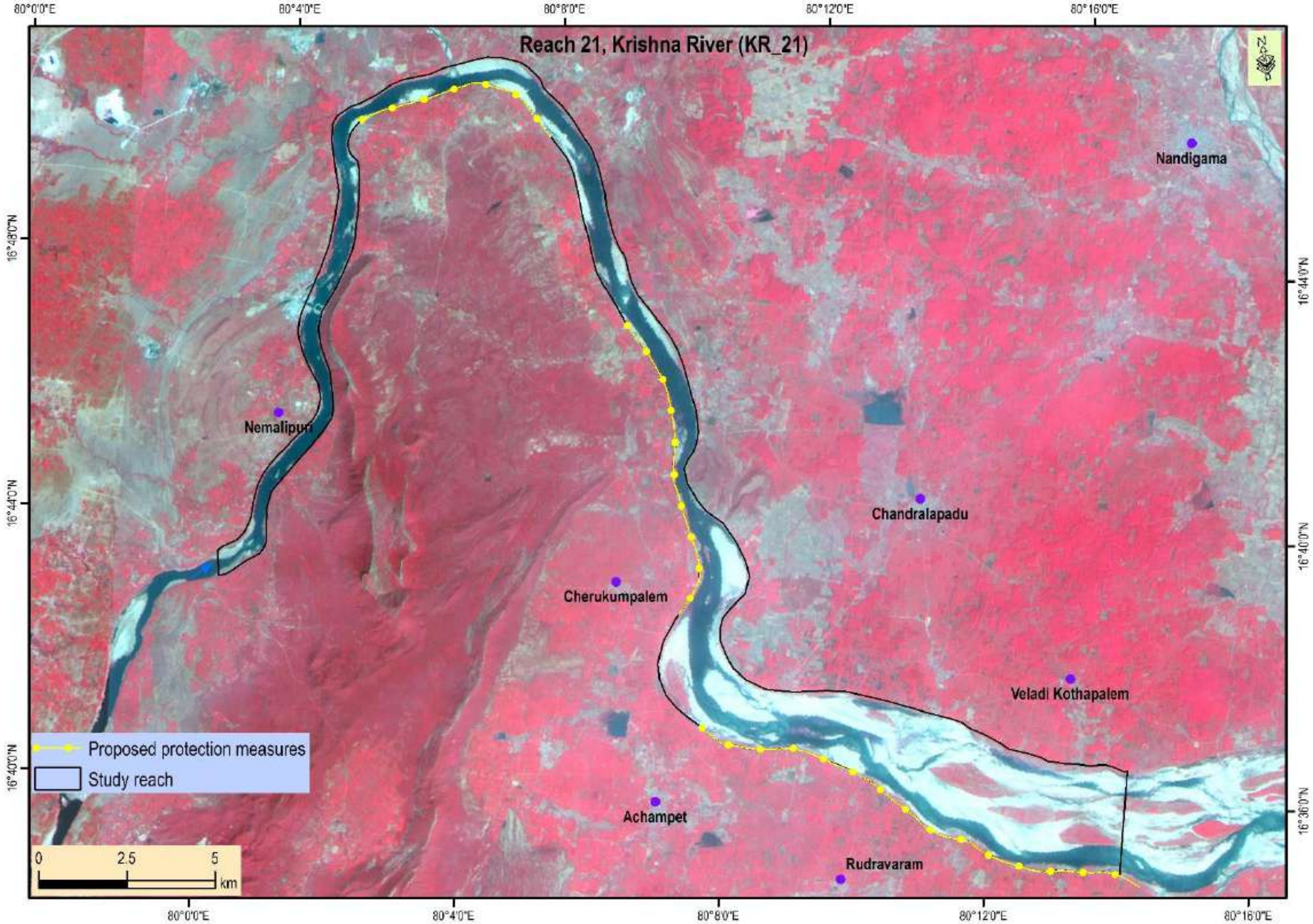

Fig. 106: Sections in the reach to be protected by various protection measures, KR_21, Krishna River

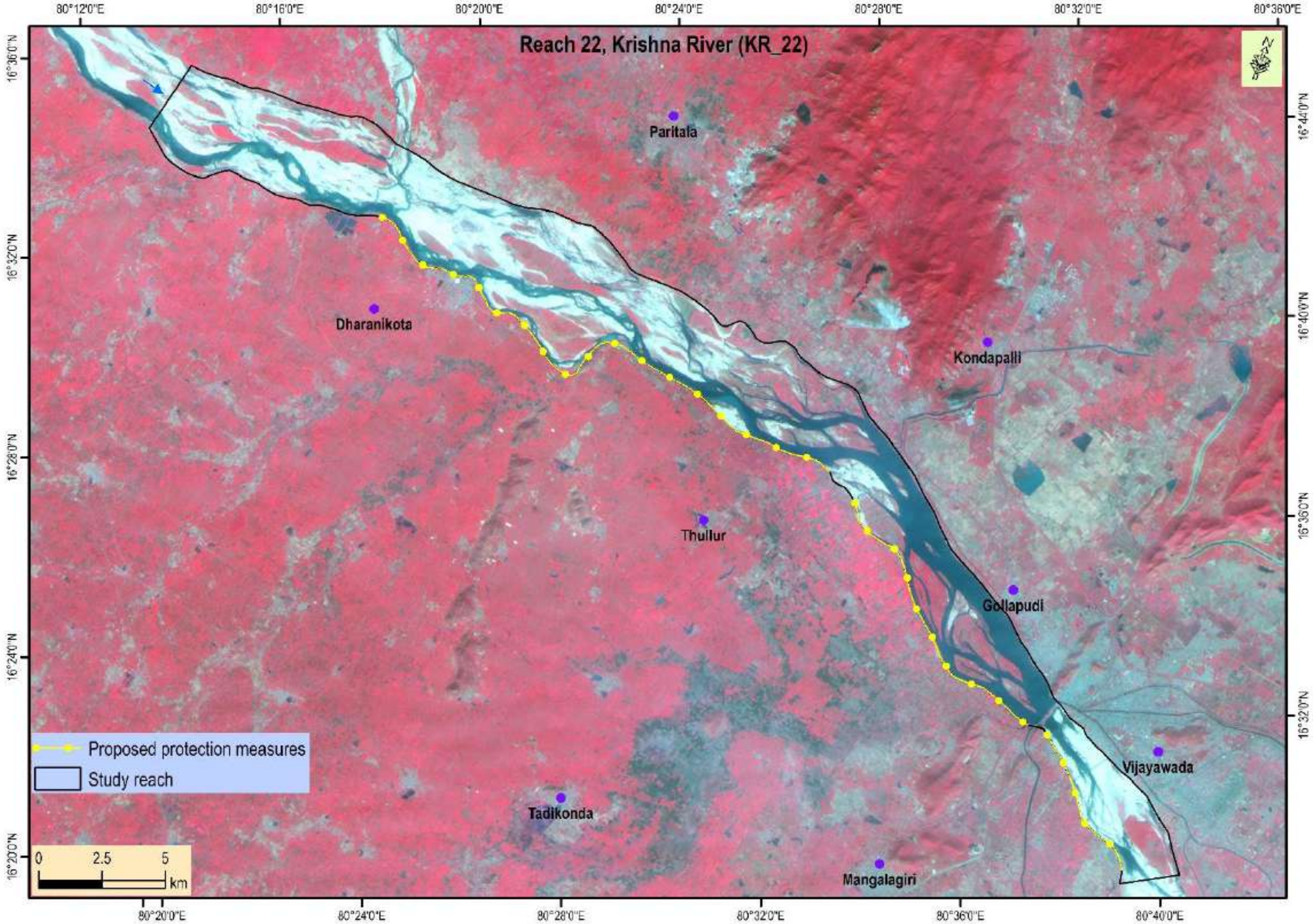

Fig. 107: Sections in the reach to be protected by various protection measures, KR_22, Krishna River

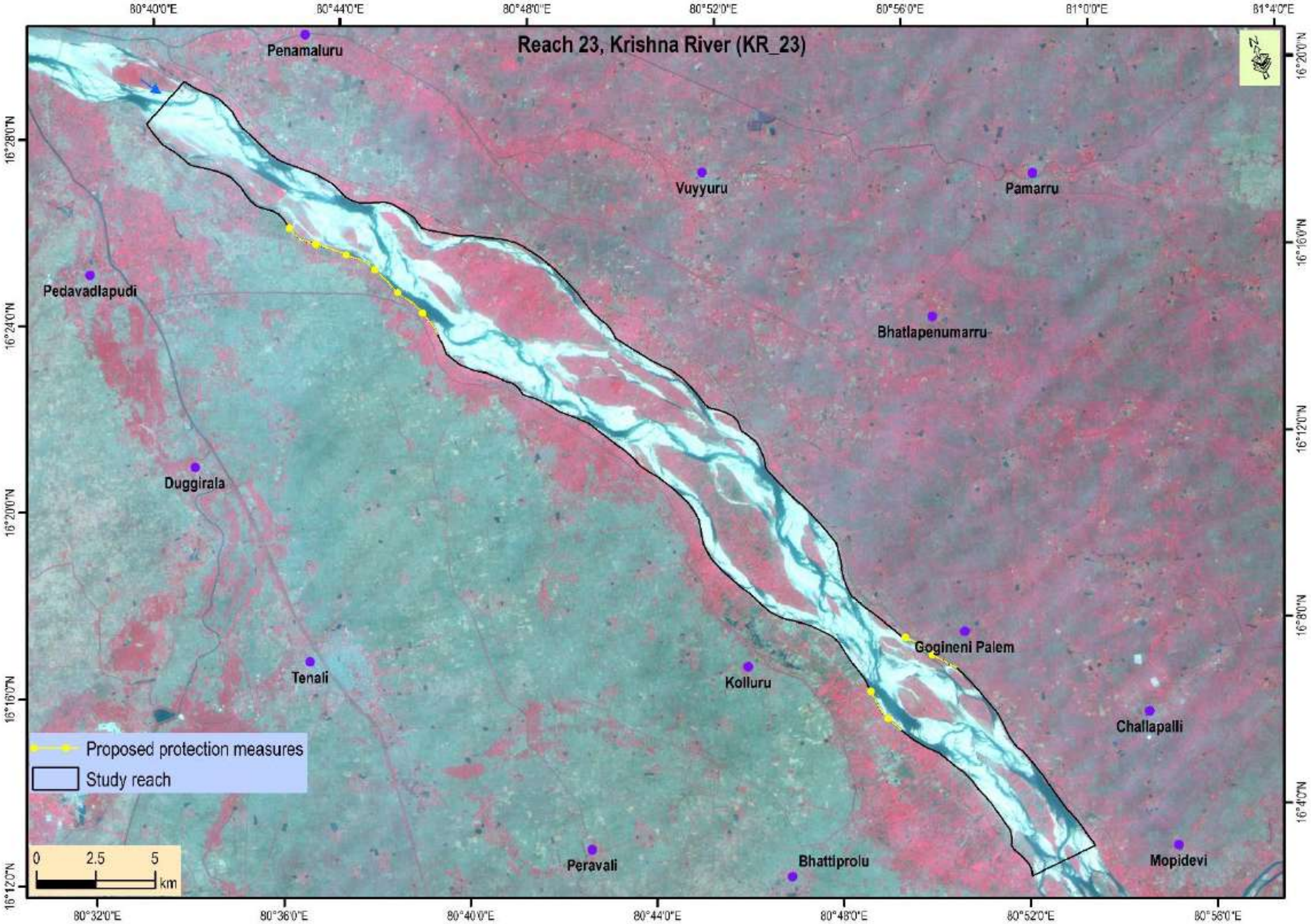

Fig. 108: Sections in the reach to be protected by various protection measures, KR_23, Krishna River

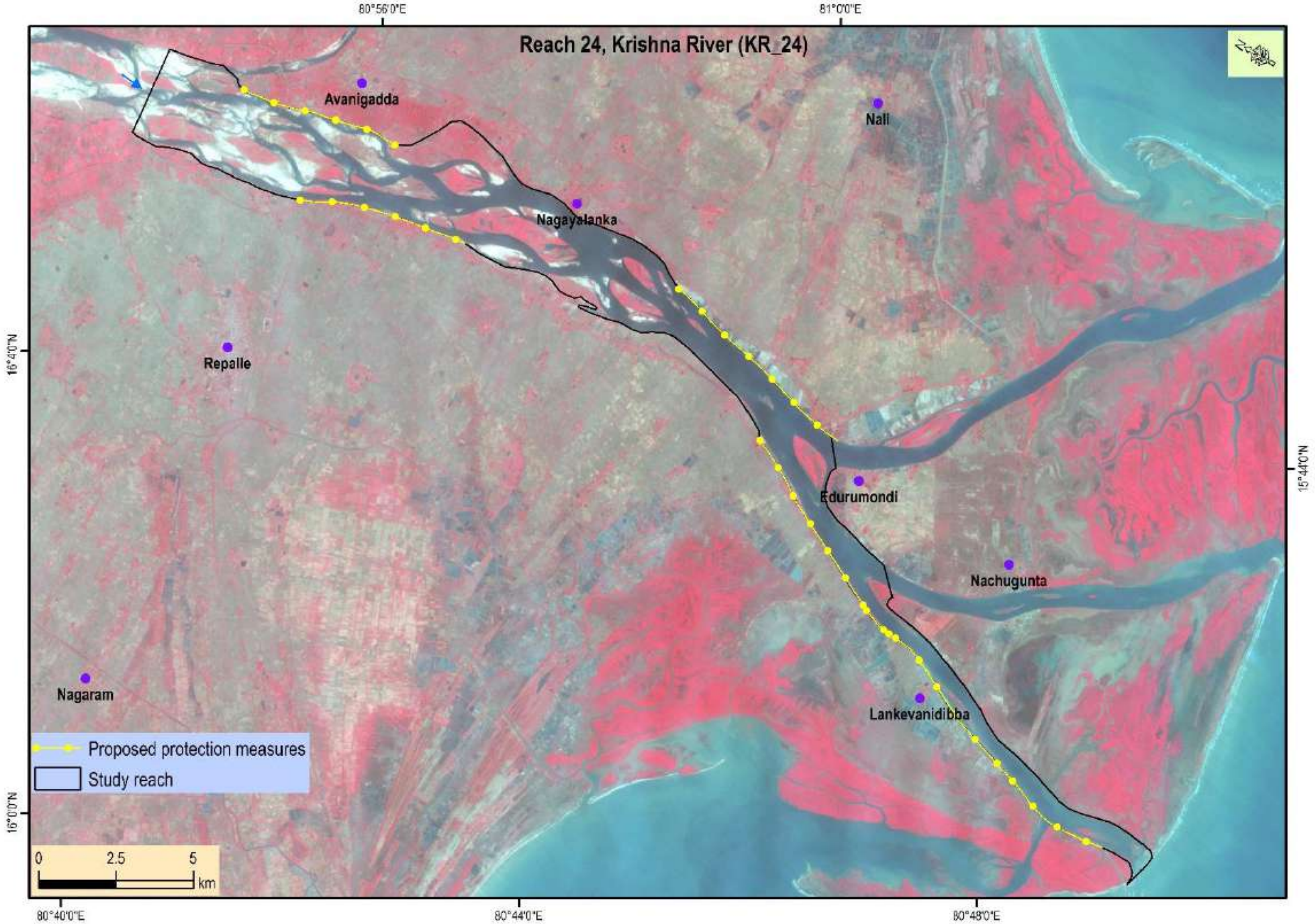

Fig. 109: Sections in the reach to be protected by various protection measures, KR_24, Krishna River

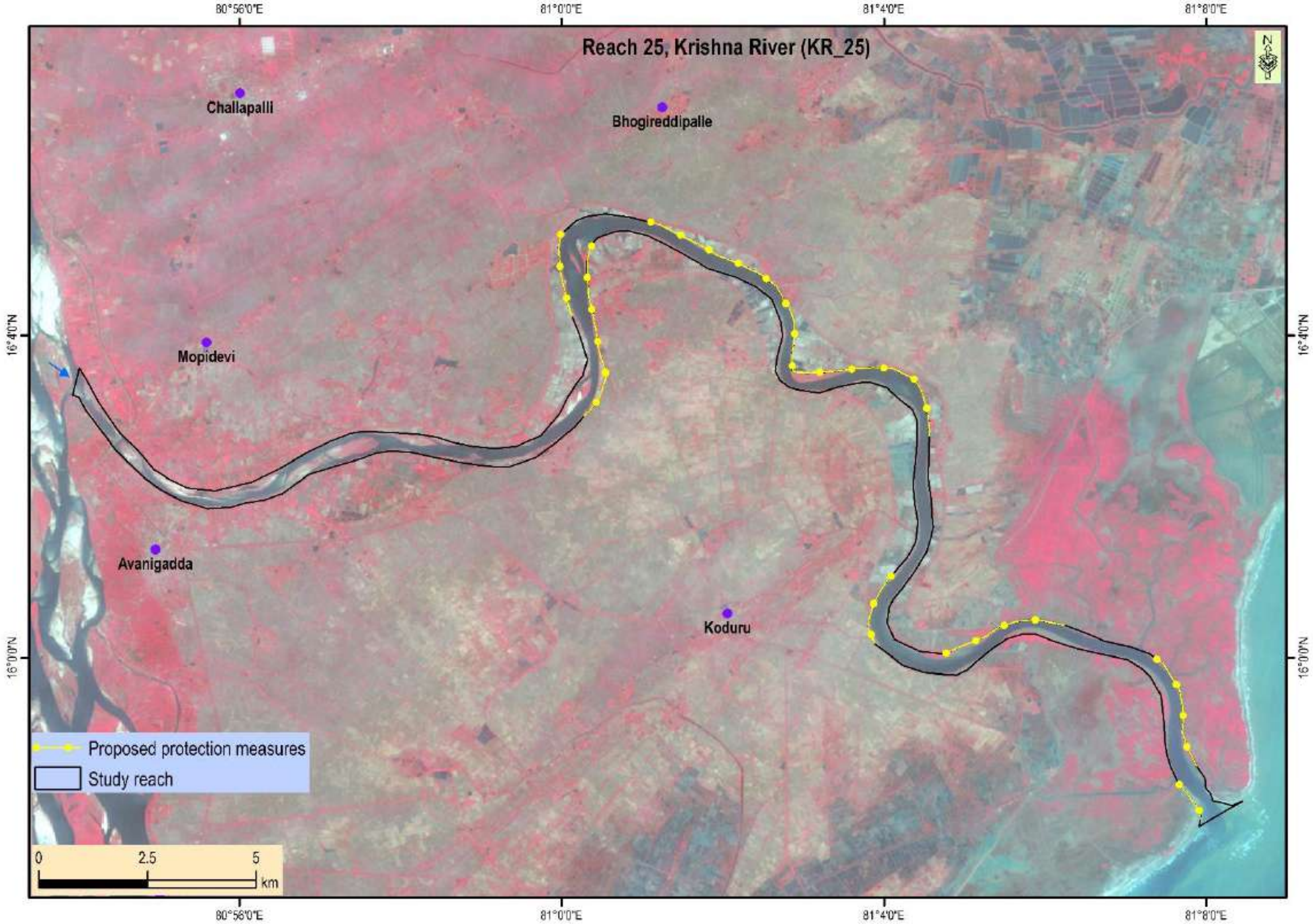

Fig. 110: Sections in the reach to be protected by various protection measures, KR_25, Krishna River

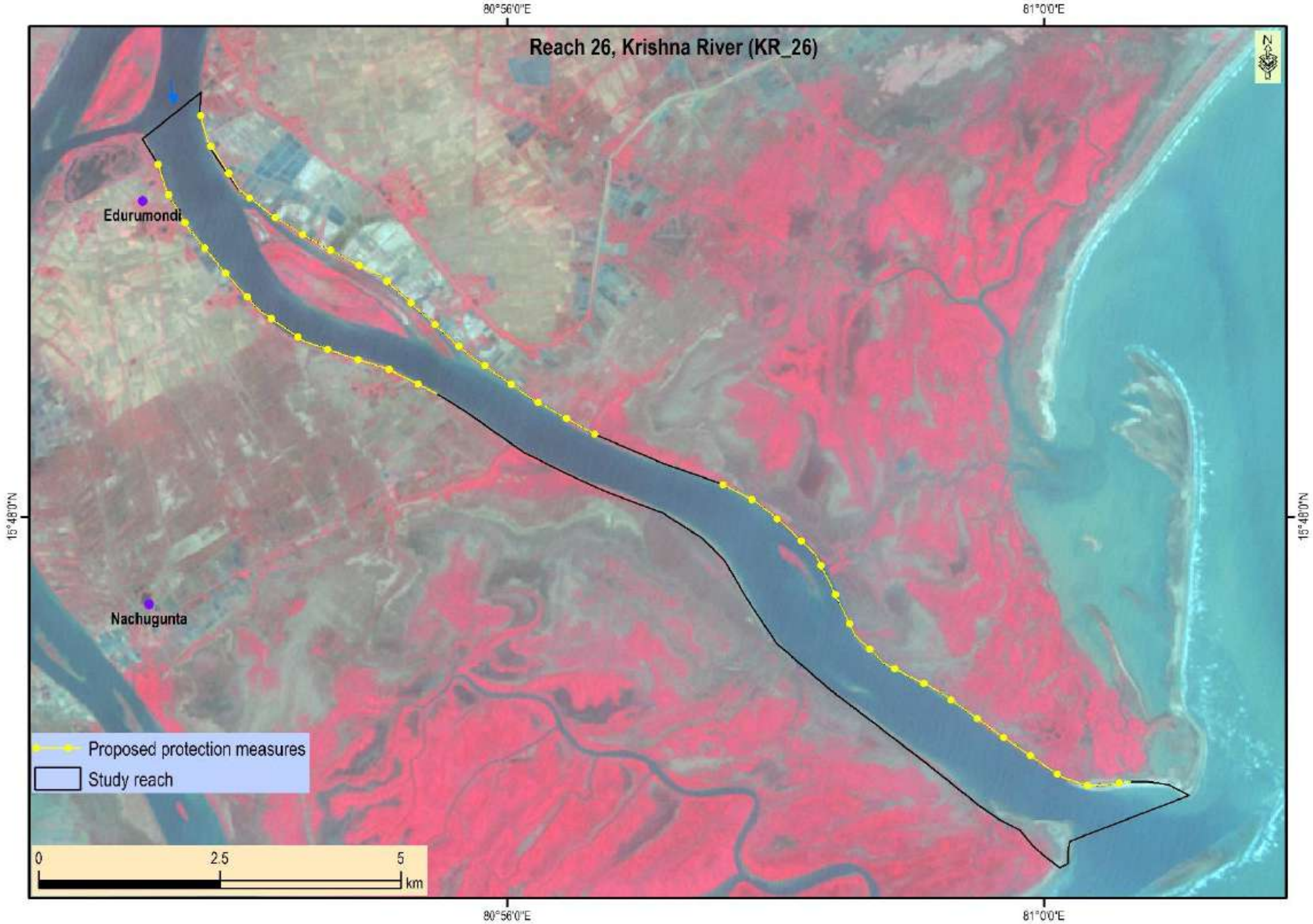

Fig. 111: Sections in the reach to be protected by various protection measures, KR_26, Krishna River

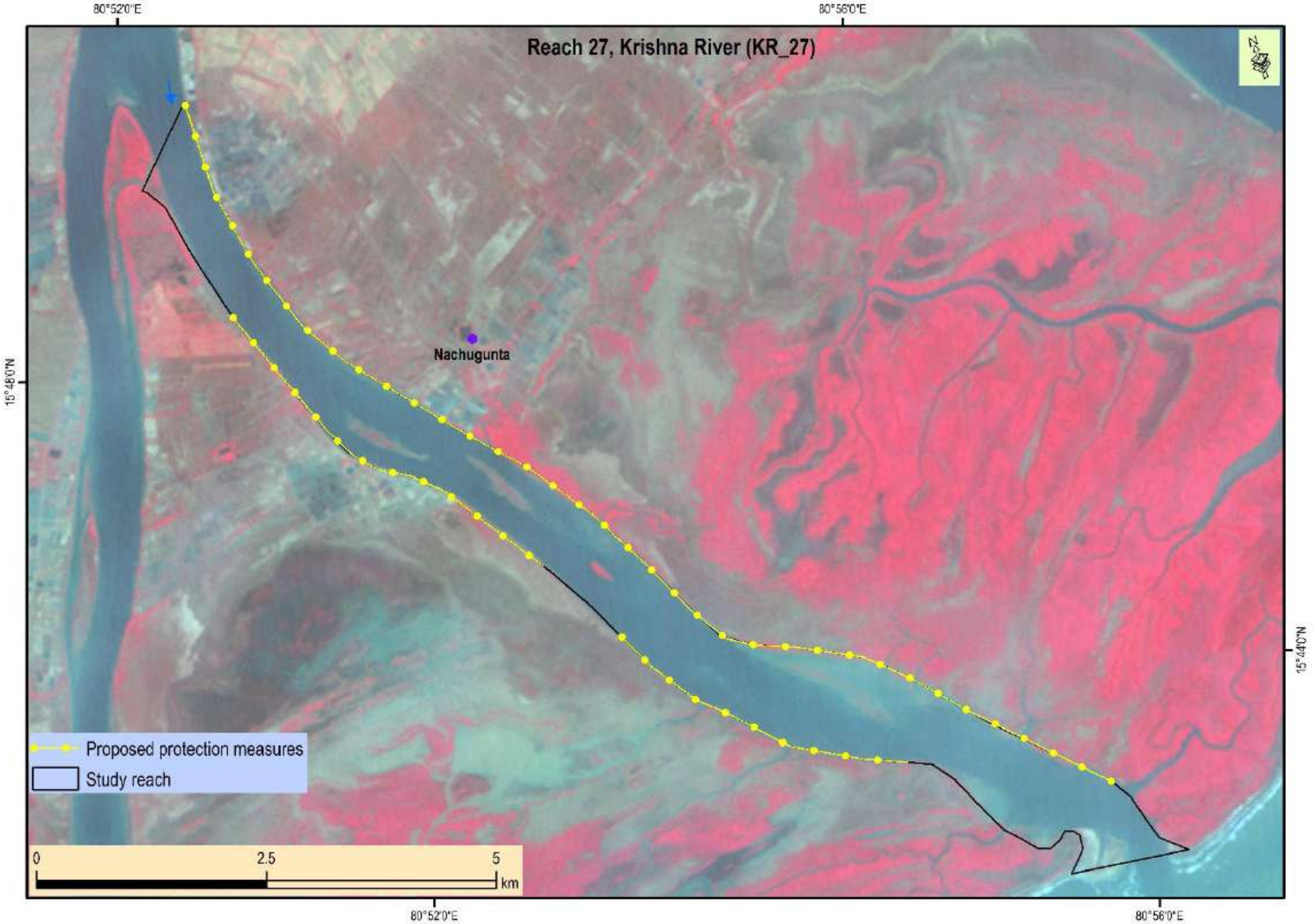

Fig. 112: Sections in the reach to be protected by various protection measures, KR_27, Krishna River

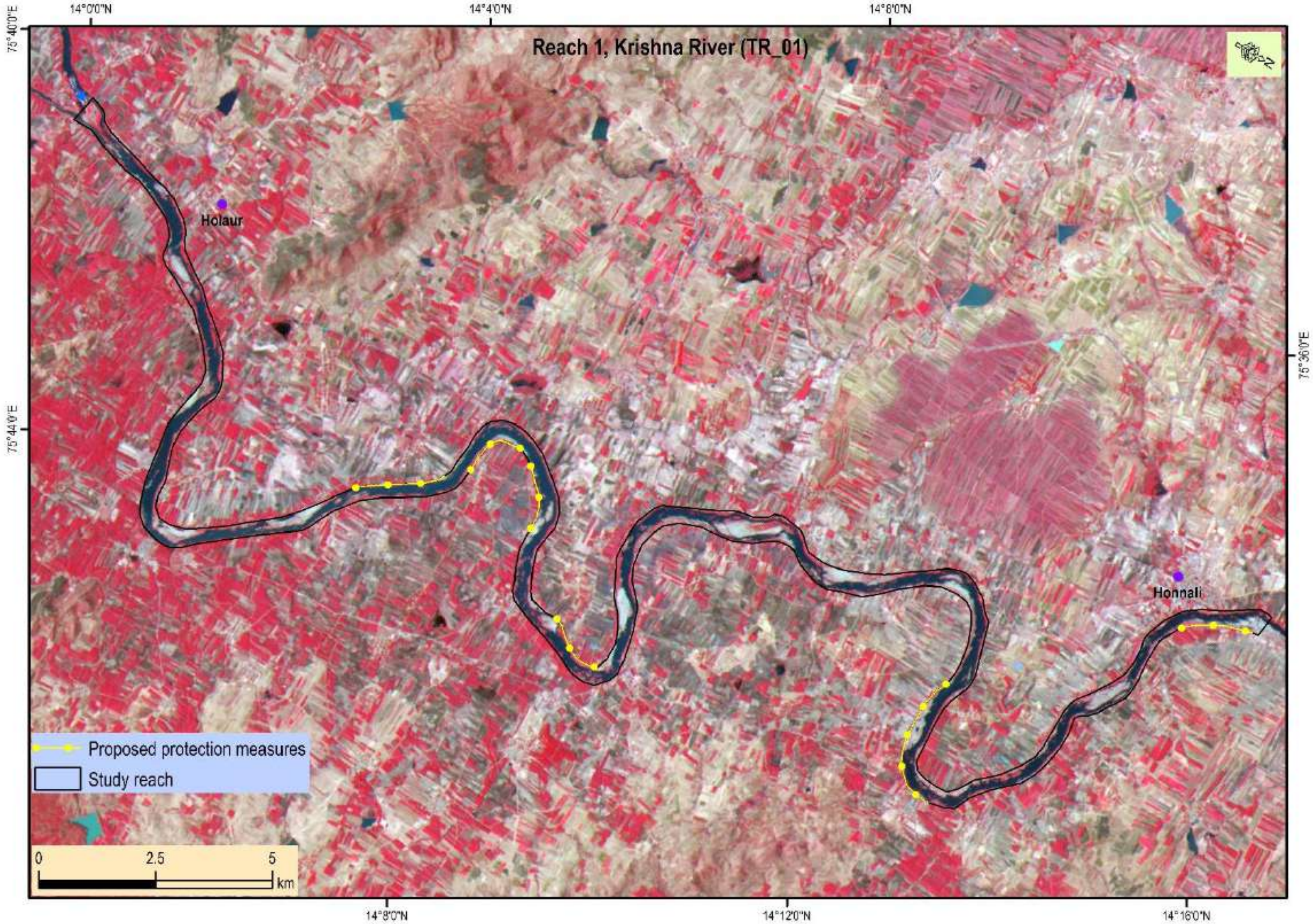

Fig. 113: Sections in the reach to be protected by various protection measures, TR_01, Tungabhadra River

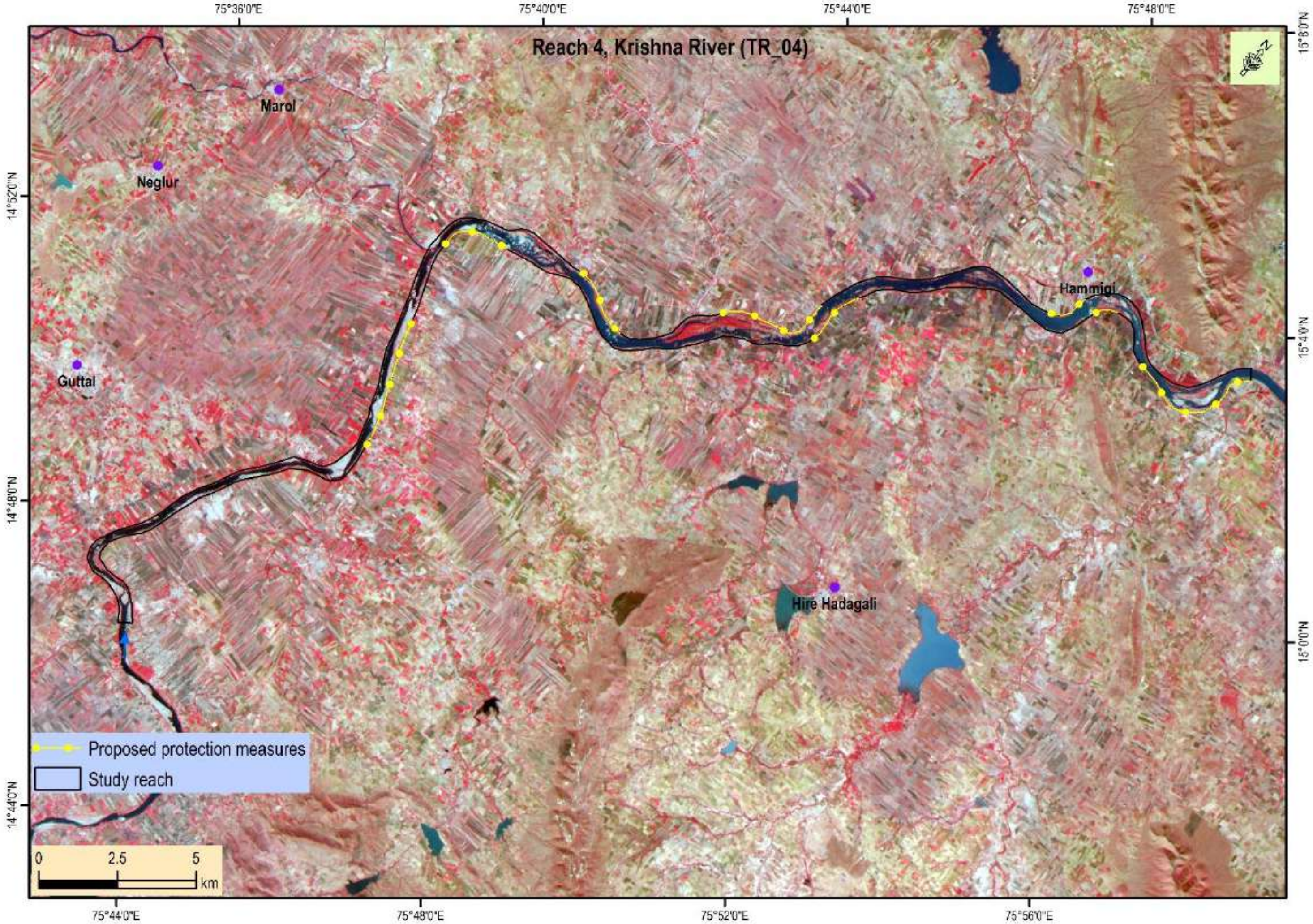

Fig. 114: Sections in the reach to be protected by various protection measures, TR_04, Tungabhadra River

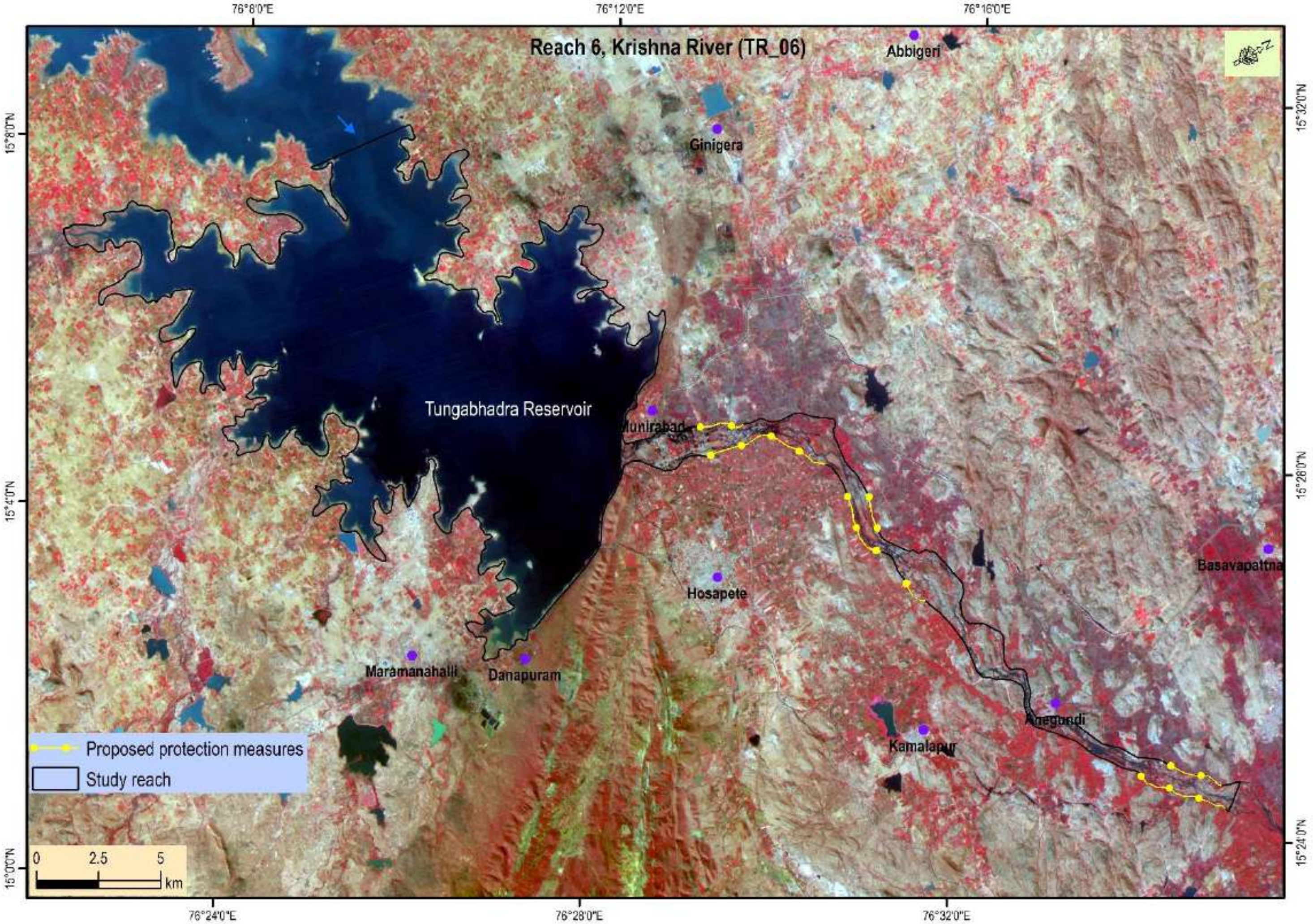

Fig. 115: Sections in the reach to be protected by various protection measures, TR_06, Tungabhadra River

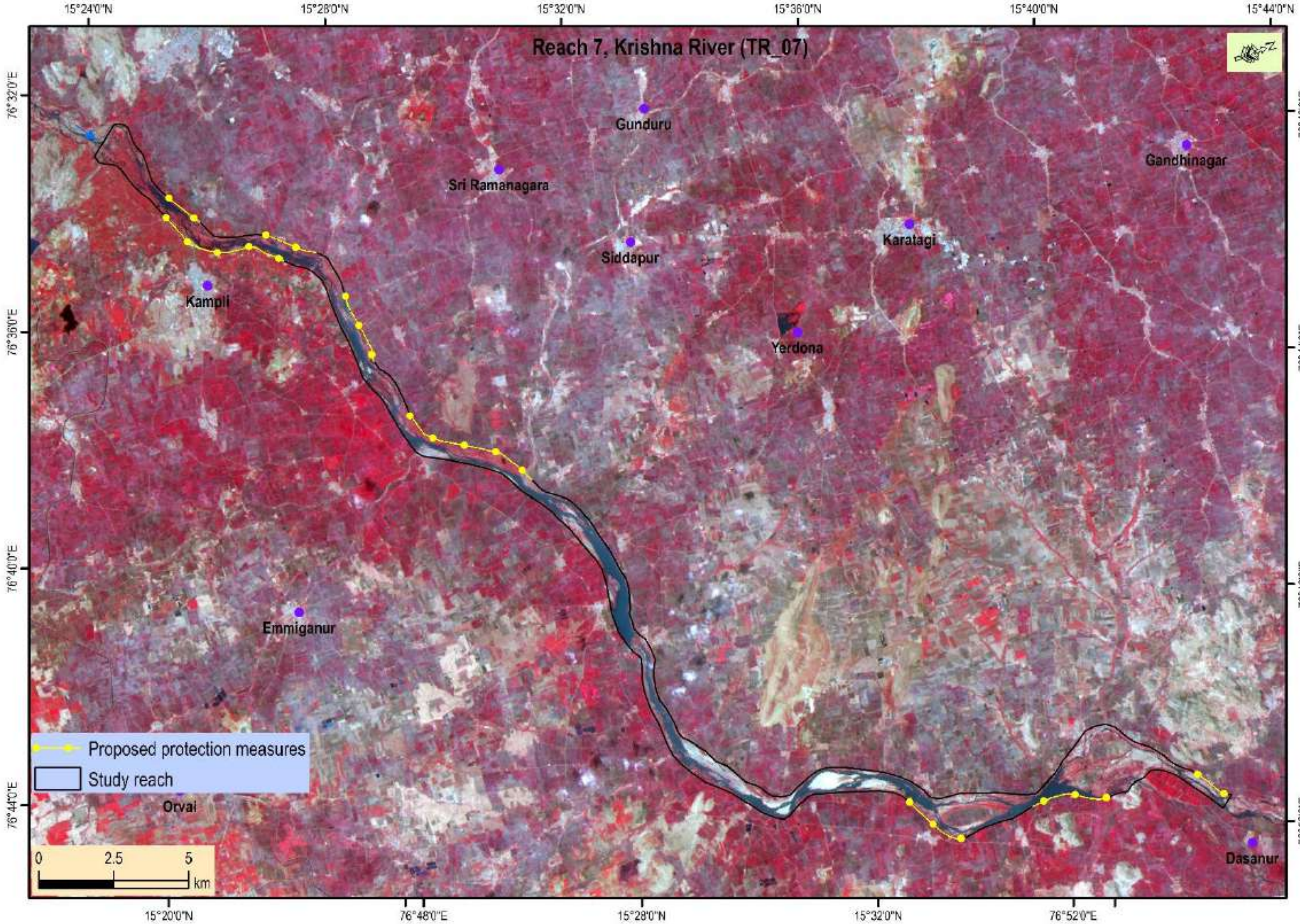

Fig. 116: Sections in the reach to be protected by various protection measures, TR_07, Tungabhadra River

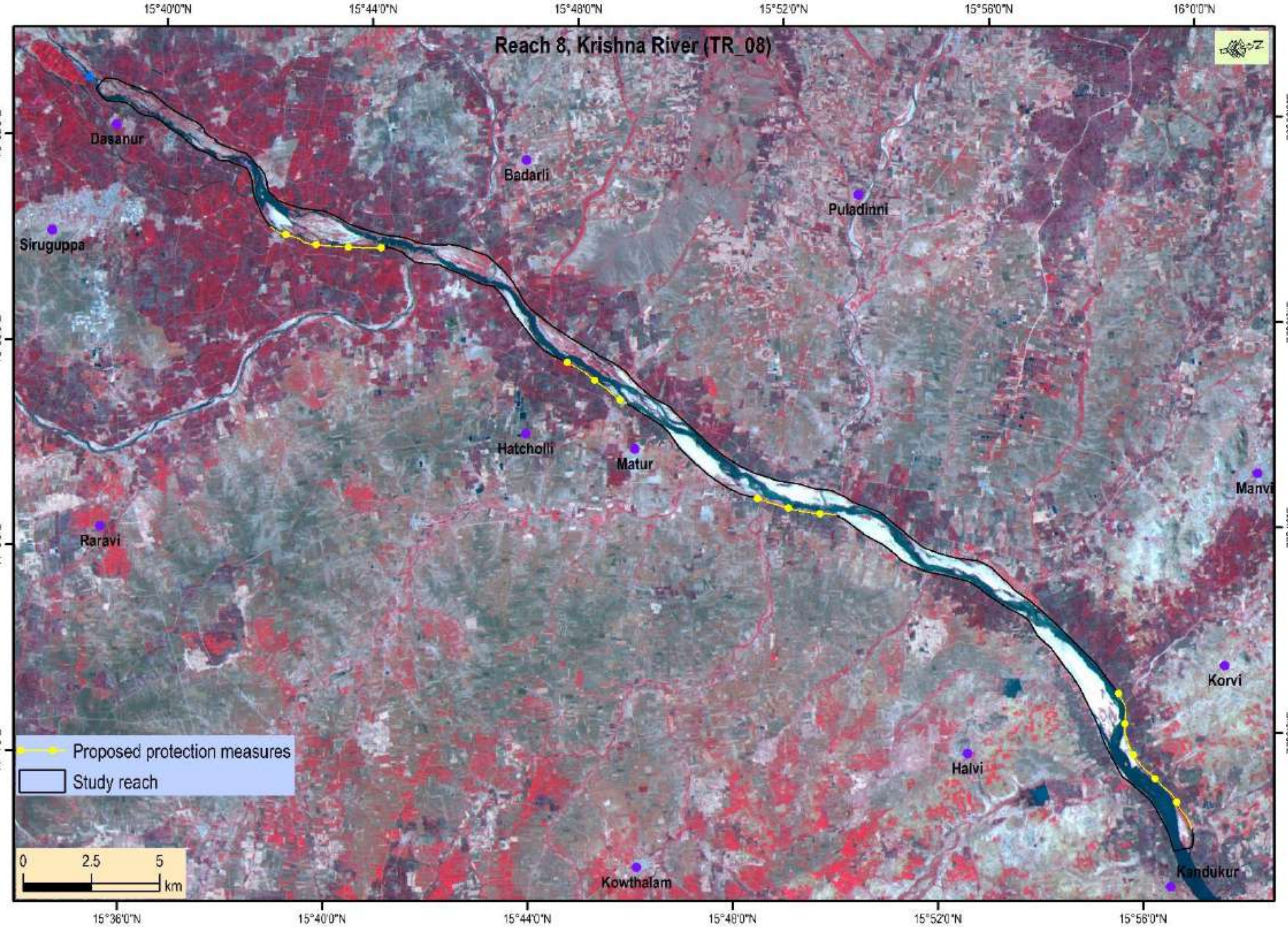

Fig. 117: Sections in the reach to be protected by various protection measures, TR_08, Tungabhadra River

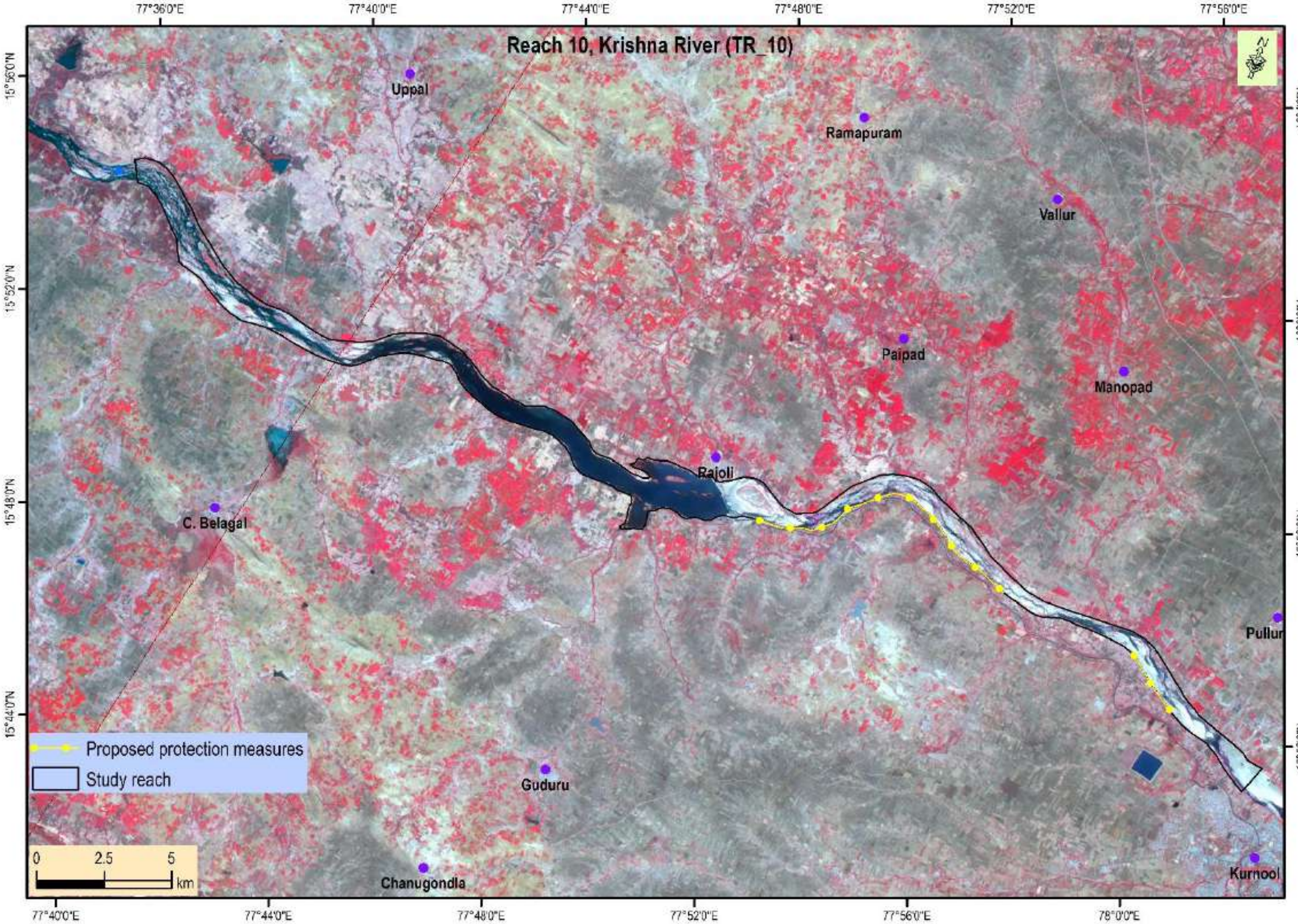

Fig. 118: Sections in the reach to be protected by various protection measures, TR_10, Tungabhadra River

SECTION 13
FLOOD AFFECTED AREAS

13.1. Historical floods

The major causative factors of floods in Indian rivers are varying, which include heavy monsoon rains and cloudbursts, cyclonic disturbances, snow or glacier ice melting as well as the failure of dams. Among these factors, floods in the peninsular rivers are associated with active monsoon conditions over the Western Ghats and/or tropical cyclones originating over the Bay of Bengal and the Arabian Sea. Since the precipitation over the northern part of the Indian Peninsula is strongly concentrated in the summer monsoon season, the rivers in this part have a seasonal discharge related to the monsoon (Kale et al., 1997).

The KRB has witnessed high rainfall and consequent floods of various intensities during the last many years, and are recorded in many of the H.O. stations (Appendix XII). Floods in the KRB are related to high-intensity rainfall and/or releases of water from reservoirs in the upper reaches. This basin has also experienced altered rainfall pattern during the last few years which was evident due to the occurrence of droughts followed up by the incidences of flooding in recent years. The flooding situation becomes exacerbated because of obstructions to flow, sediment deposition along the river bed and bed aggradation. According to NRAA (2011), the major recorded flood events in the KRB occurred in 1903, 1913, 2005, 2006 and 2009.

In the year 1903, flood discharge recorded at the Prakasam barrage was 1.08 million cusecs (30,578 $m^3 s^{-1}$), whereas the flood event in 1913 was exceptionally high in the basin. Markings corresponding to this flood level are seen on ghats on the banks of Krishna River at Kurundwad. The high flood levels during the recent major events during 2005 and 2006 were lower than these marks. The 2005 and 2006 flood events occurred in the upper Krishna basin, and the flood discharge of 2005 event recorded at K2 and K7 were 9,381 and 10,236 $m^3 s^{-1}$ respectively, and that recorded at B6 was 8299 $m^3 s^{-1}$, whereas the flood discharge of the 2006 event recorded at K2 and K7 were 7,505 and 9,193 $m^3 s^{-1}$ respectively. Further, the flood discharge of the 2006 event at B4 and B6 were 7,672 and 9,807 $m^3 s^{-1}$ (NRAA, 2011).

The flood discharge during October 2009 exceeded the record in 1903 and is about 1.10 million cusecs (31,144 $m^3 s^{-1}$). The Srisailam dam is designed for a thousand-year return flood of 20.20 lakh cusecs and for discharge of 11.1 lakh cusecs at FRL +885 ft and 13.2 lakh cusecs at MWL 892 ft including the power draft, while the flood received peaked to 25.40 lakh cusecs. The previous maximum flood received at Srisailam was 9.11 lakh cusecs. The flood resulted in building up of water at the Srisailam dam to a level of +896.5 ft. which is above the maximum water level (MWL) of +892 ft. Similar to Srisailam, Nagarjuna Sagar dam which is designed for 15.9 lakh cusecs discharge at MWL and Prakasam barrage which is designed for 11.9 lakh cusecs also exceeded its maximum capacity for the first time in the history (Source: APWRDC).

13.2. Flood affected areas

According to the estimates of NRAA (2011), the total flood-prone area in the basin is estimated as 5500 km^2. The flood affected areas during 2005 and 2006 flood events, as well as 2009 flood, is shown in Fig. 119. Some of the reaches and nearby areas are highly prone to flooding due to the characteristically lower slope and typical valley configuration as well as the hydraulic structures downstream. The catchment area of Panchganga and Dhoodhganaga are highly prone to flooding. The neighborhood of Sangli (upstream of the confluence of Panchaganga with Krishna) is one such area, where the bed slope becomes flatter i.e. from 1:5000 to 1:13000. The 60 km stretch along the river course from Audumber to Maharashtra-Karnataka border is also subjected to frequent flooding. Similarly, the areas below Bhima-Nira confluence up to the State border (Pandharpur, Gopalpur, and Takali) also face frequent flooding. The downstream of Alamatti and Narayanpura projects is also highly vulnerable to flooding. However, in 2009, the backwater of Srisailam crossed the maximum water level and gushed into Kurnool town and surrounding villages. Further, the 2009 event submerged most of the river reaches (except the incised segments) and adjacent areas in the midstream and downstream reaches of Krishna as well as downstream reaches of Tungabhadra River.

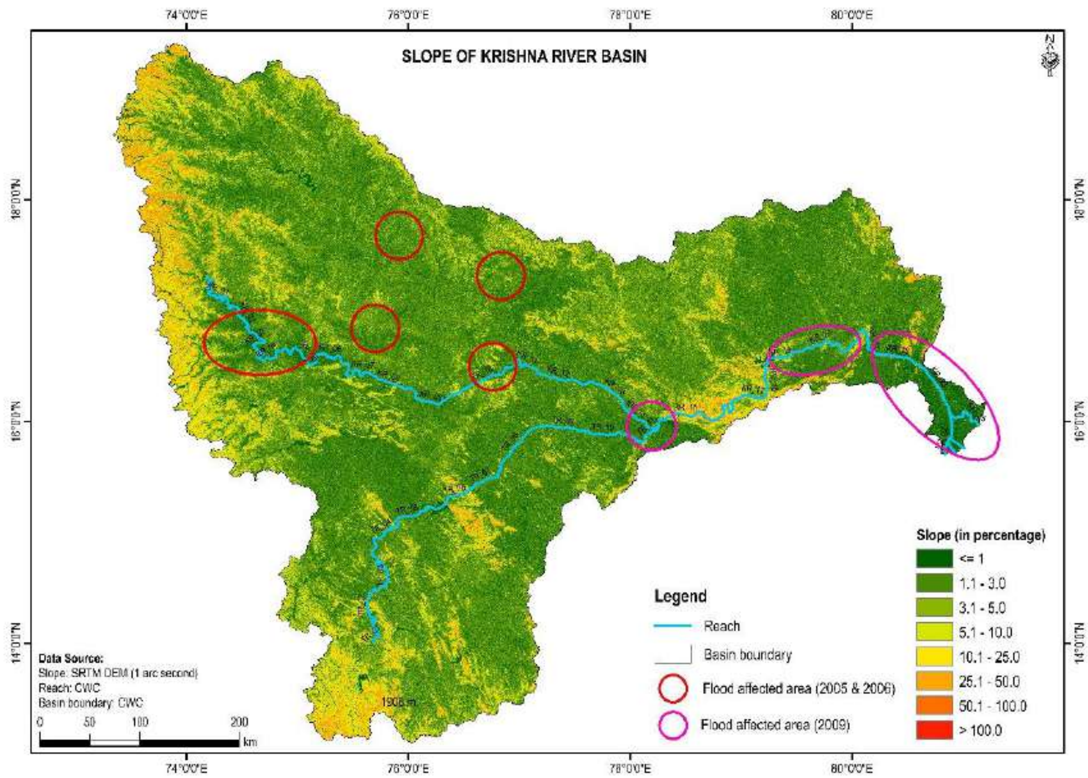

Fig. 119: Slope map of KRB. The flood affected areas of 2005, 2006 and 2009 flood events are also marked.

13.3. Impacts of floods

Even though flood events have serious negative implications in the context of river morphology as well as socio-economic aspects, they have several positive impacts on the natural resources (e.g., increase in groundwater potential) of the basin. During 2005 and 2006 floods, a large number of villages in the districts of Kolhapur, Sangli, Belgaum, Bijapur, and Gulbarga, and to a lesser extent Sholapur and Raichur were inundated and agricultural fields submerged. According to the official figures, these floods claimed 110 human lives, affected 1250 villages (150 of which were fully submerged), damaged 25 lakh houses and destroyed crops and property worth Rs.590 crores. Standing crops of sugarcane, maize, turmeric, banana and sunflower in about 100,000 ha valued at Rs.142.39 crores, were ravaged. During October 2009, heavy floods exceeding the record of once in 100 years were witnessed in the basin, temporally isolating 350 villages. The Kurnool city was submerged with 3-4 m deep water for nearly 3 days. Further, the flood-affected 87 mandals in Kurnool, Mahbubnagar, Krishna, Guntur, and Nalgonda districts of Andhra Pradesh. The flood-prone agriculture area in Sangli and Kolhapur district is submerged for more than two weeks. Flooding has also resulted in the physical changes in the river and the river banks, including bank erosion, breach of levees, causing the removal of vegetation and subsequent impacts on the soil and vegetation of the flood-affected areas.

SECTION 14
RESULTS AND RECOMMENDATIONS

River channel morphology is a function of the water and sediment discharges, and hence, the mechanisms controlling water and sediment discharges, such as the construction of hydraulic structures, modification of land use/land cover pattern of the catchment as well as climate change have crucial significance in the alteration of river morphology. Hence, the changes in channel morphology of Krishna and Tungabhadra rivers across different periods (1973-2011) were assessed using remote sensing techniques to understand the environmental changes responsible for the changes of the river morphology, which in turn helpful for developing sustainable river management plans as well as restoration of the degraded reaches. The study was performed on 27 reaches of Krishna (KR_01 to KR_27) and 11 reaches of Tungabhadra rivers (TR_01 to TR_11), and the key findings of the study are as follows:

- The streamflow of the basins is heavily regulated in that the basin accommodates roughly 855, which includes 660 dams, 12 barrages, 58 weirs, 6 anicuts, and 119 lifts to meet the demands from the domestic, irrigation, agriculture, and hydropower sectors.
- Croplands are the dominant land use/ land cover of the basin, which accounts for more than 80% of the basin area.
- The impact of the human-made interventions in the KRB on the river morphology was evident from the hydrological analysis. In general, the discharge from the KRB significantly reduced after the 1960's and similarly sediment discharge in the downstream of the river decreases plausibly sue to the construction of dams and reservoirs in the upstream reaches. No flow conditions were also observed in some of the intermittent streams after the construction of dams. The flow duration curves indicated a change in low-flow and high flow regimes as the time progressed. In most of the reaches, the flow duration curve was flat in both high flows as well as in low flows indicating highly regulated flows in the KRB.
- Mean width of the reaches of both Krishna and Tungabhadra rivers increases towards downstream as a result of the increasing discharges, except in a few reaches, where valley geomorphology plays a significant role.
- Temporal variability in the width of the river reaches shows hardly any significant differences in both Krishna and Tungabhadra rivers. Further, the temporal variability of the PFI values of the downstream reaches indicates little changes in the braiding intensity and pattern.
- The total bank erosion of both the banks occurred in the study reaches of Krishna River during the entire period (i.e., 1973-2011) is 47.5 km^2, where the erosion area along the left bank is 21.9 km^2 and that of the right bank is 25.6 km^2. The total area of erosion along both the banks of the study reaches

of Tungabhadra River during the period is 14.7 km^2, where the total area of erosion along the left bank is 5.0 km^2, and the total area of erosion along the right bank is 9.7 km^2.

- The erosion of the banks shows significant variability across the reaches as well as across the time periods in both Krishna and Tungabhadra rivers.
- In general, erosion of both the banks of the reaches of Krishna are almost same, with the exceptions of a few reaches and during 1991-2001, whereas in Tungabhadra, the erosion more severe in the right bank of the reaches, compared to the left bank during all the time periods, except during 2001-2011.
- The bank erosion/deposition pattern of the reaches of the Krishna River indicates that the downstream reaches exhibit a higher rate of erosion as well as deposition across the time periods. However, the study reaches of Tungabhadra River shows relatively high rates of deposition, compared to the erosion rates, during all the assessment periods, except 2001-2011.
- Based on the temporal changes in the channel planform as well as the rate of erosion along the banks during the different short-term as well as long-term assessment periods, 12 critical reaches were identified in Krishna (KR_01, KR_04, KR_05, KR_06, KR_10, KR_21, KR_22, KR_23, KR_24, KR_25, KR_26 and KR_27) and 6 in Tungabhadra (TR_01, TR_04, TR_06, TR_07, TR_08 and TR_10).
- Even though the flow of the rivers are regulated, the effects of recent floods (during 2001-2010) on channel morphology are evident (e.g., extensive bank erosion and channel widening as well as redistribution and deposition of coarse sediments within the channel and along the banks) in many of the river reaches.
- The hydraulic structures in the rivers exert significant control on the modification of channel morphology as the channel segment immediate downstream of the reservoirs show high erosion rates on both the banks, compared to other parts of the reaches.
- A few reaches in Krishna and Tungabhadra rivers and nearby areas are highly prone to flooding due to the characteristically lower slope and typical valley configuration as well as the hydraulic structures downstream.

Based on the estimates of the mean width of erosion and deposition of the left and right banks, the net shift in the course of the study reaches of Krishna and Tungabhadra rivers were estimated (Tables 47 and 48). Tables 47 and 48 evidently indicate the vulnerability of the critical reaches of Krishna and Tungabhadra rivers with respect to the shifting of river channel bank lines across the study period. The scale of data capture is a major issue that seriously affects delineation of channel boundary while using multi-temporal remote sensing data, and hence, inaccuracies pertaining to the scale of the data are included in the decadal shift estimates.

Table 47: Decadal shift (in m) in study reaches with respect to the base year, Krishna River

Reach-ID	1973-1977		1977-1991		1991-2001		2001-2011		1973-2011	
	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank
KR_01	-6.4	0.6	-6.4	-2.9	-2.4	5.6	0.7	-1.9	-14.6	1.5
KR_02	-2.7	-1.4	1.8	7.1	-1.4	7.5	-1	-6.2	-3.3	7.1
KR_03	-1.4	-0.2	3.4	-2.8	-1.1	7	-2.4	0.4	-1.4	4.3
KR_04	-6.1	0	-6.6	27.1	-7.5	-4.3	-9.6	-3.2	-30	19.7
KR_05	1.1	-9.8	-2.9	18.4	2.2	-5	-37.2	-28.5	-36.8	-24.9
KR_06	7.3	4.7	-12.5	42.7	10.7	11	-22.9	-30	-17.5	28.6
KR_07	-22.8	6.4	-9.7	28.5	0	4	-3.8	-4	-2	0.8
KR_08	-11.5	22	-7.6	6.4	-6.6	-24.2	9.7	-8.9	-3.7	-30.3
KR_09	-16.8	11.6	2.6	1.8	0	-5.1	1.2	2.4	0.5	3.6
KR_10	-10	10.9	5.6	2.4	2.4	-6.7	-0.8	-12.7	-2.8	-6
KR_11	2.4	17.7	12.5	-5.7	-12.3	-11.5	-0.1	8.4	2.5	8.8
KR_12	6.4	13.3	22.1	-8	-1.9	7.2	-1	7.1	25.6	20.3
KR_13	0.2	0.2	15	-22.6	-6.1	4.1	-14.2	-8.3	-0.3	-19.4
KR_14	3.8	12.3	-0.5	-6.1	-3.1	2.1	-1.3	-1.8	3.9	-6.4
KR_15	9.9	15	0	0	0	0	0	0	0	0
KR_16	-9.5	4.1	0	0	0	0	0	0	0	0
KR_17	-8.1	-4.2	-5.9	-1.9	5.6	0.6	-8.2	-4.7	-15	-11.7
KR_18	0	0	0	0	0	0	0	0	0	0
KR_19	-0.1	-10.5	5.6	-3.4	14.8	9.2	-4.2	-16.2	16.1	-20.8
KR_20	19	-5.8	14.4	18.2	13.2	11.4	-8	-16.5	38.6	7.2
KR_21	14.7	-9.7	38	-29.2	20.6	13.3	-21.4	-19.3	51.7	-45
KR_22	27.3	-20.2	77.7	-47.1	16.9	29.2	-12.1	-22.8	109.8	-60.7

Reach-ID	1973-1977		1977-1991		1991-2001		2001-2011		1973-2011	
	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank
KR_23	-23.4	-31.9	39.9	14.2	20.5	19.4	-16.1	-10.2	21.1	-8.4
KR_24	2.3	-16.1	-3.2	-15.5	-6.3	-4.9	-7.4	-1	-23.9	-29.6
KR_25	-5.6	-7.3	-11.8	14.1	6.7	6.5	-9.6	-4.1	-19	6.8
KR_26	19.1	-17.2	-60.5	28.1	-46.1	18.7	1.8	-2	-97.4	20.1
KR_27	44	-60.7	-116.2	29.3	-53.6	21	13.2	-9.6	-97.4	-25.5

*Negative values indicate shift due to bank erosion, whereas positive values denote shift due to deposition

Table 48: Decadal shift (in m) in study reaches with respect to the base year, Tungabhadra River

Reach-ID	1973-1977		1977-1991		1991-2001		2001-2011		1973-2011	
	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank
TR_01	14.8	6.7	-1.8	7.9	9.6	3.3	-1.6	-1.8	21	16.1
TR_02	5	7.3	14.1	0.4	21.4	-2.3	-0.1	-4	40.3	1.4
TR_03	-9.1	13.4	30.6	4.3	16.6	0.8	2.2	-2.4	40.3	16.1
TR_04	18.4	-11.4	15.4	3.8	6.4	9.2	-3.8	-1	36.4	0.6
TR_05	-5.2	-1.5	7.1	-4.4	1.9	-2.2	-1.8	3.5	3.3	-6.8
TR_06	1.2	-17.1	14.1	0.7	11.9	-5.5	-8.8	1.5	18.4	-20.5
TR_07	13.7	1.8	11.2	3.9	-2.1	-2.3	-6.1	5.7	16.5	9.1
TR_08	7.7	-5.4	37.7	9.7	5.5	5.6	-12.3	0.7	38.7	10.8
TR_09	58.2	7.1	37.1	9.3	18.6	12.2	-3.6	0.4	110.2	29
TR_10	-3	-17.3	28.6	11.7	24.8	0.7	-31.7	-20.7	18.5	-25.6
TR_11	2.6	-2.3	-3.5	1.7	2.5	-1.6	3.4	-10.7	12.8	-22.3

*Negative values indicate shift due to bank erosion, whereas positive values denote shift due to deposition

In the context of the findings of the present study, the following recommendations are recorded for sustainable management of the river resources of KRB.

- The major changes to the fluvial system (especially in the critical reaches) of Krishna and Tungabhadra rivers are caused by river regulations, water abstractions, modifications of river morphology as well as floodplain structure, creating different kinds of pressures, which needs to be restored using suitable river training works.
- Even though critical reaches have been identified on the basis of the total area of erosion occurring along the reach, many of the reaches have highly localized erosion pockets, which also need to be considered.
- River restoration protocols need to be developed on the basis of a holistic approach, which needs to cover the full range of physical conditions, morphological types, the degree of artificial alterations, and amount of channel adjustments. This also enables to understand cause-effect relationships between hydromorphological and biological indicators.

Suggestions for future investigations

- A detailed flood modeling study has to be carried out to understand the impacts of floods on the bank erosion as well as to understand the inundation in the downstream reaches, especially in the context of the changing climate.
- Since floods impacted the morphology of the rivers, detailed studies need to be conducted to assess the effects of integrated reservoir operations in flood management, and thereby river morphological stability.
- As the river segments support diverse aquatic fauna (e.g., Otter Conservation Reserve in Tungabhadra River), detailed studies are required to understand the effects of morphological changes and hydrologic variability on the river biodiversity.

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Report on

"The workshop on Morphological Study of Krishna and Tungabhadra Basins using Remote Sensing Technique"

1. Introduction

The workshop was conducted to disseminate the findings of the study on "Morphological studies of Krishna and Tungabhadra Rivers using Remote Sensing Technique". The study was sponsored by the Central Water Commission (CWC) and executed by IIT Madras. The workshop was jointly organized by CWC in association with IIT Madras. The workshop was held at Hotel DV Manor, Vijayawada during 18-19 January 2019. Fifty-one officials participated in the workshop, including delegates from CWC (New Delhi, Hyderabad, Pune, and Vijayawada). The workshop included three technical sessions and field visits along lower parts of the Krishna River. The report has been broadly categorized into the details of invited delegates, programme schedule, technical sessions and the details of the field visit.

2. List of the Invitees/Delegates

No.	Name	Designation	Address	E-mail	Contact Number	Remarks
1.	Principal Secretary, Department of Irrigation & CAD, Telangana		Room No. 408, B block, 4th floor, Telangana Secretariat, Hyderabad - 500022	prlsecy_i&cad@telangana.gov.in	040-29801057	Invited but not attended
2.	Engineer-in-Chief, (I) Irrigation &CAD Department		O/o The Engineer In Chief (I) Irrigation &CAD Department, 2nd floor, Jalasoudha, Errum Manzil, Hyderabad, Telangana - 500082	enc_major@yahoo.co.in	9440907000	Invited but not attended
3.	Secretary, Department of Minor, Medium and Major Irrigation, Government of Andhra Pradesh		Room No. 216, 4th block, 1st floor, B First floor, Andhra Pradesh Secretariat, Velagapudi, Amaravathi - 522237	psdwrap15@gmail.com	08632444248	Invited but not attended
4.	Engineer-in-Chief, Administration, Irrigation &CAD, Government of Andhra Pradesh		G V R Complex, 20C, 48-10-20C, NH 16 Service Road, Gunadala Centre, opposite Kodavala Hyundai, near health university, Gunadala, Vijayawada, Andhra Pradesh 520008	irrigationwingemc@yahoo.com	9618322788	Invited but not attended

No.	Name	Designation	Address	E-mail	Contact Number	Remarks
5.	Secretary		Water Resources Department, Bengaluru, Karnataka	sectech-wr@karnataka.gov.in	08022255524	Invited but not attended
6.	Chief Engineer, Water Resources Development Organization, Government of Karnataka		Chief Engineer, Water Resources Development Organization, Anand Rao Circle, Bengaluru - 560009	bngwrdo@nic.in	08022871174	Invited but not attended
7.	Principal Secretary, Water Resources Department, Government of Maharashtra		3rd floor, Main Building, Mantralaya, Mumbai 400032	psecwr.wrd@maharashtra.gov.in	02222023038	Invited but not attended
8.	Executive Director, Maharashtra Krishna Valley Development Corporation		Executive Director, Maharashtra Krishna Valley Development Corporation, Sinchan Bhavan, Barne Road, Pune 11	dmkvdcpune@gmail.com	0202615263	Invited but not attended
9.	Mr. Ajay Kumar Sinha	Director	Morphology Dte, CWC, 901, Sewa Bhawan, R K Puram, New Delhi	dirmorpho_cwc@nic.in	9560444535	Participated
10.	Mr. Rajeev Sinhal	Director	Monitoring and Appraisal Dte, CWC, Hyderabad	dirmahydrabad-cwc@nic.in	8600998070	Invited but not attended
11.	Mr. A. Mohan Reddy	Deputy Director	Morphology Dte, CWC, 901, Sewa Bhawan, R K Puram, New Delhi	dirmorpho-cwc@nic.in	8368987677	Invited but not attended

No.	Name	Designation	Address	E-mail	Contact Number	Remarks
12.	Ms. M. Ganga Bhavani	Deputy Director	O/o Chief Engineer, KGBO, CWC, Hyderabad	bhawanigangam@gmail.com	9246369523	Participated
13.	Mr. Karthic S.R.	Deputy Director	NWIC, 4th floor, Sewa Bhawan, New Delhi	karthicsr111@gmail.com	8197977771	Participated
14.	Mr. A. Radha Krishna	Deputy Director	Water Resources Department, Farmer Training Center, Governerpet, Vijayawada	arkak1965@gmail.com	9849676331	Participated
15.	Ms. Sobhika Singh	Assistant Director	Morphology Dte, CWC, 901, Sewa Bhawan, R K Puram, New Delhi	dirmorpho-cwc@nic.in	8130986942	Participated
16.	Mr. Cherupalli Sanjeev	Assistant Director II	KGBO, CWC, Hyderabad	sanjeev.cherupalli@gov.in	9291546506	Participated
17.	Mr. Ravi Shankar	Chief Engineer	P & D Organization, CWC, New Delhi	cplndev@nic.in	9864031171	Participated
18.	Mr. D. Ranga Reddy	Chief Engineer	KGBO, CWC, A C Gaurds, Lakadi ka pul, Hyderabad	cekgbo_cwc@nic.in	9900823440	Participated
19.	Dr. B. Venkatesh	Scientist	NIH, RC, Belgaum			Invited but not attended

No.	Name	Designation	Address	E-mail	Contact Number	Remarks
20.	Dr. P.C. Nayak	Scientist D	National Institute of Hydrology, Kakinada, Andhra Pradesh	nayakpc@gmail.com	9492776420	Participated
21.	Dr. T. Thomas	Scientist D	National Institute of Hydrology, Bhopal, Madhya Pradesh	thomas.nihr@gov.in	9893686808	Participated
22.	Dr. K.P. Sudheer	Professor	EWRE Division, Department of Civil Engineering	sudheer@iitm.ac.in	9444256675	Participated
23.	Dr. K. Srinivasan	Professor	EWRE Division, Department of Civil Engineering	ksrini@iitm.ac.in	8217638705	Participated
24.	Dr. Balaji Narasimhan	Associate Professor	EWRE Division, Department of Civil Engineering	nbalaji@iitm.ac.in	9962466161	Participated
25.	Dr. Sachin S. Gunthe	Associate Professor	EWRE Division, Department of Civil Engineering	s.gunthe@iitm.ac.in	9962604979	Participated
26.	Mr. M Raghuram	Superintending Engineer	Godavari Circle, CWC, Hyderabad	segchydrabad-cwc@nic.in	8373987620	Invited but not attended
27.	Dr. Jobin Thomas	Senior Project Officer	EWRE Division, Department of Civil Engineering	jobin.cgist@gmail.com	9447426297	Participated
28.	Ms. M.N.R. Mehar Vani	Executive Engineer	Lower Krishna Division, CWC, Hyderabad	mehervani.cwc@gmail.com	9866239563	Participated

No.	Name	Designation	Address	E-mail	Contact Number	Remarks
29.	Mr. Harish Girish Umbarge	Executive Engineer	Upper Krishna Division, NWA complex, Singhad, CWC, Pune	ukdcwc@gmail.com	9947243510	Participated
30.	Mr. N.V. Ramana	Executive Engineer	Water Quality lab Level-II, WRD, Dowlaiswaram	nvr253@gmail.com	8185981679	Participated
31.	Mr. R. Srinivasa Rao	Deputy Executive Engineer	DIVI sub Division, Puligada, Vijayawada		8919205233	Participated
32.	Mr. Venkateshwara Rao	Deputy Executive Engineer	DIVI sub Division, Puligada, Vijayawada		9640658089	Participated
33.	Mr. Akki Ravi Kumar	Deputy Executive Engineer	Water Resources Department, O/o Research Officer, water quality level II lab, Dowlaiswaram	assistantdirectordow@gmail.com	9676028365	Participated
34.	Mr. Chandra Sekhar	Deputy Executive Engineer	O/o Chief Engineer, Hydrology, Bhavanipuram, Vijayawada	krosurusekhar@gmail.com	9963132741	Participated
35.	Mr. Mohan Sreeramdass	Deputy Executive Engineer	O/o Chief Engineer, Hydrology, Vijayawada	mohansreeramdaa@yahoo.com	7032229673	Participated
36.	Ms. S. Sridevi	Deputy Executive Engineer	O/O Chief Engineer, Hydrology, Vijayawada	sreedevi609@gmail.com	9989337702	Participated

No.	Name	Designation	Address	E-mail	Contact Number	Remarks
37.	Mr. M.D. Zakir Hussain	Assistant Executive Engineer	O/o Assistant Director, Water Resources Department, Kurnool	zakirhussain_ce@yahoo.com	8008104265	Participated
38.	Ms. Manasa Munagala	Assistant Executive Engineer	O/o Chief Engineer, Hydrology, WRD, H No. 76-16-16, 2nd floor, Besides Reliance Smart, Bhavanipuram, Vijayawada	manasamunagala@ap.gov.in	7032229648	Participated
39.	Ms. Modurouthu Anusha	Assistant Executive Engineer	WRD, Hydrology, H No. 76-16-16, 2nd floor, Besides Reliance Smart, Bhavanipuram, Vijayawada	manushiiitn@gmail.com	7032229631	Participated
40.	Ms. K.N.L. Jayasri	Assistant Executive Engineer	WRD, Hydrology, H No. 76-16-16, 2nd floor, Besides Reliance Smart, Bhavanipuram, Vijayawada	nagalakshmijayasri@gmail.com	9985344480	Participated
41.	Mr. Pawan Muddineni	Assistant Executive Engineer	O/o Chief Engineer, Hydrology, WRD, H No. 76-16-16, 2nd floor, Besides Reliance Smart, Bhavanipuram, Vijayawada	pavan.muddineni@gmail.com	9676588277	Participated
42.	Mr. M.D. Ananda Babu	Assistant Executive Engineer	O/o ENC (Admin), Water Resources Department, Vijayawada	murathoti.anand@gmail.com	8106654364	Participated

No.	Name	Designation	Address	E-mail	Contact Number	Remarks
43.	Ms. Ponnada Bala Tripura Sundari	Assistant Executive Engineer	O/o Executive Engineer, Gauging Division, Guntur	sundari.aee@gmail.com	8985821801	Participated
44.	Ms. Dundi Vijaya Latha Devi	Assistant Executive Engineer	O/o gauging section No. 4, gauging sub-division no 2, maharaipeta, Water Resources Department, Vishakhapatnam	vijaya.devi77@gmail.com	9494659584	Participated
45.	Ms. G. Shamala	Assistant Executive Engineer	O/o Chief Engineer, Hydrology Unit, WRDO, Bengaluru	shamala27mohan@yahoo.com	8050170386	Participated
46.	Ms. A. Chandrakala	Assistant Executive Engineer	O/o Chief Engineer, WRDO, Anandrao Circle, Bengaluru	chandu92009@gmail.com	9481459600	Participated
47.	Mr. M.V.S.K. Renuka Prasad	Assistant Executive Engineer	O/o Chief Engineer, Hydrology, Vijayawada	mvskrp_2006@yahoo.co.in	7893963434	Participated
48.	Mr. B.D.J. Raju	Assistant Executive Engineer	Middle Krishna Sub Division – II, Jalbhawan, CWC, B camp, Kurnool	bdjraju1986@gmail.com	9490528994	Participated
49.	Ms. Lakshmi Sirisha Devi	Assistant Executive Engineer	O/o Chief Engineer, Hydrology, H No. 76-16-16, 2nd floor, Besides Reliance Smart, Bhavanipuram, Vijayawada	siriram.itp2008@gmail.com	8008191113	Participated

No.	Name	Designation	Address	E-mail	Contact Number	Remarks
50.	Mr. Avinash Chittipothula	Assistant Executive Engineer	O/o Chief Engineer, Hydrology, WRD, Vijayawada	avinash.ch@gmail.com	7981326863	Participated
51.	Ms. M. Sri Lakshmi	Assistant Executive Engineer	O/o Dy. Executive Engineer, Gauging sub-division, WRD, Eluru,	srilakshmikonakalla76@gmail.com		Participated
52.	Mr. Balban Qhudrat-Ur-Rahman	Assistant Executive Engineer	O/o Engineer-In-Chief (Admin), WRD, NH Feeder road, Ramavarpado, Vijayawada	bqrahman@gmail.com	9885261768	Participated
53.	Ms. Poornima H.C.	Assistant Engineer	O/o Chief Engineer, Geomatics Centre, Anandrao Circle, Bengaluru	poornima073@gmail.com	9740027391	Participated
54.	Mr. Sannidhi Proprietor	Assistant Engineer	O/o Chief Engineer, Hydrology, H No. 76-16-16, 2nd floor, Bhavanipuram Bypass road, Vijayawada	sproprietor@gmail.com	7032801297	Participated
55.	Mr. Umeshchandra M. Pataki	Assistant Engineer	O/o Assistant Executive Engineer, No 1 Irrigation Investigation sub-division, Dharwad	umpataki@gmail.com	9483933464	Participated
56.	Mr. Ramesh	Assistant Engineer	O/o AEE, No. 4 II Sub division, Yermasus Camp, Raichur	rameshjrcs@gmail.com	9449260525	Participated

No.	Name	Designation	Address	E-mail	Contact Number	Remarks
57.	Mr. P. Arjun Rao	Sub Divisional Engineer	O/o SE, K&CC, CWC, Hyderabad	arjunraoponugoti@gmail.com	8498058050	Participated
58.	Mr. T.V.J. Rao	Sub Divisional Engineer	O/o SE, K&CC, CWC, Hyderabad	tvjrao@gmail.com	9703932023	Participated
59.	Ms. G. Vijayalakshmi	Sub Divisional Engineer	LKSD II, CWC, Vijayawada	vijayagondi21@gmail.com	9848482006	Participated
60.	Ms. Vartika	Junior Engineer	M&CC, CWC, 901, Sewa Bhawan, R K Puram, New Delhi	dirmorpho-cwcw@nic.in	9810575719	Participated
61.	Mr. Dharavat Chaitanya	Junior Engineer	LKSD II, CWC, Vijayawada	dharavatchaitanya@gmail.com	9494399049	Participated
62.	Ms. Jayaprathiga M.	Research Scholar	EWRE Division, Department of Civil Engineering	yathiga1012@gmail.com	9444180415	Participated
63.	Ms. Abhinanda Roy	Junior Research Fellow	EWRE Division, Department of Civil Engineering	abhinandaroy123@gmil.com	9995798535	Participated

3. Programme schedule

Date/Day	Time	Particulars
18/01/2019 (Friday)	9:30 - 9:32	Invocation
	9:32 - 9:35	Welcome Prof. K P Sudheer, IIT Madras
	9:35 - 9:40	Presidential Address Prof. K Srinivasan, IIT Madras
	9:40 - 9:50	Inaugural Address Sri. Ravi Shankar, CE, CWC, New Delhi
	9:50 - 9:55	Felicitation Sri. D Ranga Reddy, CE, KGBO, CWC, Hyderabad
	9:55 - 10:00	Vote of Thanks Prof. Balaji Narasimhan, IIT Madras
	10:00 - 10:15	Tea break
	10:15 - 11:15	Presentation by IIT Madras (Morphology of Krishna/Tungabhadra basin)
	11:15 - 12:00	Presentation by CE, KGBO, CWC, Hyderabad
	12:00 -12:45	Presentation by Scientists, National Institute of Hydrology
	12:45 - 13:15	Discussion
	13:15 - 14:00	Lunch
	14:00 - 17:00	Field Visit
19/01/2019 (Saturday)	9:00 - 12:00	Field Visit
	12:00 - 12:15	De-briefing & closing ceremony
	12:15 - 13:30	Lunch

4. Details of the Programme

The workshop was scheduled in two days (18-01-2019 and 19-01-2019) and was inaugurated on 18-01-2019. Followed by the inauguration, technical sessions were started, which involved three presentations, including the dissemination of the results of the present study. The discussions provided an interactive platform for the delegates to interact with the experts, and also to discuss various issues being faced by them in the field. Field engineers participating in the workshop provided various practical suggestions also. Field visits were scheduled on the afternoon session of 18-01-2019 and forenoon session of 19-01-2019. The workshop was officially concluded by the afternoon of 19-01-2019.

a) Technical session

i). "Morphological Study of Krishna and Tungabhadra Basins using Remote Sensing Technique" by Prof. K.P. Sudheer (IIT Madras)

The presentation disseminated the findings of the project on the morphological study of the Krishna and Tungabhadra river basins using remote sensing technique. The speaker discussed the intensity of bank erosion and deposition along the river channels and associated planform changes in the river course, which were attributed to the river regulations as well as the infrequent floods of high intensity. The study identified 12 critical reaches in Krishna River and 6 critical reaches in Tungabhadra River, along with suitable river training measures. The study recommended the development of river restoration protocols after considering all the aspects, such as physical condition, morphological types, the degree of artificial alterations and amount of channel adjustments in the river channels.

ii). "Reassessment of water availability studies in Krishna Basin" by Mr. Ranga Reddy (Chief Engineer, KGBO, CWC, Hyderabad)

The presentation discussed the water resources availability in Godavari and Brahmani-Bitarani river basin using satellite-based inputs, which was jointly conducted by CWC and NRSC. The study observed decreasing trends in observed discharge at Vijayawada, mainly due to the construction of water resources structures, predominantly after 1995.

iii). "Project-wise water availability for all major and medium projects in the Krishna River Basin" and "Hydrologic Regionalization for flood predictions in ungauged basins in Krishna Basin" by Dr. T. Thomas (Scientist D, NIH, RC, Bhopal)

The presentation on project-wise water availability for all major and medium projects in the Krishna River Basin water availability discussed the water availability at sub-basin scale, which discussed the spatial variability in the water availability and demand. The second presentation discussed flood prediction in the ungauged basins using regionalization. The presentation extended to the applicability of index flood models, regional flood estimation models, and regional flood frequency curves.

b) Field Visit

The field visits were scheduled in two sessions, viz., afternoon session of 18-01-2019 and forenoon session of 19-01-2019. The objective of the field was to visit the river protection works carried out in the upstream of Prakasam Barrage, Vijayawada. The groynes constructed along the right bank of Krishna River help to reduce the bank erosion and associated loss of fertile lands. Following the visit to the groynes, the confluence point of the Polavaram water diversion canal (from the Godavari) and Krishna River, which is termed as the "Pavithra Sangamam", was also visited.

On 19-01-2019, the team visited the Campbell aquaduct cum road bridge near Puligadda (in KR_25, one of the distributaries in Krishna Delta), where the field engineers discussed the constraints of sustainable water resources management for the region. The team also visited the deltaic area, including the Krishna Wildlife Sanctuary, which is a Mangrove-dominated ecosystem.

The details of the programme as well as the inferences from the study, including the observations during the field visit have been published in the regional newspaper also (appended below), which helps the dissemination of the findings to the grass root level.

కల్యాణం జరిపిస్తున్న అర్చకులు

తరలివచ్చారు. ఆలయ ఈవో దాసరి శ్రీరామవరప్రసాదరావు ఏర్పాట్లు పర్యవేక్షించారు.

అక్విడెక్ట్‌ను సందర్శించిన అధికారులు

పులిగడ్డలో పర్యటించిన అధికారుల బృందం

పులిగడ్డ (అవనిగడ్డ రూరల్), జనవరి 19 : కృష్ణానది నైసర్గిక స్వరూపాన్ని అధ్యయనం చేయటంతోపాటు గతంలో నదిలో ప్రవహిస్తున్న నీరు, ప్రస్తుతం నీటి శాతాన్ని బేరీజు వేసేందుకు అధికార బృందం శనివారం పులిగడ్డ అక్విడెక్ట్‌ను పరిశీలించింది. కృష్ణానది పరివాహక ప్రాంతాన్ని సెంట్రల్ వాటర్ కమిషన్ న్యూఢిల్లీతోపాటు తుంగభద్ర బోర్డు, ధవళేశ్వరం ప్రాజెక్టు కమిటీ సభ్యులు పరిశీలించారు. దివిసీమలోని కరకట్టలు, వాటి స్థితిగతులు, కృష్ణానదిలో సముద్రపు నీరు చొచ్చుకుని వచ్చే భూగర్భ జలాలు ఎంతశాతం ఉప్పుకయ్యలుగా మారుతున్నాయనే విషయాన్ని క్షుణ్ణంగా పరిశీలించి ప్రభుత్వానికి నివేదిక సమర్పిస్తామని సెంట్రల్ వాటర్ కమిషన్ బోర్డు అధ్యక్షుడు రవిశంకర్ తెలిపారు. ఈ సందర్భంగా పులిగడ్డ అక్విడెక్ట్‌ను, మోపిదేవి వార్పు వద్ద ఉన్న కరకట్ట, దివిసీమ ప్రధాన కాలువలను వారు పరిశీలించారు. కృష్ణానది పరివాహక ప్రాంతంలోని కరకట్ట కోతకు గురికాకుండా తీసుకోవాల్సిన జాగ్రత్తలపై కూడా వారు సమీక్షించారు. అనంతరం కోడూరు మండలం పాలకాయితిప్ప, సాగరసంగమ ప్రాంతాలకు తరలివెళ్లారు. ఈ కార్యక్రమంలో తుంగభద్ర బోర్డు చైర్మన్ నరసింహనాయక్, హైడ్రాలిక్ ఎగ్జిక్యూటివ్ ఇంజనీర్ రమణ, రంగారెడ్డి సీఈ సుధీర్‌కుమార్, రవిశంకర్, జలవనరుల శాఖ డీఈఈ పి.వెంకటేశ్వరరావు, ఏఈ పులిగడ్డ వెంకటేశ్వరరావు తదితరులు పాల్గొన్నారు.

దివిసీమలో సీడబ్ల్యూసీ బృందం పర్యటన

- అక్విడెక్టు, కృష్ణానది పరిశీలన
- ఎగువకు ప్రవహిస్తున్న ఉప్పునీటిపై అధ్యయనం

పులిగడ్డ(అవనిగడ్డ): న్యూఢిల్లీ నుంచి వచ్చిన సెంటర్ వాటర్ కమిషన్ (సీడబ్ల్యూసీ) బృందం మండల పరిధిలోని పులిగడ్డ అక్విడెక్టు, కృష్ణాపరీవాహక ప్రాంతాన్ని శనివారం పరిశీలించారు. సీడబ్ల్యూసీ బృందం, తుంగభద్ర బోర్డు, ధవళేశ్వరం ప్రాజెక్టు నిర్వహణ కమిటీతో కూడిన బృందం దివిసీమలో పర్యటించింది. తొలుత అక్విడెక్టుని పరిశీలించారు. నిర్మాణతీరు, కాల పరిమితి, ఆయకట్టు పరిస్థితిని స్థానిక అధికారులను అడిగి తెలుసుకున్నారు. అనంతరం రేగుల్లంకలో కోతకు గురైన ప్రాంతాన్ని పులిగడ్డ ఎగువున కృష్ణానదిలో ఉప్పునీటి ప్రవాహం పరిస్థితిని పరిశీలించారు. కరకట్టలను పరిశీలించి కోతకు గురికాకుండా తీసుకోవాల్సిన చర్యలపై చర్చించారు. సీడబ్ల్యూసీ చీఫ్ ఇంజినీర్ రవిశంకర్ మాట్లాడుతూ దివిసీమ నైసర్గిక, కృష్ణానది పరీవాహాన్ని పరిశీలించేందుకు

అక్విడెక్టును పరిశీలిస్తున్న సీడబ్ల్యూసీ బృందం సభ్యులు

వచ్చామని చెప్పారు. ఈ ప్రాంత నైసర్గిక స్వరూపం, సాగునీటి వసతి, నదీ పరీవాహక ప్రాంతం కోతకు గురవుతున్న పరిస్థితిని, ఉప్పునీరు ఎగువకు వెళ్లడానికి గల కారణాలు, భూగర్భ జలాల పరిస్థితిని అంచనావేసి, వాటి నివారణకు తీసుకోవాల్సిన చర్యలను కేంద్ర ప్రభుత్వానికి నివేదిస్తామని చెప్పారు. కార్యక్రమంలో హైదరాబాద్ సీడబ్ల్యూసీ సీఈ రంగారెడ్డి, హైడ్రాలిక్ ఎగ్జిక్యూటివ్ ఇంజినీర్ రమణ, ఐఐటీ ఎండీఎస్ సుధీర్‌కుమార్, నరసింహన్, ఎన్ఐహెచ్ కేకేడీ నాయక్, ఈఈ రమణ, డీఈఈ ఆర్. శ్రీనివాస రావు, డీఈ వెంకటేశ్వరరావు పాల్గొన్నారు.

Snapshots from the Workshop on "Morphological Study of Krishna and Tungabhadra Basins using Remote Sensing Technique" on 18-19, January, 2019 at Vijayawada


Lack of river channel morphological
Less dynamic, compared to
Heavily regulated hydrologic
Active dominantly during







Appendix I: List and description of dams in KRB (after, MoWR, 2014)

Sl. No.	Name of dam	River	Type of dam	Year of completion	Catchment area (km²)	Length of dam (m)	Max height above foundation (m)	GSC (MCM)	LSC (MCM)	Type of spillway	Submergence area (Th. Ha)	Purpose
1.	Achakdani	Local Nallah	Earthen	1970		628	11.15	1.35	1.35			IR
2.	Achler	Local Nallah	Earthen	1978		135	13.5	1.13	0.96		0.03	IR
3.	Adale	Local Nallah	Earthen	1985		365	19.17	1.27	0.97		0.02	IR
4.	Aheri-Jumbagi	Aheri-Jumbagi	Earthen/Gravity/Masonry	1989		1018	10.59	1.8	1.5		0.65	IR
5.	Aigali	Local Nallah Krishna /Malaprabha	Earthen	1969		526.5	15.66	1.44	1.19		0.04	IR
6.	Akkampalli											
7.	Akkapalem		Earthen			433	11.1	1.85	1.85			IR
8.	Alegaonpaga	Ambi	Earthen	1971		289	15.24	2.03	1.81			IR
9.	Almatti	Krishna	Earthen/Gravity/Masonry	2000	33375	1564.83	52.24	1196	861	Ogee	54.01	HE, IR
10.	Alsund	Local Nallah	Earthen	1989		771	13.98	0	0		0.05	IR
11.	Alur	Local Nallah	Earthen	1975		934	11.99	1.12	0.97		0.02	IR
12.	Amarja	Amarja	Earthen/Gravity/Masonry	1998	530.95	960	31.85	44.01	40.07	Ogee	0.64	IR
13.	Ambegaon		Earthen	1979		575	21.78	1.93	0.19		0.03	IR
14.	Ambeohal	Ambeohal			33.84	2185	27.585	35.11	32.63		0.33	IR
15.	Ambi	Local Nallah	Earthen	1972		418	11.6	1.53	1.29		0.04	IR
16.	Ambligola	Vrushbhavathi	Earthen	1964	144	881	20.77	12.2	11.7	Ogee	0.45	IR
17.	Amboli	Local Nallah	Earthen	1979		390	27	1.78	1.73		0.12	IR

Sl. No.	Name of dam	River	Type of dam	Year of completion	Catchment area (km^2)	Length of dam (m)	Max height above foundation (m)	GSC (MCM)	LSC (MCM)	Type of spillway	Submergence area (Th. Ha)	Purpose
18.	Anala	Local Nallah	Earthen	1972	20.2	1290	23.34	8.99	7.8	Ogee	0.05	IR
19.	Andhali	Man	Earthen	1997	129.5	2040	18.6	9.27	7.42	Ogee	0.21	IR
20.	Andra	Andra	Gravity/Masonry	2003	214.46	330	40.45	82.75	82.19	Ogee	1.07	IR
21.	Andur		Earthen	1982		430	24.51	5.75	5.69		0.06	IR
22.	Anjanapura	Kumudavathy	Earthen	1936	520	1600	21.33	39.76	20	Ogee	0.11	IR
23.	Ankamanhal	Krishna/Tungabhadra	Earthen	1988		278	21.29	1.93	1.72		0.04	IR
24.	Antri (Bk)	Local Nallah	Earthen	1989		907	22.79	2.82	2.65		0.06	IR
25.	Appenahalli	Krishna/Tungabhadra	Earthen	1981		525	13.75	1.78	1.78		0.04	IR
26.	Arabwadi	Baba	Earthen	1977		870	17.95	1.89	1.75		0.04	IR
27.	Arala Kalmodi	Arala	Gravity/Masonry		40.61	295	36.8	42.67	42.47	Ogee	0.27	IR
28.	Aralihalli	Krishna/Tungabhadra	Earthen	1983		1920	11.86	3.45	3.01		0.25	IR
29.	Arbenchi	Arbenchi Nallah	Earthen	1980		312	17.65	1.57	1.27		0.02	IR
30.	Areshankar	Areshankar	Earthen/Gravity	1957	177	1189	19.2	8.58	7.22	Ogee	0.23	IR
31.	Arjunwadi	Local Nallah	Earthen	2002		459	17.52					IR
32.	Arli	Local Nallah	Earthen			771	12.35	0.89	0.81		0.04	IR
33.	Arsoli	Local Nallah	Earthen	1990		6561	23.3	9.23	7.33		0.18	IR
34.	Ashti (Nimgaon Choba)	Kadi	Earthen	2000		2291	14.67	8.15	6.55			IR
35.	Ashti	Ashti	Earthen	1883	238.28	3871	17.6	23.01	23.01		1.18	IR
36.	Asundinala	Local Nallah	Earthen	1989		1595	15.7	5.5	4.57		0.23	IR

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37.	Atpadi	Local Nallah	Earthen	1972		1139	16.5	8.67	7.95			IR
38.	Babaleshwara	Sindi Halla	Earthen	1961		975	12.11	1.91	1.36		0.73	IR
39.	Babhulgaon	Local Nallah	Earthen	2003		16.5	16.93	56.1			0.23	IR
40.	Bagalwadi	Local Nallah	Earthen	1972		662	15	1.57	1.33		0.05	IR
41.	Balakundi	Balakundi	Earthen/Gravity/Masonry	1979		1640	14.15	7.46	4.78		0.25	IR
42.	Balgawade	Local Nallah	Earthen	1987		950	13.4	1.13	1.03		0.05	IR
43.	Ballalwadi	Ramnagar	Earthen	1996		430	20.16	0				IR
44.	Ballasamudra		Earthen	1940		785	12	5.09	4.75		0.2	IR
45.	Banganga	Banganga	Earthen	1955		1631	16.76	6.5	6.49		0.26	IR
46.	Banganga	Banganga	Earthen	1975	56.64	1170	19.2	5.93	4.96		0.17	IR
47.	Banpuri	Local Nallah	Earthen	1971		510	13.8	1.41	1.23			IR
48.	Bardari	Mehakari	Earthen	1973		420	16.18	1.86	1.54		0.04	IR
49.	Barki	Local Nallah	Earthen	2005		335	25.66	1.64	1.58		0.02	IR
50.	Basavapattana	Basavapattana	Earthen/Gravity/Masonry	1964		90	14.16	1.37	1.26		0.05	IR
51.	Bassappawadi	Local Nallah (Agrani)	Earthen	1980	133	1770	16.9	7.77	6.27		0.28	IR
52.	Beeranahalli	Local/Mullamari (K-6)	Earthen	1988		485	30.02	6.93	5.8		0.07	IR
53.	Belgaon	Local Nallah	Earthen	1981		181	14.8	2.85	2.8		0.01	IR
54.	Bellary	Bellary Nallah	Earthen/Gravity/Masonry		253.82	440.6	36.55	37.26	33.92	Ogee	0.33	IR
55.	Bellikindi	Bellikindi	Earthen/Gravity/Masonry	1972		457	11.91	1.08	0.99		0.04	IR

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56.	Belunki	Local Nallah	Earthen	1997		970	14	0.07	0.06			IR
57.	Benikre	Local Nallah	Earthen	1973		595	20.99	0			0.03	IR
58.	Benitura	Benitura	Earthen	1994	179.58	1797	13.38	12.84	11.5		0.64	IR
59.	Bennithora	Bennithora	Earthen/Gravity/Masonry	2001	2204.09	2340	31.39	149.98	145.78	Ogee	3.05	IR
60.	Bhadra	Bhadra	Earthen/Gravity/Masonry	1965	1968	1708	76.81	2025.87	1785	Ogee	11.25	HE, IR
61.	Bhairapur	Local Nallah Krishna/ Malaprabha	Earthen	1991		600.5	15.3	1.36	1.18		0.03	IR
62.	Bhairavanithippa	Pedda Hagari (Vedavathi) River	Earthen	1961	14	2235	20	74.31	65.32	Ogee	1.55	IR
63.	Bhakuchiwadi	Local Nallah	Earthen	1989		1770	19.7	0.01	0.01		0.02	IR
64.	Bhama Asakhed	Bhama	Earthen		198.08	1425	51.125	230.47	217.1	Ogee	2.16	IR
65.	Bhambarde	Local Nallah	Earthen	1972		635	22	1.32	0.96			I R
66.	Bhandalwadi	Local Nallah	Earthen	1966		796	13.2	4.56	4.54			IR
67.	Bharamasagara Doddakere	Kattahalla	Earthen			1220	12	4.05	3.68		0.2	IR
68.	Bharatagi	Bharatagi	Earthen/Gravity/Masonry	1975		1076	13.02	2.8	2.27		0.11	IR
69.	Bhatghar		Gravity/Masonry	1927	331.5	1625	57.92	670.65	665.59	Ogee	3.19	HE, IR
70.	Bhatodi	Mehekari	Earthen	1892		706	15.24	2.9	2.52		0.08	IR
71.	Bheemanpally	Bheemanpally	Earthen	1954		2019	16	6.26	5.69			IR
72.	Bheemasamudra	Jinigihalla	Earthen		118.11	840	14.2	25.62	20.5		0.86	IR

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73.	Bhivargi	Patan	Earthen	2001		1606	15.85	11.2	8.63			IR
74.	Bhopgaon	Chambali	Earthen	2004		875	14.5	0				IR
75.	Bhose (Sangli)		Earthen	1974		456	15.18	1.03	0.94			IR
76.	Bhose (Solapur)	Local Nallah	Earthen	1977		925	11.58	2.18	1.73			IR
77.	Bhudihal	Belwan	Earthen	1966		2975	18.5	32.05	27.95			IR
78.	Bhugaon	Local Nallah	Earthen	1983		550	21.19	1.9	1.8		0.42	IR
79.	Bhurikavathe	Local Nallah	Earthen	1991			14.8	1.84	1.84			IR
80.	Bhutnal Lake											
81.	Bhutwada	Wincharna	Earthen	1973		305	23.46	3.06	2.49		0.03	IR
82.	Bidi	Local Nallah Krishna/ Malaprabha	Earthen	1989		580	11.67	1.21	1.05		0.03	IR
83.	Biggerahalla	Tungabhadra	Earthen	1986	9.71	450	15.16	0.63	0.58		0.19	IR
84.	Billur (Arwali)	Local Nallah	Earthen	1995		621	16.25	0			0.01	IR
85.	Bilur (Kesaral)	Local Nallah	Earthen	1995		420	14.31	1.47	1.44		0	IR
86.	Birnal	Local Nallah	Earthen	1977		403	18.6	2.43	2.13			IR
87.	Bommanahalli	Bommanahalli	Earthen/Gravity/Masonry	1981		770	12.7	2.55	2.02		0.09	IR
88.	Boodikere	Local Nallah	Earthen	1950		540	12	1.49	1.35		0.03	IR
89.	Boranakanive	Suvarnamuki SS VI	Gravity/Masonry	1892		39.6	24	6.43	6.18		1.35	IR
90.	Borgaon (Sangli)	Local Nallah	Earthen	1987		469	13.79	1.63	1.48		1.16	IR

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91.	Borgaon (Solapur)	Local Nallah	Earthen	1984		435	14.7	2.11	0.06		0.01	IR
92.	Bori	Bori Nallah	Earthen	2005	1253	960	17.23	19.25	17.14	Ogee	0.65	IR
93.	Brahmangaon	Local Nallah	Earthen	1978		1097	15	1.66	1.46		0	IR
94.	Budhpur		Earthen		15.5	4976	15	37.19	34.16			I R
95.	Buggavagu	Buggavagu	Earthen	1961	828.8	2576	31					IR
96.	Bukkambudi Doddekere	Local Nallah/Veda Series	Earthen		9.14	1160	13	0.35	0.32		0.16	IR
97.	Bukkapatna	Suvarnamukhi SS	Earthen			500	11.5	3.74	3.37		0.16	IR
98.	Bullapura	Kumadavati	Earthen	1952		114.6	18	0.71	0.64		0.01	IR
99.	Chafal	Local Nallah	Earthen	1983		576	21.5	1.45	1.32		0.05	IR
100.	Chalkewadi	Local Nallah	Earthen	1991		366	21.53	0			0.02	IR
101.	Chandani	Chandani	Earthen	1965	606	1920	17.18	23.78	21.58		0.96	IR
102.	Chandoli	Local Nallah	Earthen	2001		313	22.66	1.76	1.4		0	HE, IR
103.	Chandrampalli	Sarnala	Earthen	1973	440	926.54	28.65	34.19	31.4	Chute	0.36	IR
104.	Changliar	Local/Mullamari (K-6)	Earthen	1988		505	17.89	1.8	1.65		0.04	IR
105.	Chare	Local Nallah	Earthen	1983		512.5	16.5	1.5	1.34		0.04	IR
106.	Charkali	Local Nallah	Earthen	1995		472	17.37	3.43	3.16		0.04	IR
107.	Chaskaman	Bhima	Earthen/Gravity/Masonry	1999	305.56	956	46.28	241.69	213.38	Ogee	1.89	HE, IR
108.	Chichondipatil	Kal	Earthen	1977		590	15.06	2.8	2.17		0.31	IR
109.	Chikhalgi	Dodda	Earthen	1990		1290	18.19	8.94	5.95			IR

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110.	Chikkalingadalli	Local/Mullamari (K-6)	Earthen	1982		701.04	14.48	4.26	3.57		0.07	IR
111.	Chikkanagaon	Local/Mullamari (K-6)	Earthen	1981		365	15.95	0.97	0.88		0.02	IR
112.	Chikkasandra	Suvarnamukhi	Earthen			960	9	7.51	6.25		0.21	IR
113.	Chikkehalli	Local Nallah	Earthen	1983		608	11.15	1.89	1.71			IR
114.	Chikotra	Chikotra	Earthen	2001	29.03	983	64.8	43.12	43.05	Ogee	0.26	HE, IR
115.	Chilewadi	Mandvi	Earthen	2000	103.94	440	62.56	27.17	24.61	Ogee	6.74	IR
116.	Chinchani (Ambak)	Local Nallah	Earthen	1989		1447	17.46	0			0.12	IR
117.	Chincholi	Local Nallah	Earthen	1966		793	15.24	2.71	2.71			IR
118.	Chinchwad	Local Nallah	Earthen	1984		610	20.92	1.53	1.45		0	IR
119.	Chitri	Chitri	Earthen	2001	27.85	1569	55.1	53.41	52.48	Ogee	0.29	IR
120.	Chittawadagi	Chittawadagi	Earthen/Gravity/Masonry	1971	145.04	481	12	5.79	5.2	Ogee	0.21	IR
121.	Chi-Umberga	Local Nallah	Earthen	1975		1381	14	2.82	2.47		0.15	IR
122.	Dafalapur	Local Nallah	Earthen	1992		930	12.8	1.78	1.13		0	IR
123.	Dahiwadi	Local Nallah	Earthen	1973		350	17.68	1.35	1.03			IR
124.	Danpakanicheru, Allapur/ Dantakani Cheruvu	Lower Krishna	Earthen			671	12.04	2.58				IR
125.	Darfal Bb	Local Nallah	Earthen	1983			12.15	2.89	2.89			IR
126.	Daruj	Daruj	Earthen	1956		869	16.46	2.88	2.65		0.09	IR
127.	Dasanahalli	Krishna/Tungabhadra	Earthen	1986		780	11.83	1.24	1.12		0.16	IR

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128.	Deulgaon Sidhi	Bongari	Earthen	1972		732	15.4	2.32	1.71		0.07	IR
129.	Deur	Local Nallah	Earthen	1994		966	18.6	0			0.04	IR
130.	Devarabillikere	Shagalihalla & Sulekere Halla	Earthen	1985		1204	17.4	2.62	2.36		0.65	IR
131.	Devaramardikere	Suvarnamukhi SS	Earthen	1980		407	10.67	1.41	1.27		0.07	IR
132.	Dhakani	Local Nallah	Earthen	1994		820	18.5	3.05	2.66		0.07	IR
133.	Dhamani	Kumbhi	Earthen		44.36	1290	74.64	109.1	105.91	Ogee	0.69	IR
134.	Dhamari	Local Nallah	Earthen	1978		450	14.34	1.15	0.87			IR
135.	Dhangarwadi	Local Nallah	Earthen	1999		518	19.28	2.64	2.33		0.06	IR
136.	Dharma	Dharma Nallah	Earthen	1964	97.77	1448.2	23.25	23.24	22.24	Ogee	0.65	I R
137.	Dhavaleshwar	Local Nallah	Earthen	1996		806	14.09	0.09	0.08		0.01	IR
138.	Dhom Balakwadi	Krishna	Earthen	2006	42.77	1211	65.1	115.53	112.13	Ogee	0.56	HE, IR
139.	Dhom	Krishna	Earthen/Gravity/Masonry	1977	217.56	2478	50	382.32	331.05	Ogee	2.5	HE, IR
140.	Dhondpargaon	Nandini	Earthen	1977		720	18.35	2.48	2.18		0.04	IR
141.	Dhubdhubi	Dhubdhubi	Earthen	2005		1520	11.83	7.3				IR
142.	Dhumalwadi	Local Nallah	Earthen	1975		348	11.63	1.34	1.25			IR
143.	Diggi	Local Nallah	Earthen	1997			15.16	1.6	1.43		0.03	IR
144.	Dighanchi	Local Nallah	Earthen	1976		880	15.8	4	3.33			IR

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145.	Dimbhe		Gravity/Masonry	2000	412	852	67.65	382.06	353.75	Ogee	1.75	HE, IR
146.	Dindi		Earthen	1943	3920	2329	25	59.07	38.51	Ogee	0.7	IR
147.	Dinshi	Dinshi Nallah	Earthen	1986		360	17.1	0.93	0.84		0.02	IR
148.	Divale	Gunjawani	Earthen	1985		490	20.83	2.14	2		0.04	IR
149.	Doddaagrahara											
150.	Doddanalla	Dodda Nallah	Earthen	1987	106	1870	16.2	6.5	4.78		0.23	IR
151.	Dongargaon	Veer	Earthen	1977		1362	10.06	1.52	1.21			I R
152.	Dudhebhavi	Local Nallah	Earthen	1983		480	19.33	3.98	3.45		0	IR
153.	Dudhganga	Dudhganga	Earthen/Gravity/Masonry		196	1280	75	719.12	664	Ogee		HE, IR
154.	Ekrukh	Adela	Earthen	1871	411.78	2360	21.45	61.17	61.16		1.79	IR
155.	Erandol	Local Nallah	Earthen	1999		442	30.27	4.21	3.94		0.05	IR
156.	Fondshiras	Local Nallah	Earthen	1991		430	16.03	2.92	2.39			IR
157.	Fox Sagar, Jeedimetla		Earthen			1610	10	0.93				IR
158.	Gaddavane (Shindewadi)	Local Nallah	Earthen	2007		260	26.2	1.86	1.81		0.01	IR
159.	Gajuladinne (Sanjeevaiah Sagar)	Handri	Earthen	1979	1300	4400	19	148.78	121.2	Ogee	2.79	IR
160.	Galorgi	Local Nallah	Earthen	1977		564	12.75	2.07	2.07			IR
161.	Gandabommanahalli	Krishna/Tungabhadra	Earthen	1970		1104	23.15	7.32	7.32		0.18	IR
162.	Gandorinala	Gandorinala	Earthen/Gravity/Masonry	2002	371	1813.5	24.27	53.45	49.45	Ogee	0.66	IR

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163.	Gangoti	Local Nallah	Earthen	1978		890	14.4	1.79	1.35			IR
164.	Gantenahalli	Suvarnamuki SS VI	Earthen	1987		1020	22.25	3.99	3.6		0.11	IR
165.	Gaosud	Local Nallah	Earthen	1995		773	16.75	1.7	1.51		0.04	IR
166.	Garade	Karha	Earthen	1979		373	18.82	1.65	1.56		0.05	I R
167.	Gavase	Local Nallah	Earthen	2006		290.5	23.87	1.21	1.15		0.02	IR
168.	Gayathri	Suvarnamuki	Earthen/Gravity/Masonry	1963	1831	1021.53	17.07	27.6	18.1	Ogee	0.79	IR
169.	Ghagargaon	Local Nallah	Earthen	2003		323	11.93	1.31	1.18			IR
170.	Ghanand	Local Nallah	Earthen	1986		812	15.46	0			0	IR
171.	Ghataprabha	Ghatprabha	Earthen	2009	58.33	1088	48.3	42.75	42.74	Ogee	0.3	HE, IR
172.	Gheradi	Local Nallah	Earthen	1943		500	13	2.82	2.82			IR
173.	Ghod	Ghod	Earthen	1965	3628	3300	29.6	216.3	154.8	Ogee	3.09	IR
174.	Ghodegaon		Earthen	1975		892	16.4	2.51	2.29		0.06	IR
175.	Ghorpadi	Local Nallah	Earthen	1988		390	13.62	1.5	1.28		0.01	IR
176.	Ghorvadi	Ghorwadi	Earthen	1996		960	19.81	1.91	1.59		0.05	IR
177.	Girzani	Local Nallah	Earthen	1989		385	17	1.55	1.46		0.04	IR
178.	Gobbur	Gobbur Nallah	Earthen	1993		1525	10.3	3.02	2.39		0.15	IR
179.	Gohe	Local Nallah	Earthen	1996		140	17.49	1.29	1.11		0.03	IR
180.	Gopaldinne		Earthen			975		10.48		Other		
181.	Goradwadi	Local Nallah	Earthen	1976		530	11.94	1.1	0.95			IR

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182.	Gormala	Local Nallah	Earthen	1985		127	12.9	1.29	1.15		0.04	IR
183.	Gormale	Local Nallah	Earthen	1983		660	10.87	1.74	1.4			IR
184.	Gudipalligattu	Krishna										IR, WS
185.	Gugawad	Local Nallah	Earthen	1987		580	14.4	1.58	1.03			IR
186.	Gundwan At Site-I	Gundwan-I	Earthen/Gravity/Masonry	1979		973	13.05	2.18	1.77		0.1	IR
187.	Gundwan At Site-II	Gundwan-II	Earthen/Gravity/Masonry	1962		690	11.21	1.84	1.72		0.07	IR
188.	Gunjwani	Kanandi	Earthen/Gravity/Masonry		50.61	1730	52.82	104.69	104.48	Ogee	0.64	HE, IR
189.	Gunodi	Shanala	Earthen	1955		793	14.93	6.38	5.68		0.02	IR
190.	Gurav Pimpri	Bhokri	Earthen	1954		945	14.33	3.85	3.14		0.01	IR
191.	Hadashi I	Walki	Earthen	1990		720	21.83	3.07	2.98		0.35	IR
192.	Hadashi II	Local Nallah	Earthen			390	20.45	1.41	1.31		0.02	IR
193.	Hagari Bommanahalli	Hagari	Earthen	1972	2347	1759	15.24	6.37	5.62	Chute	1.35	IR
194.	Haihole	Haihole	Earthen	1979		688	21	5.11	3.72		0.1	IR
195.	Halchincholi	Local Nallah	Earthen	1979		622	13.3	2.33	2.18			IR
196.	Halkarni	Local Nallah	Earthen	2005		504	14	0			0.02	I R
197.	Haludyamanahalli	Kattehole	Earthen	1975		690	13.7	1.38	1.14		0.05	IR
198.	Hanabarwadi	Local Nallah	Earthen	1998		304	23.65	2.67	2.4		0.03	IR
199.	Hanajagi	Hanajagi	Earthen/Gravity/Masonry	1968		785	12.81	1.5	1.42		0.07	IR
200.	Hanamapur	Local Nallah	Earthen	1978		375.75	14.33	1.12	0.97		0.05	IR

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201.	Hanamgaon	Local Nallah	Earthen	1974			11.1	2.9	2.9			IR
202.	Hanchinal	Hanchinal	Earthen/Gravity/Masonry	1973		655	11.05	1.59	1.25		0.06	IR
203.	Hanga	Hanga	Earthen	1978		390	15.84	1.85	1.34		0.05	IR
204.	Hangarga	Local Nallah	Earthen	1973		1506	12.81	2	1.88		0.09	IR
205.	Hangargi	Local Nallah	Earthen	1977		975	12.3	1.83	1.33			IR
206.	Hanjagi	Local Nallah	Earthen	1983		811	12.1	1.63	1.42			IR
207.	Harinala	Harinala	Earthen	2004	101	3120	19.41	13.81	12.08	Ogee	0.39	IR
208.	Harni	Harni	Earthen	1965	188.42	3059	16.55	12.58	11.18	Ogee	0.72	IR
209.	Haroli	Local Nallah	Earthen	1987		818	13.96	1.32	1.21			IR
210.	Hateghar	Hateghar Nallah	Earthen	2011	7.74	1048	38.55	7.37	7.29	Ogee	0.09	HE, IR
211.	Hattikuni	Hattikuni stream	Earthen	1973	137.89	923	22.88	9.97	7.93	Ogee	0.12	I R
212.	Hebbal	Local Nallah Krishna /Malaprabha	Earthen	1989		530	12.64	0.64	0.55		0.01	IR, WS
213.	Here	Local Nallah	Earthen	1998		523	27.32	3.88	3.81		0.04	IR
214.	Hidkal	Ghataprabha	Earthen/Gravity/Masonry	1977	1412	10183	62.48	1444.32	1387	Chute	6.34	HE, IR
215.	Himayat Sagar	Eesa	Earthen/Gravity/Masonry	1927	1307.94	2256	34	189.65	182.18			WS
216.	Hingangaon (Sangali)	Mandani	Earthen	1998		2010	16.02	0.6			0.06	IR
217.	Hingangaon	Ardeshi	Earthen	1975		1032	17.53	1.48	1.24		0.01	IR
218.	Hingani (Pangaon)	Bhogawati	Earthen	1977		2193	21.87	45.51	31.97			IR

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219.	Hingani	Kumbhar	Earthen	1974		750	16.6	2.22	1.85			IR
220.	Hipparga	Local Nallah	Earthen			850	12.27	1.71	1.56		0.05	IR
221.	Hirehalla	Hirehalla & Veerapur Halla	Earthen/Gravity/Masonry	2002	937.5	3606.6	17.62	47.6	37.95	Ogee	1.25	IR
222.	Hirekop	Local Nallah	Earthen	1966		785.4	12.39	1.47	1.2		0.04	IR
223.	Hiresangagutti	Hiresangagutti	Earthen/Gravity/Masonry	1993		260	11.45				0.03	IR
224.	Hivare	Wanganga	Earthen	1974		740	18.14	2.74	2.3		0.07	IR
225.	Hokarani	Hokarani	Earthen/Gravity/Masonry	1966		755	11.72	1.18	1.11		0.05	I R
226.	Horti	Local Nallah	Earthen	1978		607	14.7	1.35	1.24		0.04	IR
227.	Hotagi	Local Nallah	Earthen	1944		350	12.5	5.27	5.27			IR
228.	Hulikunta	Tungabhadra	Earthen	1979		550	28.65	2.72	2.58		0.05	IR
229.	Huljanti	Local Nallah	Earthen	1980		807	12.25	1.35	1			IR
230.	Ijoli	Local Nallah	Earthen	2005		207	19.65	0.81	0.69		0.01	IR
231.	Indirammasagar, Anajpur	Musi	Earthen			1189	11.87	1.33				IR
232.	Itagi	Malaprabha	Earthen	1979		757	15.25	0.99	0.86		0.02	IR
233.	Itkal	Local Nallah	Earthen	1985		88	10	1.19	1.07		0.05	IR
234.	Jadhavwadi		Earthen	2001		1215	35.52	12.03	11.53		0	IR
235.	Jakapur	Local Nallah	Earthen	1977	121.73	1768	14.8	10.18	7.45		0.4	IR
236.	Jalgaon Supe	Local Nallah	Earthen	2002		527	10.34	0.56	0.45			IR
237.	Jalihal Bk.	Local Nallah	Earthen	1984		648	14.05	2.23	1.91		0.01	IR

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238.	Jamb	Local Nallah	Earthen	2000		823	17.3	2.21	1.87		0.04	I R
239.	Jambadahalla	Jambadahalla	Earthen/Gravity/Masonry	1968	155.4	838.1	31.7	9.69	6.91	Ogee	0.16	IR
240.	Jambhulani (Sangali)	Local Nallah	Earthen	1975		1285	15.87	2.85	2.15			IR
241.	Jambhulani	Local Nallah	Earthen	1982		1040	15.21	2.42	2.27			IR
242.	Jambre		Earthen		19.97	1018	38.06	23.23	23.2	Ogee	0.13	HE, IR
243.	Jangamhatti	Honhal	Earthen	1995	21.4	960	28.9	34.21	33.21	Ogee	0.01	HE, IR
244.	Jawahar	Shiruguppi	Earthen/Gravity/Masonry	1961		676.16	21.64	1.84	1.27		0.04	WS
245.	Jawalgaon	Nagzari	Earthen	2005	223	1229	21.71	34.75	29	Ogee	0.67	IR
246.	Jigajinagi	Jigajinagi	Earthen/Gravity/Masonry	1982		1420	11.93	4.04	3.77		0.17	IR
247.	Jiregaon	Local Nallah	Earthen	2002		515	11.44	1.24	0.84			IR
248.	Julugade-I	Local Nallah	Earthen	2000		198	29.98	4.86	4.72		0.05	IR
249.	Jutpally Weir/ Jutepally	Jutepalli vagu	Earthen	1966		1177	22	8.72	7.94			IR
250.	Kacharewasti	Local Nallah	Earthen	1974		1238	18.75	3.13	1.88			IR
251.	Kada	Local Nallah	Earthen	1965	169.08	2374	15.45	9.99	8.85	Other	0.2	IR
252.	Kadasagatti	Local Nallah	Earthen	1991		706	10.68	0.34	0.29		0.04	IR
253.	Kadatana Begewadi	Local Nallah	Earthen	1965		594.5	13.55	1.04	0.91		0.03	I R
254.	Kadatnal	Local Nallah/ Malaprabha	Earthen	1970		470	13.75	1.29	1.12		0.05	IR
255.	Kadavi	Potphuji	Earthen	2000	23.32	1519	36.05	71.24	70.56	Ogee	0.46	IR
256.	Kadegaon	Local Nallah	Earthen			915	11.1		1.38			IR

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257.	Kadi	Kari	Earthen	1970	96.2	697	21.18	7.64	6.38		0.22	IR
258.	Kadlewadi	Kadlewadi	Earthen/Gravity/Masonry	1990		1080	11.52	2.45	2.16		0.08	IR
259.	Kadus		Earthen	1986		890	18.5	3.62	2.26		0.03	IR
260.	Kakarvani		Earthen			2378	12.96					IR
261.	Kalamba		Earthen	1983		1237	16.26	2.75			0.06	IR
262.	Kalambwadi	Local Nallah	Earthen	1983		653	14.7	0.71	0.59			IR
263.	Kalasakoppa	Kalasakoppa	Earthen/Gravity/Masonry	1960	130	585	15.8	6.82	6.48	Ogee	0.2	IR
264.	Kalasgade	Local Nallah	Earthen	2000		524	16.26	1.91	1.84		0.05	IR
265.	Kallambella	Suvarnamukhi	Earthen			1920	8.77	7.02	6.32		0.29	IR
266.	Kamargaon		Earthen	1969		488	13.33	2.24	1.92		0.01	I R
267.	Kambali	Kambali	Earthen	1958	130.25	1500	15.6	3.8	3.1		0.16	IR
268.	Kamtha	Local Nallah	Earthen	1970		643	14.8	1.38	1.24		0.04	IR
269.	Kanakanala	Kanakanala	Earthen	1975	192	975.65	20.12	6.37	5.61		0.19	IR
270.	Kandalgaon	Local Nallah	Earthen	1980		670	19.41	1.7	1.65			IR
271.	Kaneriwadi	Local Nallah	Earthen	1974		907	17.5	2.6	2.22		0.06	IR
272.	Kanher		Earthen/Gravity/Masonry	1986	204.69	1955	50.34	286	271.68	Ogee	2	HE, IR
273.	Kankatrewadi	Local Nallah	Earthen	1978		726	19.51	1.24	1.04		0.04	IR
274.	Kanvikervinkoppa	Local Nallah Krishna/ Malaprabha	Earthen	1982		454	16.76	0.49	0.42		0.02	IR

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275.	Karambali	Local Nallah	Earthen	2007		549	27.44	2.91	2.79		0.03	IR
276.	Karandewadi	Local Nallah	Earthen	1995		124	18.45	1.36				
277.	Karanjgaon	Local Nallah	Earthen	1998		615	30.7	3.44	2.55		0.03	IR
278.	Karanjiwane	Local Nallah	Earthen	1989		495	21	0			0.02	IR
279.	Kari	Local Nallah	Earthen	1973		945	15.72	1.7	1.47			IR
280.	Karunde	Local Nallah	Earthen	1972		881	13.05	2.2	1.97			IR
281.	Karve	Local Nallah	Earthen	1974		1099	16.86	1.64	1			IR
282.	Kasari	Kasari	Earthen	1990	33.28	297	44.24	78.56	77.96	Ogee	0.77	HE, IR
283.	Kasarsai	Kasarsai Nallah	Earthen	1995	39.45	1170	29.36	17.37	16.25	Ogee	0.2	IR
284.	Katral	Katral	Earthen/Gravity/Masonry	1979		1240	11.22	2.38	2.26		0.12	IR
285.	Kaudgaon	Jamb	Earthen	1973		450	15.55	2.49	2.11		0.05	IR
286.	Kazikanbas	Local Nallah	Earthen	1989		805	19.8	0			0.07	IR
287.	Kesakarwadi	Local Nallah	Earthen	1998		633	29	5.68	5.62		0.05	IR
288.	Kesarjawada	Local Nallah	Earthen	1997		620	13.27	1.25	1.17		0.02	IR
289.	Kesavari Samudram	Nallavagu	Earthen			1389	10.02	8.15	7.33			IR
290.	Khadakwasla	Mutha	Earthen/Gravity/Masonry	1880	501.8	1539	32.9	86	56	Ogee	1.48	IR
291.	Khairy	Khar	Earthen	1989	207.8	1210	18.91	15.11	14.34	Ogee	0.05	IR
292.	Khamboli	Local Nallah	Earthen	2000		308	25.34	1.68	1.61		0.03	IR
293.	Khamkarwadi	Local Nallah	Earthen	2004		204	26.34	1.09	1.09		0	IR

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294.	Khanapur (Kolhapur)	Local Nallah	Earthen	1988		240	21.35	0			0.02	IR
295.	Khandala	Local Nallah	Earthen	1973	72.11	276	24.49	6.26	5.24		0.09	I R
296.	Khandeshar	Vali	Earthen	1978	120.32	1257	17.14	10.84	8.82	Ogee	0.3	IR
297.	Khasapur	Ulup	Earthen	1956	554.26	1882	13.78	13.59	13.04		0.43	IR
298.	Kini	Local Nallah	Earthen	1967		648	11.43	1.36	1.24		0.05	IR
299.	Kitwad	Local Nallah	Earthen	2000		270	30.5	5.53	5.23		0.05	IR
300.	Kode	Local Nallah	Earthen	1989		530	24.77	0.01	0.01		0.08	IR
301.	Kodli-Allapur	Local/Mullamari	Earthen	2000		510	16.93	5.01	4.51		0.1	IR
302.	Kohalli	Hire Halla	Earthen	1975		659	14.63	2.47	2.14		0.1	IR
303.	Koil Sagar	Peddavagu	Earthen/Gravity/Masonry	1955	1836.32	1037	16	64.45	59.89			IR
304.	Kolgaon	Hanga	Earthen	1956		1038	12.74	2.88	2.49		0.01	IR
305.	Kolgaon Dolas	Local Nallah	Earthen	1981		815	10.46	1.06	0.87			IR
306.	Kondej	Local Nallah	Earthen	1974		945	10.82	1.79	1.49			IR
307.	Kondoshi	Local Nallah	Earthen	2000		380	35.68	2.76	2.62		0.03	IR
308.	Koragaonwadi	Local Nallah	Earthen	1974		1346	11.13	1.44	1.33		0.07	IR
309.	Koregaon	Koregaon	Earthen	1988		437	21.64	1.96	1.9			I R
310.	Koregaon	Local Nallah	Earthen			1818	11.95	4.61	3.68		0.14	IR
311.	Kosari	Local Nallah	Earthen	1970		610	10.9	1.45	1.39			IR
312.	Kothacheru, Mamdabad	Lower Krishna	Earthen			873	10.01	0.68				IR

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313.	Kotij	Local Nallah	Earthen	1993		796	14.6	1.47			0.05	IR
314.	Kotipally Vagu	Kotepallyvagu	Earthen	1967	294	2189	26	44.51	36.87		0.72	IR
315.	Kottur	Krishna/Tungabhadra	Earthen	1888		1777	15	4.91	4.87		0.27	IR
316.	Koyna	Koyna	Earthen	1964	891.78	807.72	103.02	2980.68	2835.68	Ogee	1.15	HE
317.	Krishnasamudram		Earthen	1963		978	12.27	0.31				IR
318.	Krishyal	Krishyal	Earthen/Gravity/Masonry	1964		730	10.91	1.62	1.46		0.07	IR
319.	Kuchi	Local Nallah	Earthen	1961		551	13.3	2.23	2.2		0.3	IR
320.	Kudnur	Local Nallah	Earthen	2005		316	20.99	11.93	1.06		0.02	IR
321.	Kumari	Kumari Nallah	Earthen	1998		510	23.64	2.59	2.53		0.04	IR
322.	Kumbhawade	Local Nallah	Earthen	1999		677	25.16	5.53	5.53		0.05	IR
323.	Kumbhej	Local Nallah	Earthen	1982		1016	10.68	1.35	1.18			IR
324.	Kumbhi	Kumbhi	Earthen	2007	21.2	906	42.58	76.88	76.5	Ogee	0	HE, IR
325.	Kundali	Kundali	Earthen			205	38.26	6.34	6.34			H E
326.	Kunigal Thimmanahalli	Thimmanahalli Nallah	Earthen	1980		330	14.2	2.17	1.96		0.07	IR
327.	Kunsawali	Local Nallah	Earthen	1997		466	15.04	1.17	1.06		0.02	IR
328.	Kuppakaddi	Kuppakadi	Earthen/Gravity/Masonry	1969		865	11.27	1.84	1.66		0.07	IR
329.	Kurnur	Bori	Earthen	1968		1206	23.7	35.26	31.3		0.57	IR
330.	Kuvalgi Aheri	Kuvalgi Aheri	Earthen/Gravity/Masonry	1981		518	13.55	1.44	1.3		0.05	IR
331.	Lakhnapur	Pargi stream	Earthen	1968		1263	15.85	8.61	7.93			IR

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332.	Lakhya	Lakhya hole	Earthen	1994		1048	108	273.79	245		0.61	WS
333.	Lakikatti	Local Nallah	Earthen	2000		535	36.34	9.24	8.98		0.08	IR
334.	Lakshmisagar	Suvarnamukhi	Earthen			960	10.5	6.7	6.09		0.21	IR
335.	Landgewadi	Local Nallah	Earthen	1973		408	11.37	1.04	0.97		0.27	IR
336.	Lankasagar	Kottaleru	Earthen/Gravity/Masonry	1968	207.2	2718	11.6	20.38	17.29		2.98	IR
337.	Large, Garla	Kamepalli	Earthen			1500	10.34	19.38				IR
338.	Large, Husnabad	Local vagu	Earthen			1787	11.5	5.61	3.98			I R
339.	Large, Ibrahimpatnam		Earthen			930	13	1.9	0.93			IR
340.	Large, Raviryal		Earthen			2132	12	14.42				IR
341.	Large, Shamirpet/ Shameerpet		Earthen			1680	12	15.96				IR
342.	Lavangi	Local Nallah	Earthen	1977		1025	10	1.19	0.83			IR
343.	Lengare		Earthen	1974		505	14.4	0.03	0.03			IR
344.	Lengarpath	Local Nallah	Earthen	1979		660	14.8	2.21	1.96		0.01	IR
345.	Lingnoor	Local Nallah	Earthen	1975		970	14.27	2.43	1.96			IR
346.	Lodhawade	Local Nallah	Earthen	1975		555	16.03	0.99	0.07		0.07	IR
347.	Lodhe	Kapur	Earthen	1996		1114	16.76	0			0.11	IR
348.	Lonavala	Indrayani	Gravity/Masonry	1916	14	1544	15.35	11.73	11.5		0	HE, IR
349.	Loni	Local Nallah	Earthen	1979		1194	14.13	1.49	1.34		0.05	IR

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350.	Loni Mawala	Local Nallah	Earthen	1981		958	10	1.08	0.88		0	IR
351.	Lower Hirenala											
352.	Lower Mullamari	Mullamari	Earthen/Gravity/Masonry	2001	730.68	1546	24.46	49.13	43.27	Ogee	0.85	IR
353.	Madagamasur	Kumadavati	Earthen	1908		950	32.87	1.6	1.47		0.19	I R
354.	Madanwadi	Local Nallah	Earthen	2003		985	12.58	5.7	4.84			IR
355.	Mahabaleshwarwadi	Local Nallah	Earthen	1975		864	13.42	1.72	1.5			IR
356.	Mahakoshi	Ambavade	Earthen	1998		455	24	2.28	1.96			IR
357.	Mahu	Kudali	Earthen	2011	28.62	1250	54.35	31.05	30.88	Ogee	0.2	HE,IR
358.	Mahur	Khopu	Earthen	1978		275	23	2.36	1.81			IR
359.	Majjur	Dodda Halla Nallah,	Earthen	1974		413.5	19.51	6.38	5.8		0.1	IR
360.	Makhanpur	Makhanpur	Earthen/Gravity/Masonry	1961		951	13.75	2.69	2.53		0.1	IR
361.	Malad	Malad	Earthen	1979		485	15.63	1.74	1.23		0.04	IR
362.	Malaprabha	Malaprabha	Gravity/Masonry	1972	2564	154.52	43.13	1068	972	Ogee	13.58	HE,IR
363.	Malatwadi	Local Nallah	Earthen	2004		325	18.07	1.52	1.11		0.02	IR
364.	Malawandi	Local Nallah	Earthen	2000		410	20.45	3.68	3.29		0.02	IR
365.	Malikacheru, Mamdabad		Earthen			472	11	1.44				IR
366.	Malkapur	Local Nallah	Earthen	1995			22.8	2.37	2.22			I R
367.	Mallammacheruvu Saralnagar		Earthen			929	11	0.55				IR

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368.	Mamdapur	Local Nallah	Earthen	1983		1189	14.5	2.52	1.83			IR
369.	Mandave	Local Nallah	Earthen	1998		940	15.13	1.74	1.74		0.05	IR
370.	Mandve (Satara)		Earthen	1994		1080	19.5	3.15	3.15		0.05	IR
371.	Mangalore	Mangalore	Earthen/Gravity/Masonry	1970		124	16.38	1.59	1.29		0.03	IR
372.	Mangi	Kanola	Earthen	1966		1475	22.95	32.72	32.72			IR
373.	Manikdoh	Kukadi	Gravity/Masonry	2005	129	930	50.36	307.91	288.1	Ogee	1.84	HE, IR
374.	Manoli	Local Nallah	Earthen	2000		308	29.5	5.2	4.91		0.04	IR
375.	Manpadale	Local Nallah	Earthen	1971		612	20.8	1.43	1.29		0.03	IR
376.	Markandeya	Markandeya	Gravity/Masonry	2005	432	475	47	113.27	93.73	Ogee	0.9	IR
377.	Marnewadi	Local Nallah	Earthen	1998		430	18.33	0.87	0.84		0.01	IR
378.	Maroli	Local Nallah	Earthen	1981		1050	11.3	1.98	1.53			IR
379.	Masalwadi	Local Nallah	Earthen	1973		463	15.25	2.41	2.02		0.07	IR
380.	Maskinala	Maskinala	Earthen/Gravity/Masonry	2003	800.31	814	29.88	13.11	10.7	Ogee	0.17	IR
381.	Masla	Local Nallah	Earthen			1380	10.95	1.56	1.36		0.06	I R
382.	Matkuli	Local Nallah	Earthen	1997			15.39	1.76	1.49			IR
383.	Matoba	Mulamutha	Earthen	1978		1662	17.5	4.55	4.52		0.19	IR
384.	Mavinahole	Local Nallah	Earthen	1928		585	20.11	1.84	1.54		0.04	IR
385.	Mayani	Chand	Earthen	1872		1098	18	1.46	1.45		0.15	IR
386.	Medleri	Local Nallah	Earthen			701.5	10.68	1.74	1.74		0.07	IR

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387.	Megholi	Local Nallah	Earthen	2000		495	32.9	2.79	2.66		0.03	IR
388.	Mehakari		Earthen	1966	338.77	1308	27.63	16.13	13		0.35	IR
389.	Melammacheru/ Melmacheru	Local Stream	Earthen			610	11	2.73				IR
390.	Mhaiswadi	Local Nallah	Earthen	1945		780	12.23	2.04	1.53			IR
391.	Mhaswad	Man	Earthen	1887	1243.15	2473	24.32	47.88	46.21		1.63	IR
392.	Mirwad	Local Nallah	Earthen	1980		1130	14.4	1.58	1.39		0.01	IR
393.	Mohari (Jamkhed)	Mujdul	Earthen	1968		427	14.1	1.77	1.52		0.09	IR
394.	Morale	Local Nallah	Earthen	1971		381	16.1	0.65	0.54			I R
395.	Morana (Gureghar)	Morna	Earthen	2010	55.94	560	47.02	39.55	36.99	Ogee	0.34	HE, IR
396.	Morna (Shirala)	Morna	Earthen	1985	85.5	1015	31.2	21.2	16.51		0.23	IR
397.	Motewadi	Local Nallah	Earthen	1976		533	13.07	1.09	0.83			IR
398.	Muchakhandi	Muchakhandi	Gravity/Masonry	1984		158	18.3	1.89	1.64		0.36	IR
399.	Mugaon	Local Nallah	Earthen	1975		623	11.2	1	0.82		0	IR
400.	Mukherthihal	Mukherthihal	Earthen/Gravity/Masonry	1979		852	10.41	1.45	1.45		0.06	IR
401.	Mulikwadi	Local Nallah	Earthen	2003		1350	13.44	1.65	1.35		0.03	IR
402.	Mulshi	Mula	Gravity/Masonry	1927		1533.38	48.8	52.23			0.38	HE, IR
403.	Mundawad	Shirahatti Nala	Earthen	1994		994	20.19	2.96	2.69		0.14	IR
404.	Munneru - New, Munnuru,	Kagna	Earthen/Gravity/Masonry	1982		600	14		1.12			IR

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	Somaram											
405.	Murakumbi	Local Nallah	Earthen	1970		726	16.94				0.05	IR
406.	Musi	Musi	Earthen	1963		4694	28	136.77	130.26			IR
407.	Nagarjuna Sagar	Krishna	Earthen	1974	220000	4865	124.66	11561.3	5733.31		28.5	HE, IR
408.	Nagarjunasagar Tail Pond	Krishna	Earthen			592	29	5.66	0.82			IR
409.	Nagathan	Nagathan nala	Earthen/Gravity/Masonry	1961	68	1125	10.63	2.78	2.41	Ogee	0.13	IR
410.	Nagewadi	Local Nallah	Earthen	1999	11.91	1090	40.02	6.47	5.99	Ogee	0.01	IR
411.	Nagurur		Earthen	1971		800	28.05	1.14	1.14			IR
412.	Naigaon	Khar	Earthen	1978		668	15.96	2.37	1.9		0.06	IR
413.	Naigaon Deogaon	Gunjawani	Earthen	1979		272	22.49	1.33	1.07		0.02	IR
414.	Naigaon I	Local Nallah	Earthen	1983		800	18	1.34	1.12		0.29	IR
415.	Naigaon II	Local Nallah	Earthen	1983		520	16.46	0			0.03	IR
416.	Nallacheru, Irvin		Earthen	1990		1480	10.05	0.39	0.34			IR
417.	Nandari	Local Nallah	Earthen	1999		443	26.4	3.21	3.11		0.03	IR
418.	Nandgad											
419.	Nandgaon	Local Nallah	Earthen	1998		275	22.51	1.98	1.62		0.31	IR
420.	Nandwal (Kolhapur)	Local Nallah	Earthen	2005		524.5	18.65	0.94	0.8		0.02	IR
421.	Nandwal	Vasana	Earthen	1986		886	20.25	1.79	1.62		0.04	IR
422.	Nangole	Local Nallah	Earthen	1978		636	15.45	1.85	1.29			IR

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423.	Narayanapura	Krishna	Earthen/Gravity/Masonry	1982	47850	10637.52	29.72	1066	863	Ogee	13.21	HE, IR
424.	Narewadi	Local Nallah	Earthen	1981		455	23.75	2.22	2.07		0.04	I R
425.	Narihalla	Narihalla	Earthen/Gravity/Masonry	1981	427	295	32.92	22.94	20.87	Chute	0.25	IR
426.	Nazare		Earthen	1974	397.82	2021	22.54	22.32	16.65	Ogee	0.39	IR
427.	Nerle	Local Nallah	Earthen	1977		1230	12.15	2.24	2.1			IR
428.	New, Bellempally	Bollampallyvagu	Earthen	1988		740	12.8	0.94	0.82			IR
429.	Nhavi	Local Nallah	Earthen	1984		995	17.48	2.19	2.01		0	IR
430.	Nher	Yerala	Earthen	1889	154.1	1470	22.5	9.12	1.17	Other	0.33	IR
431.	Nimbawade	Local Nallah	Earthen	1986		1070	16.13	6.68	5.68		0.23	IR
432.	Nimgaon (Madha)	Local Nallah	Earthen	1983		1202	10.4	1.72	1.46			IR
433.	Nimgaon	Gumera	Earthen	1985		1279	19.3	5.06	4.4		0.15	IR
434.	Nimgaon Mahalungi	Kamini	Earthen	1971		3140	17.3	3.37	2.97			IR
435.	Nira Deoghar	Nira	Earthen	2008	114.48	2330	58.525	337.39	332.13	Ogee	1.6	HE, IR
436.	Nittur-I	Local Nallah	Earthen	2000		425	22.55	1.9	1.87		0.03	IR
437.	Nittur-II	Local Nallah	Earthen	2000		567	27.82	4.38	4.28		0.05	IR
438.	Olwan	Local Nallah	Earthen	1996		327	24.74	1.88	1.79		0.02	I R
439.	Ookachettivagu	Ookachettivagu	Gravity/Masonry	1980	4071.43	254.95		10.87		Ogee		IR
440.	Osman Sagar	Musi	Earthen/Gravity/Masonry	1920		2630	41	15.7				IR, WS
441.	Otur Vaghadara	Ramnagar	Earthen	1991		402	15.48	0				IR

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442.	Padasali	Local Nallah	Earthen	1997		450	29.15	6.9	3.83		0.1	IR
443.	Padawalkarwadi	Koni Kunur	Earthen	1973	55.68	822.96	15.17	2.99	2.12		0.12	IR
444.	Pakhal Lake	Pakhal vagu	Earthen/Gravity/Masonry	1902	21.76	1370	19	95.88			2.18	IR
445.	Palair	Paleru	Earthen/Gravity/Masonry	1928	0	3697	21	72.45	66.19			IR
446.	Palasdeo	Local Nallah	Earthen	1953		518	15.55	2.67	2.53		0.08	IR
447.	Palasnilgaon	Local Nallah	Earthen	1997			14.65	5.68	4.97		0.02	IR
448.	Pandhari	Local Nallah	Earthen	1982		71	13.86	1.14	1.01		0.01	IR
449.	Panshet	Ambi	Earthen/Gravity/Masonry	1972	120.3	1039	59.94	310.6	301.61	Ogee	1.56	HE, IR
450.	Parashuramapura New	Malenura Halla	Earthen	1959		1650	12.19	5.2	4.27		0.27	IR
451.	Pare	Local Nallah	Earthen	1972		498	18.4	1.53	1.29			IR
452.	Parewadi	Local Nallah	Earthen	1966		1050	12.58	5.19	4.04			IR
453.	Pargaon	Local Nallah	Earthen	1976		1200	13.65	1.08	0.9			I R
454.	Pargaon Sudrik	Surswati	Earthen	1969		313	14.5	1.1	0.82		0	IR
455.	Parite	Local Nallah	Earthen	1979		439	11.69	1	0.8			IR
456.	Parunde	Local Nallah	Earthen	1989		345	20.02	0			0.02	IR
457.	Patane	Local Nallah	Earthen	2001		364	27.39	4.55	4.45		0.04	IR
458.	Patgaon	Vedganga	Earthen	1990	26.08	1101.5	39.19	105.24	104.77		0	HE, IR
459.	Patgaon Saddle-I	Vedganga	Earthen		26.08	1155	21	105.24	104.77		0	IR
460.	Patgaon Saddle-III	Vedganga	Earthen		26.08	610	7.85	105.24	104.77		0	IR

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461.	Pathari	Local Nallah	Earthen	1905		2070	18.43	11.88	11.62			IR
462.	Pathrud	Local Nallah	Earthen	1997		960	13.8	2.35	2.04		0.02	IR
463.	Pawana	Pawana	Earthen/Gravity/Masonry	1972	119.96	1329	42.37	305	274	Ogee	0.24	HE, IR
464.	Ped	Local Nallah	Earthen	1972		489	19.04	1.57	1.34			IR
465.	Pedda Cheru, Challasamudram		Earthen			700	12.2					IR
466.	Pedda Cheru, Chintapalli	Krishna	Earthen			1216	15	1.3	1.17			IR
467.	Pedda Cheru, Inapur		Earthen			560	10	3.09	2.92			IR
468.	Pedda Cheru, Indurthy	Local Stream	Earthen			1364	10	3.94				IR
469.	Pedda Cheru, Kodad	Krishna	Earthen			2307.64	10	3.97	3.57			IR
470.	Pedda Cheru, Shivanagudem	Krishna	Earthen			1364	20	3.94	3.55			IR
471.	Pedda Cheru, Swamulavari Lingotam	Local Stream	Earthen			518	10	1.12				IR
472.	Pedda Cheru, Thangadpally	Local Stream	Earthen			690	13	3.88				IR
473.	Pedda Cheru, Lokaram	Lokaramv agu	Earthen	1968		1600	10.06					IR
474.	Pedda Cheru, Lokurthy	Peddavagu	Earthen			1101	11	1.07	0.76			IR
475.	Peddacheru, Ragaboinagudem	Ragaboinagudem vagu	Earthen	1942		1200	13.3	6.24	4.44			IR
476.	Peddarayanicheru, Lingal		Earthen			326	17.3	1.35				IR
477.	Perval		Earthen				15	4.28	3.17			IR
478.	Phaye	Local Nallah	Earthen	2004		355.65	34.13	3.93	0.04		0.04	IR

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479.	Pilanwadi	Rudraganga	Earthen	1978		320	22.77	1.94	1.82		0.04	IR
480.	Pimpalgaon (Dhale)	Sina Nallah	Earthen		288	2310	18.7	12.66	9.86	Ogee		IR
481.	Pimpalgaon Alwa	Kanhuri river	Earthen	1979		660	14.03	2.85	2.42		0.06	IR
482.	Pimpalgaon Joge	Pushpavati	Earthen	2001	91	1560	28.6	235.53	110.32	Ogee	3.07	IR
483.	Pimpla	Local Nallah	Earthen	1972		680	11.91	0.86	0.74		0.03	I R
484.	Pimpoli	Mula	Earthen	1984		401	22.13	1.53	1.41		0.03	IR
485.	Pingali		Earthen	1978		1693	16	2.38	2.36		0.11	IR
486.	Pingori	Local Nallah	Earthen	1969		221	22.13	0.61	0.56			IR
487.	Piserve	Local Nallah	Earthen	1958		625	14.63	1.65	1.56			IR
488.	Pohner	Local Nallah	Earthen			636	14.8	1.17	1.04		0.04	IR
489.	Pokharapur	Local Nallah	Earthen	1981		1202	10.33	1.86	1.65			IR
490.	Polkicheru, Pangal		Earthen/Gravity/Masonry			707	15.7	1.3				IR
491.	Pombre	Local Nallah	Earthen	1985		488	24.11	6.5	6.36		0.08	IR
492.	Pondewadi	Local Nallah	Earthen	2003		382	12.1	1.77	1.5			IR
493.	Prakruthi	Gundire halla	Earthen	1979		840	16.17				0.16	IR
494.	Pratappur	Local Nallah	Earthen	1987		824	16.9	1.66	1.44		0.05	IR
495.	Priyadarshini Jurala/Jurala	Krishna	Earthen/Gravity/Masonry	1996	130000	4534	40	338.1	192.3	Ogee	6.77	HE, IR
496.	Punadi	Local Nallah	Earthen	1987		476	17	0			0	I R
497.	Purdal											

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498.	Radhanagari	Bhogawati	Gravity/Masonry	1954	110.08	1036.58	38.41	236.79	219.97	Ogee	1.83	HE, IR
499.	Raghuchiwadi	Local Nallah	Earthen	1976		646	16.55	5.67	1.34		0.06	IR
500.	Raiwadi	Local Nallah	Earthen	1976		867	20.35	2.16	1.88			IR
501.	Rajuri	Local Nallah	Earthen	1981		609	19.3	2.49	2.08			IR
502.	Rakkaskop	Markandeya	Earthen/Gravity/Masonry	1962		358.37	26.34	16.62	16.12		0.35	WS
503.	Rakshaswadi Bk	Local Nallah	Earthen	1986		840	12.27	1.23	1.06		0.01	IR
504.	Rakshaswadi	Khosara Nallah	Earthen	1979		648	12.88	1.6	1.6		0.06	IR
505.	Ramalingapura	Suvarnamukhi	Earthen			830	12	6.74	6.07		0.22	IR
506.	Ramanahalli	Navalli Nallah	Earthen	1958	368.5	1619	16.5	14.47	7.79		0.46	IR
507.	Ramganga	Ulup	Earthen	1977	44.53	1217	29.97	6.14	5.35		0.14	IR
508.	Ramjiwadi	Meena	Earthen	1983		314	21.48	1.72	1.55		0.02	IR
509.	Rampur	Local Nallah	Earthen	1973		1646	10.64	3.06	2.76			I R
510.	Ranand	Waghzai	Earthen	1958	158.7	1260	19.32	7.12	6.42		0.12	IR
511.	Ranganayanadurga	Jinagihalla	Earthen			900	19.88	14.16	13.13		0.32	IR
512.	Rangasamudra	Rangasamudra	Earthen/Gravity/Masonry	1978		317	23.8	4.69	3.7		0.07	IR
513.	Rangasamudram		Earthen		120.69	2460	29	51.49	32.81			IR
514.	Ranikere	Garnihalla	Earthen	1907	159	960	12.19	15.26	14.26		0.58	IR
515.	Rasulacheru		Earthen			1558	11	1.29				IR
516.	Ratnapur	Local Nallah	Earthen	1985		1135	17.2	2.37	1.38			IR

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517.	Revnal	Local Nallah	Earthen	1978		247	18.6	2.37	2.19			IR
518.	Rihe	Local Nallah	Earthen	1977		285	21.94	1.58	1.2		0.03	IR
519.	Ronihal	Ronihalla	Earthen/Gravity/Masonry	1979		689	13.02	1.35	1.22		0.05	IR
520.	Rooty		Earthen	1939	147.2	2091	16.77	8.13	6.57		0.25	IR
521.	Rui Chatrapati	Gopal Ganga	Earthen	1980		420	10.77	1.04	0.76		0	IR
522.	Sakat	Dudhana	Earthen	1994	195.84	1805	19.8	14.43	13.44		0.34	IR
523.	Sangambanda	Krishna			896	4287	19.45	93.93	48.82	Ogee	4.7	IR
524.	Sangavi	Local Nallah	Earthen	1935			13.29	2.5	2.5			I R
525.	Sangavi Shirval	Local Nallah	Earthen	1993		850	18	1.34	0.9			IR
526.	Sangenahalli	Jinigehalla	Earthen	1968		1341	15.55	11.03	10.3		0.34	IR
527.	Sangvikati	Local Nallah	Earthen			706	11.3	1.26	1.07		0.07	IR
528.	Sankarasamudram	Krishna			284.1	3275	10.145		25.37	Ogee		IR
529.	Sankh	Bor	Earthen	1995	520.6	3282	17.66	14.9	9.82	Ogee	0.08	IR
530.	Sanmadi	Local Nallah	Earthen	1979		485	17.46	1.98	1.67			IR
531.	Saptne	Local Nallah	Earthen	1965		1292	12.01	2.83	2.72			IR
532.	Sarala Sagar	Chinnavagu	Earthen	1959	756.7	1524	12	14				IR
533.	Sarfnalla		Earthen		11.88	1355	33.327	18.94	18.18	Ogee	0.26	HE, IR
534.	Sarpanapally	Sarpanapallyvagu	Earthen	1989		1204	18.44	7.09	5.58			IR
535.	Satewadi	Local Nallah	Earthen			730	13.6	1.04	0.84		0.04	IR

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536.	Seegehalla	Seegehalla	Earthen	1979		660	16.5	3	2.9		0.06	IR
537.	Shalgaon	Local Nallah	Earthen	1976		900	15	2.28	2.06			IR
538.	Sheelavantanakoppa D. Kere	Jamboor Halla	Earthen			200	13.28	8.62	8.44		0.14	I R
539.	Shegaon	Local Nallah	Earthen	1975		498	19.92	8.08	5.81			IR
540.	Shelgaon	Local Nallah	Earthen	1983		1155	11.45	3.27	2.69			IR
541.	Shendri	Local Nallah	Earthen	1981		625	20.14	1.81	1.74			IR
542.	Shere	Local Nallah	Earthen	1998		205	22.98	1.76	1.68			IR
543.	Shetphal	Shetphal Nallah	Earthen	1901		3211	20.11	21.18	20.47		0.35	IR
544.	Shirsufal	Local Nallah	Earthen	1879		741	20.11	10.1	9.52		0.16	IR
545.	Shirvalwadi	Local Nallah	Earthen	1978		600	16.1	3.28	2.95			IR
546.	Shirvata	Indrayani	Gravity/Masonry	1920	28	2212	38.71	185.98	185.11	Ogee	0	HE
547.	Shivani	Local Nallah	Earthen	1991		1014	16.23	0			0.04	IR
548.	Siddasamudra	Local Nallah/ Malaprabha	Earthen	1967		712	13.72	2.16	1.88		0.1	IR
549.	Siddhewadi	Agrani	Earthen	1981	168.35	959	19	8.57	6.1		0.15	IR
550.	Siddhnath	Local Nallah	Earthen	1977	302.95	784	18.81	6.43	4.89			IR
551.	Sidewad	Local Nallah	Earthen			810	10.15	0.75	0.57		0.04	IR
552.	Sina	Sina	Earthen	1986	1582.48	1580	28.5	67.95	52.3	Ogee	1.39	IR
553.	Sina Kolegaon	Sina	Earthen	2007	5569	1770	26.1	150.49	89.34	Ogee	3.13	IR
554.	Singahallidalvayikere	Suvarnamukhi SS	Earthen			870	11.45	3.18	2.87		0.12	IR

Sl. No.	Name of dam	River	Type of dam	Year of completion	Catchment area (km²)	Length of dam (m)	Max height above foundation (m)	GSC (MCM)	LSC (MCM)	Type of spillway	Submergence area (Th. Ha)	Purpose
555.	Sir Pirajirav Talav	Local Nallah	Earthen	1923		1295	21.95	2.91				I R
556.	Sonali	Local Nallah	Earthen	1979		638	12.15	1.08	1.06		0.03	IR
557.	Sonari	Local Nallah	Earthen	1965		938	16.5	1.49	1.3		0.05	IR
558.	Sordi	Local Nallah	Earthen	1983		620	18.08	4.4	3.35		0.07	IR
559.	Soudagar	Soudagar Nala	Earthen	1987	55.58	600	27.03	8.12	7.41		0.15	IR
560.	Sowlanga	Hirehalla	Earthen	1928		900	12	9.44	8.99		0.18	IR
561.	Srisailam (N.S.R.S.P)	Krishna	Earthen	1984	206000	512	145	8722	7165.83			HE, IR
562.	Srivari Samudram, Singotam	Kalawakolevagu	Earthen			1105	14	0.02	0.01			IR
563.	Sulkod	Sulkod Nala	Earthen/Gravity/Masonry	1964		762.2	10.9	1.34	1.22		0.06	IR
564.	Suryanarayana cheru	Musi	Earthen			1142	10.35	1.21	0.76			IR
565.	Tadavalga	Tadavalga Nala	Earthen/Gravity/Masonry	1965		1070	11.02	1.84	1.32		0.07	IR
566.	Takali Khandeshwari	Local Nallah	Earthen	1981		1100	10.9	1.27	0.96		0.01	IR
567.	Takave	Local Nallah	Earthen	1989		837	24.81	0			0.01	IR
568.	Talakal	Krishna/Tungabhadra	Earthen	1983		1200	14.02	1.15	0.98		0.07	IR
569.	Talegaonghogaon		Earthen	1980		740	21.18	1.59	1.38			IR
570.	Talsangi	Bhavani	Earthen	1976		792	15.24	2.42	2.42			IR
571.	Talwar	Talwar	Earthen	1958	89.9	1584	14.36	3.78	3.24		0.17	I R
572.	Tambve	Sharand	Earthen	1968		1310	18	5.42	4.85		0.15	IR
573.	Tarali	Tarali	Gravity/Masonry		81.45	1096	73.41	165.71	165.46	Ogee	0.56	HE, IR

Sl. No.	Name of dam	River	Type of dam	Year of completion	Catchment area (km²)	Length of dam (m)	Max height above foundation (m)	GSC (MCM)	LSC (MCM)	Type of spillway	Submergence area (Th. Ha)	Purpose
574.	Tarangawadi	Local Nallah	Earthen	1953		593	14.3	1.76	1.74			IR
575.	Tatikunta		Earthen			55	17.9					IR
576.	Tawadi	Local Nallah	Earthen	1983		1811	11.9	1.23	1.04			IR
577.	Telengshi	Kharnalla	Earthen	1975		622	17.12	1.07	0.96		0.03	IR
578.	Temghar	Mutha	Earthen/Gravity/Masonry	2010	37.7	1075	42.5	107.9	105.01		5.55	HE, IR
579.	Terni	Local Nallah	Earthen	1996		960	20.66	3.48	3.17		0.02	IR
580.	Therodi		Earthen	1977		1106	11.97	3.12	2.49		0.14	IR
581.	Thitewadi	Vel	Earthen	2003		1320	21.1	9.86	7.15		0.19	IR
582.	Thokarwadi	Indrayani	Gravity/Masonry	1922	124.32	741	59.44	363.7	321.2	Ogee	0	HE
583.	Thoseghar	Tarali	Earthen	1989		259	18.05	0			0.03	IR
584.	Tikondi-I	Local Nallah	Earthen	1980		1077	14.65	3.24	2.81		0.01	IR
585.	Tikondi-II	Local Nallah	Earthen	1986		879	14.45	2.45	2.2		0.01	I R
586.	Tintraj	Local Nallah	Earthen	1982		535	15.5	1.39	1.14	Ogee		IR
587.	Tippehalli	Local Nallah	Earthen	1975		444	18.12	2.02	1.47	Ogee		IR
588.	Tisangi	Local Nallah	Earthen	1966	10.4	2866	20.82	24.46	22.76	Ogee	0.56	IR
589.	Tulshi	Tulshi		1978	34.92	1512	48.68	98.29	89.91	Ogee	0.05	HE, IR
590.	Tungabhadra	Tungabhadra	Earthen/Gravity/Masonry	1953	28180	2443	49.39	3766	3700	Ogee	34.92	HE, IR
591.	Turori	Local Nallah	Earthen	1983	88.47	1192	17.5	7.66	5.74		0.22	IR
592.	Uduvalli											

Sl. No.	Name of dam	River	Type of dam	Year of completion	Catchment area (km²)	Length of dam (m)	Max height above foundation (m)	GSC (MCM)	LSC (MCM)	Type of spillway	Submergence area (Th. Ha)	Purpose
593.	Ughadewadi	Local Nallah	Earthen	1994		594	12.5	1.38	1.08	Ogee	0	IR
594.	Ujjani	Bhima	Earthen/Gravity/Masonry	1980	14850	3141.4	56.4	3320.01	1520.87	Ogee	29	HE, IR
595.	Umarani	Local Nallah	Earthen	1999		220	15.33			Ogee		IR
596.	Upavade	Marhol	Earthen	1996	3.5	415	32.31	2.85	2.83		0.03	IR
597.	Upper Hirenala	Hirenala	Earthen	1989	191.66	1935	18.27	6.54	5.66		0.17	IR
598.	Upper Mullamari	Mullamri	Earthen	1984	207	810	28.4	21.22	18.88		0.63	IR
599.	Upper Tunga	Tunga	Earthen/Gravity/Masonry	2005	94700	791.39	17.5	91.86	50.24	Other	1.63	HE,WS, IR
600.	Urmodi	Urmodi	Earthen	2001	135.85	1860	50.1	282.14	273.27	Ogee	0.02	HE, IR
601.	Urwade	Local Nallah	Earthen	1983		693	23.48	2	1.9	Ogee	0.1	IR
602.	Utchil	Local Nallah	Earthen	2001		454	17.01	3.06	2.94	Ogee	0.09	IR
603.	Utkoor Marepally											
604.	Uttarmand	Uttarmand	Earthen	2001	43.69	1420.5	46.45	24.93	24.59	Ogee	0.24	HE, IR
605.	Vadgaon	Mand	Earthen	1980		526	21.7	2.97	2.56	Ogee		IR
606.	Vadiwale	Kundali	Earthen	1999	46.88	488	29	40.87	30.39	Ogee	0.36	IR
607.	Vairag	Local Nallah	Earthen	1963		534	10.65	1.46	1.44	Ogee		IR
608.	Vairagwadi	Local Nallah	Earthen	1984		845	20.34	1.5	1.25	Ogee	0.03	IR
609.	Vanivilasa Sagar	Vedavathy	Earthen/Gravity/Masonry	1907	1554	405.4	43.28	850.3	802.5		8.76	IR
610.	Varadaraja Swamy Gudi	Munimadugula vagu	Earthen	2000		588	22	11.02	10.21	Ogee		IR
611.	Varkute	Local Nallah	Earthen	1978		1093	12.2	1.43	1.27	Ogee		IR

Sl. No.	Name of dam	River	Type of dam	Year of completion	Catchment area (km^2)	Length of dam (m)	Max height above foundation (m)	GSC (MCM)	LSC (MCM)	Type of spillway	Submergence area (Th. Ha)	Purpose
612.	Veerladevi Cheru	Local Stream	Earthen/Gravity/Masonry			1918	11	5.16				IR
613.	Veet	Local Nallah	Earthen	1974		390	10.21	2.52	2.04			IR
614.	Vejegaon	Local Nallah	Earthen	1979		811	16.77	2.21	1.29			IR
615.	Vemular	Vemular	Earthen	1959		2040	12	9.9	8.88			I R
616.	Vesraf	Rupani	Earthen	1984		603	19.21	3.37	3.31		0	IR
617.	Vibhutiwadi	Local Nallah	Earthen	1983		1027	16.21	0			0.03	IR
618.	Vinchurni	Local Nallah	Earthen	1974			11.62	1.33	1.05			IR
619.	Vir	Nira	Earthen	1965	1756	3629	35.81	287.5	266	Ogee	3.17	HE, IR
620.	Vir	Rudra Nallah	Earthen	1996		975	21.81	2.55	2		0.13	IR
621.	Visapur	Hanga	Earthen	1936	412.59	2692	25.6	25.61	22.39	Other	0.62	IR
622.	Vishnusamudra	Veda Series	Earthen		24.6	1740	12.8	0.85	0.82		0.06	IR
623.	Wadaj	Meena	Earthen/Gravity/Masonry	1983	155	1935	28	35.94	33.11	Ogee	0.05	IR
624.	Wadgaon Tandli	Bangari	Earthen	1975		1005	13.75	1.9	1.45		0.01	IR
625.	Wadji	Local Nallah	Earthen	1998		232	22.97	1.75	1.58		0.02	IR
626.	Wadshivane	Local Nallah	Earthen	1902		984	14.56	4.35	4.26			IR
627.	Wafgaon	Vel	Earthen	1978		426	14.25	3.12	2.69			IR
628.	Wagajwadi	Local Nallah	Earthen	2001		370	20.47	1.66	1.58		0.03	IR
629.	Waki	Local Nallah	Earthen	2002		465	12.8	2.83	2.31			I R
630.	Wakurde	Morna	Earthen	1985		269	19.25	1.61	1.59			IR

Sl. No.	Name of dam	River	Type of dam	Year of completion	Catchment area (km²)	Length of dam (m)	Max height above foundation (m)	GSC (MCM)	LSC (MCM)	Type of spillway	Submergence area (Th. Ha)	Purpose
631.	Wakwad	Local Nallah	Earthen	1996			16.8	1	0.15		0.01	IR
632.	Walekhindi	Local Nallah	Earthen	1973		800	16.18	4.13	3.1			IR
633.	Walen	Walki	Earthen	1989		410	20.75	5.11	5.07		0.03	IR
634.	Walgud	Local Nallah	Earthen	1969		1036	15	1.62	1.46		0.05	IR
635.	Walki	Walumbe	Earthen	1977		1290	12.63	3.08	1.86		0.01	IR
636.	Walunj	Local Nallah	Earthen	1977		883	17.86	1.69	1.42			IR
637.	Walwad	Local Nallah	Earthen	1983		822	14.68	1.19	0.92			IR
638.	Walwan	Indrayani	Gravity/Masonry	1916	14.2	1356	26.36	72.5	72.12	Ogee	1.43	HE
639.	Wang	Wang	Earthen		73.34	1200	50.63	77.29	77.06	Ogee	0.53	HE, IR
640.	Warasgaon	Mose	Earthen/Gravity/Masonry	1993	130	780	66.6	375.36	363.13	Ogee	1.86	HE, IR
641.	Warna	Varna	Earthen/Gravity/Masonry	2000	301	1580	88.8	974.19	779.35	Ogee	0	HE, IR
642.	Watephal	Local Nallah	Earthen	2000		680	15.06	4.27	3.92		0.01	IR
643.	Welpuri	Local Nallah	Earthen	1979		521	20.5	1.78	1.59			I R
644.	Wyra	Munneru	Earthen	1930	709.66	1768.3	26.82	70	60	Other	7.04	IR
645.	Y. Urumundinakere	Veda series	Earthen		5.19	1930	10	0.73	0.71		0.07	IR
646.	Yallammavadi	Local Nallah Krishna/ Malaprabha	Earthen	1990		775	10.3	1.48	1.29		0.07	IR
647.	Yallur	Local Nallah/ Markandeya	Earthen	1965		393	15.5	0.44	0.43		0.01	IR
648.	Yarazarvi	Local Nallah	Earthen	1969		699	12.16	1.34	1.16		0.04	IR
649.	Yedgaon	Kukadi	Earthen/Gravity/Masonry	1977	461	4470	24.6	93.43	79.28	Ogee	0.17	IR

Sl. No.	Name of dam	River	Type of dam	Year of completion	Catchment area (km^2)	Length of dam (m)	Max height above foundation (m)	GSC (MCM)	LSC (MCM)	Type of spillway	Submergence area (Th. Ha)	Purpose
650.	Yelavi	Local Nallah	Earthen	1982		764	15.25	22.26	2.18			IR
651.	Yeliv	Nanhi	Earthen	1975		1200	15.9	2.26	1.86		0.08	IR
652.	Yellur	Krishna										IR, WS
653.	Yenechiwandi	Local Nallah	Earthen	1996		611	21.65	1.55	1.43		0.02	IR
654.	Yenere	Local Nallah	Earthen	1979		774	19.5	2.07	1.92			IR
655.	Yenukunta	Krishna			1.75	1775	14	53.66	2.6	Ogee		IR
656.	Yeralwadi	Yerla	Earthen	1973		2115	19.5	33.02	18.06			IR
657.	Yermala	Local Nallah	Earthen	1998		237	15.27	1.41	1.29		0.2	I R
658.	Yesodi	Local Nallah	Earthen	1999		625	12.8	1.63				IR
659.	Yewati Masoli	Yeoti Nallah	Earthen	1989	31.99	973	36	7.05	6.8		0.09	IR
660.	Zildartippa, Molachintapalli	Mahabubnagar	Earthen			288	10	1.58				IR

Appendix II: List and description of barrage/weirs/anicuts in KRB (after, MoWR, 2014)

Sl. No.	Name of barrage/weir/anicut	River	Length (m)	Height up to crest (m)	Catchment area (Th. Ha)	Design flood discharge (m^3 s^{-1})	Purpose
1.	Ainapur Weir	Chitri	14.15	4.46		0	IR
2.	Ane Weir	Wang	81		320	2237.19	IR
3.	Are Weir	Tulshi	49.09	6.43		0	IR
4.	Asifnahar Barrage	Musi	0			0	IR
5.	Bachani Weir	Tulshi	45	5.5		0	IR
6.	Barjar Bhogaon Weir	Kasari	67.38	3.66		0	IR
7.	Bhadra Anicut	Bhadra	250			3400	IR
8.	Bhadwan Weir	Chitri	86.5	4.5		0	IR
9.	Bhatanwadi Weir	Tulshi	38.5	6.17		0	IR
10.	Biur K.T. Weir	Morna	0			0	IR
11.	Chandewadi Weir	Chitri	56	4.1		0	IR
12.	Dabhil Weir	Hiranyakeshi	0			0	IR
13.	Devarde Weir	Hiranyakeshi	0			0	IR
14.	Dhamod Weir	Tulshi	82	6.02		0	IR
15.	Dhumalwadi K.T. Weir	Morna	0			0	IR
16.	Dhupdal Weir	Ghataprabha	2084.98			0	HE
17.	Gajargaon Weir	Chitri	77.05	4.25		0	IR
18.	Ghattarga Barrage	Bhima	329			0	
19.	Ghungurwadi Weir	Tulshi	35.31	5.4		0	IR
20.	Gijwane Weir	Chitri	67.36	5.18		0	IR
21.	Haldi Weir	Bhogawati	94	3.2		0	IR

Sl. No.	Name of barrage/weir/anicut	River	Length (m)	Height up to crest (m)	Catchment area (Th. Ha)	Design flood discharge ($m^3 s^{-1}$)	Purpose
22.	Hipparagi Barrage	Krishna	5460	26	230000	19810	IR
23.	Jarli Weir	Chitri	94.9	5.5		0	IR
24.	Joladadagi Gudur Barrage	Bhima	550			0	IR
25.	Kadhane Weir	Wang	70.5		570	3176	IR
26.	Kallur Barrage	Bhima	253			0	IR
27.	Kanchanwadi Weir	Tulshi	83.4	4.7		0	IR
28.	Karanjphen Weir	Kasari	60	10.61		0	IR
29.	Khadk Koge Weir	Bhogawati	126	4.57		0	IR
30.	Khale Weir	Wang	74		240	1924.47	IR
31.	Khodashi Weir	Krishna	345	7	3400	0	HE,IR
32.	Koge Weir	Bhogawati	57	4.14		0	IR
33.	Kolchi Weir	Malaprabha	0			0	IR
34.	Kole Weir	Wang	65		91	3382	IR
35.	Koparde Weir	Kadvi	54	4.5		0	IR
36.	Kote Weir	Tulshi	45	6.95		0	IR
37.	Krishna Barrage	Krishna	209			6809.44	IR
38.	Kumbhewadi Weir	Kasari	46.4	6.2		0	IR
39.	Maldan Weir	Wang	80		590	2470	IR
40.	Manewadi Weir	Wang	38		270	2052.51	IR
41.	Mangale K.T. Weir	Morna	0			0	IR
42.	Manjara Weir	Kasari	40.2	5.03		0	IR
43.	Mhaisal K.T. Weir	Krishna	0			0	IR

Sl. No.	Name of barrage/weir/anicut	River	Length (m)	Height up to crest (m)	Catchment area (Th. Ha)	Design flood discharge ($m^3 s^{-1}$)	Purpose
44.	Muniyeru Anicut	Munniyeru	531	2.1	2400	2832.26	IR
45.	Narayanapur Anicut	Vedavati	0			0	IR
46.	Navalachiwadi Weir	Kasari	49.4	5.03		0	IR
47.	Nher Weir	Yerala	0			0	IR
48.	Nilji Weir	Chitri	91.8	3.65		0	IR
49.	Potale Weir	Wang	74		320	2258.28	IR
50.	Prakasam Barrage	Krishna	1138.73		250000	33984	IR
51.	Pulichintala Anicut		0			0	HE, IR
52.	Pushpavati Weir	Pushpavati	0			0	IR
53.	Rajaram Weir	Panchganga	93	5.48		0	IR
54.	Rajolibunda Anicut	Tungabhadra	820	332.232	35.32	21240	IR
55.	Rashivade Weir	Bhogawati	82	3.2		0	IR
56.	Rui Weir	Panchganga	81	4.67		0	IR
57.	Rukadi Weir	Panchganga	80	7.36		0	IR
58.	Salgaon Weir	Hiranyakeshi	0			0	IR
59.	Sarud Patne Weir	Kadvi	45.17	4.5		0	IR
60.	Satapewadi Barrage		0			0	IR
61.	Shelap Weir	Hiranyakeshi	0			0	IR
62.	Shirgaon Weir	Kadvi	43.4	4.5		0	IR
63.	Shirgaon Weir	Bhogawati	82	3.15		0	IR
64.	Shirol Weir	Panchganga	107	2.57		0	IR
65.	Singatalur/Hammigi Barrage	Tungabhadra	387.5			14725	IR

Sl. No.	Name of barrage/weir/anicut	River	Length (m)	Height up to crest (m)	Catchment area (Th. Ha)	Design flood discharge ($m^3 s^{-1}$)	Purpose
66.	Sohale Weir	Hiranyakeshi	0			0	IR
67.	Sonna Barrage	Bhima	2250	18.4	53328	26274	IR
68.	Sunkesula Anicut		633			14866.34	IR
69.	Surve Weir	Panchganga	113	6		0	IR
70.	Tarale Weir	Bhogawati	85	4.36		0	IR
71.	Tembhu Barrage	Krishna	326	8.13	5500	5016	HE,IR
72.	Terwad Weir	Panchganga	97	5.48		0	IR
73.	Waloli Weir	Kasari	88	6.41		0	IR
74.	Yadgir Barrage	Bhima	425			0	
75.	Yelur Weir	Kadvi	55	4.5		0	IR
76.	Yevluj Porle Weir	Kasari	48.46	5.8		0	IR

Appendix III: List and description of major/medium irrigation projects in KRB (after, MoWR, 2014)

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
1.	Amarja Medium Irrigation Project	Medium	Amarja	Amarja	Completed		10.53	8.9	8.9	Gulbarga
2.	Ambligola Medium Irrigation Project	Medium	Endigere	Vrushbhavathi	Completed	1964	4.35	2.95		Bijapur, Shimoga
3.	Andhali Medium Irrigation Project	Medium	Man	Man	Ongoing		2.2	2.06	1.5	Satara
4.	Andhrakhore Irrigation Project	Medium		Andra	Completed			2.59	2.33	Pune
5.	Anjanapura Medium Irrigation Project	Medium	Kumudavathy	Kumudavathy	Completed	1936	10.52	6.07		Shimoga
6.	Areshankar Medium Irrigation Project	Medium	Areshankar	Areshankar	Completed		10.19	1.24		Bijapur
7.	Ashti Lift Irrigation Project	Major		Ashti	Ongoing		17.3	13.48	9	Solapur
8.	Ashti Medium Irrigation Project	Medium	Ashti	Ashti	Completed	1883		6.81	9	Sholapur
9.	Asifnahar Medium Irrigation Project	Medium			Completed	1908	13.39	5.06		Nalgonda
10.	Bandardi (Banganga) Medium Irrigation Project	Medium	Banganga	Banganga	Completed			0.86		Osmanabad
11.	Barshi Lift Irrigation Project	Major	Sina	Sina	Ongoing		29	23.2	15	Solapur, Osmanabad
12.	Basappawadi Medium Irrigation Project	Medium		Local Nalla (Agrani)	Completed	1980	1.27	1.08	1.08	Sangli
13.	Basapur Lift Irrigation Project	Medium	Varada	Varada	Completed		6.67	2.27	2.27	Hassan
14.	Bellaryanala Medium Irrigation Project	Medium	Bellary Nalla	Bellary Nalla	Ongoing		9.55	8.2		Belgaum
15.	Benitura Medium Irrigation Project	Medium	Benitura Nallah	Benitura	Completed		2.83	2.55	2.29	Osmanabad
16.	Bennihalla Lift Irrigation Project	Medium		Bennihalla	Ongoing			3.87	3.87	Gadag
17.	Bennithora Major Irrigation Project	Major	Bennithora	Benithora	Ongoing		24.86	20.23	20.23	Gulbarga
18.	Bhadra Major Irrigation Project	Major	Krishna	Bhadra	Completed			121.5	105.57	Chickmagalur, Shimoga
19.	Bhadra Anicut Medium Irrigation Project	Medium	Bhadra	Bhadra	Completed	1923	6.94	4.47		Chickamagalur

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
20.	Bhairavanithippa Medium Irrigation Project	Medium	Krishna	Pedda Hagari (Vedhavathi)	Completed		7.39	4.86		Ananthpur
21.	Bhama Askheda Major Irrigation Project	Major	Bhama	Bhama	Ongoing		49.35	29.01	23.11	Pune
22.	Bhima Lift Irrigation Project	Major	Bhima	Bhima	Ongoing		30.28	24.29	24.29	Gulbarga
23.	Bhima Major Irrigation Project	Major	Krishna	Bhima	Completed	2009	205.28	199.11	259.54	Solapur, Pune, Ahmednagar
24.	Bhima Sina Link Canal Lift Irrigation Project	Major		Bhima	Completed			37.72	43.4	Solapur
25.	Bori (S) Major Irrigation Project	Major	Bori Nalla	Bori Nalla	Ongoing		24.15	19.3	19.88	Solapur
26.	Buddhiyal Medium Irrigation Project	Medium		Belwan	Completed			5.45		Solapur
27.	Chandani Medium Irrigation Project	Medium	Chandani	Chandani	Completed			2.89	2.02	Osmanabad
28.	Chandrampalli Medium Irrigation Project	Medium	Sarnala	Sarnala	Completed		8.55	5.22	8446	Gulbarga
29.	Chaskaman Major Irrigation Project	Major	Bhima	Bhima	Completed		71.71	55.21	32.83	Pune
30.	Chikotra Medium Irrigation Project	Medium	Chikotra	Chikotra	Completed	2008		5.41	5.63	Kolhapur
31.	Chillewadi Medium Irrigation Project	Medium	Mandvi	Mandvi	Ongoing		7.96	7.17	7.14	Pune
32.	Chitri Medium Irrigation Project	Medium	Chitri	Chitri	Completed	2001	13.09	9.16	5.85	Kolhapur
33.	Chitwadgi Medium Irrigation Project	Medium	Kadalappana	Chittawadagi	Completed	1971	0.9	0.89		Bijapur, Raichur
34.	Dhaigaon Major Irrigation Project	Major			Ongoing			0	13.3	Solapur
35.	Dhamini Medium Irrigation Project	Medium		Dhamni	Ongoing			1.75	1.4	Kolhapur
36.	Dhangarwadi Lift Irrigation Project	Medium			Proposed			3.03	2.5	Satara
37.	Dharma Medium Irrigation Project	Medium	Dharma	Dharma Nala	Completed		10.95	5.67		Dharwad, Uttara Kannada
38.	Dhom Balkawadi Tunnel Major Irrigation Project	Major	Krishna	Krishna	Ongoing		48.45	28.1	12.67	Satara, Pune

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
39.	Dindi Medium Irrigation Project	Medium	Krishna	Dindi	Completed		12.72	5.18		Nalgonda
40.	Doddanalla Medium Irrigation Project	Medium	Bor	Dodda Nallah	Completed	1987		1.25	1.22	Sangli
41.	Dudhganga Major Irrigation Project Karnataka	Major	Dudhganga	Dudhganga	Ongoing		24.48	12.86	13	Belgaum
42.	Dudhganga Major Irrigation Project Maharashtra	Major	Dudhganga	Dudhganga	Ongoing			68.24	68.98	Belgaum and Kolhapur
43.	Ekrukh Lift Irrigation Project	Major	Adhela Nallah	Adela	Ongoing			30.3	23.44	Solapur
44.	Ekrukh Medium Irrigation Project	Medium		Adela	Completed	1871	6.94	6.87	2.61	Sholapur
45.	Feeder Canal To Ranikere Medium Irrigation Project	Medium	Garnihalla	Garnihalla	Completed			3.24		Chitradurga
46.	Gajuladinne Medium Irrigation Project	Medium			Completed	1987	15.32	9.86	0.01	Kurnool
47.	Galeru Nagari Sujala Sravanthi (GNSS) Major Irrigation Project	Major	Krishna		Ongoing		204.31	105.22	105.22	Chittoor, Cuddapah
48.	Gandipalem Medium Irrigation Project	Medium	Munneru		Completed	1986		6.48	6.48	Nellore
49.	Gandorinala Medium Irrigation Project	Medium	Gandorinala	Gandorinala	Completed	2010	26.42	8.09	11.65	Gulbarga
50.	Gayathri Medium Irrigation Project	Medium	Suvarnamukhi	Suvarnamuki	Completed	1963	2.96	2.31		Chitradurga
51.	Ghataprabha Major Irrigation Project	Major	Ghataprabha	Ghatprabha	Completed			139.38		Belgaum, Bijapur
52.	Ghatprabha Medium Irrigation Project	Medium	Ghatprabha	Ghatprabha	Completed			5.46	4.78	Kolhapur
53.	Ghod Major Irrigation Project	Major	Ghod	Ghod	Completed	1965	52.37	41.46		Pune, Ahmednagar
54.	Gokak Canals Medium Irrigation Project	Medium	Ghataprabha		Completed	1897	10.4	5.72		Belgaum
55.	Guddada Mallapura Medium Irrigation Project	Medium	Varada	Varada	Ongoing		7.26	5.26	5.26	Haveri
56.	Gunjawani Major Irrigation Project	Major	Kanand	Kanandi	Ongoing		31.42	19.48	16.5	Pune

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
57.	Guntur Canal Medium Irrigation Project	Medium	Krishna	Krishna	Completed		41.34	10.93	9.56	Guntur
58.	Guru Raghanvendra Lift Irrigation Project	Major	Tungabhadra		Ongoing		39.56	20.75		Kurnool
59.	Hagari Bommanahalli Medium Irrigation Project	Medium		Hagari	Completed	1978	4.4	2.98		Bellary
60.	Hanbarwadi Lift Irrigation Project	Medium			Proposed			3.15	2.6	Satara
61.	Handri Neeva Sujala Sravanti (HNSS) Major Irrigation Project	Major			Ongoing		705.21	243.83	243.77	Kurnool, Cuddapah, Ananthpur, Chittoor
62.	Harinala Medium Irrigation Project	Medium	Harinala	Harinala	Completed	2004		3.48	3.46	Belgaum
63.	Harni Medium Irrigation Project	Medium	Local Nallah	Harni	Completed			2.59		Solapur, Osmanabad
64.	Hathikuni Medium Irrigation Project	Medium	Hathikone halla	Hattikuni stream	Completed	1973		2.14		Gulbarga
65.	Hatiz (Hingni) Medium Irrigation Project	Medium	Nagzari	Nagzari	Completed	2005		5.57	5.34	Solapur, Osmanabad
66.	Hingni Pangaon Medium Irrigation Project	Medium	Bhogawati	Bhogawati	Completed			6.48	6.75	Solapur
67.	Hippargi Major Irrigation Project	Major	Krishna	Krishna	Ongoing		93.43	59.69	59.69	Bagalkot, Belgaum
68.	Hiranyakeshi Lift Irrigation Project	Medium		Ghataprabha	Ongoing			0	0	Belgaum
69.	Hiranyakshi (Ambeohol) Medium Irrigation Project	Medium	Ambeohol	Ambeohal	Ongoing			4.27	5.34	Kolhapur
70.	Hiranyakshi (Surfnalla) Medium Irrigation Project	Medium	Sarfnalla	Sarfnalla	Ongoing			3.18	3.39	Kolhapur
71.	Hirehalla Medium Irrigation Project	Medium	Hirehalla	Hirehalla	Ongoing		20.99	8.33	8.33	Raichur
72.	Hodirayanhalla Medium Irrigation Project	Medium	Hodiravana		Ongoing			2.63	1.38	C.R. Nagar
73.	Itagi Susalwad Medium Irrigation Project	Medium	Tungabhadra	Tungabhadra	Ongoing		3.01	1.98	1.98	Gadag

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
74.	Jakapur Medium Irrigation Project	Medium	Local Nallah	Local Nallah	Completed	1977		2.12	1.67	Osmanabad
75.	Jambadahalla Medium Irrigation Project	Medium	Jambadahalla	Jambadahalla	Completed		3.1	1.54		Chickamagalur
76.	Jambre Medium Irrigation Project	Medium	Tamraparni		Ongoing			4.72	3.77	Kolhapur
77.	Janai Shirsai Lift Irrigation Project	Major			Ongoing			0	14.08	Pune
78.	Jangamhatti Medium Irrigation Project	Medium	Honhal	Honhal	Completed	2008		4.46	3.7	Kolhapur
79.	Javalahalla Medium Irrigation Project	Medium		Haul Halla	Completed			0	1.92	Belgaum
80.	Jawahar (Nettampadu) Lift Irrigation Project	Major	Krishna		Ongoing		84.7	80.94	80.9	Mahboobnagar
81.	Jine Kathapur Lift Irrigation Project	Major		Krishna	Ongoing		59.45	35.54	27.5	Satara
82.	Jurala (Priyadarshini) Major Irrigation Project	Major	Krishna		Completed		74.35	41.26	41.3	Mahboobnagar
83.	JutapallIVagu Medium Irrigation Project	Medium	Kagna River	Jutepally vagu	Completed		2.58	0.84		Rangareddy
84.	Kada Medium Irrigation Project	Medium	Local Nallah	Local Nallah	Completed			1.8		Beed
85.	Kadavi Medium Irrigation Project	Medium	Kadvi	Potphuji	Completed		12.23	9.91	9.22	Kolhapur
86.	Kadi Medium Irrigation Project	Medium	Local Nallah	Kari	Completed			0.95		Beed
87.	Kalascope Medium Irrigation Project	Medium	Endigere		Completed		1.67	1.14		Bijapur
88.	Kalmodi Medium Irrigation Project	Medium	Arala	Arala	Ongoing		7.04	5.63	5.07	Pune
89.	Kambali Medium Irrigation Project	Medium		Kambali	Completed			1.05		Beed
90.	Kanakanala Medium Irrigation Project	Medium	Kanakanala	Kanakanala	Completed	1975	2.06	2.06		Raichur
91.	Kasari Medium Irrigation Project	Medium	Kasari	Kasari	Completed		12.14	10	9.46	Kolhapur
92.	Kasarsai Medium Irrigation Project	Medium	Kasarsai Nalla	Kasarsai Nalla	Completed			5.15	6.59	Pune
93.	Kavathe Kenjal Lift Irrigation Project	Medium			Proposed		9.1	6.83		Satara

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
94.	Kenchanagudda Lift Irrigation Project	Medium		Tungabhadra	Ongoing			0		Bellary
95.	Khadakwasla Major Irrigation Project	Major	Mutha	Mutha	Completed	2005	97.1	88.46	62.15	Pune
96.	Khairi Medium Irrigation Project	Medium	Khar	Khar	Completed	1989		3.25	3.08	Ahmednagar, Osmanabad
97.	Khandala Medium Irrigation Project	Medium	Local Nallah	Local Nallah	Completed			2.02	1.33	Osmanabad
98.	Khasapur Medium Irrigation Project	Medium	Local Nallah	Ulup	Completed			3.57		Osmanabad
99.	Koil Sagar Lift Irrigation Project	Major	Peddavagu		Completed		22.36	8.51	177.26	Mahboobnagar
100.	Kolchi Lift Irrigation Project	Medium		Bennihalla	Ongoing			0		Gadag
101.	Kolchi Medium Irrigation Project	Medium	Endigere	Mallaprabha	Completed		8.01	1.27		Belgaum
102.	Konnur Lift Irrigation Project	Medium			Ongoing			1.59		Gadag
103.	Koornoor Medium Irrigation Project	Medium		Bori	Completed			6.48		Osmanabad
104.	Kotipallivagu Medium Irrigation Project	Medium		Kotepallyvagu	Completed		12.19	3.72		Rangareddy
105.	Krishna Barrage (including old Krishna Delta system)	Major			Completed		714.44	475.65	529	Krishna, Prakasam
106.	Krishna Canal Medium Irrigation Project	Medium	Krishna	Krishna	Completed		16.67	14.39	11.29	Sangli, Satara
107.	Krishna Koyna Lift Irrigation Project	Major	Krishna	Krishna	Ongoing		206.93	172.47	121.26	Satara, Sangli, Kolhapur
108.	Krishna Major Irrigation Project	Major	Krishna	Krishna	Completed	2009	103.56	74	74	Satara, Sangli
109.	Kudali Medium Irrigation Project	Medium		Kudali	Ongoing		6.96	5.98	6.96	Satara
110.	Kukadi Major Irrigation Project	Major	Kukadi	Kukadi	Completed	2009	280.87	224.67	156.28	Pune, Ahmednagar, Solapur
111.	Kumbhi Medium Irrigation Project	Medium	Kumbhi	Kumbhi	Completed	2007	10.19	9.17	8.71	Kolhapur
112.	Kurnool Cuddapah Canal Major Irrigation	Major		Tungabhadra	Completed	1882		44.29		Cuddapah

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
	Project									
113.	Lakhnapur Medium Irrigation Project	Medium		Pargi stream	Completed		1.46	1.07		Rangareddy
114.	Lankasagar Medium Irrigation Project	Medium	Kattalair River	Kottaleru	Completed			3.05		Krishna
115.	Londhanala Medium Irrigation Project	Medium			Ongoing			0	0.67	Kolhapur
116.	Lower Mullamari Medium Irrigation Project	Medium	Mullamari	Mullamari	Completed		11.52	9.72	9.3	Gulbarga
117.	Mahathma (Kalwakurthy) Lift Irrigation Project	Major	Krishna		Ongoing		318.09	101.18	10.17	Mahboobnagar
118.	Malaprabha Major Irrigation Project	Major	Malaprabha	Malaprabha	Completed		344.77	196.13	196.13	Mysore
119.	Markendaya Major Irrigation Project	Major	Bhima	Markandeya	Ongoing		32.83	19.11	19.15	Belgum
120.	Maskinala Medium Irrigation Project	Medium	Mullamari	Maskinala	Completed	2007	3.29	2.83	2.83	Raichur
121.	Mehekari Medium Irrigation Project	Medium	Mehakari	Mehekri	Completed			5.08	4.05	Beed
122.	Mhaswad Major Irrigation Project	Major	Man	Man	Completed	1897		17.08		Satara
123.	Morana Gureghar Medium Irrigation Project	Medium	Morna	Morna	Ongoing		5.29	4.23	3.08	Satara
124.	Morna (WM) Irrigation Project	Medium	Morna	Morna	Completed	1987	2.31	2.08		Sangli
125.	Mulshi Medium Irrigation Project	Medium	Mula	Mula	Ongoing			0	6.5	Pune
126.	Muniyeru Medium Irrigation Project	Medium			Completed	1902	30.55	6.65		Krishna
127.	Musi Medium Irrigation Project	Medium		Musi	Completed		26.68	13.36		Nalgonda
128.	Nagarjuna Sagar Major Irrigation Project	Major	Krishna		Completed	1960	1769.93	868	868	Nalgonda, Khammam, Guntur, Krishna, Prakasam, W/Godavari
129.	Nagathana Medium Irrigation Project	Medium	Kyadgihalla	Nagathan Nallah	Completed		0.95	0.65		Bijapur

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
130.	Nagewadi Medium Irrigation Project	Medium	Local Nallah	Local Nalla	Ongoing		2.1	1.9	1.56	Satara
131.	Narayanapur Anicut Medium Irrigation Project	Medium	Vedavathy	Vedavati	Completed	1997	13.39	1.62		Chitradurga
132.	Narihalla Medium Irrigation Project	Medium	Narihalla	Narihalla	Completed		4.42	2.01		Bellary
133.	Nazare Medium Irrigation Project	Medium	Karha	Karha	Completed		3.9	3.2	3.2	Pune
134.	Neera Left Bank Canal Major Irrigation Project	Major	Neera	Nira	Completed	1928	81.38	68.77		Pune
135.	Neera Right Bank Canal Major Irrigation Project	Major	Neera	Nira	Completed	1927		181.17		Satara, Solapur
136.	Nher Tank Medium Irrigation Project	Medium	Yerala	Yerala	Completed	1889		4.32		Satara
137.	Nira Deoghar Major Irrigation Project	Major	Nira	Nira	Ongoing		90.1	62.71	43.05	Satara, Pune, Solapur
138.	Okachetti Vagu Medium Irrigation Project	Medium	Krishna	Ookachettivagu	Completed			0	2.71	Mahboobnagar
139.	Padwal Karwadi Major Irrigation Project	Major	Mangal	Koni Kunur	Completed			0.43	0.46	Sholapur
140.	Pakhal Medium Irrigation Project	Medium	Munneru	Pakhal vagu	Completed	1923		7.36		Warangal
141.	Patgaon Medium Irrigation Project	Medium	Vedganga	Vedganga	Completed			10	11.74	Kolhapur
142.	Pimpalgaon (Dhale) Medium Irrigation Project	Medium	Sina Nalla	Sina Nalla	Completed		3.32	2.82	3.29	Solapur
143.	Purandhar Major Irrigation Project	Major	Mula- Mutha	Mutha	Ongoing			25.1	25.1	Pune
144.	Pushpavati Medium Irrigation Project	Medium		Pushpavati	Completed			1.69	1.63	Pune
145.	Radhanagri Major Irrigation Project	Major	Bhogawati	Bhogawati	Completed		59.11	47.29	26.56	Kolhapur
146.	Rajiv Bhima Lift Irrigation Project	Major	Krishna		Ongoing		126.39	83.78		Mahabubnagar
147.	Rajolibanda Irrigation Project Andhra Pradesh	Major	Tungabhadra		Completed		74.5	35.41	35.41	Mahboobnagar
148.	Rajolibanda Irrigation Project Karnataka	Medium	Tungabhadra	Tungabhadra	Completed		7.78	2.39	2.39	Raichur
149.	Ramanahalli Medium Irrigation Project	Medium	Krishna	Navalli Nalla	Completed	1958	5.53	1.94		Bijapur

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
150.	Rameshwara Lift Irrigation Project	Medium		Ghatprabha	Ongoing		18.02	13.8	13.8	Belgaum
151.	Ramthala Lift Irrigation Project	Major	Tungabhadra	Krishna	Ongoing		39.12	0	22.26	Bijapur
152.	Ranand Medium Irrigation Project	Medium	Wagzari	Waghzai	Completed	1958		3.88	1.09	Satara
153.	Rolli Manikeri Medium Irrigation Project	Medium			Ongoing			2.35	2.35	Bagalkot
154.	Rooty Medium Irrigation Project	Medium	Bokdi	Bokdi	Completed	1938		2.33		Beed
155.	Sakat Medium Irrigation Project	Medium	Dudhana	Dudhana	Completed			3.14		Osmanabad
156.	Sankh Medium Irrigation Project	Medium	Bor	Bor	Completed	1997	4.07	3.54	3.1	Sangli
157.	Sarala Sagar Medium Irrigation Project	Medium	Krishna	Chinnavagu	Completed			1.7		Mahboobnagar
158.	Saudagar Medium Irrigation Project	Medium	Saudagar Nala		Completed	1987		1.42		Gulbarga, Bidar
159.	Shahajani Aurad Medium Irrigation Project	Medium			Completed			0	1.27	Osmanabad
160.	Shirapur Lift Irrigation Project	Major		Sina	Ongoing			16	10	Solapur, Osmanabad
161.	Siddhewadi Medium Irrigation Project	Medium	Agrani	Agrani	Completed		1.33	1.16	1.7	Sangli
162.	Sina (Bhosekhind) Irrigation Project	Medium		Sina	Ongoing			0	6.82	Solapur
163.	Sina Kolegaon Major Irrigation Project	Major	Sina	Sina	Ongoing			14.11	12.1	Osmanabad, Solapur
164.	Sina Madha Lift Irrigation Project	Major	Bhima	Sina	Ongoing		30.23	24.38	24.55	Solapur
165.	Sina Medium Irrigation Project	Medium	Sina	Sina	Completed		14.04	9.68	8.45	Ahmednagar, Beed
166.	Singatalur Major Irrigation Project	Major	Tungabhadra	Tungabhadra	Ongoing		125.53	67.58	47.75	Bellary, Gadag
167.	Srisailam Left Bank Canal Major Irrigation Project	Major			Ongoing			0		
168.	Srisailam Right Bank Canal Major Irrigation	Major	Krishna		Completed	1981	115.68	76.89	100.87	Nalgonda, Kurnool, Cuddapah

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
	Project									
169.	Talwar Medium Irrigation Project	Medium	Local Nallah	Talwar	Completed	1961		0.67		Beed
170.	Tarakarama Krishnaveni Lift Irrigation Project	Major	Krishna		Ongoing			0	22.66	Krishna
171.	Tarali Major Irrigation Project	Major	Tarali	Tarali	Ongoing		23.3	18.13	19.5	Satara
172.	Tegi Siddapur Medium Irrigation Project	Medium		Krishna	Ongoing			3	3	Bagalkot
173.	Telugu Ganga Major Irrigation Project	Major			Ongoing		386.88	233	233	Kurnool, Cuddapah, Nellore, Chittoor
174.	Tembhu Lift Irrigation Project	Major	Krishna	Krishna	Ongoing		197.02	149.63	80.47	Satara, Solapur, Sangli
175.	Temghar Major Irrigation Project	Major	Mutha	Mutha	Ongoing		2	1.6	1.83	Pune
176.	Thimmapura Lift Irrigation Project	Medium		Krishna	Proposed			0	1.69	Haveri
177.	Tulshi (Landhanala) Major Irrigation Project	Major	Tulshi	Tulshi	Completed		4.58	4.5	5.71	Kolhapur
178.	Tunga Anicut Medium Irrigation Project	Medium		Tunga	Completed		17.05	8.7	8.7	Shimoga
179.	Tungabhadra High Level Canal Stage I Irrigation Project Andhra Pradesh	Major	Tungabhadra		Completed		358.42	45.82	45.82	Anantpur, Cuddapah
180.	Tungabhadra Left Bank Canal & Dam Major Irrigation Project	Major	Tungbhadra	Tungabhadra	Completed		366.89	323.74	244.2	Bellary, Raichur
181.	Tungabhadra Low Level Right Bank Canal Major Irrigation Project Andhra Pradesh	Major			Completed		214.74	61.1	63.52	Kurnool, Cuddapah
182.	Tungabhadra Right Bank High Level Canal Major Irrigation Project Karnataka	Major	Tungbhadra	Tungabhadra	Completed			100.77	80	Bellary, Raichur
183.	Tungabhadra Right Bank Low Level Canal	Major	Tungbhadra	Tungabhadra	Completed		150.2	104.03	37.5	Bellary

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
	Major Irrigation Project Karnataka									
184.	Turori Medium Irrigation Project	Medium	Turori	Local Nallah	Completed			0.97		Osmanabad
185.	Ubrani Anruthapura Lift Irrigation Project	Medium		Bhadra	Ongoing			0	7.69	Chikkaamagalur, Dhavangere
186.	Upper Heranalla Medium Irrigation Project	Medium		Hirenala	Completed		2.85	1.9		
187.	Upper Krishna Stage - I Major Irrigation Project	Major	Krishna	Krishna	Ongoing		549	425	458.89	Bijapur, Gulbarga, Raichur, Bagalkot
188.	Upper Krishna Stage - II Major Irrigation Project	Major	Krishna	Krishna	Ongoing		268.18	197.12	226.69	Bijapur, Gulbarga, Raichur, Bagalkot
189.	Upper Mullamari Medium Irrigation Project	Medium	Mullamari	Mullamri	Completed		6.47	3.28	3.28	Gulbarga
190.	Upper Tunga Major Irrigation Project	Major	Tunga	Tunga	Ongoing		163.98	94.69	80.5	Shimoga, Dharwad, Chitradurga
191.	Urmodi Major Irrigation Project	Major	Urmodi	Urmodi	Ongoing		48	37	43.87	Satara
192.	Uttarmand Medium Irrigation Project	Medium	Uttarmand	Uttarmand	Ongoing		6.67	6	5.28	Satara
193.	Vadiwale Medium Irrigation Project	Medium	Kundali	Kundali	Completed		5	4.45	5	Pune
194.	Vanivilas Sagar Major Irrigation Project	Major	Vedavathy	Vedavathy	Completed	1908	13.81	9.19		Chitradurga
195.	Varadarajaswamy Gudi (DP) Medium Irrigation Project	Medium	Krishna		Completed		20.22	5.35	5.35	Kurnool
196.	Vasana Lift Irrigation Project	Medium			Ongoing			0	4.86	Satara
197.	Veer Major Irrigation Project	Major	Nira	Nira	Completed		226.58	181.27	16.11	Solapur, Satara
198.	Veligonda (Polsubbarai) Major Irrigation Project	Major			Ongoing		322.9	177.26	181.1	Prakasam

Sl. No.	Name of Project	Type	River	Tributary	Status	Year of completion	GCA (Th. Ha)	CCA (Th. Ha)	Ultimate irrigation potential	Beneficiary district(s)
199.	VIjayanagar Channels Major Irrigation Project	Major	Tungabhadra		Completed	1600	14.83	12.21		Bellary, Raichur
200.	VIsapur Medium Irrigation Project	Medium	Hanga	Hanga	Completed	1927	10.33	8.26		Ahmednagar
201.	Wakurde Lift Irrigation Project	Major		Varna	Ongoing			33	38.52	Kolhapur
202.	Wang Medium Irrigation Project	Medium	Wang	Wang	Ongoing		9.13	8.55	7.07	Satara
203.	Wangana Lift Irrigation Project	Medium			Ongoing			0	4.2	Satara
204.	Warna Major Irrigation Project	Major	Warna	Varna	Ongoing		128.7	109.7	121.92	Kolhapur, Sangli, Satara
205.	Watephal Medium Irrigation Project	Medium	Local Nallah	Local Nalla	Completed			1.7	1.47	Osmanabad
206.	Wyra Medium Irrigation Project	Medium	Munneru	Munneru	Completed	1933	9.5	7.04		Khammam
207.	Y. Kaggal Major Irrigation Project	Major		Hagari	Ongoing			0	2.69	Bellary
208.	Yeleru Reservoir Project Ph. I	Major			Completed		51.47	27.36	85.63	East Godavari, Vizag
209.	Yeralwadi Medium Irrigation Project	Medium	Yerala	Yerla	Completed			3.92	3.45	Sangli, Satara
210.	Yewati Masoli Medium Irrigation Project	Medium	Yewati	Yeoti Nalla	Completed	1994	2.27	1.93		Satara
211.	Zurreru Medium Irrigation Project	Medium		Zurreru	Completed		1.66	0.61		Kurnool

Appendix IV: List of Landsat 1 MSS scenes downloaded for the morphological study

Sl. No.	Path	Row	Date of acquisition
1.	152	048	20-01-73
2.	152	049	20-01-73
3.	153	047	21-01-73
4.	153	048	21-01-73
5.	153	049	21-01-73
6.	154	047	22-01-73
7.	154	048	22-01-73
8.	154	049	22-01-73
9.	154	050	22-01-73
10.	154	051	22-01-73
11.	155	047	23-01-73
12.	155	048	23-01-73
13.	155	049	23-01-73
14.	155	050	23-01-73
15.	155	051	23-01-73
16.	156	047	24-01-73
17.	156	048	24-01-73
18.	156	049	24-01-73
19.	156	050	24-01-73
20.	156	051	24-01-73
21.	157	047	25-01-73
22.	157	048	25-01-73
23.	157	049	25-01-73
24.	157	050	25-01-73
25.	157	051	25-01-73
26.	158	046	26-01-73
27.	158	047	26-01-73
28.	158	048	26-01-73

Appendix V: List of Landsat 2 MSS scenes downloaded for the morphological study

Sl. No.	Path	Row	Date of acquisition
1.	152	048	26-01-77
2.	152	049	26-01-77
3.	153	047	27-01-77
4.	153	048	27-01-77
5.	153	049	27-01-77
6.	154	047	28-01-77
7.	154	048	28-01-77
8.	154	049	28-01-77
9.	154	050	28-01-77
10.	154	051	28-01-77
11.	155	047	29-01-77
12.	155	048	29-01-77
13.	155	049	29-01-77
14.	155	050	29-01-77
15.	155	051	29-01-77
16.	156	047	30-01-77
17.	156	048	30-01-77
18.	156	049	30-01-77
19.	156	050	30-01-77
20.	156	051	30-01-77
21.	157	047	31-01-77
22.	157	048	31-01-77
23.	157	049	31-01-77
24.	157	050	31-01-77
25.	157	051	31-01-77
26.	158	046	14-01-77
27.	158	047	14-01-77
28.	158	048	14-01-77

Appendix VI: List of Landsat 5 TM scenes downloaded for the morphological study

Sl. No.	Path	Row	Date of acquisition
1.	142	047	18-03-91
2.	142	048	18-03-91
3.	142	049	18-03-91
4.	143	047	25-03-91
5.	143	048	25-03-91
6.	143	049	25-03-91
7.	143	050	10-04-91
8.	144	047	16-03-91
9.	144	048	16-03-91
10.	144	049	16-03-91
11.	144	050	16-03-91
12.	144	051	16-03-91
13.	145	047	23-03-91
14.	145	048	23-03-91
15.	145	049	23-03-91
16.	145	050	07-03-91
17.	145	051	23-03-91
18.	146	047	14-03-91
19.	146	048	14-03-91
20.	146	049	14-03-91
21.	146	050	10-02-91
22.	146	051	10-02-91
23.	147	046	21-03-91
24.	147	047	05-03-91
25.	147	048	05-03-91
26.	147	049	05-03-91

Appendix VII: List of Landsat 7 ETM^+ scenes downloaded for the morphological study

Sl. No.	Path	Row	Date of acquisition
1.	142	047	22-04-01
2.	142	048	22-04-01
3.	142	049	22-04-01
4.	143	047	24-02-01
5.	143	048	24-02-01
6.	143	049	24-02-01
7.	143	050	24-02-01
8.	144	047	03-03-01
9.	144	048	03-03-01
10.	144	049	03-03-01
11.	144	050	03-03-01
12.	144	051	03-03-01
13.	145	047	26-03-01
14.	145	048	26-03-01
15.	145	049	26-03-01
16.	145	050	26-03-01
17.	145	051	26-03-01
18.	146	047	02-04-01
19.	146	048	02-04-01
20.	146	049	02-04-01
21.	146	050	02-04-01
22.	146	051	02-04-01
23.	147	046	25-04-01
24.	147	047	24-03-01
25.	147	048	24-03-01
26.	147	049	24-03-01

Appendix VIII: List of IRS P6 LISS III scenes downloaded for the morphological study

Sl. No.	Path	Row	Date of acquisition
1.	094	58	31-01-2011
2.	094	59	31-01-2011
3.	094	60	31-01-2011
4.	095	59	05-02-2011
5.	095	60	05-02-2011
6.	095	61	05-02-2011
7.	095	62	05-02-2011
8.	096	59	10-02-2011
9.	096	60	10-02-2011
10.	096	61	10-02-2011
11.	096	62	10-02-2011
12.	096	63	10-02-2011
13.	097	59	22-01-2011
14.	097	60	22-01-2011
15.	097	61	22-01-2011
16.	097	62	22-01-2011
17.	097	63	22-01-2011
18.	097	64	22-01-2011
19.	098	59	27-01-2011
20.	098	60	27-01-2011
21.	098	61	27-01-2011
22.	098	62	27-01-2011
23.	098	63	27-01-2011
24.	098	64	27-01-2011
25.	099	59	01-02-2011
26.	099	60	01-02-2011
27.	099	61	01-02-2011
28.	099	62	01-02-2011
29.	099	63	01-02-2011
30.	099	64	01-02-2011
31.	100	60	06-02-2011
32.	100	61	06-02-2011
33.	100	62	06-02-2011
34.	100	63	06-02-2011
35.	100	64	06-02-2011
36.	101	60	11-02-2011
37.	101	61	11-02-2011

Sl. No.	Path	Row	Date of acquisition
38.	101	62	11-02-2011
39.	102	60	30-12-2010
40.	102	61	30-12-2010
41.	102	62	30-12-2010
42.	103	61	28-01-2011
43.	103	62	28-01-2011

Appendix IX: Hydrologic data characteristics of various H.O. stations of KRB

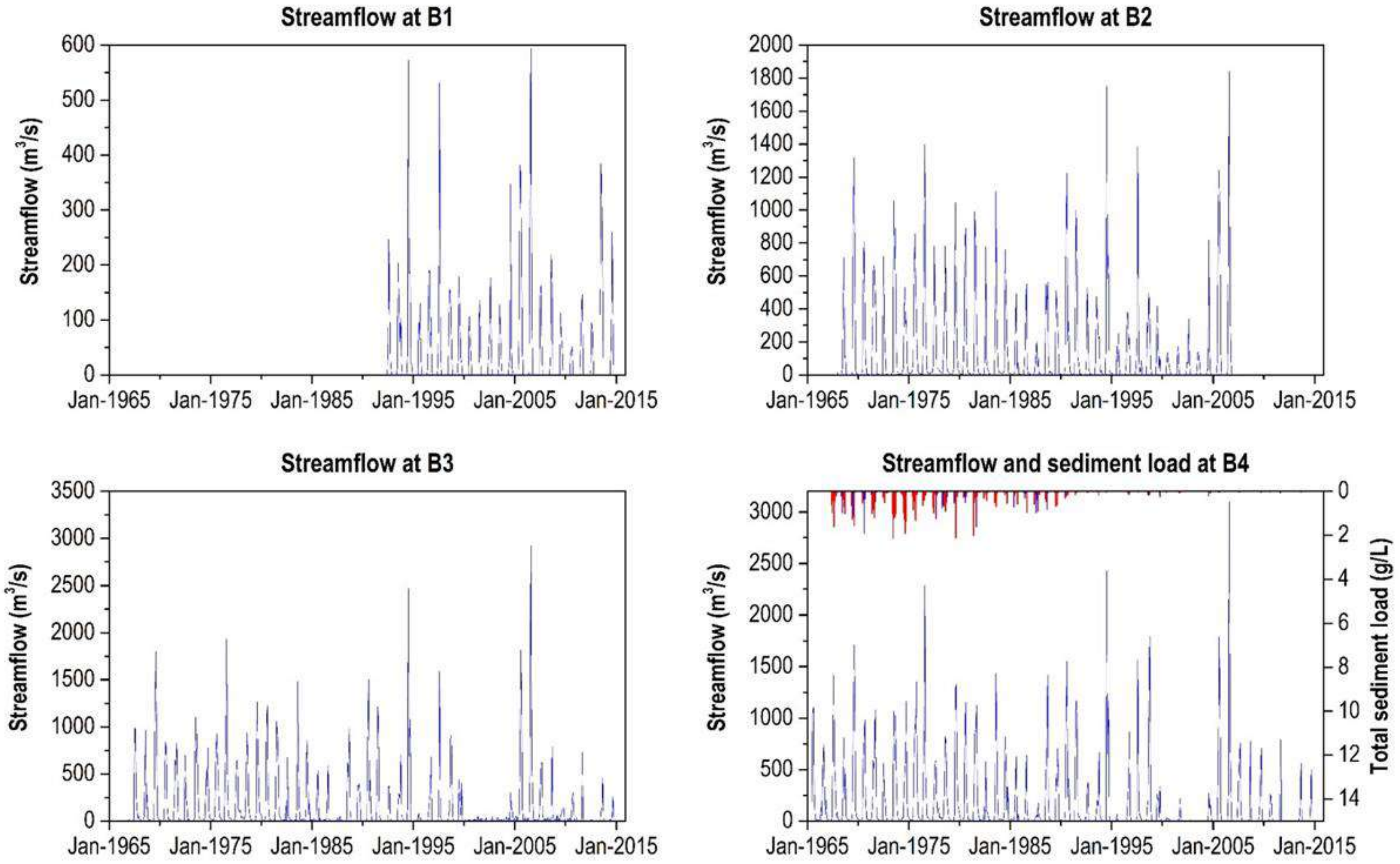
Code	Station Name	River	Status	Activity	Site Type	Gauge		D		BD		SS		XS	
						Period	Time Scale	Period	Time Scale	Period	Time Scale	Period	Time Scale	Period	Time Scale
K1	Karad	Krishna	E	HO	GDSQ	1965-2016	Daily	1965-2015	Daily	2006-2015	Seasonal	1965-2015	Daily	1996-2013	Yearly
K2	Arjunwad	Krishna	E	HO/FF	GD	1969-2015	Daily	1969-2014	Daily					2000-2013	Yearly
K3	Kurundwad	Krishna	E	HO	GDSQ	1972-2016	Daily	1972-2015	Daily			2003-2014	Daily	2000-2013	Yearly
K4	Almatti	Krishna	E	HO/FF	G	1965-1990	Daily	1965-1976	Daily						
K5	Dhannur	Krishna	C	HO	GDS	1968-1976	Daily	1968-1976	Daily			1973-1976	Daily		
K6	Narayanpura Dam	Krishna	E	HO/FF	G										
K7	Huvinhedgi	Krishna	E	HO	GD	1976-2015	Daily	1976-2015	Daily			1976-2014	Daily	1990-2013	Yearly
K8	Deosugur	Krishna	E	HO	G	1965-2014	Daily	1965-1984	Daily					2002	Yearly
K9	P.D. Jurala	Krishna	E	HO/FF	G										
K10	K. Agraharam	Krishna	E	HO	G	1981-2014	Daily	1981-2007	Daily			1982-2006	Daily	1990-2009	Yearly
K11	Yaparla	Krishna	C	HO	GD	1971-1981	Daily	1971-1981	Daily						
K12	Morvakonda	Krishna	C	HO	GDS	1965-1981	Daily	1965-1981	Daily			1973-1981	Daily		
K13	Srisailam	Krishna	E	HO/FF	G	1971-2013	Daily	1971-1978	Daily						
K14	N.S. Dam	Krishna	E	HO	G										
K15	Damarapadu	Krishna	C	HO	GDS	1965-1975	Daily	1965-1975	Daily			1969-1975	Daily		
K16	Pondugala	Krishna	C	HO	GDSQ	1975-2007	Daily	1975-2007	Daily			1975-2006	Daily	1982-2006	Yearly
K17	Wadenapalli	Krishna	E	HO	GDSQ	1965-2015	Daily	1965-2015	Daily	2006-2015	Seasonal	1966-2015	Daily	1980-2013	Yearly
K18	Vijayawada	Krishna	E	HO	GDQ	1965-2015	Daily	1965-2015	Daily			1965-2014	Daily	1967-2013	Yearly
K19	Prakasam Barrage	Krishna	E	HO/FF	G										

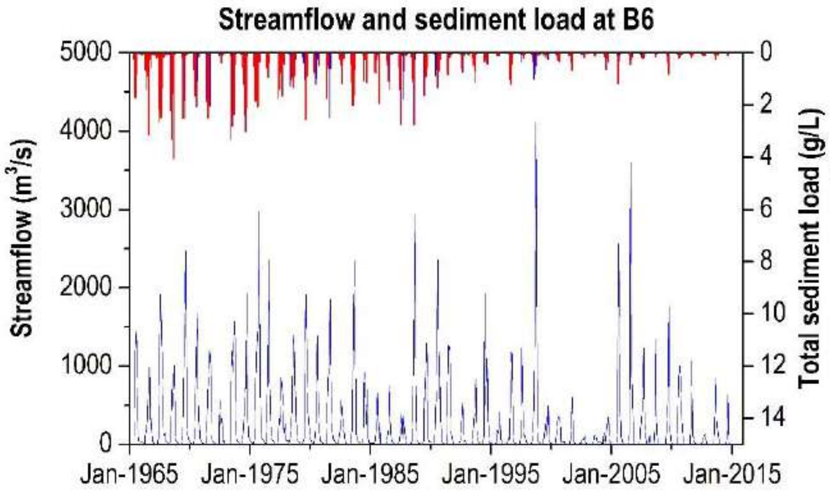
Code	Station Name	River	Status	Activity	Site Type	Gauge		D		BD		SS		XS	
						Period	Time Scale	Period	Time Scale	Period	Time Scale	Period	Time Scale	Period	Time Scale
KT1	Koyna at Koynanaga	Koyna	C	HO	GDSQ	1972-2007	Daily	1972-2007	Daily					1996-2006	Yearly
KT2	Warunji	Koyna	E	HO	GD	1964-2016	Daily	1966-2015	Daily			1974-2015	Daily	1996-2013	Yearly
KT3	Samdoli	Varna	E	HO	GD	1964-2015	Daily	1964-2014	Daily			2014-2014	Daily	2000-2014	Yearly
KT4	Terwad	Panchganga	E	HO	GD	1979-2014	Daily	1979-2014	Daily					2000-2013	Yearly
KT5	Vandur	Dudhganga	E	HO	GD	1979-2007	Daily	1979-2007	Daily					1996-2006	Yearly
KT6	Sadalga	Dudhganga	E	HO	GD	1965-2014	Daily	1969-2014	Daily					2000-2013	Yearly
KT7	Pandegaon	Agrani	C	HO	GD	1979-2006	Daily	1979-2006	Daily					1979-2007	Yearly
KT8	Daddi	Ghatprabha	C	HO	GD	1978-2007	Daily	1978-2007	Daily					2000-2006	Yearly
KT9	Gotur	Hiranyakeshi	C	HO	GD	1979-2007	Daily	1980-2007	Daily					2000-2006	Yearly
KT10	Gokak Falls	Ghatprabha	E	HO/FF	GD	1971-2014	Daily	1971-2014	Daily					2000-2013	Yearly
KT11	Mudhol	Ghatprabha	C	HO	GDSQ	1998-2007	Daily	2000-2007	Daily			2003-2006	Daily	2000-2006	Yearly
KT12	Bagalkot	Ghatprabha	C	HO	GDSQ	1966-2001	Daily	1966-2001	Daily			1972-2000	Daily		
KT13	Navalgund	Bennihala	C	HO	GD	1990-2006	Daily	1991-2006	Daily					2000-2006	Yearly
KT14	Cholachguda	Malaprabha	E	HO	GDSQ	1982-2014	Daily	1982-2014	Daily	2006-2015	Seasonal	1982-2014	Daily	2000-2013	Yearly
KT15	Huvanur	Malaprabha	C	HO	GDS	1967-1982	Daily	1967-1982	Daily			1973-1982	Daily		
KT16	Talikot	Don	E	HO	GD	1990-2014	Daily	1995-2014	Daily					2000-2013	Yearly
KT17	Halia	Halia	E	HO	GDQ	1984-2015	Daily	1984-2015	Daily					1984-2014	Yearly
KT18	Damercharla	Musi	E	HO	GDQ	1968-2015	Daily	1968-2015	Daily			2013-2014	Daily	2000-2013	Yearly
KT19	Paleru Bridge	Paleru	E	HO	GQ	1965-2015	Daily	1965-2015	Daily			2014-2014	Daily	1968-2013	Yearly
KT20	Purushothamagudem	Akeru	C	HO	GD	1987-2006	Daily	1987-2006	Daily					2001-2005	Yearly

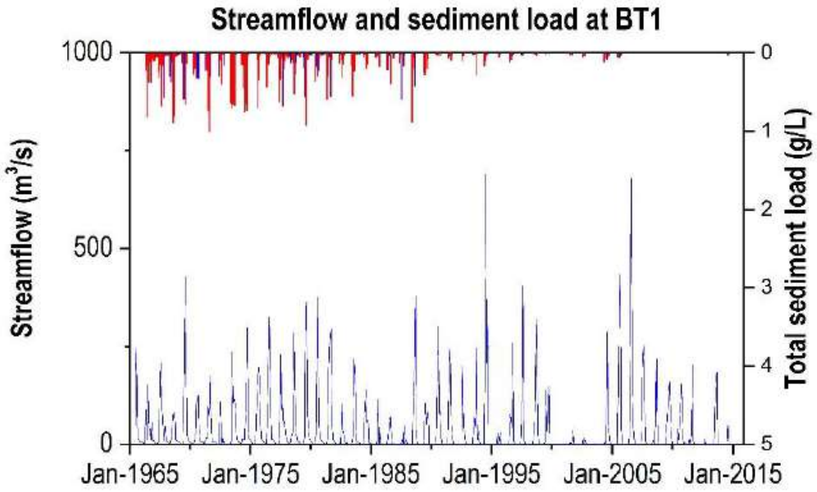
Code	Station Name	River	Status	Activity	Site Type	Gauge		D		BD		SS		XS	
						Period	Time Scale	Period	Time Scale	Period	Time Scale	Period	Time Scale	Period	Time Scale
KT21	Madhira	Wyra	E	HO	GDS	1984-2015	Daily	1984-2015	Daily			2014-2015	Daily	1985-2013	Yearly
KT22	Keesara	Munneru	E	HO	GDQ	1965-2015	Daily	1965-2015	Daily			1965-2015	Daily	1977-2013	Yearly
B1	Phulgaon	Bhima	E	HO	GDQ	1986-2014	Daily	1992-2014	Daily					2000-2014	Yearly
B2	Dhond	Bhima	E	HO	G	1967-2014	Daily	1967-2007	Daily			1967-2007	Daily	2000-2007	Yearly
B3	Narasingpur	Bhima	E	HO	GD	1965-2015	Daily	1966-2015	Daily					2000-2014	Yearly
B4	Takli	Bhima	E	HO	GDSQ	1965-2016	Daily	1965-2015	Daily	2006-2015	Seasonal	1966-2015	Daily	2000-2014	Yearly
B5	Deongaon Bridge	Bhima	E	HO/FF	G										
B6	Yadgir	Bhima	E	HO	GDSQ	1965-2015	Daily	1965-2015	Daily	2006-2015	Seasonal	1965-2015	Daily	1995-2014	Yearly
BT1	Sarati	Nira	E	HO	GD	1965-2015	Daily	1965-2015	Daily			1966-2014	Daily	2001-2014	Yearly
BT2	Siddhewadi	Man	C	HO	G										
BT3	Shirdhon	Doddanala	E	HO	G	1979-2013	Daily	1979-2006	Daily					2003-2014	Yearly
BT4	Kokangaon	Bornala	E	HO	G	1979-2013	Daily	1979-2013	Daily					2004-2014	Yearly
BT5	Ridhore	Sina	C	HO	G										
BT6	Wadakbal	Sina	E	HO	GD	1965-2015	Daily	1965-2015	Daily			1965-2009	Daily	2000-2014	Yearly
BT7	Jeewangi	Kagna	E	HO	G	1978-2014	Daily	1978-2006	Daily					1990-2013	Yearly
BT8	Malkhed	Kagna	E	HO	GDSQ	1989-2015	Daily	1990-2015	Daily	2006-2015	Seasonal	1992-2015	Daily	1995-2014	Yearly
T1	Holehonnur	Bhadra	E	HO	GDQ	1997-2016	Daily	2004-2016	Daily					1999-2012	Yearly
T2	Honnali	Tungabhadra	E	HO	GDSQ	1978-2015	Daily	1980-2015	Daily			1995-2015	Daily	1999-2012	Yearly
T3	Haralahalli	Tungabhadra	E	HO	GDSQ	1965-2015	Daily	1966-2015	Daily			1972-2014	Daily	1999-2012	Yearly
T4	T.B. Dam	Tungabhadra	E	HO/FF	G										

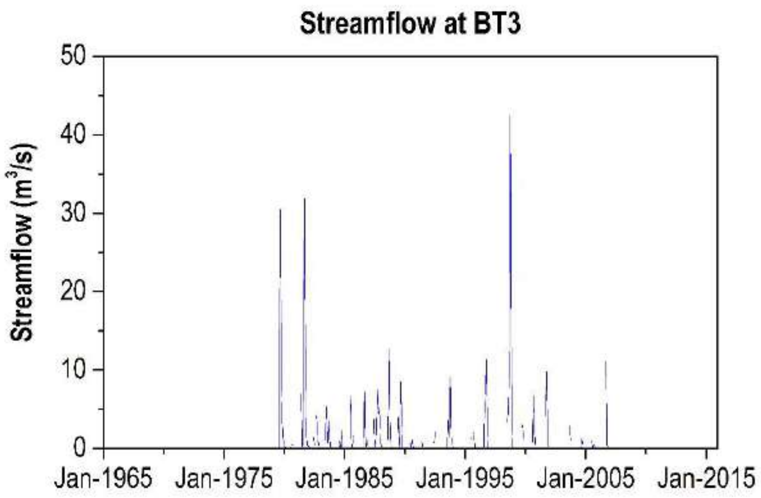
Code	Station Name	River	Status	Activity	Site Type	Gauge		D		BD		SS		XS	
						Period	Time Scale	Period	Time Scale	Period	Time Scale	Period	Time Scale	Period	Time Scale
T5	Oollenur	Tungabhadra	E	HO	G	1972-2015	Daily	1972-2015	Daily			1973-2002	Daily	2000-2001	Yearly
T6	Mantralayam	Tungabhadra	E	HO/FF	GD	1972-2015	Daily	1972-2015	Daily			1977-2014	Daily	1990-2014	Yearly
T7	Bawapuram	Tungabhadra	E	HO	GDSQ	1965-2015	Daily	1965-2015	Daily	2006-2015	Seasonal	1965-2015	Daily	1992-2014	Yearly
TT1	Lakkavali	Tungabhadra	C	HO	GD	1972-1980	Daily	1972-1980	Daily						
TT2	Shimoga	Tunga	E	HO	GDSQ	1971-2015	Daily	1972-2015	Daily			1972-2015	Daily	1999-2012	Yearly
TT3	Kuppelur	Kumudavathi	E	HO	GDQ	1990-2015	Daily	1990-2015	Daily					1999-2012	Yearly
TT4	Byaladahalli	Haridra	E	HO	GDSQ	1985-2015	Daily	1985-2015	Daily			1997-2015	Daily	1999-2012	Yearly
TT5	Marol	Varada	E	HO	GDSQ	1965-2015	Daily	1966-2015	Daily			1972-2015	Daily	1999-2014	Yearly
TT6	Kellodu	Vedavathi	E	HO	GDQ	1990-2015	Daily	1990-2015	Daily					1999-2012	Yearly
TT7	Hoovinahole	Swarnamukhi	E	HO	GDQ	1998-2015	Daily	2002-2015	Daily					1999-2012	Yearly
TT8	A.K. Bridge	Chikkahagari	C	HO	GD	1979-2004	Daily	1980-2004	Daily					2001-2003	Yearly
TT9	T. Ramapuram	Hagari	E	HO	GDQ	1965-2014	Daily	1965-2014	Daily					2000-2014	Yearly
TT10	Lakshmipuram	Handri	C	HO	GD	1984-2005	Daily	1984-2005	Daily						

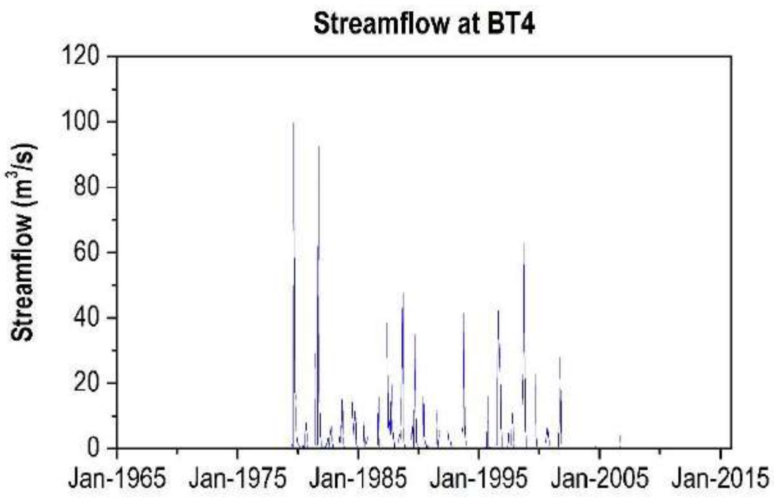
Appendix X: Temporal variability in streamflow and sediment discharge measured at different H. O. stations in Krishna and Tungabhadra rivers

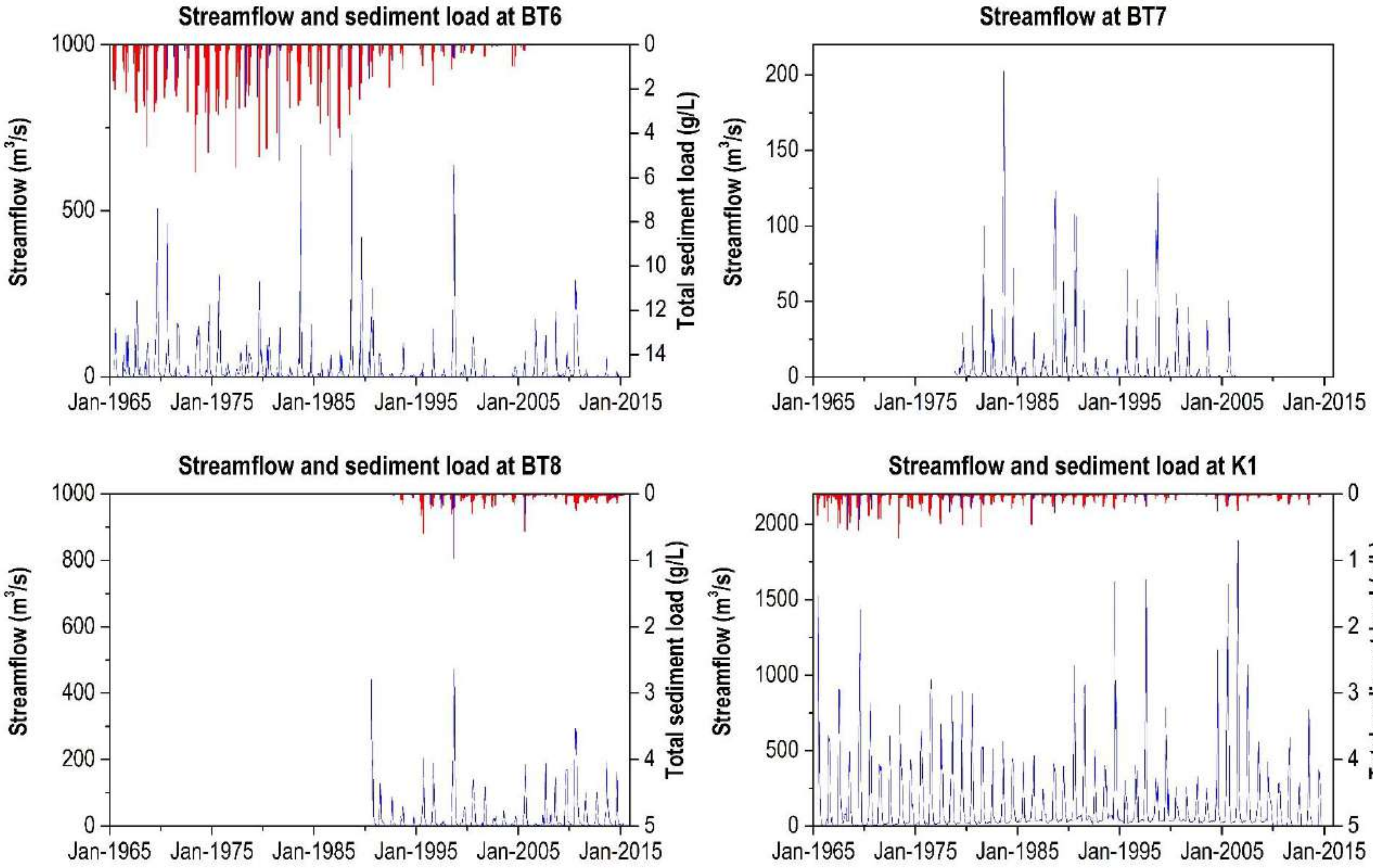


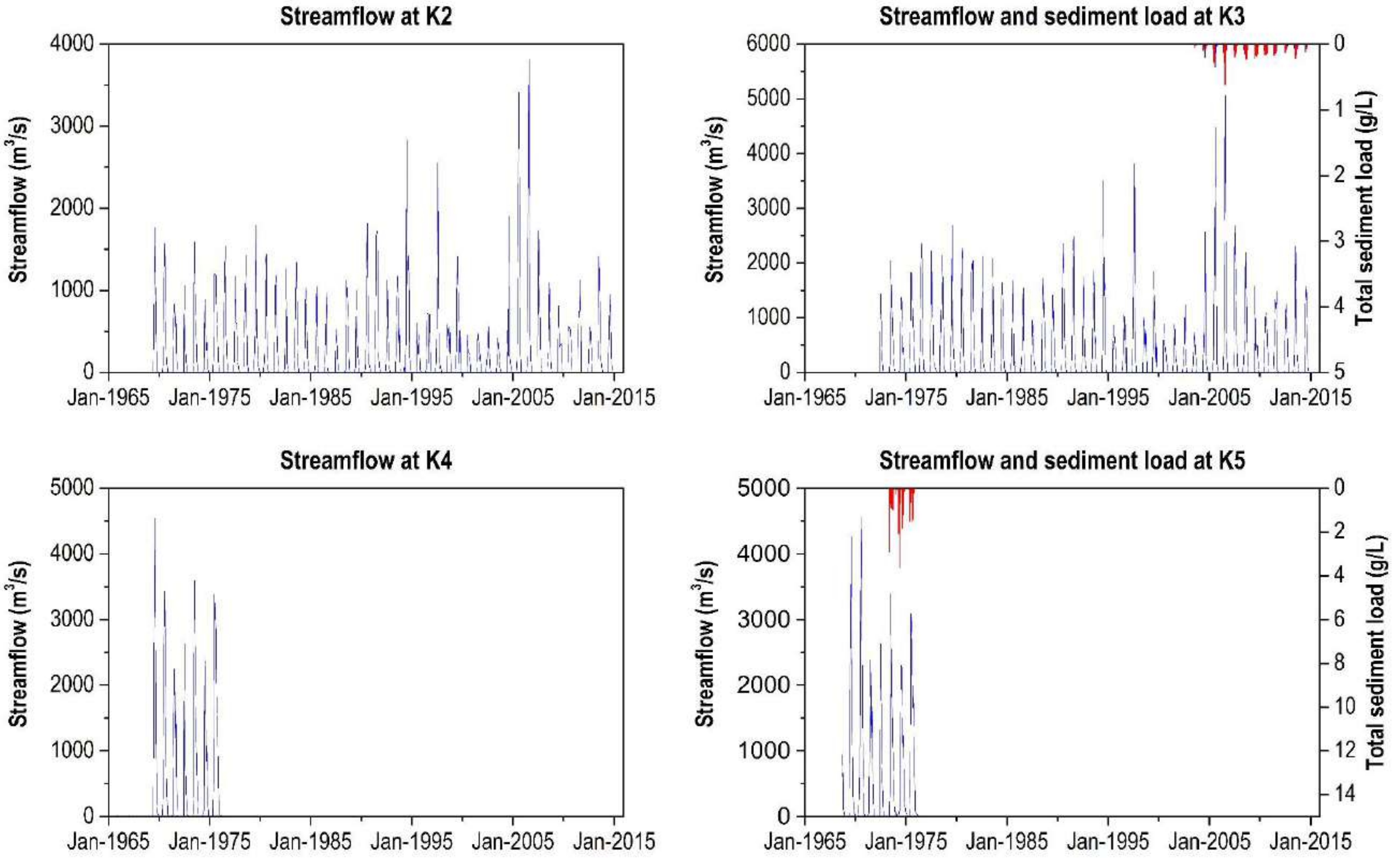

Streamflow and sediment load at B6
Streamflow (m³/s)
Total sediment load (g/L)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015


Streamflow and sediment load at BT1
Streamflow (m³/s)
Total sediment load (g/L)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

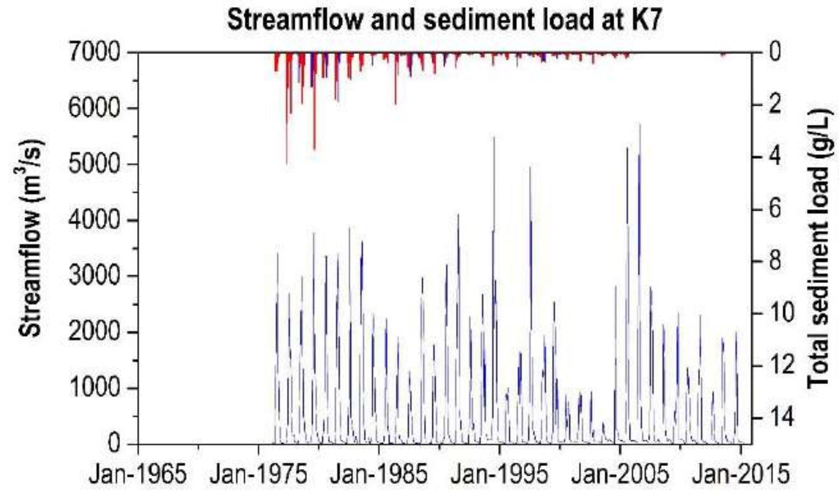

Streamflow at BT3
Streamflow (m³/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

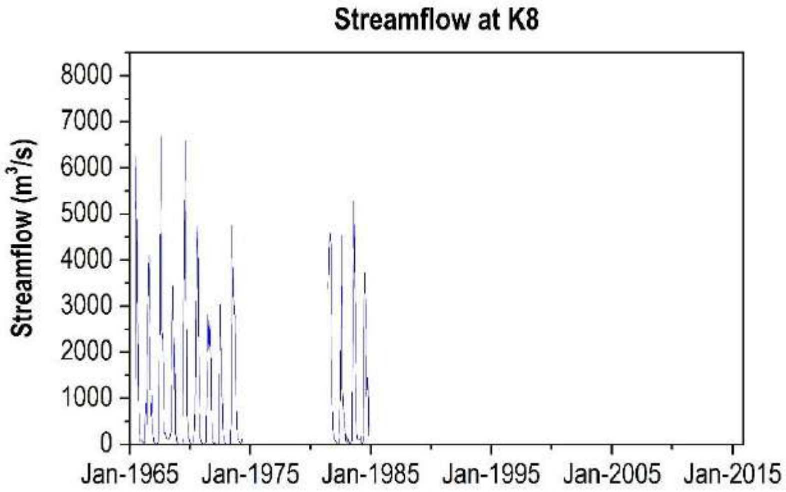

Streamflow at BT4
Streamflow (m³/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

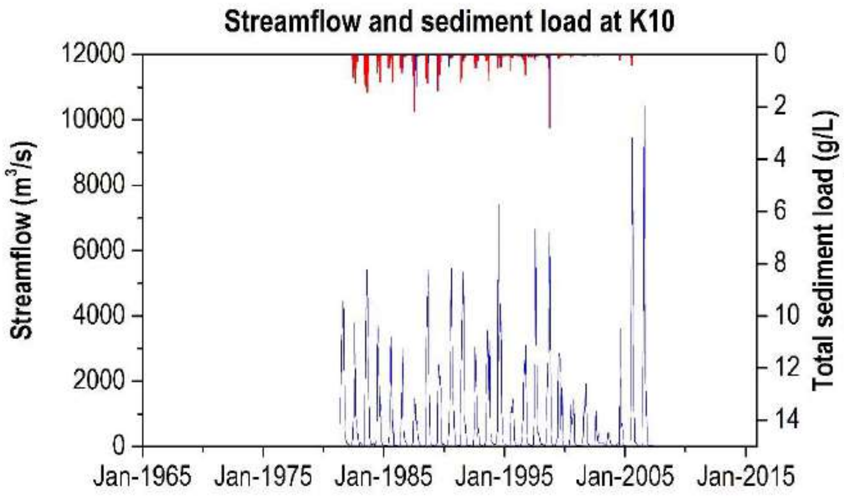

Streamflow and sediment load at BT6
Streamflow at BT7
Streamflow and sediment load at BT8
Streamflow and sediment load at K1
Streamflow (m³/s)
Total sediment load (g/L)
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

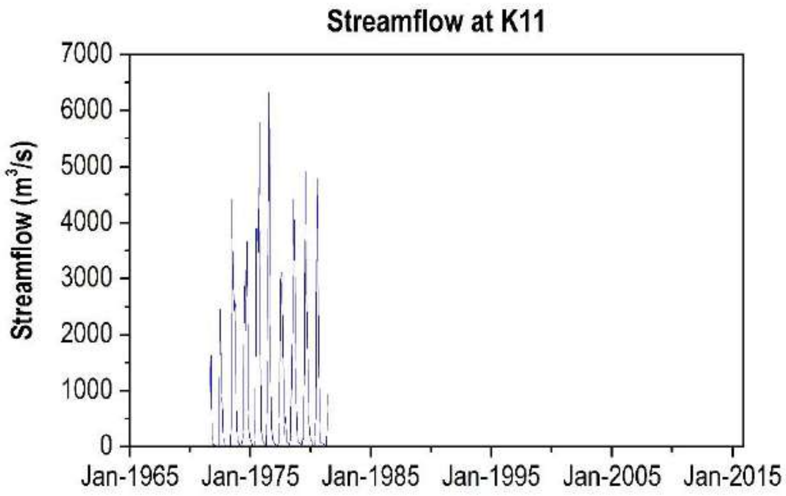


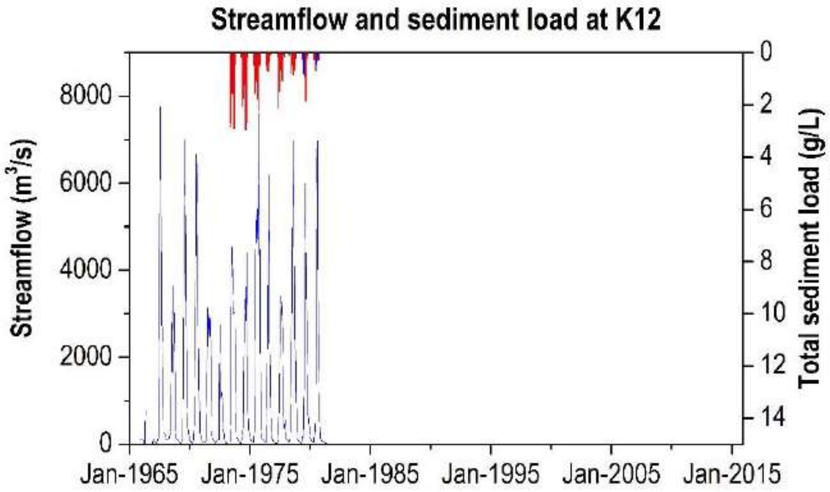
Streamflow at K2
Streamflow (m³/s)
0
1000
2000
3000
4000
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015
Streamflow and sediment load at K3
Streamflow (m³/s)
0
1000
2000
3000
4000
5000
6000
Total sediment load (g/L)
0
1
2
3
4
5
Streamflow at K4
Streamflow (m³/s)
0
1000
2000
3000
4000
5000
Streamflow and sediment load at K5
Total sediment load (g/L)
0
2
4
6
8
10
12
14


Streamflow and sediment load at K7
Streamflow (m3/s)
Total sediment load (g/L)
0
2
4
6
8
10
12
14
7000
6000
5000
4000
3000
2000
1000
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

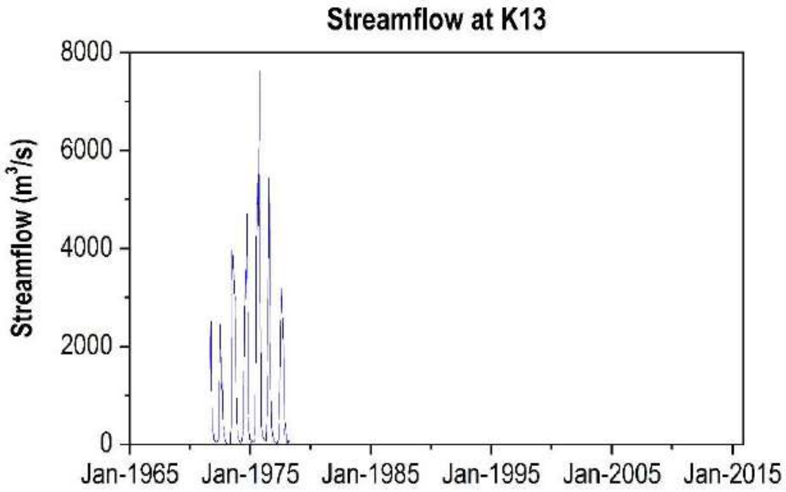

Streamflow at K8
Streamflow (m3/s)
8000
7000
6000
5000
4000
3000
2000
1000
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015


Streamflow and sediment load at K10
Streamflow (m3/s)
Total sediment load (g/L)
12000
10000
8000
6000
4000
2000
0
0
2
4
6
8
10
12
14
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

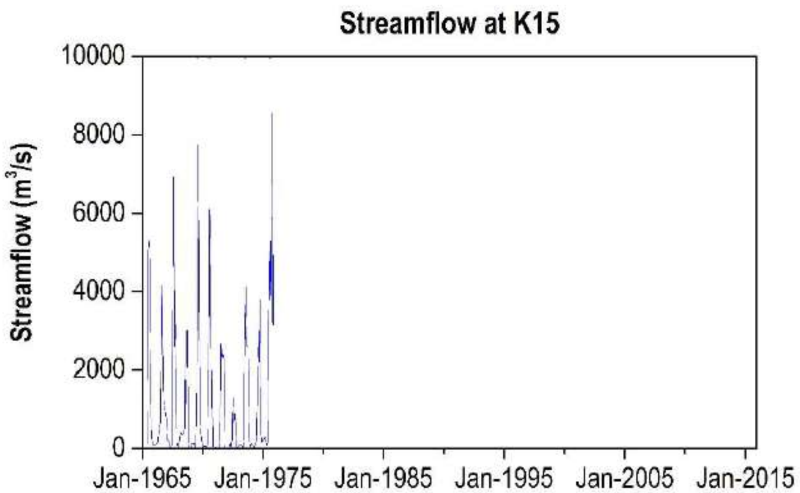

Streamflow at K11
Streamflow (m3/s)
7000
6000
5000
4000
3000
2000
1000
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015



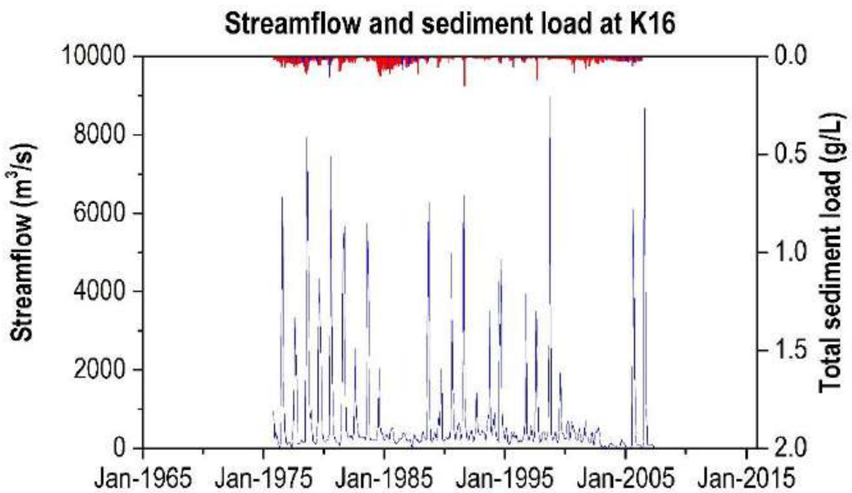
Streamflow and sediment load at K12
Streamflow (m3/s)
Total sediment load (g/L)
0
2000
4000
6000
8000
2
4
6
8
10
12
14
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015



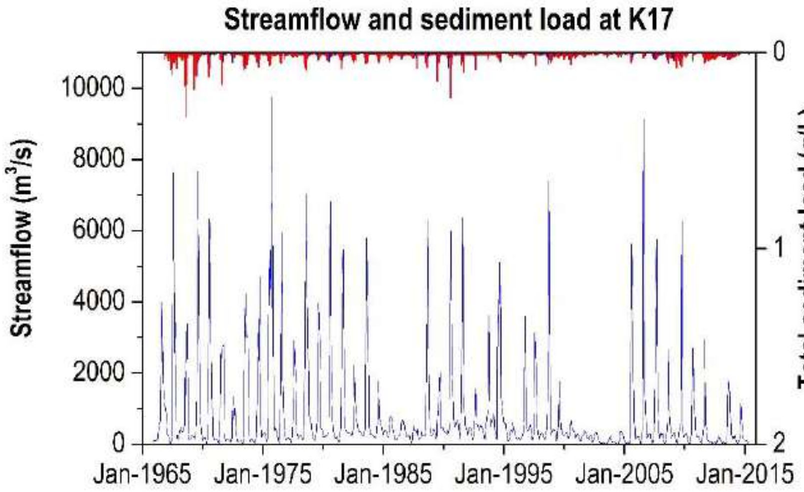
Streamflow at K13
Streamflow (m3/s)
0
2000
4000
6000
8000
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

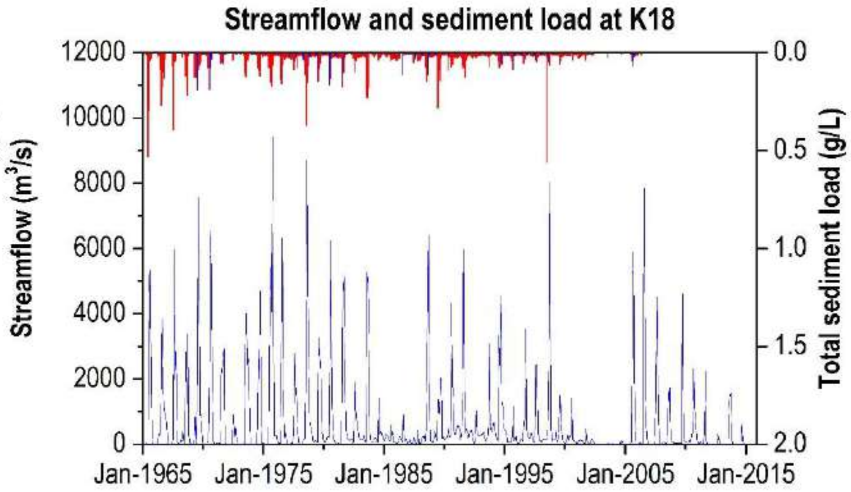


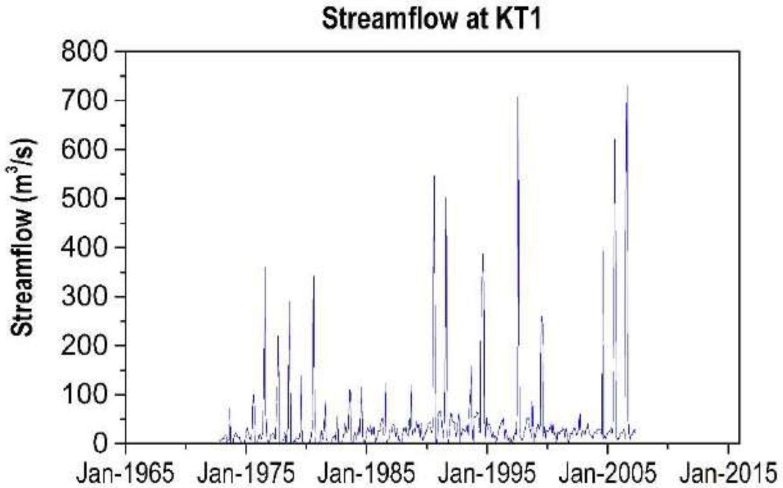
Streamflow at K15
Streamflow (m3/s)
0
2000
4000
6000
8000
10000
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

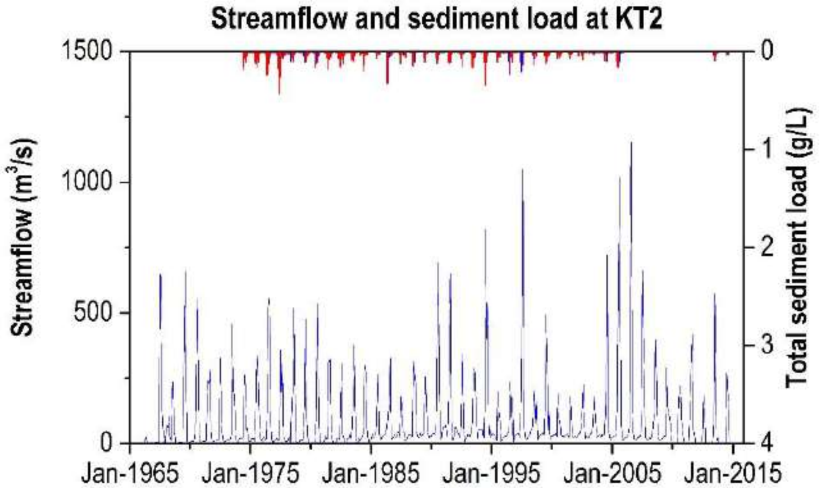


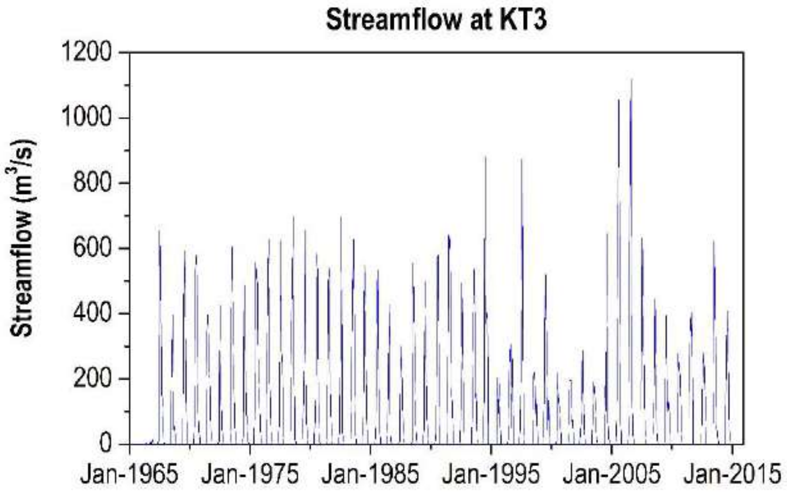
Streamflow and sediment load at K16
Streamflow (m3/s)
Total sediment load (g/L)
0
2000
4000
6000
8000
10000
0.0
0.5
1.0
1.5
2.0
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

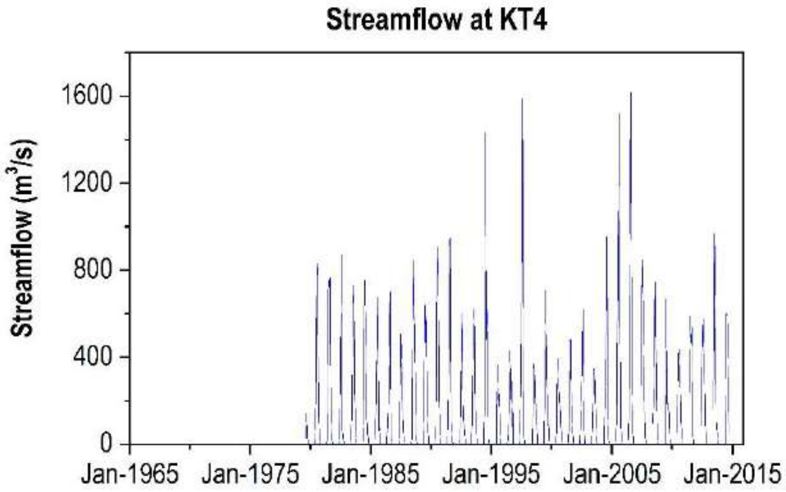

Streamflow and sediment load at K17
Streamflow (m³/s)
Total sediment load (g/L)
0
2000
4000
6000
8000
10000
0
1
2
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

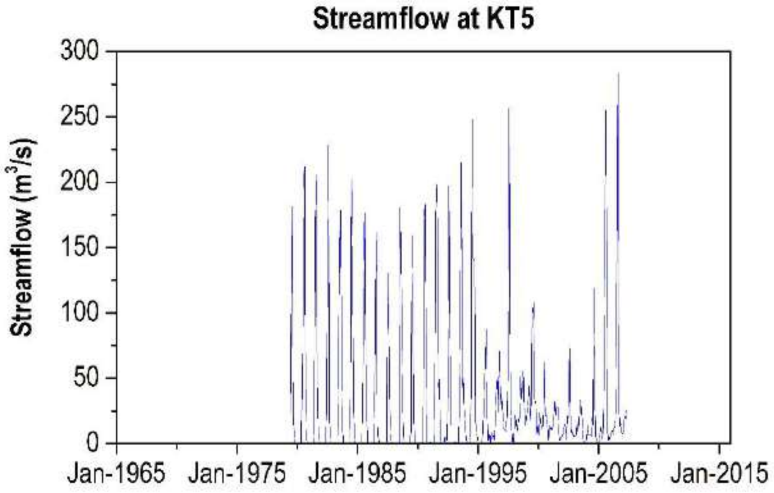

Streamflow and sediment load at K18
Streamflow (m³/s)
Total sediment load (g/L)
0
2000
4000
6000
8000
10000
12000
0.0
0.5
1.0
1.5
2.0
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

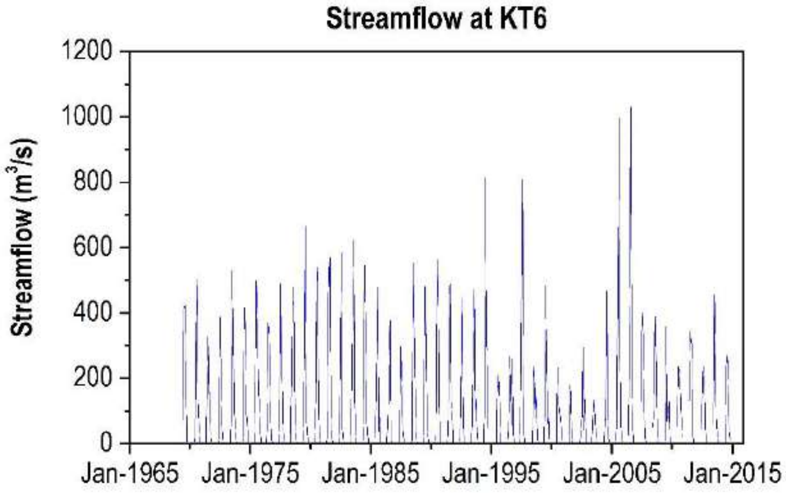

Streamflow at KT1
Streamflow (m³/s)
0
100
200
300
400
500
600
700
800
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

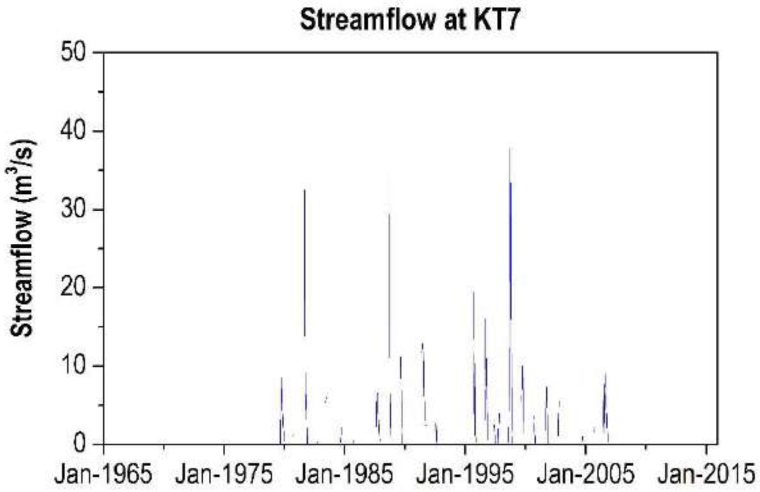

Streamflow and sediment load at KT2
Streamflow (m³/s)
Total sediment load (g/L)
0
500
1000
1500
0
1
2
3
4
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015


Streamflow at KT3
Streamflow (m3/s)
0
200
400
600
800
1000
1200
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

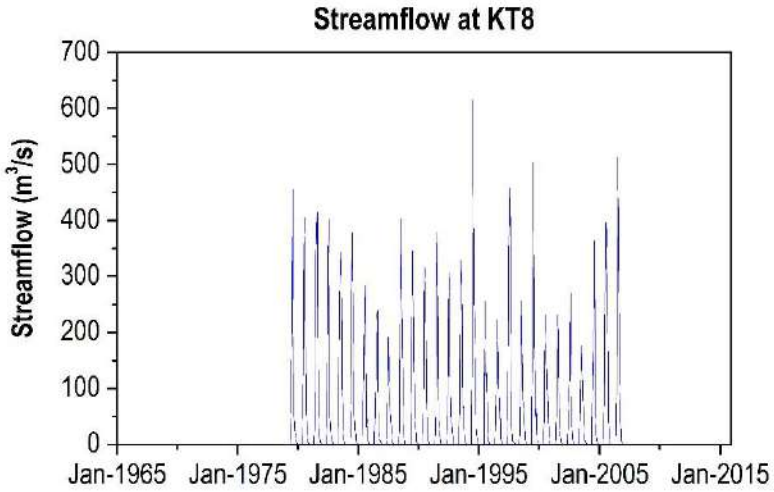

Streamflow at KT4
Streamflow (m3/s)
0
400
800
1200
1600
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015


Streamflow at KT5
Streamflow (m3/s)
0
50
100
150
200
250
300
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

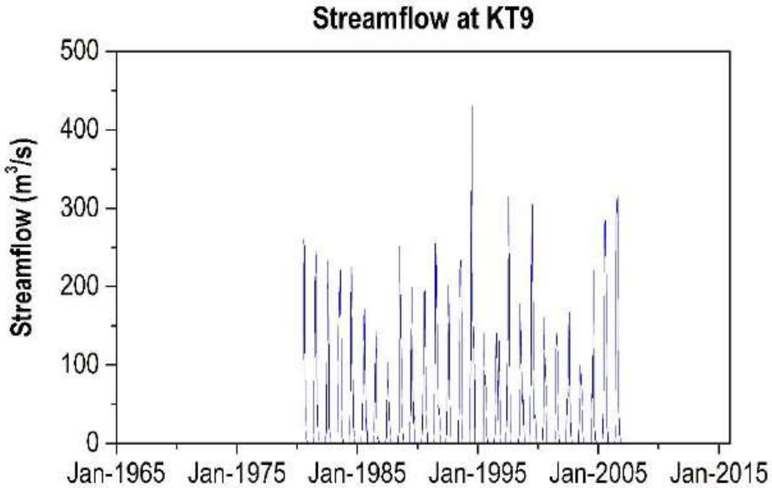

Streamflow at KT6
Streamflow (m3/s)
0
200
400
600
800
1000
1200
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015



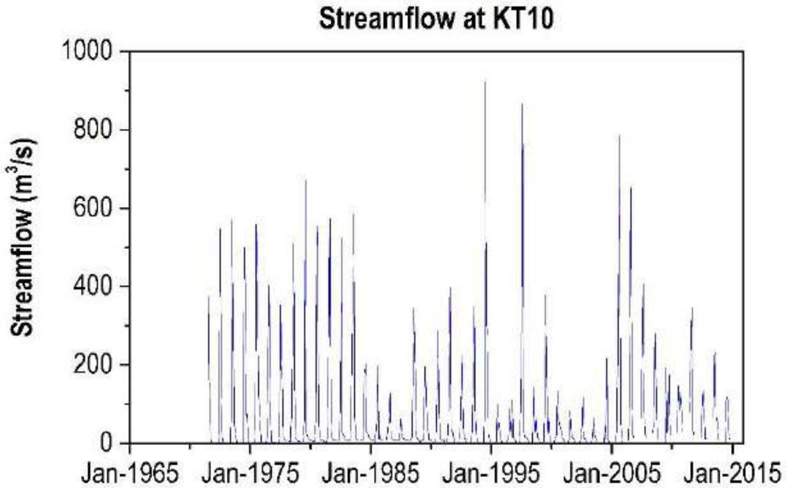
Streamflow at KT7
Streamflow (m³/s)
50
40
30
20
10
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015



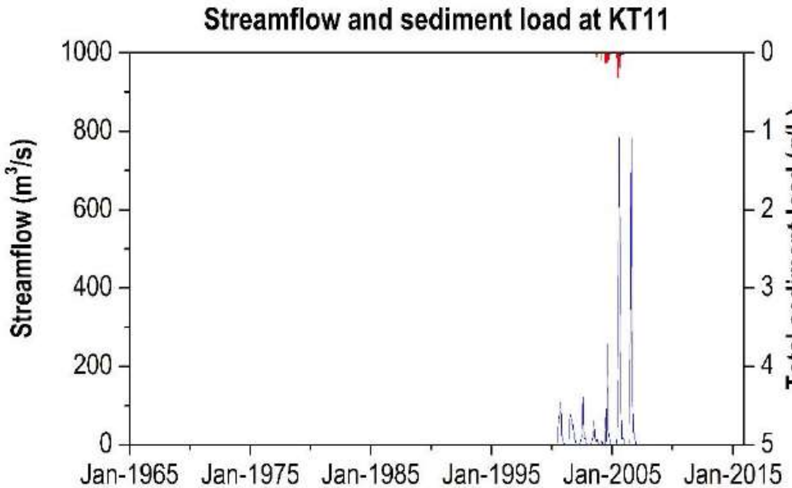
Streamflow at KT8
Streamflow (m³/s)
700
600
500
400
300
200
100
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

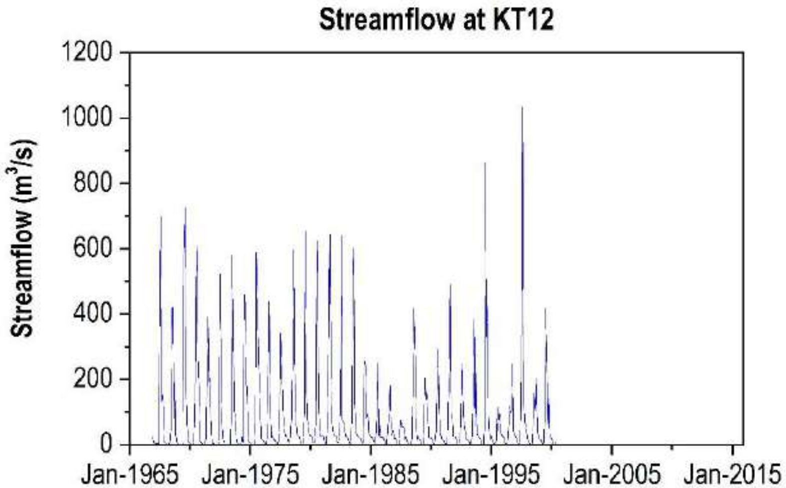


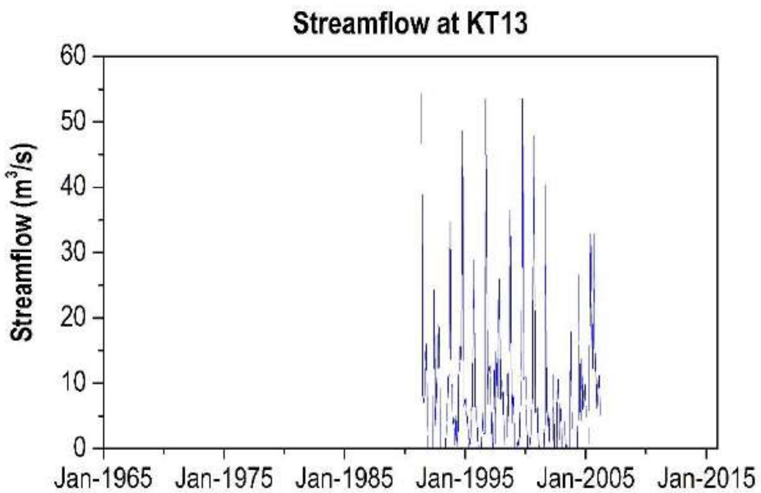
Streamflow at KT9
Streamflow (m³/s)
500
400
300
200
100
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

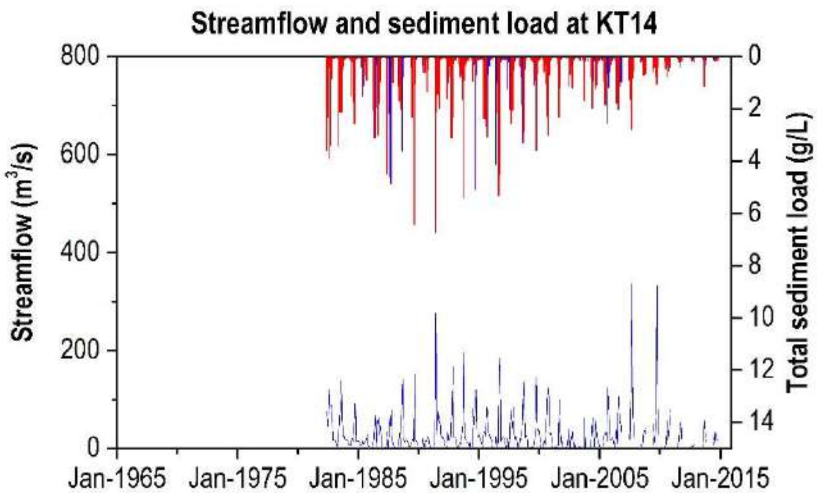


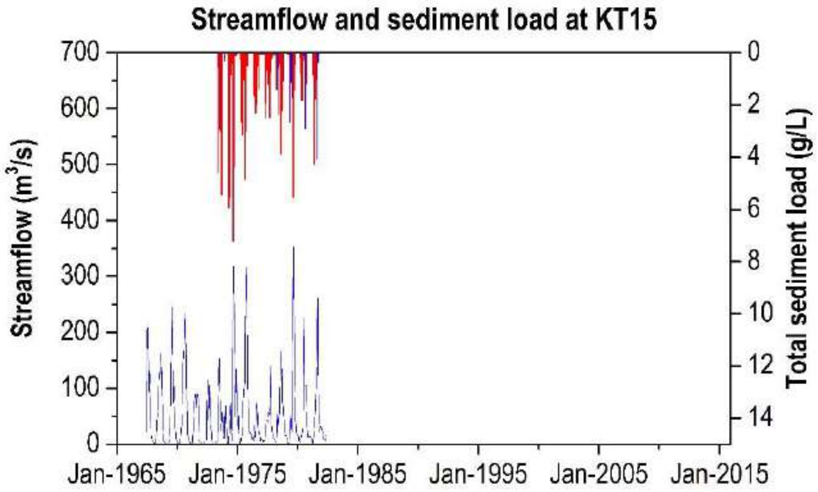
Streamflow at KT10
Streamflow (m³/s)
1000
800
600
400
200
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

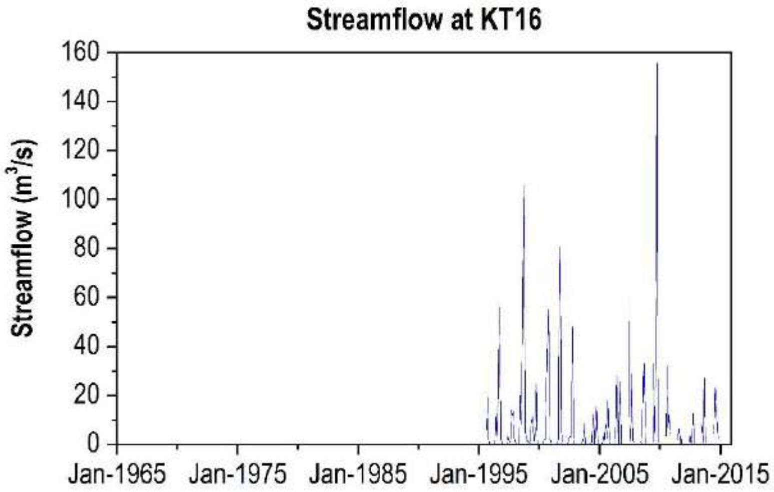

Streamflow and sediment load at KT11
Streamflow (m3/s)
Total sediment load (g/L)
1000
800
600
400
200
0
0
1
2
3
4
5
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

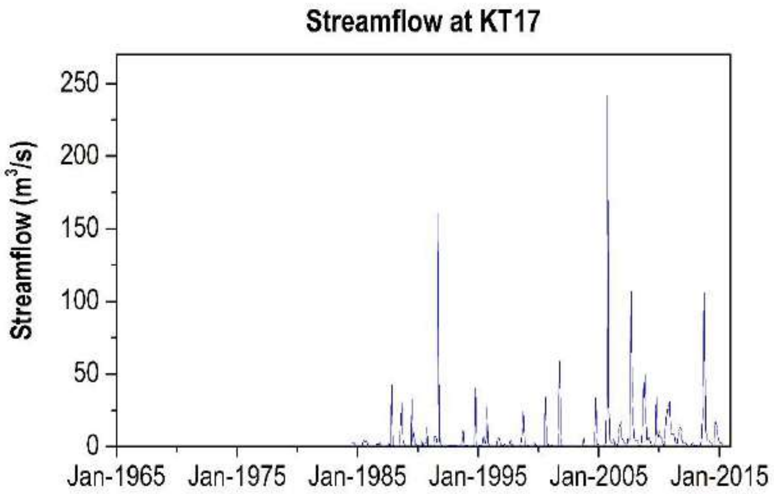

Streamflow at KT12
Streamflow (m3/s)
1200
1000
800
600
400
200
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

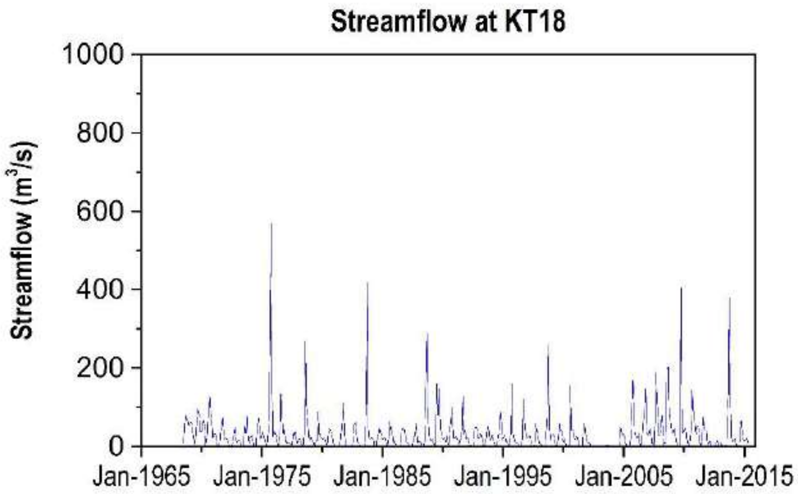

Streamflow at KT13
Streamflow (m3/s)
60
50
40
30
20
10
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

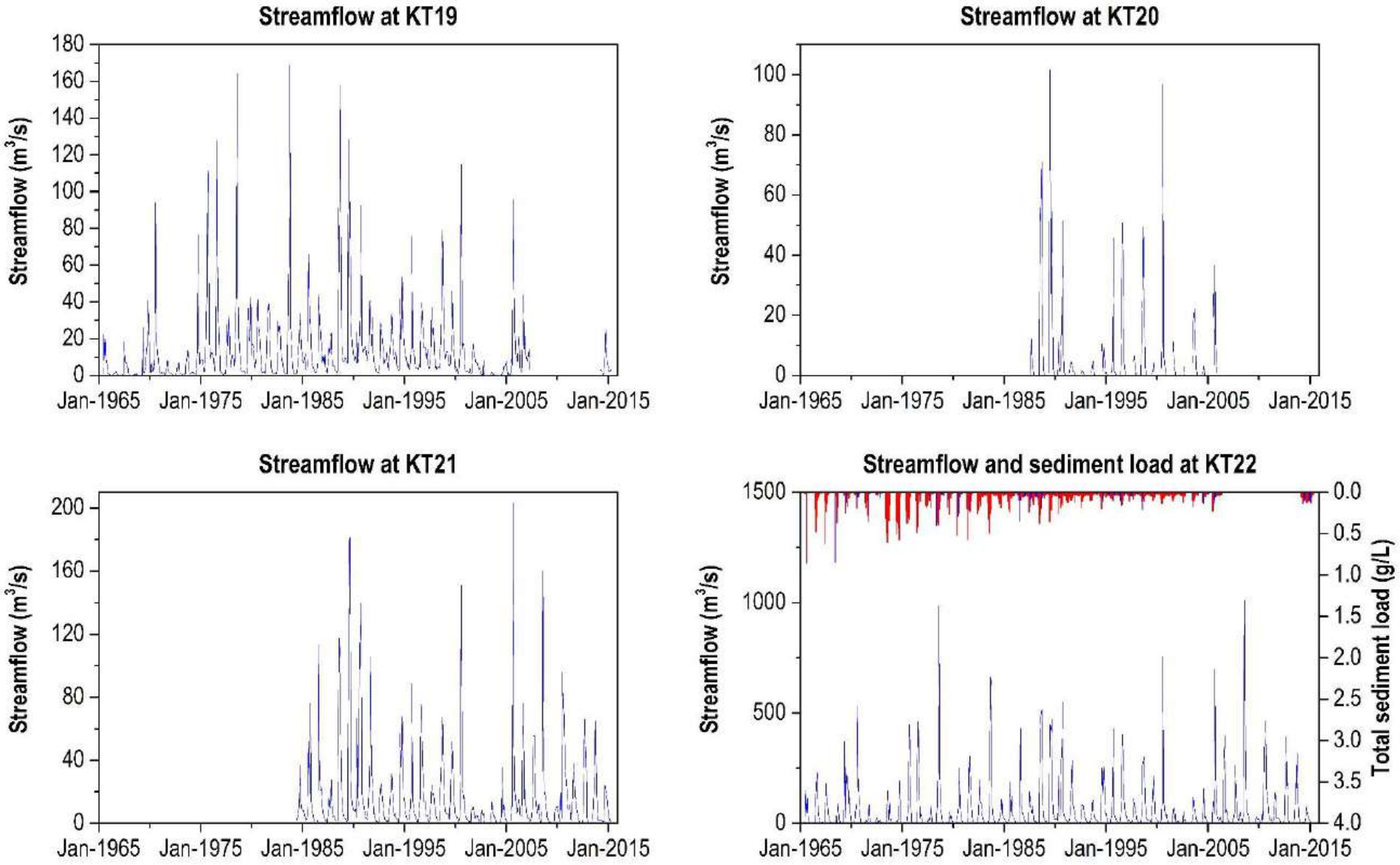

Streamflow and sediment load at KT14
Streamflow (m3/s)
Total sediment load (g/L)
800
600
400
200
0
0
2
4
6
8
10
12
14
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

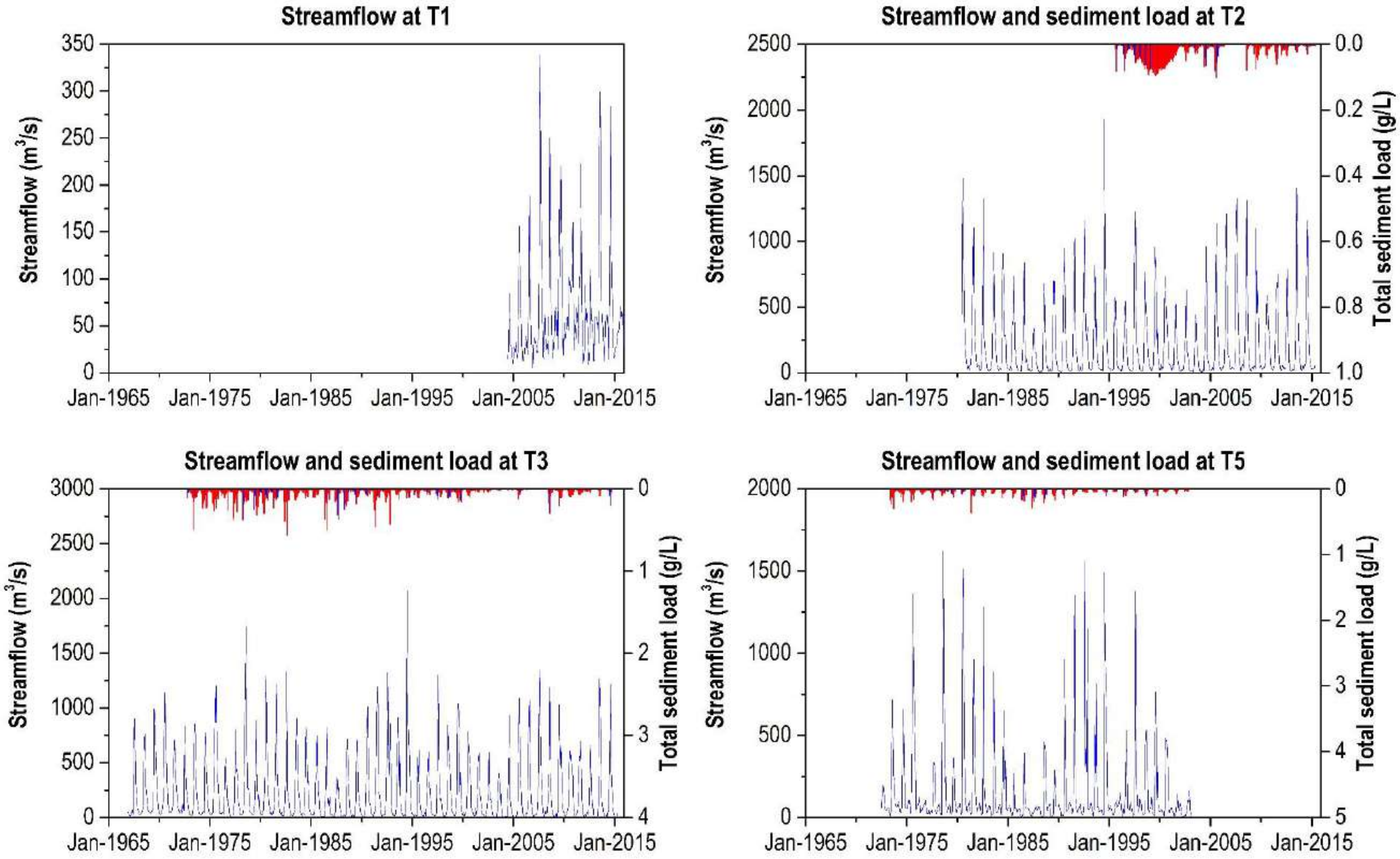

Streamflow and sediment load at KT15
Streamflow (m3/s)
Total sediment load (g/L)
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

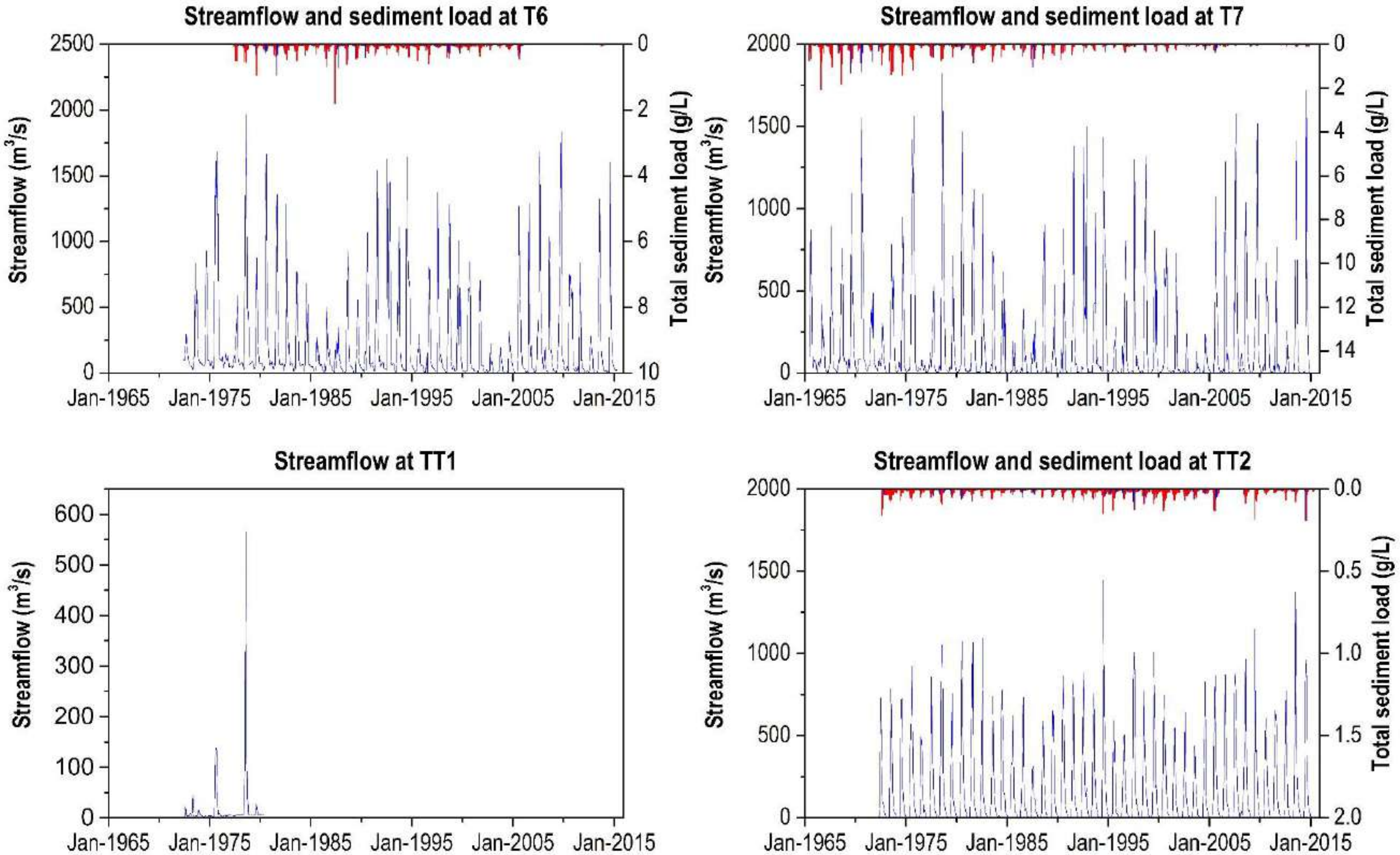

Streamflow at KT16
Streamflow (m3/s)
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

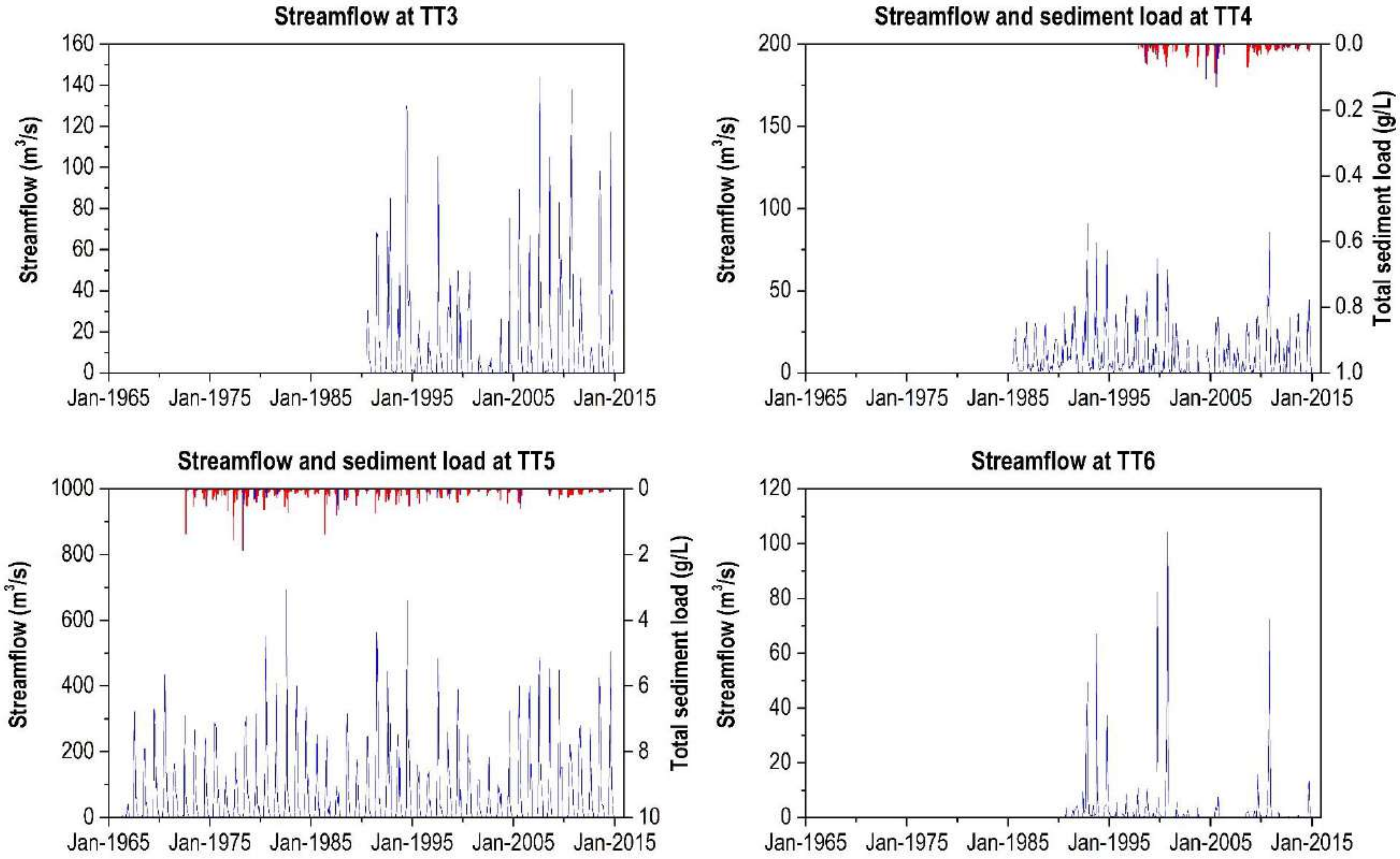

Streamflow at KT17
Streamflow (m3/s)
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015


Streamflow at KT18
Streamflow (m3/s)
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015

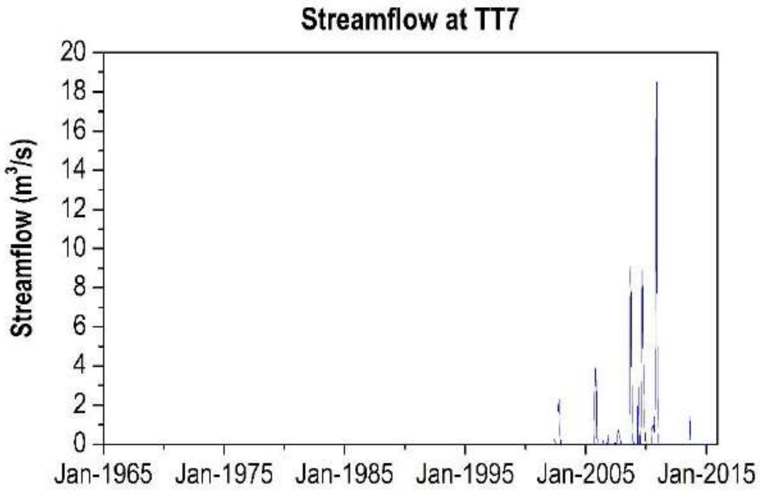

Streamflow at KT19
Streamflow (m3/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015
Streamflow at KT20
Streamflow (m3/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015
Streamflow at KT21
Streamflow (m3/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015
Streamflow and sediment load at KT22
Streamflow (m3/s)
Total sediment load (g/L)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

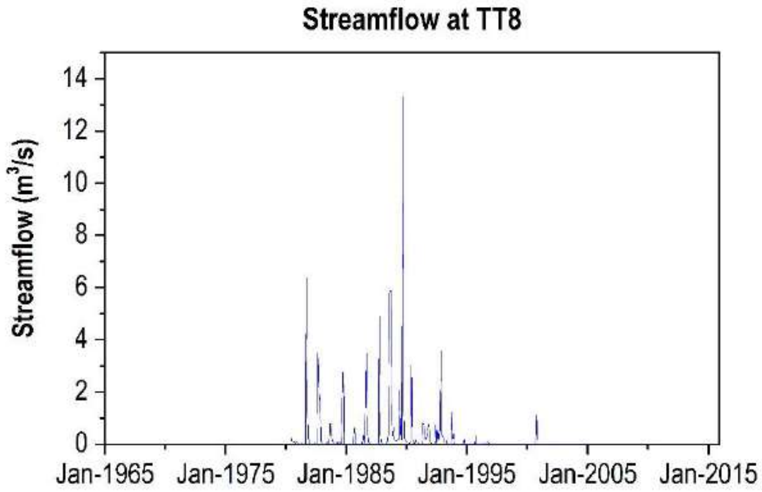

Streamflow at T1
Streamflow (m³/s)
350
300
250
200
150
100
50
0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015
Streamflow and sediment load at T2
Streamflow (m³/s)
2500
2000
1500
1000
500
0
Total sediment load (g/L)
0.0
0.2
0.4
0.6
0.8
1.0
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015
Streamflow and sediment load at T3
Streamflow (m³/s)
3000
2500
2000
1500
1000
500
0
Total sediment load (g/L)
0
1
2
3
4
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015
Streamflow and sediment load at T5
Streamflow (m³/s)
2000
1500
1000
500
0
Total sediment load (g/L)
0
1
2
3
4
5
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

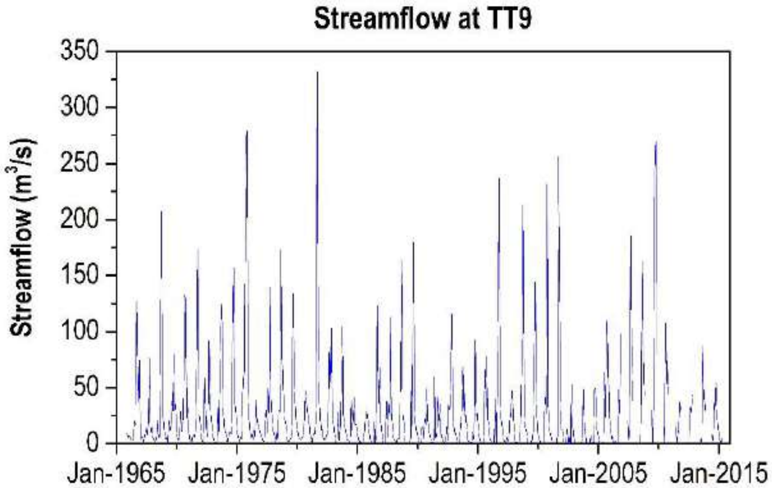

Streamflow and sediment load at T6
Streamflow (m³/s)
Total sediment load (g/L)
2500
2000
1500
1000
500
0
0
2
4
6
8
10
Jan-1965
Jan-1975
Jan-1985
Jan-1995
Jan-2005
Jan-2015
Streamflow and sediment load at T7
Streamflow (m³/s)
Total sediment load (g/L)
2000
1500
1000
500
0
0
2
4
6
8
10
12
14
Streamflow at TT1
Streamflow (m³/s)
600
500
400
300
200
100
0
Streamflow and sediment load at TT2
Streamflow (m³/s)
Total sediment load (g/L)
2000
1500
1000
500
0
0.0
0.5
1.0
1.5
2.0

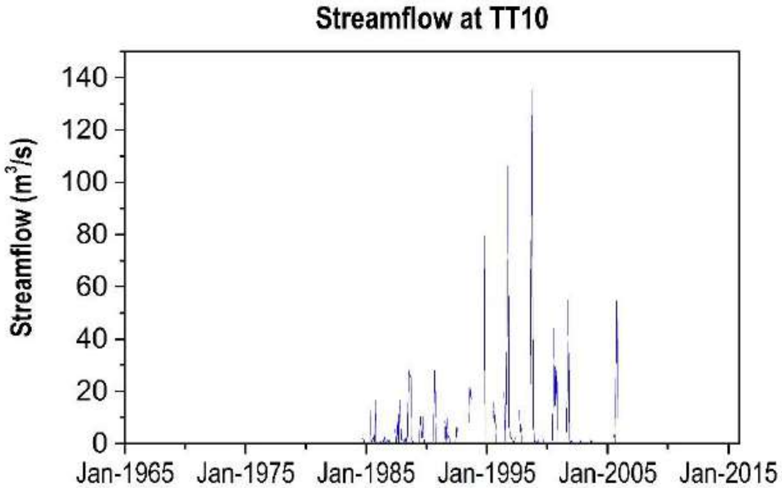


Streamflow at TT3
Streamflow (m3/s)
Streamflow and sediment load at TT4
Streamflow (m3/s)
Total sediment load (g/L)
Streamflow and sediment load at TT5
Streamflow (m3/s)
Total sediment load (g/L)
Streamflow at TT6
Streamflow (m3/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

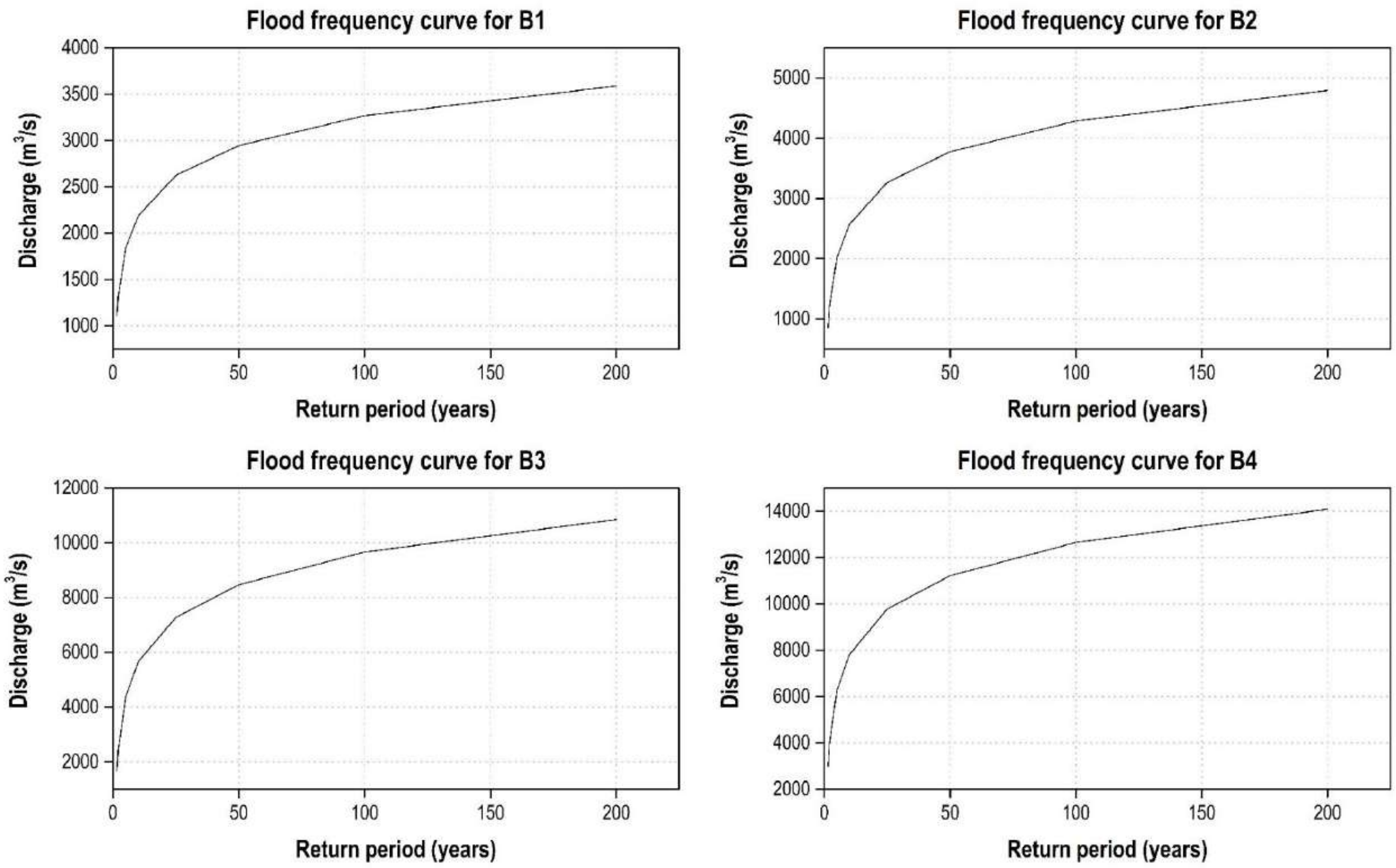

Streamflow at TT7
Streamflow (m3/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

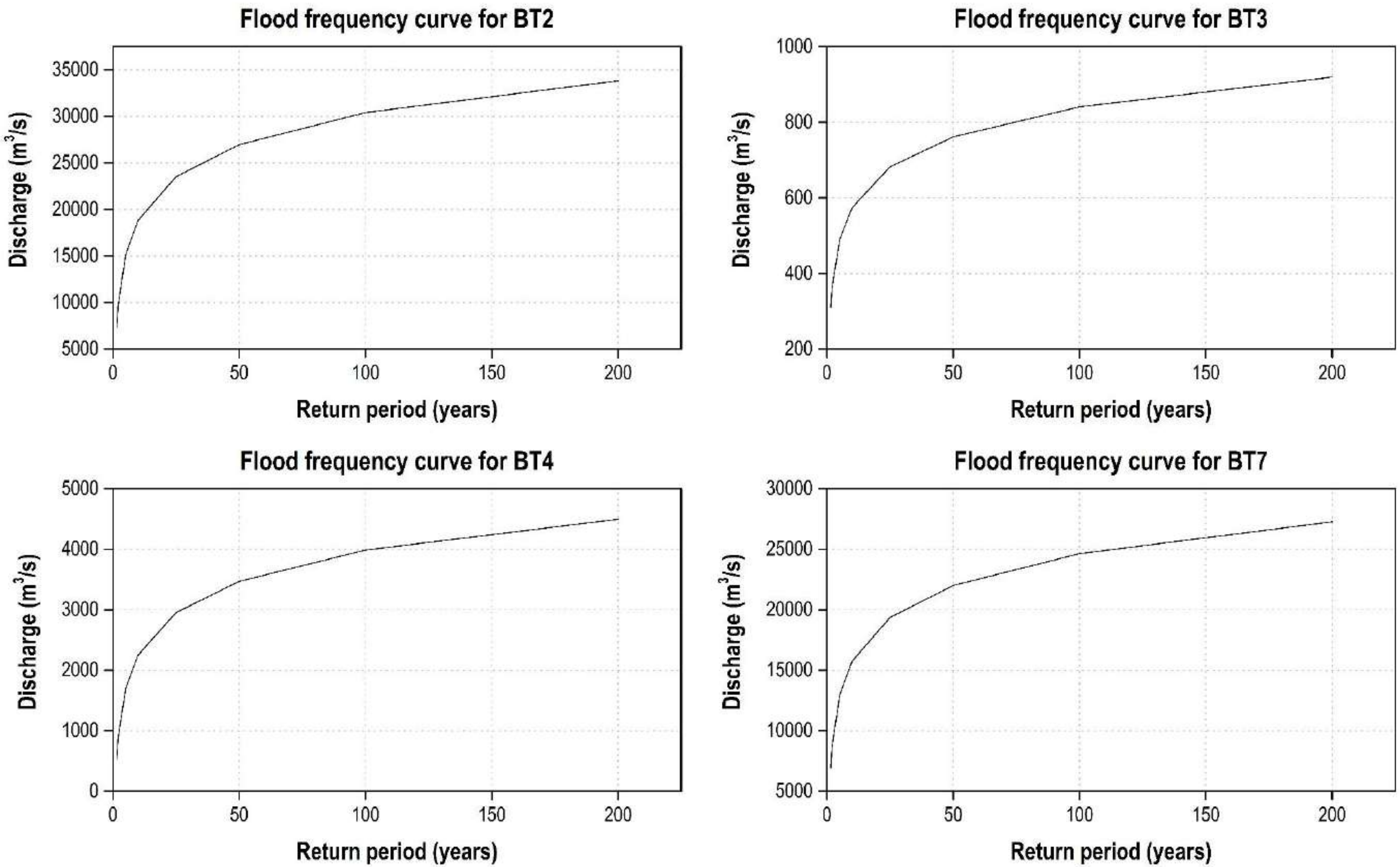

Streamflow at TT8
Streamflow (m3/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

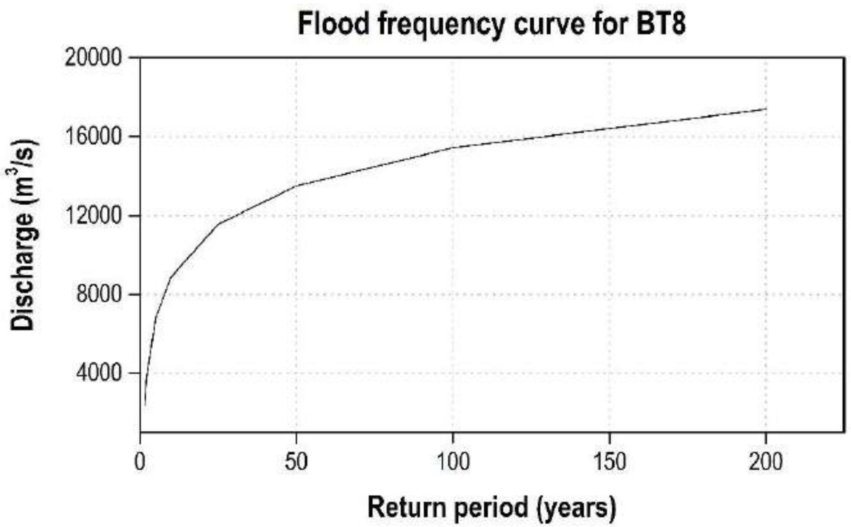

Streamflow at TT9
Streamflow (m3/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

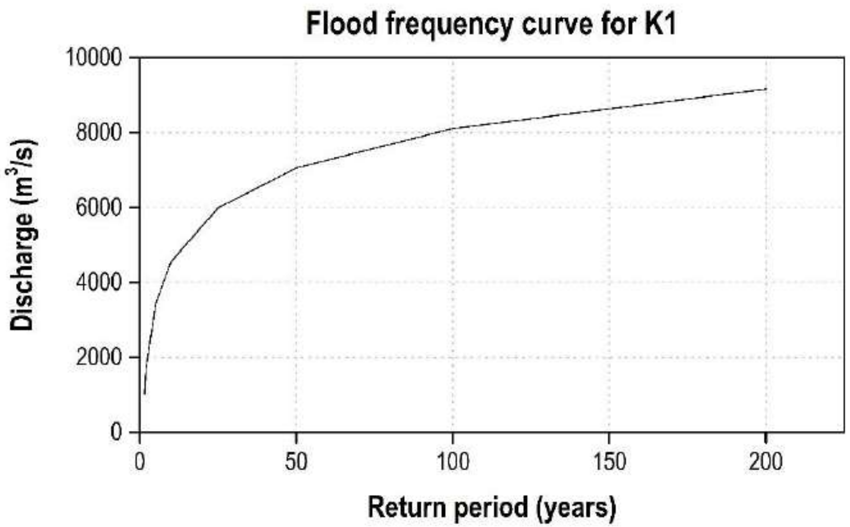

Streamflow at TT10
Streamflow (m3/s)
Jan-1965 Jan-1975 Jan-1985 Jan-1995 Jan-2005 Jan-2015

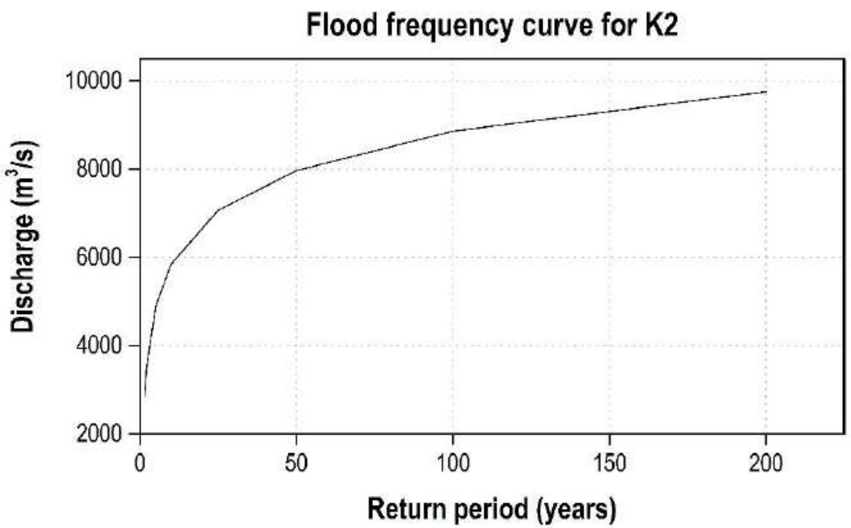
Appendix XI: Flood frequency curve for the different H.O. stations of Krishna and Tungabhadra rivers

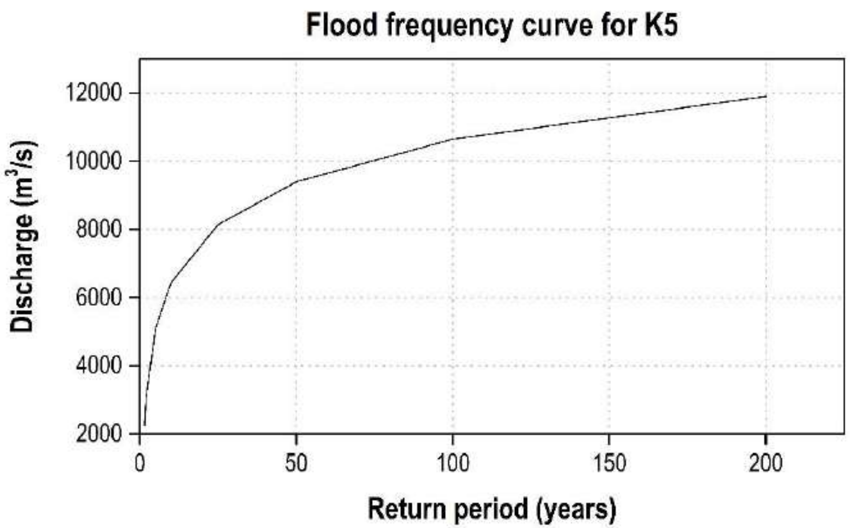


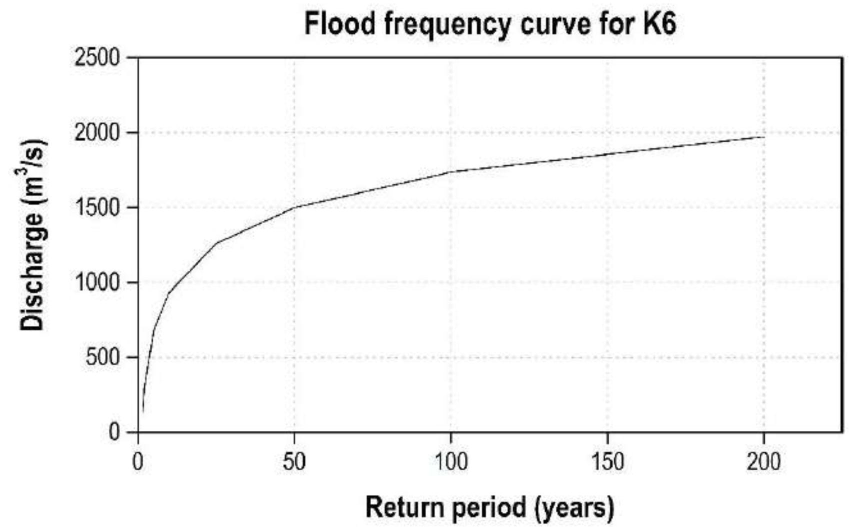

Flood frequency curve for BT2
Discharge (m3/s)
35000
30000
25000
20000
15000
10000
5000
0
50
100
150
200
Return period (years)
Flood frequency curve for BT3
Discharge (m3/s)
1000
800
600
400
200
0
50
100
150
200
Return period (years)
Flood frequency curve for BT4
Discharge (m3/s)
5000
4000
3000
2000
1000
0
0
50
100
150
200
Return period (years)
Flood frequency curve for BT7
Discharge (m3/s)
30000
25000
20000
15000
10000
5000
0
50
100
150
200
Return period (years)


Flood frequency curve for BT8
Discharge (m³/s)
Return period (years)

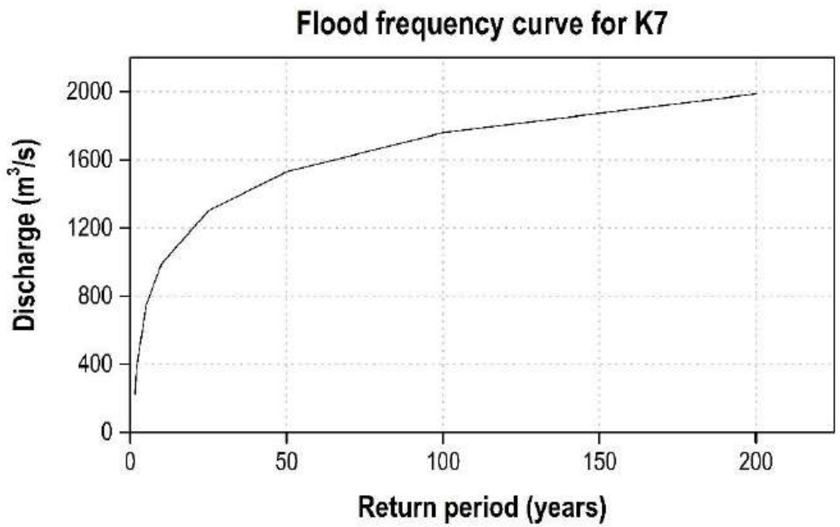

Flood frequency curve for K1
Discharge (m³/s)
Return period (years)


Flood frequency curve for K2
Discharge (m³/s)
Return period (years)

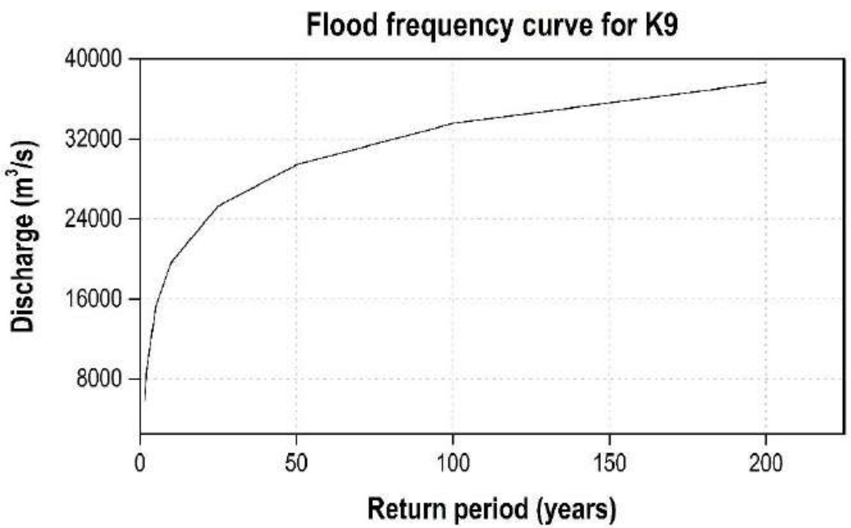

Flood frequency curve for K5
Discharge (m³/s)
Return period (years)



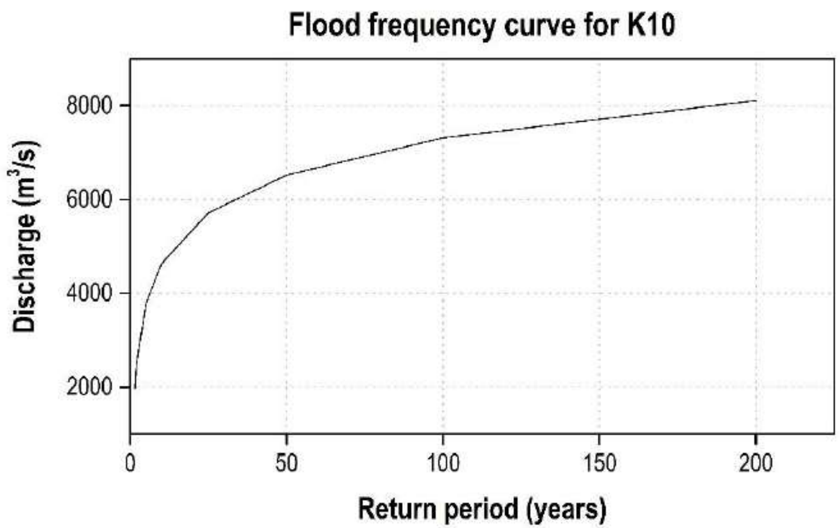
Flood frequency curve for K6
Discharge (m³/s)
2500
2000
1500
1000
500
0
0
50
100
150
200
Return period (years)



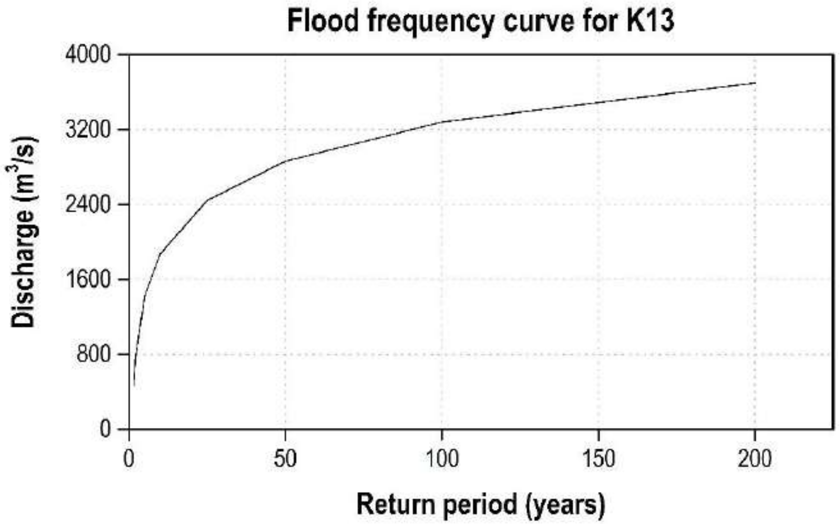
Flood frequency curve for K7
Discharge (m³/s)
2000
1600
1200
800
400
0
0
50
100
150
200
Return period (years)

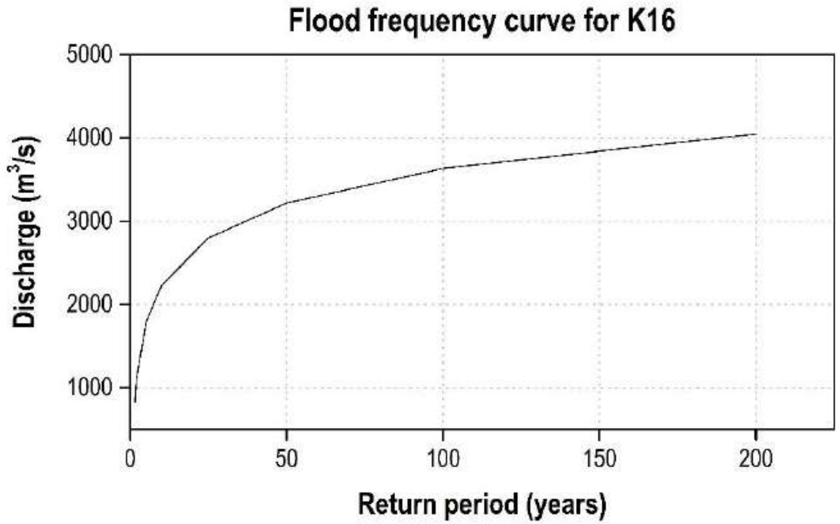


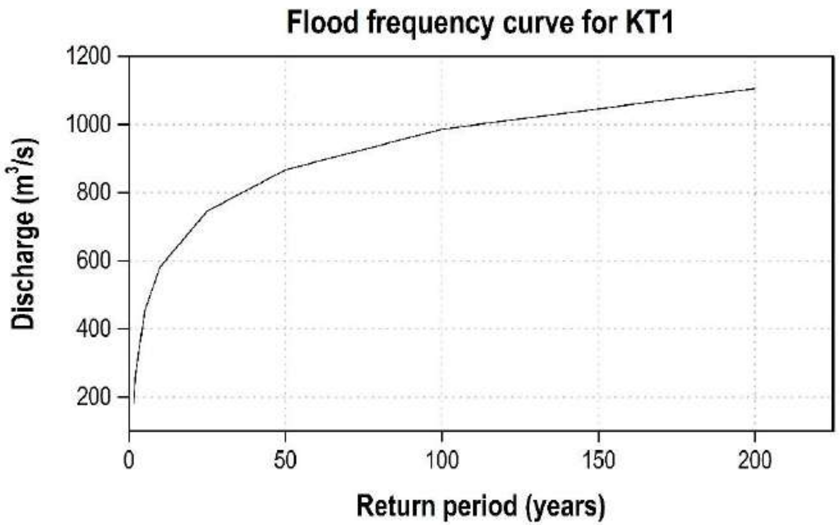
Flood frequency curve for K9
Discharge (m³/s)
40000
32000
24000
16000
8000
0
50
100
150
200
Return period (years)

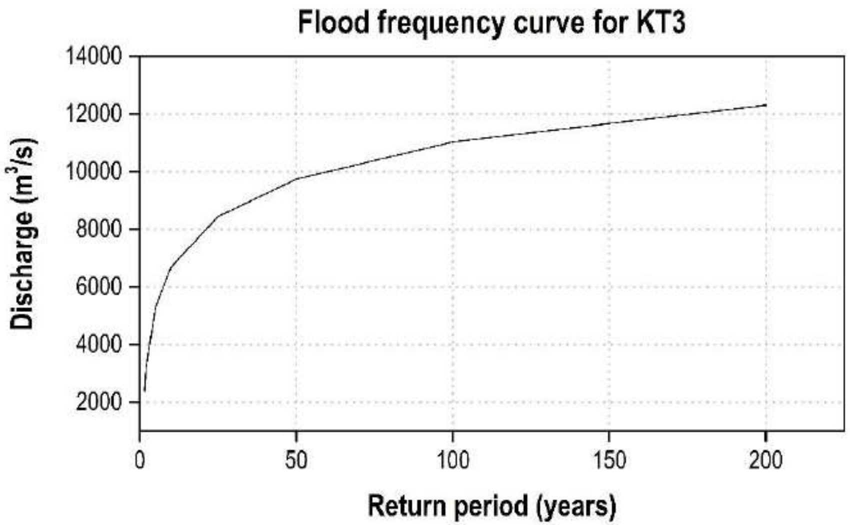


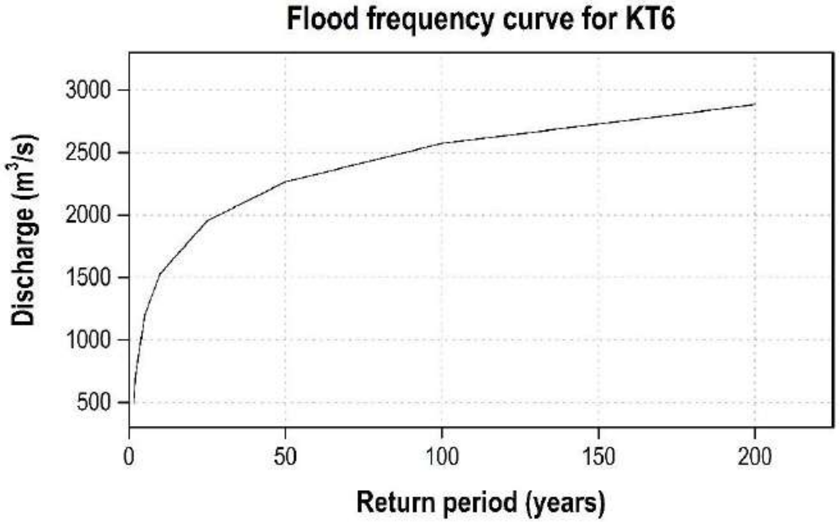
Flood frequency curve for K10
Discharge (m³/s)
8000
6000
4000
2000
0
50
100
150
200
Return period (years)


Flood frequency curve for K13
Discharge (m³/s)
4000
3200
2400
1600
800
0
0
50
100
150
200
Return period (years)

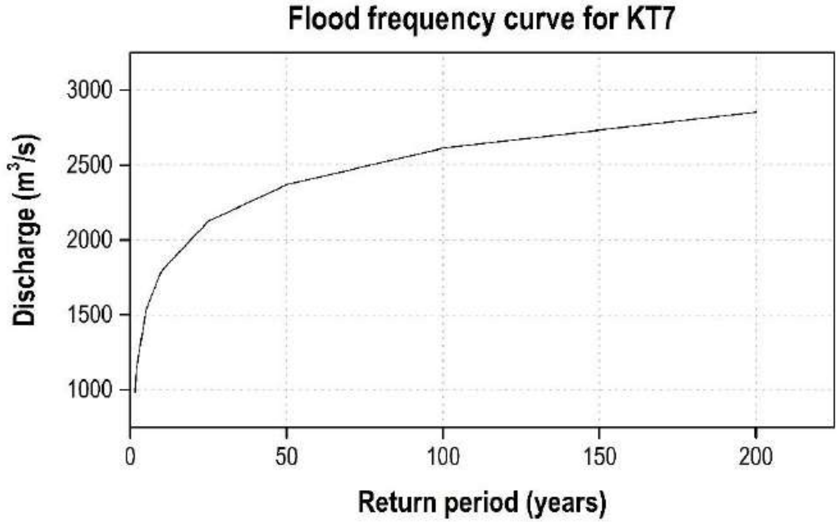

Flood frequency curve for K16
Discharge (m³/s)
5000
4000
3000
2000
1000
0
50
100
150
200
Return period (years)


Flood frequency curve for KT1
Discharge (m³/s)
1200
1000
800
600
400
200
0
50
100
150
200
Return period (years)

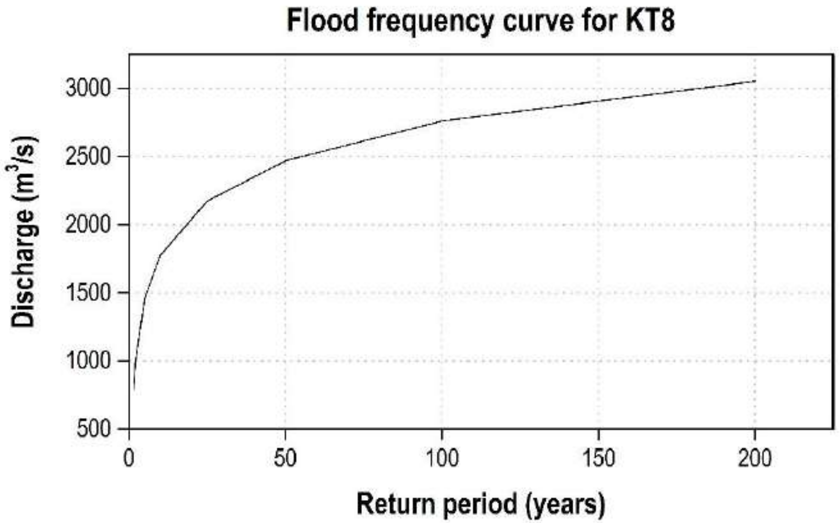

Flood frequency curve for KT3
Discharge (m³/s)
14000
12000
10000
8000
6000
4000
2000
0
50
100
150
200
Return period (years)



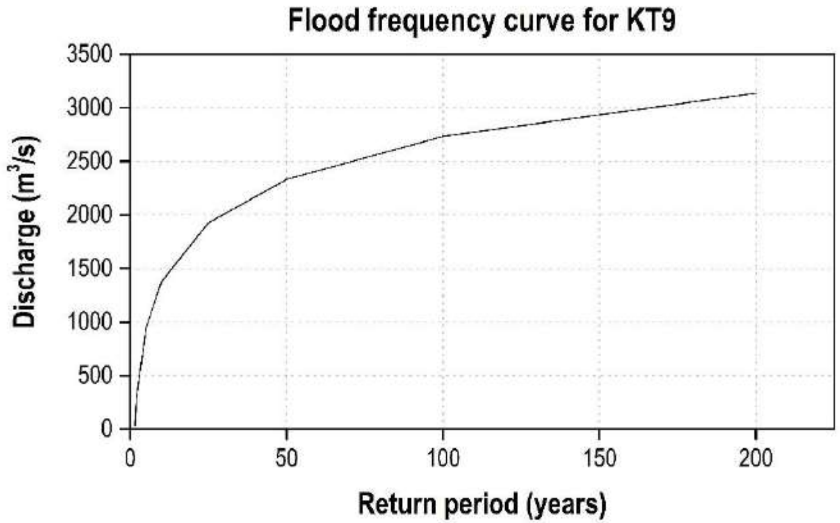
Flood frequency curve for KT6
Discharge (m³/s)
3000
2500
2000
1500
1000
500
0
50
100
150
200
Return period (years)



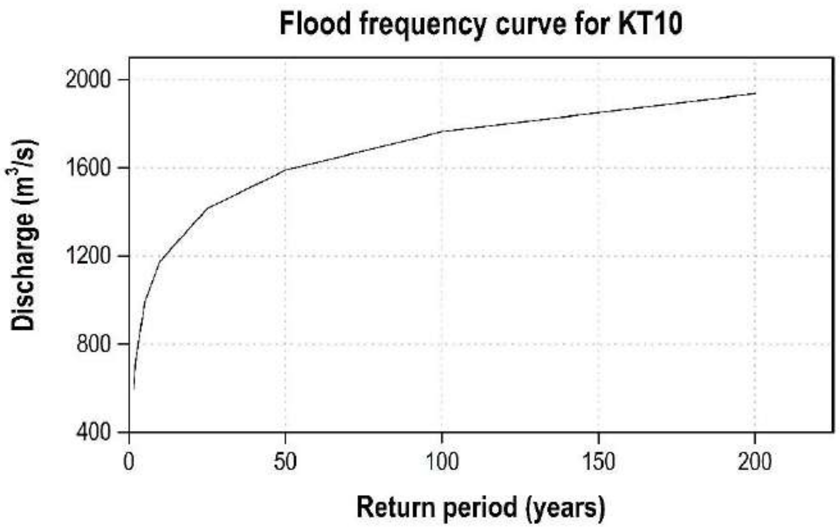
Flood frequency curve for KT7
Discharge (m³/s)
3000
2500
2000
1500
1000
0
50
100
150
200
Return period (years)

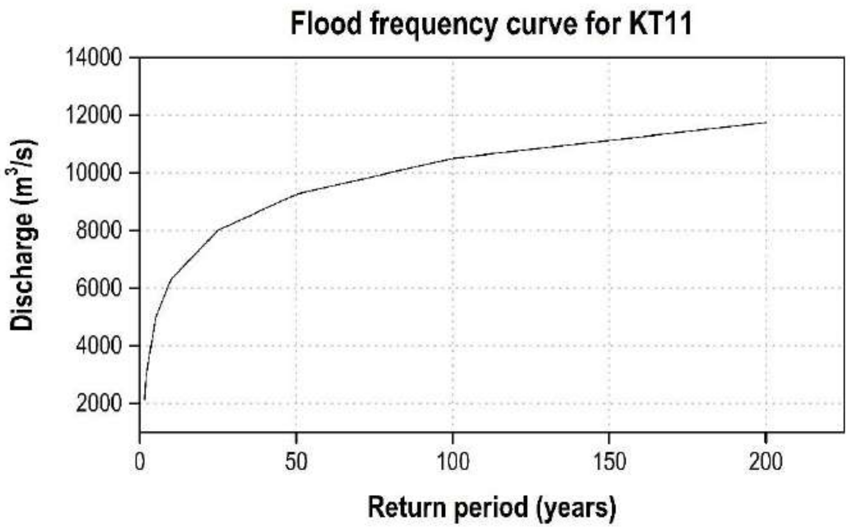


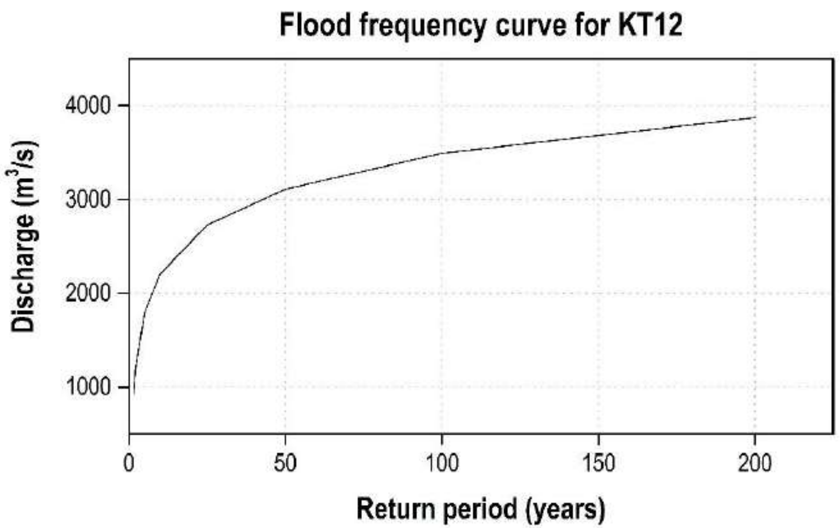
Flood frequency curve for KT8
Discharge (m³/s)
3000
2500
2000
1500
1000
500
0
50
100
150
200
Return period (years)

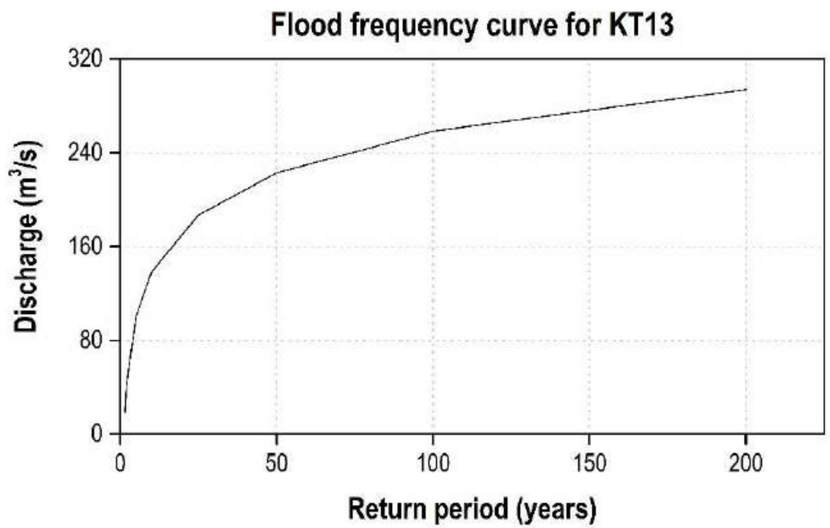


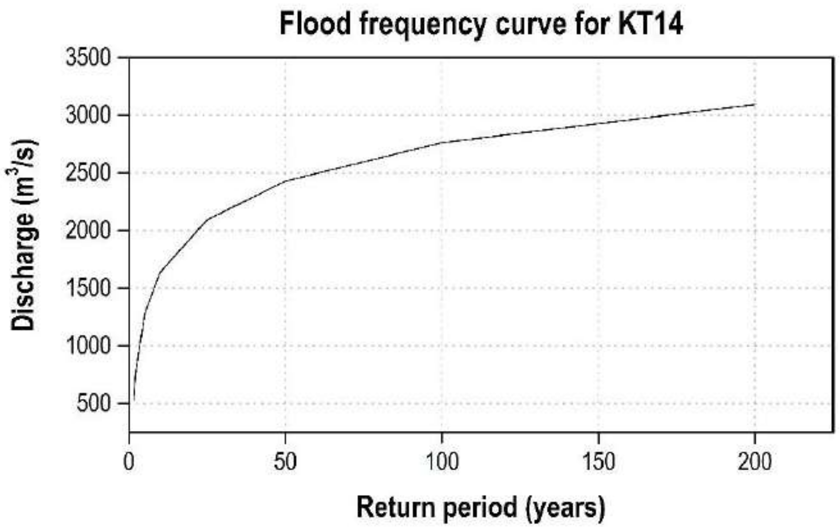
Flood frequency curve for KT9
Discharge (m³/s)
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
Return period (years)

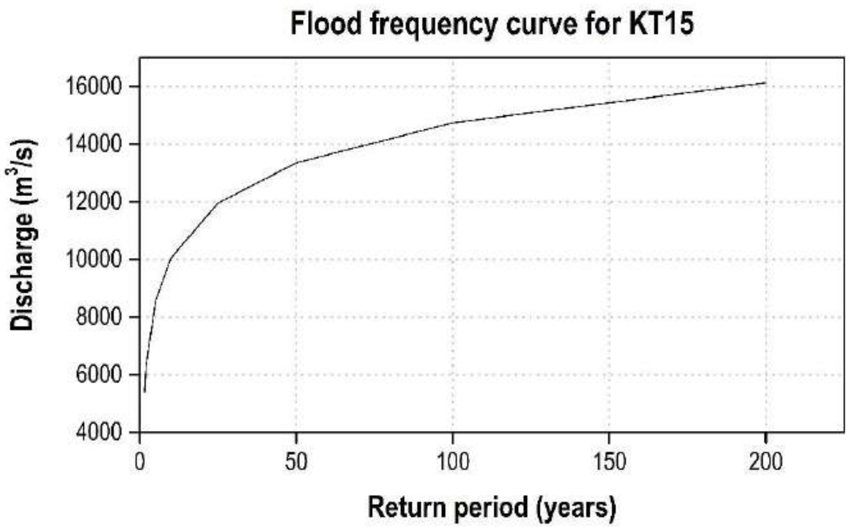

Flood frequency curve for KT10
Discharge (m3/s)
2000
1600
1200
800
400
0
50
100
150
200
Return period (years)

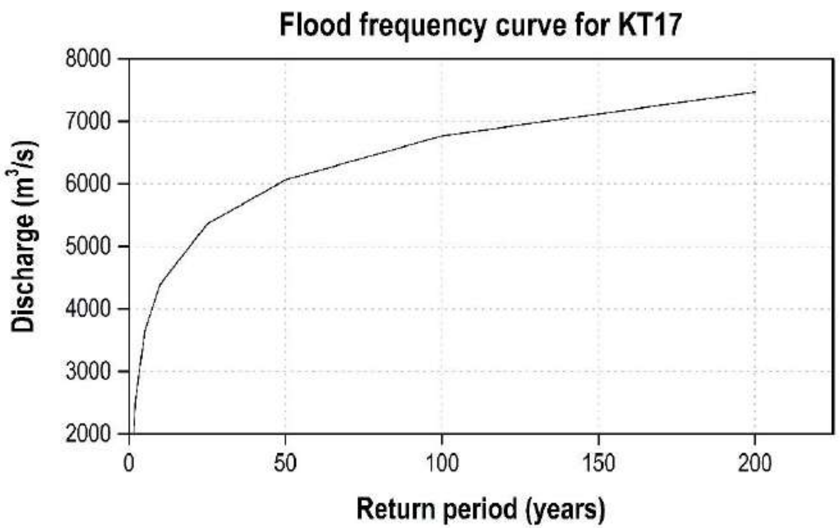

Flood frequency curve for KT11
Discharge (m3/s)
14000
12000
10000
8000
6000
4000
2000
0
50
100
150
200
Return period (years)

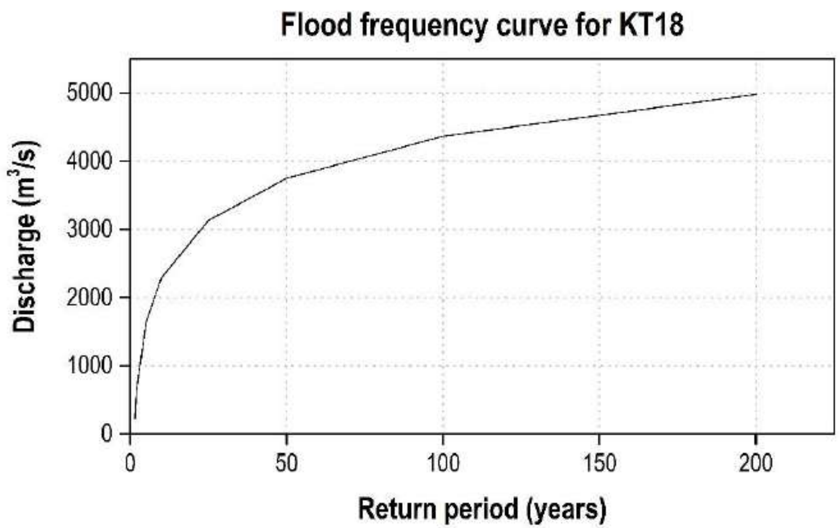

Flood frequency curve for KT12
Discharge (m3/s)
4000
3000
2000
1000
0
50
100
150
200
Return period (years)

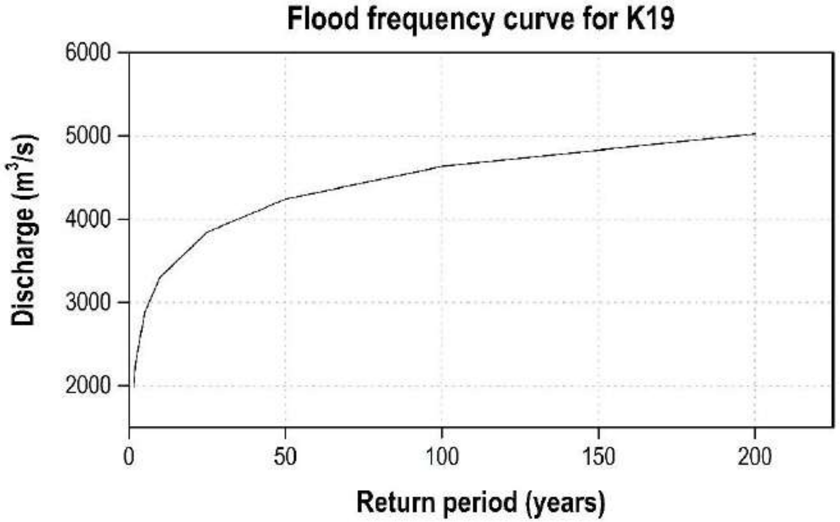

Flood frequency curve for KT13
Discharge (m3/s)
320
240
160
80
0
0
50
100
150
200
Return period (years)


Flood frequency curve for KT14
Discharge (m^3/s)
Return period (years)
3500
3000
2500
2000
1500
1000
500
0
50
100
150
200

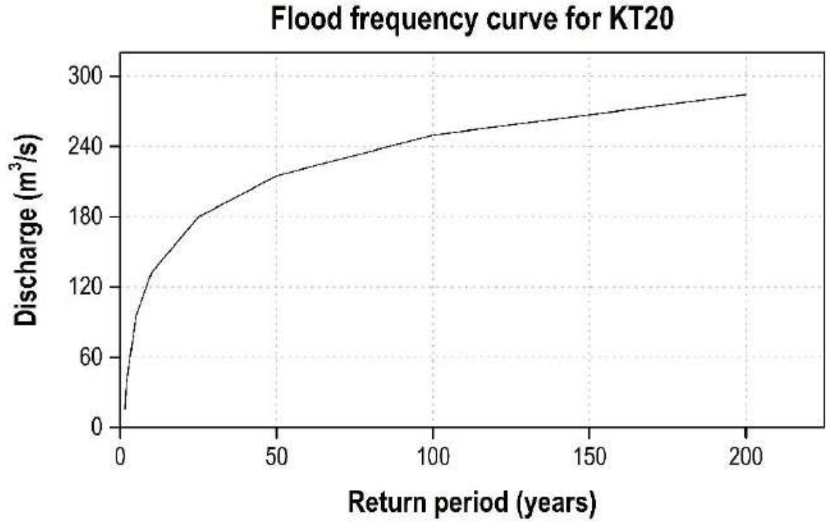

Flood frequency curve for KT15
Discharge (m^3/s)
Return period (years)
16000
14000
12000
10000
8000
6000
4000
0
50
100
150
200


Flood frequency curve for KT17
Discharge (m^3/s)
Return period (years)
8000
7000
6000
5000
4000
3000
2000
0
50
100
150
200

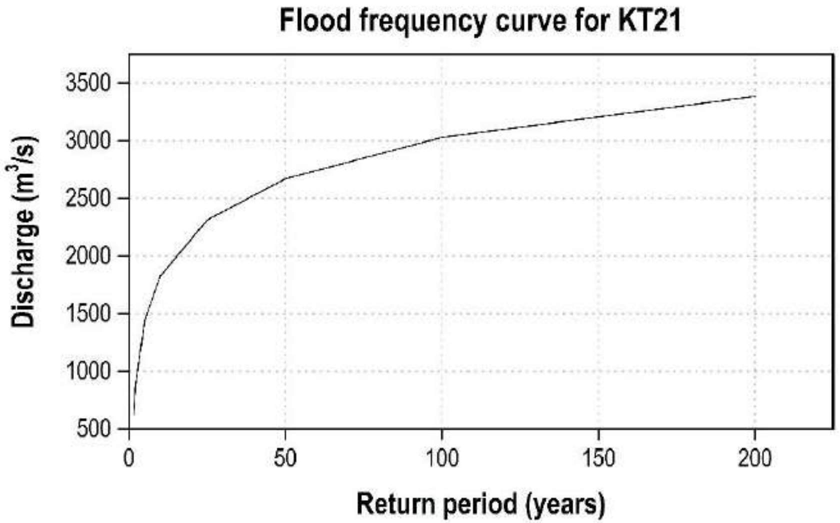

Flood frequency curve for KT18
Discharge (m^3/s)
Return period (years)
5000
4000
3000
2000
1000
0
0
50
100
150
200



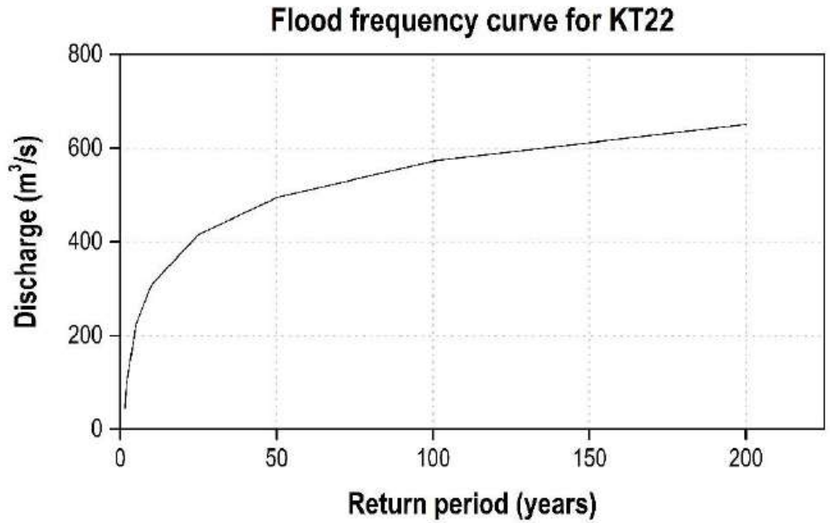
Flood frequency curve for K19
Discharge (m³/s)
6000
5000
4000
3000
2000
0
50
100
150
200
Return period (years)



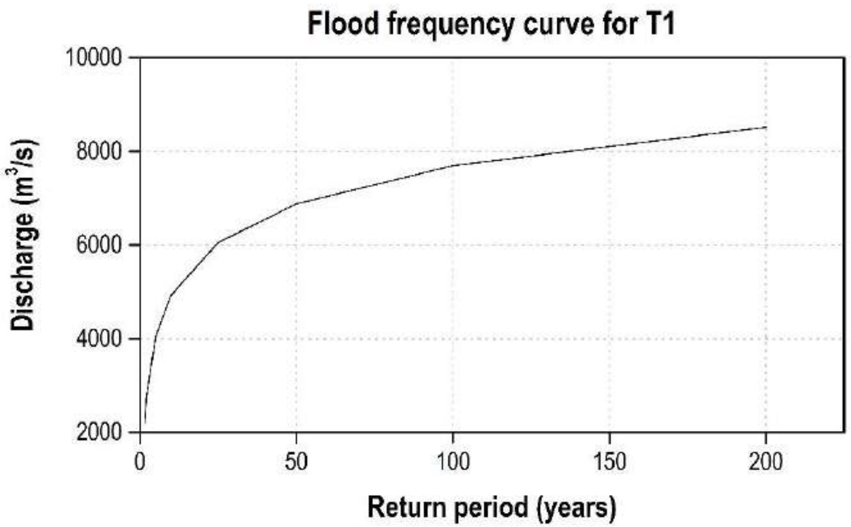
Flood frequency curve for KT20
Discharge (m³/s)
300
240
180
120
60
0
0
50
100
150
200
Return period (years)

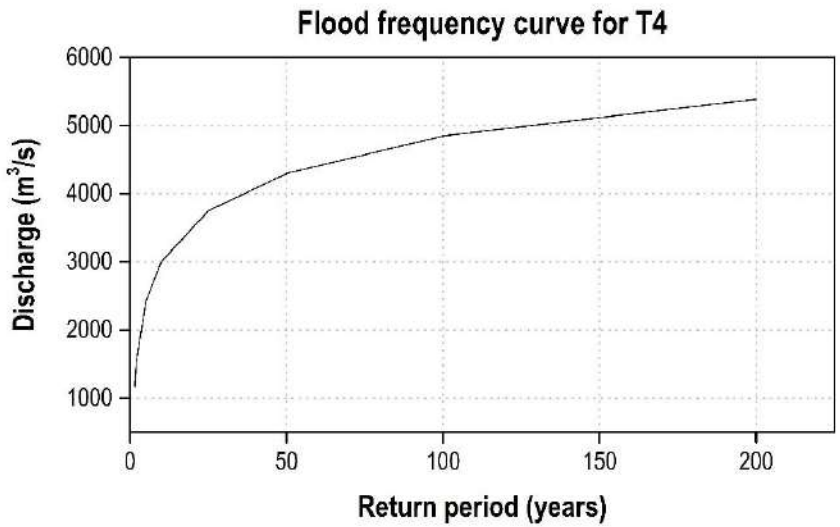


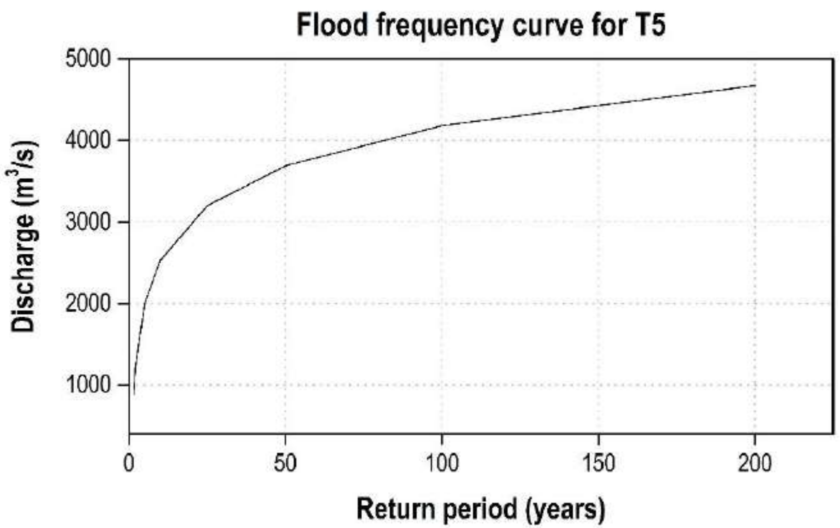
Flood frequency curve for KT21
Discharge (m³/s)
3500
3000
2500
2000
1500
1000
500
0
50
100
150
200
Return period (years)

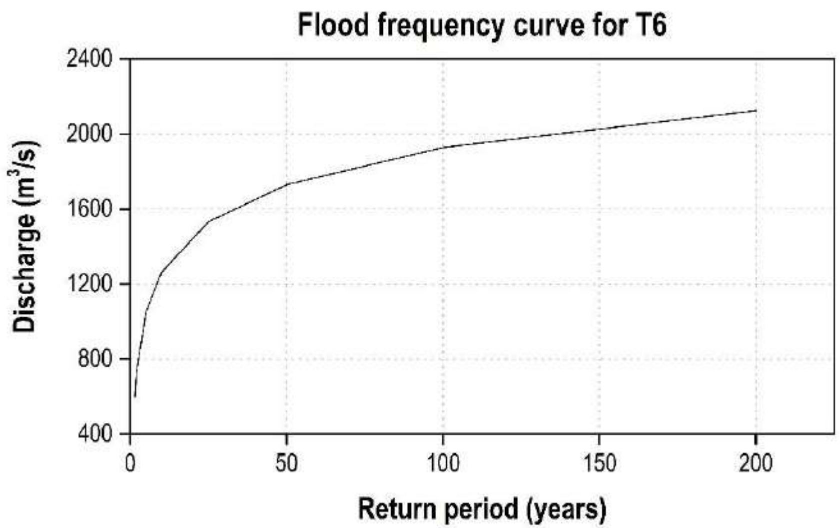


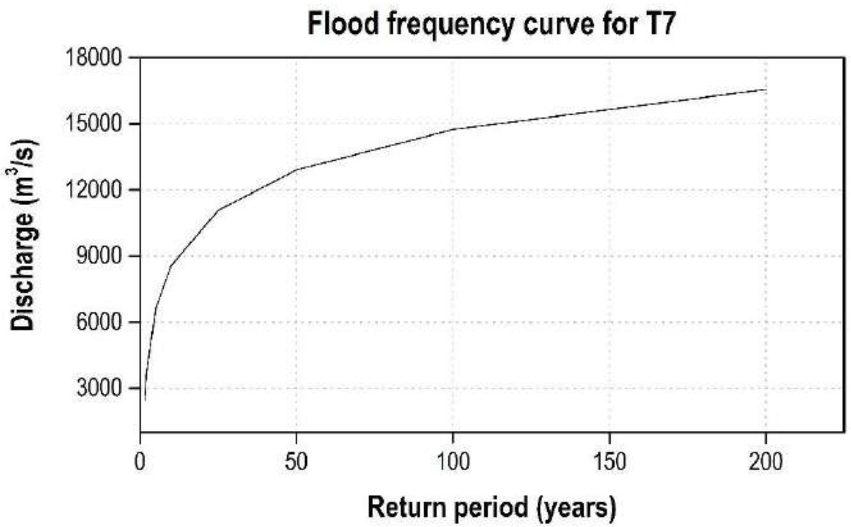
Flood frequency curve for KT22
Discharge (m³/s)
800
600
400
200
0
0
50
100
150
200
Return period (years)

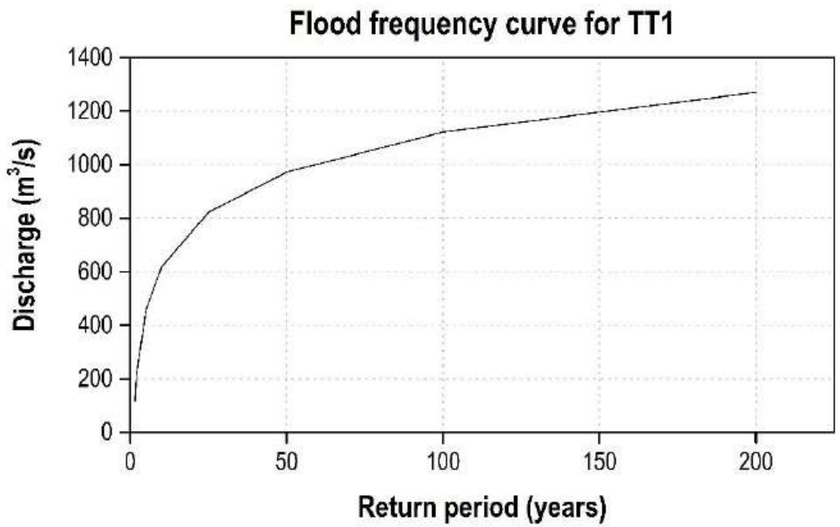

Flood frequency curve for T1
Discharge (m³/s)
Return period (years)
10000
8000
6000
4000
2000
0
50
100
150
200

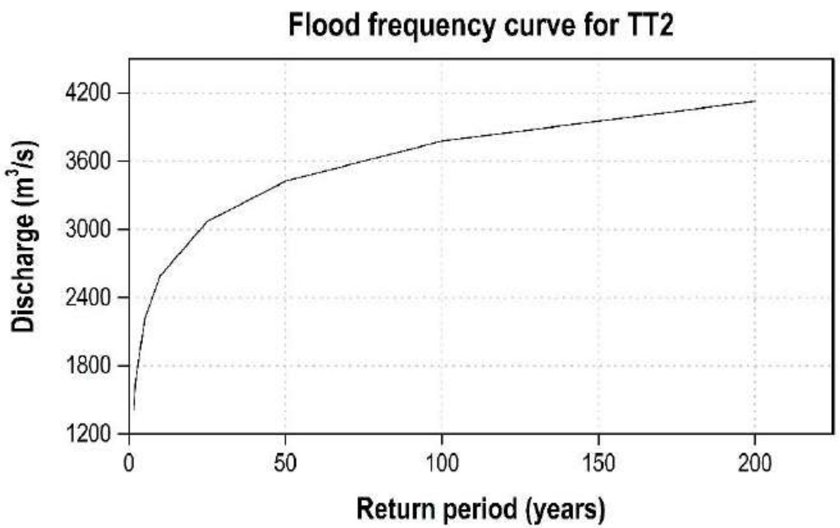

Flood frequency curve for T4
Discharge (m³/s)
Return period (years)
6000
5000
4000
3000
2000
1000
0
50
100
150
200

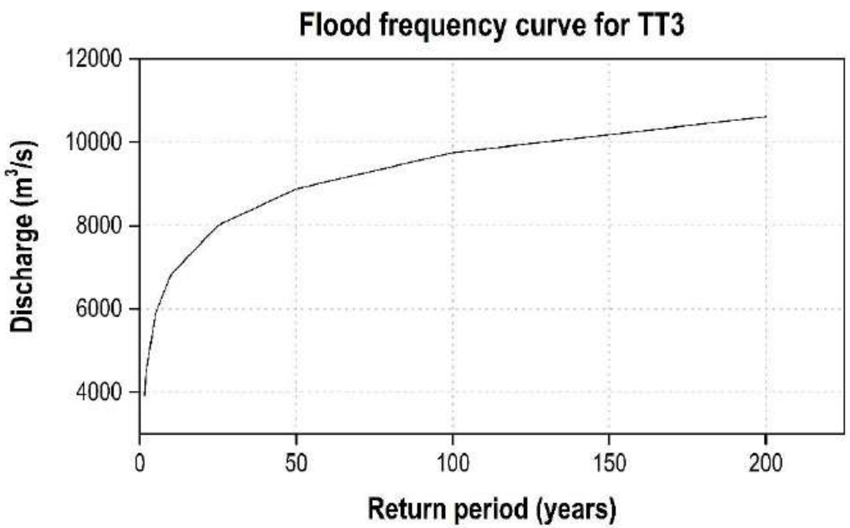

Flood frequency curve for T5
Discharge (m³/s)
Return period (years)
5000
4000
3000
2000
1000
0
50
100
150
200

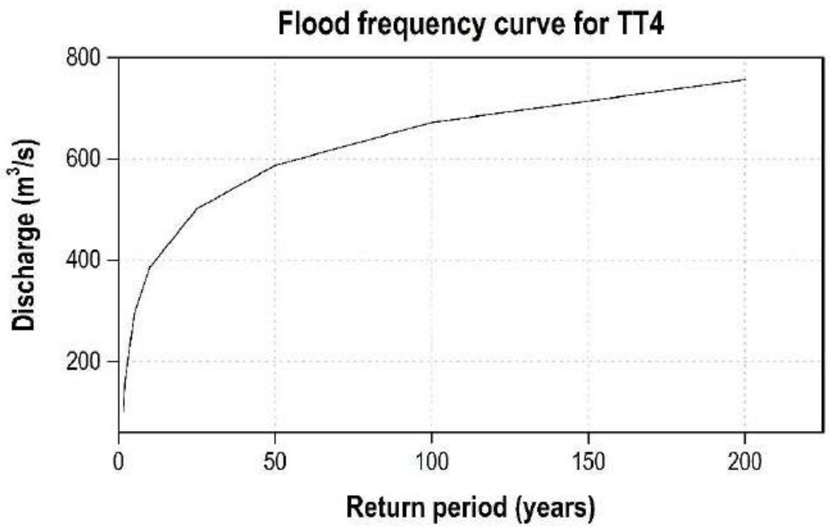

Flood frequency curve for T6
Discharge (m³/s)
Return period (years)
2400
2000
1600
1200
800
400
0
50
100
150
200

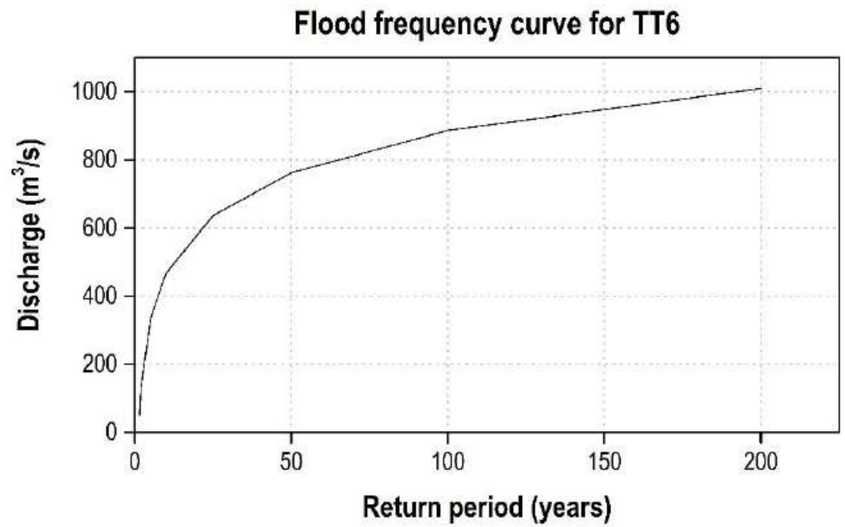

Flood frequency curve for T7
Discharge (m³/s)
18000
15000
12000
9000
6000
3000
0
50
100
150
200
Return period (years)

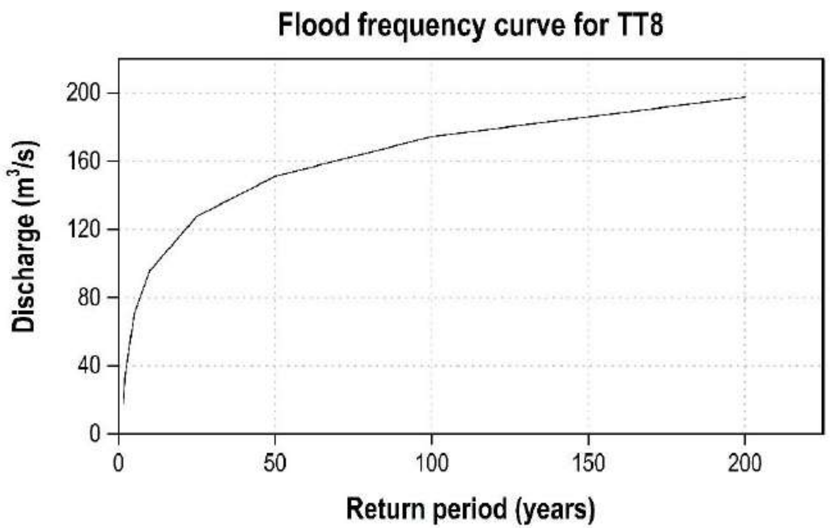

Flood frequency curve for TT1
Discharge (m³/s)
1400
1200
1000
800
600
400
200
0
50
100
150
200
Return period (years)

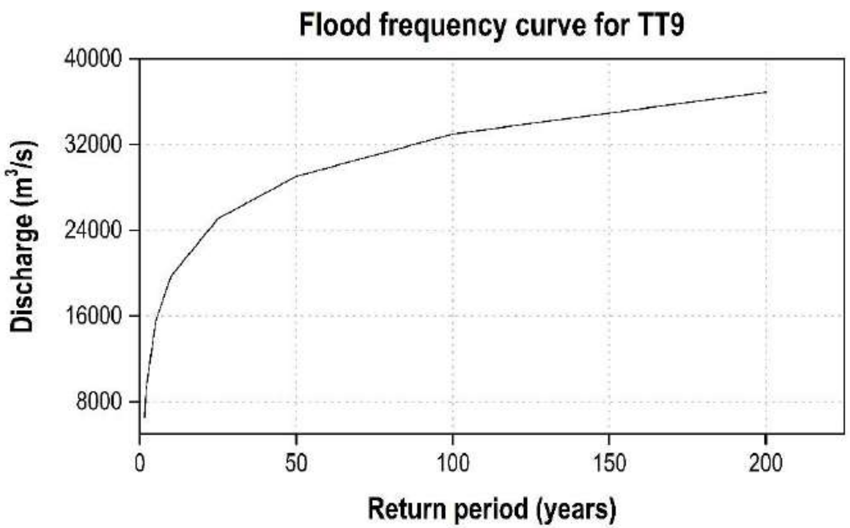

Flood frequency curve for TT2
Discharge (m³/s)
4200
3600
3000
2400
1800
1200
0
50
100
150
200
Return period (years)

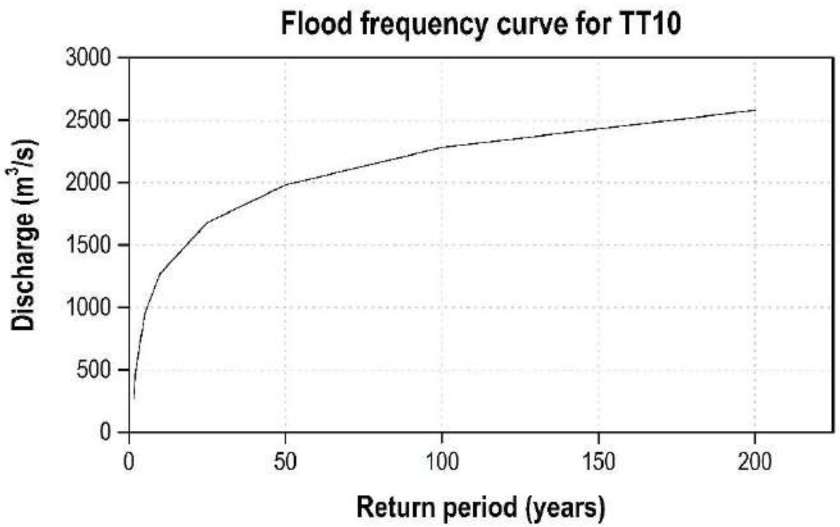

Flood frequency curve for TT3
Discharge (m³/s)
12000
10000
8000
6000
4000
0
50
100
150
200
Return period (years)


Flood frequency curve for TT4
Discharge (m³/s)
800
600
400
200
0
50
100
150
200
Return period (years)


Flood frequency curve for TT6
Discharge (m³/s)
1000
800
600
400
200
0
0
50
100
150
200
Return period (years)


Flood frequency curve for TT8
Discharge (m³/s)
200
160
120
80
40
0
0
50
100
150
200
Return period (years)


Flood frequency curve for TT9
Discharge (m³/s)
40000
32000
24000
16000
8000
0
50
100
150
200
Return period (years)



Flood frequency curve for TT10
Discharge (m^3/s)
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
Return period (years)

Appendix XII: Historical flood events of various return periods measured at various H. O. stations of KRB

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
B1	1992 (2) 1994 (7) 1995 (1) 1996 (3) 1997 (6) 2003 (1) 2004 (2) 2005 (6) 2006 (8) 2007 (1) 2008 (2) 2011 (3) 2013 (6) 2014 (2)	1994 (4) 1995 (1) 1996 (1) 1997 (5) 2003 (1) 2004 (2) 2005 (5) 2006 (6) 2007 (1) 2008 (1) 2011 (3) 2013 (1)	1994 (1) 1997 (2) 2003 (1) 2004 (2) 2005 (2) 2006 (1)	1994 (1) 1997 (1) 2005 (1)	Nil	Nil	Nil	Nil
B2	1968 (2) 1969 (9) 1971 (5) 1972 (4) 1973 (6) 1975 (4) 1976 (9) 1977 (2) 1978 (2) 1979 (4) 1980 (3) 1981 (5) 1983 (4) 1984 (2) 1985 (1) 1988 (2) 1989 (2) 1990 (8) 1991 (4) 1992 (1) 1994 (13)	1969 (4) 1971 (4) 1972 (1) 1973 (2) 1976 (6) 1979 (2) 1980 (2) 1981 (3) 1983 (3) 1984 (1) 1988 (1) 1989 (2) 1990 (4) 1991 (3) 1994 (5) 1997 (4) 2004 (2) 2005 (7) 2006 (8)	1969 (2) 1976 (3) 1983 (2) 1989 (1) 1994 (2) 1997 (2) 2005 (3) 2006 (3)	1976 (2) 1983 (1) 1994 (1) 1997 (2) 2005 (1) 2006 (2)	1976 (1) 1994 (1) 1997 (1)	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1997 (6) 2004 (2) 2005 (11) 2006 (9)							
B3	1967 (7) 1968 (6) 1969 (16) 1971 (5) 1972 (3) 1973 (9) 1975 (6) 1976 (13) 1977 (5) 1978 (2) 1979 (11) 1980 (12) 1981 (11) 1982 (4) 1983 (9) 1984 (3) 1985 (1) 1986 (4) 1988 (11) 1989 (4) 1990 (17) 1991 (8) 1993 (2) 1994 (24) 1996 (3) 1997 (6) 1998 (4) 2005 (17) 2006 (17) 2007 (3) 2008 (2) 2011 (5)	1967 (6) 1968 (2) 1969 (9) 1971 (4) 1972 (3) 1973 (1) 1975 (2) 1976 (9) 1979 (6) 1980 (6) 1981 (3) 1983 (6) 1984 (1) 1988 (2) 1989 (1) 1990 (9) 1991 (4) 1994 (16) 1996 (2) 1997 (5) 1998 (1) 2005 (13) 2006 (15) 2011 (3) 2013 (1)	1967 (4) 1969 (2) 1971 (1) 1976 (5) 1981 (2) 1983 (3) 1994 (5) 1997 (4) 2005 (5) 2006 (8) 2011 (1)	1967 (1) 1976 (2) 1981 (1) 1983 (2) 1994 (2) 1997 (3) 2005 (3) 2006 (5)	2006 (2)	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	2013 (1)							
B4	1965 (9) 1966 (3) 1967 (8) 1968 (2) 1969 (16) 1971 (5) 1972 (3) 1973 (5) 1974 (1) 1975 (7) 1976 (13) 1979 (12) 1980 (9) 1981 (8) 1983 (9) 1984 (3) 1986 (2) 1988 (11) 1989 (6) 1990 (16) 1991 (7) 1994 (19) 1996 (3) 1997 (5) 1998 (10) 2005 (11) 2006 (18) 2008 (1) 2009 (2) 2011 (5) 2013 (2)	1965 (4) 1966 (2) 1967 (6) 1969 (7) 1971 (5) 1972 (1) 1973 (1) 1975 (2) 1976 (8) 1979 (8) 1980 (2) 1981 (5) 1983 (7) 1988 (5) 1989 (2) 1990 (7) 1991 (2) 1994 (14) 1996 (3) 1997 (5) 1998 (8) 2005 (9) 2006 (16) 2009 (1) 2011 (2) 2013 (1)	1967 (4) 1969 (1) 1976 (6) 1979 (2) 1983 (3) 1994 (5) 1997 (2) 1998 (1) 2005 (4) 2006 (6)	1967 (3) 1976 (5) 1979 (1) 1994 (1) 1997 (2) 2005 (3) 2006 (3)	1979 (1)	Nil	Nil	Nil
B6	1965 (8) 1966 (3) 1967 (18) 1968 (3)	1965 (3) 1967 (11) 1969 (8) 1970 (1)	1967 (4) 1969 (1) 1979 (3) 1981 (1)	1969 (1) 1979 (2) 1989 (1) 1998 (4)	1969 (1) 1998 (2) 2006 (1)	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1969 (12) 1970 (3) 1971 (7) 1973 (5) 1974 (3) 1975 (23) 1976 (9) 1978 (3) 1979 (11) 1981 (8) 1983 (18) 1984 (3) 1988 (15) 1989 (8) 1990 (12) 1991 (4) 1994 (12) 1996 (2) 1997 (5) 1998 (29) 2005 (14) 2006 (17) 2007 (1) 2008 (2) 2009 (7) 2010 (1) 2011 (4) 2013 (4)	1971 (1) 1973 (4) 1974 (2) 1975 (6) 1976 (7) 1978 (1) 1979 (5) 1981 (4) 1983 (12) 1984 (1) 1988 (6) 1989 (5) 1990 (5) 1994 (6) 1996 (1) 1997 (4) 1998 (19) 2005 (9) 2006 (12) 2009 (7) 2011 (2)	1983 (1) 1988 (2) 1989 (3) 1998 (6) 2005 (2) 2006 (5) 2009 (3)	2005 (1) 2006 (3) 2009 (1)				
BT1	1965 (5) 1966 (3) 1967 (4) 1969 (5) 1971 (3) 1972 (1) 1973 (1) 1974 (2)	1966 (1) 1967 (3) 1969 (3) 1971 (1) 1974 (1) 1975 (1) 1976 (5) 1979 (7)	1966 (1) 1967 (2) 1969 (1) 1976 (2) 1979 (2) 1980 (1) 1981 (1) 1983 (2)	1967 (1) 1969 (1) 1976 (1) 1979 (1) 1983 (1) 1994 (1)	1979 (1)	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1975 (3) 1976 (8) 1977 (3) 1978 (5) 1979 (10) 1980 (5) 1981 (5) 1983 (3) 1985 (1) 1988 (5) 1989 (1) 1990 (7) 1991 (3) 1992 (3) 1994 (17) 1996 (3) 1997 (3) 1998 (4) 2004 (3) 2005 (10) 2006 (13) 2007 (3) 2008 (1) 2009 (3) 2011 (2) 2013 (4)	1980 (4) 1981 (3) 1983 (2) 1985 (1) 1988 (4) 1990 (2) 1992 (2) 1994 (14) 1996 (3) 1997 (3) 2004 (2) 2005 (4) 2006 (11) 2007 (2) 2009 (1) 2011 (1) 2013 (2)	1994 (2) 1996 (1) 1997 (2) 2005 (1) 2006 (2)					
BT3	1979 (13) 1981 (25) 1982 (2) 1983 (6) 1984 (1) 1985 (4) 1986 (2) 1987 (8) 1988 (6) 1989 (4)	1979 (3) 1981 (10) 1982 (1) 1985 (1) 1986 (1) 1987 (3) 1988 (1) 1989 (1) 1993 (1) 1996 (1)	1979 (2) 1981 (5) 1998 (5)	1979 (2) 1981 (1) 1998 (3)	1979 (2) 1981 (1)	1979 (2)	1979 (2)	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1990 (1) 1993 (6) 1995 (1) 1996 (8) 1998 (30) 2000 (1) 2001 (11) 2006 (2)	1998 (10) 2001 (1) 2006 (2)						
BT4	1979 (13) 1980 (1) 1981 (19) 1982 (1) 1983 (4) 1984 (3) 1985 (1) 1986 (2) 1987 (7) 1988 (9) 1989 (5) 1990 (2) 1991 (2) 1993 (7) 1995 (2) 1996 (9) 1998 (16) 1999 (1) 2000 (1) 2001 (6)	1979 (4) 1980 (1) 1981 (9) 1983 (1) 1987 (2) 1988 (2) 1989 (2) 1990 (1) 1993 (1) 1996 (2) 1998 (4) 2001 (1)	1979 (2) 1981 (2)	1979 (2) 1981 (1)	1979 (2)	1979 (2)	1979 (1)	1979 (1)
BT6	1965 (4) 1966 (4) 1967 (10) 1968 (2) 1969 (15) 1970 (8) 1971 (10)	1965 (3) 1966 (3) 1967 (4) 1968 (1) 1969 (11) 1970 (6) 1971 (7)	1965 (1) 1966 (2) 1967 (1) 1969 (5) 1970 (3) 1971 (1) 1979 (1)	1966 (1) 1969 (3) 1970 (2) 1983 (3) 1989 (1) 1998 (2)	1969 (1) 1970 (2) 1989 (1)	1970 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1973 (9) 1974 (9) 1975 (10) 1977 (1) 1978 (4) 1979 (8) 1980 (3) 1981 (1) 1983 (19) 1984 (3) 1985 (1) 1986 (1) 1987 (2) 1988 (18) 1989 (12) 1990 (14) 1991 (1) 1993 (1) 1996 (2) 1998 (26) 2000 (3) 2001 (1) 2005 (1) 2006 (1) 2007 (1) 2008 (3) 2010 (7)	1973 (2) 1975 (7) 1977 (1) 1978 (2) 1979 (4) 1980 (1) 1981 (1) 1983 (13) 1984 (2) 1988 (12) 1989 (7) 1990 (2) 1998 (17) 2000 (2) 2008 (2) 2010 (5)	1983 (6) 1988 (6) 1989 (1) 1998 (7)					
BT7	1980 (1) 1981 (5) 1982 (1) 1983 (15) 1984 (2) 1986 (1) 1988 (9) 1989 (4) 1990 (7)	1981 (5) 1982 (1) 1983 (5) 1984 (1) 1988 (2) 1989 (2) 1990 (5) 1991 (1) 1995 (1)	1983 (3) 1984 (1) 1988 (1) 1990 (3) 1998 (2)	1983 (1) 1984 (1) 1990 (1) 1998 (1)	1983 (1) 1984 (1)	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1991 (2) 1992 (1) 1995 (2) 1996 (2) 1998 (11) 2000 (3) 2001 (1) 2003 (1) 2005 (1)	1998 (5) 2000 (1) 2001 (1) 2003 (1)						
BT8	1990 (8) 1991 (2) 1992 (2) 1995 (3) 1996 (3) 1998 (16) 2000 (1) 2001 (1) 2003 (1) 2005 (4) 2007 (2) 2008 (3) 2009 (6) 2010 (9) 2011 (1) 2013 (3) 2014 (2)	1990 (5) 1991 (1) 1992 (2) 1995 (2) 1996 (1) 1998 (9) 2000 (1) 2001 (1) 2005 (1) 2007 (2) 2008 (1) 2009 (5) 2010 (6) 2011 (1) 2013 (1) 2014 (2)	1990 (1) 1998 (5) 2000 (1) 2008 (1) 2011 (1)	1990 (1) 1998 (3)	1990 (1)	1990 (1)	Nil	Nil
K1	1965 (12) 1966 (2) 1967 (8) 1969 (12) 1970 (2) 1971 (1) 1972 (1) 1973 (2) 1974 (1) 1975 (5)	1965 (9) 1966 (1) 1967 (8) 1969 (4) 1973 (2) 1974 (1) 1975 (1) 1976 (10) 1977 (2) 1980 (3)	1965 (2) 1967 (1) 1969 (1) 1976 (3) 1990 (2) 1994 (2) 1997 (2) 2004 (1) 2005 (5) 2006 (7)	1965 (1) 1997 (1) 2005 (3) 2006 (4)	1997 (1) 2005 (2) 2006 (1)	2006 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1976 (13) 1977 (2) 1978 (4) 1979 (3) 1980 (6) 1988 (1) 1989 (1) 1990 (5) 1991 (6) 1992 (1) 1994 (19) 1996 (3) 1997 (12) 1999 (3) 2004 (4) 2005 (17) 2006 (23) 2007 (7) 2008 (1) 2011 (4) 2013 (6)	1988 (1) 1989 (1) 1990 (3) 1991 (4) 1994 (7) 1996 (2) 1997 (21) 1999 (3) 2004 (6) 2005 (30) 2006 (40) 2007 (12) 2008 (2) 2011 (7) 2013 (7)	2007 (1) 2011 (1)					
K10	1981 (7) 1983 (18) 1984 (3) 1985 (3) 1986 (6) 1988 (15) 1989 (10) 1990 (13) 1991 (7) 1993 (1) 1994 (25) 1996 (4) 1997 (16) 1998 (17) 1999 (5)	1981 (5) 1983 (8) 1984 (1) 1988 (8) 1989 (4) 1990 (8) 1991 (5) 1994 (20) 1996 (2) 1997 (14) 1998 (6) 2005 (16) 2006 (22)	1983 (2) 1994 (3) 1997 (4) 1998 (3) 2005 (12) 2006 (14)	1994 (1) 1998 (1) 2005 (5) 2006 (5)	2005 (3)	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	2001 (1) 2004 (1) 2005 (30) 2006 (23)							
K16	1976 (21) 1977 (14) 1978 (44) 1979 (18) 1980 (25) 1981 (25) 1982 (11) 1983 (29) 1988 (25) 1989 (8) 1990 (14) 1991 (17) 1993 (5) 1994 (26) 1996 (7) 1997 (8) 1998 (23) 1999 (2) 2000 (1) 2005 (33) 2006 (16)	1976 (12) 1977 (2) 1978 (18) 1979 (13) 1980 (15) 1981 (10) 1983 (14) 1988 (5) 1989 (3) 1990 (10) 1991 (10) 1993 (2) 1994 (15) 1996 (4) 1997 (5) 1998 (13) 2005 (12) 2006 (15)	1976 (3) 1978 (2) 1979 (4) 1980 (1) 1996 (2) 1998 (4) 2005 (6) 2006 (10)	1998 (4)	1998 (4)	1998 (3)	Nil	Nil
K17	1966 (6) 1967 (21) 1968 (8) 1969 (27) 1970 (19) 1971 (2) 1973 (17) 1974 (9) 1975 (45) 1976 (18) 1977 (2)	1966 (4) 1967 (10) 1969 (12) 1970 (10) 1974 (5) 1975 (24) 1976 (7) 1978 (9) 1979 (11) 1980 (13) 1981 (7)	1967 (6) 1969 (2) 1974 (1) 1975 (4) 1978 (2) 1979 (2) 1990 (1) 1994 (1) 1998 (4) 2005 (3) 2006 (9)	1967 (1) 1979 (1) 1998 (3) 2009 (3)	2009 (3)	2009 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1978 (23) 1979 (17) 1980 (16) 1981 (16) 1982 (1) 1983 (26) 1988 (22) 1989 (6) 1990 (14) 1991 (15) 1993 (5) 1994 (24) 1996 (4) 1997 (6) 1998 (19) 2005 (24) 2006 (19) 2007 (19) 2008 (5) 2009 (9) 2011 (7) 2013 (2)	1983 (12) 1988 (6) 1989 (2) 1990 (12) 1991 (7) 1993 (3) 1994 (15) 1996 (4) 1997 (5) 1998 (9) 2005 (8) 2006 (16) 2007 (12) 2009 (7) 2011 (4) 2013 (1)	2007 (1) 2009 (6)					
K18	1965 (20) 1966 (6) 1967 (13) 1968 (1) 1969 (25) 1970 (17) 1973 (3) 1974 (6) 1975 (41) 1976 (14) 1978 (21) 1979 (13) 1980 (14) 1981 (10)	1965 (15) 1966 (3) 1967 (8) 1969 (11) 1970 (11) 1974 (4) 1975 (18) 1976 (8) 1978 (11) 1979 (8) 1980 (11) 1981 (7) 1983 (10) 1986 (2)	1967 (1) 1975 (3) 1978 (6) 1979 (2) 1983 (2) 1989 (1) 1998 (4) 2005 (5) 2009 (4)	1998 (1) 2009 (2)	2009 (1)	2009 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1983 (22) 1986 (1) 1988 (18) 1989 (8) 1990 (12) 1991 (14) 1993 (3) 1994 (18) 1996 (4) 1997 (5) 1998 (17) 2000 (1) 2005 (21) 2006 (17) 2007 (12) 2008 (2) 2009 (7) 2011 (4) 2013 (2)	1988 (25) 1989 (13) 1990 (18) 1991 (21) 1993 (3) 1994 (32) 1996 (6) 1997 (10) 1998 (25) 2000 (1) 2005 (32) 2006 (33) 2007 (20) 2008 (3) 2009 (13) 2011 (7) 2013 (3)						
K2	1969 (10) 1970 (7) 1971 (1) 1972 (3) 1973 (5) 1975 (6) 1976 (16) 1977 (1) 1979 (9) 1980 (10) 1981 (3) 1983 (1) 1984 (1) 1985 (2) 1986 (1) 1988 (4) 1989 (5)	1969 (4) 1970 (6) 1973 (4) 1975 (4) 1976 (12) 1977 (1) 1979 (5) 1980 (5) 1988 (2) 1989 (4) 1990 (5) 1991 (6) 1994 (16) 1996 (2) 1997 (11) 2004 (4) 2005 (15)	1970 (1) 1973 (2) 1975 (1) 1979 (1) 1988 (1) 1989 (1) 1990 (3) 1991 (1) 1994 (5) 2005 (13) 2006 (12)	1990 (2) 1991 (1) 1994 (2) 2005 (12) 2006 (10)	2005 (7) 2006 (4)	2005 (6)	2005 (2)	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1990 (7) 1991 (12) 1992 (1) 1994 (25) 1996 (4) 1997 (17) 1999 (5) 2004 (8) 2005 (17) 2006 (26) 2007 (12) 2008 (6) 2011 (7) 2013 (12)	2006 (21) 2007 (4) 2011 (2) 2013 (7)						
K3	1972 (2) 1973 (6) 1975 (7) 1976 (17) 1977 (6) 1979 (12) 1980 (14) 1981 (4) 1983 (6) 1984 (2) 1985 (3) 1986 (5) 1988 (8) 1989 (6) 1990 (8) 1991 (9) 1992 (1) 1993 (1) 1994 (21) 1996 (4) 1997 (16) 2004 (8)	1973 (4) 1975 (3) 1976 (13) 1977 (4) 1979 (9) 1980 (9) 1981 (4) 1983 (3) 1986 (2) 1988 (6) 1989 (4) 1990 (5) 1991 (6) 1994 (14) 1996 (1) 1997 (16) 2004 (3) 2005 (16) 2006 (22) 2007 (11) 2008 (7) 2011 (1)	1976 (5) 1979 (1) 1989 (2) 1991 (3) 1997 (5) 2005 (15) 2006 (18)	1976 (1) 2005 (14) 2006 (14)	2005 (9) 2006 (4)	2005 (5)	2005 (3)	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	2005 (19) 2006 (27) 2007 (15) 2008 (7) 2011 (3) 2013 (11) 2014 (3)	2013 (9)						
K7	1976 (14) 1977 (6) 1978 (2) 1979 (8) 1980 (14) 1981 (5) 1982 (8) 1983 (17) 1984 (1) 1985 (1) 1988 (13) 1989 (5) 1990 (6) 1991 (8) 1993 (1) 1994 (27) 1997 (17) 1998 (1) 1999 (5) 2005 (19) 2006 (23) 2007 (16) 2008 (7) 2009 (5) 2010 (2) 2011 (5) 2013 (7)	1976 (9) 1979 (7) 1980 (11) 1981 (3) 1982 (3) 1983 (10) 1984 (1) 1988 (9) 1989 (5) 1990 (5) 1991 (6) 1994 (22) 1997 (13) 1999 (2) 2005 (14) 2006 (20) 2007 (6) 2008 (7) 2009 (5) 2010 (1) 2011 (4) 2013 (3)	1976 (2) 1979 (3) 1983 (4) 1988 (1) 1991 (1) 1994 (3) 1997 (1) 2005 (13) 2006 (6) 2009 (4)	1994 (1) 2005 (1) 2009 (3)	2009 (2)	2009 (1)	Nil	Nil
KT1	1975 (4) 1976 (10)	1975 (3) 1976 (8)	1976 (1) 1980 (2)	1990 (1) 1994 (2)	2005 (1) 2006 (1)	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1977 (8) 1978 (8) 1979 (3) 1980 (6) 1983 (3) 1984 (3) 1986 (4) 1988 (2) 1990 (14) 1991 (13) 1993 (1) 1994 (20) 1997 (14) 1998 (1) 1999 (9) 2002 (2) 2004 (5) 2005 (20) 2006 (22)	1977 (3) 1978 (7) 1980 (5) 1983 (1) 1986 (1) 1988 (1) 1990 (10) 1991 (5) 1994 (10) 1997 (12) 1999 (8) 2004 (3) 2005 (14) 2006 (19)	1990 (3) 1994 (2) 1997 (4) 2004 (2) 2005 (5) 2006 (6)	1997 (3) 2004 (1) 2005 (3) 2006 (2)				
KT10	1971 (1) 1972 (9) 1973 (11) 1974 (6) 1975 (8) 1976 (6) 1977 (5) 1978 (5) 1979 (6) 1980 (13) 1981 (10) 1982 (7) 1983 (16) 1988 (8) 1989 (2) 1990 (1) 1991 (6)	1972 (4) 1973 (4) 1974 (2) 1975 (4) 1976 (4) 1978 (3) 1979 (6) 1980 (9) 1982 (4) 1983 (12) 1988 (4) 1989 (2) 1991 (2) 1993 (1) 1994 (12) 1997 (8) 1999 (2)	1972 (1) 1974 (1) 1975 (3) 1979 (4) 1983 (5) 1988 (1) 1994 (5) 1997 (4) 2005 (7)	1975 (1) 1979 (3) 1983 (1) 1994 (3) 1997 (2) 2005 (4)	1994 (2) 1997 (1)	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1992 (1) 1993 (6) 1994 (16) 1997 (12) 1999 (5) 2005 (14) 2006 (14) 2007 (6) 2008 (5) 2011 (8)	2005 (10) 2006 (7) 2007 (5)						
KT12	1967 (13) 1968 (4) 1969 (23) 1970 (15) 1971 (4) 1972 (6) 1973 (7) 1974 (3) 1975 (7) 1976 (5) 1977 (4) 1978 (4) 1979 (6) 1980 (13) 1981 (9) 1982 (7) 1983 (14) 1988 (6) 1989 (2) 1991 (2) 1993 (3) 1994 (20) 1996 (1) 1997 (16) 1999 (6)	1967 (11) 1969 (13) 1970 (4) 1972 (4) 1973 (3) 1974 (1) 1975 (4) 1976 (3) 1978 (3) 1979 (6) 1980 (9) 1982 (4) 1983 (12) 1988 (3) 1994 (13) 1997 (14) 1999 (4)	1967 (3) 1969 (2) 1975 (2) 1979 (4) 1983 (3) 1994 (3) 1997 (4)	1975 (1) 1979 (1) 1983 (1) 1994 (2) 1997 (2)	Nil	Nil	Nil	Nil
KT14	1982 (3)	1982 (1)	1989 (1)	1992 (1)	2007 (2)	2009 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1983 (1) 1984 (1) 1986 (3) 1987 (1) 1988 (3) 1989 (3) 1991 (6) 1992 (2) 1993 (3) 1995 (1) 1996 (5) 1997 (1) 1998 (1) 1999 (1) 2000 (1) 2001 (1) 2003 (1) 2004 (2) 2005 (1) 2007 (5) 2009 (5) 2010 (3)	1987 (1) 1988 (2) 1989 (1) 1991 (4) 1992 (2) 1993 (2) 1996 (3) 1997 (1) 1998 (1) 2003 (1) 2004 (1) 2007 (5) 2009 (5) 2010 (1)	1991 (2) 1992 (2) 1993 (1) 1997 (3) 2007 (2) 2009 (3)	2007 (2) 2009 (2)	2009 (2)			
KT17	1984 (2) 1985 (4) 1986 (1) 1987 (11) 1988 (20) 1989 (9) 1990 (4) 1991 (12) 1993 (8) 1994 (6) 1995 (15) 1996 (5) 1997 (2) 1998 (9)	1987 (1) 1989 (1) 1991 (2) 1994 (1) 1998 (1) 2000 (1) 2001 (3) 2005 (4) 2007 (7) 2008 (1) 2013 (4)	1991 (2) 2005 (2) 2013 (1)	1991 (2) 2005 (2)	1991 (1) 2005 (1)	1991 (1) 2005 (1)	2005 (1)	2005 (1)

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1999 (1)							
	2000 (4)							
	2001 (10)							
	2003 (1)							
	2004 (7)							
	2005 (48)							
	2006 (9)							
	2007 (30)							
	2008 (52)							
	2009 (11)							
	2010 (47)							
	2011 (4)							
	2012 (1)							
	2013 (29)							
	2014 (11)							
KT18	1968 (1)	1975 (9)	1983 (2)	1983 (1)	1983 (1)	1983 (1)	1983 (1)	1983 (1)
	1970 (9)	1976 (2)	1989 (1)	1989 (1)	2009 (2)	2009 (2)		
	1971 (3)	1978 (5)	1998 (1)	2009 (2)	2013 (1)			
	1972 (1)	1979 (1)	2009 (3)	2013 (1)				
	1973 (3)	1982 (1)	2013 (1)					
	1975 (52)	1983 (6)						
	1976 (12)	1988 (4)						
	1978 (17)	1989 (2)						
	1979 (3)	1991 (2)						
	1981 (6)	1994 (1)						
	1982 (2)	1995 (1)						
	1983 (17)	1998 (4)						
	1985 (2)	2000 (3)						
	1987 (1)	2001 (1)						
	1988 (25)	2005 (1)						
	1989 (12)	2008 (3)						
	1990 (4)	2009 (4)						
	1991 (4)	2013 (5)						
	1994 (4)							
	1995 (5)							
	1996 (7)							

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1998 (6) 2000 (5) 2001 (2) 2004 (3) 2005 (14) 2006 (8) 2007 (9) 2008 (20) 2009 (4) 2010 (5) 2011 (2) 2013 (18) 2014 (3)							
KT19	1965 (2) 1969 (8) 1970 (5) 1974 (5) 1975 (19) 1976 (18) 1977 (1) 1978 (13) 1979 (1) 1981 (4) 1982 (1) 1983 (12) 1984 (1) 1985 (3) 1986 (2) 1988 (23) 1989 (17) 1990 (6) 1991 (2) 1993 (1) 1994 (5) 1995 (4) 1996 (4)	1965 (1) 1969 (1) 1970 (3) 1974 (1) 1975 (6) 1976 (3) 1978 (5) 1983 (3) 1985 (2) 1986 (1) 1988 (12) 1989 (4) 1990 (3) 1991 (1) 1994 (2) 1995 (2) 1998 (1) 2000 (6) 2005 (3)	1970 (2) 1978 (2) 1983 (2) 1988 (1) 1989 (3)	1978 (2) 1983 (2) 1988 (1) 1989 (1)	1983 (1) 1989 (1)	1983 (1) 1989 (1)	1983 (1)	1983 (1)

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1998 (11) 1999 (2) 2000 (8) 2001 (1) 2002 (1) 2005 (6) 2006 (1) 2014 (1)							
KT2	1967 (13) 1969 (4) 1970 (5) 1971 (2) 1972 (1) 1973 (3) 1974 (1) 1975 (5) 1976 (12) 1977 (2) 1978 (5) 1979 (2) 1980 (7) 1981 (1) 1983 (1) 1984 (2) 1986 (2) 1988 (2) 1989 (1) 1990 (7) 1991 (6) 1992 (1) 1994 (17) 1996 (2) 1997 (13) 1999 (6) 2004 (4) 2005 (17)	1967 (8) 1969 (1) 1973 (2) 1974 (1) 1975 (1) 1976 (9) 1977 (2) 1978 (1) 1980 (2) 1988 (1) 1989 (1) 1990 (3) 1991 (2) 1994 (6) 1996 (1) 1997 (9) 2004 (2) 2005 (11) 2006 (14) 2007 (5) 2008 (1) 2011 (4) 2013 (3)	1967 (3) 1976 (2) 1988 (1) 1990 (1) 1994 (2) 1997 (3) 2004 (1) 2005 (5) 2006 (7) 2011 (1)	1967 (1) 1997 (2) 2005 (3) 2006 (4) 2011 (1)	1967 (1) 1997 (1) 2005 (2) 2006 (3)	2005 (2) 2006 (1)	2006 (1)	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	2006 (20) 2007 (8) 2008 (3) 2011 (4) 2013 (6)							
KT21	1984 (1) 1985 (3) 1986 (3) 1988 (7) 1989 (13) 1990 (11) 1991 (2) 1994 (2) 1995 (3) 1996 (2) 1998 (1) 1999 (1) 2000 (6) 2004 (2) 2005 (5) 2006 (2) 2007 (1) 2008 (5) 2010 (4) 2012 (4) 2013 (2)	1985 (2) 1986 (3) 1988 (1) 1989 (8) 1990 (4) 1991 (1) 1995 (1) 2000 (2) 2005 (3) 2006 (2) 2008 (3)	1986 (1) 1989 (3) 1991 (1) 2005 (2) 2008 (1)	1991 (1) 2005 (2) 2008 (1)	2005 (1) 2008 (1)	2005 (1)	2005 (1)	Nil
KT22	1965 (1) 1966 (2) 1967 (1) 1969 (4) 1970 (5) 1975 (3) 1976 (5) 1978 (10) 1981 (2) 1982 (1)	1969 (3) 1970 (2) 1976 (2) 1978 (5) 1981 (2) 1983 (4) 1986 (3) 1988 (4) 1989 (5) 1990 (3)	1969 (1) 1976 (1) 1978 (2) 1983 (1) 1986 (1) 1989 (1) 1990 (2) 2005 (1) 2006 (1) 2008 (2)	1969 (1) 1978 (2) 1983 (1) 1986 (1) 1989 (1) 2005 (1) 2008 (2)	1969 (1) 1983 (1) 1989 (1) 2005 (1)	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1983 (12) 1985 (2) 1986 (3) 1987 (2) 1988 (9) 1989 (9) 1990 (8) 1991 (2) 1995 (7) 1996 (5) 1998 (3) 2000 (7) 2004 (2) 2005 (5) 2006 (5) 2008 (13) 2010 (6) 2012 (6) 2013 (3)	1991 (2) 1995 (2) 1996 (1) 2000 (4) 2005 (3) 2006 (4) 2008 (5) 2012 (1)						
KT3	1967 (13) 1969 (10) 1970 (9) 1971 (2) 1972 (3) 1973 (5) 1974 (4) 1975 (7) 1976 (18) 1977 (6) 1978 (7) 1979 (10) 1980 (9) 1981 (4) 1982 (6) 1983 (10) 1984 (4)	1967 (21) 1969 (4) 1970 (5) 1973 (2) 1974 (2) 1975 (4) 1976 (12) 1977 (4) 1978 (2) 1979 (5) 1980 (6) 1981 (2) 1982 (4) 1983 (6) 1984 (2) 1985 (3) 1986 (2)	1967 (3) 1973 (1) 1975 (2) 1976 (3) 1988 (2) 1989 (4) 1991 (2) 1994 (4) 2005 (13) 2006 (8)	1973 (1) 1989 (2) 1994 (2) 2005 (6)	2005 (3)	2005 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1985 (4)	1988 (7)						
	1986 (3)	1989 (5)						
	1988 (8)	1990 (4)						
	1989 (6)	1991 (4)						
	1990 (6)	1993 (2)						
	1991 (10)	1994 (6)						
	1992 (2)	1996 (2)						
	1993 (5)	1997 (7)						
	1994 (11)	2004 (1)						
	1996 (2)	2005 (15)						
	1997 (13)	2006 (16)						
	1999 (2)	2007 (6)						
	2004 (6)	2008 (4)						
	2005 (17)	2011 (2)						
	2006 (22)	2013 (6)						
	2007 (11)							
	2008 (5)							
	2009 (1)							
	2010 (1)							
	2011 (5)							
	2013 (11)							
	2014 (1)							
KT4	1980 (10)	1980 (7)	1990 (2)	1994 (2)	1997 (3)	1997 (2)	Nil	Nil
	1981 (4)	1981 (3)	1991 (3)	1997 (7)	2005 (3)			
	1982 (2)	1984 (3)	1994 (7)	2005 (13)				
	1983 (6)	1986 (5)	1997 (12)	2006 (4)				
	1984 (4)	1988 (8)	2005 (15)					
	1985 (3)	1989 (5)	2006 (11)					
	1986 (7)	1990 (5)						
	1988 (11)	1991 (9)						
	1989 (5)	1994 (19)						
	1990 (9)	1996 (2)						
	1991 (15)	1997 (16)						
	1993 (2)	2004 (7)						
	1994 (21)	2005 (26)						
	1996 (5)	2006 (48)						

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1997 (16) 1999 (4) 2002 (2) 2004 (8) 2005 (19) 2006 (27) 2007 (11) 2008 (7) 2010 (2) 2011 (4) 2013 (13) 2014 (4)	2007 (14) 2008 (12) 2010 (2) 2011 (6) 2013 (20) 2014 (4)						
KT5	1979 (10) 1980 (13) 1981 (5) 1982 (8) 1983 (14) 1984 (7) 1985 (5) 1986 (10) 1987 (2) 1988 (11) 1989 (6) 1990 (6) 1991 (12) 1992 (4) 1993 (7) 1994 (19) 1997 (9) 2005 (21) 2006 (16)	1979 (1) 1980 (9) 1981 (2) 1982 (4) 1983 (7) 1984 (4) 1985 (2) 1986 (7) 1987 (2) 1988 (7) 1989 (5) 1990 (4) 1991 (5) 1993 (2) 1994 (9) 1997 (4) 2005 (14) 2006 (14)	1981 (1) 1986 (1) 1988 (1) 1989 (3) 1997 (2) 2005 (3) 2006 (5)	1989 (1) 1997 (1)	Nil	Nil	Nil	Nil
KT6	1969 (3) 1970 (5) 1971 (2) 1972 (3) 1973 (5)	1969 (2) 1970 (2) 1971 (1) 1972 (1) 1973 (3)	1975 (1) 1983 (5) 1988 (3) 1989 (4) 1994 (4)	1983 (3) 1988 (1) 1989 (3) 1994 (2) 2005 (10)	1983 (1) 2005 (3)	1983 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1974 (3) 1975 (4) 1976 (2) 1977 (2) 1978 (2) 1979 (12) 1980 (7) 1981 (3) 1982 (5) 1983 (17) 1984 (6) 1985 (3) 1986 (3) 1988 (11) 1989 (6) 1990 (6) 1991 (6) 1993 (1) 1994 (9) 1996 (2) 1997 (15) 1999 (4) 2004 (3) 2005 (17) 2006 (21) 2008 (2)	1974 (1) 1975 (4) 1978 (1) 1979 (8) 1981 (2) 1982 (1) 1983 (15) 1984 (3) 1985 (1) 1988 (6) 1989 (5) 1990 (5) 1991 (4) 1994 (8) 1996 (1) 1997 (4) 2004 (2) 2005 (17) 2006 (17)	2005 (15) 2006 (7)	2006 (4)				
KT7	1979 (4) 1981 (13) 1983 (1) 1986 (1) 1987 (3) 1988 (18) 1989 (3) 1991 (11) 1995 (10) 1996 (4)	1981 (6) 1988 (8) 1989 (2) 1991 (1) 1995 (3) 1996 (2) 1998 (8) 1999 (1) 2006 (1)	1981 (4) 1988 (2) 1995 (1) 1996 (1) 1998 (3) 1999 (1)	1981 (3) 1988 (1) 1998 (2)	1988 (1) 1998 (1)	1988 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1997 (1) 1998 (22) 1999 (3) 2001 (2) 2006 (3)							
KT8	1979 (7) 1980 (8) 1981 (5) 1982 (7) 1983 (11) 1984 (2) 1985 (3) 1986 (1) 1987 (0) 1988 (7) 1989 (3) 1990 (1) 1991 (3) 1992 (1) 1993 (3) 1994 (10) 1995 (3) 1996 (0) 1997 (8) 1998 (0) 1999 (8) 2000 (0) 2001 (0) 2002 (0) 2003 (0) 2004 (3) 2005 (9) 2006 (9)	1979 (4) 1980 (2) 1981 (1) 1982 (3) 1983 (6) 1984 (2) 1985 (2) 1988 (7) 1989 (3) 1991 (3) 1993 (3) 1994 (6) 1997 (5) 1999 (7) 2004 (1) 2005 (3)	1982 (1) 1983 (3) 1988 (2) 1989 (2) 1994 (2)	1983 (2) 1988 (2) 1989 (2)	1983 (1) 1989 (1)	1983 (1)	Nil	Nil
KT9	1980 (7) 1981 (2) 1982 (1)	1980 (1) 1982 (1) 1983 (3)	1982 (1) 1983 (2) 1988 (2)	1983 (1) 1988 (1) 1989 (1)	Nil	Nil	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1983 (5) 1984 (1) 1985 (1) 1988 (3) 1989 (3) 1990 (2) 1991 (4) 1993 (3) 1994 (7) 1997 (6) 1999 (6) 2004 (3) 2005 (10) 2006 (6)	1988 (3) 1989 (3) 1991 (2) 1993 (2) 1994 (6) 1997 (5) 1999 (5) 2004 (1) 2005 (6) 2006 (2)	1989 (2) 1991 (1) 1993 (1) 1994 (3) 2005 (1)	1994 (1) 2005 (1)				
T2	1980 (10) 1981 (1) 1982 (3) 1983 (1) 1984 (2) 1986 (5) 1988 (2) 1989 (3) 1991 (5) 1992 (11) 1994 (12) 1997 (5) 1999 (3) 2000 (3) 2004 (3) 2005 (5) 2006 (7) 2007 (8) 2008 (7) 2009 (5) 2011 (4) 2012 (1)	1980 (3) 1982 (3) 1984 (1) 1988 (1) 1989 (1) 1991 (1) 1992 (5) 1994 (9) 1997 (4) 1999 (3) 2000 (3) 2004 (5) 2005 (8) 2006 (10) 2007 (14) 2008 (12) 2009 (9) 2011 (4) 2012 (2) 2013 (13) 2014 (10)	1982 (1) 1994 (1) 2007 (2) 2008 (1) 2013 (2) 2014 (1)	1994 (1) 2007 (1) 2008 (1) 2014 (1)	1994 (1) 2008 (1)	1994 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	2013 (9) 2014 (6)							
T3	1967 (3) 1969 (7) 1970 (5) 1971 (2) 1972 (2) 1973 (2) 1974 (2) 1975 (8) 1978 (14) 1980 (9) 1981 (3) 1982 (4) 1983 (3) 1984 (2) 1986 (5) 1988 (4) 1989 (3) 1990 (3) 1991 (7) 1992 (13) 1994 (18) 1997 (8) 1998 (1) 1999 (13) 2000 (4) 2004 (3) 2005 (7) 2006 (6) 2007 (7) 2008 (6) 2009 (5) 2011 (2) 2012 (1) 2013 (11)	1967 (1) 1969 (1) 1970 (1) 1971 (1) 1975 (3) 1978 (5) 1980 (3) 1981 (2) 1982 (3) 1983 (1) 1984 (1) 1988 (1) 1989 (2) 1991 (4) 1992 (12) 1994 (11) 1997 (3) 1999 (4) 2000 (2) 2004 (2) 2005 (4) 2006 (4) 2007 (6) 2008 (5) 2009 (5) 2011 (1) 2012 (1) 2013 (5) 2014 (6)	1969 (1) 1982 (1) 1992 (4) 1994 (3) 2007 (5) 2008 (3) 2013 (1) 2014 (1)	1982 (1) 1992 (2) 1994 (3) 2007 (3) 2008 (1)	1992 (1) 1994 (1)	1992 (1)	1992 (1)	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	2014 (8)							
T5	1973 (1) 1974 (2) 1975 (11) 1977 (1) 1978 (24) 1979 (1) 1980 (19) 1981 (12) 1982 (12) 1983 (5) 1984 (4) 1986 (2) 1988 (1) 1990 (10) 1991 (12) 1992 (11) 1993 (8) 1994 (23) 1996 (3) 1997 (10) 1998 (3) 1999 (8) 2000 (2)	1974 (2) 1975 (5) 1978 (7) 1980 (8) 1981 (3) 1982 (2) 1983 (5) 1984 (1) 1986 (1) 1990 (4) 1991 (8) 1992 (10) 1993 (3) 1994 (13) 1996 (1) 1997 (6) 1998 (1) 1999 (2)	1980 (2) 1992 (4) 1993 (1) 1994 (3)	1992 (3) 1993 (1)	1992 (2)	1992 (2)	1992 (2)	Nil
T6	1974 (4) 1975 (16) 1977 (1) 1978 (16) 1979 (2) 1980 (8) 1981 (7) 1982 (4) 1983 (1) 1984 (1) 1986 (2) 1988 (3)	1974 (2) 1975 (4) 1978 (3) 1980 (4) 1981 (2) 1991 (1) 1992 (7) 1993 (2) 1994 (6) 1996 (2) 1997 (1) 1998 (3)	1978 (1) 1992 (2) 1994 (2) 2007 (2) 2009 (2)	1992 (2) 2009 (2)	1992 (2) 2009 (1)	1992 (1) 2009 (1)	1992 (1) 2009 (1)	2009 (1)

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1990 (5) 1991 (11) 1992 (10) 1993 (5) 1994 (14) 1996 (4) 1997 (6) 1998 (8) 1999 (4) 2000 (5) 2001 (1) 2005 (7) 2006 (4) 2007 (12) 2008 (5) 2009 (11) 2010 (5) 2011 (2) 2013 (15) 2014 (7)	2001 (1) 2005 (3) 2006 (3) 2007 (9) 2008 (4) 2009 (4) 2010 (2) 2013 (5) 2014 (3)						
T7	1965 (7) 1966 (1) 1967 (4) 1968 (7) 1969 (2) 1970 (12) 1971 (2) 1974 (2) 1975 (15) 1978 (15) 1980 (9) 1981 (4) 1982 (1) 1983 (2) 1984 (2) 1986 (1)	1967 (2) 1968 (1) 1970 (2) 1974 (2) 1975 (3) 1978 (3) 1980 (3) 1981 (2) 1982 (1) 1991 (1) 1992 (5) 1993 (1) 1994 (5) 1996 (2) 1997 (2) 1998 (3)	1978 (1) 1992 (3) 1994 (1) 2007 (4) 2009 (2)	1992 (2) 2009 (2)	1992 (2) 2009 (1)	1992 (2) 2009 (1)	1992 (1) 2009 (1)	2009 (1)

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1988 (1) 1989 (1) 1990 (2) 1991 (6) 1992 (10) 1993 (6) 1994 (13) 1996 (3) 1997 (6) 1998 (6) 1999 (3) 2000 (1) 2001 (1) 2005 (8) 2006 (5) 2007 (12) 2008 (6) 2009 (9) 2010 (6) 2011 (1) 2013 (12) 2014 (8)	2005 (3) 2006 (3) 2007 (8) 2008 (4) 2009 (5) 2010 (3) 2011 (1) 2013 (5) 2014 (4)						
TT8	1981 (6) 1982 (4) 1984 (3) 1986 (4) 1987 (3) 1988 (3) 1989 (8) 1990 (1) 1991 (1) 1992 (2)	1981 (2) 1982 (1) 1984 (1) 1986 (2) 1987 (2) 1988 (1) 1989 (2) 1990 (1) 1992 (1)	1982 (1) 1988 (1) 1989 (2) 1990 (1)	1988 (1) 1989 (1)	1989 (1)	Nil	Nil	Nil
TT10	1985 (1) 1988 (2) 1989 (1) 1990 (1)	1985 (1) 1988 (2) 1993 (3) 1994 (3)	1994 (2) 1996 (2) 1998 (5)	1996 (2) 1998 (2)	1996 (1)	1996 (1)	Nil	Nil

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1993 (3) 1994 (7) 1995 (2) 1996 (9) 1997 (1) 1998 (12) 2000 (6) 2001 (4) 2004 (1) 2005 (6)	1996 (4) 1998 (10) 2000 (3) 2001 (2) 2004 (1)						
TT2	1973 (2) 1974 (2) 1975 (4) 1978 (8) 1979 (2) 1980 (4) 1981 (3) 1982 (3) 1983 (1) 1984 (1) 1985 (1) 1986 (2) 1988 (2) 1989 (3) 1990 (2) 1991 (2) 1992 (5) 1994 (6) 1997 (5) 1999 (7) 2000 (4) 2004 (3) 2005 (5) 2006 (3) 2007 (4) 2008 (5)	1973 (1) 1974 (2) 1975 (2) 1978 (4) 1980 (2) 1981 (2) 1982 (2) 1983 (1) 1984 (1) 1986 (2) 1988 (2) 1989 (2) 1991 (2) 1994 (4) 1997 (3) 1999 (4) 2000 (3) 2004 (1) 2005 (3) 2006 (2) 2007 (1) 2008 (5) 2009 (4) 2011 (1) 2012 (2) 2013 (5)	1978 (1) 1982 (2) 1984 (1) 1994 (2) 1997 (1) 1999 (1) 2000 (1) 2008 (2) 2009 (2) 2012 (1)	1982 (2) 2009 (1)	1982 (1)	Nil	Nil	Nil

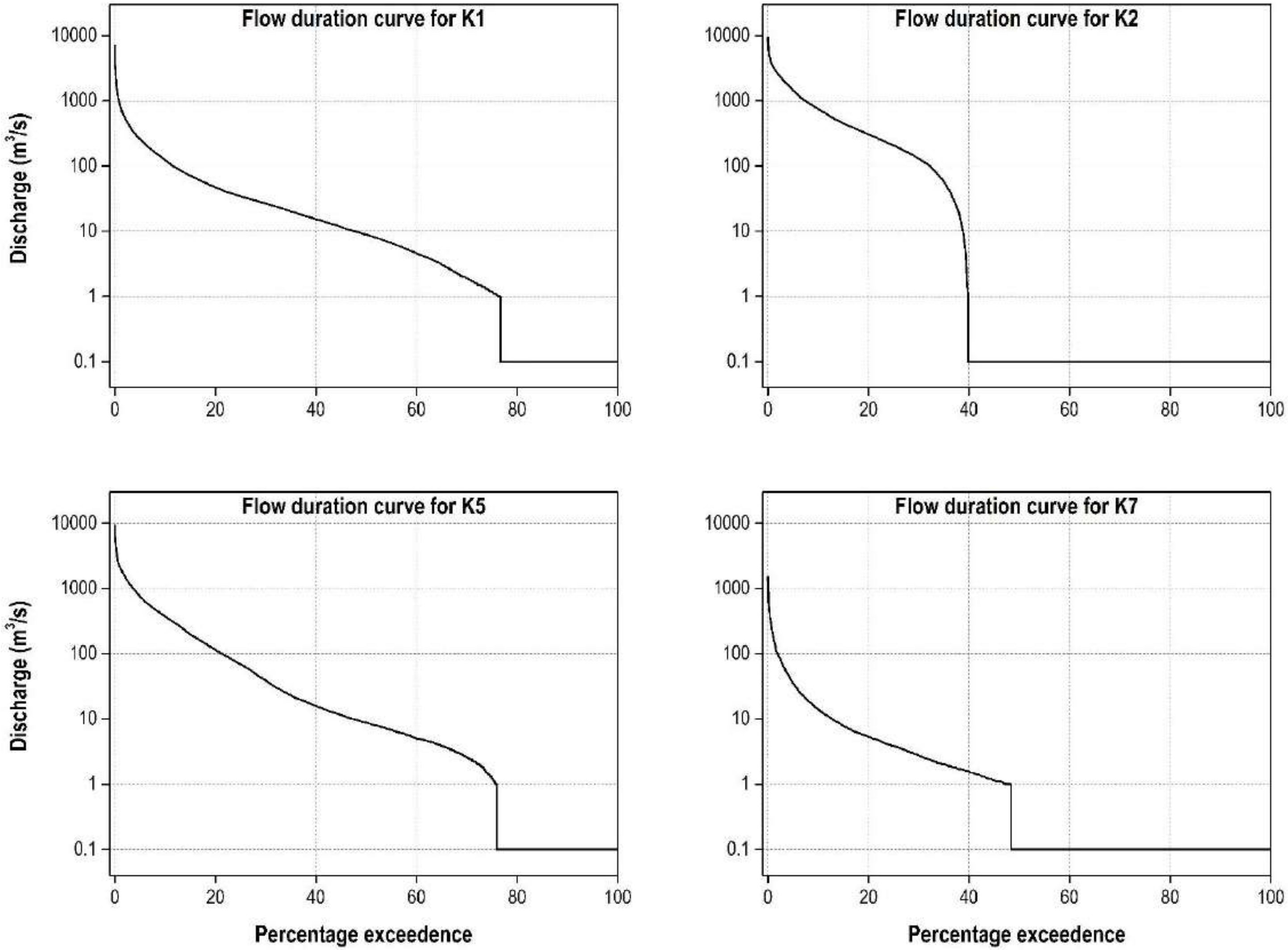
H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	2009 (6) 2010 (1) 2011 (2) 2012 (2) 2013 (10) 2014 (5)	2014 (5)						
TT3	1991 (2) 1992 (7) 1994 (16) 1997 (5) 1999 (2) 2000 (1) 2004 (4) 2005 (9) 2006 (2) 2007 (7) 2008 (6) 2009 (7) 2010 (12) 2013 (10) 2014 (5)	1992 (3) 1994 (10) 1997 (4) 1999 (1) 2005 (3) 2006 (1) 2007 (6) 2008 (5) 2009 (4) 2010 (10) 2013 (9) 2014 (5)	1992 (2) 2007 (3) 2008 (2) 2010 (5) 2013 (1)	2007 (3) 2010 (2) 2013 (1)	2007 (1) 2010 (1)	2007 (1) 2010 (1)	Nil	Nil
TT4	1985 (2) 1986 (3) 1987 (4) 1988 (1) 1991 (2) 1992 (12) 1993 (12) 1994 (8) 1995 (2) 1996 (11) 1997 (5) 1998 (10) 1999 (5) 2000 (11) 2001 (5)	1992 (6) 1993 (3) 1994 (2) 1996 (4) 1997 (1) 1998 (3) 1999 (5) 2000 (4) 2001 (2) 2005 (3) 2006 (1) 2009 (1) 2010 (6) 2012 (2) 2014 (1)	1992 (2) 2012 (1)	1992 (2)	1992 (2)	1992 (2)	1992 (1)	1992 (1)

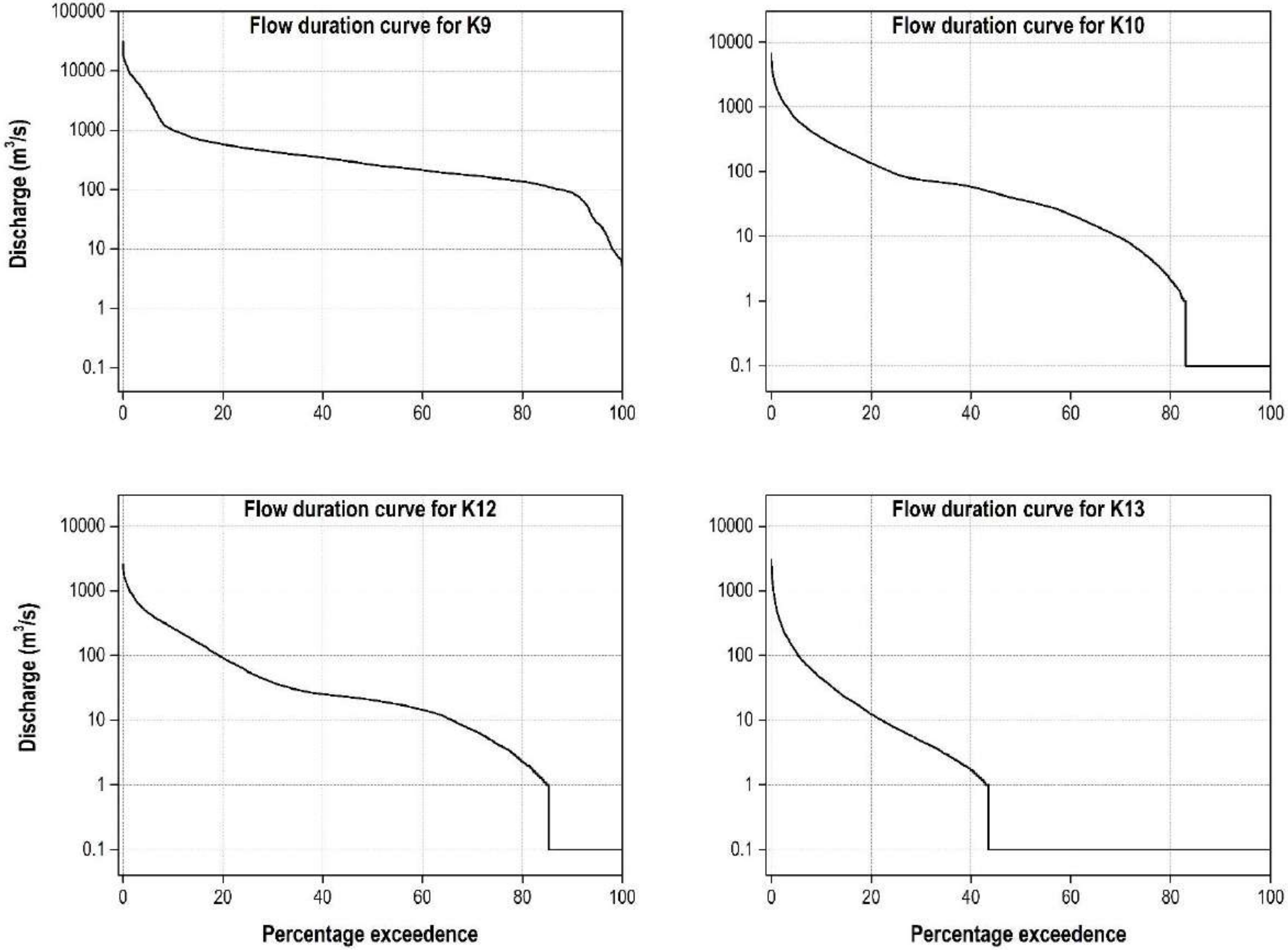
H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	2002 (2) 2003 (1) 2005 (6) 2006 (2) 2008 (1) 2009 (4) 2010 (23) 2012 (4) 2014 (2)							
TT5	1967 (10) 1969 (9) 1970 (8) 1972 (4) 1975 (4) 1978 (1) 1979 (4) 1980 (12) 1981 (1) 1982 (21) 1983 (13) 1984 (2) 1986 (3) 1988 (7) 1989 (2) 1991 (19) 1992 (16) 1993 (1) 1994 (16) 1997 (10) 1999 (12) 2000 (4) 2003 (0) 2004 (1) 2005 (13) 2006 (8) 2007 (15)	1967 (7) 1969 (5) 1970 (6) 1972 (2) 1975 (3) 1979 (2) 1980 (10) 1982 (15) 1983 (10) 1984 (1) 1986 (1) 1988 (7) 1991 (13) 1992 (13) 1994 (13) 1997 (6) 1999 (8) 2000 (2) 2005 (10) 2006 (2) 2007 (11) 2008 (6) 2009 (6) 2013 (10) 2014 (11)	1980 (4) 1982 (4) 1988 (2) 1991 (5) 1992 (3) 1994 (5) 1997 (2) 1999 (2) 2007 (5) 2008 (4) 2009 (2) 2014 (2)	1980 (3) 1982 (2) 1992 (2) 1994 (2) 2007 (4) 2008 (2)	2007 (2)	Nil	Nil	Nil

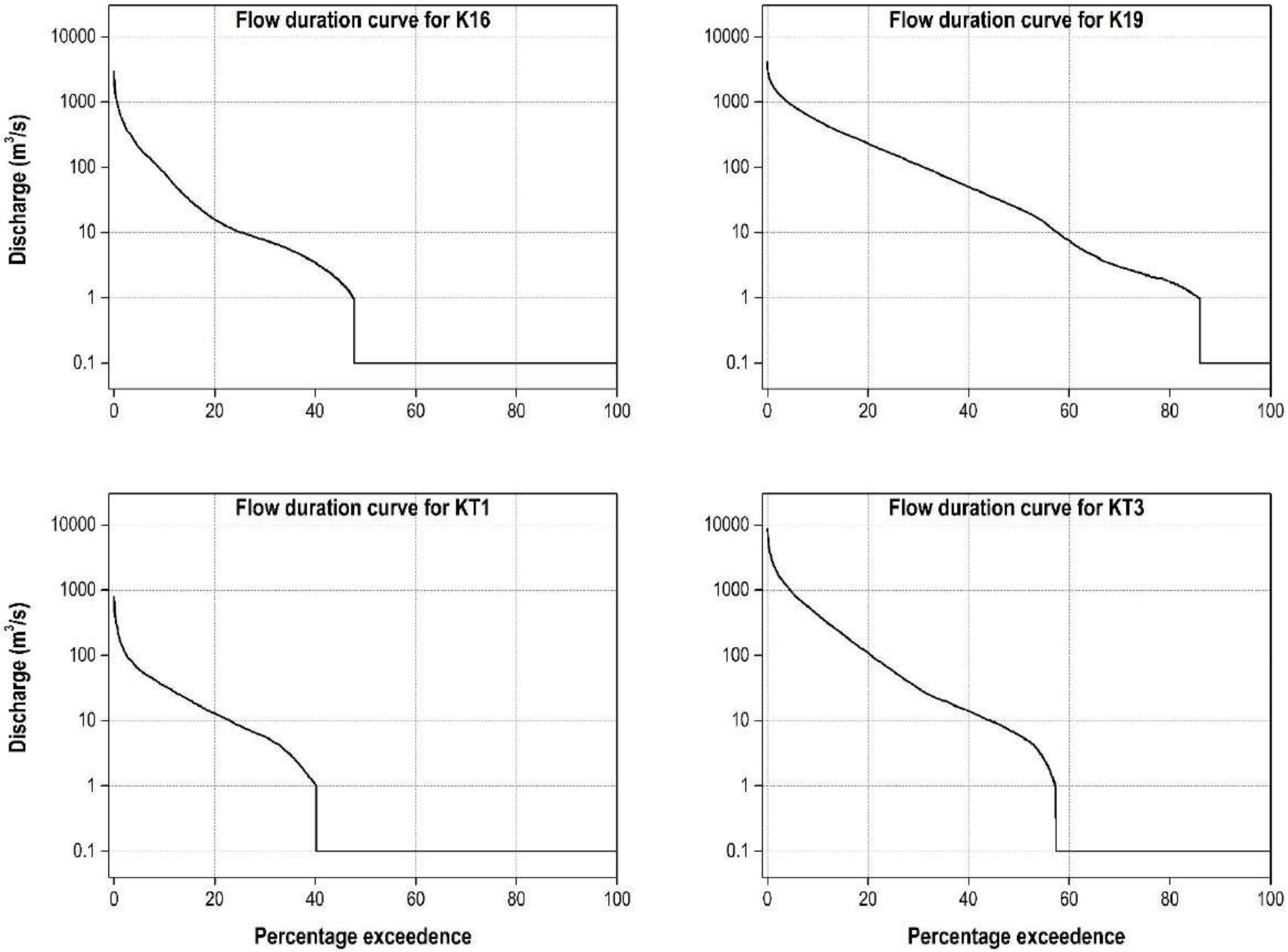
H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	2008 (8) 2009 (10) 2010 (2) 2011 (6) 2013 (14) 2014 (16)							
TT6	1990 (1) 1992 (14) 1993 (11) 1994 (7) 1996 (2) 1997 (2) 1999 (22) 2000 (30) 2001 (1) 2005 (1) 2009 (4) 2010 (24) 2011 (1) 2014 (8)	1992 (9) 1993 (8) 1994 (3) 1997 (2) 1999 (10) 2000 (17) 2009 (1) 2010 (9) 2014 (1)	1992 (3) 1993 (2) 1999 (1) 2000 (2) 2010 (1)	1992 (2) 2000 (2)	1992 (1)	1992 (1)	1992 (1)	Nil
TT9	1966 (3) 1967 (1) 1968 (5) 1969 (1) 1970 (5) 1971 (2) 1972 (2) 1973 (3) 1974 (3) 1975 (13) 1978 (4) 1981 (9) 1982 (1) 1983 (1) 1986 (2) 1987 (1)	1967 (1) 1968 (3) 1970 (1) 1971 (2) 1972 (2) 1973 (1) 1975 (8) 1978 (2) 1981 (6) 1982 (1) 1983 (1) 1986 (1) 1987 (1) 1988 (1) 1989 (4) 1992 (1)	1971 (1) 1973 (1) 1978 (2) 1996 (1) 2007 (2) 2008 (1) 2009 (4)	1971 (1) 1996 (1) 2007 (2) 2009 (2)	2009 (1)	2009 (1)	2009 (1)	2009 (1)

H. O. Code	Return period (year)							
	1.5	2	5	10	25	50	100	200
	1988 (1) 1989 (6) 1991 (1) 1992 (3) 1994 (1) 1995 (1) 1996 (7) 1998 (5) 1999 (1) 2000 (4) 2001 (9) 2005 (4) 2006 (1) 2007 (4) 2008 (5) 2009 (9) 2010 (2) 2014 (1)	1996 (4) 1998 (1) 2000 (2) 2001 (4) 2005 (2) 2006 (1) 2007 (3) 2008 (2) 2009 (5) 2010 (1)						

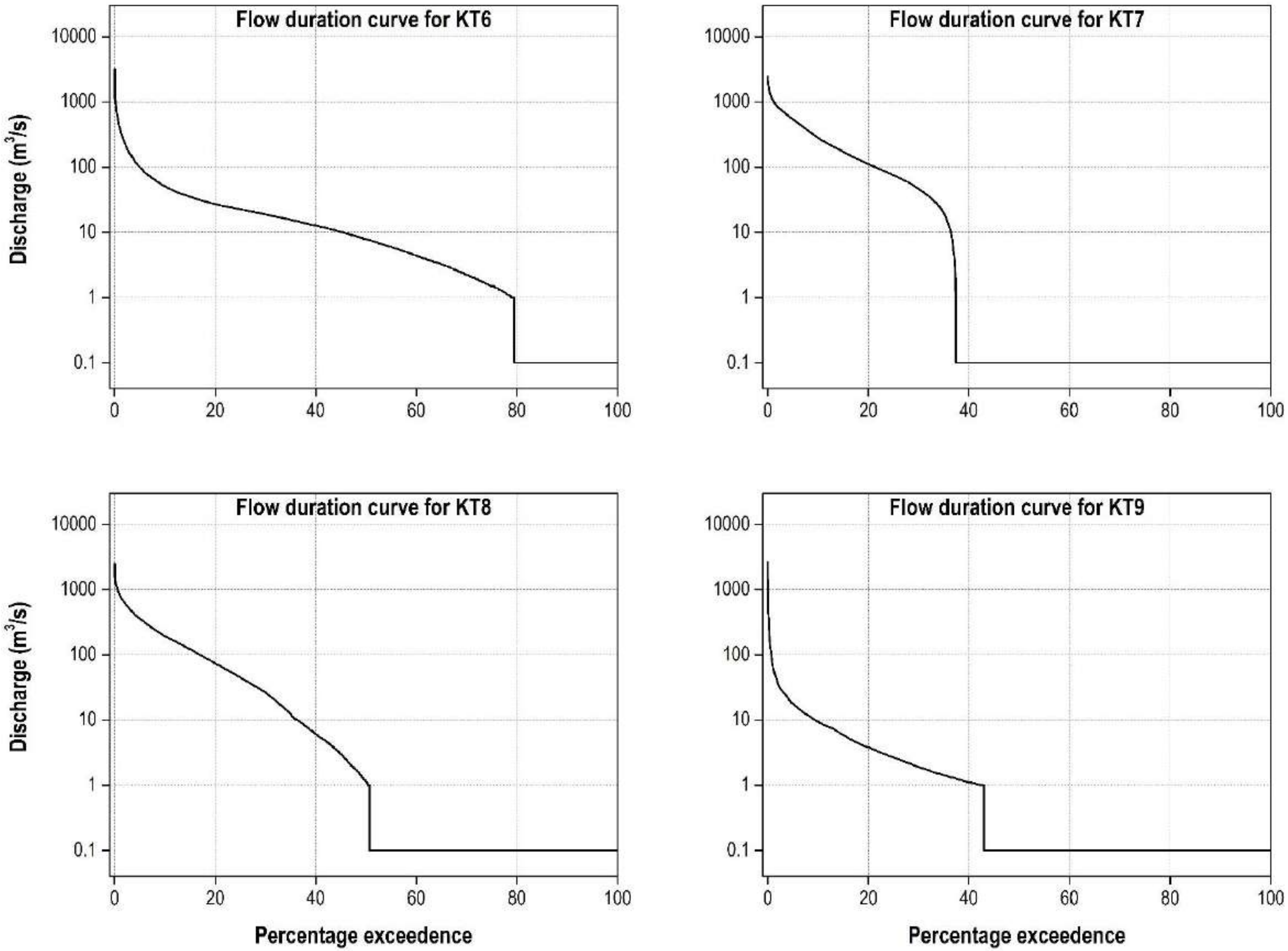
Appendix XIII: Flow duration curve for the different H.O. stations of Krishna and Tungabhadra rivers *(for plotting purpose, zeros are taken as 0.1)*

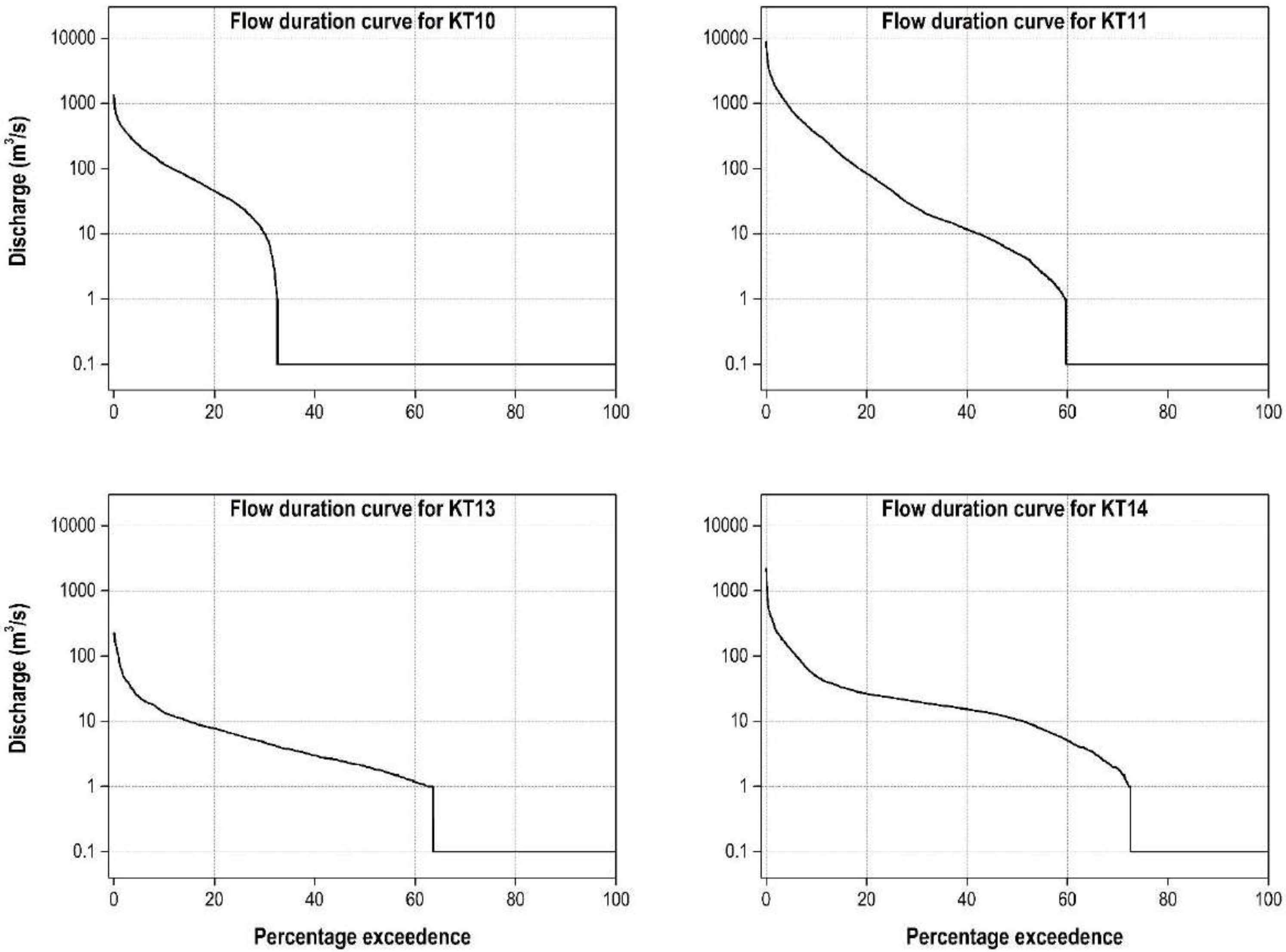



Flow duration curve for K9
Flow duration curve for K10
Flow duration curve for K12
Flow duration curve for K13
Discharge (m³/s)
Percentage exceedence
100000
10000
1000
100
10
1
0.1
0
20
40
60
80
100

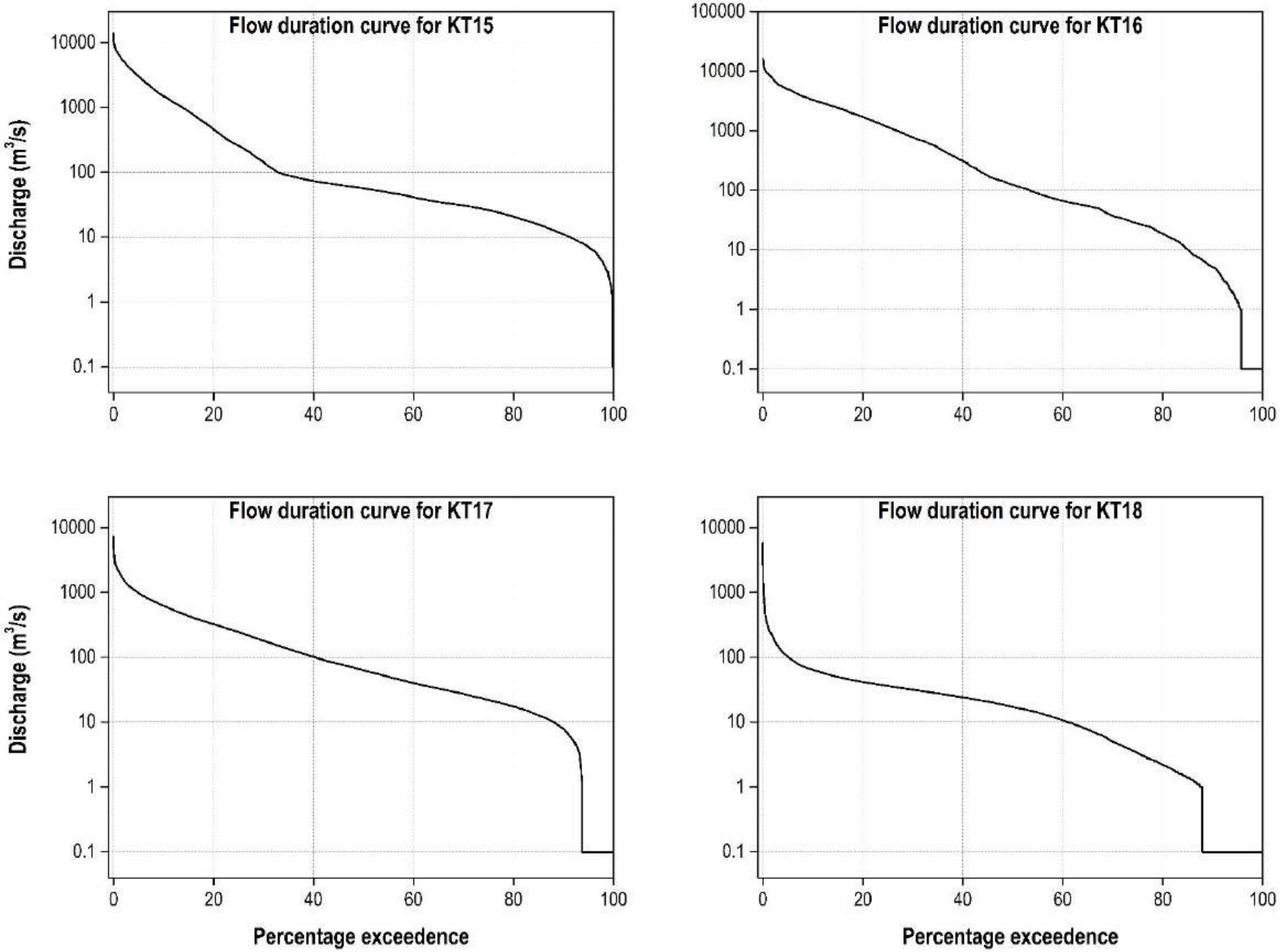


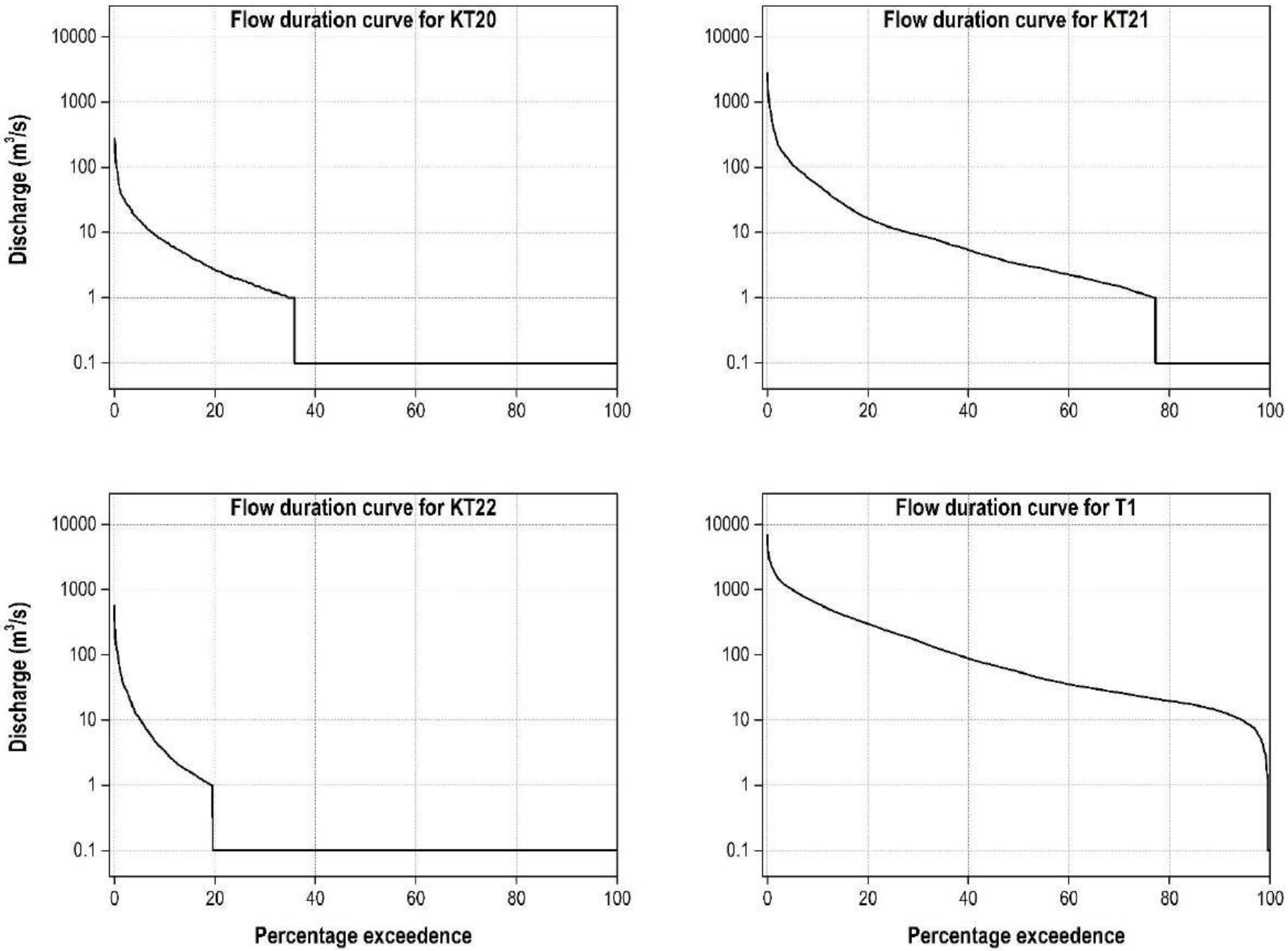
Flow duration curve for K16
Flow duration curve for K19
Flow duration curve for KT1
Flow duration curve for KT3
Discharge (m³/s)
10000
1000
100
10
1
0.1
0
20
40
60
80
100
Percentage exceedence

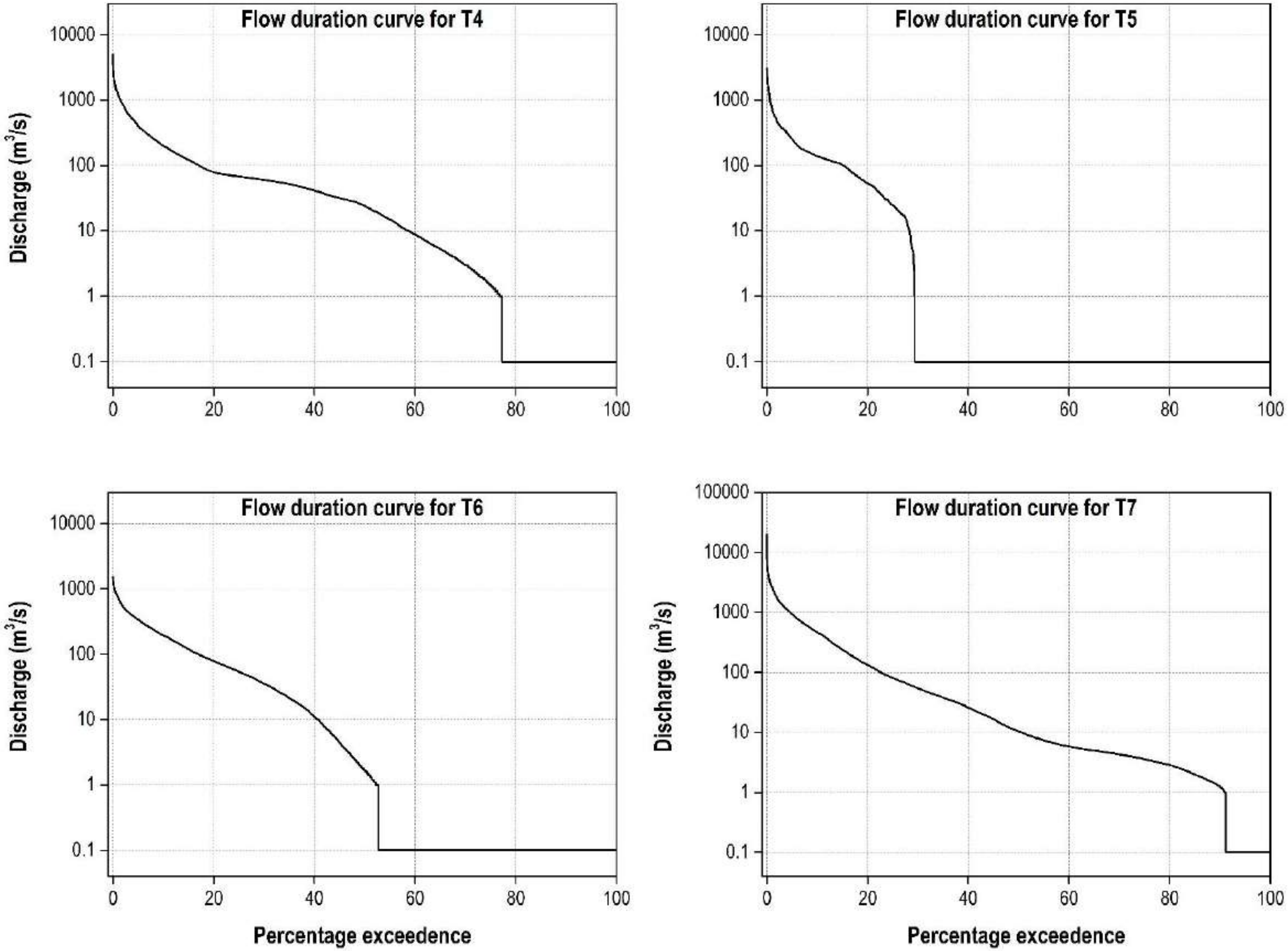

Flow duration curve for KT6
Flow duration curve for KT7
Flow duration curve for KT8
Flow duration curve for KT9
Discharge (m³/s)
Percentage exceedence
10000
1000
100
10
1
0.1
0
20
40
60
80
100

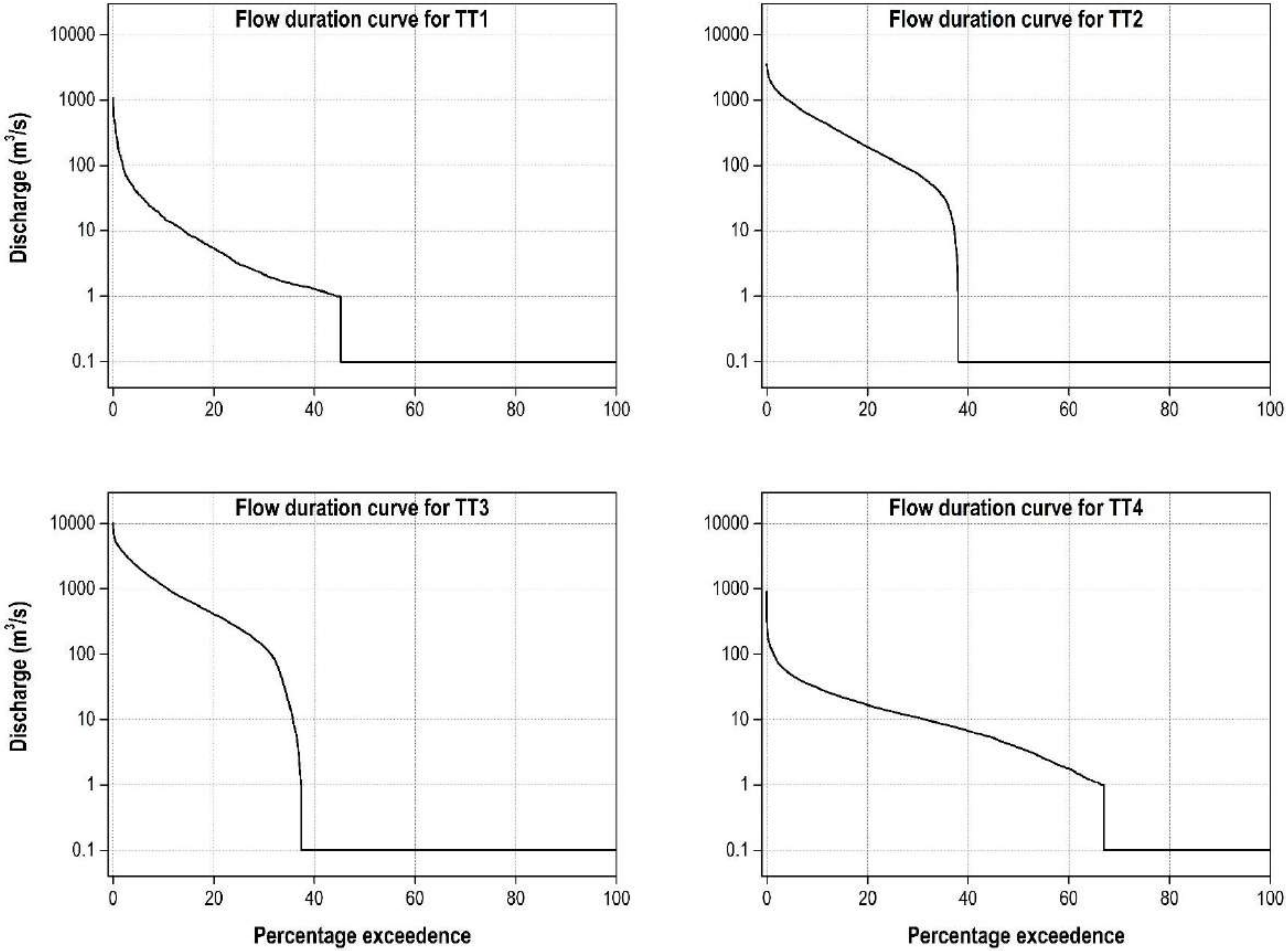


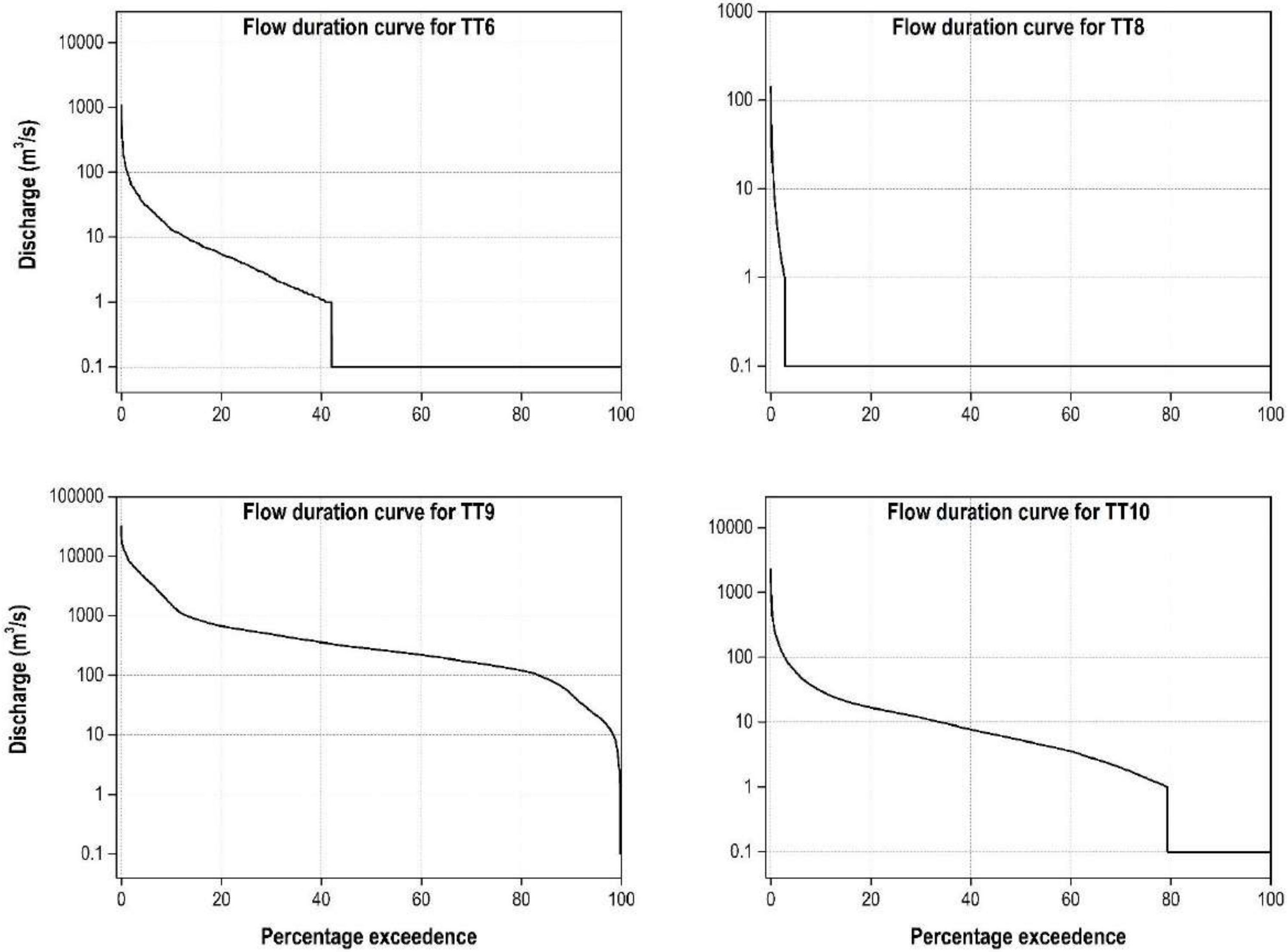
Flow duration curve for KT10
Flow duration curve for KT11
Flow duration curve for KT13
Flow duration curve for KT14
Discharge (m3/s)
Percentage exceedence
10000
1000
100
10
1
0.1
0
20
40
60
80
100

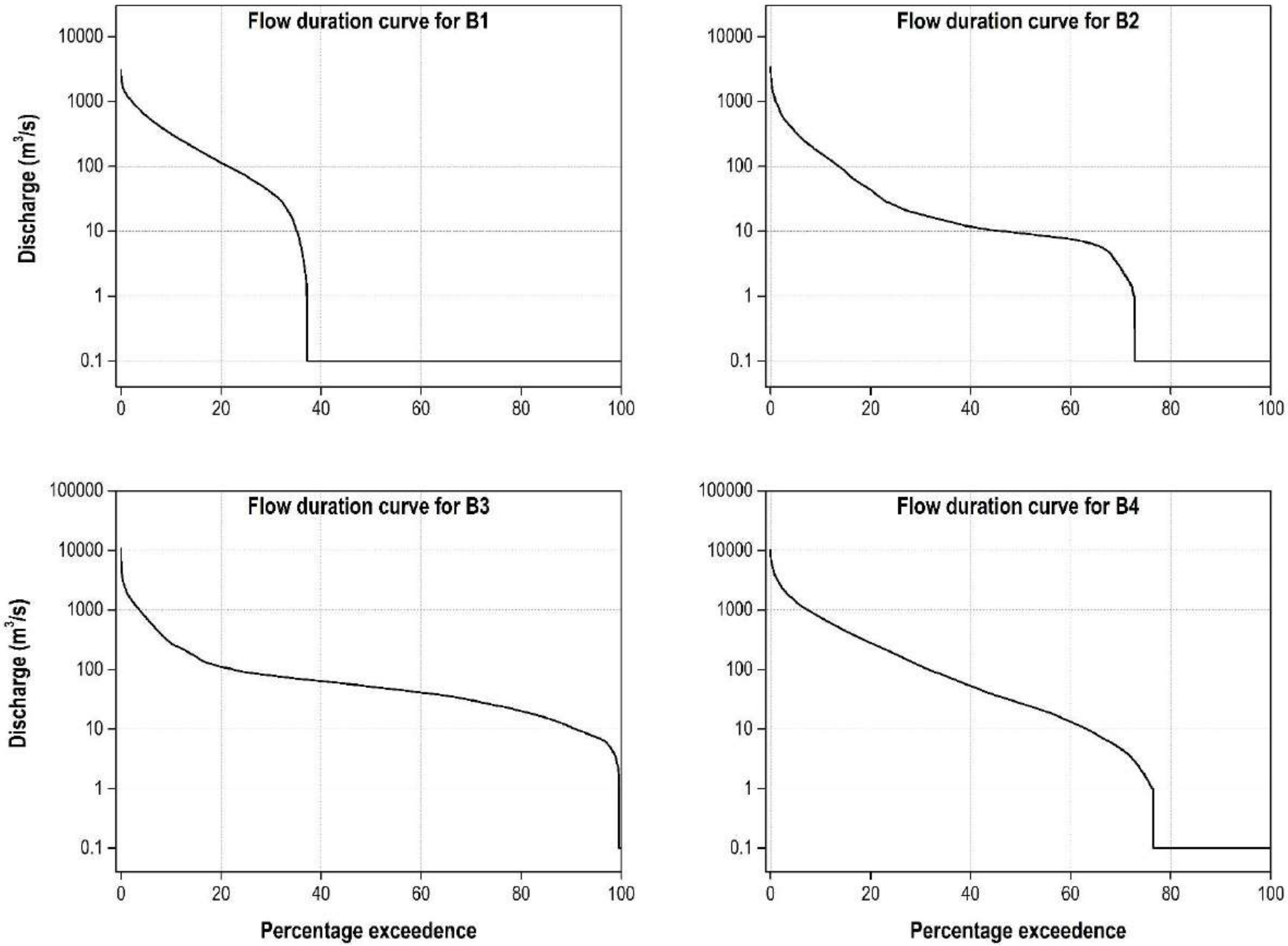

Flow duration curve for KT15
Flow duration curve for KT16
Flow duration curve for KT17
Flow duration curve for KT18
Discharge (m3/s)
Percentage exceedence
100000
10000
1000
100
10
1
0.1
0
20
40
60
80
100

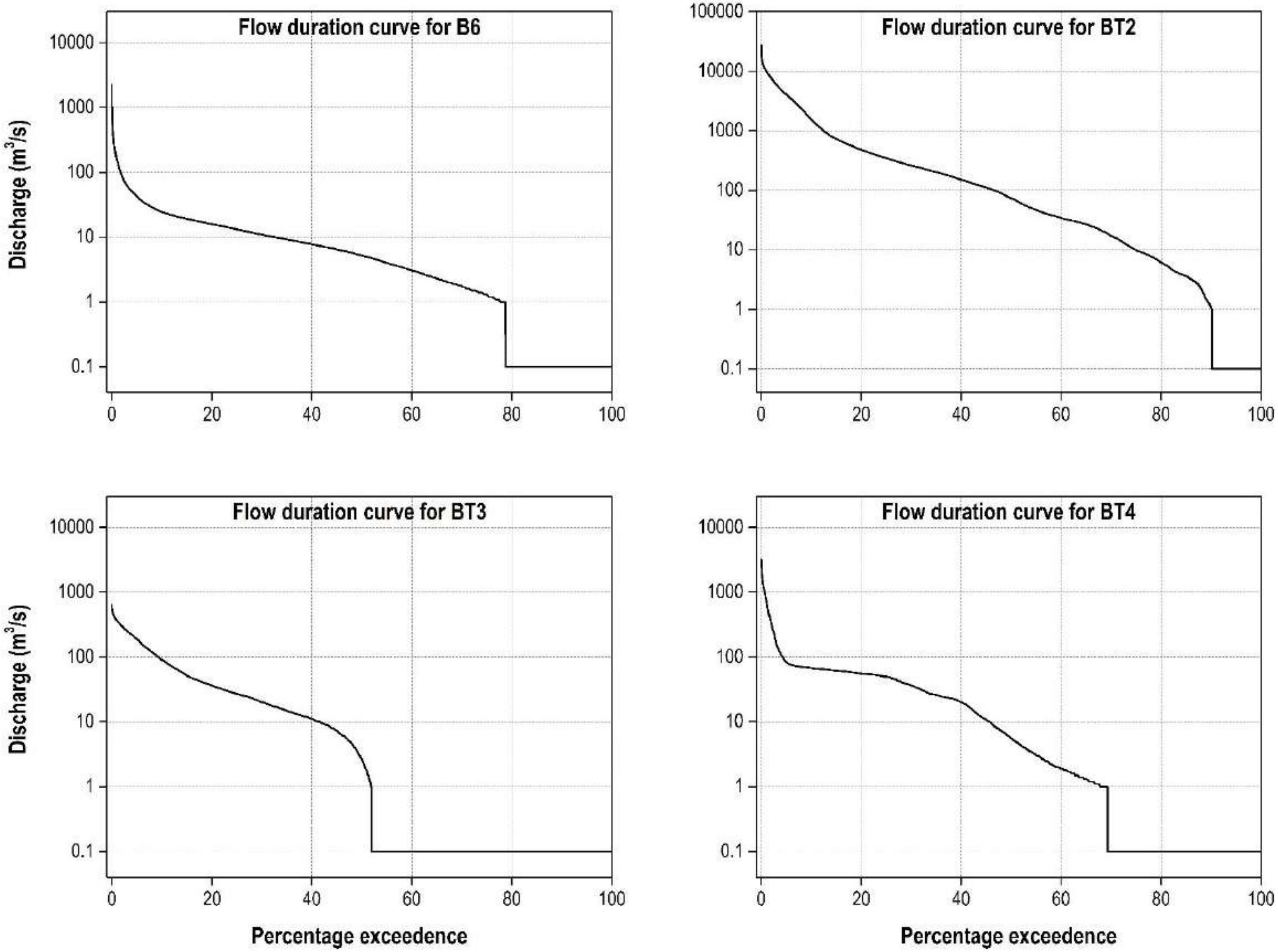

Flow duration curve for KT20
Flow duration curve for KT21
Flow duration curve for KT22
Flow duration curve for T1
Discharge (m³/s)
Discharge (m³/s)
10000
1000
100
10
1
0.1
0
20
40
60
80
100
Percentage exceedence
Percentage exceedence

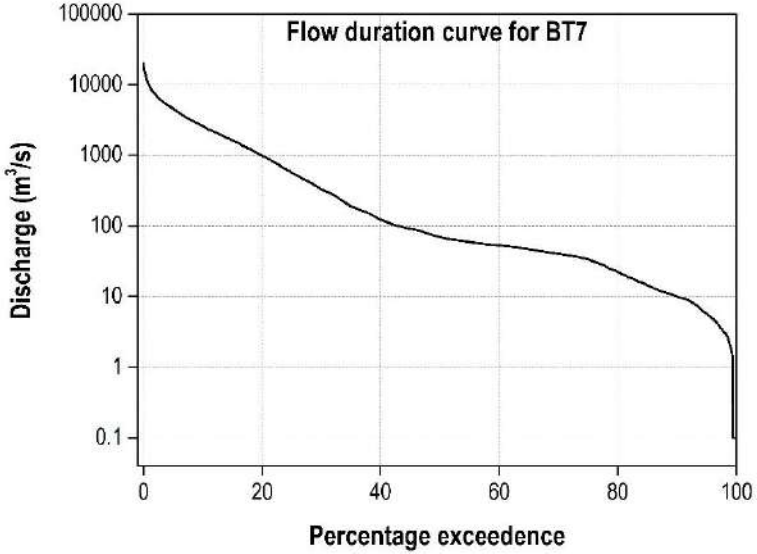
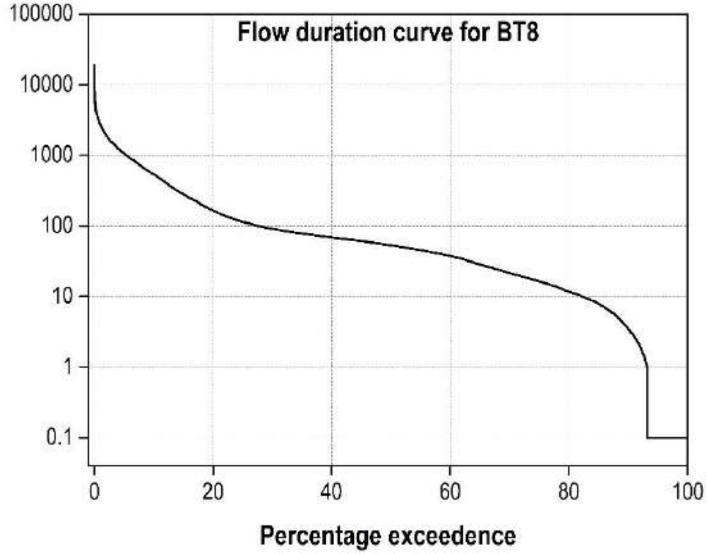

Flow duration curve for T4
Flow duration curve for T5
Flow duration curve for T6
Flow duration curve for T7
Discharge (m3/s)
Percentage exceedence
100000
10000
1000
100
10
1
0.1
0
20
40
60
80
100


Flow duration curve for TT1
Flow duration curve for TT2
Flow duration curve for TT3
Flow duration curve for TT4
Discharge (m³/s)
10000
1000
100
10
1
0.1
0
20
40
60
80
100
Percentage exceedence

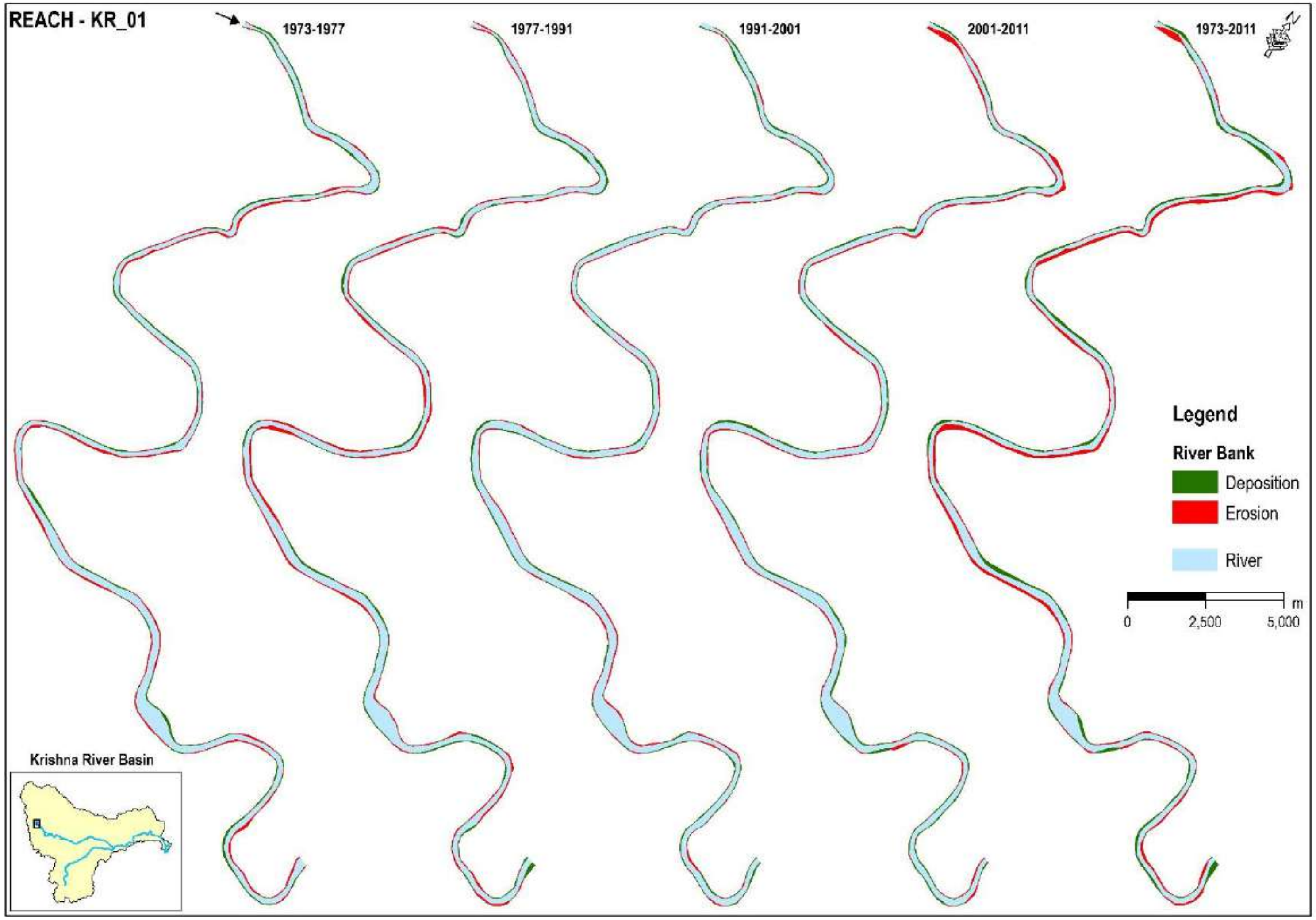

Flow duration curve for TT6
Flow duration curve for TT8
Flow duration curve for TT9
Flow duration curve for TT10
Discharge (m3/s)
Discharge (m3/s)
Percentage exceedence
Percentage exceedence
0.1
1
10
100
1000
10000
100000
0
20
40
60
80
100

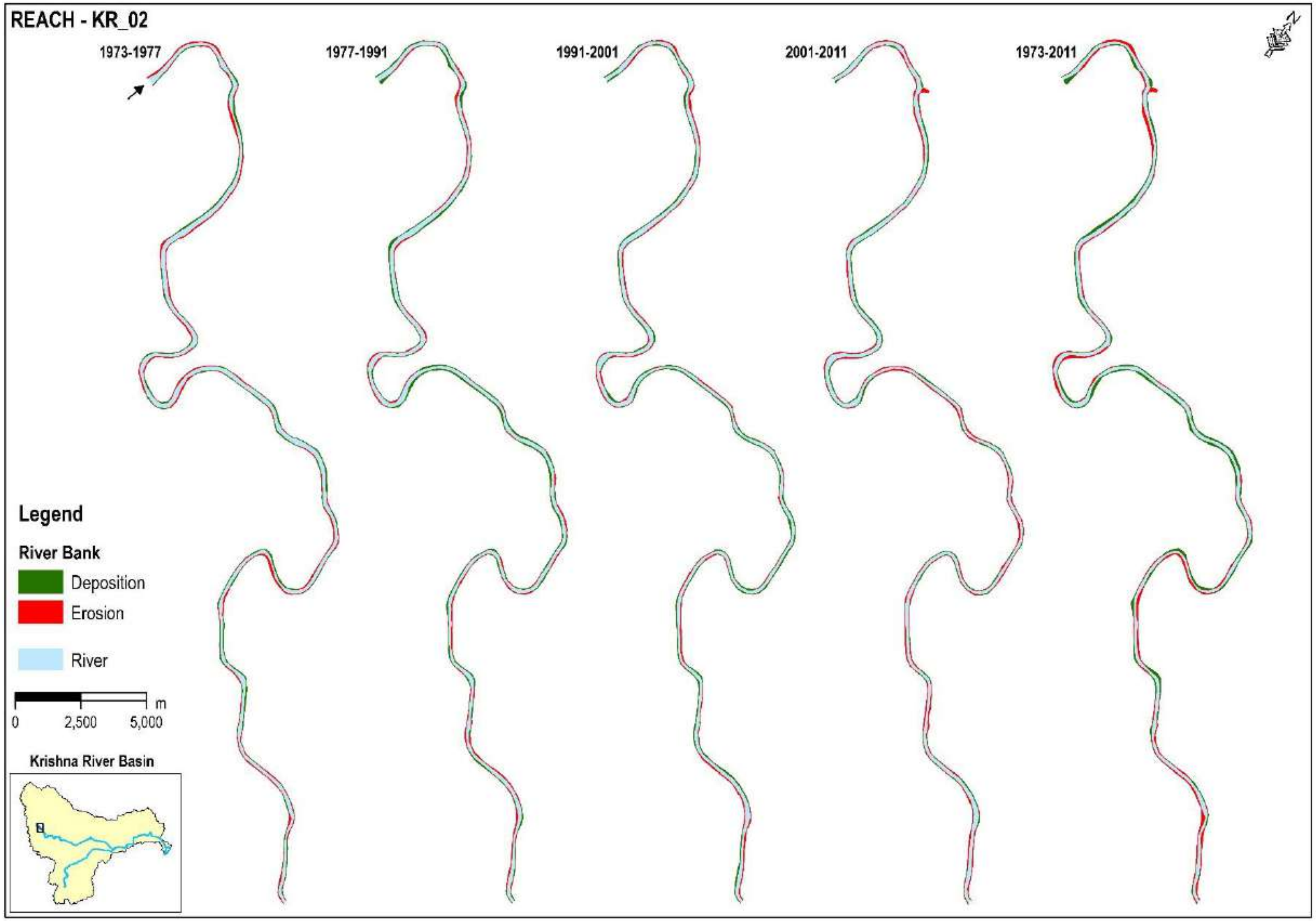

Flow duration curve for B1
Flow duration curve for B2
Flow duration curve for B3
Flow duration curve for B4
Discharge (m³/s)
Percentage exceedence
10000
1000
100
10
1
0.1
100000
0
20
40
60
80
100

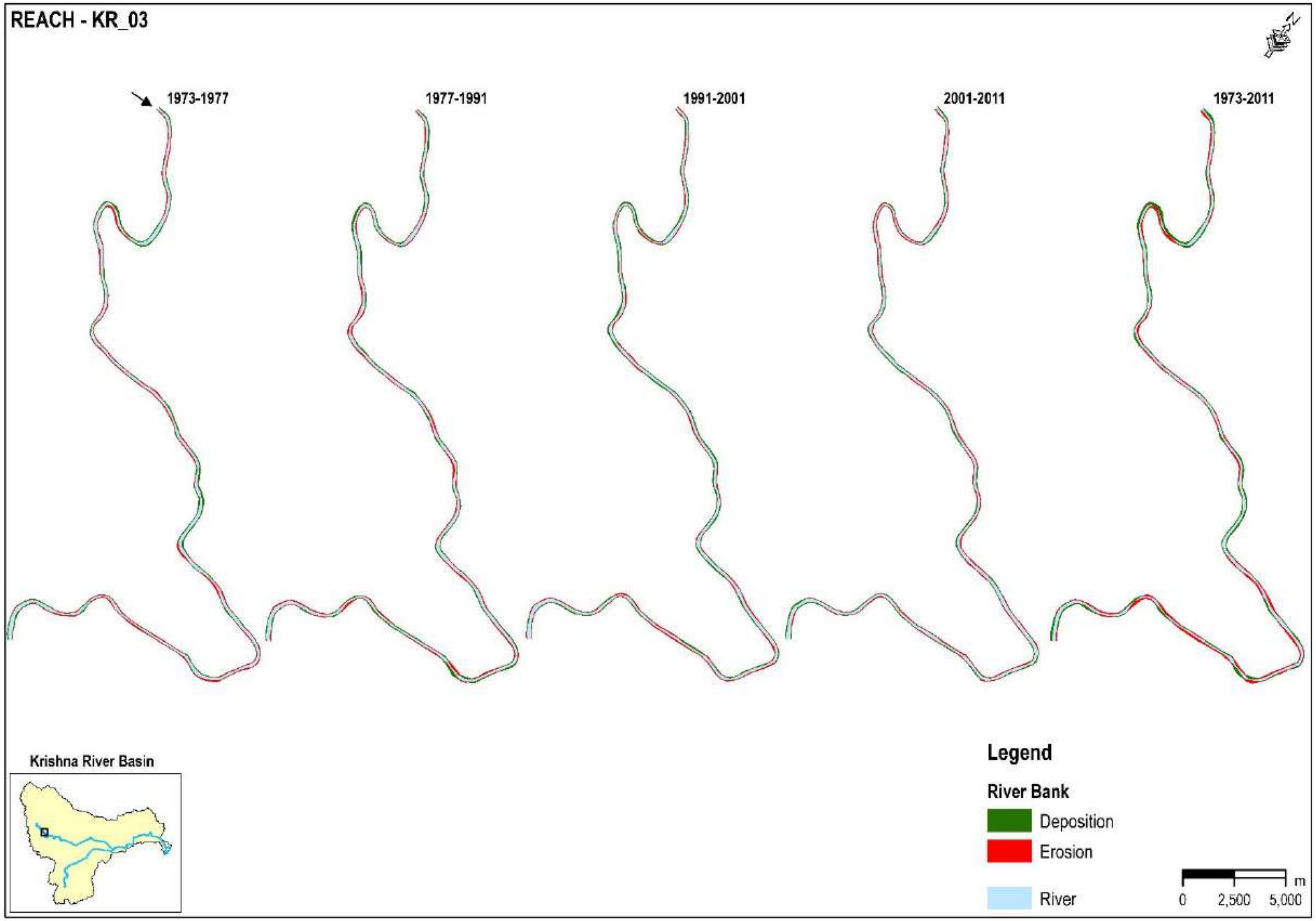

Flow duration curve for B6
Flow duration curve for BT2
Flow duration curve for BT3
Flow duration curve for BT4
Discharge (m³/s)
Percentage exceedence
0.1
1
10
100
1000
10000
100000
0
20
40
60
80
100

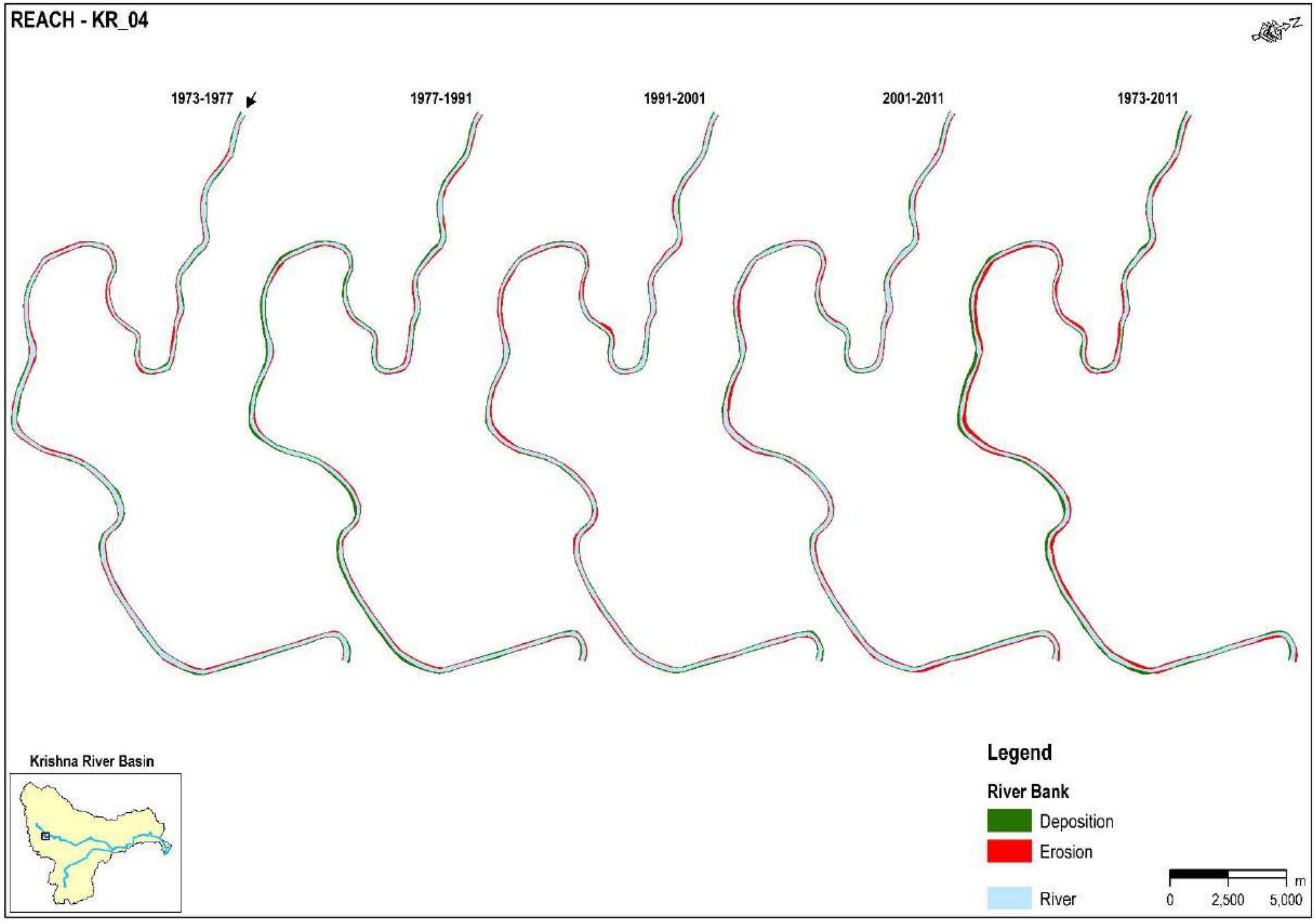

Flow duration curve for BT7
Discharge (m3/s)
100000
10000
1000
100
10
1
0.1
0
20
40
60
80
100
Percentage exceedence

Flow duration curve for BT8
100000
10000
1000
100
10
1
0.1
0
20
40
60
80
100
Percentage exceedence

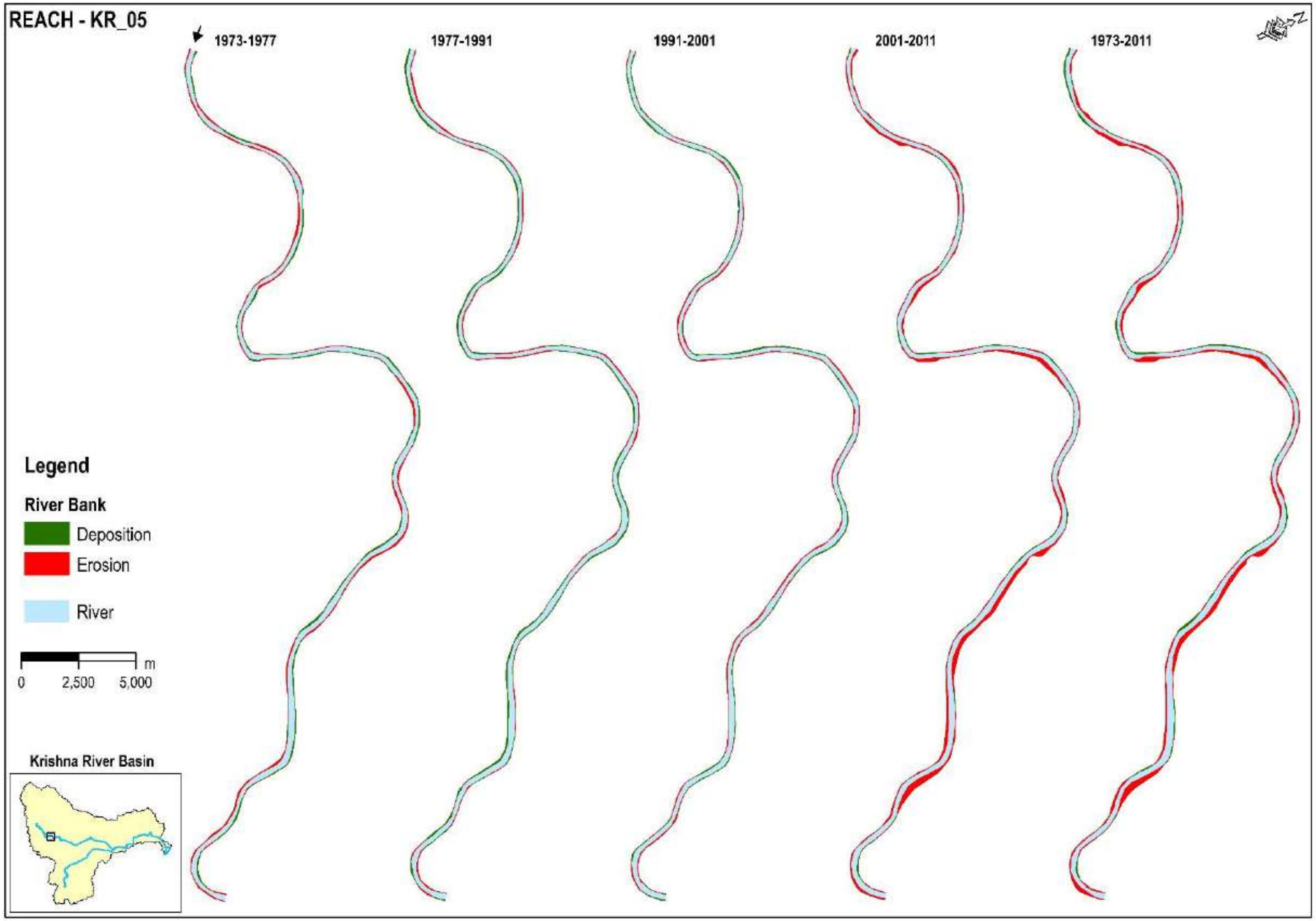
Appendix XIV: Spatio-temporal patterns of bank erosion/deposition of different reaches of Krishna (KR_01 to KR_27) and Tungabhadra (TR_01 to TR_11) rivers during 1973-2011

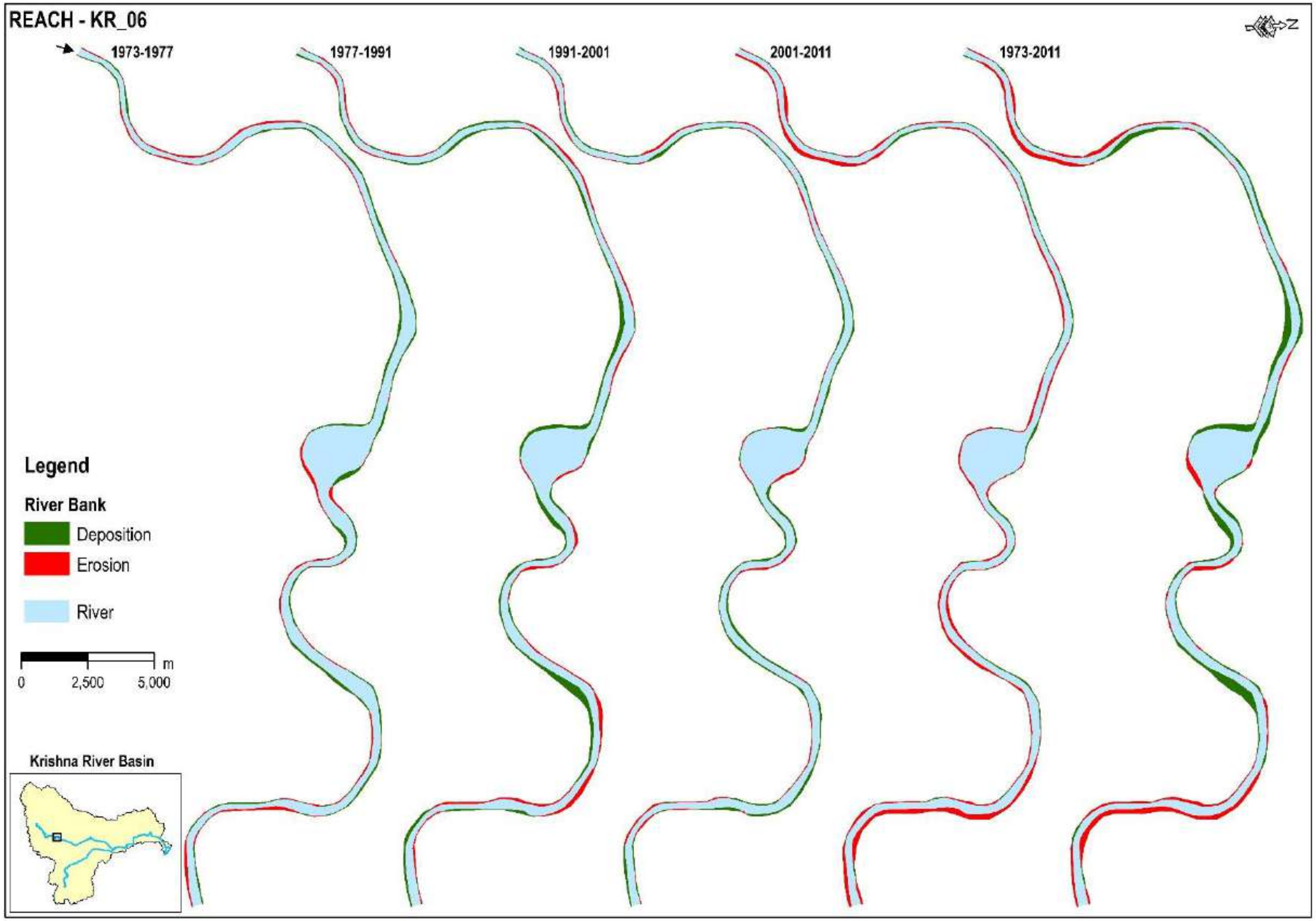



REACH - KR_02
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
N
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin

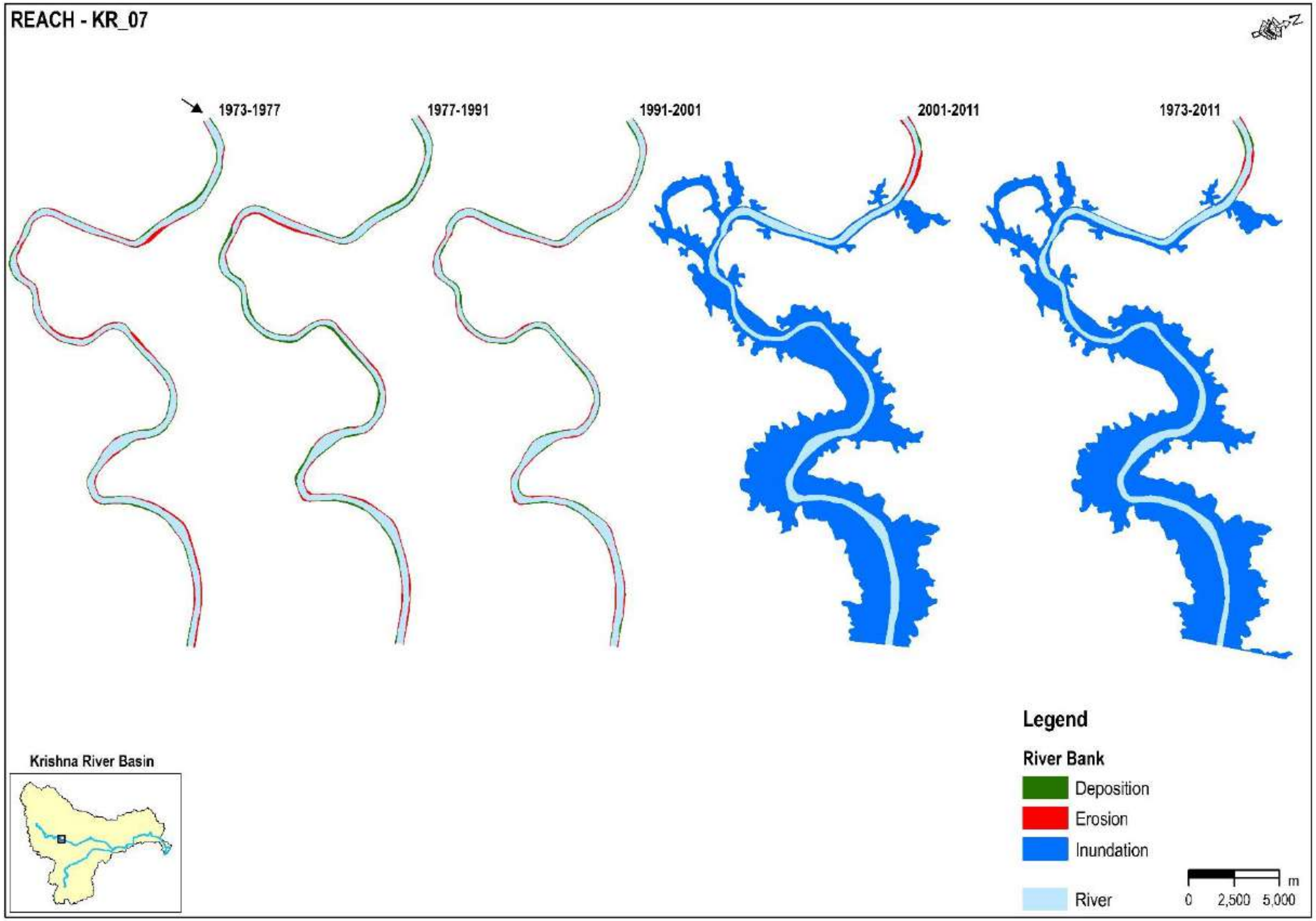

REACH - KR_03
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000

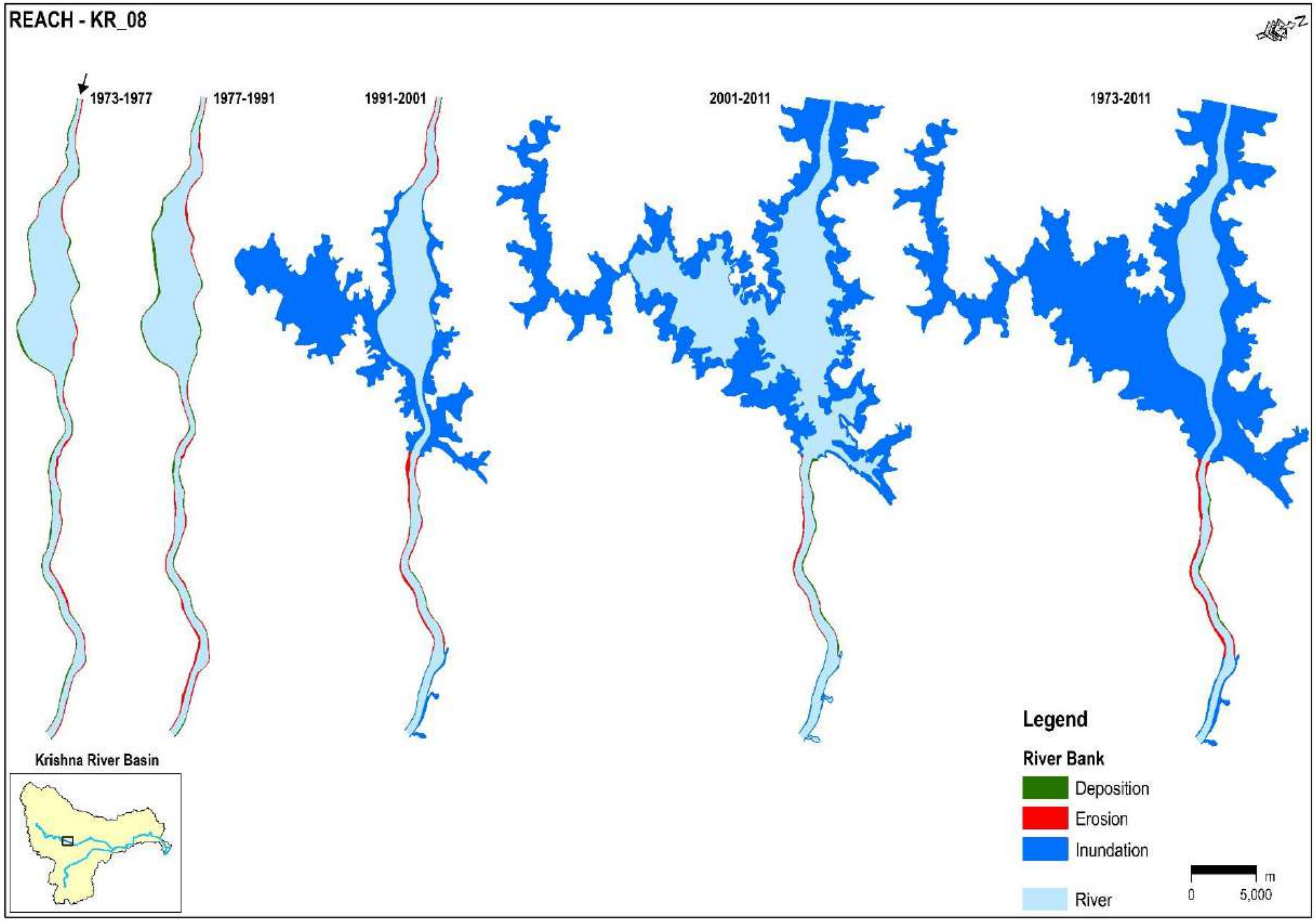

REACH - KR_04
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000

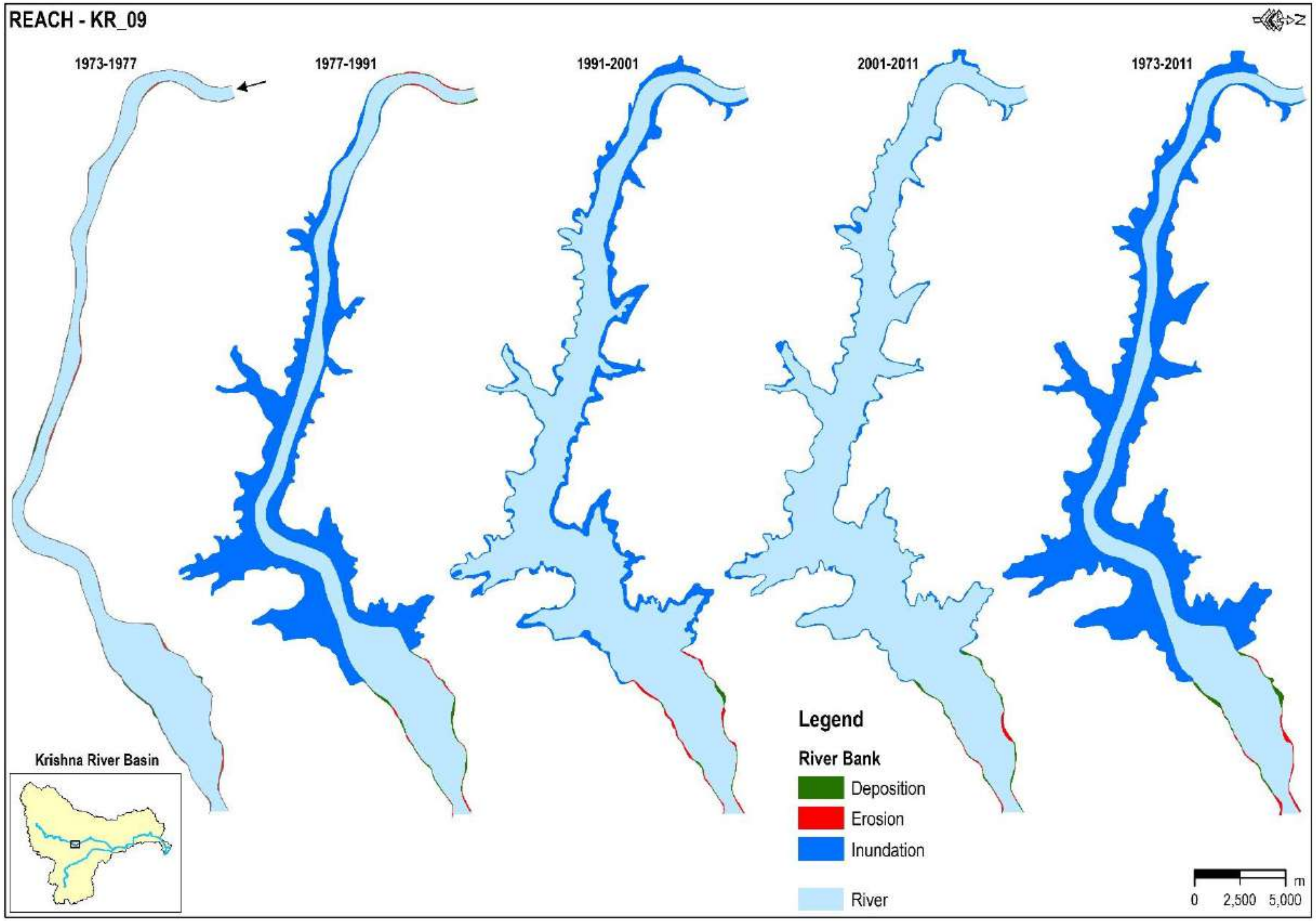

REACH - KR_05
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin

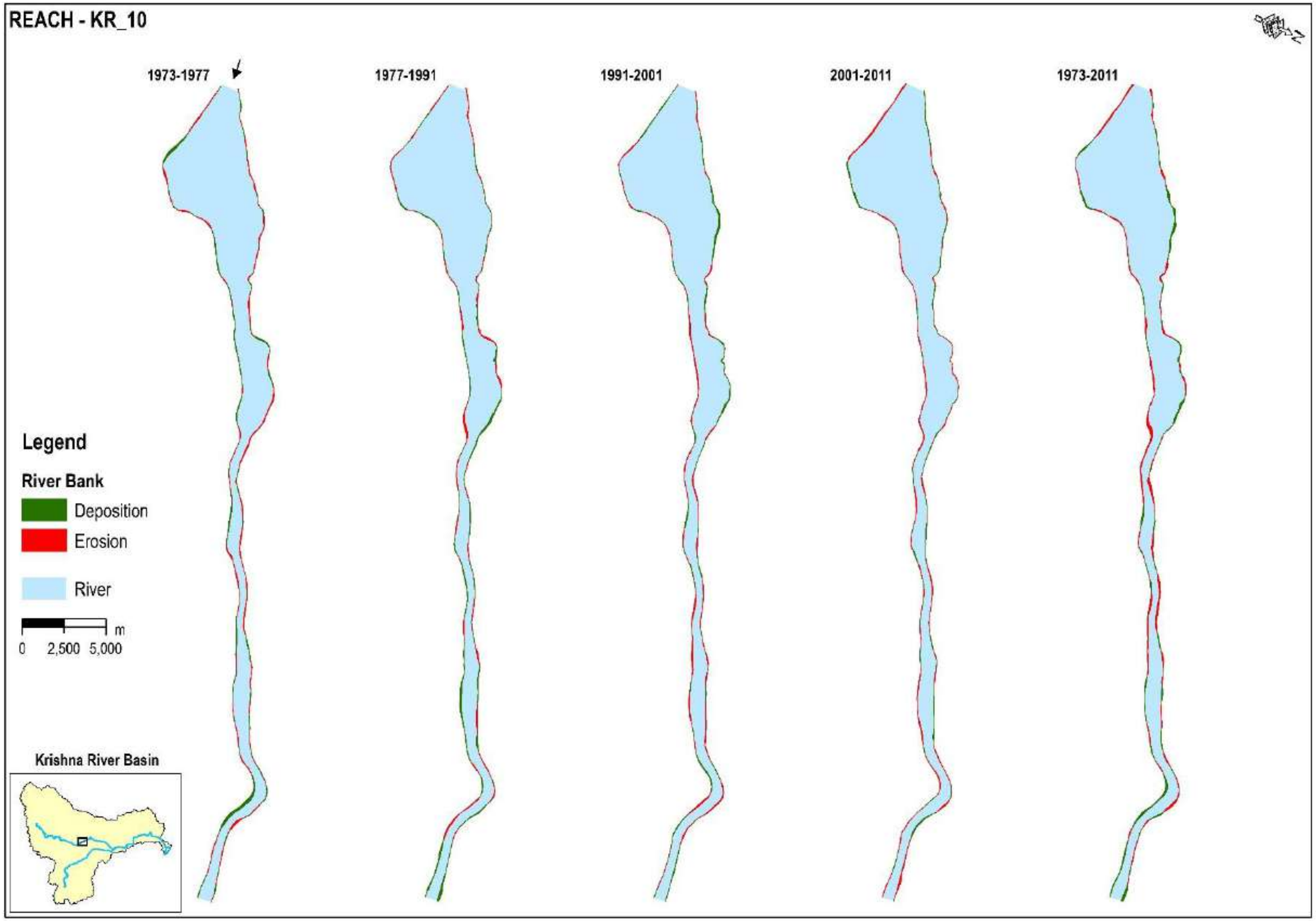


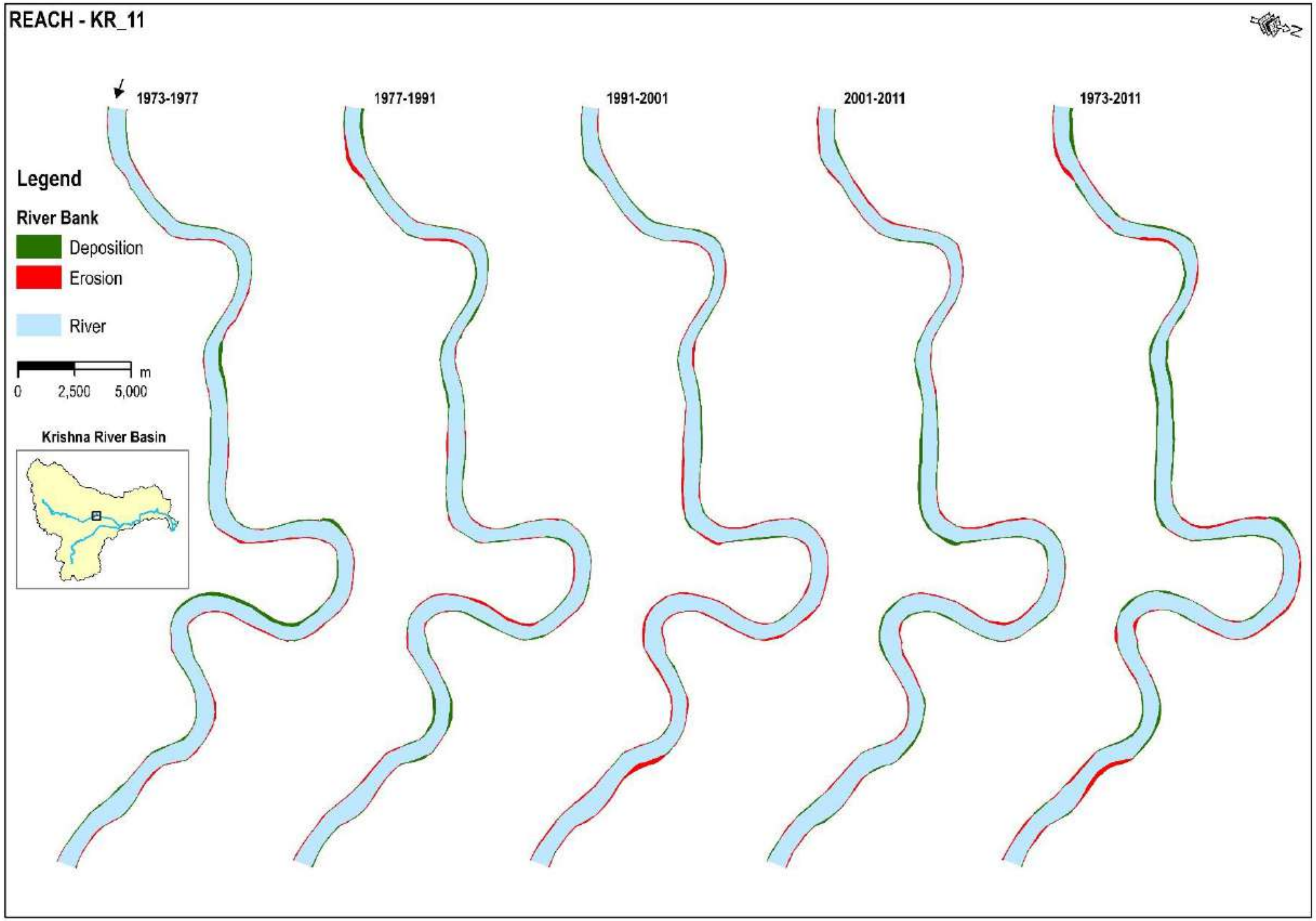
REACH - KR_06
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
N
Legend
River Bank
Deposition
Erosion
River
0
2,500
5,000
m
Krishna River Basin

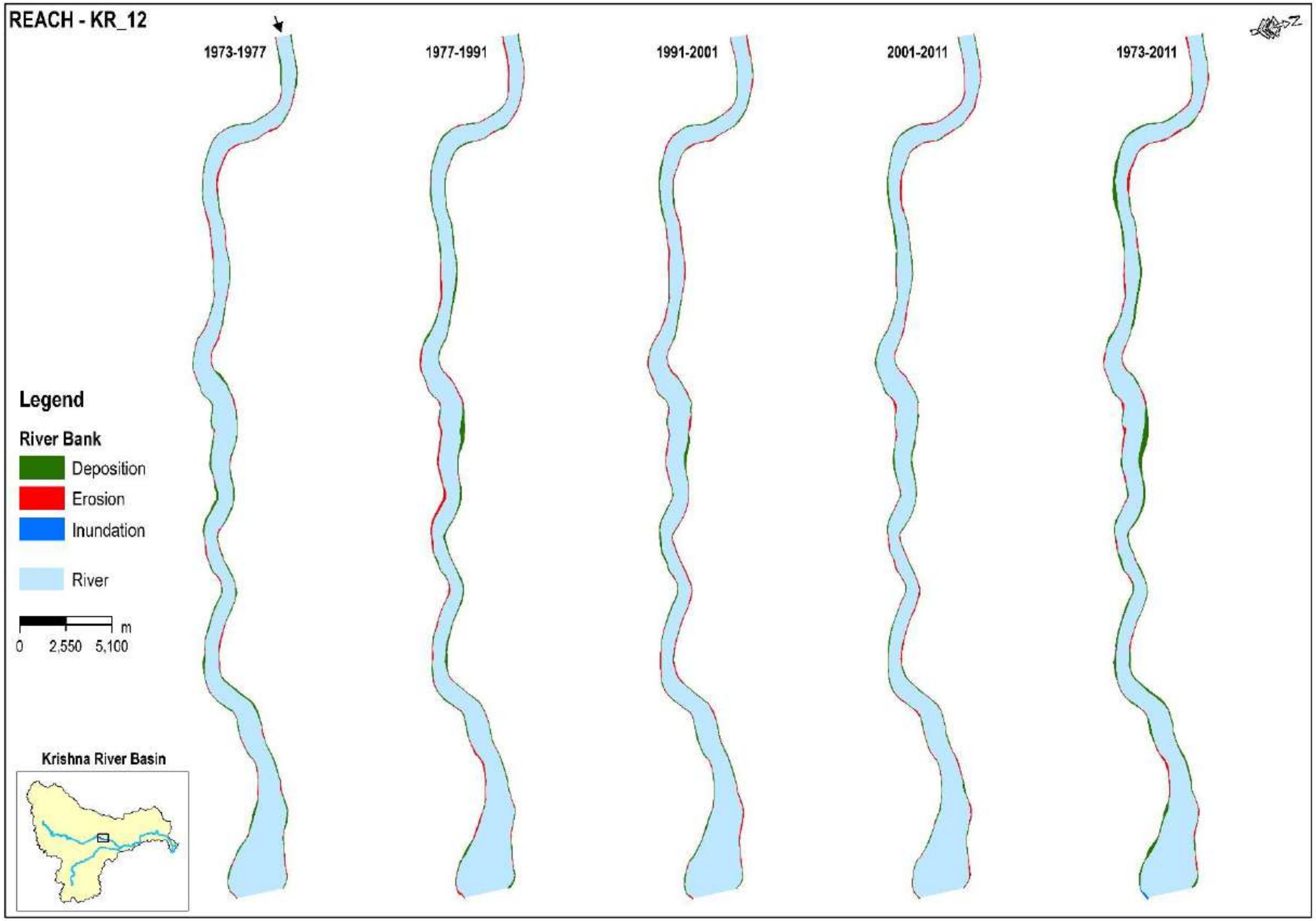

REACH - KR_07
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0 2,500 5,000

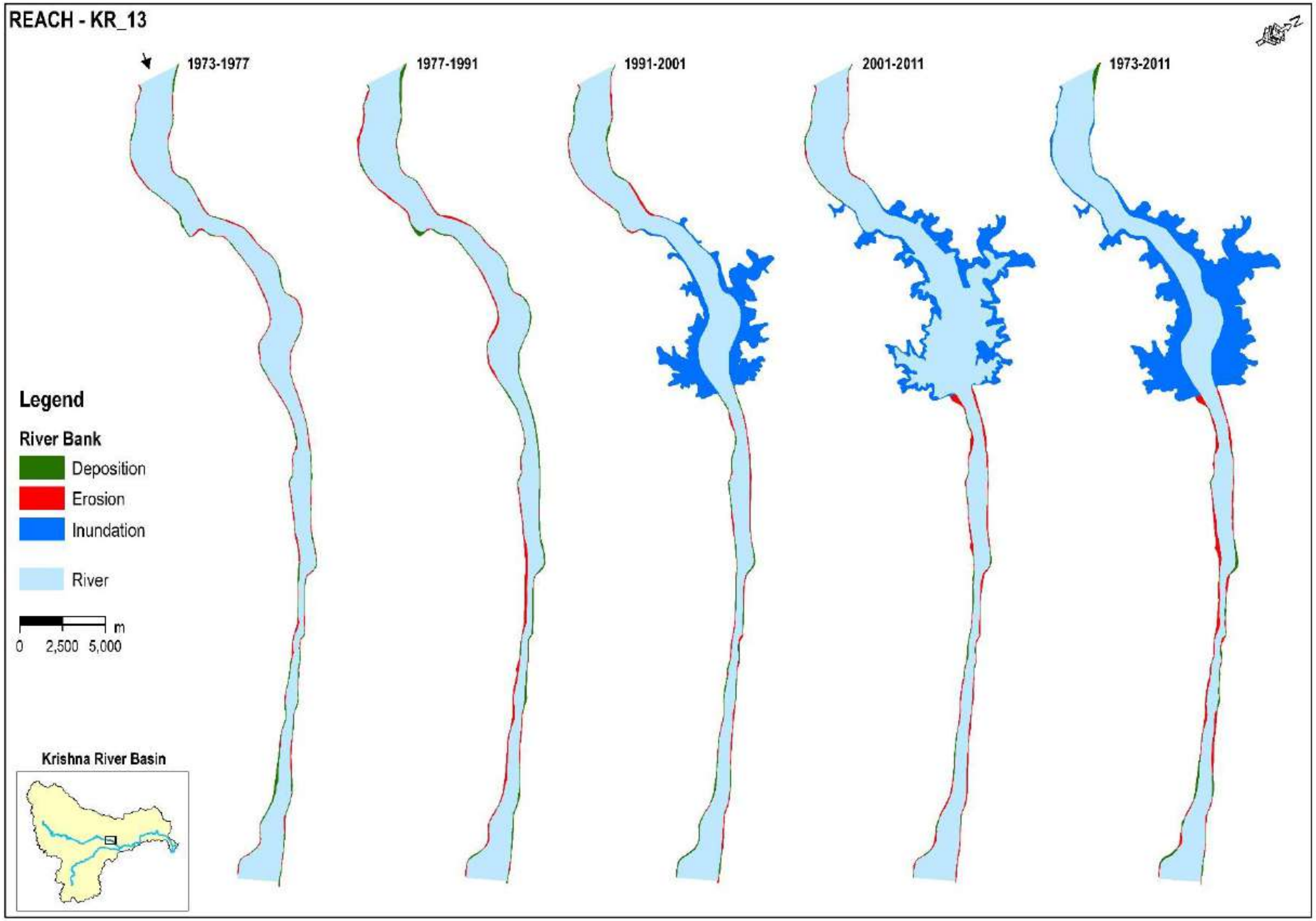

REACH - KR_08
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0
5,000


REACH - KR_09
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
Inundation
River
0 2,500 5,000
m

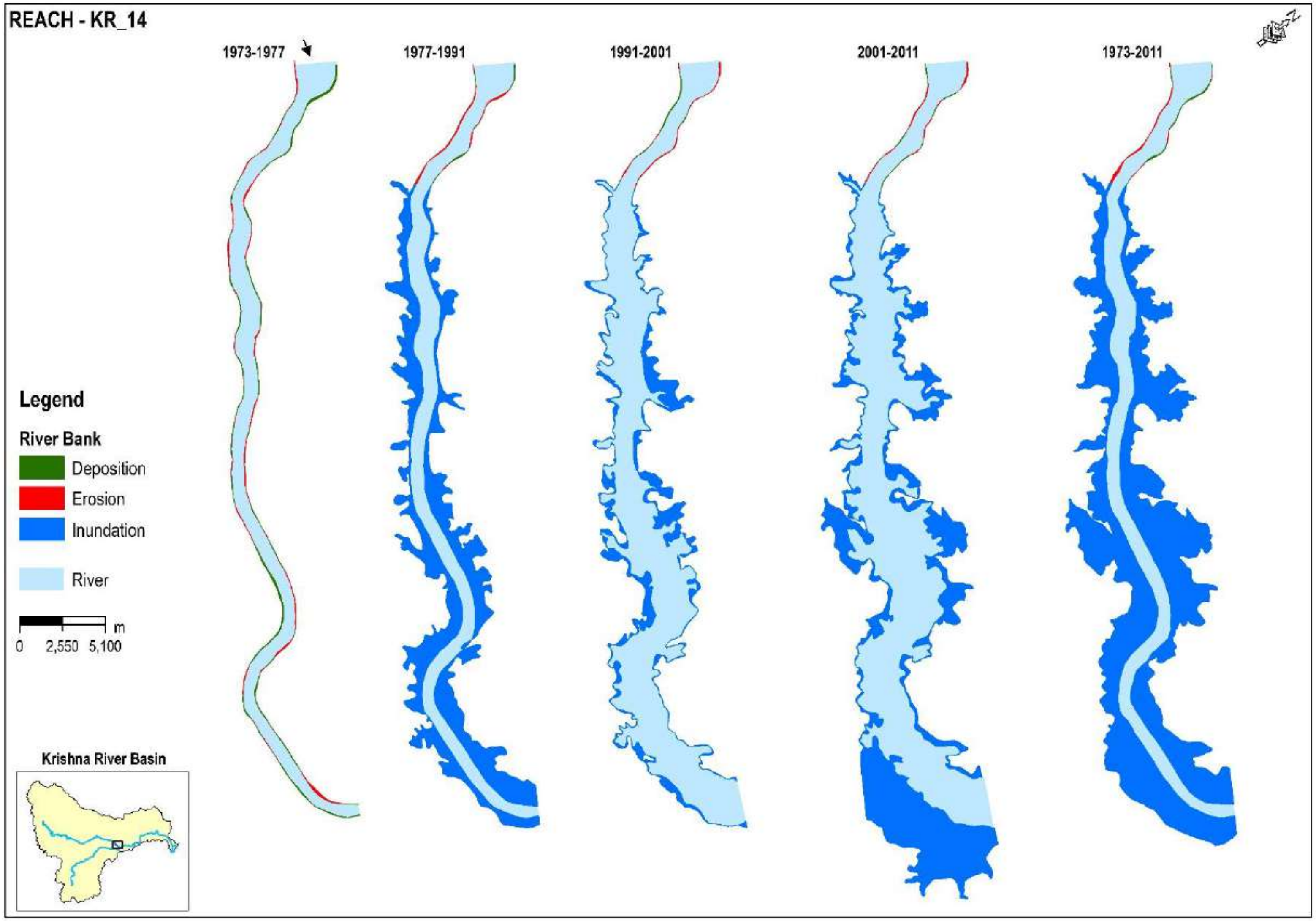

REACH - KR_10
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin

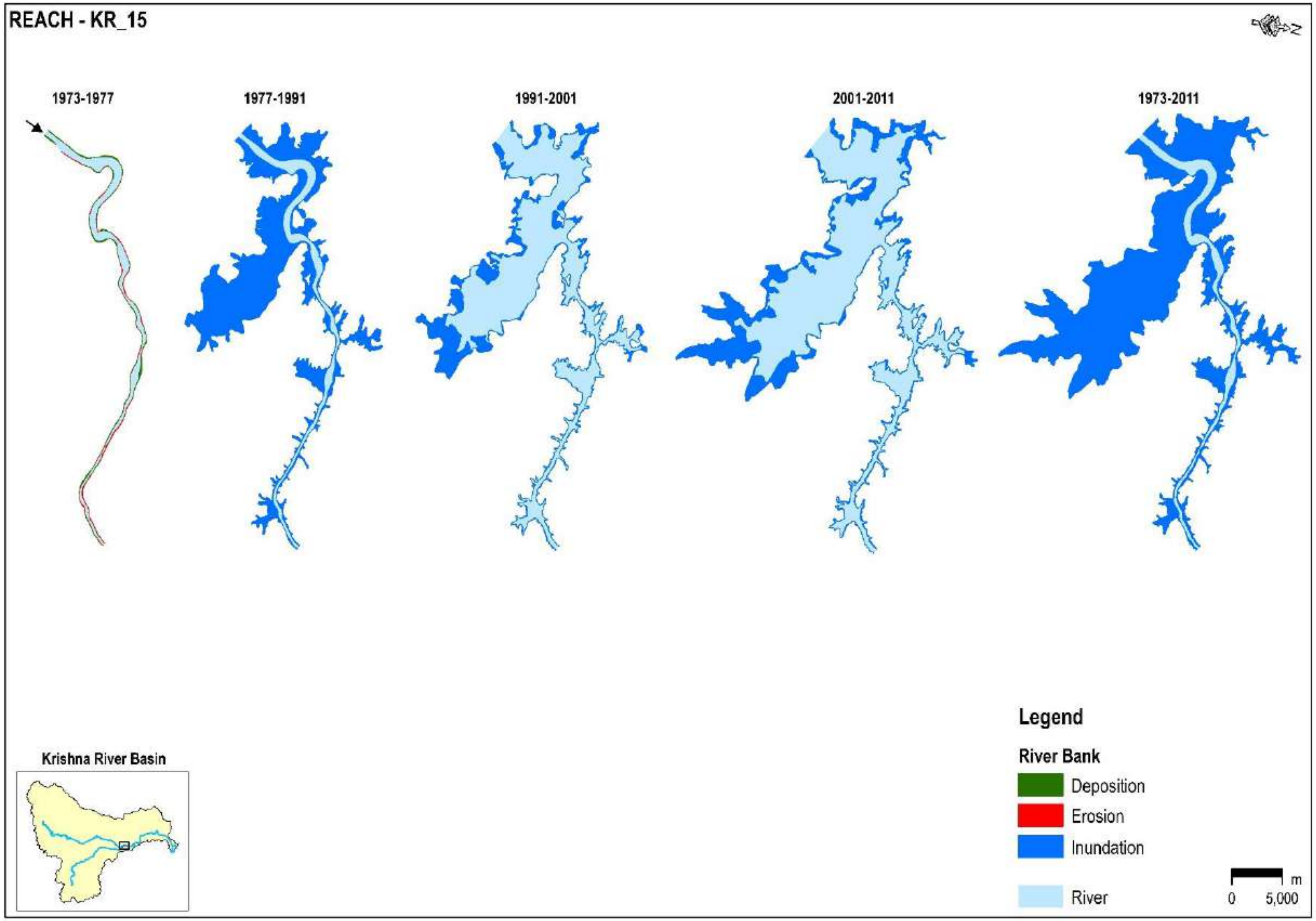

REACH - KR_11
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin


REACH - KR_12
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0 2,550 5,100
Krishna River Basin

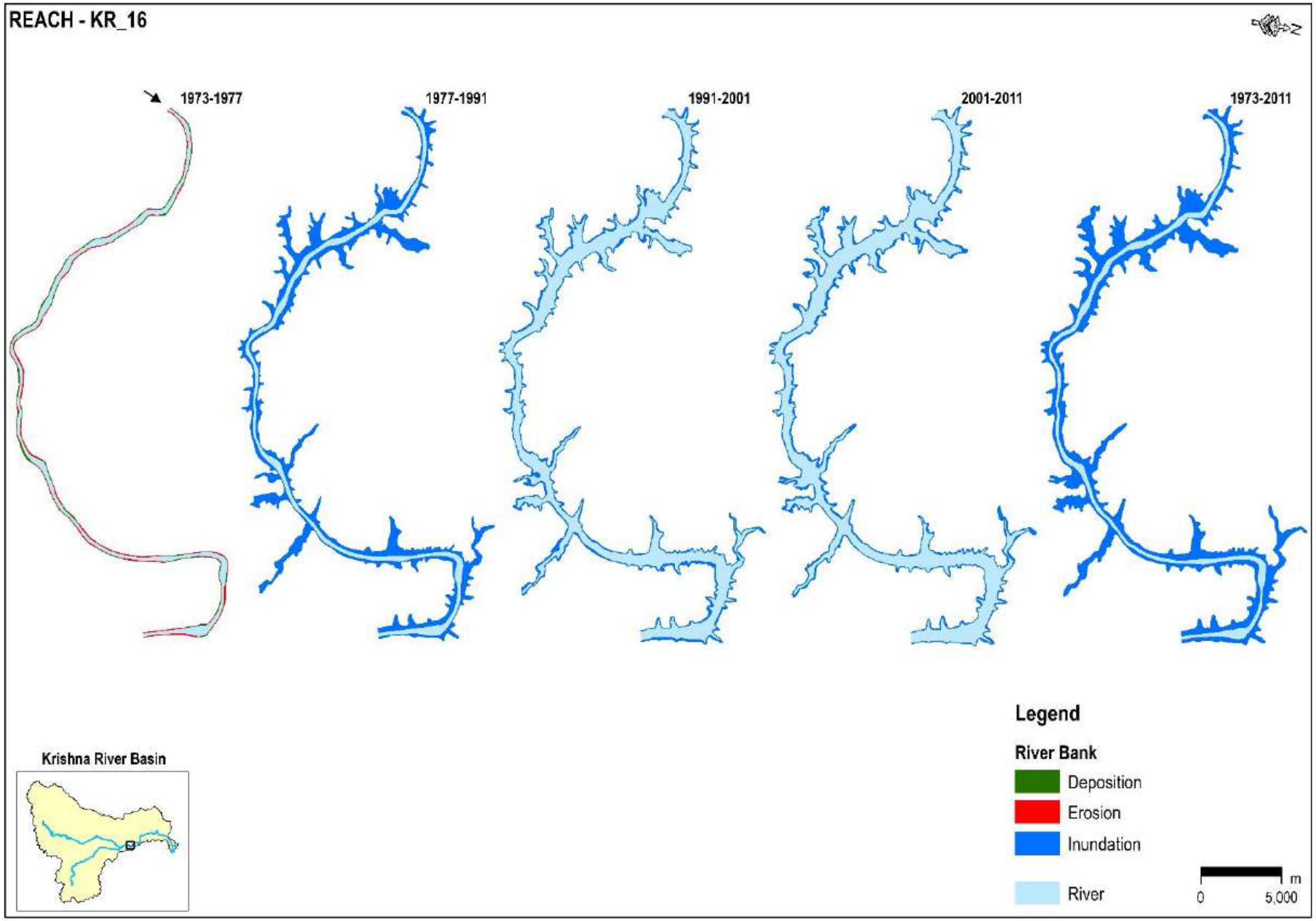


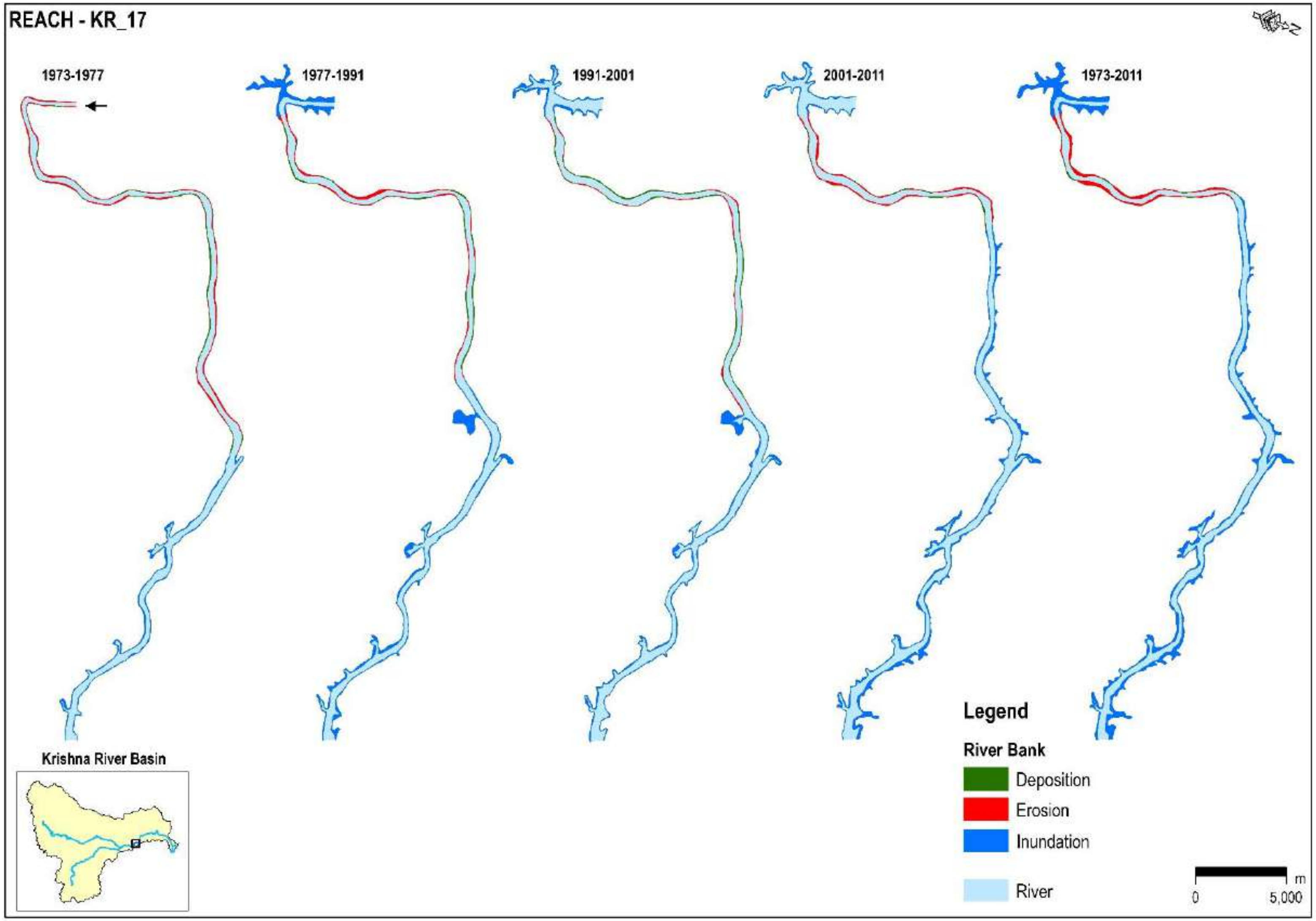
REACH - KR_13
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0 2,500 5,000
Krishna River Basin

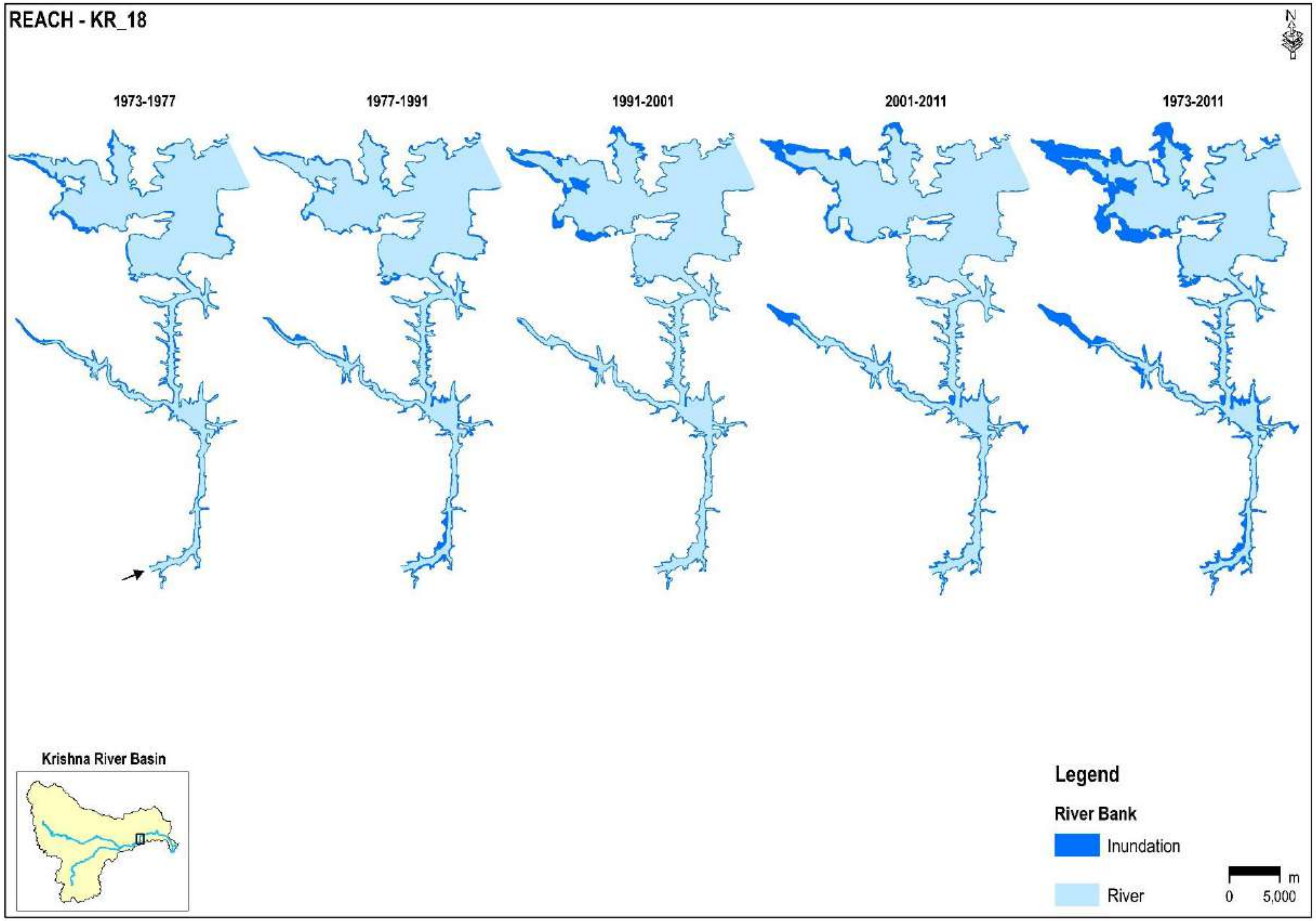

REACH - KR_14
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0 2,550 5,100
Krishna River Basin



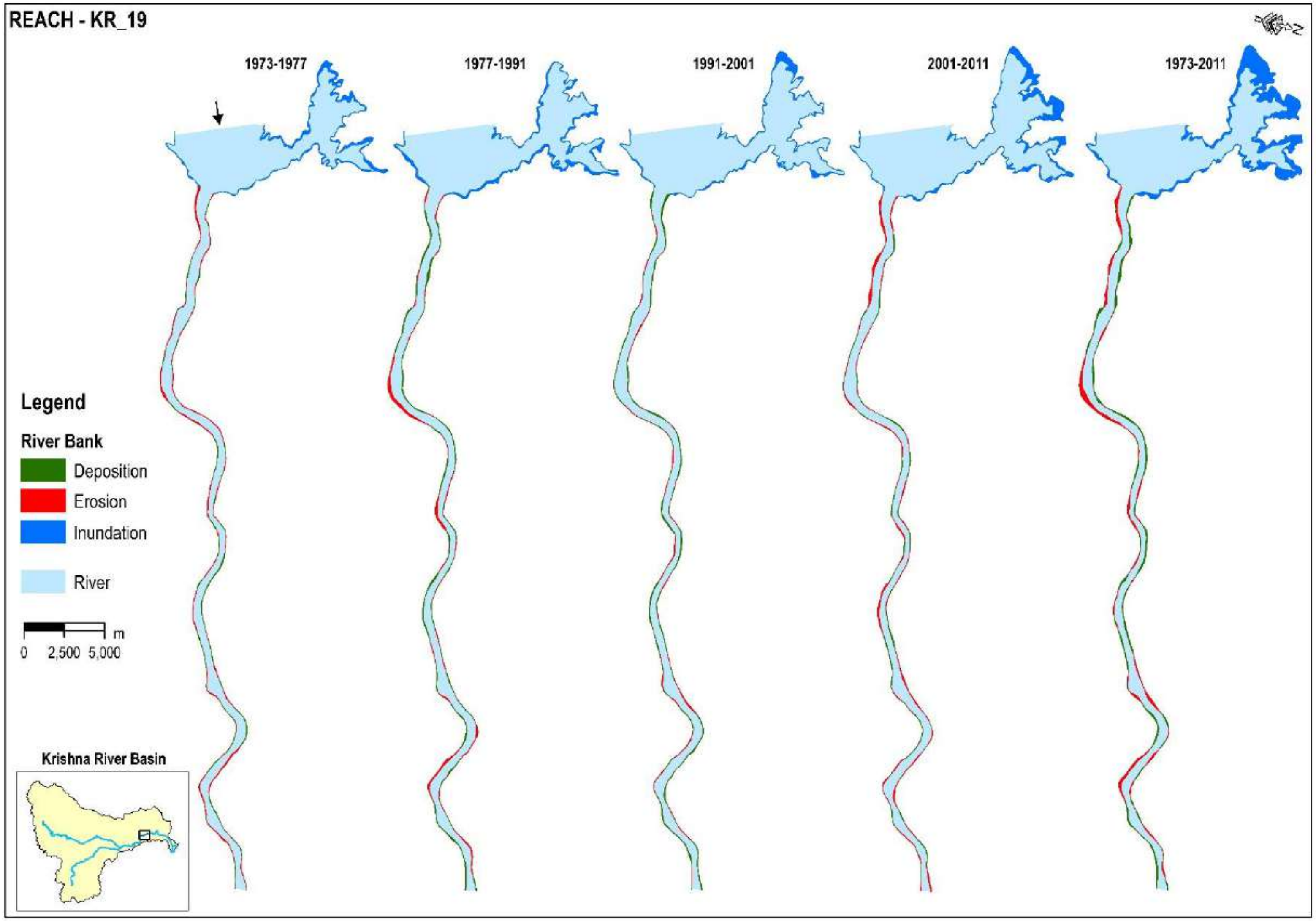
REACH - KR_15
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0
5,000

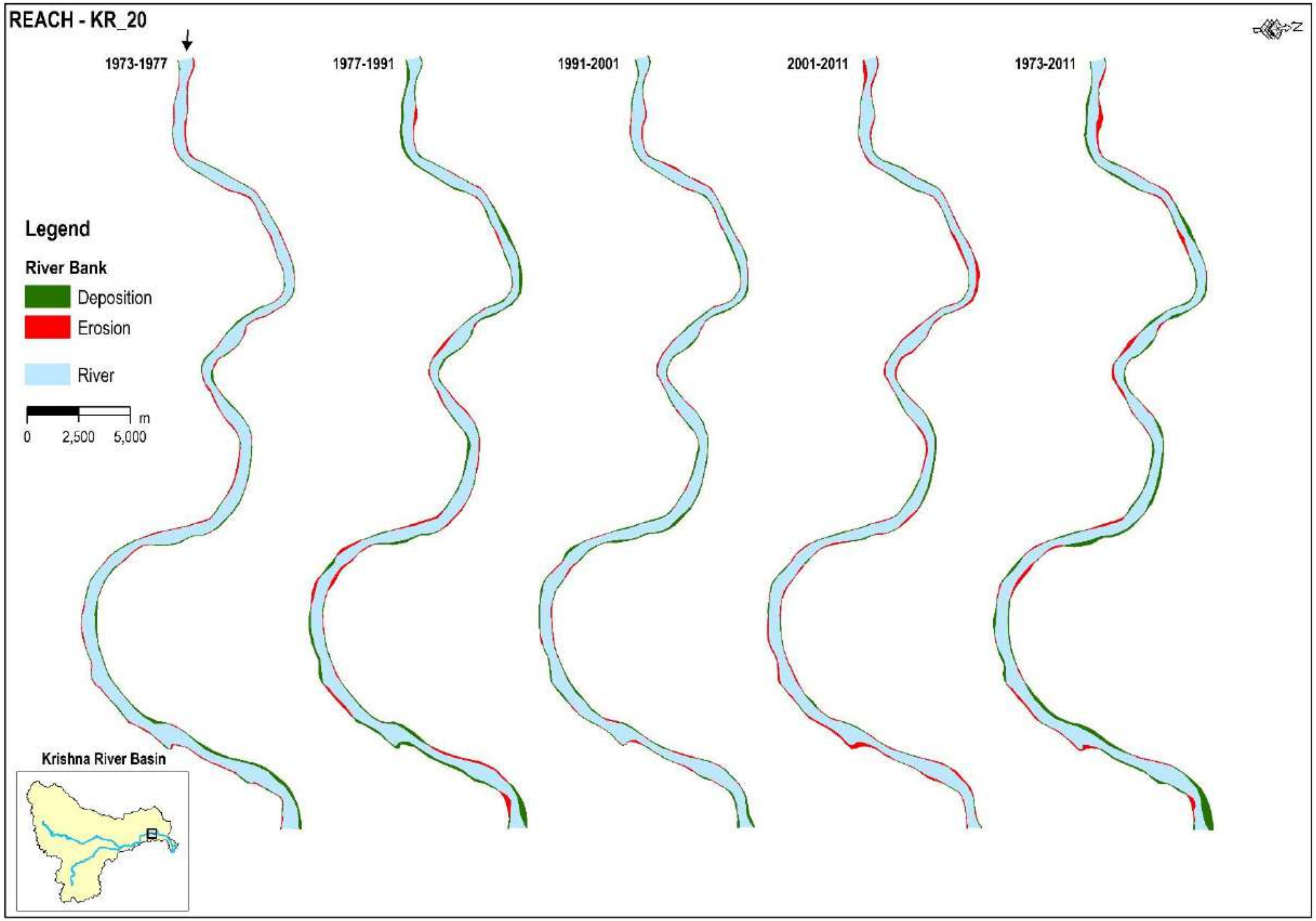

REACH - KR_16
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0
5,000


REACH - KR_17
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0
5,000

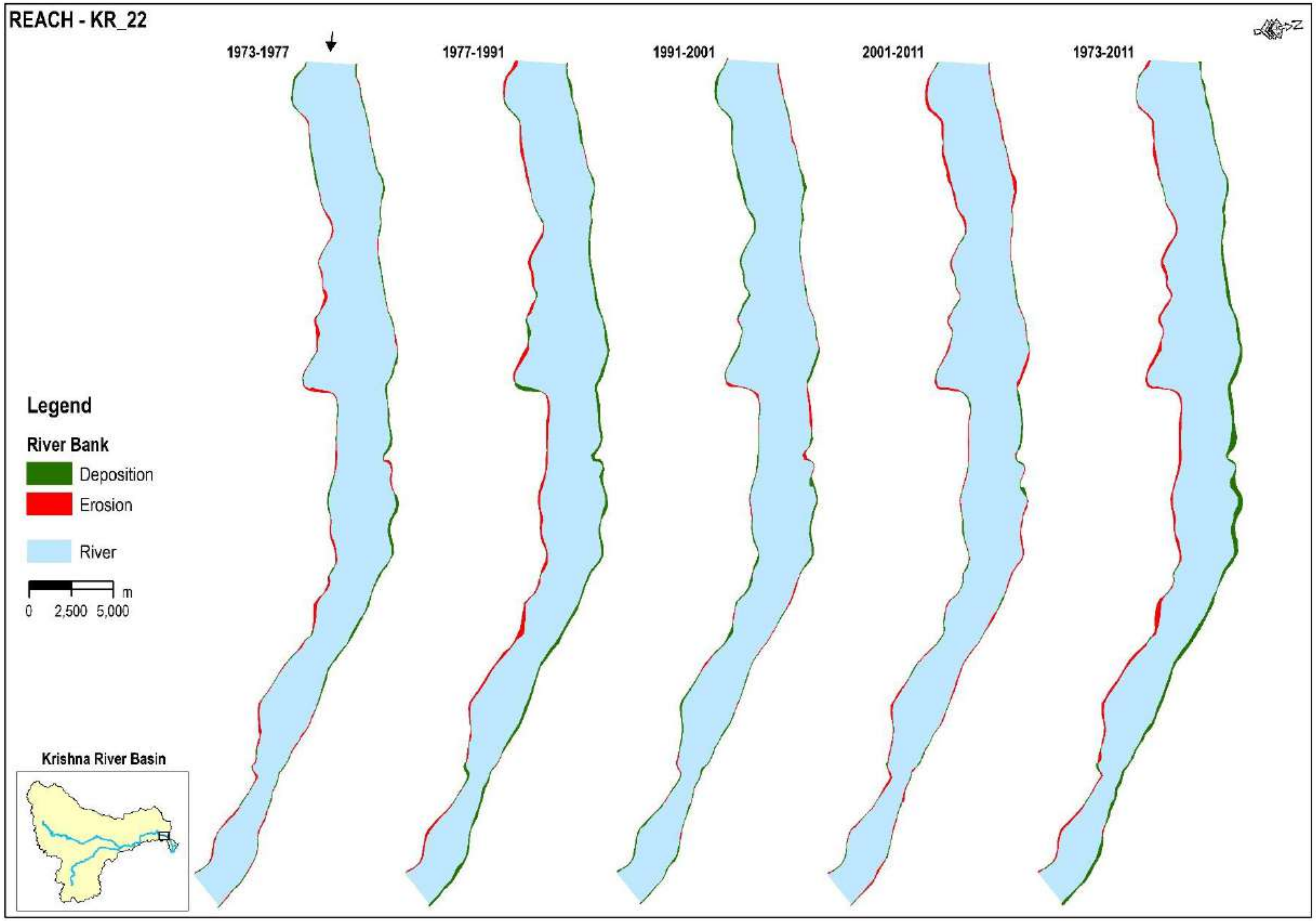


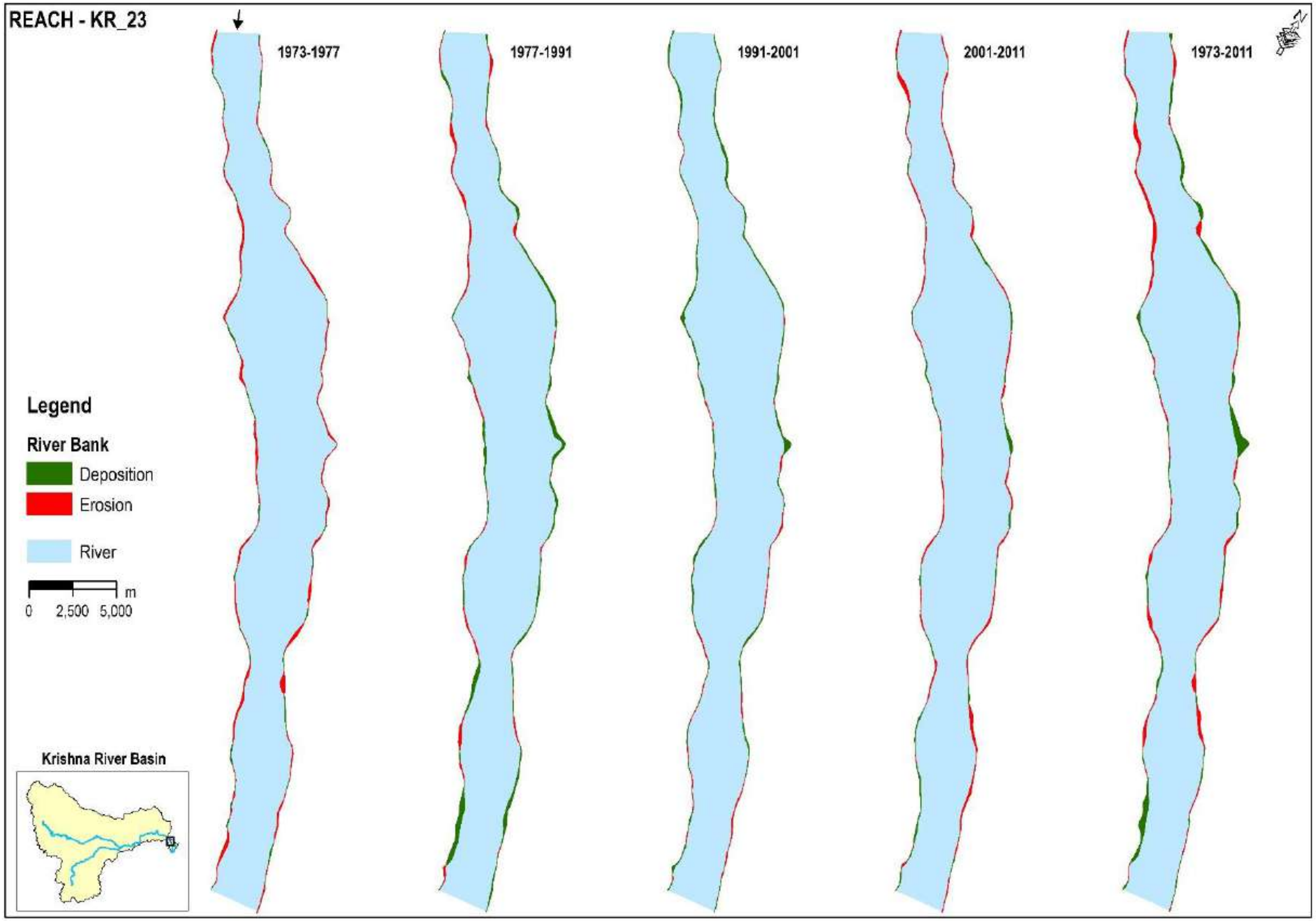
REACH - KR_18
N
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Inundation
River
m
0
5,000

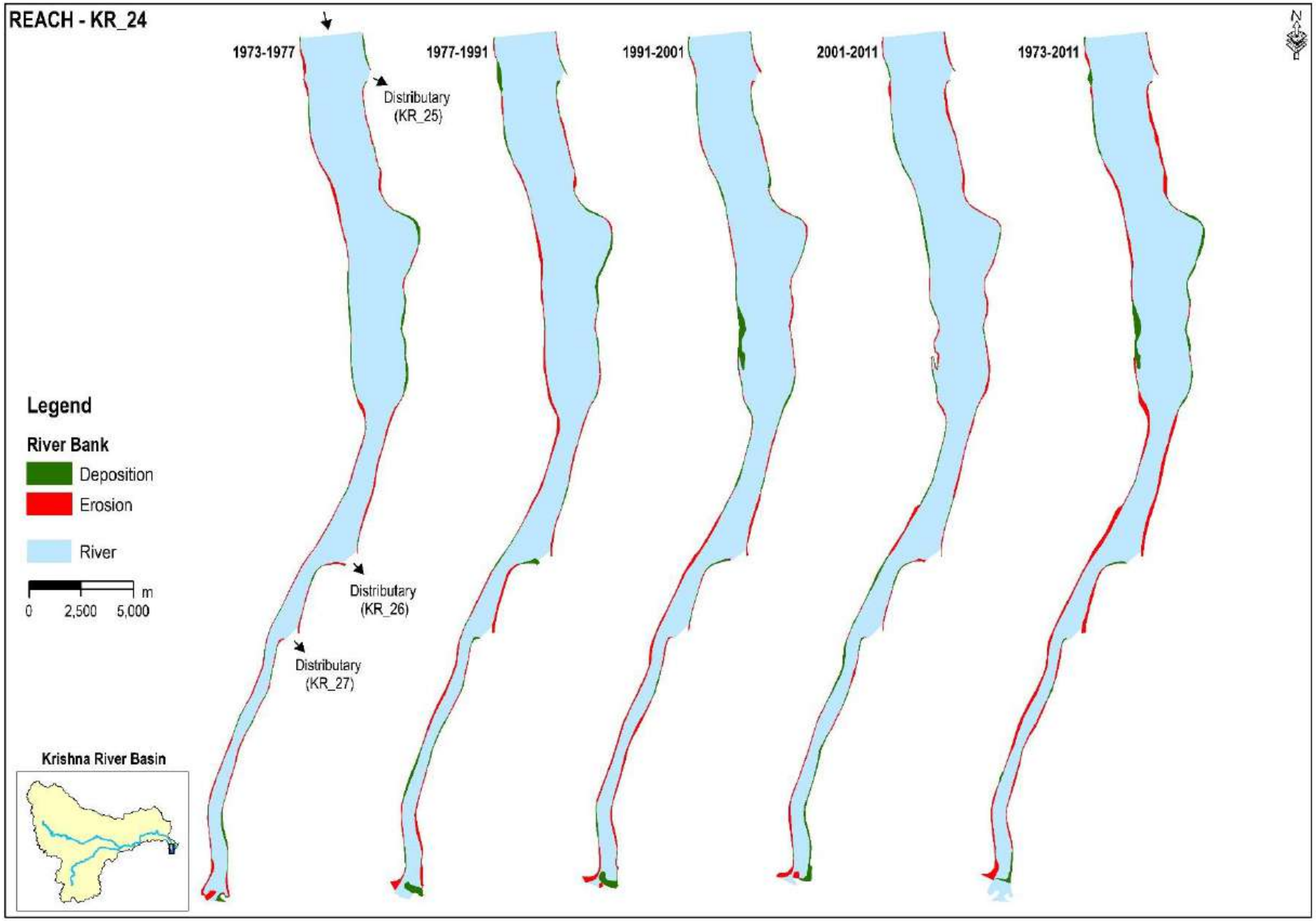

REACH - KR_19
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0 2,500 5,000
Krishna River Basin

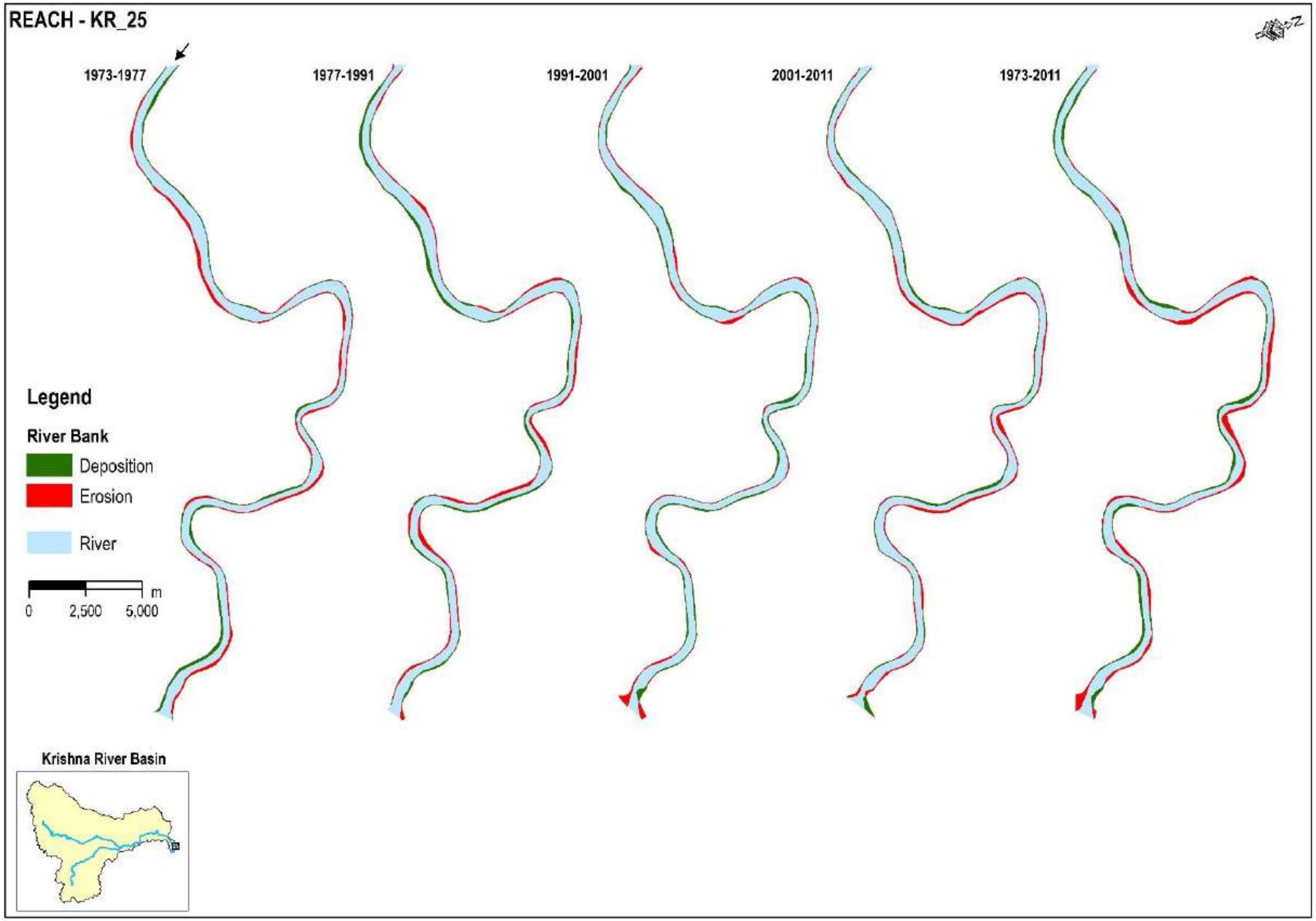

REACH - KR_20
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin
N

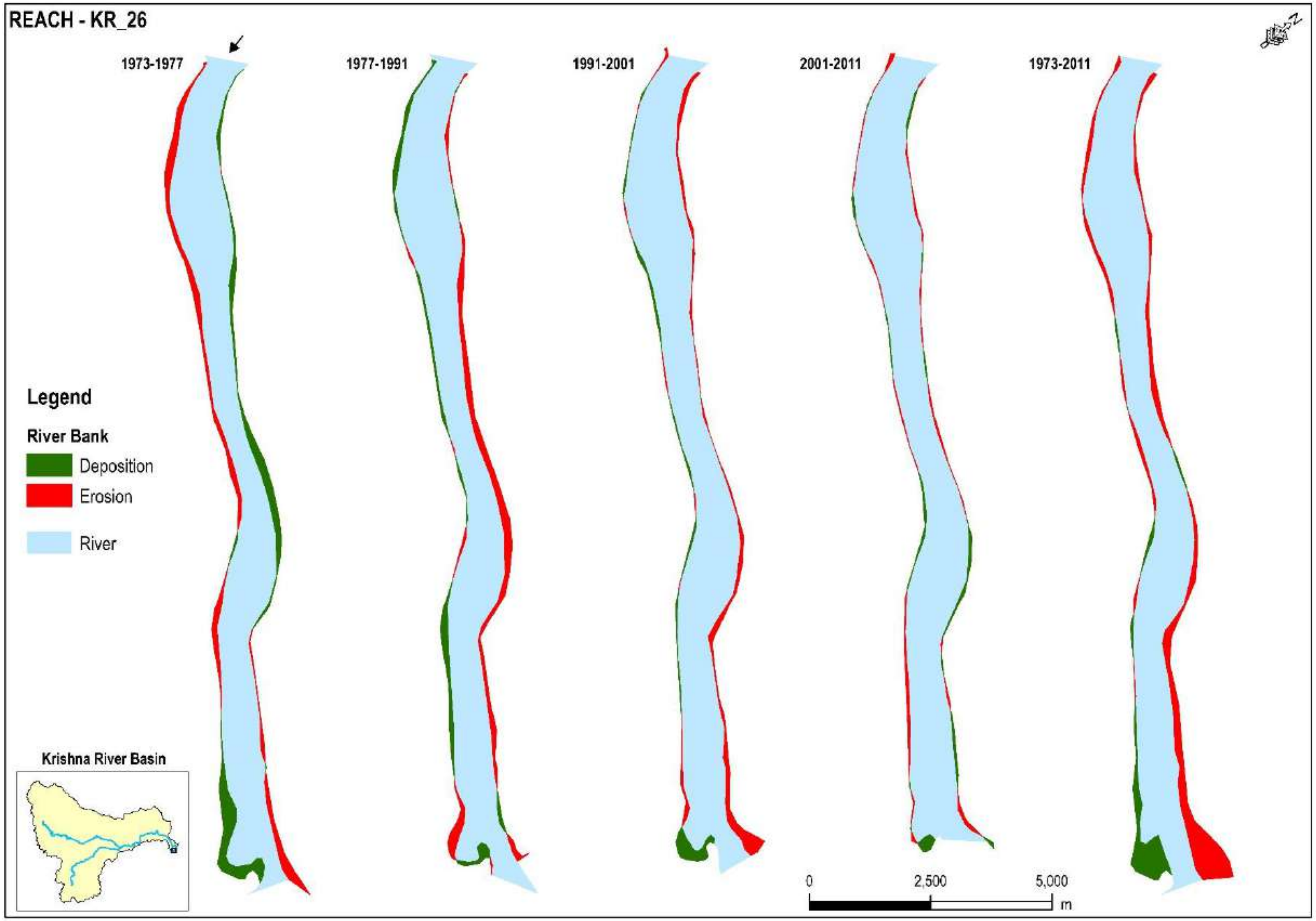

REACH - KR_21
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
River
m
0
5,000

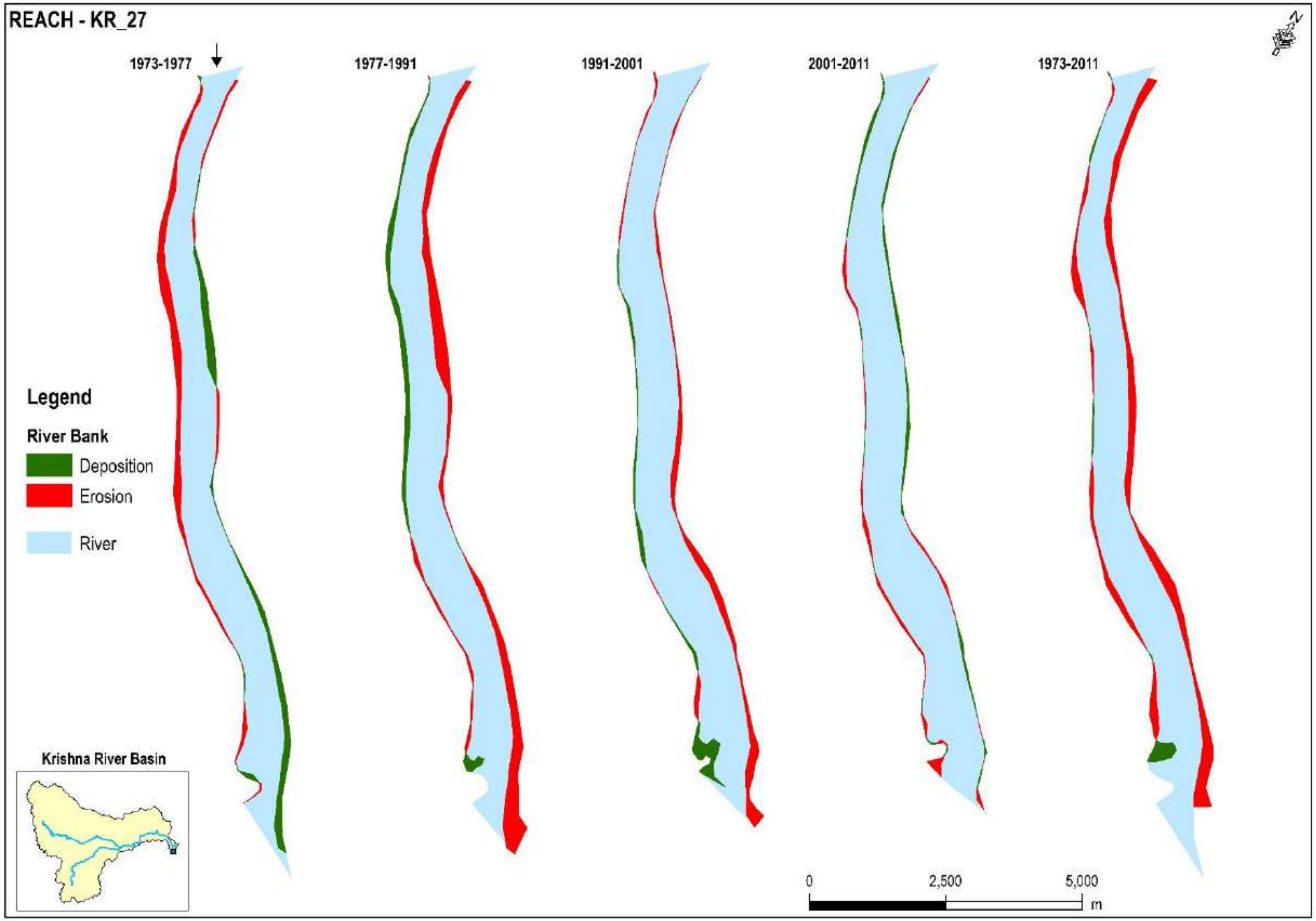

REACH - KR_22
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
N
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin

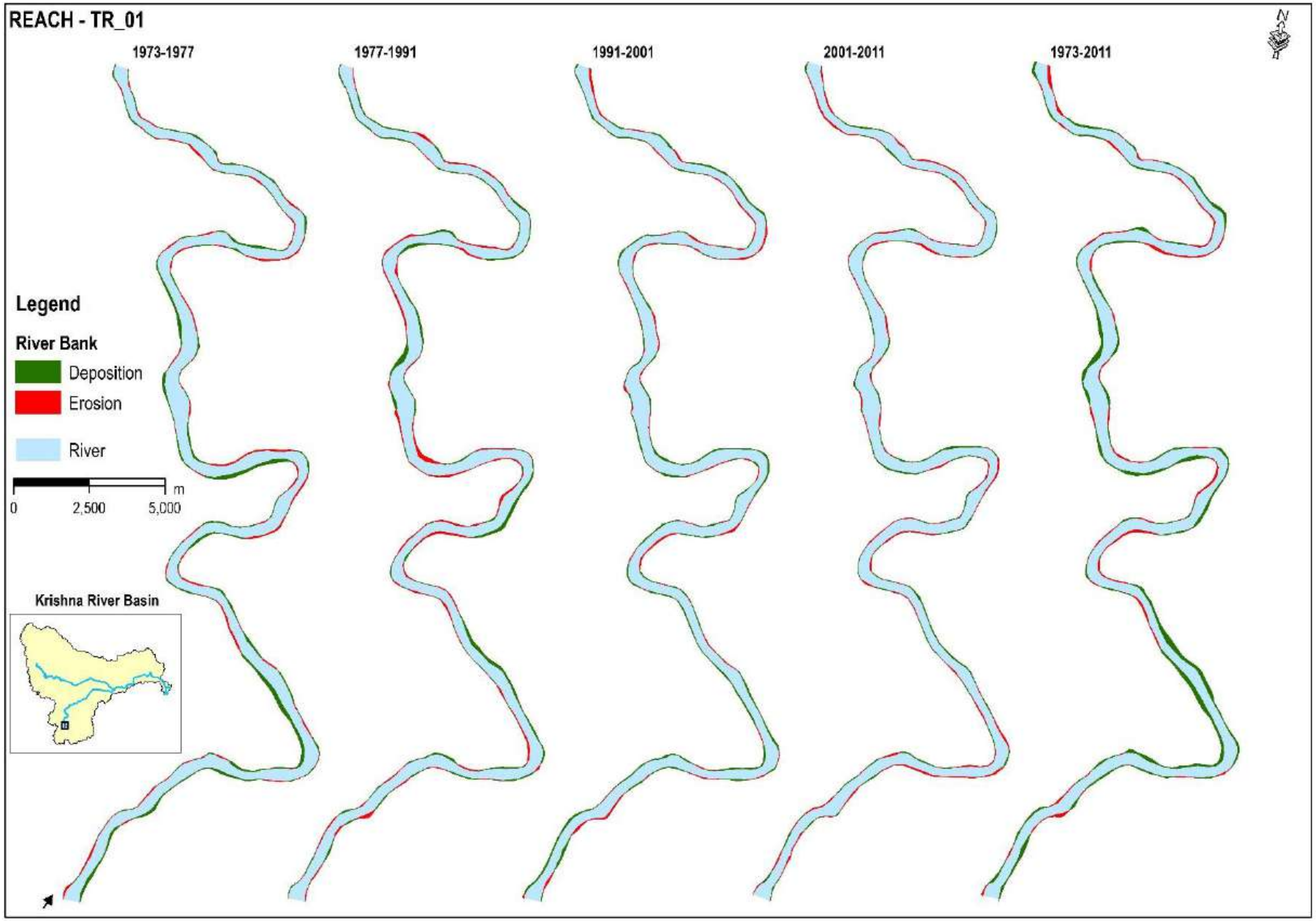

REACH - KR_23
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
0 2,500 5,000
m
Krishna River Basin

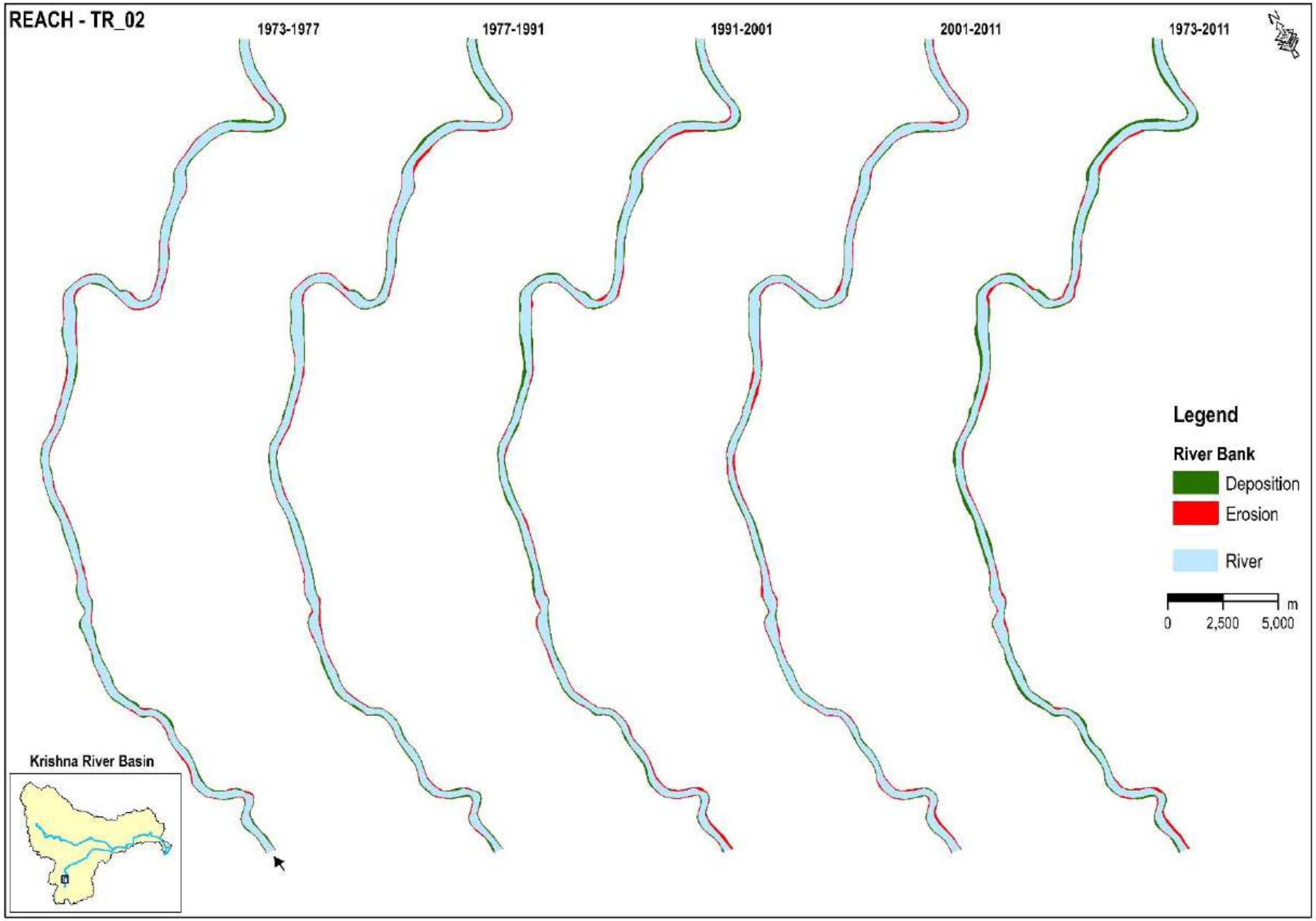

REACH - KR_24
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Distributary (KR_25)
Distributary (KR_26)
Distributary (KR_27)
Legend
River Bank
Deposition
Erosion
River
m
0 2,500 5,000
Krishna River Basin
N

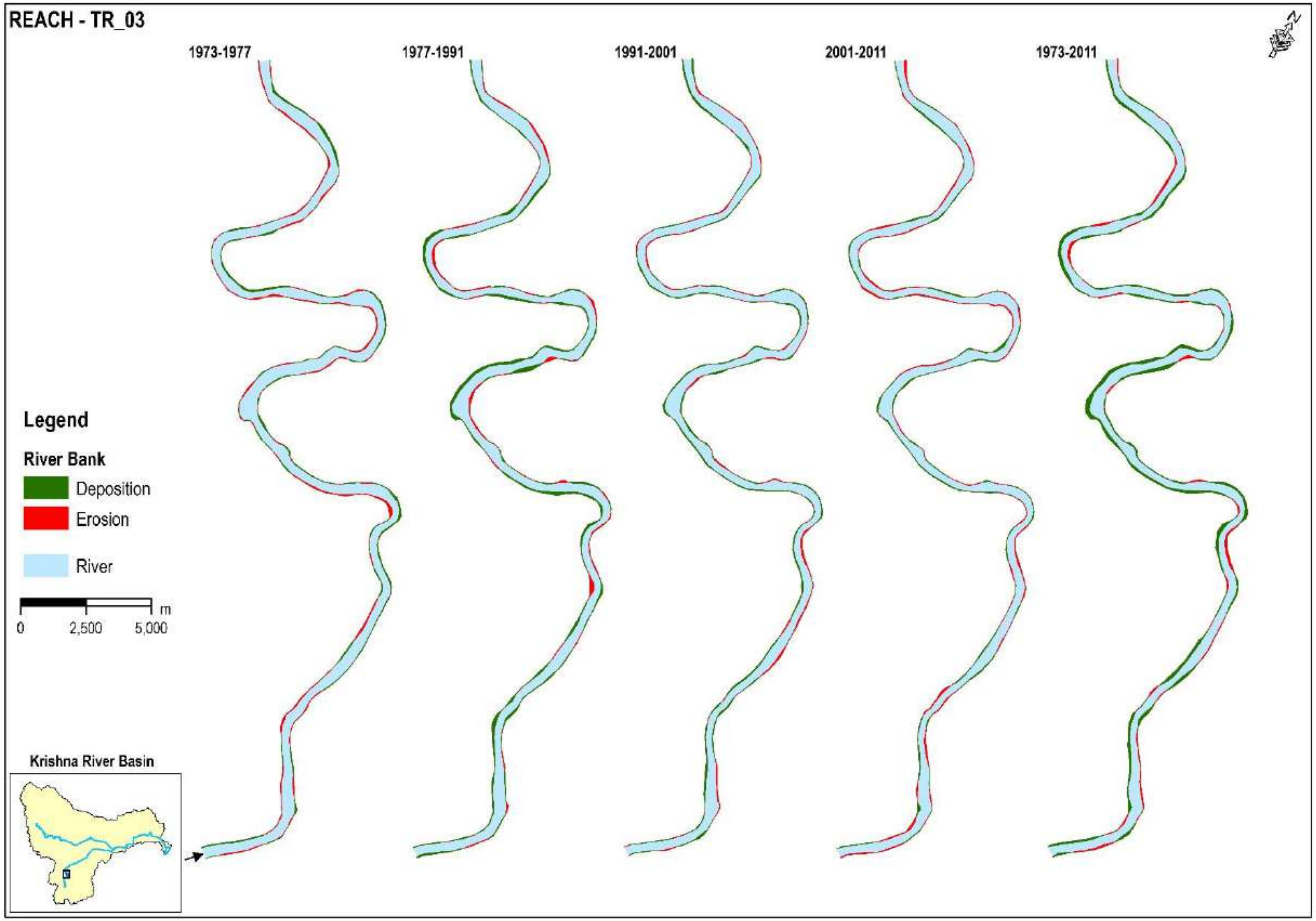

REACH - KR_25
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin

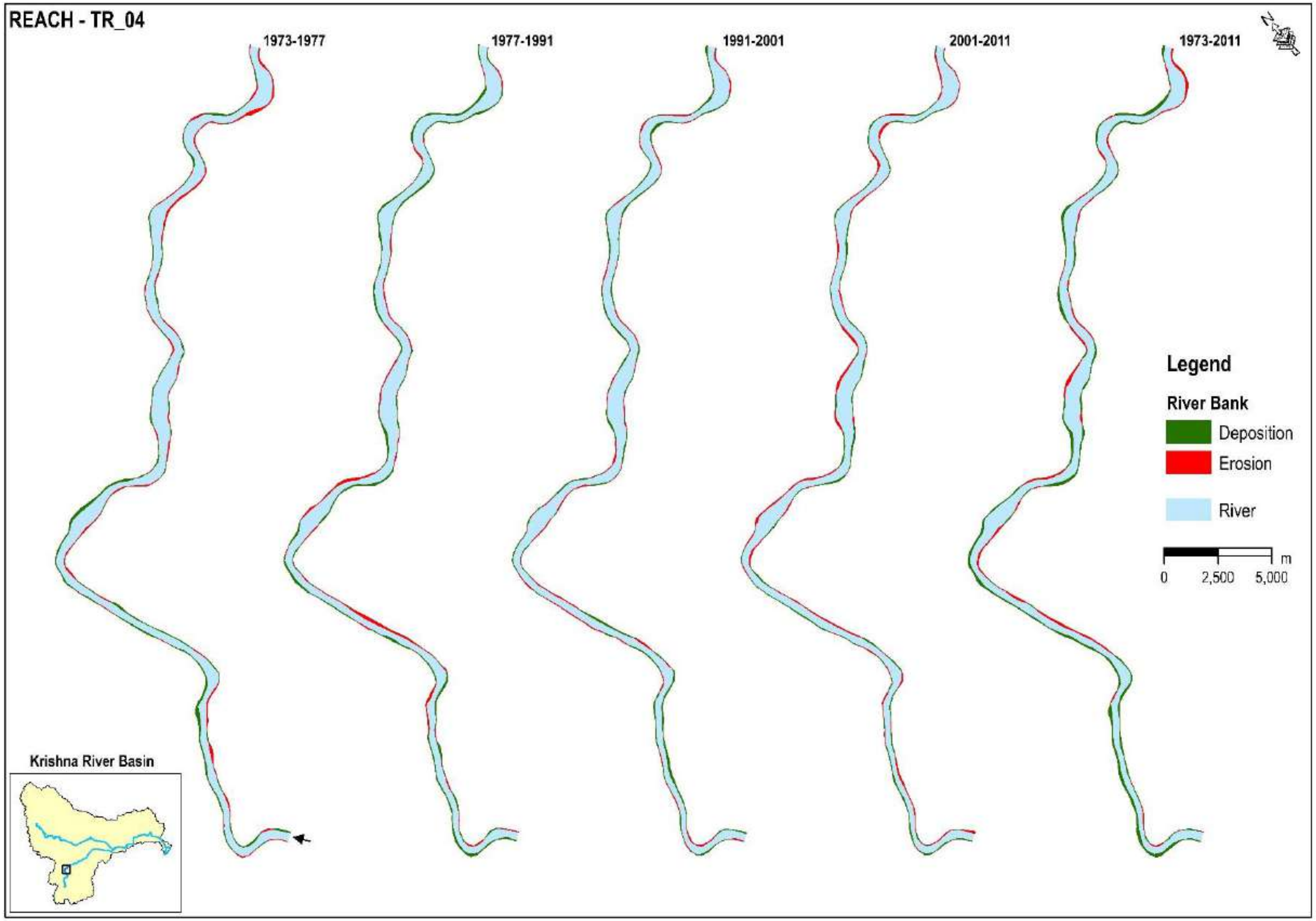

REACH - KR_26
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
Krishna River Basin
0
2,500
5,000
m

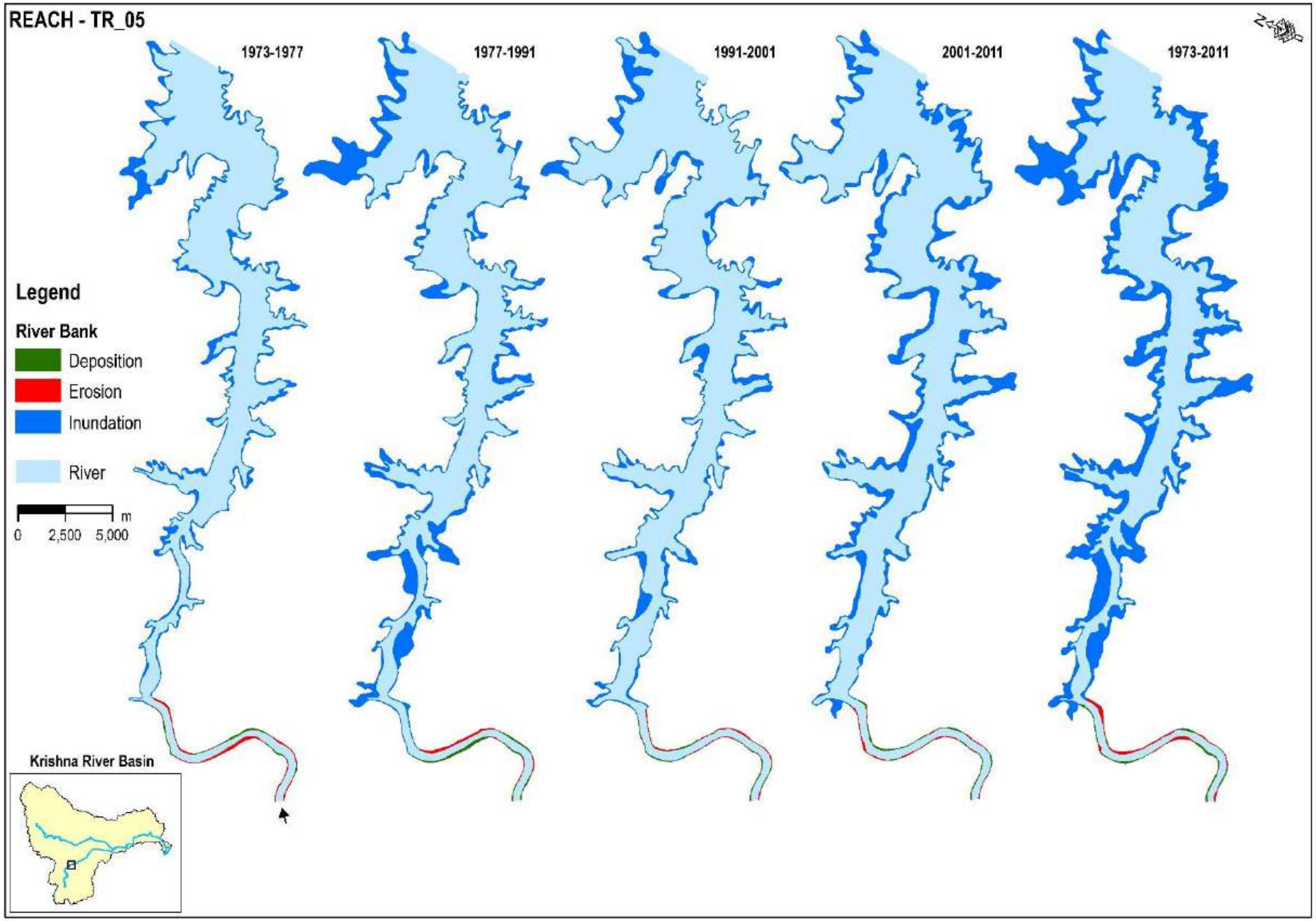

REACH - KR_27
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
Krishna River Basin
0
2,500
5,000
m

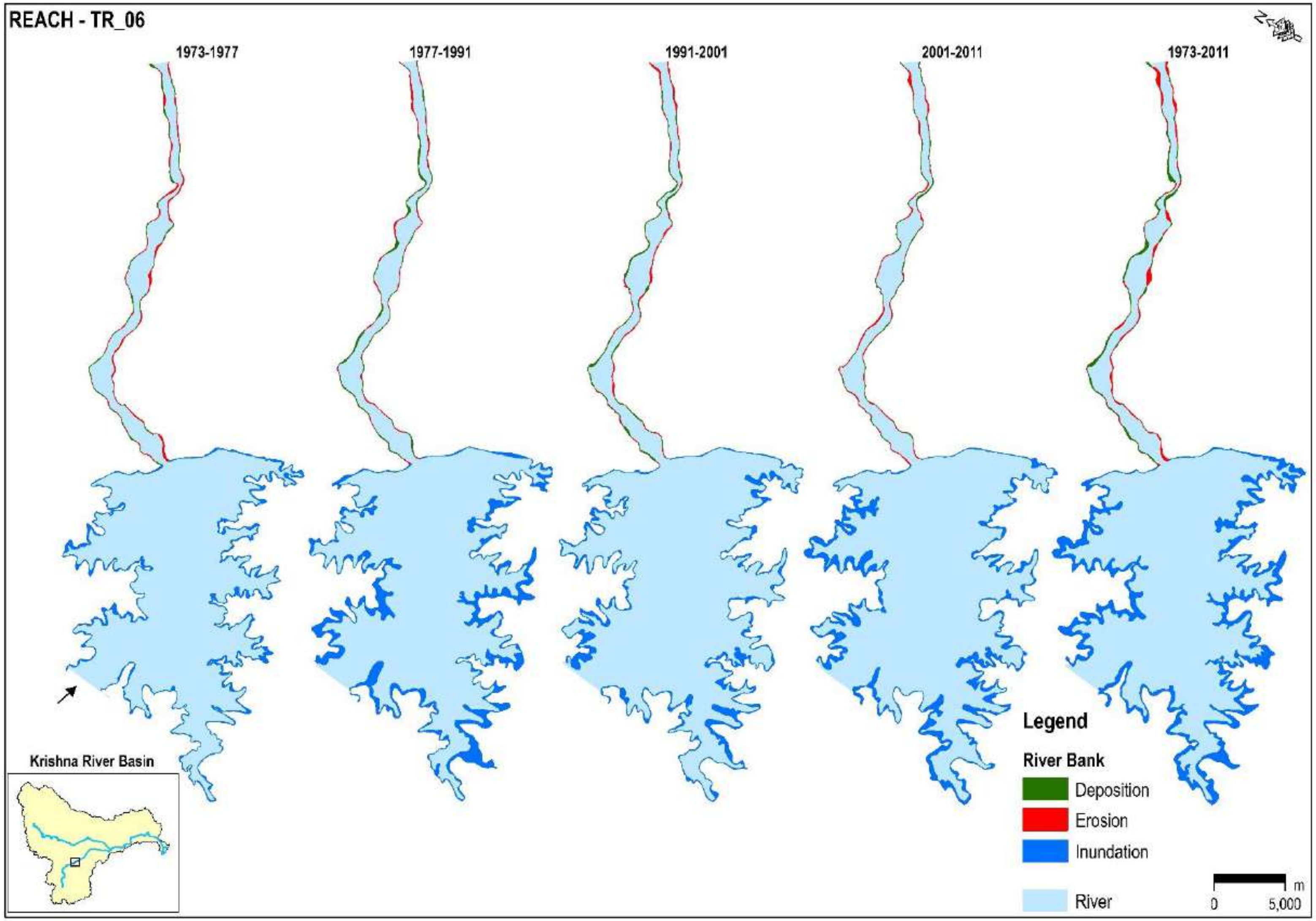

REACH - TR_01
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
0
2,500
5,000
m
Krishna River Basin


REACH - TR_02
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin

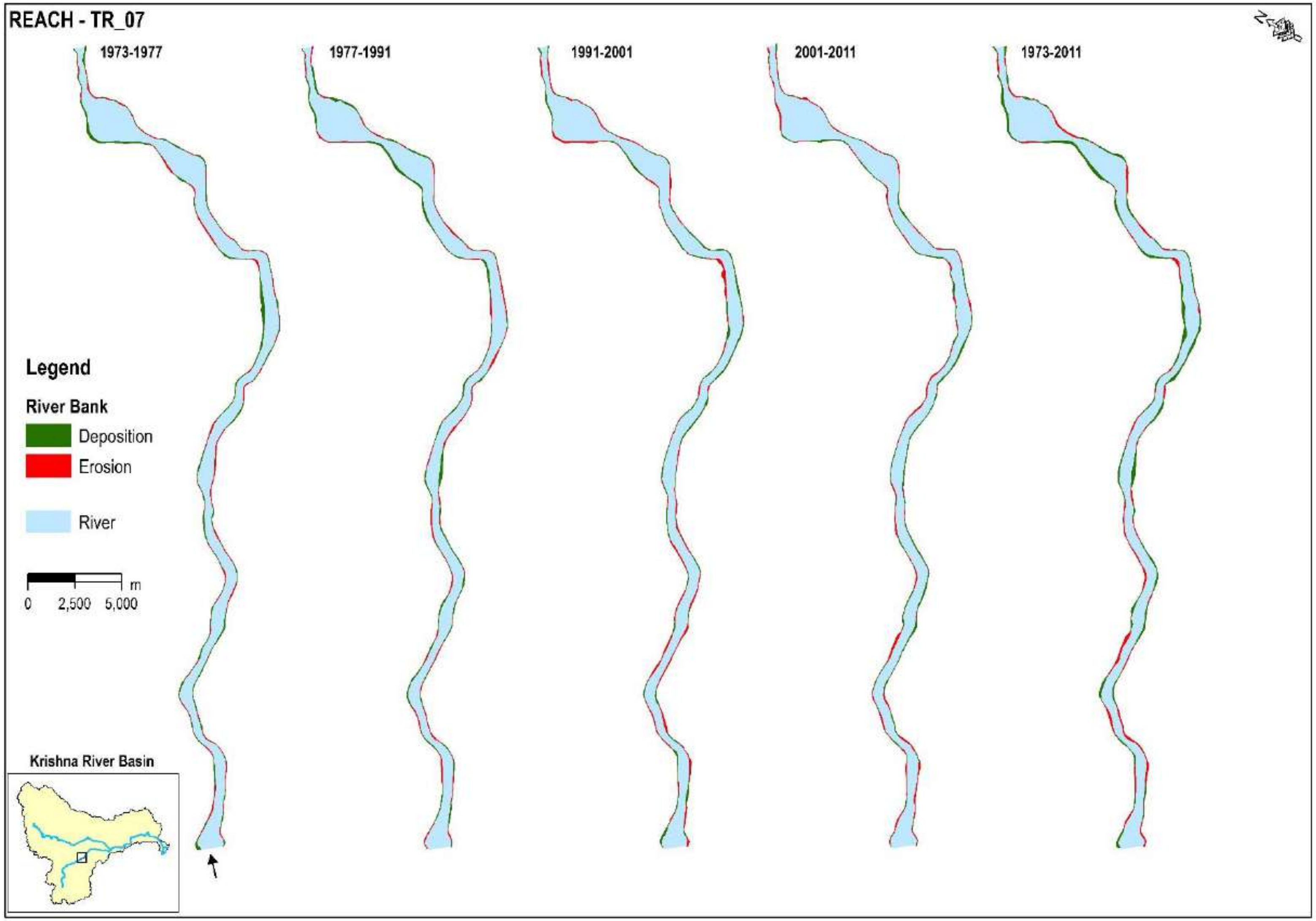

REACH - TR_03
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
N
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin

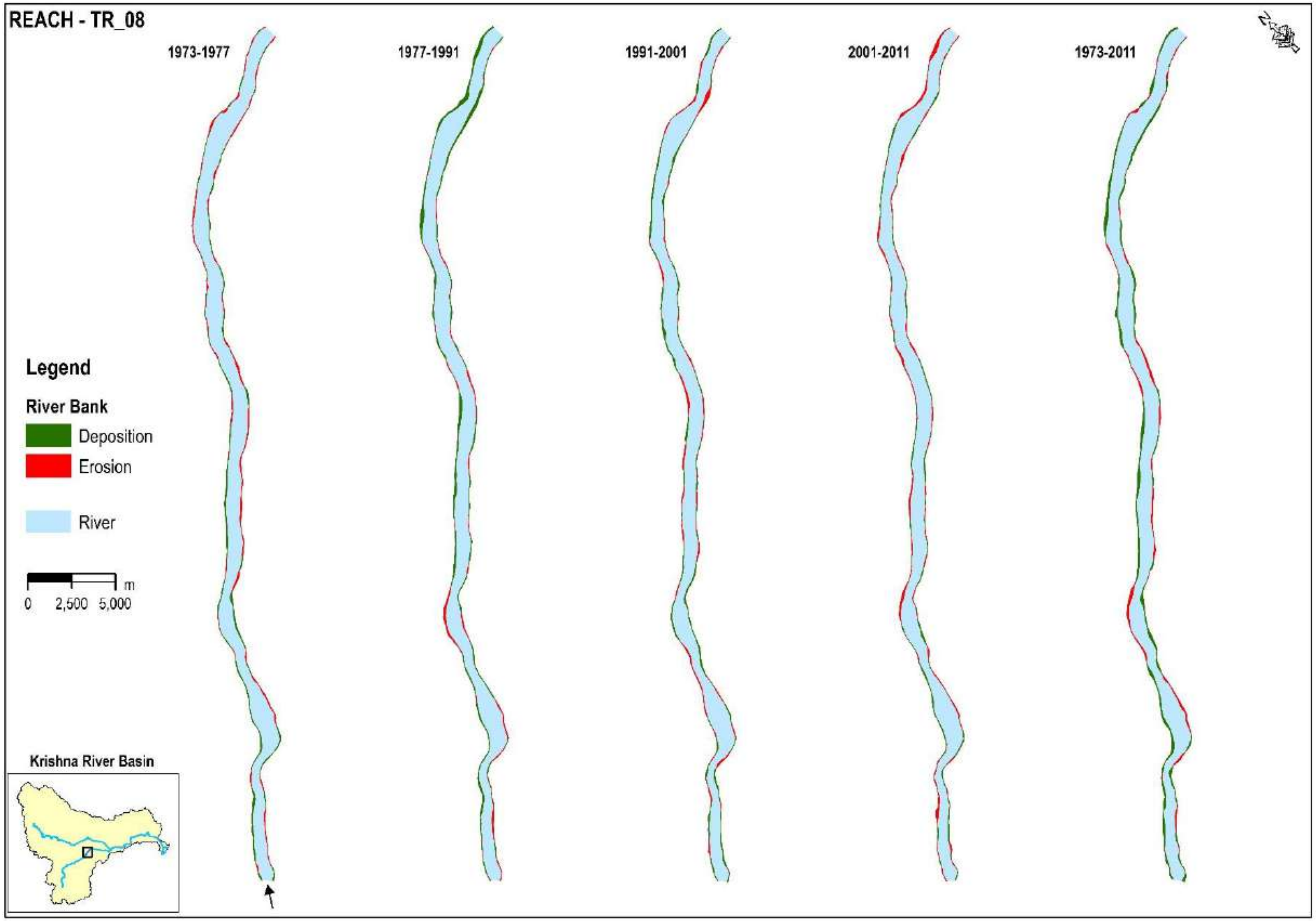

REACH - TR_04
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin

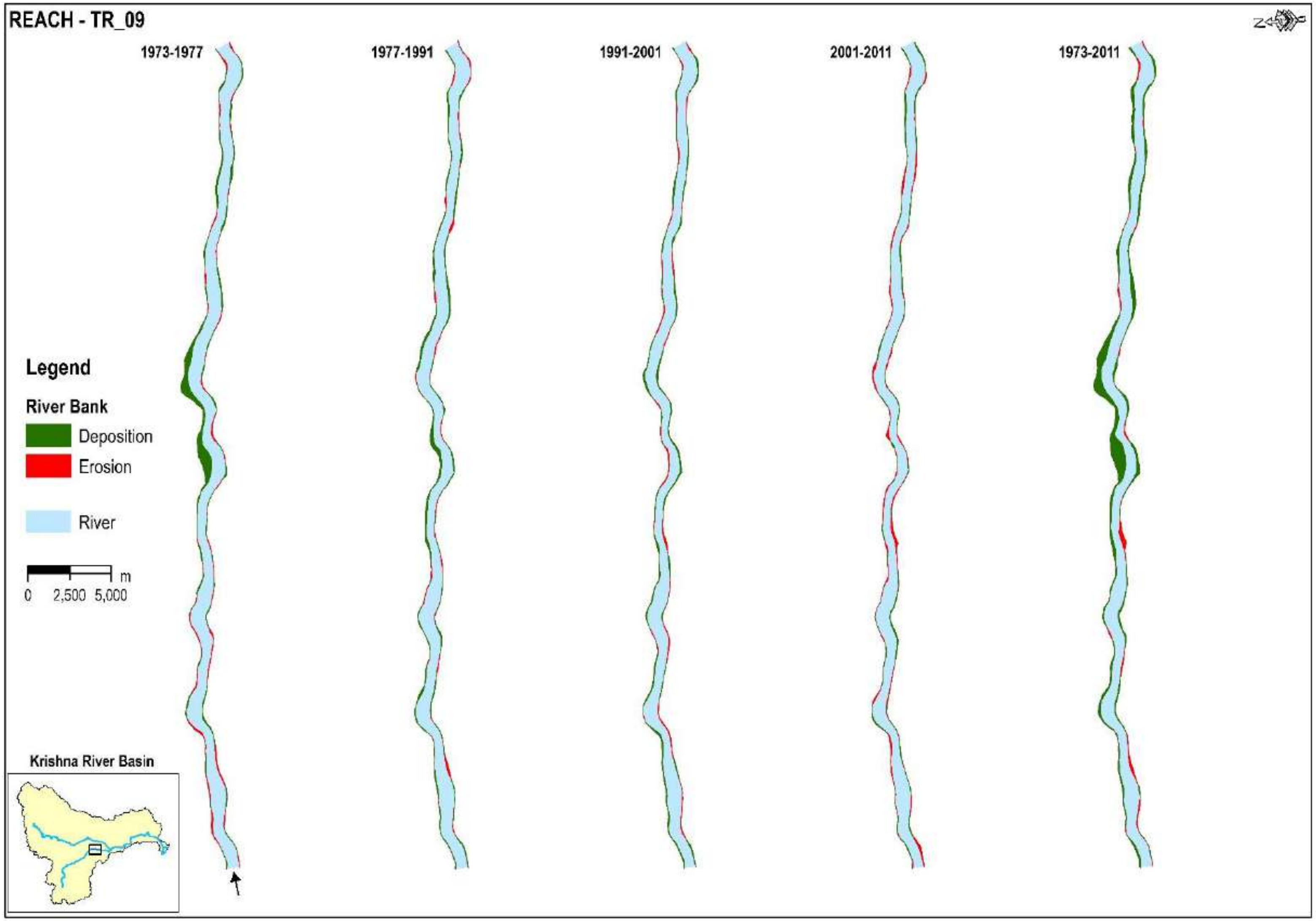

REACH - TR_05
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0
2,500
5,000
Krishna River Basin



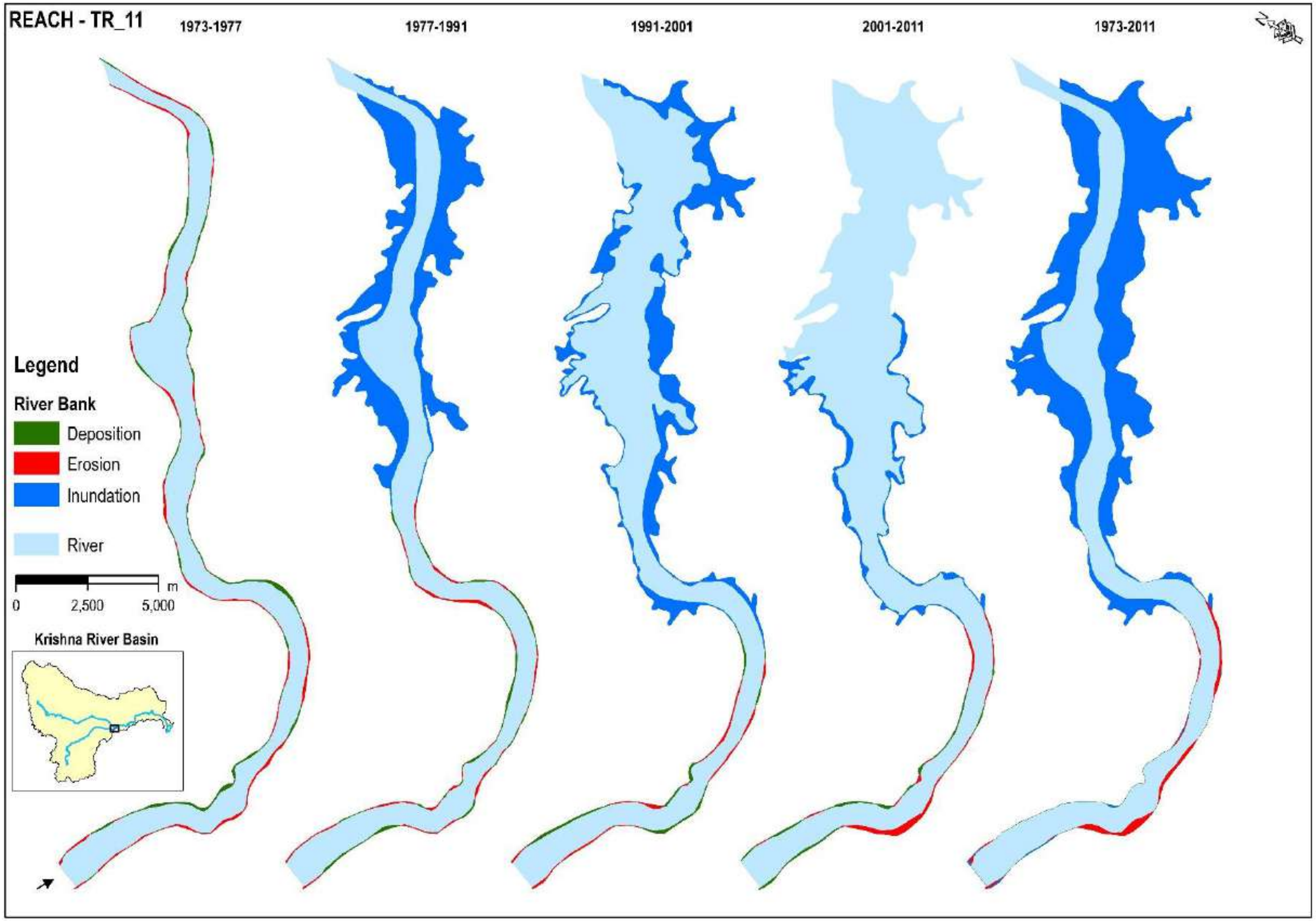
REACH - TR_06
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Krishna River Basin
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0
5,000


REACH - TR_07
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin

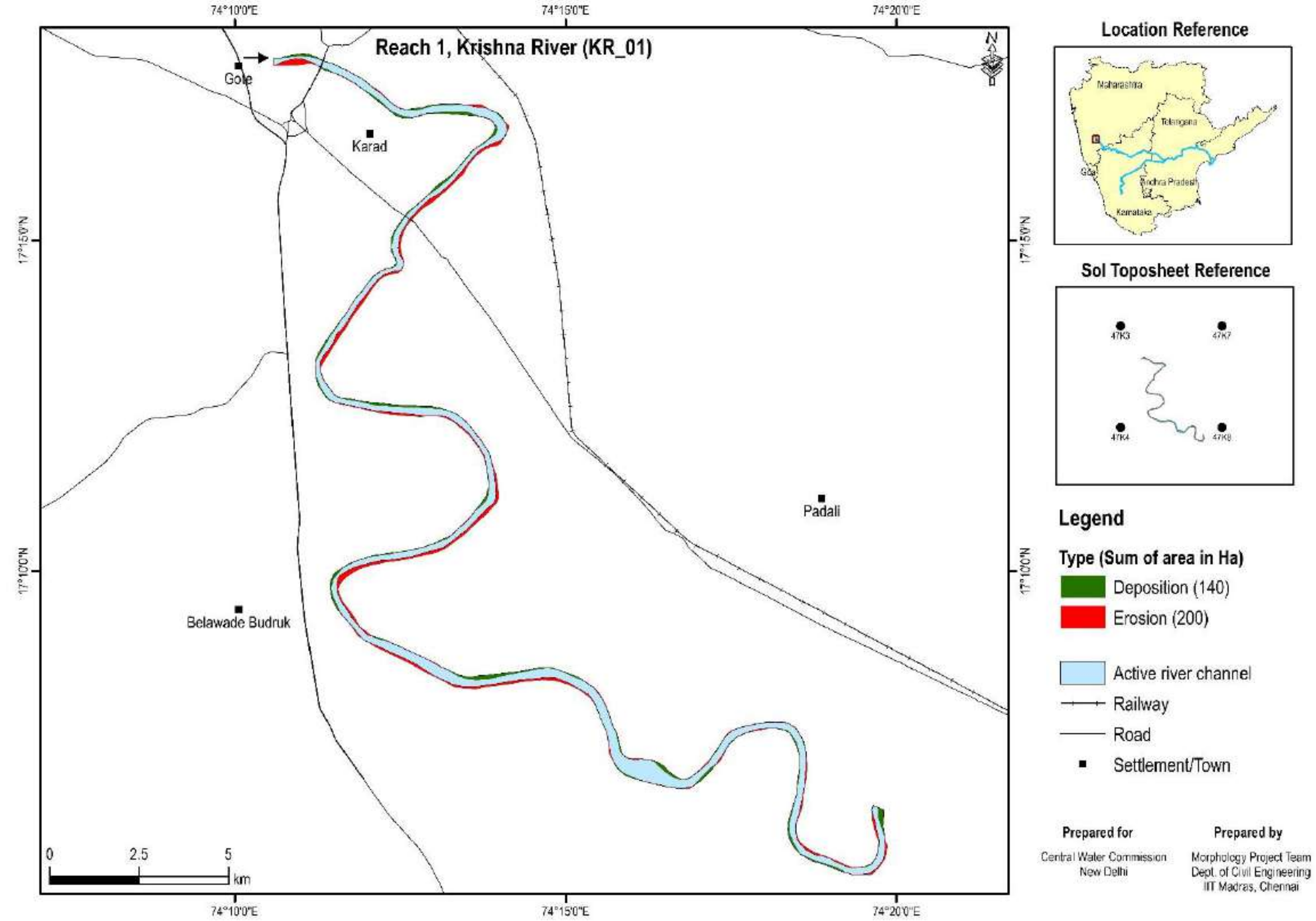

REACH - TR_08
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
0
2,500
5,000
m
Krishna River Basin

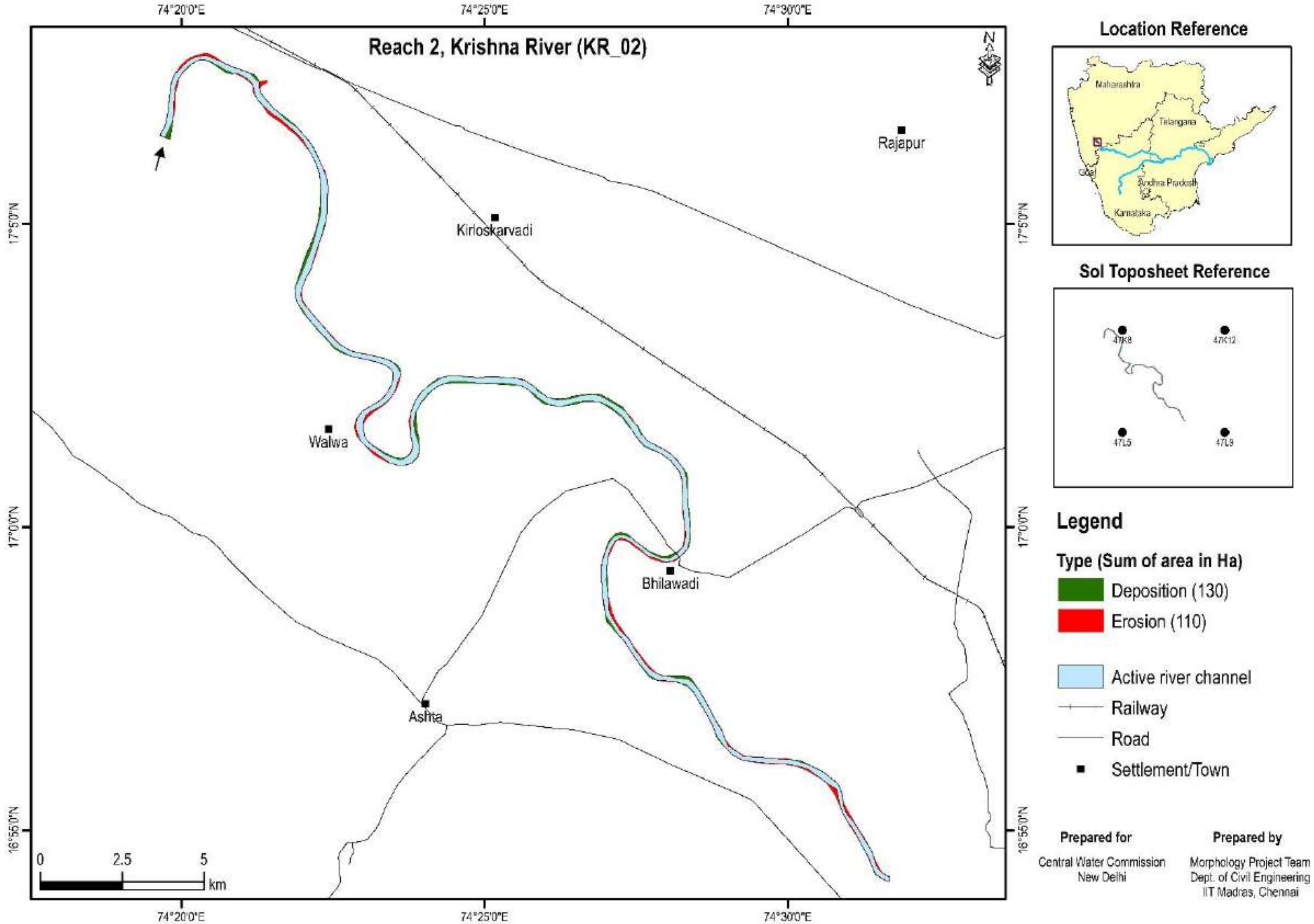

REACH - TR_09
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0 2,500 5,000
Krishna River Basin

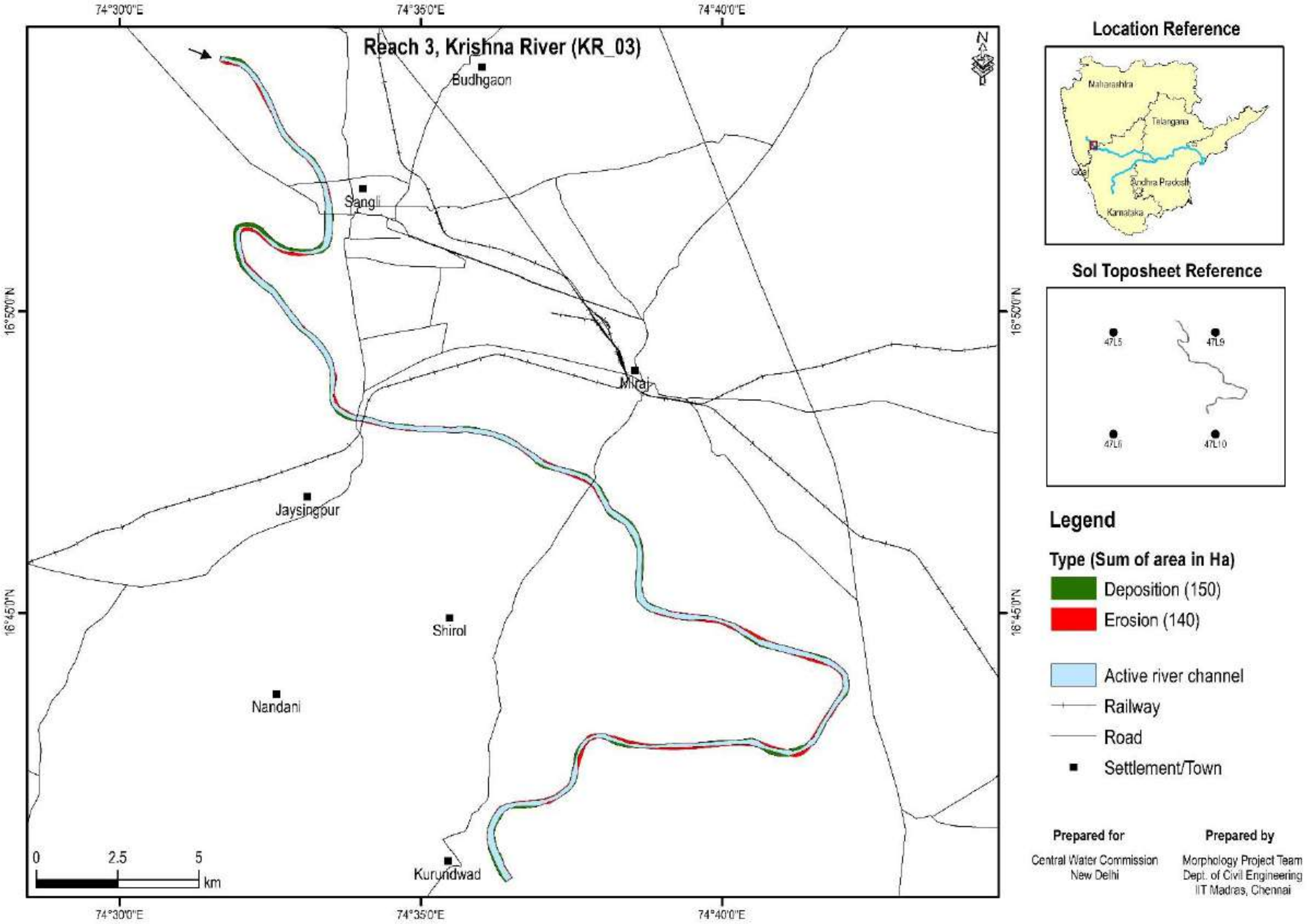

REACH - TR_10
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
River
m
0
2,500
5,000
Krishna River Basin


REACH - TR_11
1973-1977
1977-1991
1991-2001
2001-2011
1973-2011
Legend
River Bank
Deposition
Erosion
Inundation
River
m
0
2,500
5,000
Krishna River Basin

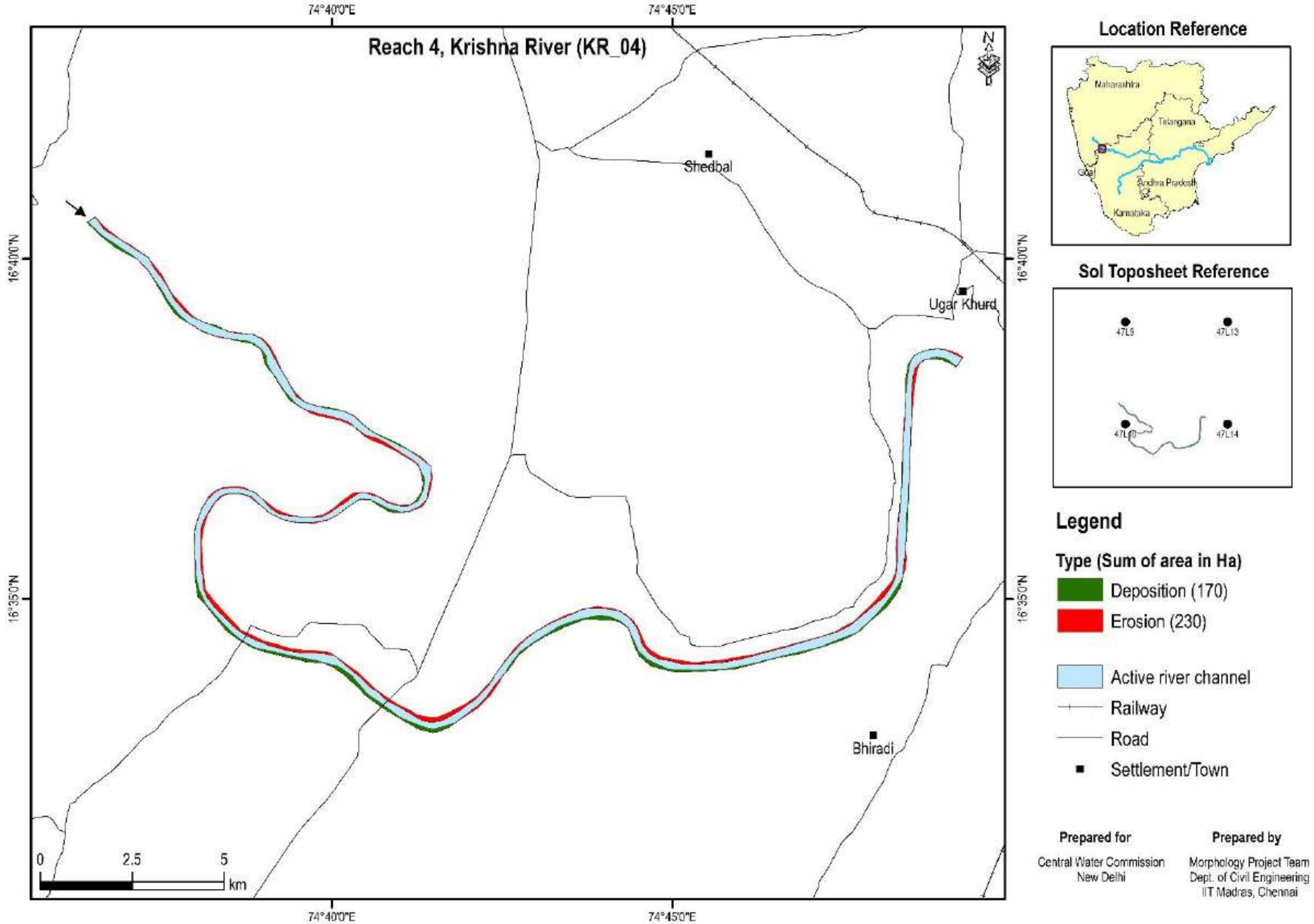
Appendix XV: Erosion and deposition map of various reaches of Krishna and Tungabhadra rivers for 1973-2011

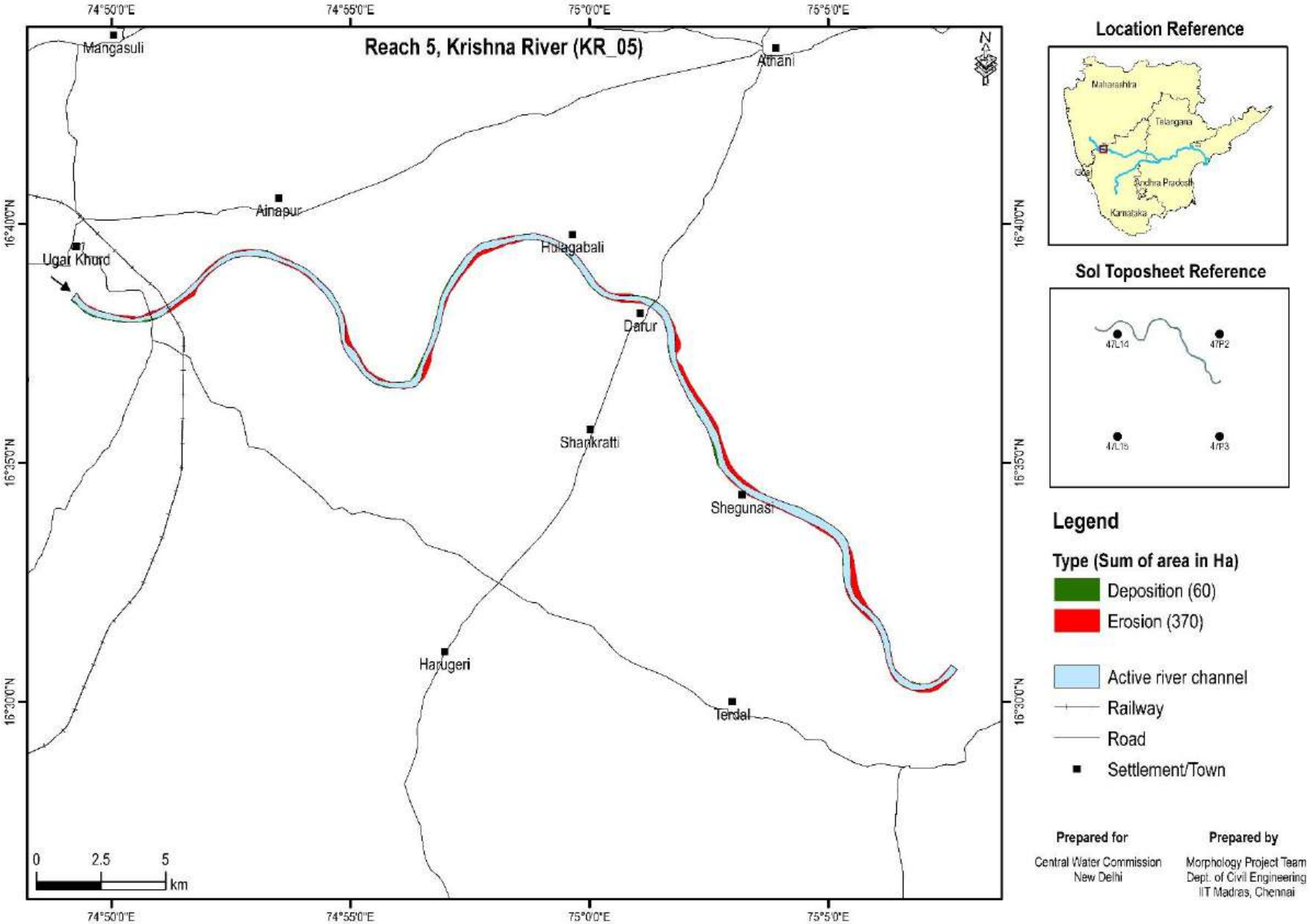



Reach 2, Krishna River (KR_02)
74°20'0"E
74°25'0"E
74°30'0"E
17°5'0"N
17°0'0"N
16°55'0"N
Rajapur
Kirloskarvadi
Walwa
Bhilawadi
Ashta
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
47K8
47K12
47L5
47L9
Legend
Type (Sum of area in Ha)
Deposition (130)
Erosion (110)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai

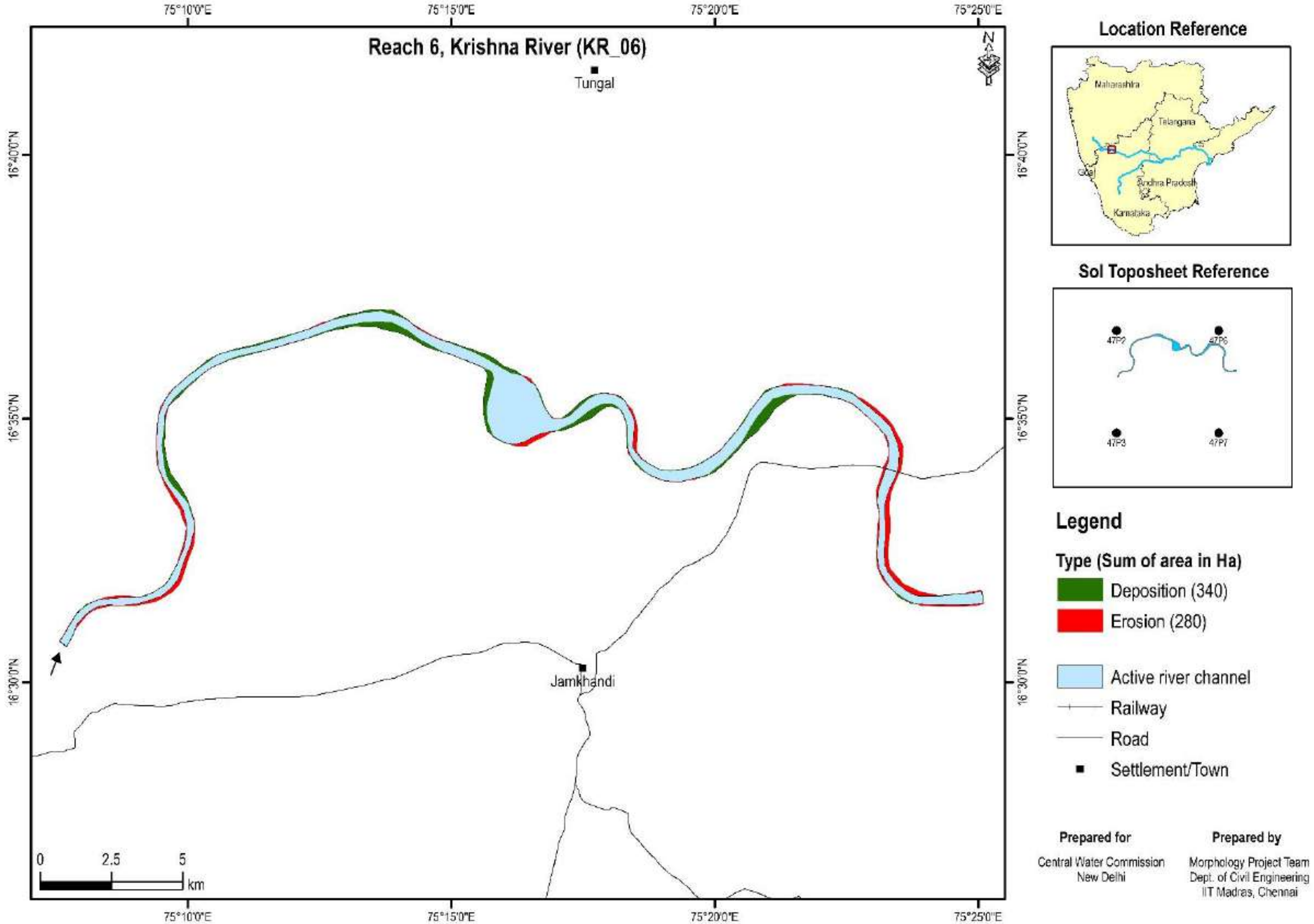


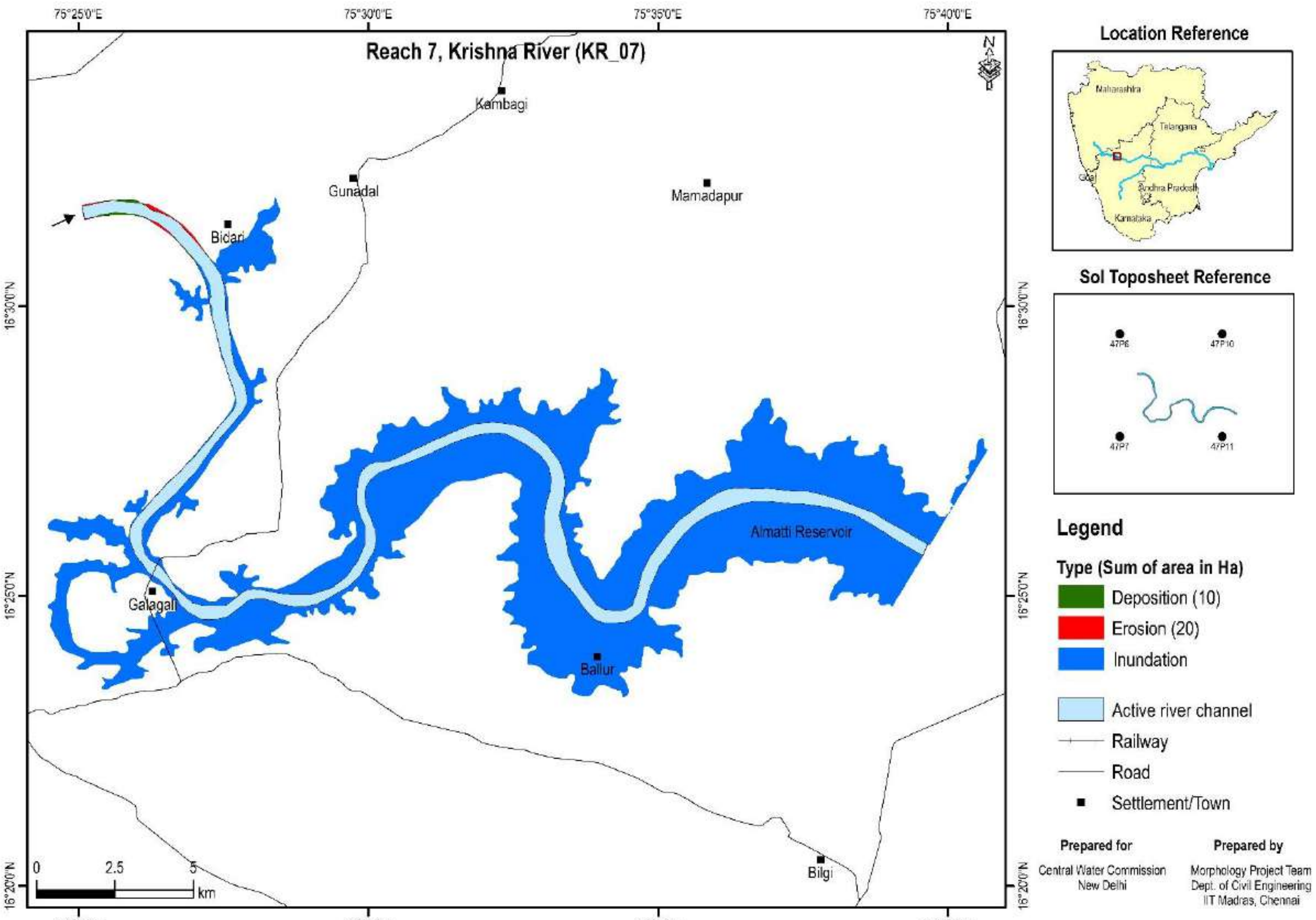
Reach 3, Krishna River (KR_03)
74°30'0"E
74°35'0"E
74°40'0"E
16°50'0"N
16°45'0"N
Budhgaon
Sangli
Miraj
Jaysingpur
Shirol
Nandani
Kurundwad
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
47L5
47L9
47L6
47L10
Legend
Type (Sum of area in Ha)
Deposition (150)
Erosion (140)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai


Reach 4, Krishna River (KR_04)
74°40'0"E
74°45'0"E
16°40'0"N
16°35'0"N
Shedbal
Ugar Khurd
Bhiradi
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
47L9
47L13
47L14
Legend
Type (Sum of area in Ha)
Deposition (170)
Erosion (230)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai

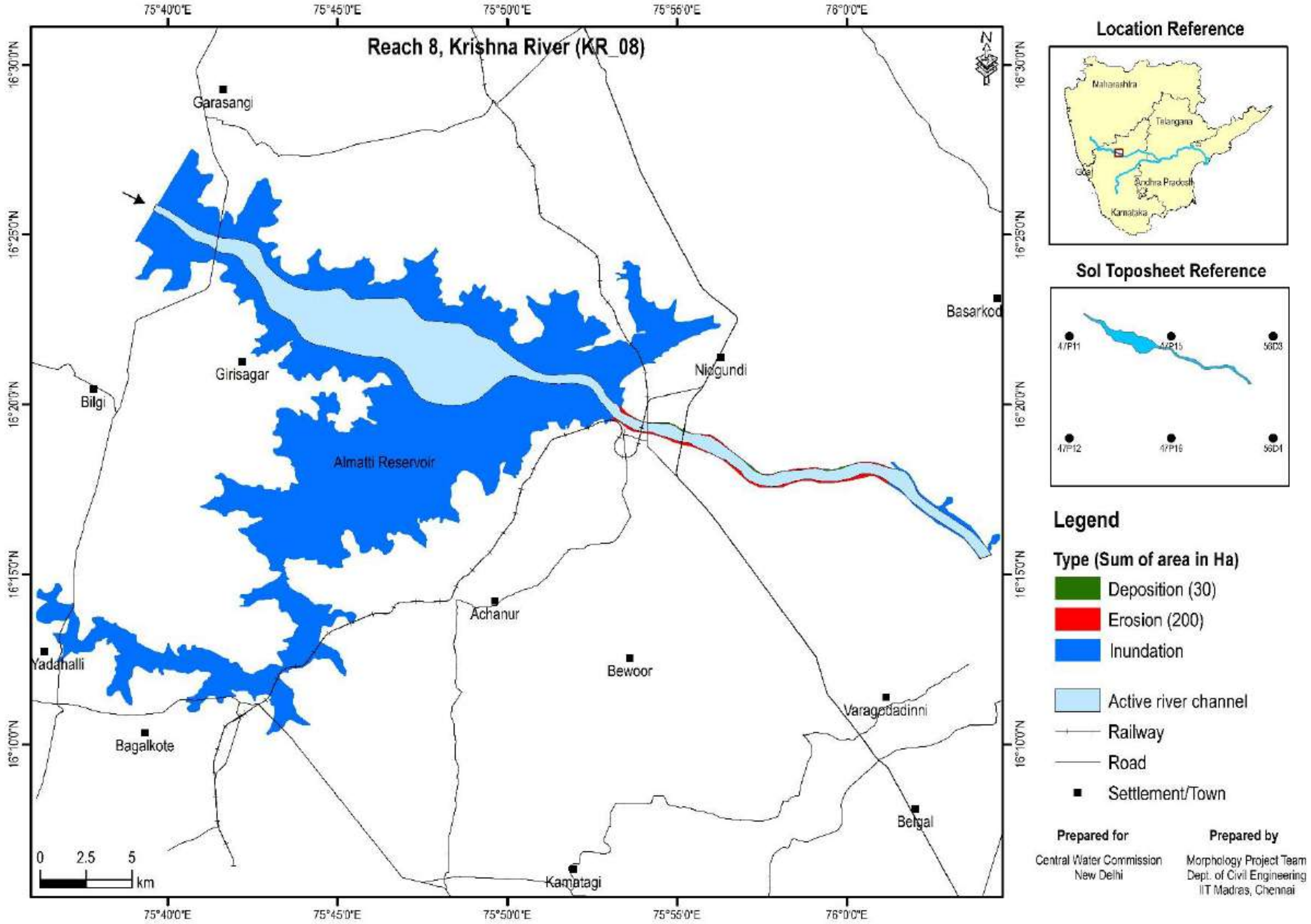


Reach 5, Krishna River (KR_05)
74°50'0"E
74°55'0"E
75°0'0"E
75°5'0"E
16°40'0"N
16°35'0"N
16°30'0"N
Mangasuli
Athani
Ainapur
Ugar Khurd
Hulagabali
Darur
Shankratti
Shegunasi
Harugeri
Terdal
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
47L14
47P2
47L15
47P3
Legend
Type (Sum of area in Ha)
Deposition (60)
Erosion (370)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai

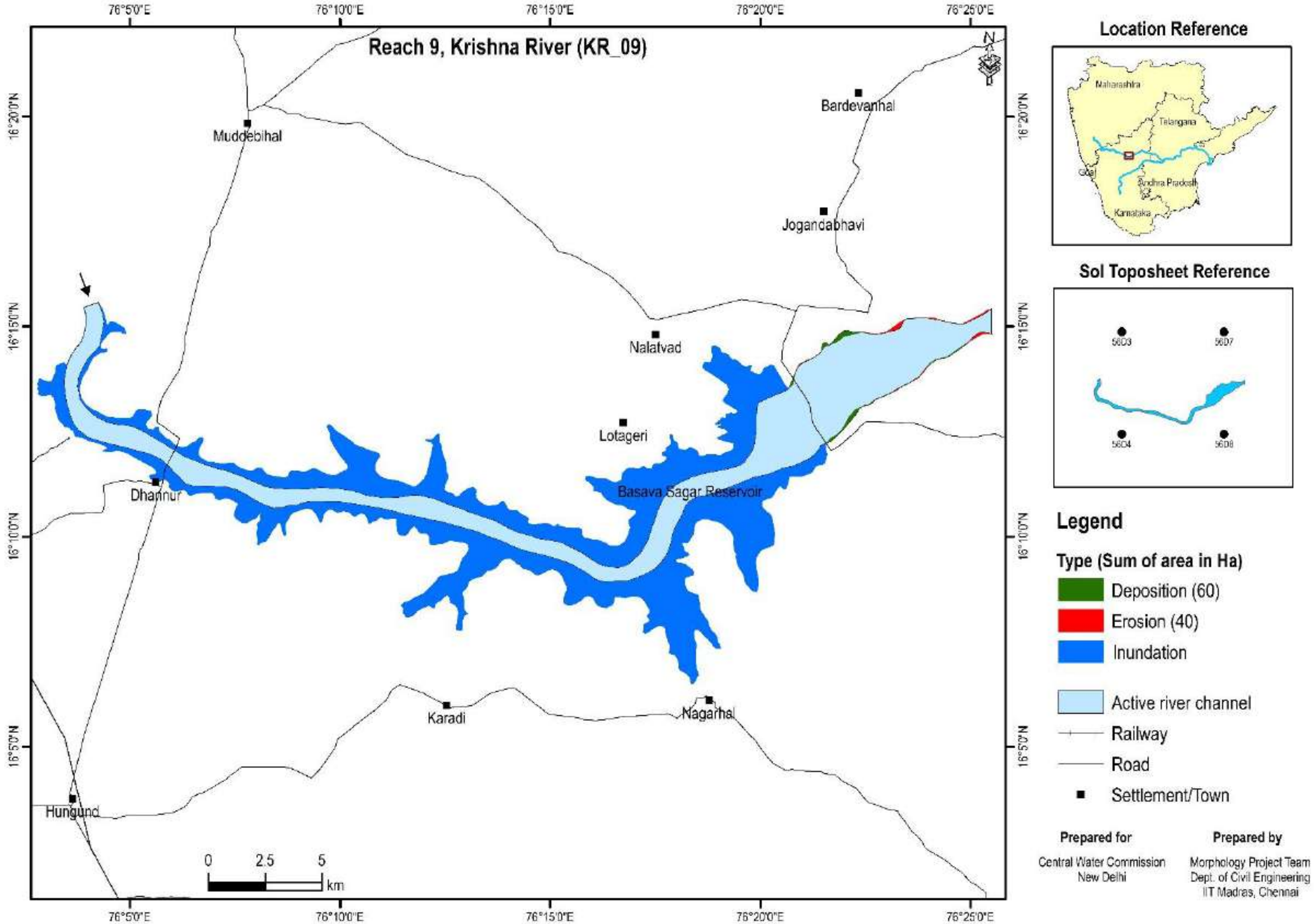

Reach 6, Krishna River (KR_06)
Tungal
Jamkhandi
75°10'0"E
75°15'0"E
75°20'0"E
75°25'0"E
16°40'0"N
16°35'0"N
16°30'0"N
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
47P2
47P6
47P3
47P7
Legend
Type (Sum of area in Ha)
Deposition (340)
Erosion (280)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai

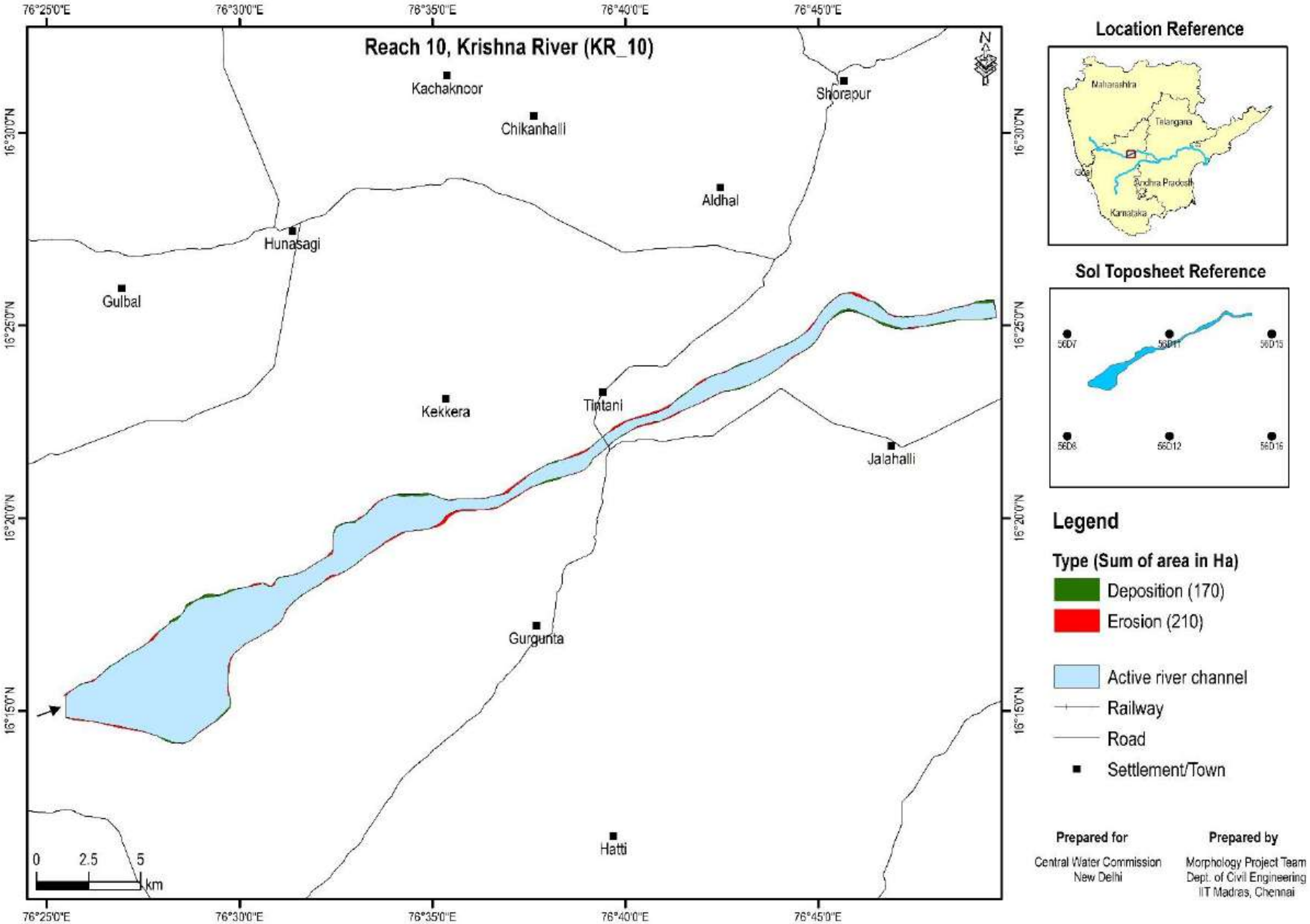


Reach 7, Krishna River (KR_07)
75°25'0"E
75°30'0"E
75°35'0"E
75°40'0"E
16°30'0"N
16°25'0"N
16°20'0"N
Kambagi
Gunadal
Mamadapur
Bidari
Galagali
Almatti Reservoir
Ballur
Bilgi
0
2.5
5
km
N
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
47P6
47P10
47P7
47P11
Legend
Type (Sum of area in Ha)
Deposition (10)
Erosion (20)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai

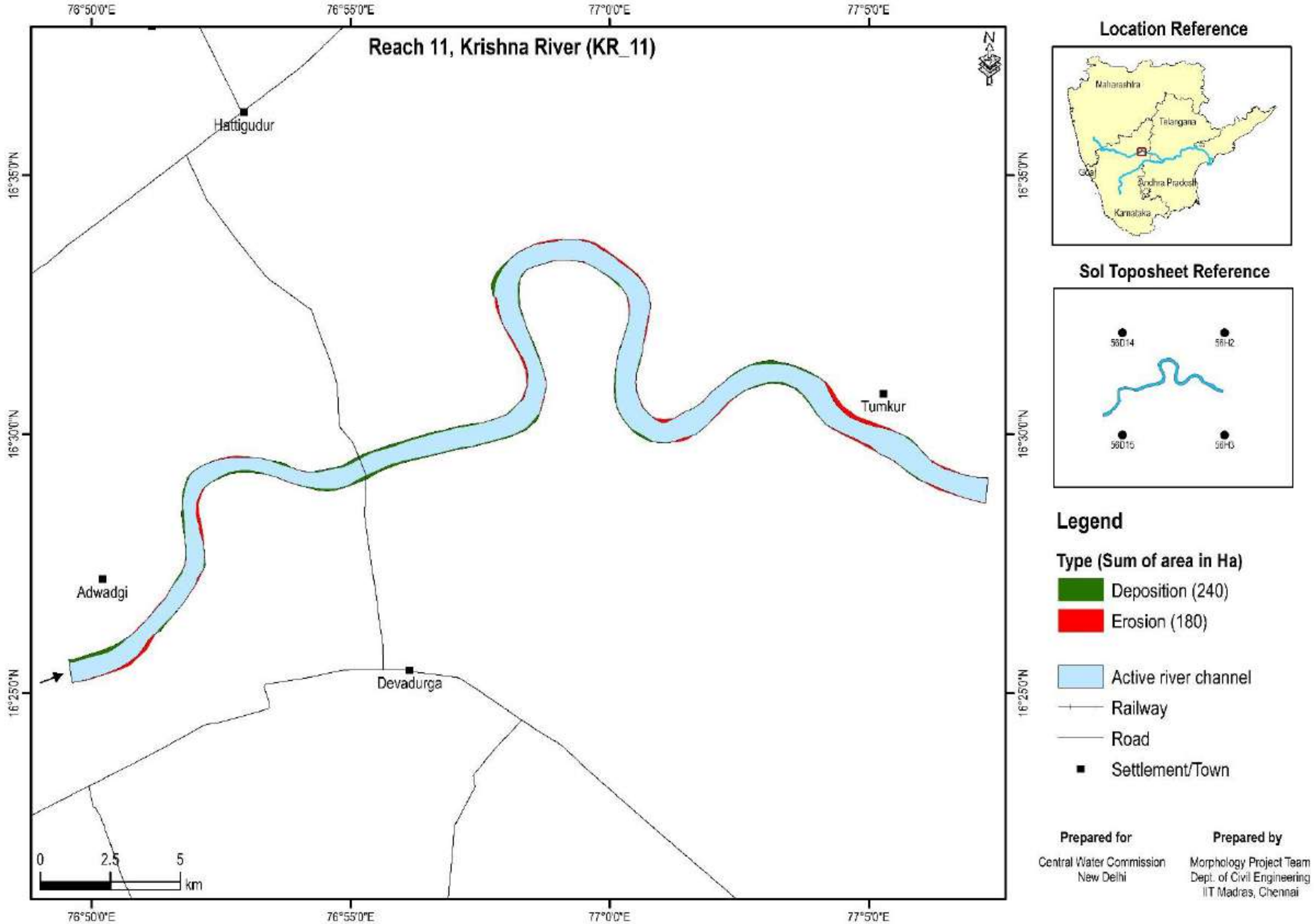


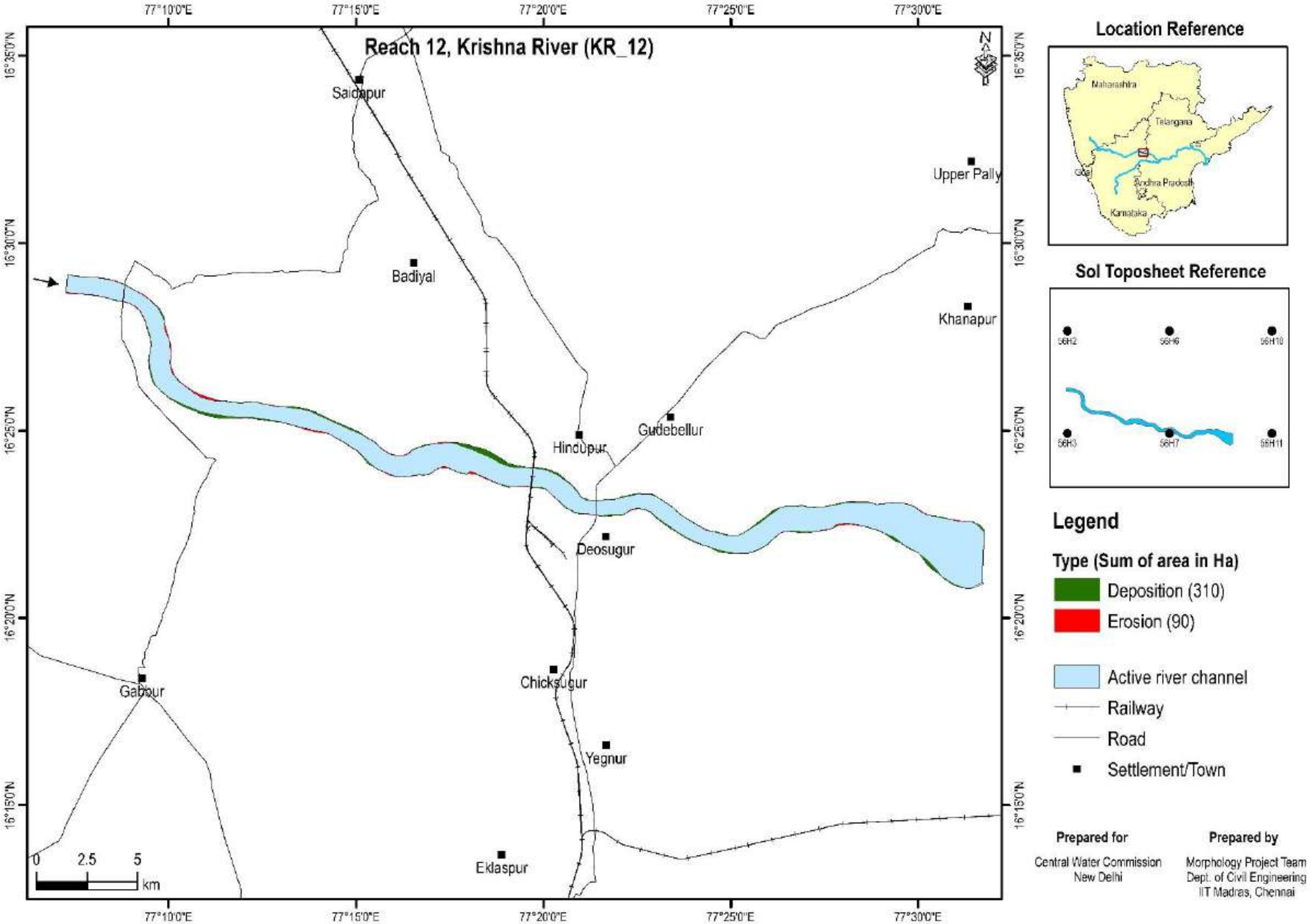
Reach 8, Krishna River (KR_08)
75°40'0"E
75°45'0"E
75°50'0"E
75°55'0"E
76°0'0"E
16°30'0"N
16°25'0"N
16°20'0"N
16°15'0"N
16°10'0"N
N
Garasangi
Girisagar
Bilgi
Almatti Reservoir
Nidgundi
Basarkod
Achanur
Bewoor
Yadahalli
Bagalkote
Varagodadinni
Belgal
Kamatagi
0 2.5 5
km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
47P11
47P15
56D3
47P12
47P16
56D4
Legend
Type (Sum of area in Ha)
Deposition (30)
Erosion (200)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai


Reach 9, Krishna River (KR_09)
Muddebihal
Bardevanhal
Jogandabhavi
Nalatvad
Lotageri
Dhannur
Basava Sagar Reservoir
Karadi
Nagarhal
Hungund
0 2.5 5 km
Location Reference
Sol Toposheet Reference
Legend
Type (Sum of area in Ha)
Deposition (60)
Erosion (40)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission New Delhi
Prepared by
Morphology Project Team Dept. of Civil Engineering IIT Madras, Chennai



Reach 10, Krishna River (KR_10)
76°25'0"E
76°30'0"E
76°35'0"E
76°40'0"E
76°45'0"E
16°30'0"N
16°25'0"N
16°20'0"N
16°15'0"N
Kachaknoor
Chikanhalli
Shorapur
Aldhal
Hunasagi
Gulbal
Kekkera
Tintani
Jalahalli
Gurgunta
Hatti
0 2.5 5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
56D7
56D11
56D15
56D8
56D12
56D16
Legend
Type (Sum of area in Ha)
Deposition (170)
Erosion (210)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai


Reach 11, Krishna River (KR_11)
76°50'0"E
76°55'0"E
77°0'0"E
77°5'0"E
16°35'0"N
16°30'0"N
16°25'0"N
Hattigudur
Tumkur
Adwadgi
Devadurga
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
56D14
56H2
56D15
56H3
Legend
Type (Sum of area in Ha)
Deposition (240)
Erosion (180)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai


Reach 12, Krishna River (KR_12)
Saidapur
Upper Pally
Badiyal
Khanapur
Gudebellur
Hindupur
Deosugur
Chicksugur
Gabbur
Yegnur
Eklaspur
0 2.5 5 km
77°10'0"E
77°15'0"E
77°20'0"E
77°25'0"E
77°30'0"E
16°35'0"N
16°30'0"N
16°25'0"N
16°20'0"N
16°15'0"N
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
56H2
56H6
56H10
56H3
56H7
56H11
Legend
Type (Sum of area in Ha)
Deposition (310)
Erosion (90)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
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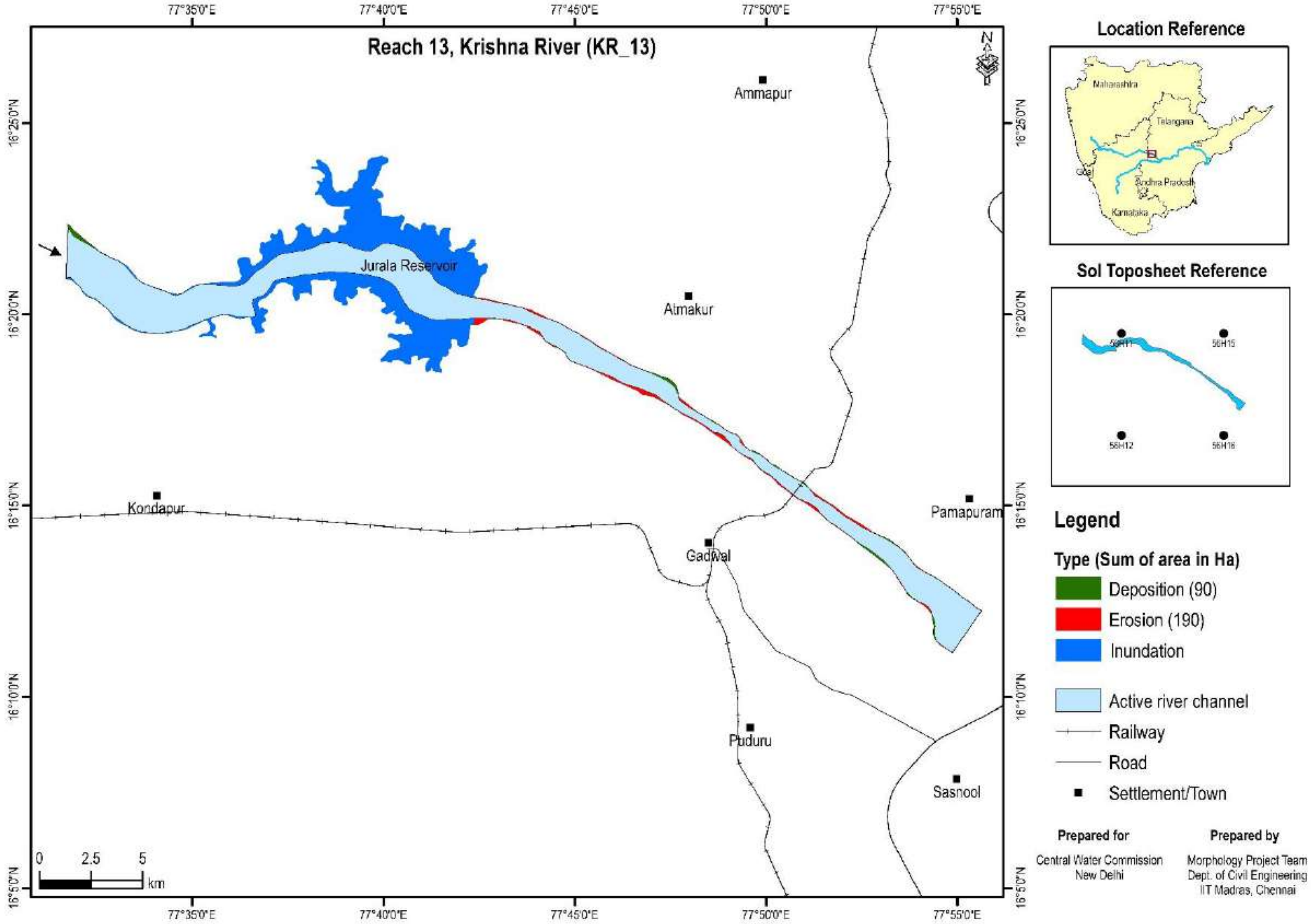
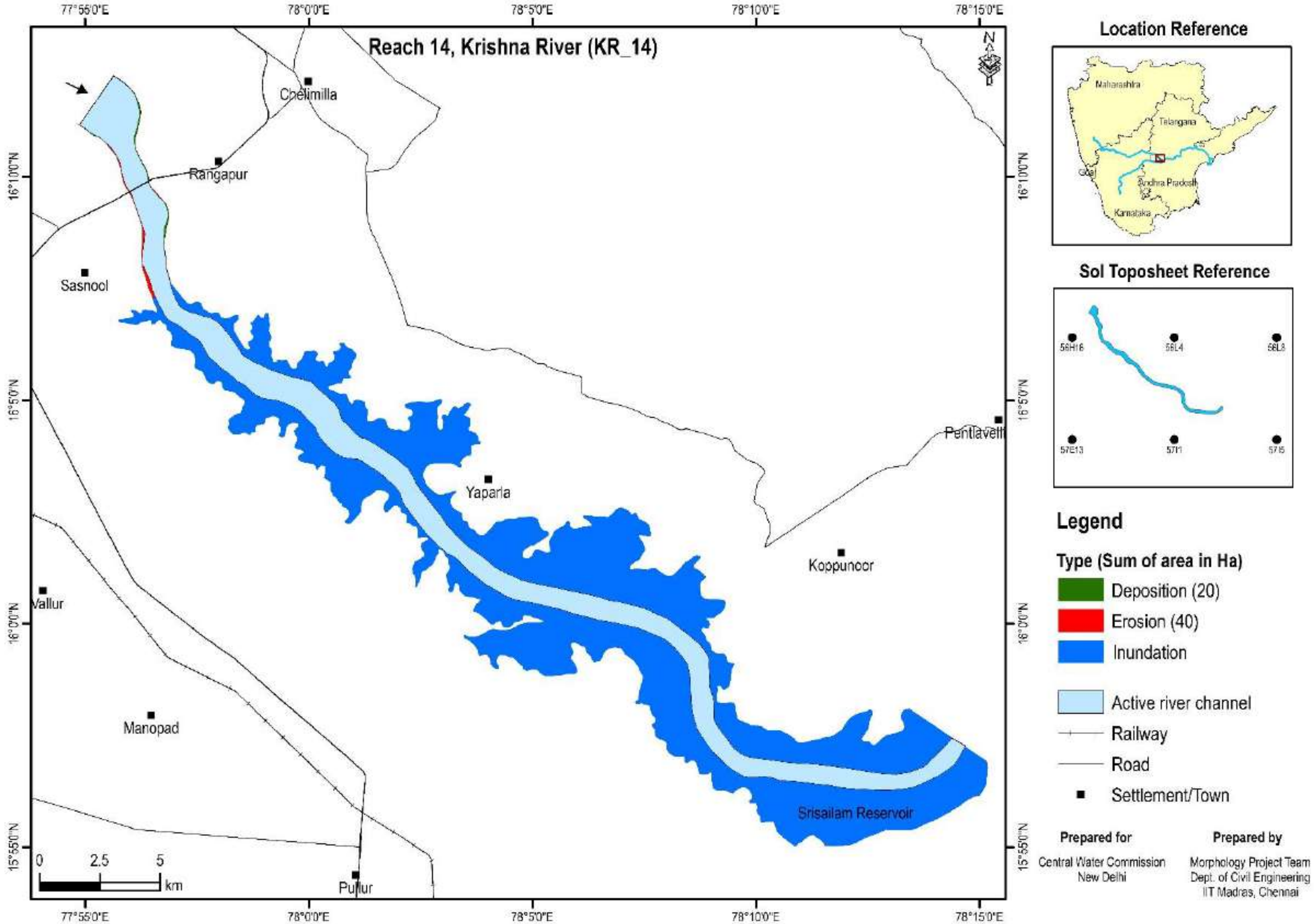


Reach 13, Krishna River (KR_13)
77°35'0"E
77°40'0"E
77°45'0"E
77°50'0"E
77°55'0"E
16°25'0"N
16°20'0"N
16°15'0"N
16°10'0"N
16°5'0"N
Ammapur
Jurala Reservoir
Atmakur
Kondapur
Gadwal
Pamapuram
Puduru
Sasnool
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
SoI Toposheet Reference
56H15
56H12
56H16
Legend
Type (Sum of area in Ha)
Deposition (90)
Erosion (190)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai


Reach 14, Krishna River (KR_14)
77°55'0"E
78°0'0"E
78°5'0"E
78°10'0"E
78°15'0"E
16°10'0"N
16°5'0"N
16°0'0"N
15°55'0"N
Chelimilla
Rangapur
Sasnool
Yaparla
Pentlavelli
Koppunoor
Vallur
Manopad
Pullur
Srisailam Reservoir
0 2.5 5 km
Location Reference
Sol Toposheet Reference
Legend
Type (Sum of area in Ha)
Deposition (20)
Erosion (40)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
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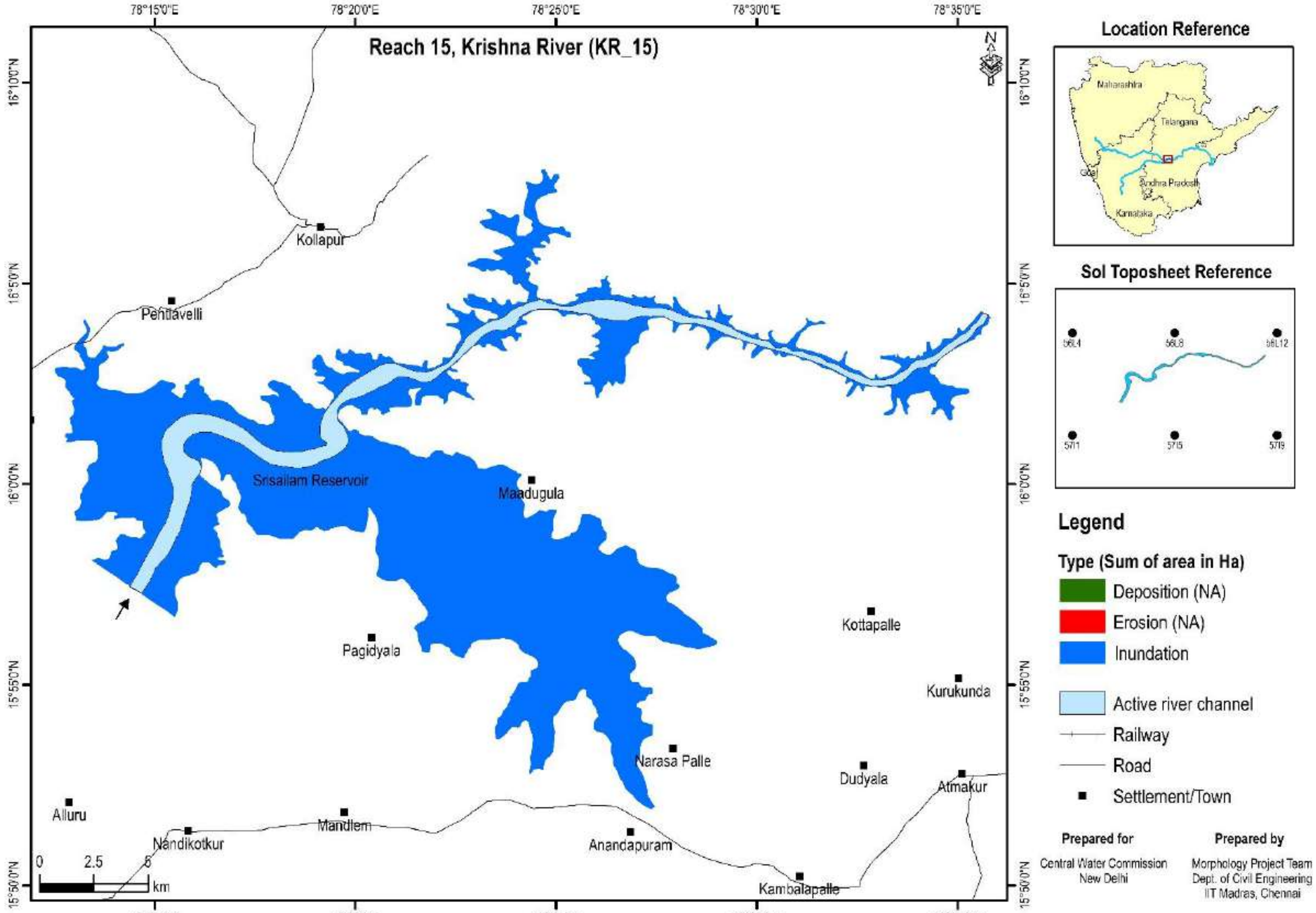
Reach 15, Krishna River (KR_15)
78°15'0"E
78°20'0"E
78°25'0"E
78°30'0"E
78°35'0"E
16°10'0"N
16°5'0"N
16°0'0"N
15°55'0"N
15°50'0"N
Kollapur
Pentlavelli
Srisailam Reservoir
Maadugula
Pagidyala
Kottapalle
Kurukunda
Narasa Palle
Dudyala
Atmakur
Alluru
Mandlem
Nandikotkur
Anandapuram
Kambalapalle
0 2.5 5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
Legend
Type (Sum of area in Ha)
Deposition (NA)
Erosion (NA)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
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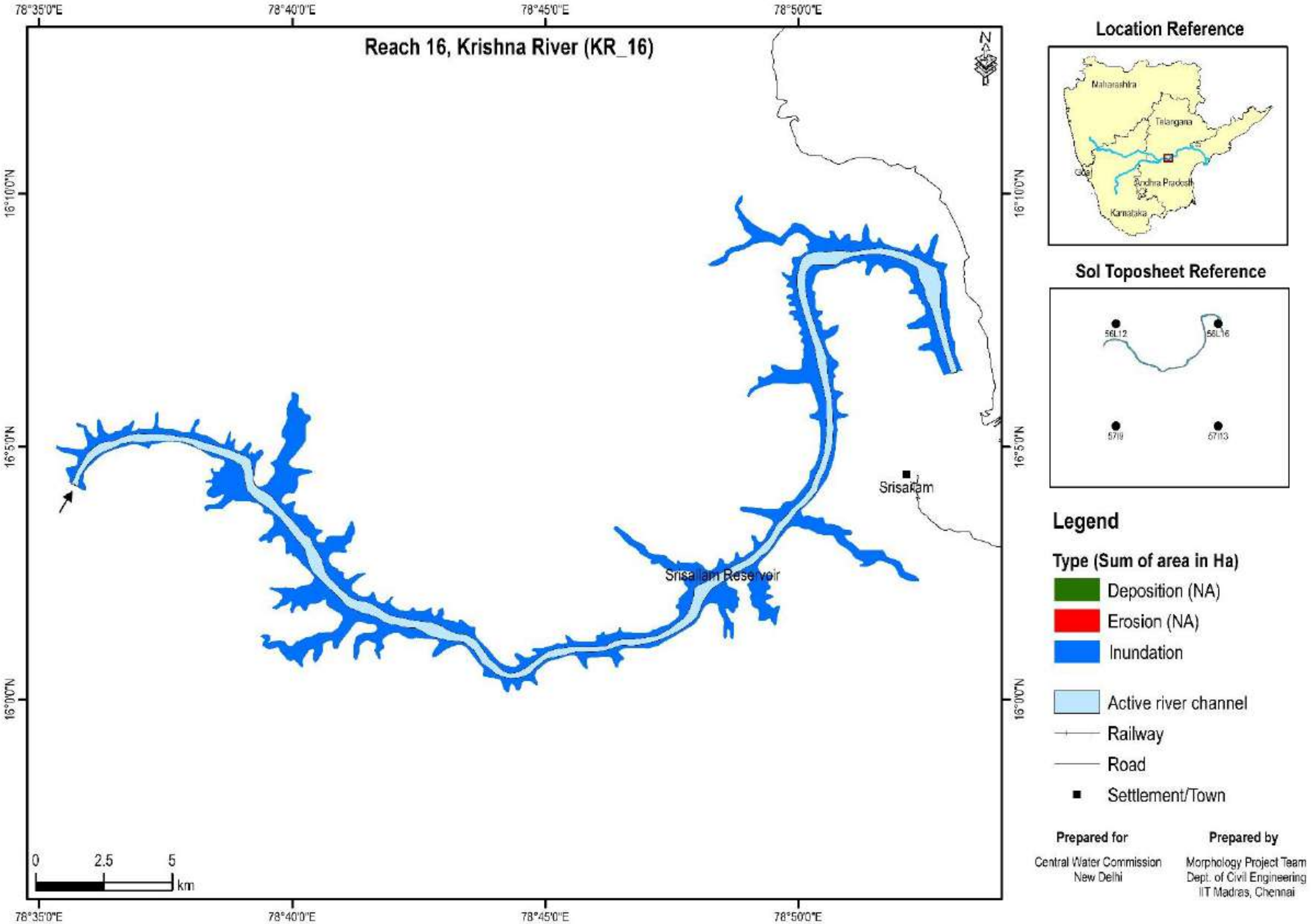
IIT Madras, Chennai



Reach 16, Krishna River (KR_16)
78°35'0"E
78°40'0"E
78°45'0"E
78°50'0"E
16°10'0"N
16°5'0"N
16°0'0"N
Srisailam
Srisailam Reservoir
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
Legend
Type (Sum of area in Ha)
Deposition (NA)
Erosion (NA)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
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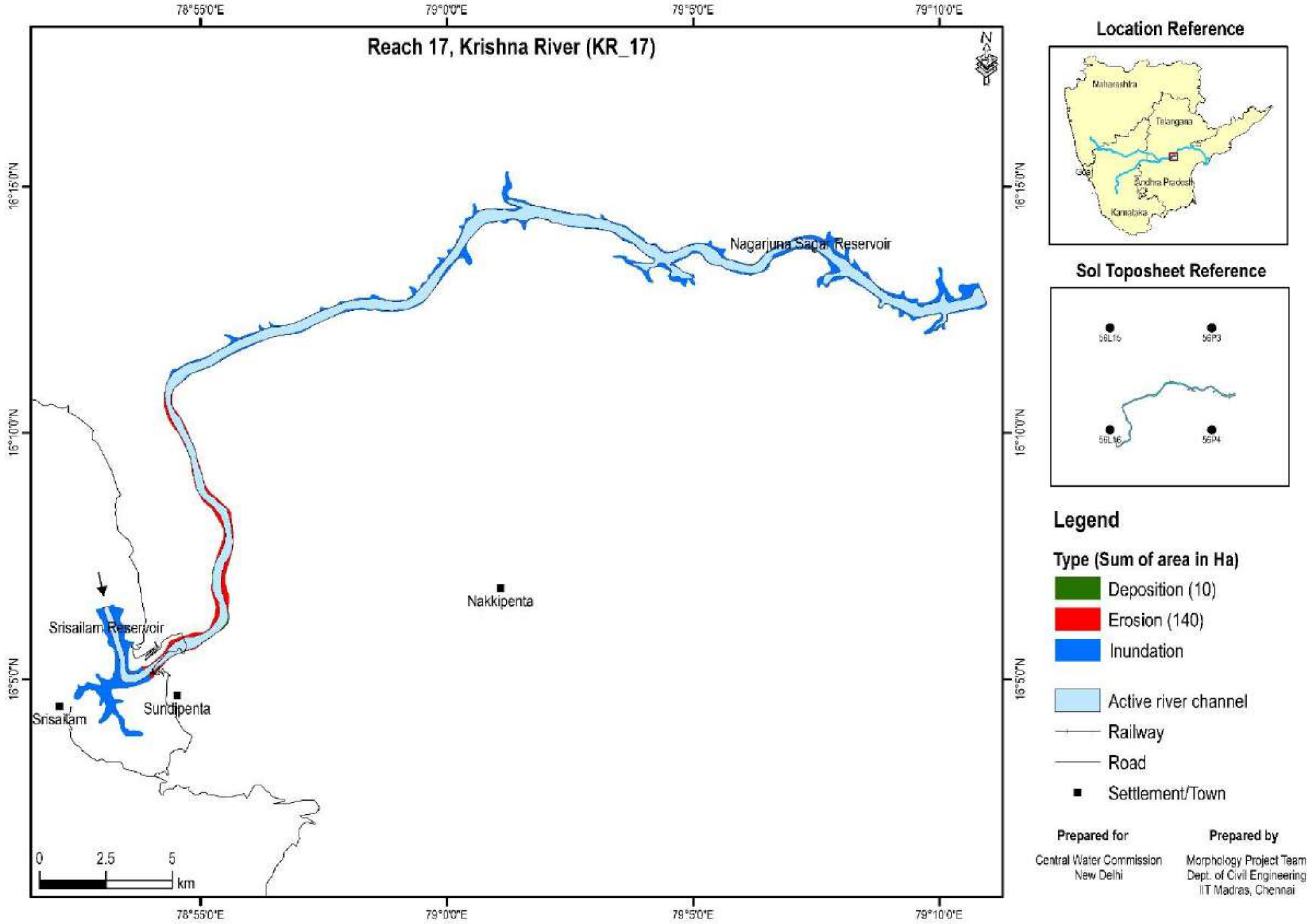

Reach 17, Krishna River (KR_17)
78°55'0"E
79°0'0"E
79°5'0"E
79°10'0"E
16°15'0"N
16°10'0"N
16°5'0"N
N
Nagarjuna Sagar Reservoir
Nakkipenta
Srisailam Reservoir
Srisailam
Sundipenta
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Goa
Karnataka
SoI Toposheet Reference
56L15
56P3
56L16
56P4
Legend
Type (Sum of area in Ha)
Deposition (10)
Erosion (140)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
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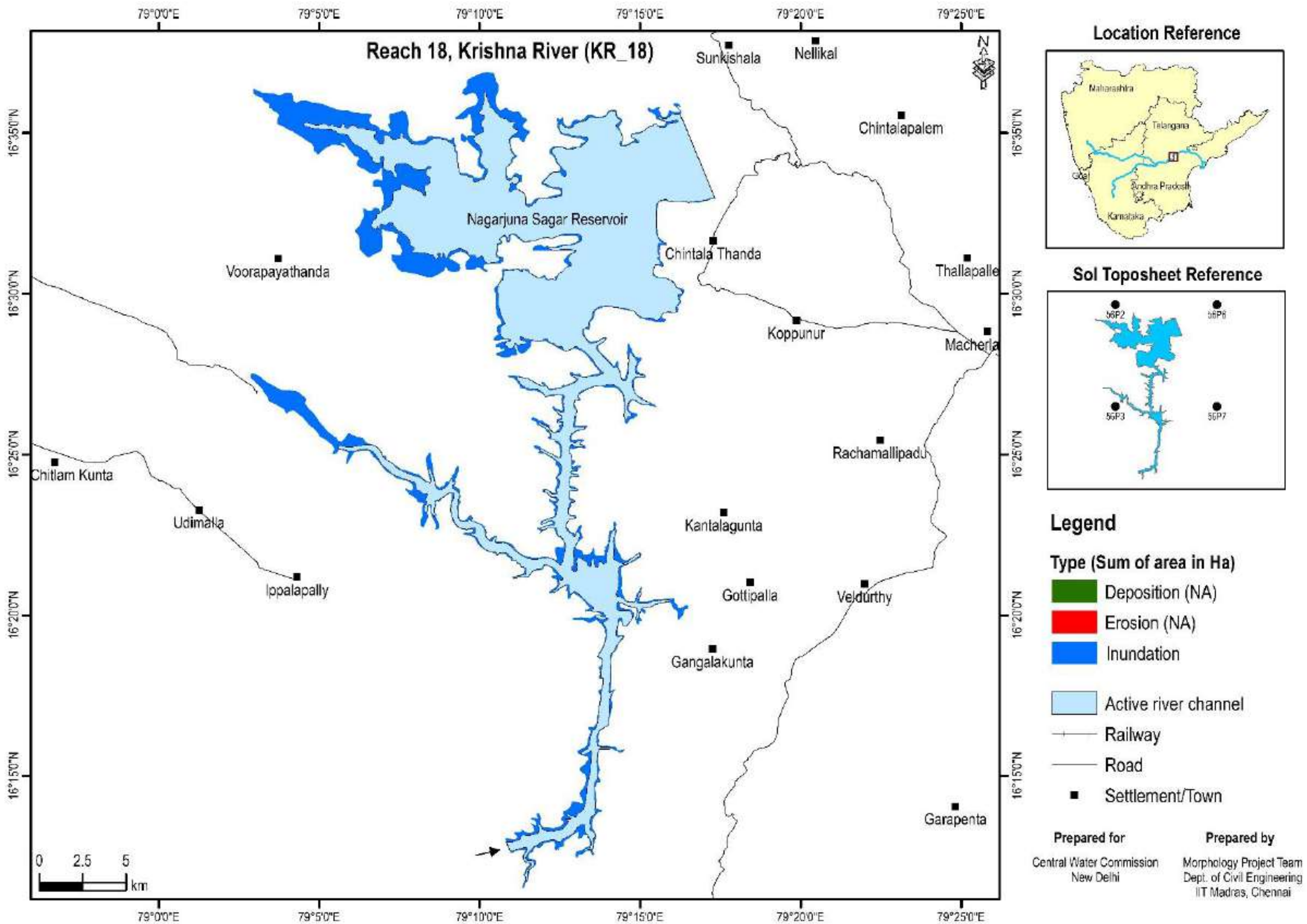
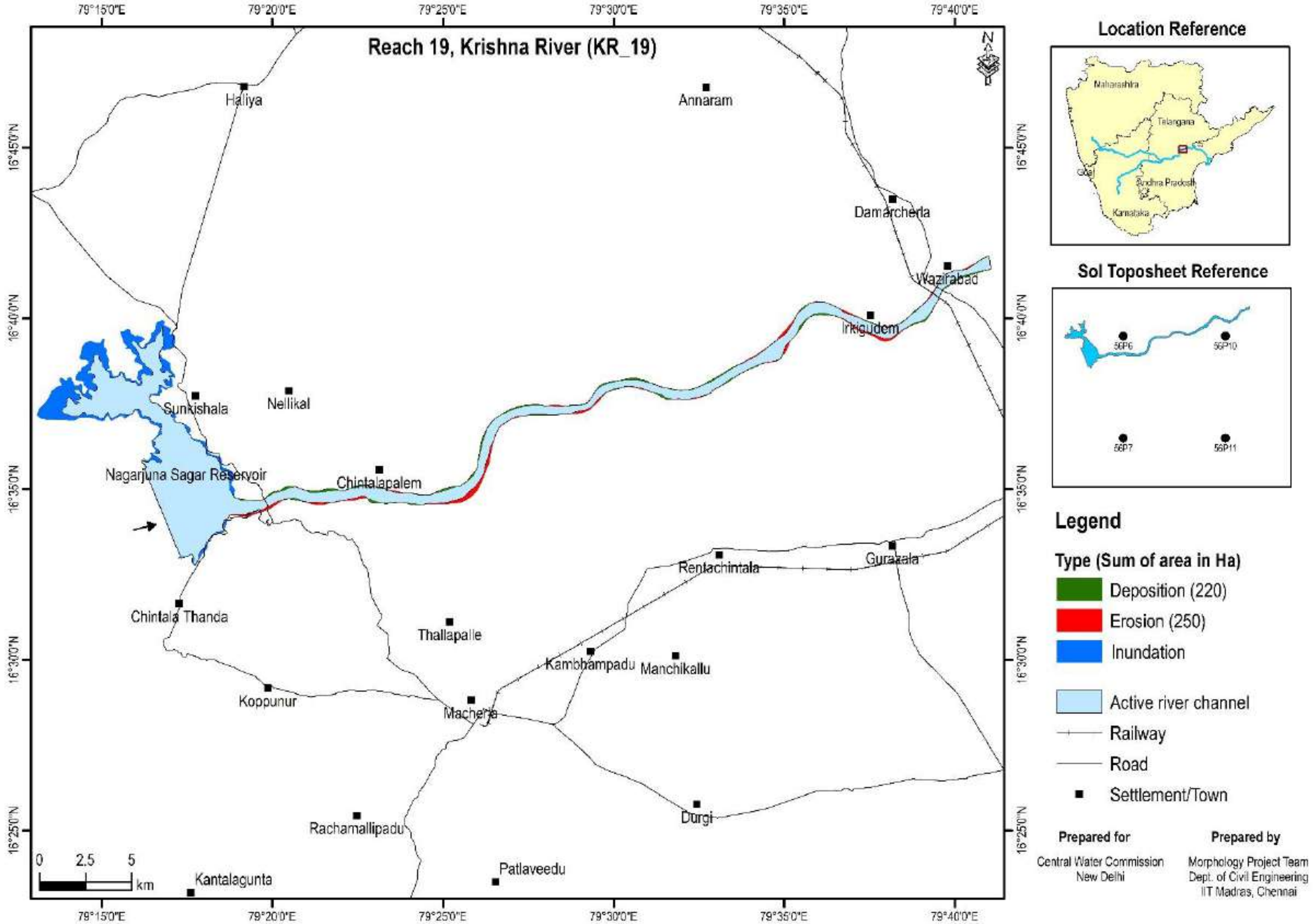
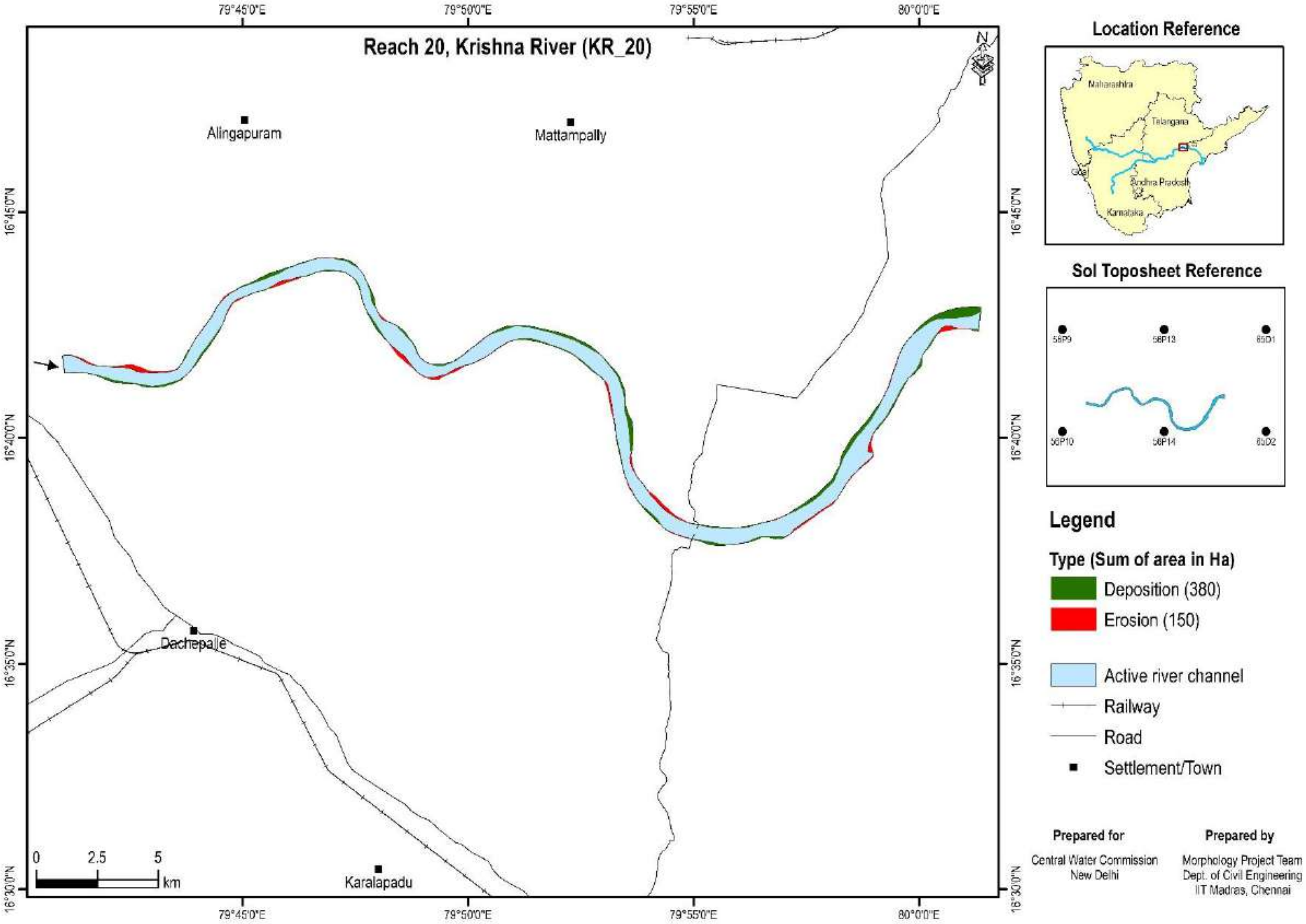

Reach 18, Krishna River (KR_18)
Nagarjuna Sagar Reservoir
Sunkishala
Nellikal
Chintalapalem
Chintala Thanda
Thallapalle
Voorapayathanda
Koppunur
Macherla
Rachamallipadu
Chitlam Kunta
Udimalla
Kantalagunta
Ippalapally
Gottipalla
Veldurthy
Gangalakunta
Garapenta
79°0'0"E
79°5'0"E
79°10'0"E
79°15'0"E
79°20'0"E
79°25'0"E
16°35'0"N
16°30'0"N
16°25'0"N
16°20'0"N
16°15'0"N
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Goa
Karnataka
SoI Toposheet Reference
56P2
56P6
56P3
56P7
Legend
Type (Sum of area in Ha)
Deposition (NA)
Erosion (NA)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai



Reach 19, Krishna River (KR_19)
79°15'0"E
79°20'0"E
79°25'0"E
79°30'0"E
79°35'0"E
79°40'0"E
16°45'0"N
16°40'0"N
16°35'0"N
16°30'0"N
16°25'0"N
Haliya
Annaram
Damarcherla
Wazirabad
Irkigudem
Sunkishala
Nellikal
Nagarjuna Sagar Reservoir
Chintalapalem
Rentachintala
Gurazala
Chintala Thanda
Thallapalle
Kambhampadu
Manchikallu
Koppunur
Macherla
Durgi
Rachamallipadu
Patlaveedu
Kantalagunta
0 2.5 5
km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
56P6
56P10
56P7
56P11
Legend
Type (Sum of area in Ha)
Deposition (220)
Erosion (250)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai


Reach 20, Krishna River (KR_20)
79°45'0"E
79°50'0"E
79°55'0"E
80°0'0"E
16°45'0"N
16°40'0"N
16°35'0"N
16°30'0"N
N
Alingapuram
Mattampally
Dachepalle
Karalapadu
0 2.5 5
km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
56P9
56P13
65D1
56P10
56P14
65D2
Legend
Type (Sum of area in Ha)
Deposition (380)
Erosion (150)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
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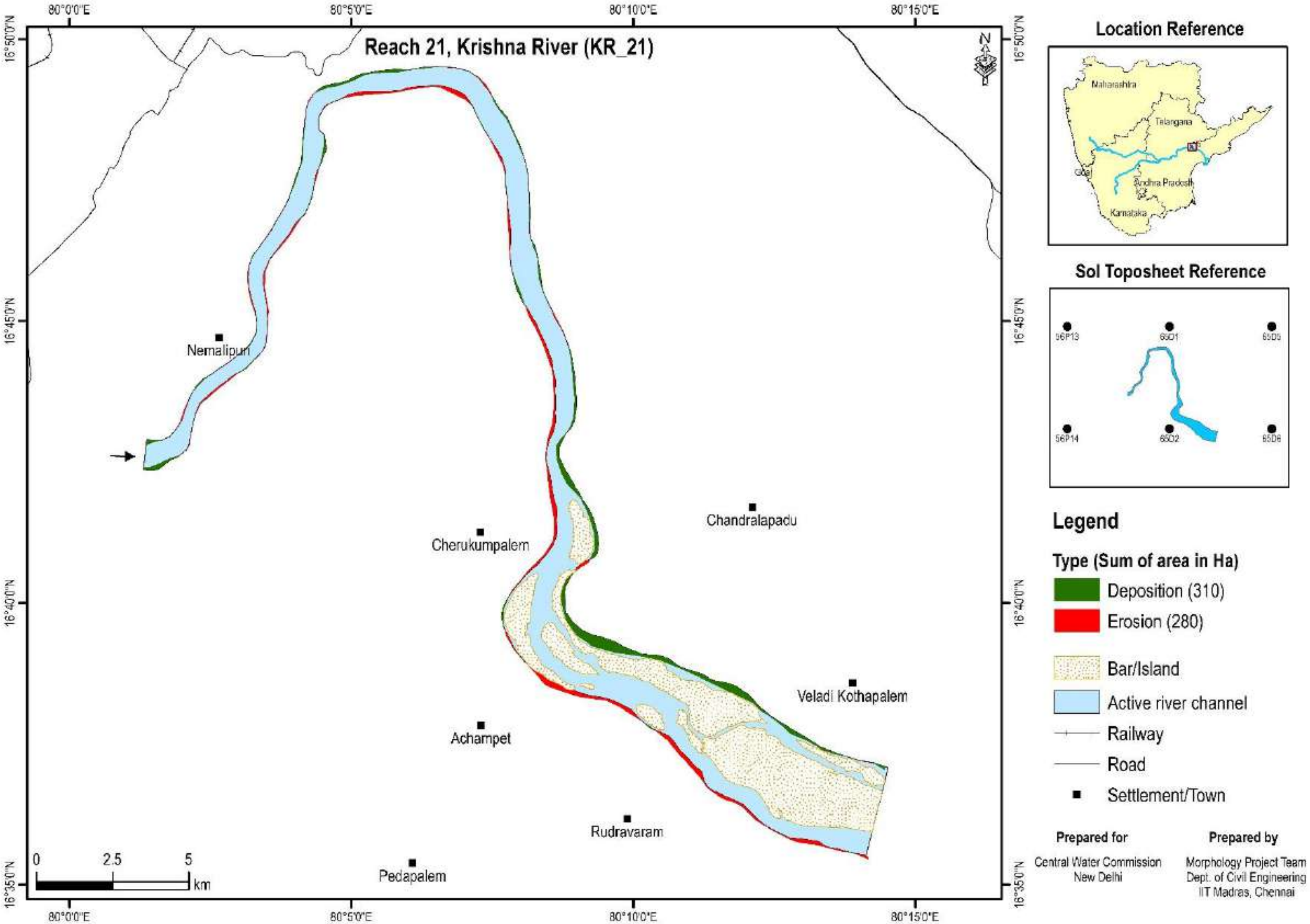
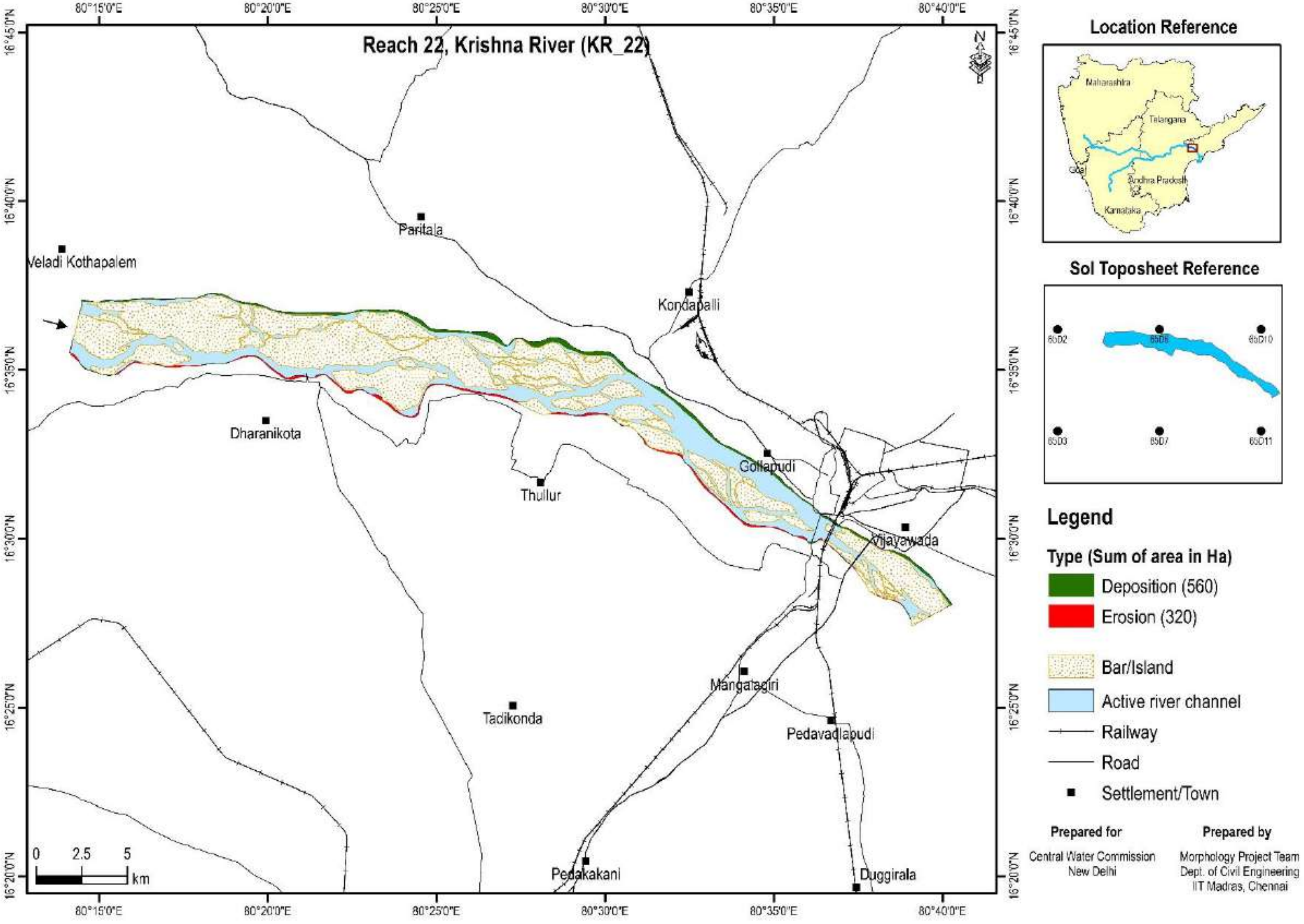
IIT Madras, Chennai


Reach 21, Krishna River (KR_21)
80°0'0"E
80°5'0"E
80°10'0"E
80°15'0"E
16°50'0"N
16°45'0"N
16°40'0"N
16°35'0"N
Nemalipuri
Cherukumpalem
Chandralapadu
Veladi Kothapalem
Achampet
Rudravaram
Pedapalem
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
56P13
65D1
65D5
56P14
65D2
65D6
Legend
Type (Sum of area in Ha)
Deposition (310)
Erosion (280)
Bar/Island
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai



Reach 22, Krishna River (KR_22)
80°15'0"E
80°20'0"E
80°25'0"E
80°30'0"E
80°35'0"E
80°40'0"E
16°45'0"N
16°40'0"N
16°35'0"N
16°30'0"N
16°25'0"N
16°20'0"N
Veladi Kothapalem
Paritala
Kondapalli
Dharanikota
Thullur
Gollapudi
Vijayawada
Mangalagiri
Tadikonda
Pedavadlapudi
Pedakakani
Duggirala
0 2.5 5 km
N
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
65D2
65D6
65D10
65D3
65D7
65D11
Legend
Type (Sum of area in Ha)
Deposition (560)
Erosion (320)
Bar/Island
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
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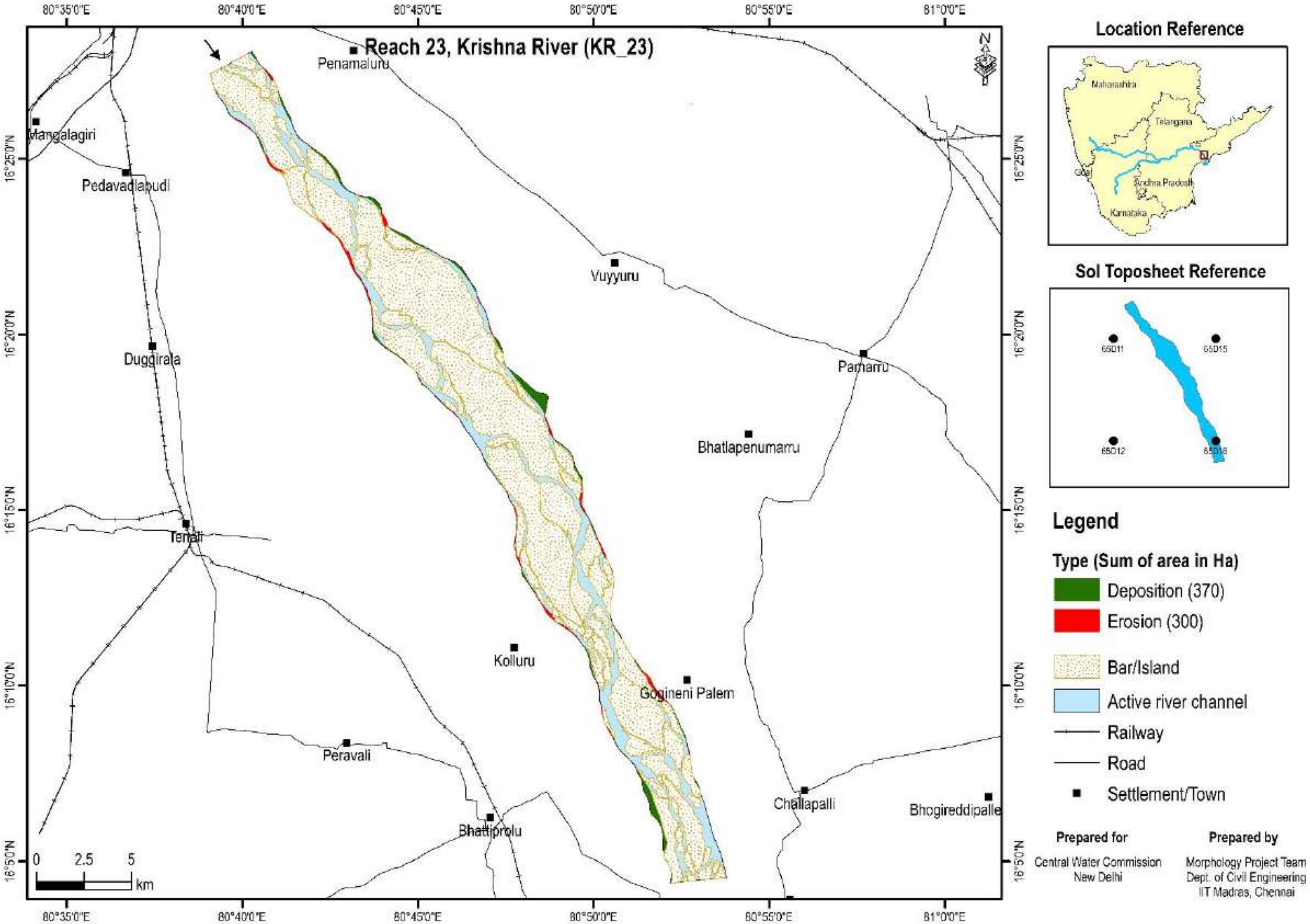
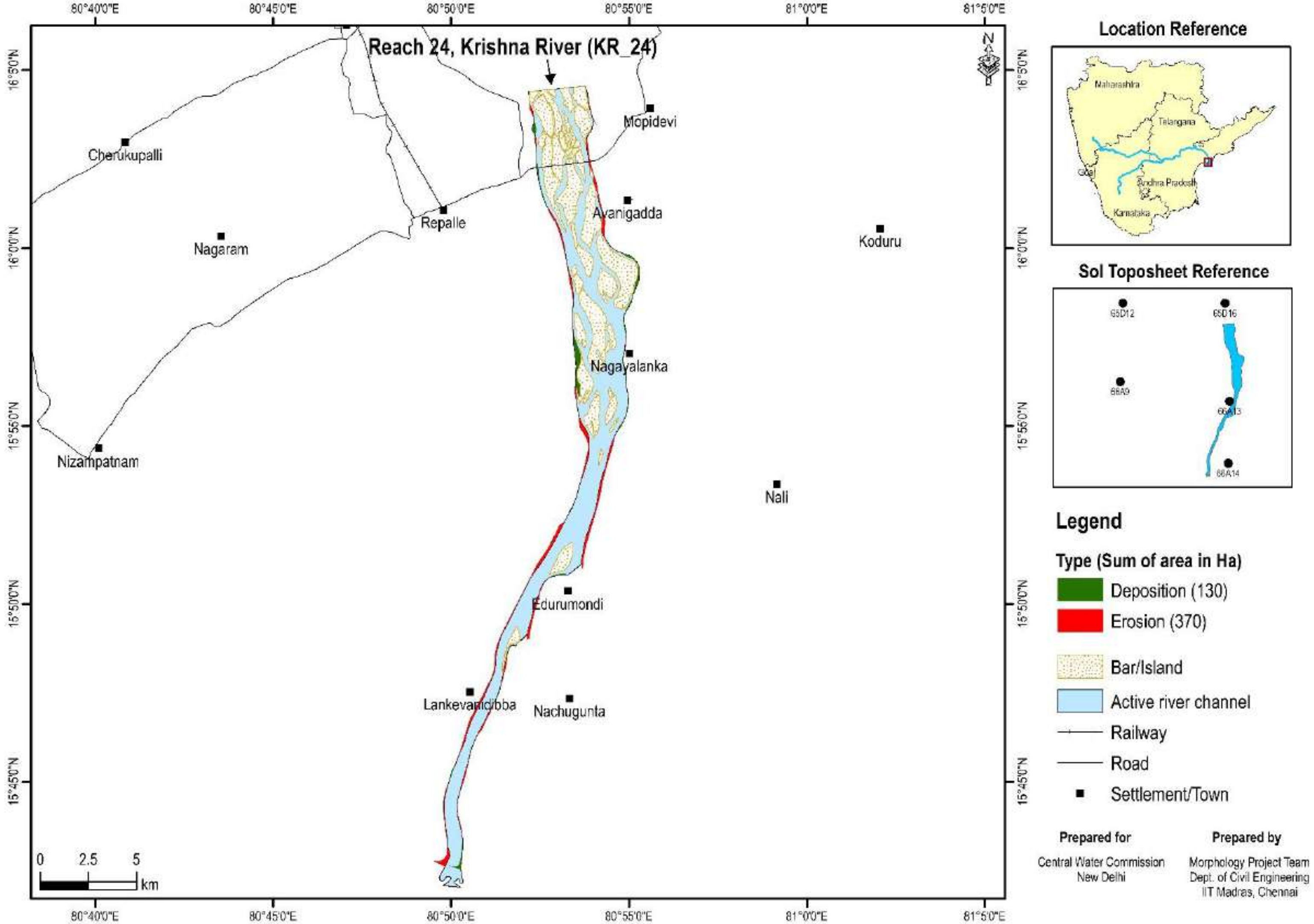

Reach 23, Krishna River (KR_23)
Penamaluru
Mangalagiri
Pedavadlapudi
Vuyyuru
Duggirala
Pamarru
Bhatlapenumarru
Tenali
Kolluru
Gogineni Palem
Peravali
Challapalli
Bhogireddipalle
Bhattiprolu
0 2.5 5 km
80°35'0"E
80°40'0"E
80°45'0"E
80°50'0"E
80°55'0"E
81°0'0"E
16°25'0"N
16°20'0"N
16°15'0"N
16°10'0"N
16°5'0"N
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
65D11
65D15
65D12
65D16
Legend
Type (Sum of area in Ha)
Deposition (370)
Erosion (300)
Bar/Island
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai



Reach 24, Krishna River (KR_24)
80°40'0"E
80°45'0"E
80°50'0"E
80°55'0"E
81°0'0"E
81°5'0"E
16°5'0"N
16°0'0"N
15°55'0"N
15°50'0"N
15°45'0"N
Mopidevi
Cherukupalli
Avanigadda
Repalle
Nagaram
Koduru
Nagayalanka
Nizampatnam
Nali
Edurumondi
Lankevanidibba
Nachugunta
0 2.5 5 km
N
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
65D12
65D16
66A9
66A13
66A14
Legend
Type (Sum of area in Ha)
Deposition (130)
Erosion (370)
Bar/Island
Active river channel
Railway
Road
Settlement/Town
Prepared for
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New Delhi
Prepared by
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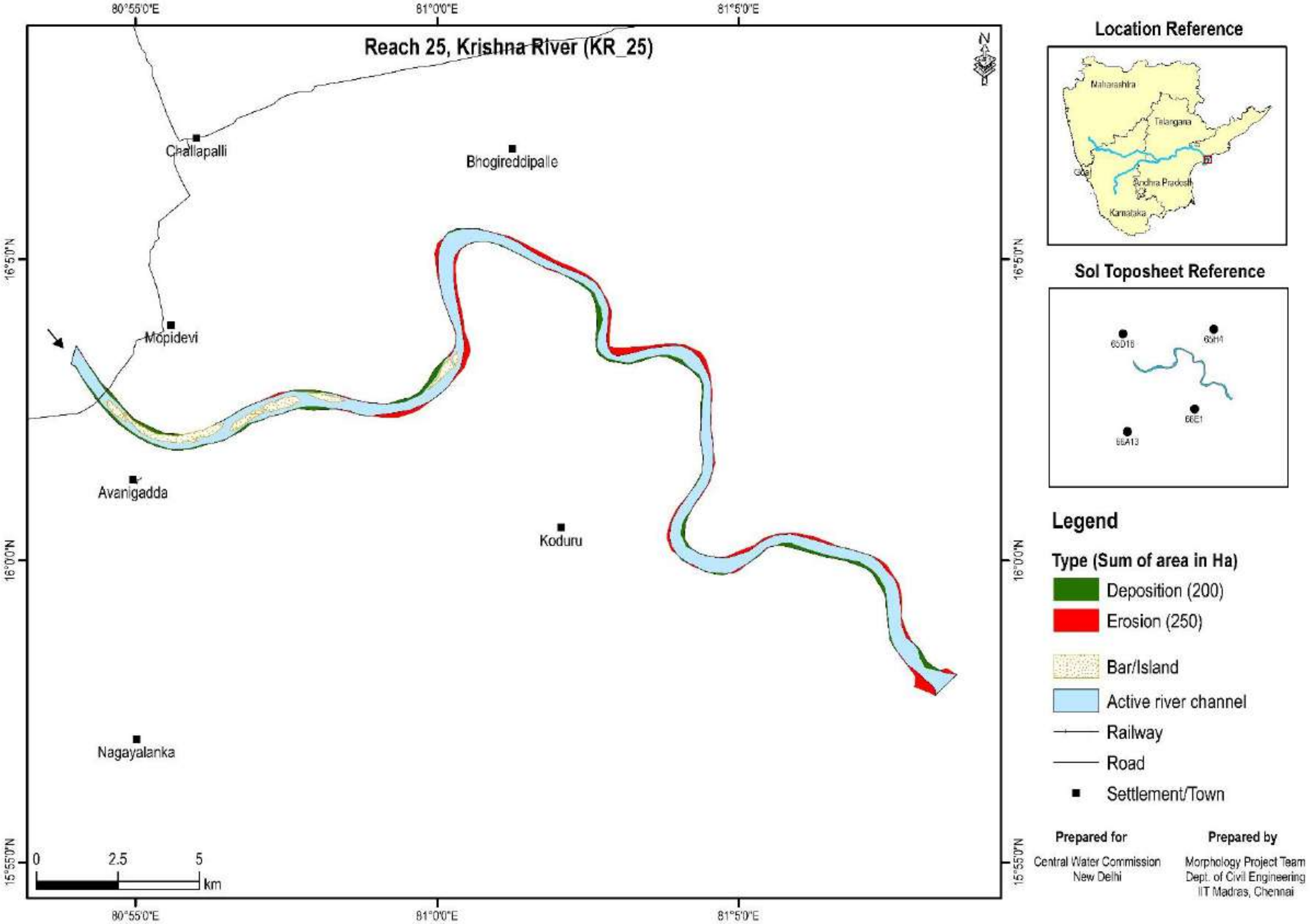
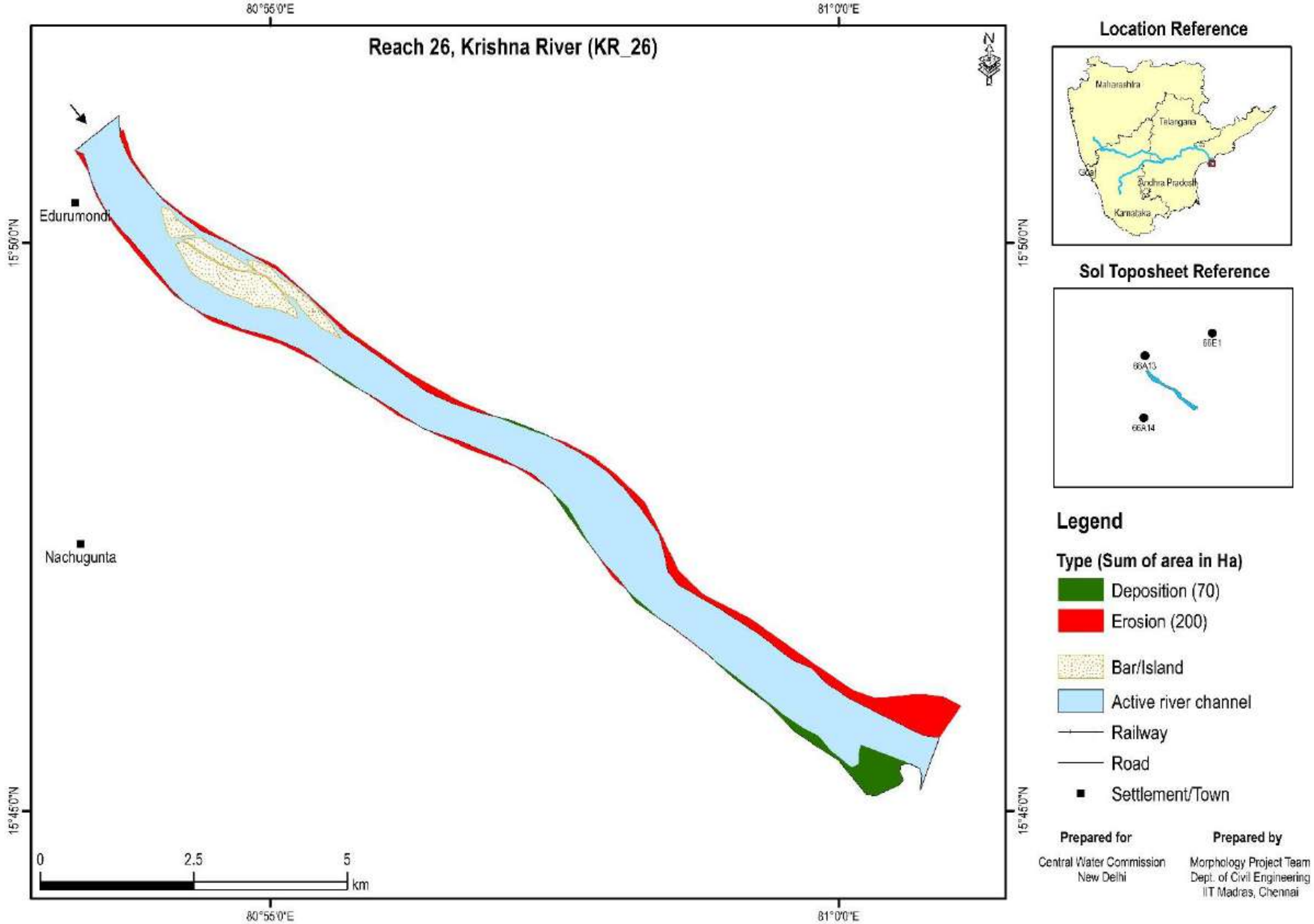

Reach 25, Krishna River (KR_25)
80°55'0"E
81°0'0"E
81°5'0"E
16°5'0"N
16°0'0"N
15°55'0"N
Challapalli
Bhogireddipalle
Mopidevi
Avanigadda
Koduru
Nagayalanka
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
65D16
65H4
66E1
66A13
Legend
Type (Sum of area in Ha)
Deposition (200)
Erosion (250)
Bar/Island
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai



Reach 26, Krishna River (KR_26)
80°55'0"E
81°0'0"E
15°50'0"N
15°45'0"N
Edurumondi
Nachugunta
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
SoI Toposheet Reference
66E1
66A13
66A14
Legend
Type (Sum of area in Ha)
Deposition (70)
Erosion (200)
Bar/Island
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
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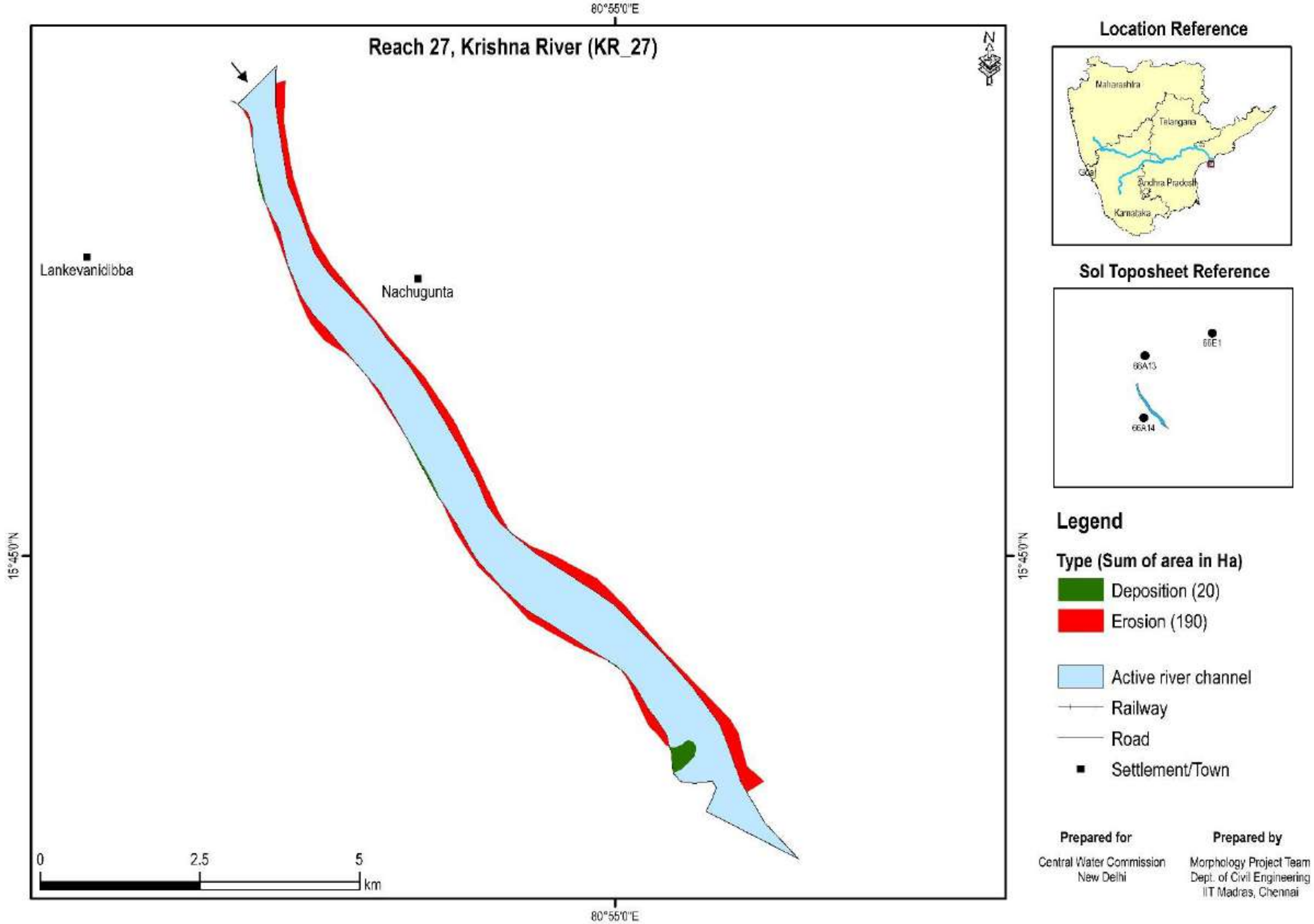
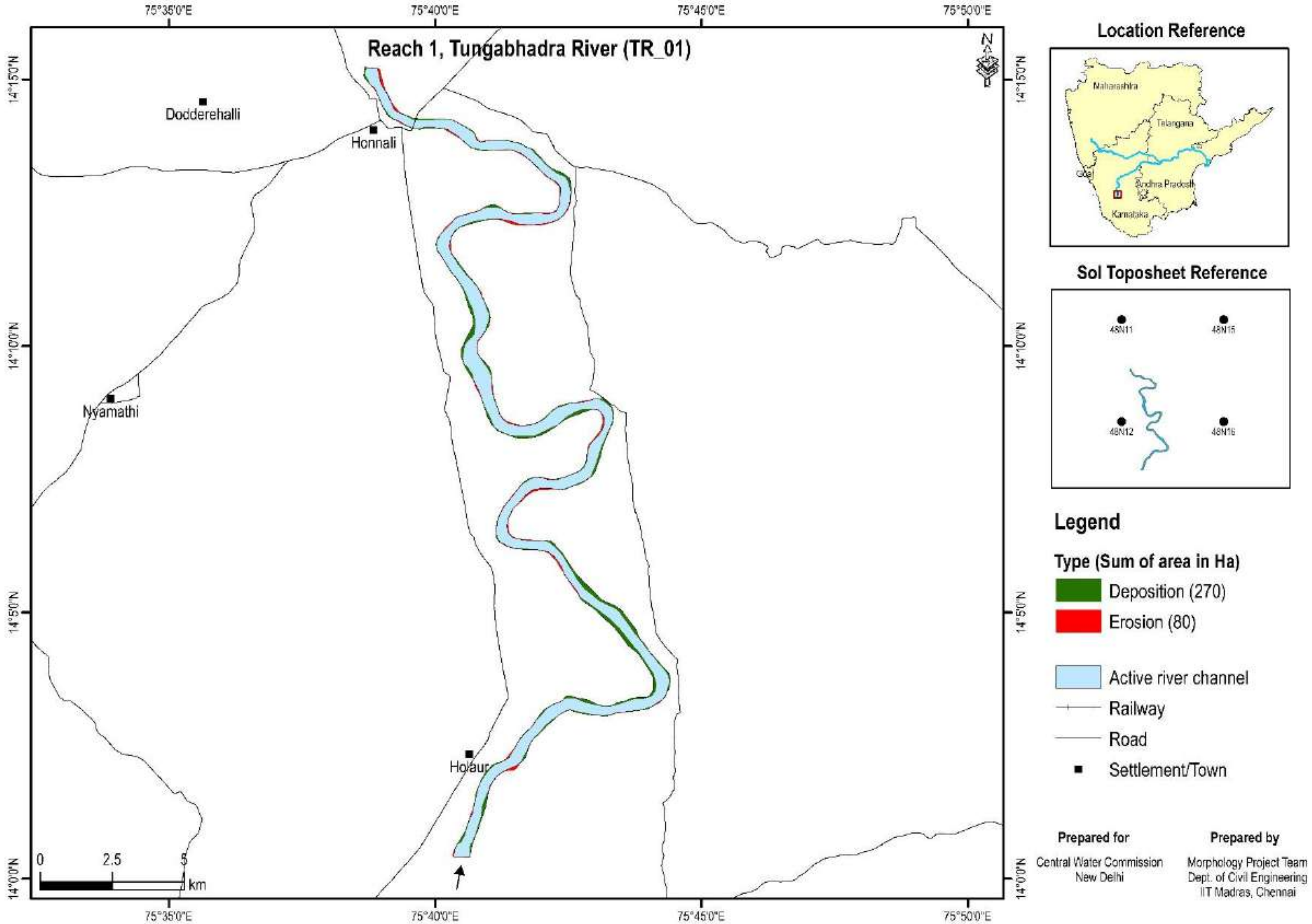


Reach 27, Krishna River (KR_27)
80°55'0"E
15°45'0"N
Lankevanidibba
Nachugunta
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
SoI Toposheet Reference
66E1
66A13
66A14
Legend
Type (Sum of area in Ha)
Deposition (20)
Erosion (190)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai


Reach 1, Tungabhadra River (TR_01)
75°35'0"E
75°40'0"E
75°45'0"E
75°50'0"E
14°15'0"N
14°10'0"N
14°5'0"N
14°0'0"N
Dodderehalli
Honnali
Nyamathi
Holaur
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
48N11
48N15
48N12
48N16
Legend
Type (Sum of area in Ha)
Deposition (270)
Erosion (80)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
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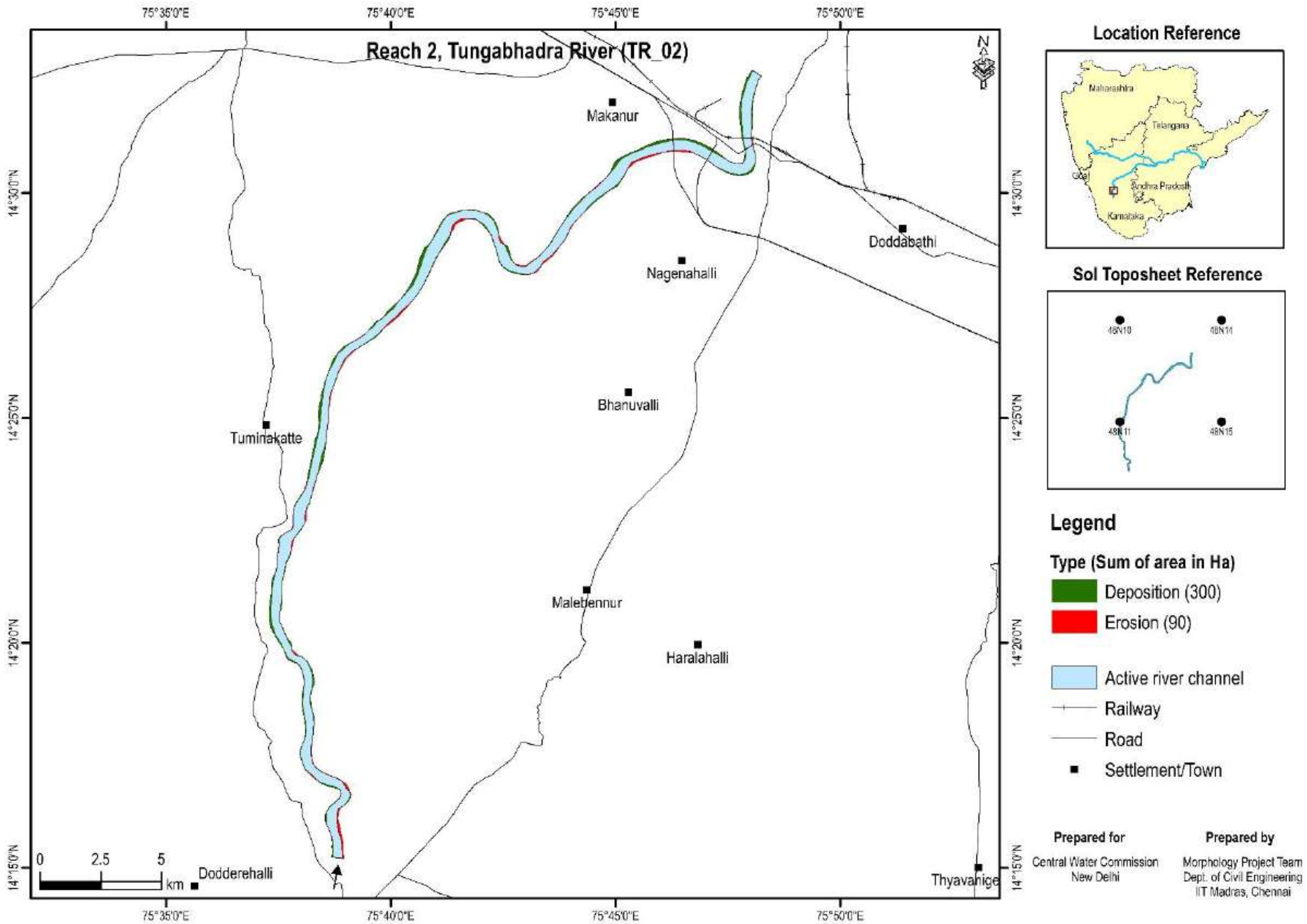
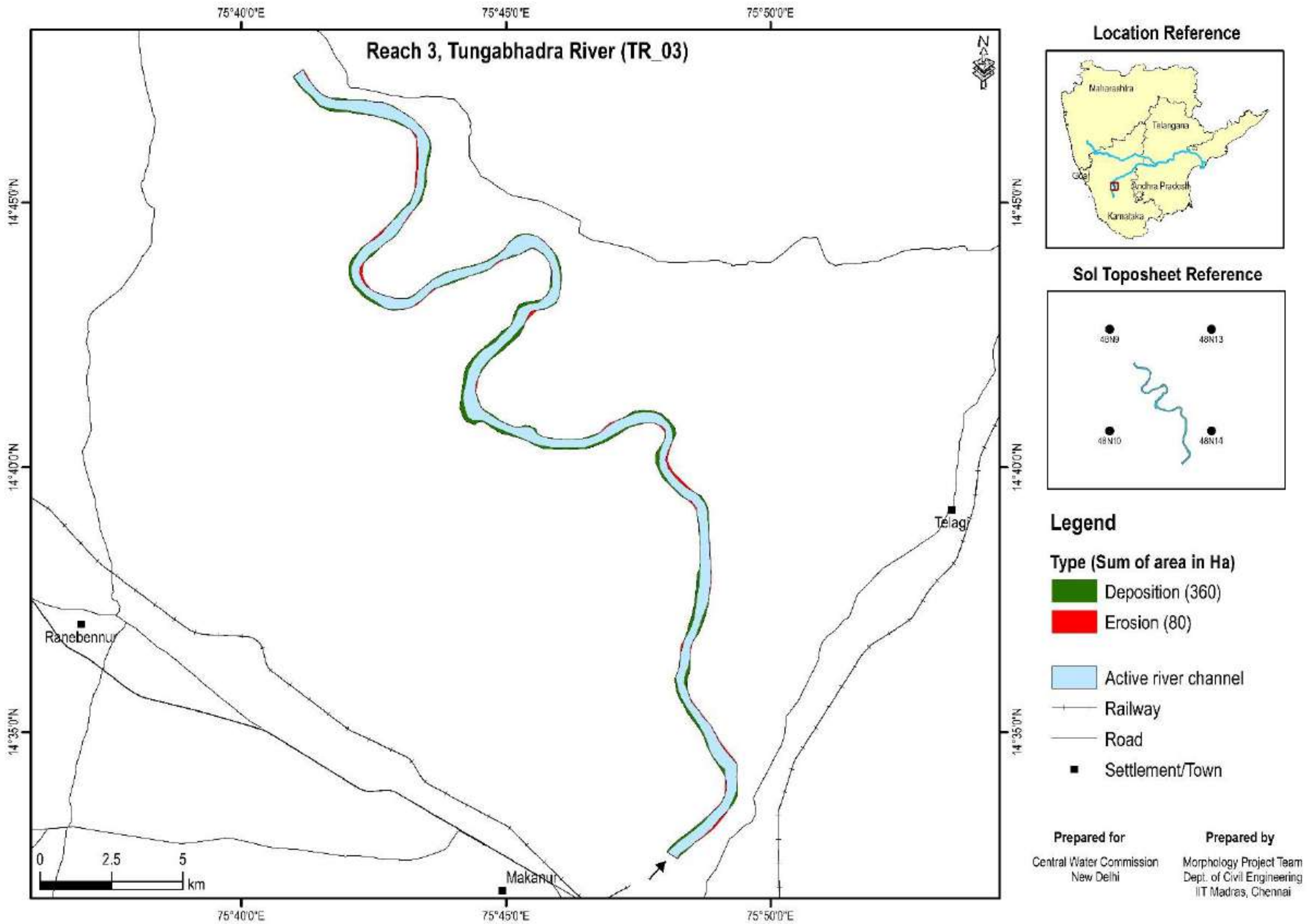
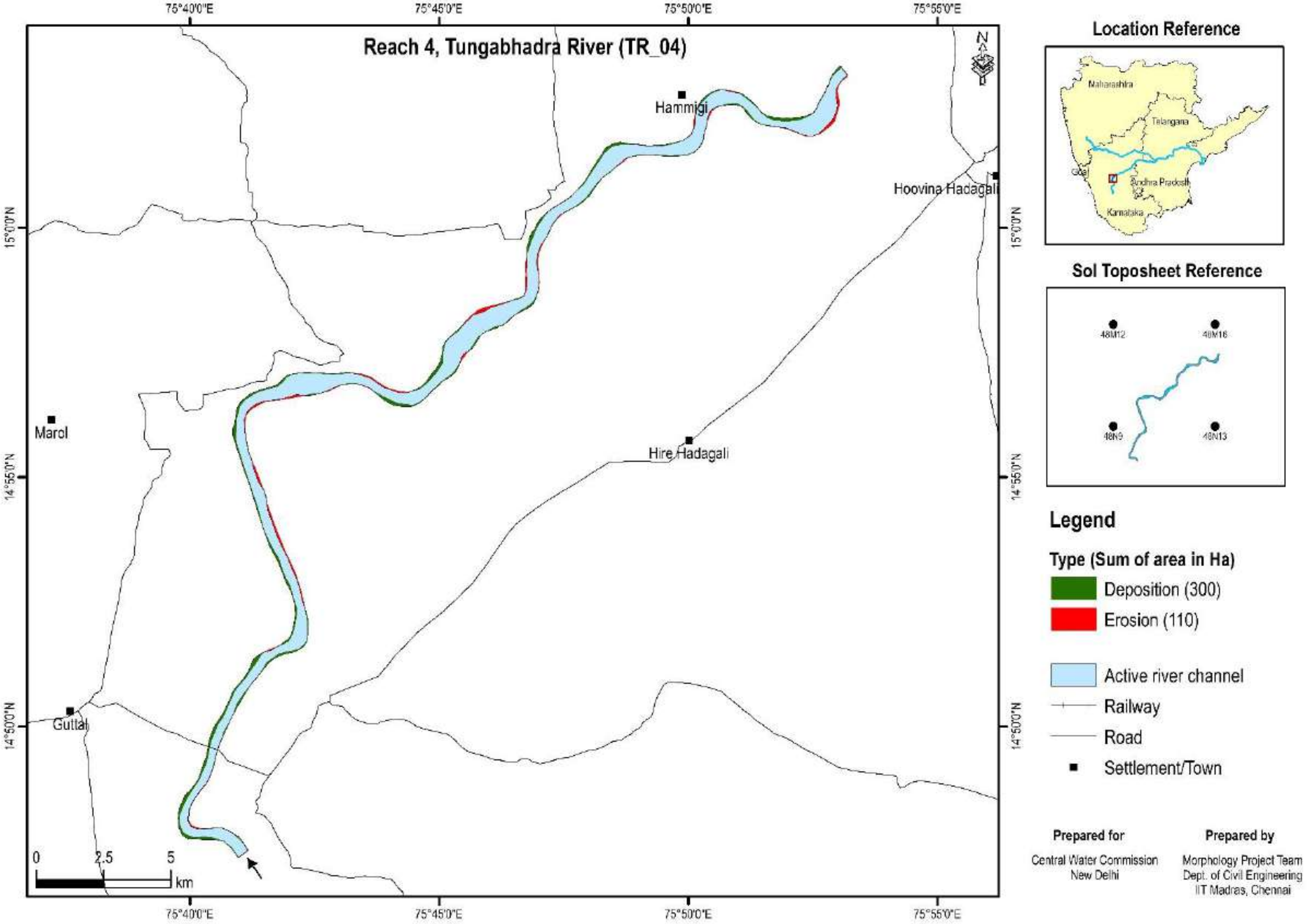
IIT Madras, Chennai

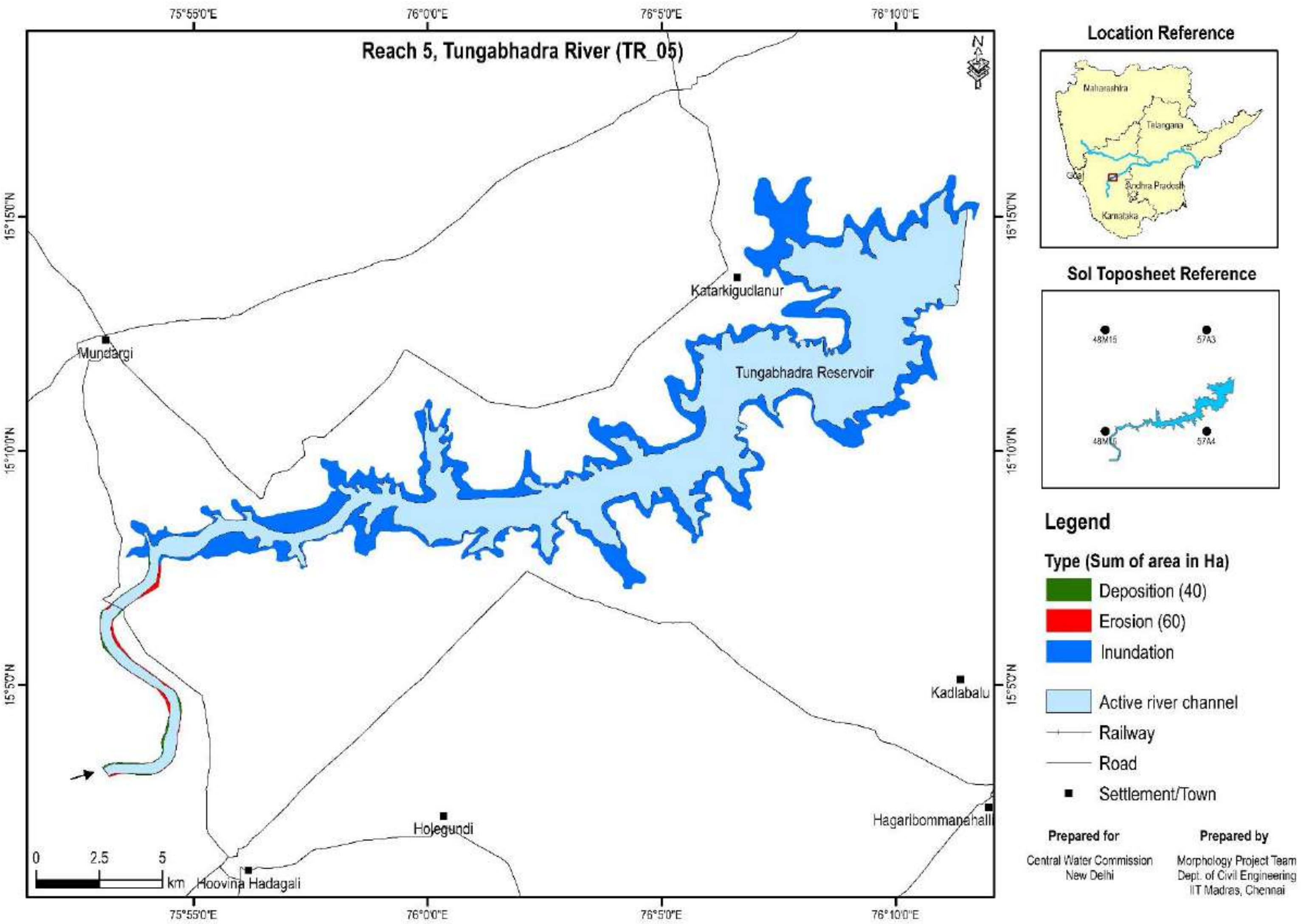


Reach 2, Tungabhadra River (TR_02)
75°35'0"E
75°40'0"E
75°45'0"E
75°50'0"E
14°30'0"N
14°25'0"N
14°20'0"N
14°15'0"N
N
Makanur
Doddabathi
Nagenahalli
Bhanuvalli
Tuminakatte
Malebennur
Haralahalli
Dodderehalli
Thyavanige
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
48N10
48N14
48N11
48N15
Legend
Type (Sum of area in Ha)
Deposition (300)
Erosion (90)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai

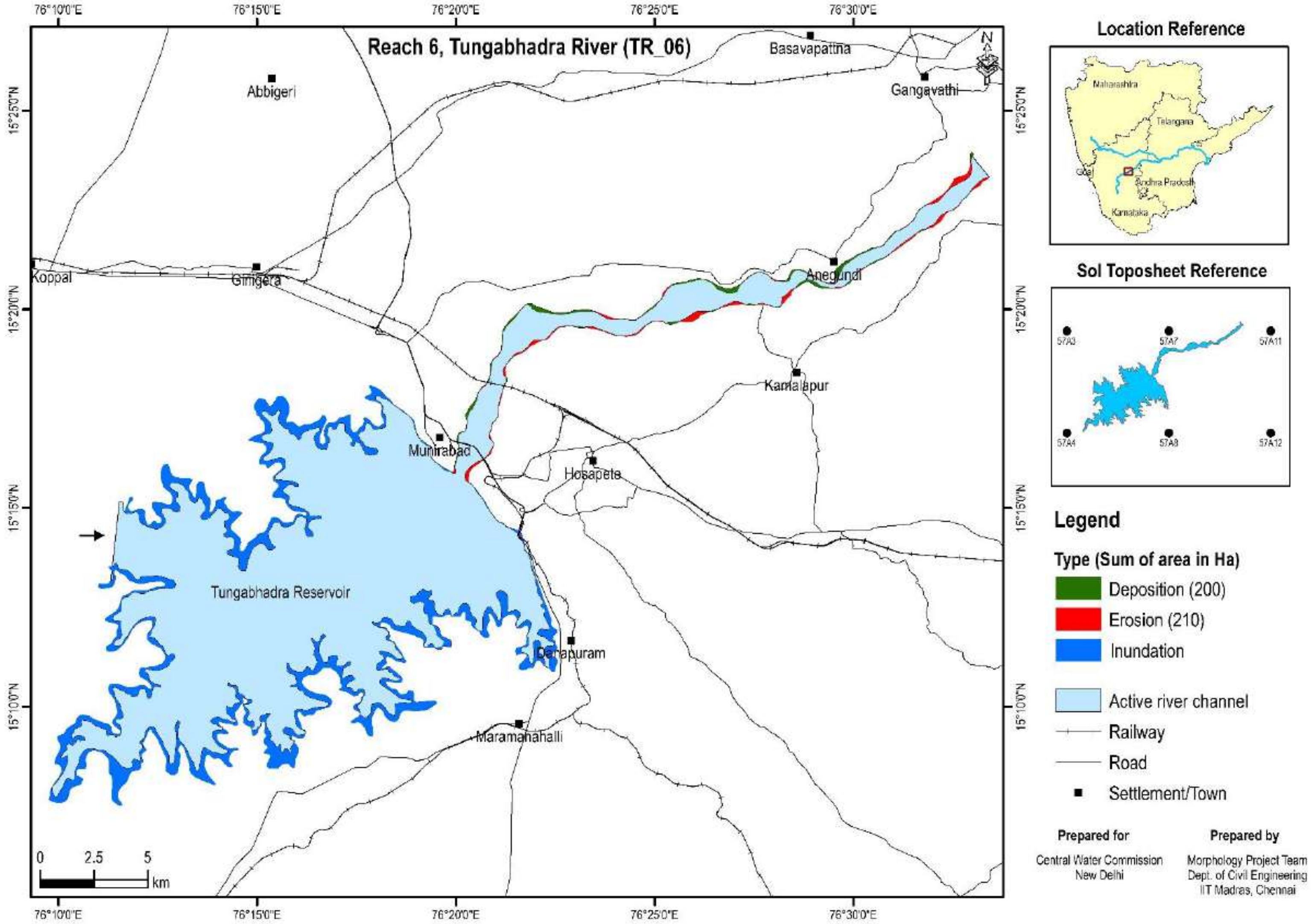

Reach 3, Tungabhadra River (TR_03)
75°40'0"E
75°45'0"E
75°50'0"E
14°45'0"N
14°40'0"N
14°35'0"N
Telagi
Ranebennur
Makanur
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
48N9
48N13
48N10
48N14
Legend
Type (Sum of area in Ha)
Deposition (360)
Erosion (80)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai



Reach 4, Tungabhadra River (TR_04)
75°40'0"E
75°45'0"E
75°50'0"E
75°55'0"E
15°0'0"N
14°55'0"N
14°50'0"N
Hammigi
Hoovina Hadagali
Marol
Hire Hadagali
Guttal
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
48M12
48M16
48N9
48N13
Legend
Type (Sum of area in Ha)
Deposition (300)
Erosion (110)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai



Reach 5, Tungabhadra River (TR_05)
75°55'0"E
76°0'0"E
76°5'0"E
76°10'0"E
15°15'0"N
15°10'0"N
15°5'0"N
Katarkigudlanur
Mundargi
Tungabhadra Reservoir
Kadlabalu
Holegundi
Hagaribommanahalli
Hoovina Hadagali
0
2.5
5
km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
48M15
57A3
48M16
57A4
Legend
Type (Sum of area in Ha)
Deposition (40)
Erosion (60)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai



Reach 6, Tungabhadra River (TR_06)
76°10'0"E
76°15'0"E
76°20'0"E
76°25'0"E
76°30'0"E
15°25'0"N
15°20'0"N
15°15'0"N
15°10'0"N
Basavapattna
Abbigeri
Gangavathi
Koppal
Ginigera
Anegundi
Kamalapur
Munirabad
Hosapete
Tungabhadra Reservoir
Darapuram
Maramahahalli
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
57A3
57A7
57A11
57A4
57A8
57A12
Legend
Type (Sum of area in Ha)
Deposition (200)
Erosion (210)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
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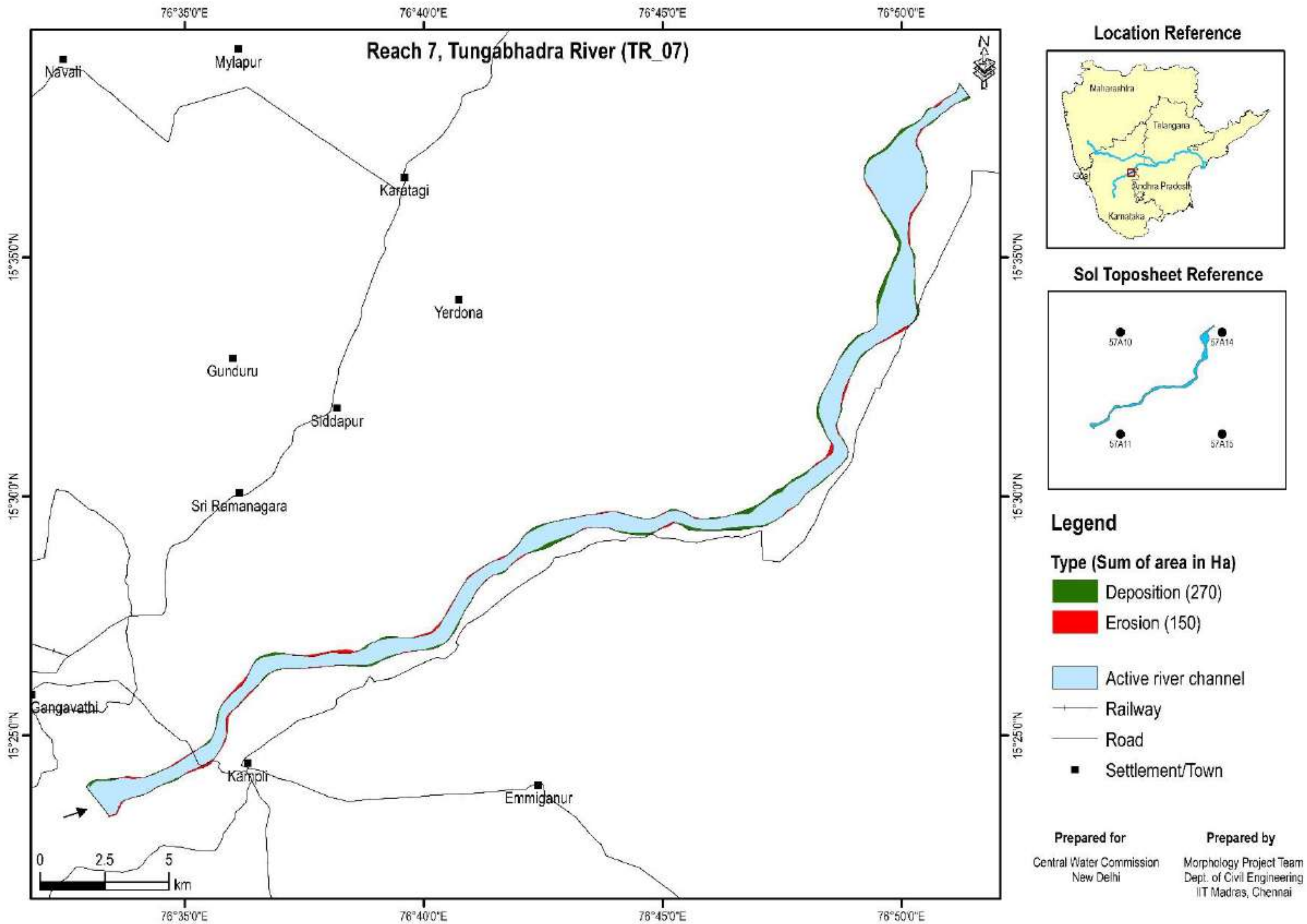
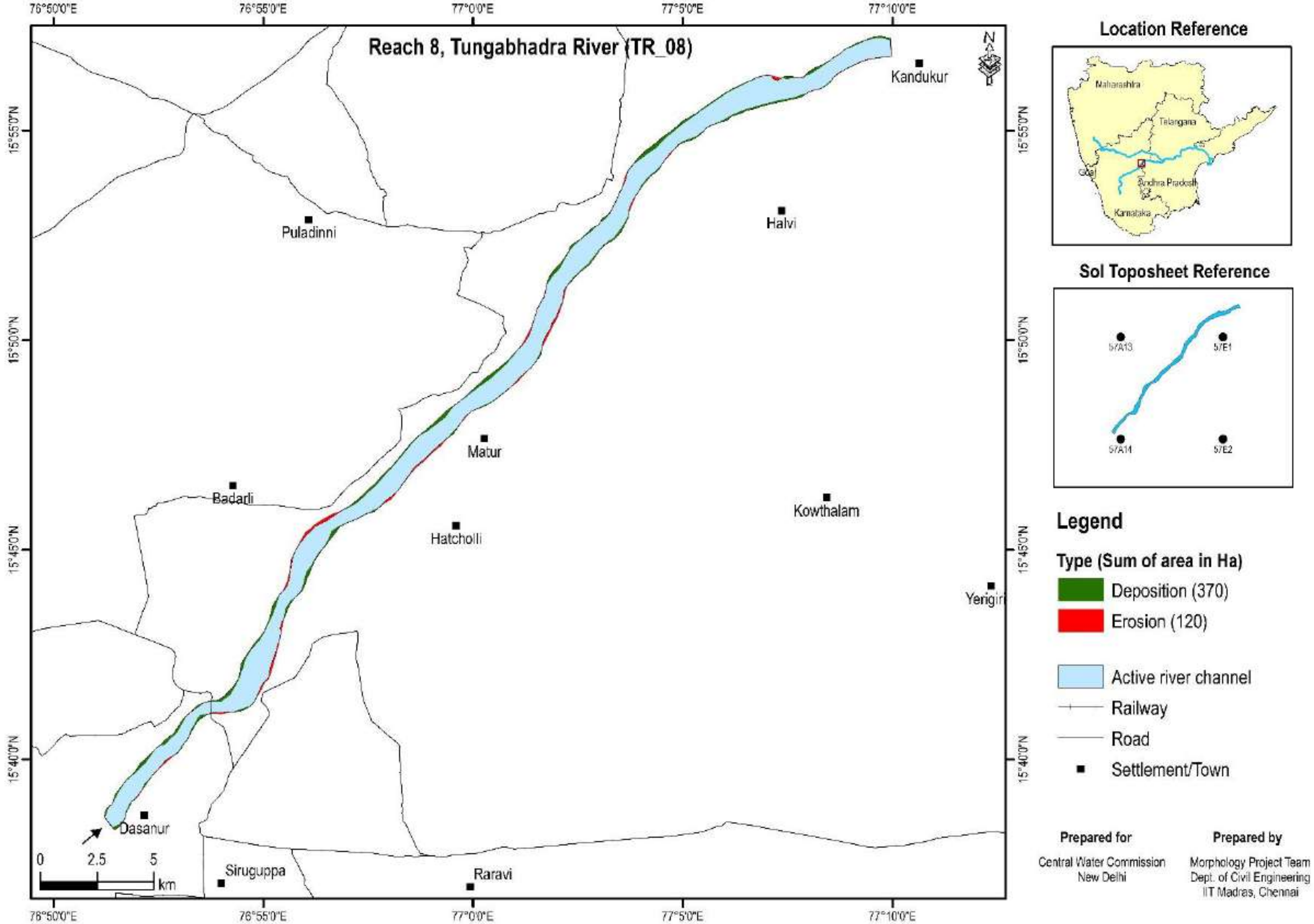
IIT Madras, Chennai


Reach 7, Tungabhadra River (TR_07)
76°35'0"E
76°40'0"E
76°45'0"E
76°50'0"E
15°35'0"N
15°30'0"N
15°25'0"N
Navali
Mylapur
Karatagi
Yerdona
Gunduru
Siddapur
Sri Ramanagara
Gangavathi
Kampli
Emmiganur
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Goa
Karnataka
SoI Toposheet Reference
57A10
57A14
57A11
57A15
Legend
Type (Sum of area in Ha)
Deposition (270)
Erosion (150)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai



Reach 8, Tungabhadra River (TR_08)
76°50'0"E
76°55'0"E
77°0'0"E
77°5'0"E
77°10'0"E
15°55'0"N
15°50'0"N
15°45'0"N
15°40'0"N
Kandukur
Puladinni
Halvi
Matur
Badarli
Kowthalam
Hatcholli
Yerigiri
Dasanur
Siruguppa
Raravi
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
57A13
57E1
57A14
57E2
Legend
Type (Sum of area in Ha)
Deposition (370)
Erosion (120)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
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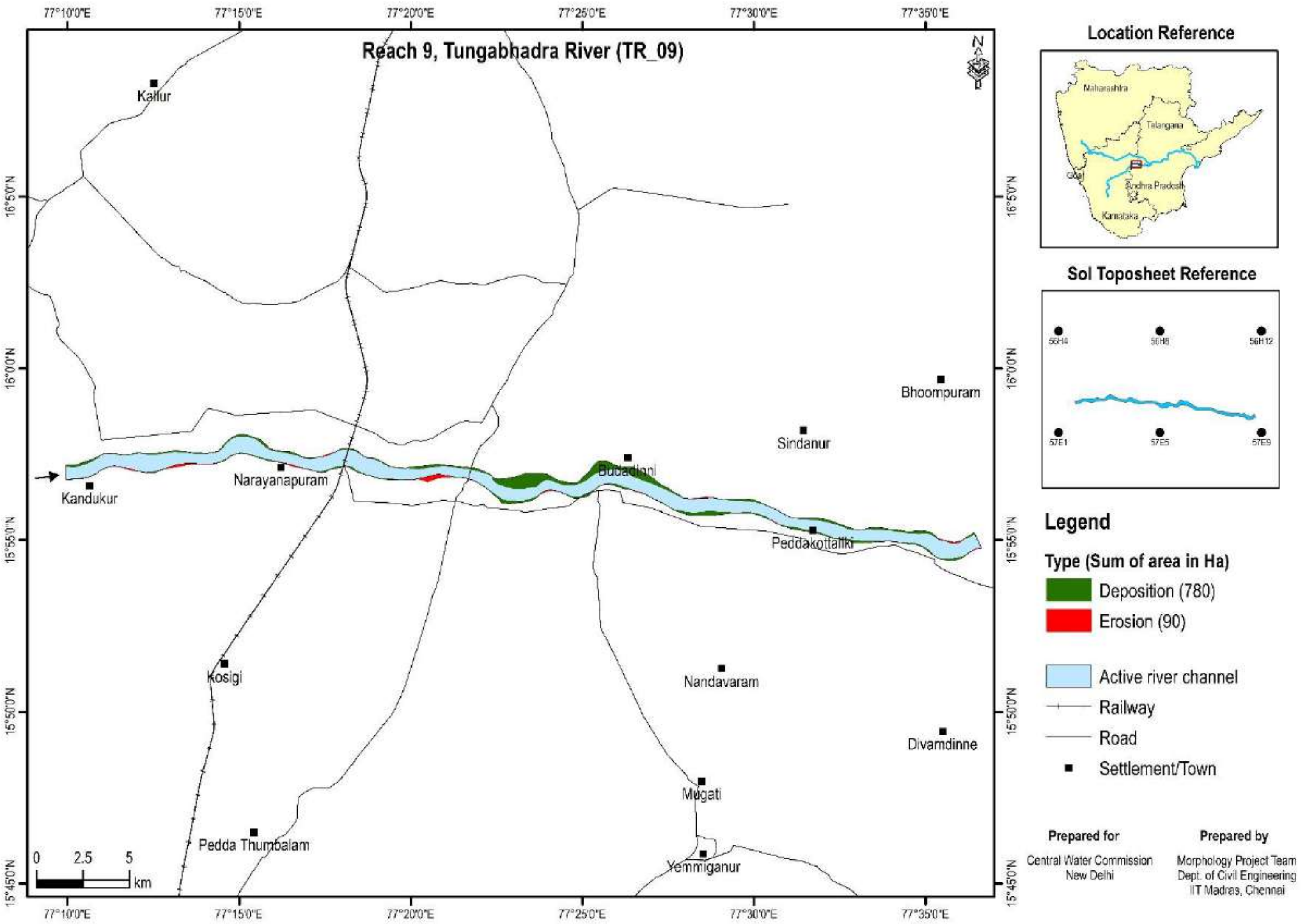
Reach 9, Tungabhadra River (TR_09)
77°10'0"E
77°15'0"E
77°20'0"E
77°25'0"E
77°30'0"E
77°35'0"E
16°5'0"N
16°0'0"N
15°55'0"N
15°50'0"N
15°45'0"N
Kallur
Bhoompuram
Sindanur
Budadinni
Narayanapuram
Kandukur
Peddakottaliki
Kosigi
Nandavaram
Divamdinne
Mugati
Pedda Thumbalam
Yemmiganur
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Goa
Andhra Pradesh
Karnataka
SoI Toposheet Reference
56H4
56H8
56H12
57E1
57E5
57E9
Legend
Type (Sum of area in Ha)
Deposition (780)
Erosion (90)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
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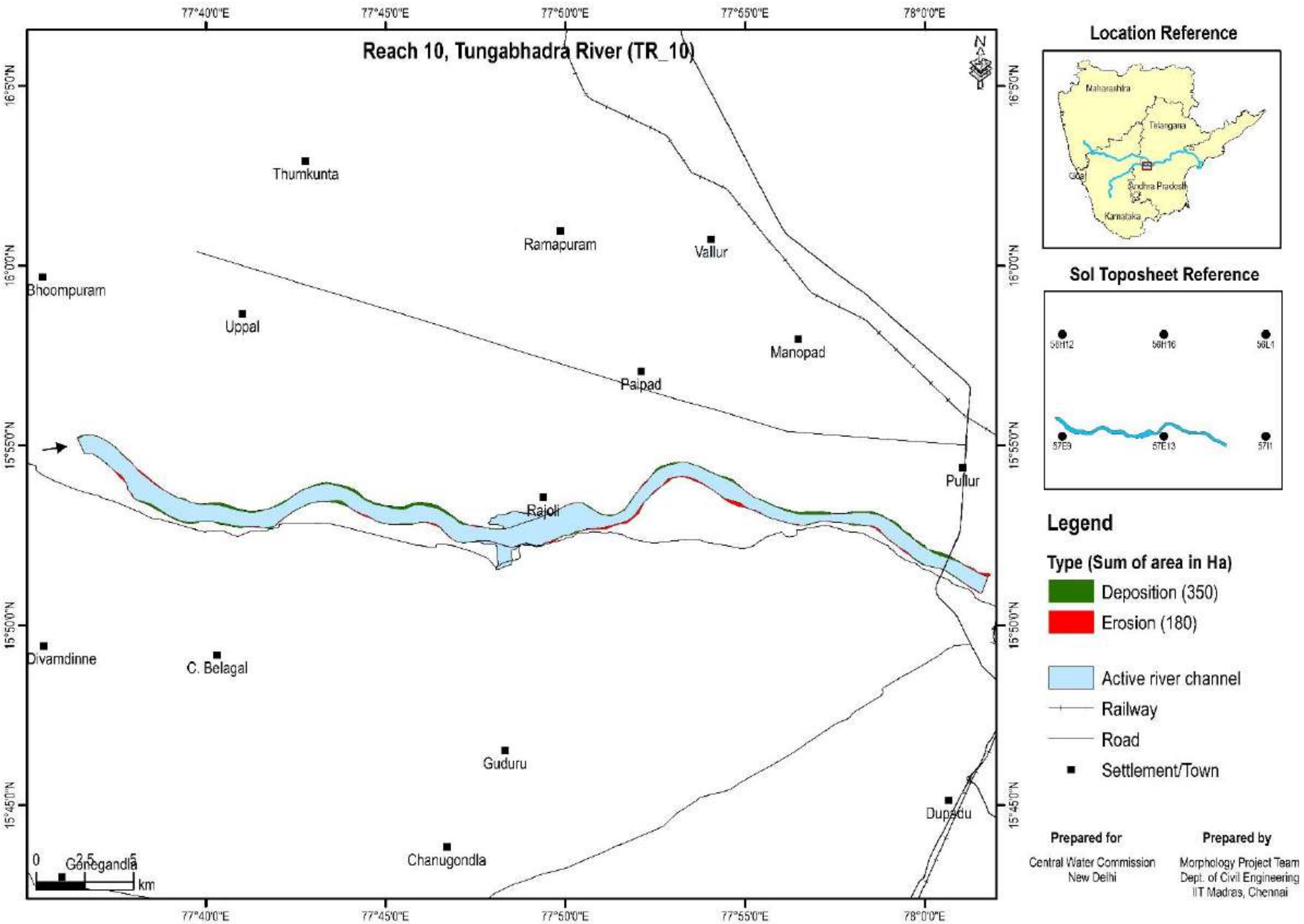
Reach 10, Tungabhadra River (TR_10)
77°40'0"E
77°45'0"E
77°50'0"E
77°55'0"E
78°0'0"E
16°5'0"N
16°0'0"N
15°55'0"N
15°50'0"N
15°45'0"N
Thumkunta
Ramapuram
Vallur
Bhoompuram
Uppal
Manopad
Paipad
Pullur
Rajoli
Divamdinne
C. Belagal
Guduru
Dupadu
Chanugondla
Gonegandla
0 2.5 5 km
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
SoI Toposheet Reference
Legend
Type (Sum of area in Ha)
Deposition (350)
Erosion (180)
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
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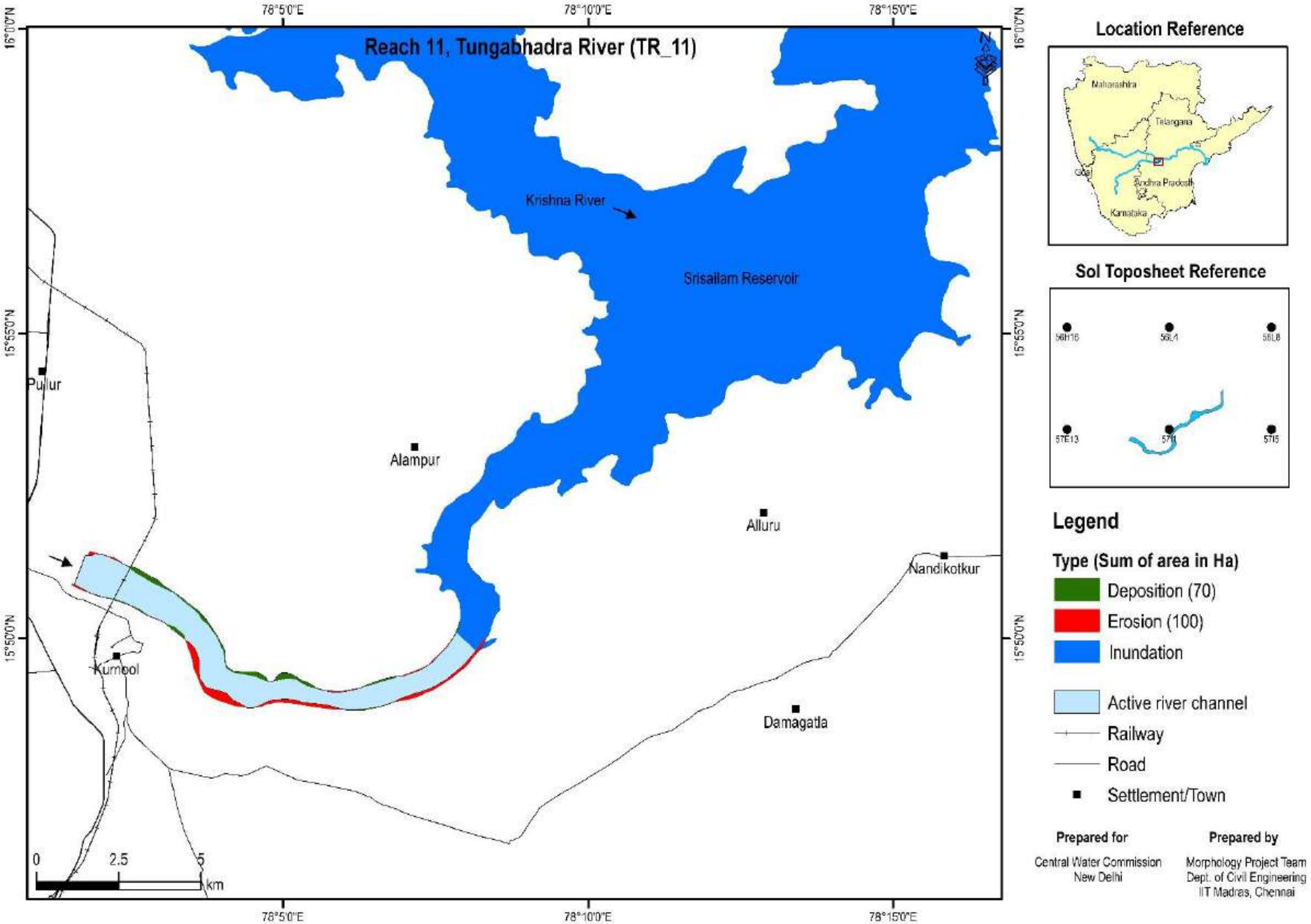
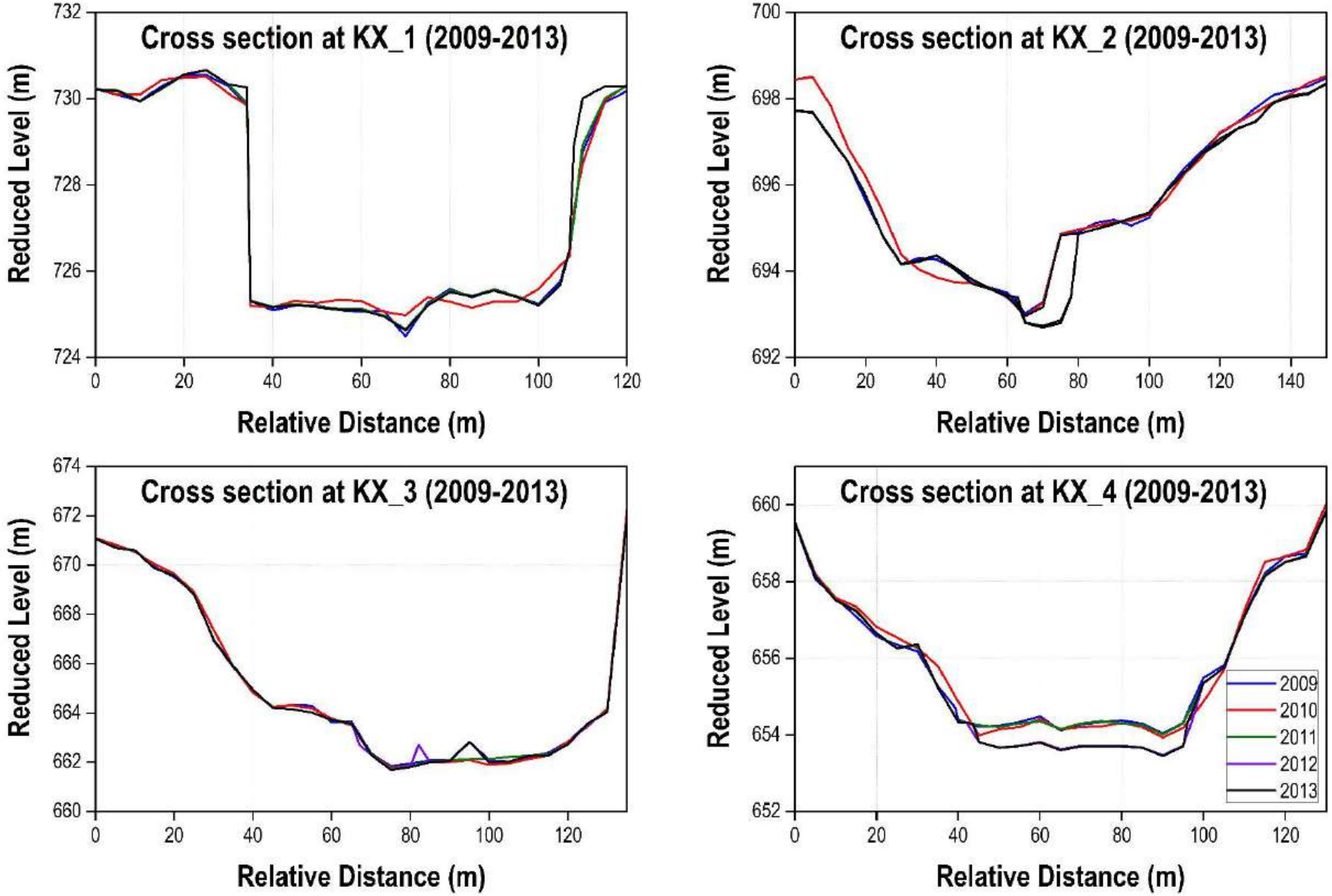
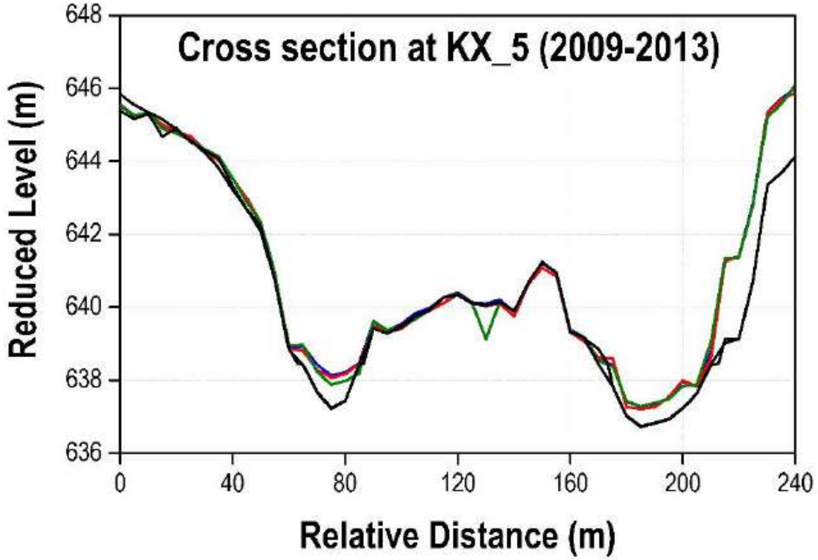
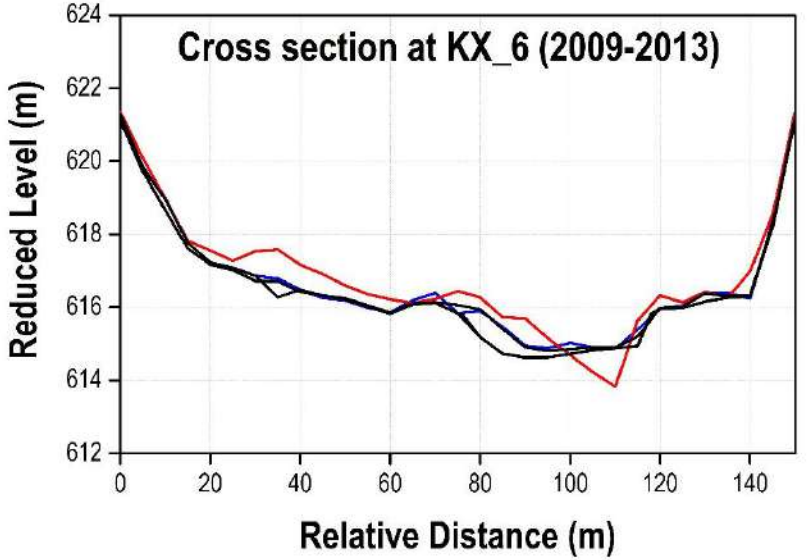


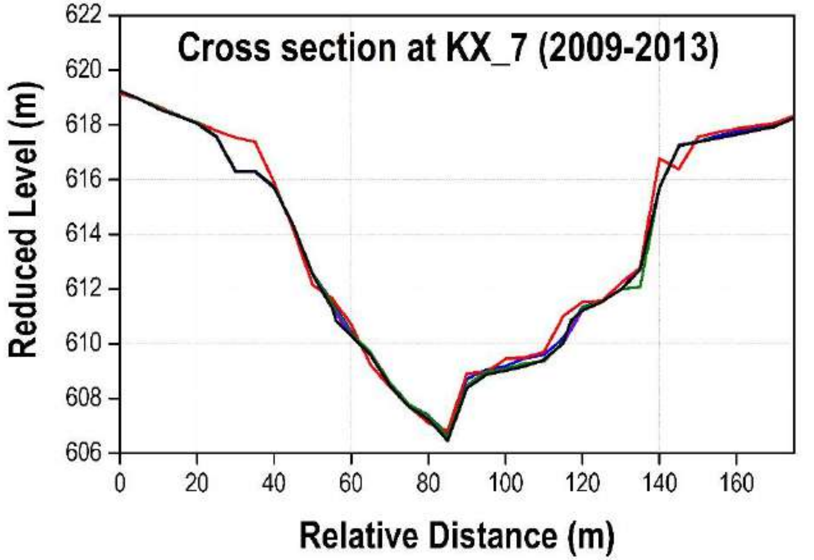
Reach 11, Tungabhadra River (TR_11)
Krishna River
Srisailam Reservoir
Pullur
Alampur
Alluru
Nandikotkur
Kurnool
Damagatla
0
2.5
5
km
78°5'0"E
78°10'0"E
78°15'0"E
16°0'0"N
15°55'0"N
15°50'0"N
Location Reference
Maharashtra
Telangana
Andhra Pradesh
Karnataka
Goa
SoI Toposheet Reference
Legend
Type (Sum of area in Ha)
Deposition (70)
Erosion (100)
Inundation
Active river channel
Railway
Road
Settlement/Town
Prepared for
Central Water Commission
New Delhi
Prepared by
Morphology Project Team
Dept. of Civil Engineering
IIT Madras, Chennai

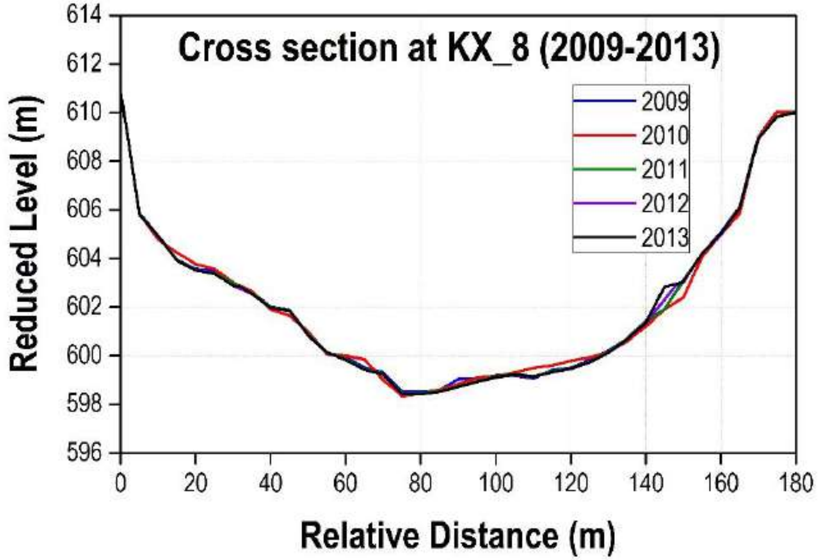
Appendix XVI: Cross-section diagram of the transects of Krishna and Tungabhadra rivers

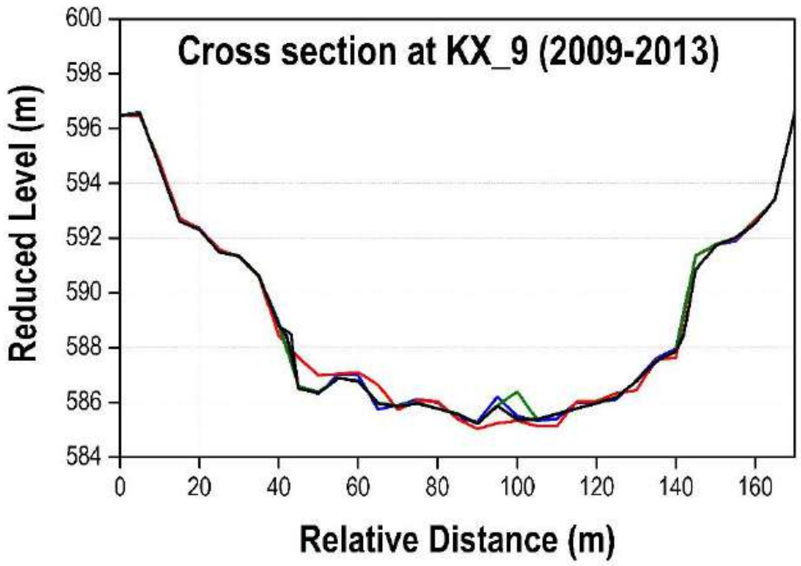


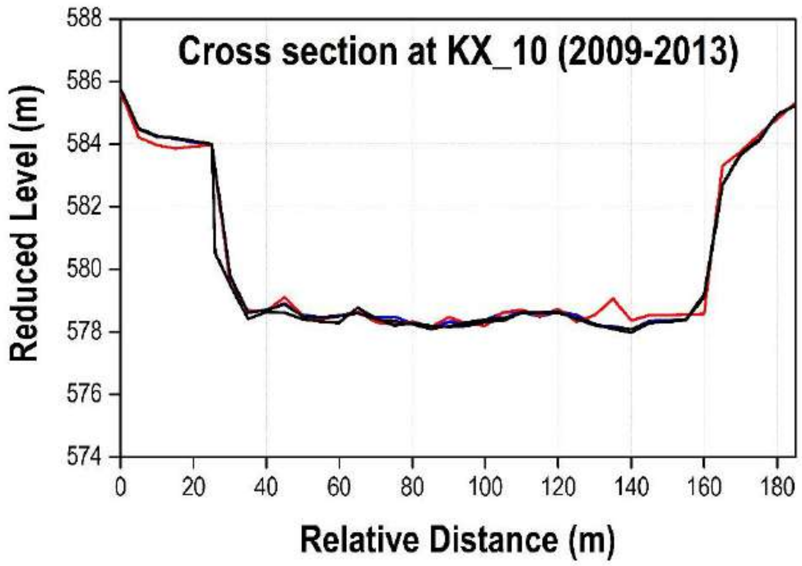

Cross section at KX_5 (2009-2013)
Reduced Level (m)
Relative Distance (m)
636
638
640
642
644
646
648
0
40
80
120
160
200
240

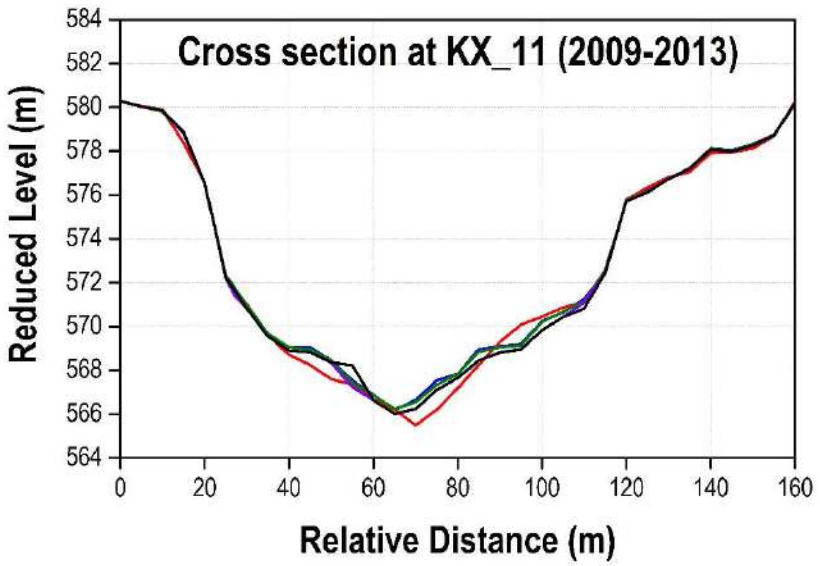

Cross section at KX_6 (2009-2013)
Reduced Level (m)
Relative Distance (m)
612
614
616
618
620
622
624
0
20
40
60
80
100
120
140

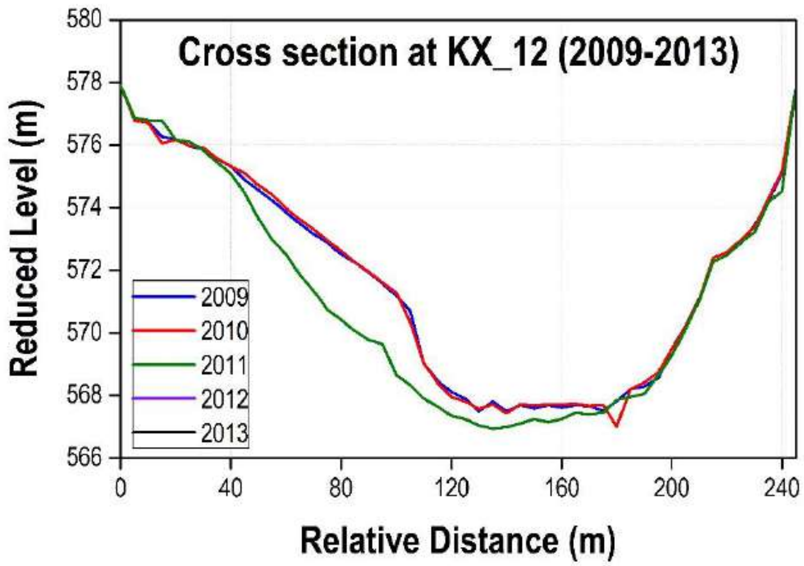

Cross section at KX_7 (2009-2013)
Reduced Level (m)
Relative Distance (m)
606
608
610
612
614
616
618
620
622
0
20
40
60
80
100
120
140
160

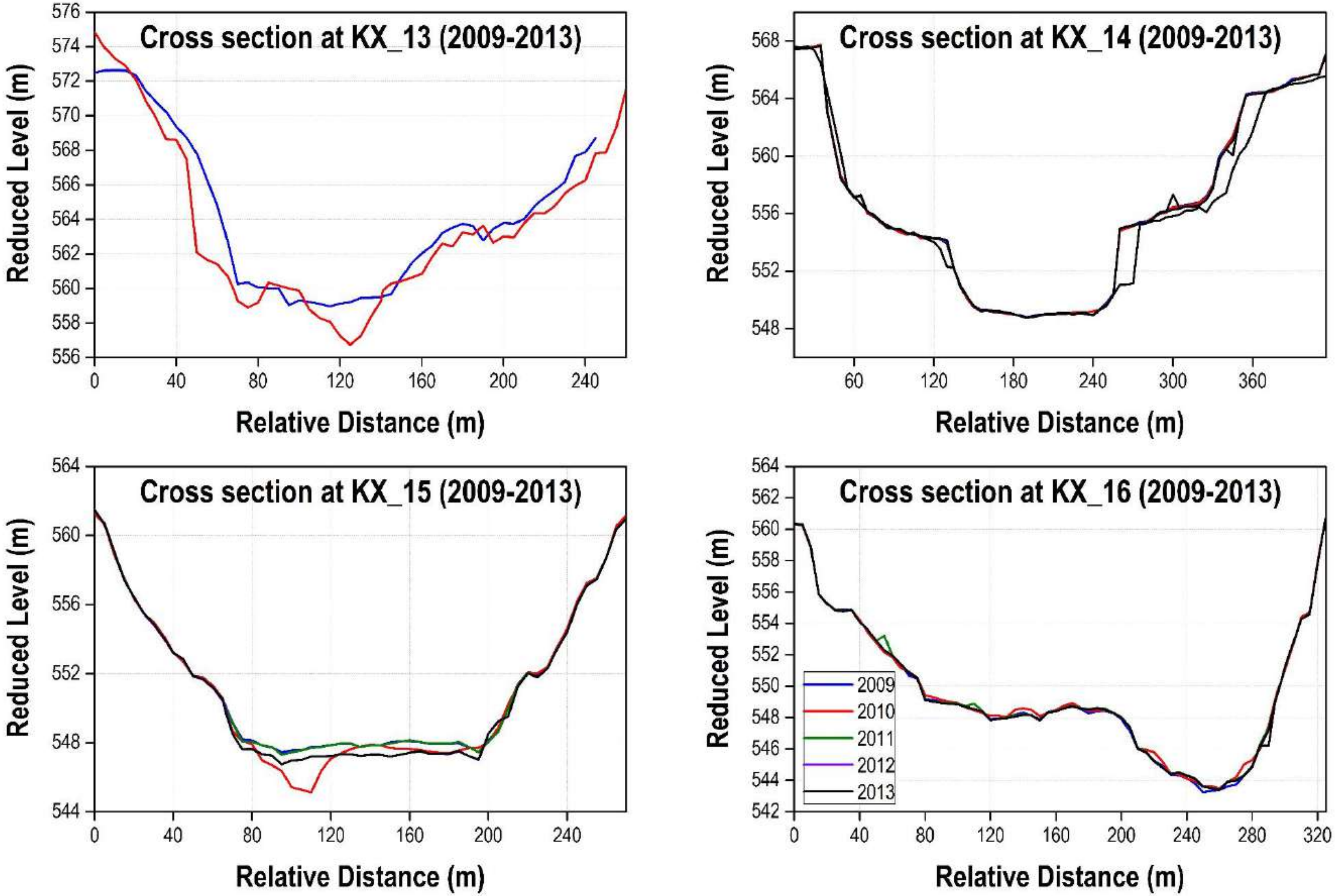

Cross section at KX_8 (2009-2013)
2009
2010
2011
2012
2013
Reduced Level (m)
Relative Distance (m)
596
598
600
602
604
606
608
610
612
614
0
20
40
60
80
100
120
140
160
180


Cross section at KX_9 (2009-2013)
Reduced Level (m)
Relative Distance (m)

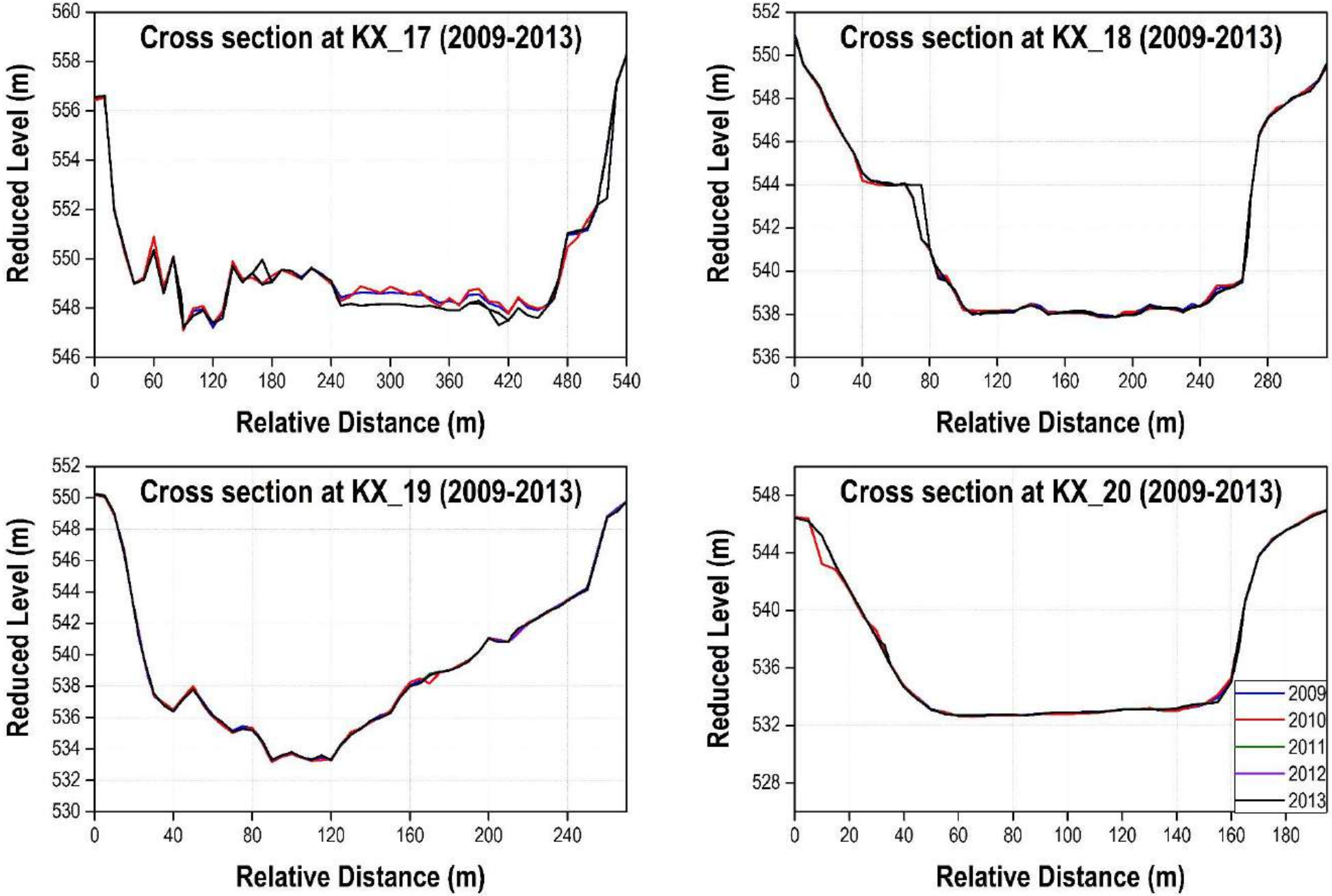

Cross section at KX_10 (2009-2013)
Reduced Level (m)
Relative Distance (m)


Cross section at KX_11 (2009-2013)
Reduced Level (m)
Relative Distance (m)

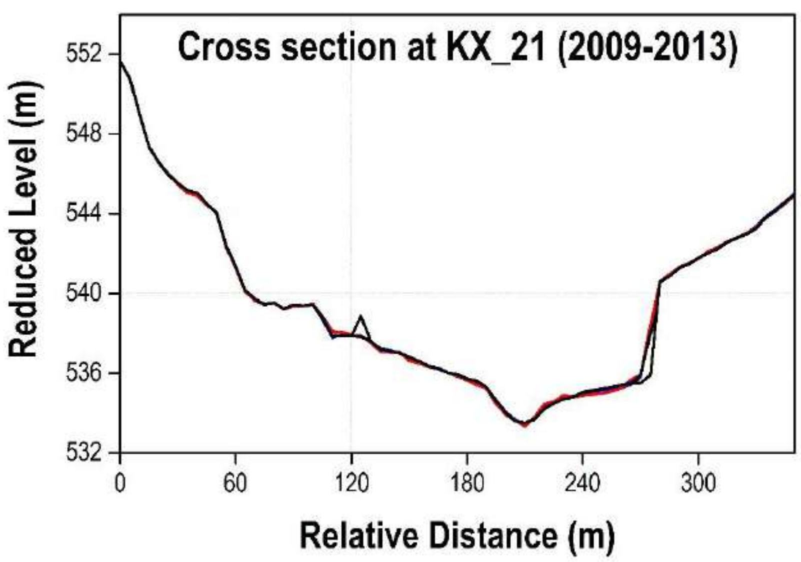

Cross section at KX_12 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013

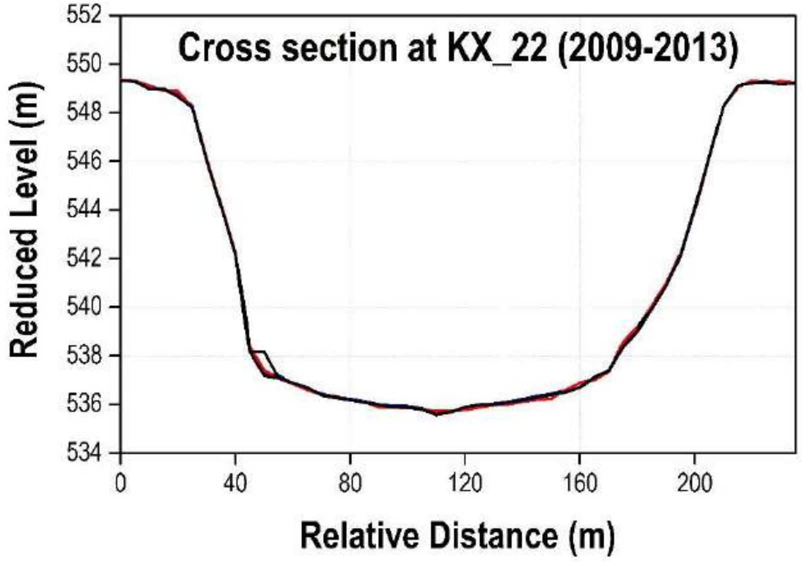


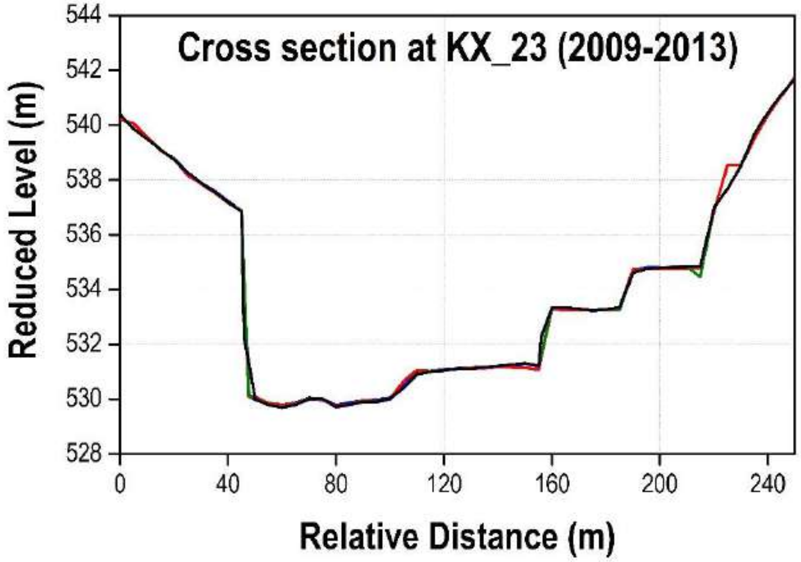
Cross section at KX_13 (2009-2013)
Cross section at KX_14 (2009-2013)
Cross section at KX_15 (2009-2013)
Cross section at KX_16 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013

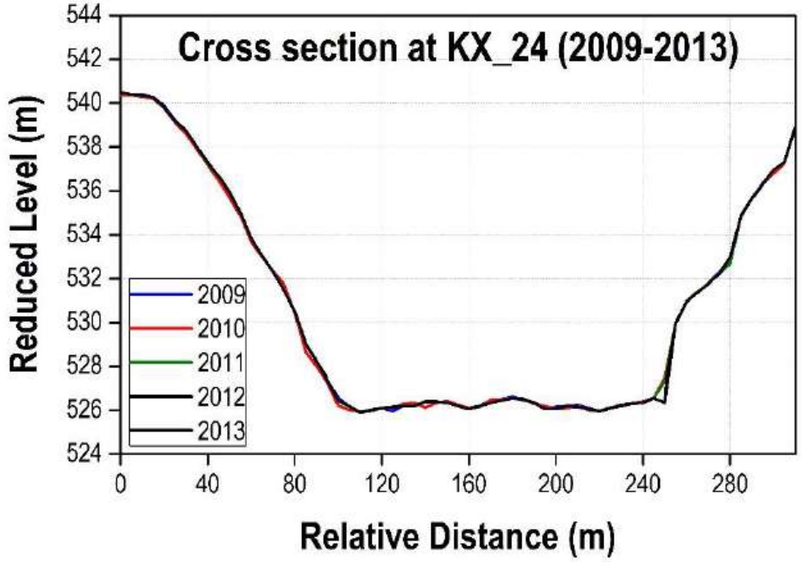


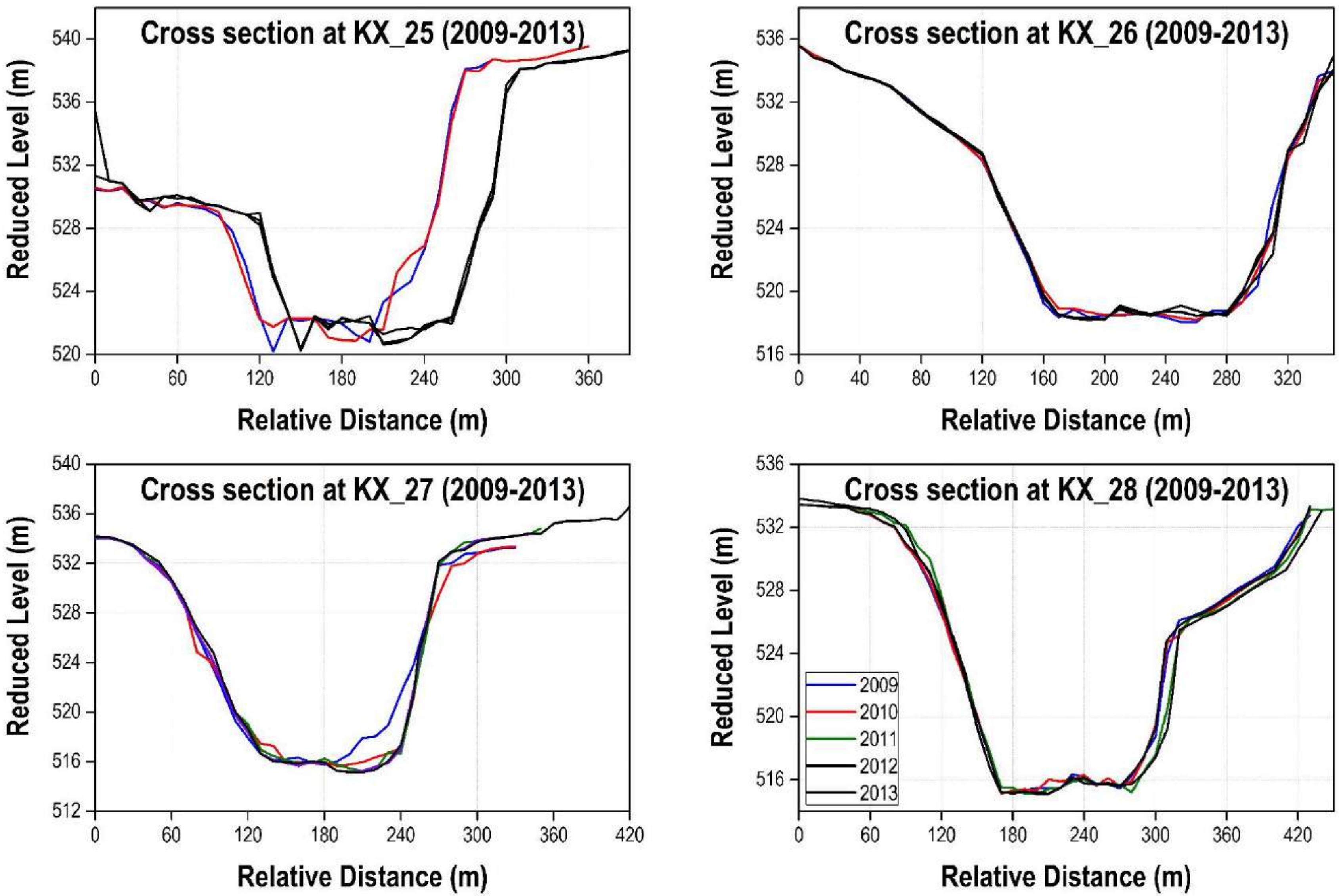
Cross section at KX_17 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_18 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_19 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_20 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013

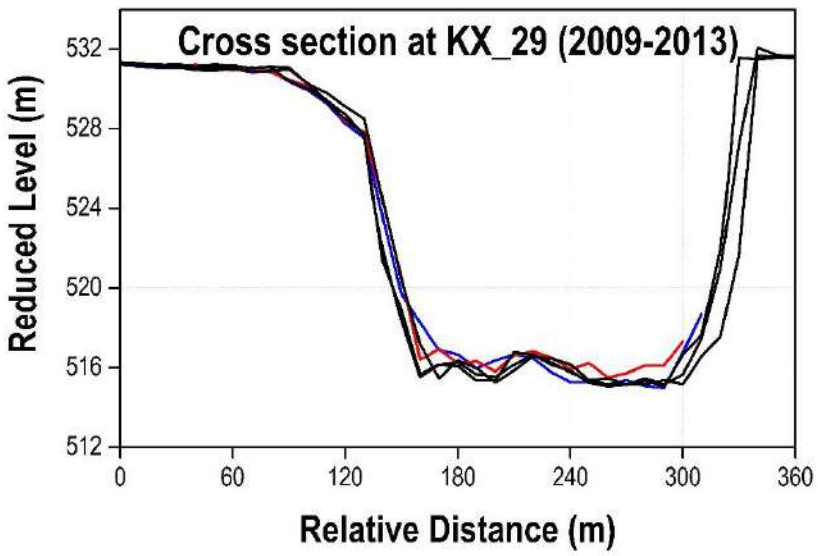

Cross section at KX_21 (2009-2013)
Reduced Level (m)
Relative Distance (m)

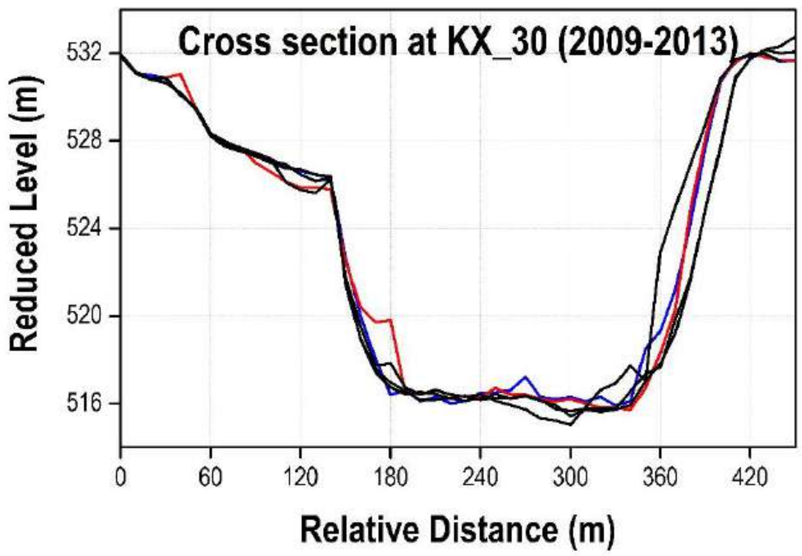

Cross section at KX_22 (2009-2013)
Reduced Level (m)
Relative Distance (m)

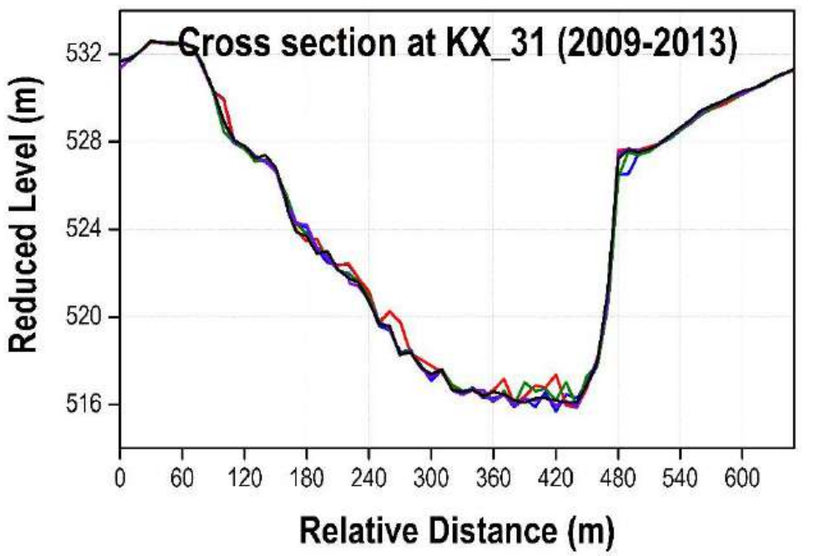

Cross section at KX_23 (2009-2013)
Reduced Level (m)
Relative Distance (m)

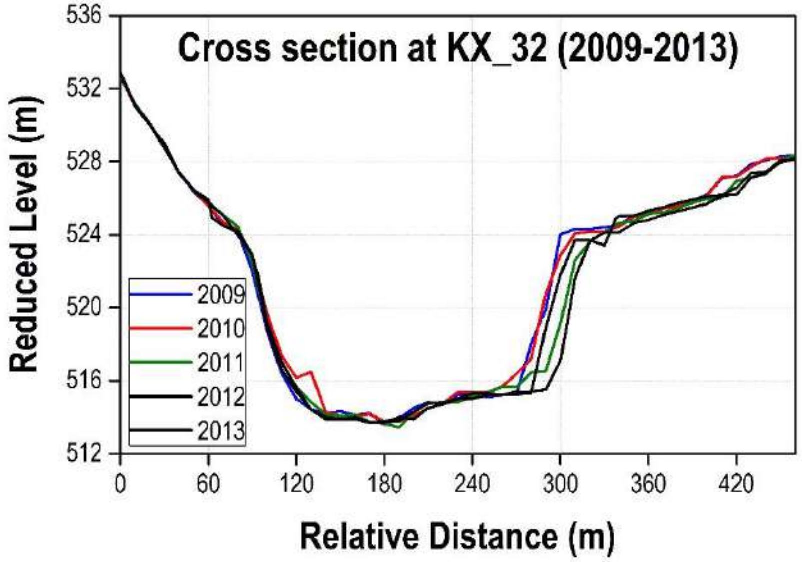

Cross section at KX_24 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013

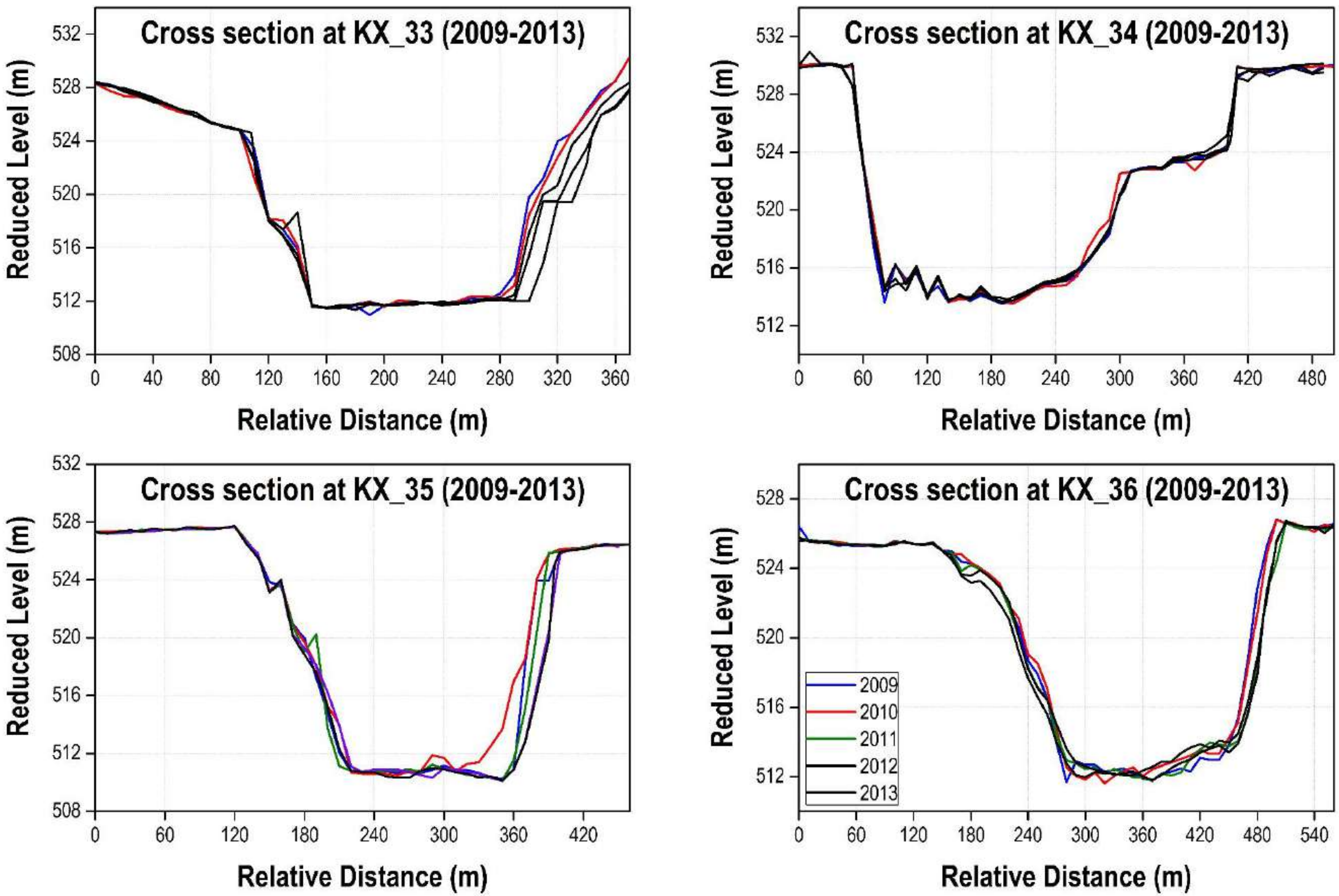

Cross section at KX_25 (2009-2013)
Cross section at KX_26 (2009-2013)
Cross section at KX_27 (2009-2013)
Cross section at KX_28 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013

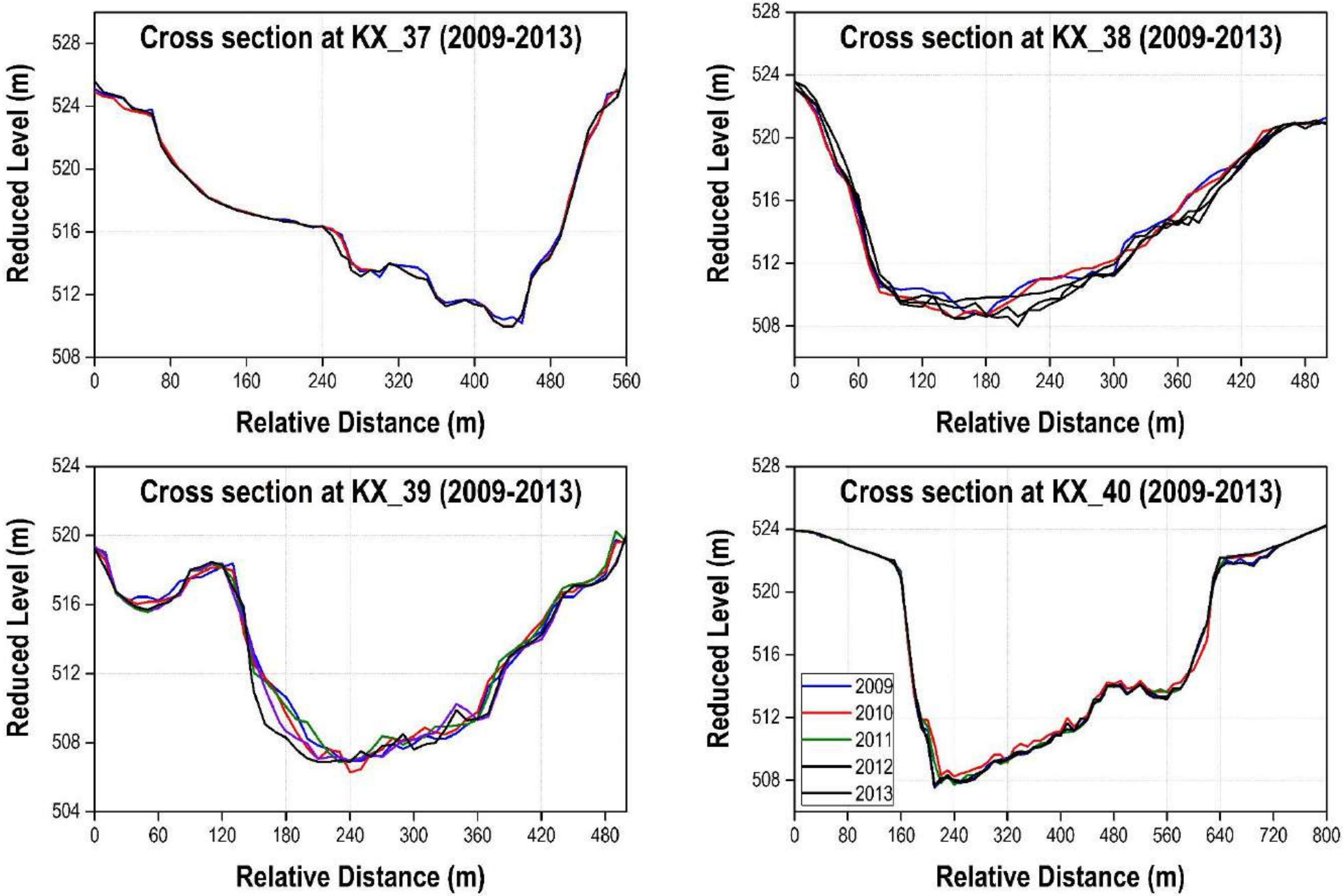

Cross section at KX_29 (2009-2013)
Reduced Level (m)
Relative Distance (m)
532
528
524
520
516
512
0
60
120
180
240
300
360

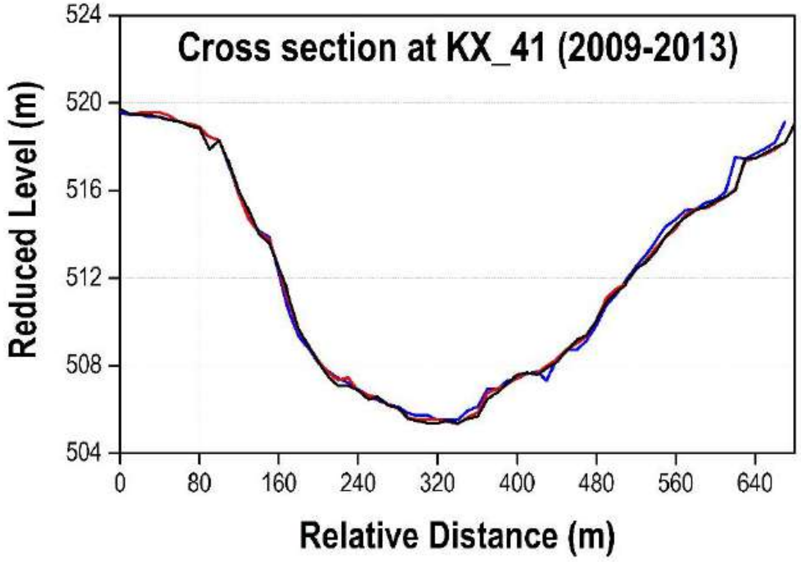

Cross section at KX_30 (2009-2013)
Reduced Level (m)
Relative Distance (m)
532
528
524
520
516
0
60
120
180
240
300
360
420


Cross section at KX_31 (2009-2013)
Reduced Level (m)
Relative Distance (m)
532
528
524
520
516
0
60
120
180
240
300
360
420
480
540
600

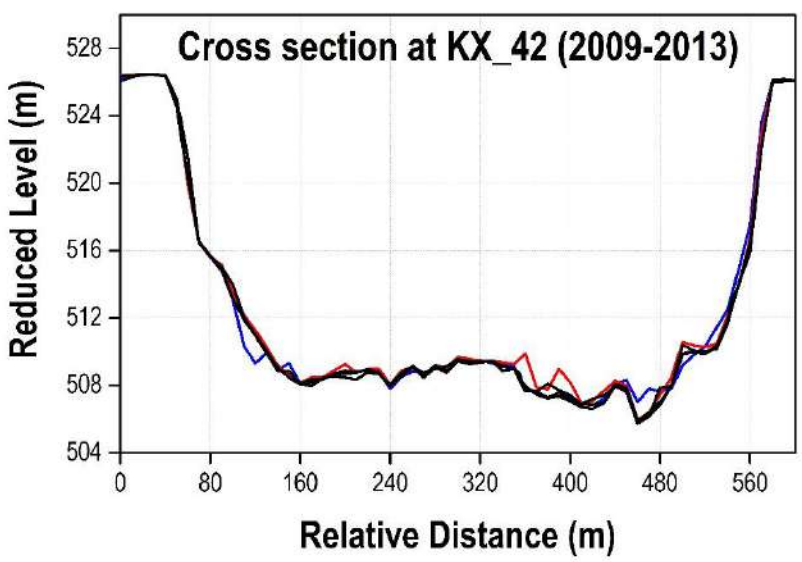

Cross section at KX_32 (2009-2013)
Reduced Level (m)
Relative Distance (m)
536
532
528
524
520
516
512
0
60
120
180
240
300
360
420
2009
2010
2011
2012
2013


Cross section at KX_33 (2009-2013)
Cross section at KX_34 (2009-2013)
Cross section at KX_35 (2009-2013)
Cross section at KX_36 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013

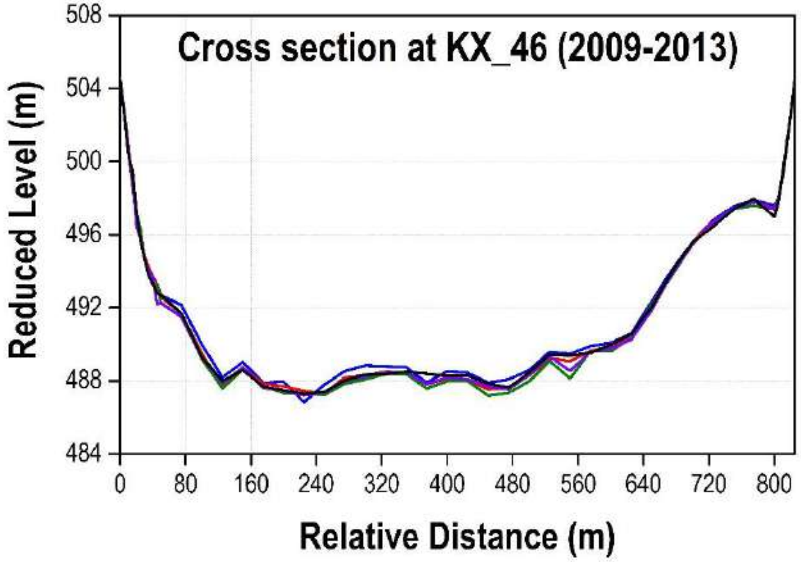

Cross section at KX_37 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_38 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_39 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_40 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013



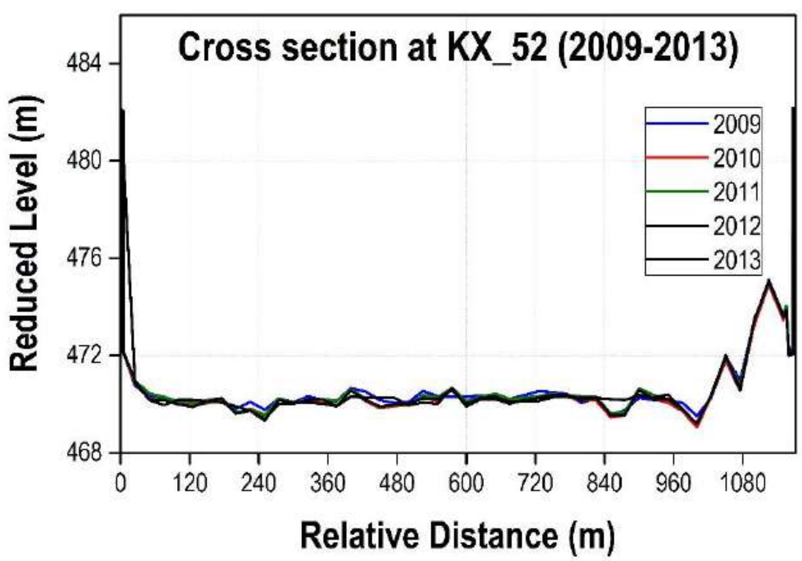
Cross section at KX_41 (2009-2013)
Reduced Level (m)
Relative Distance (m)



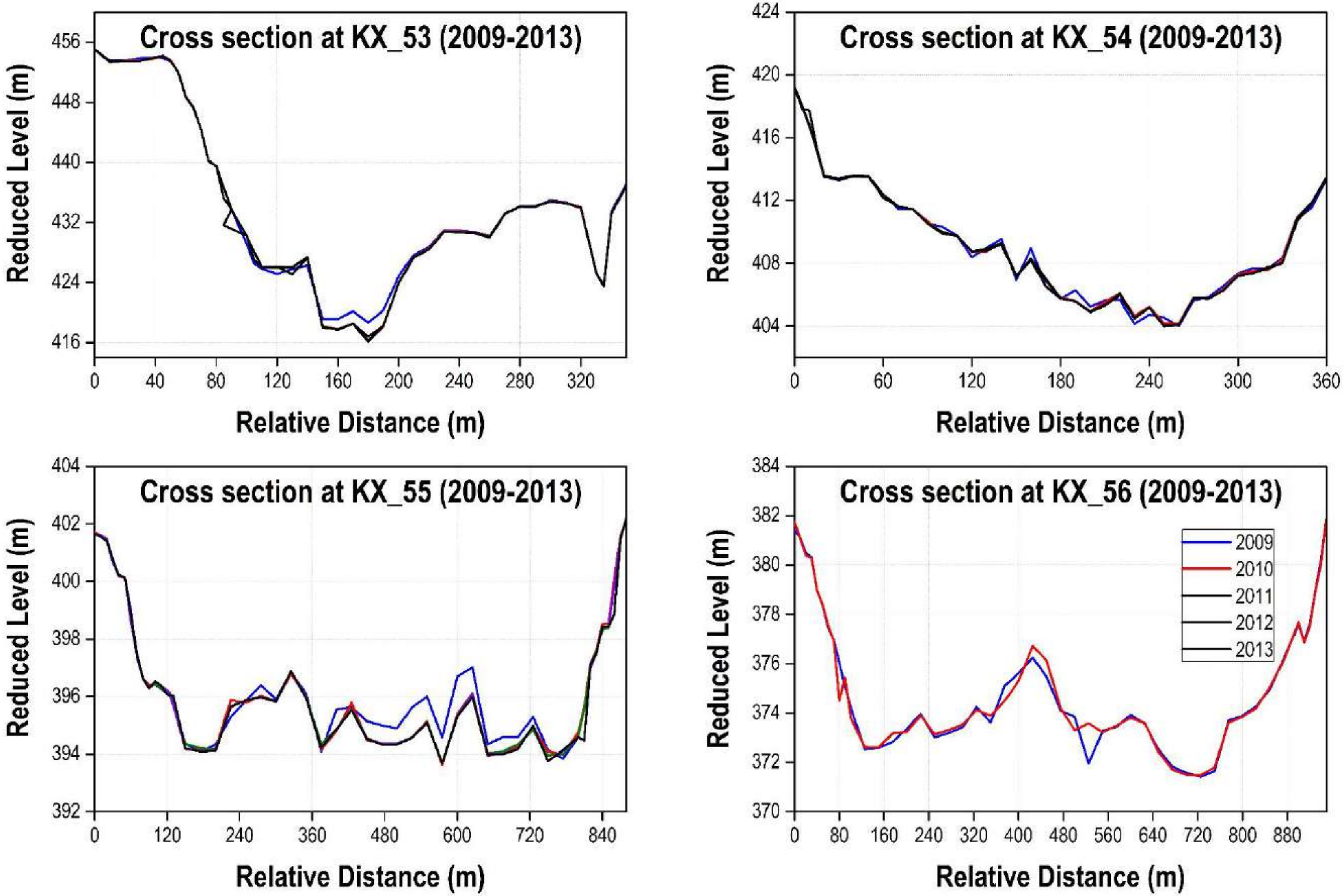
Cross section at KX_42 (2009-2013)
Reduced Level (m)
Relative Distance (m)

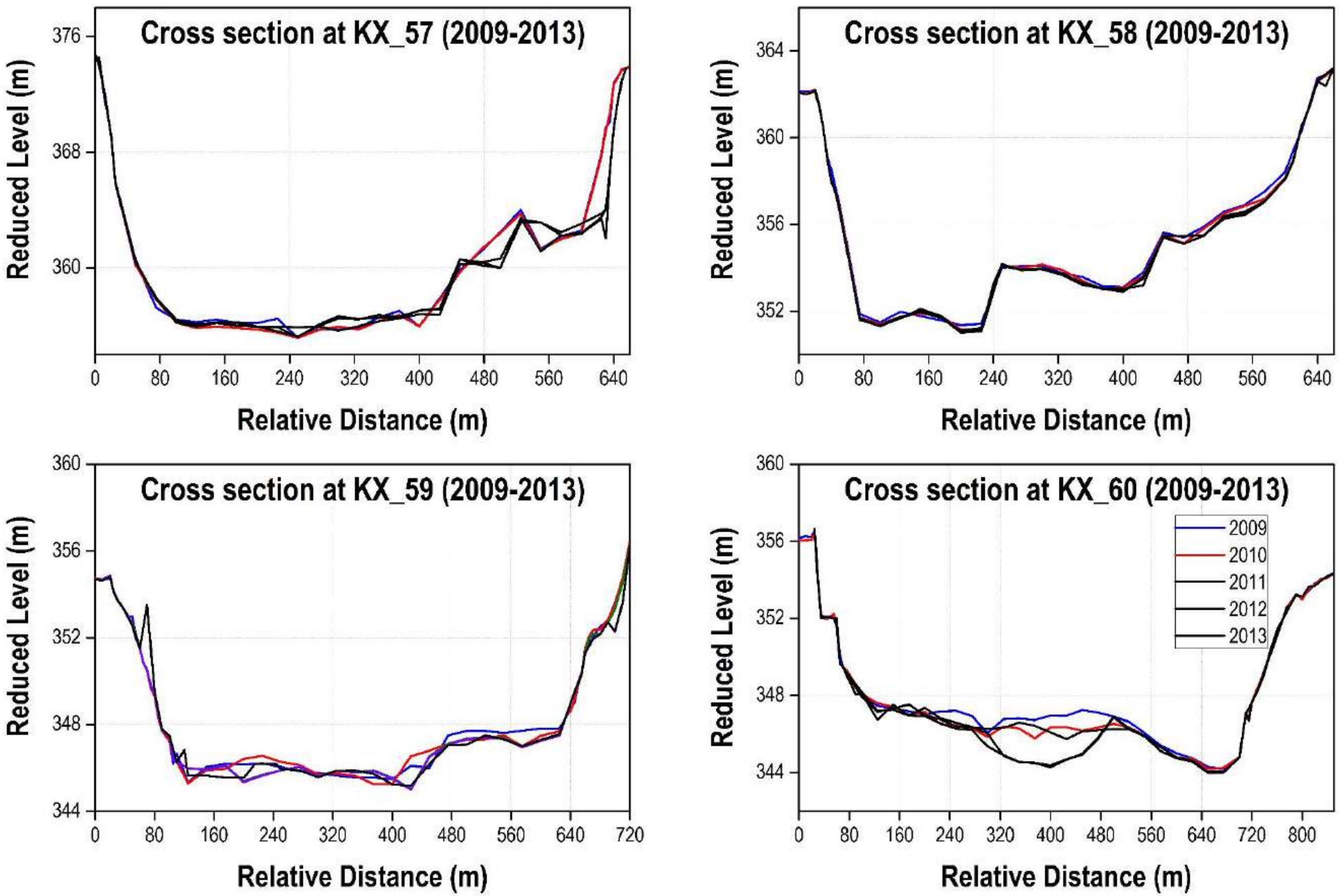


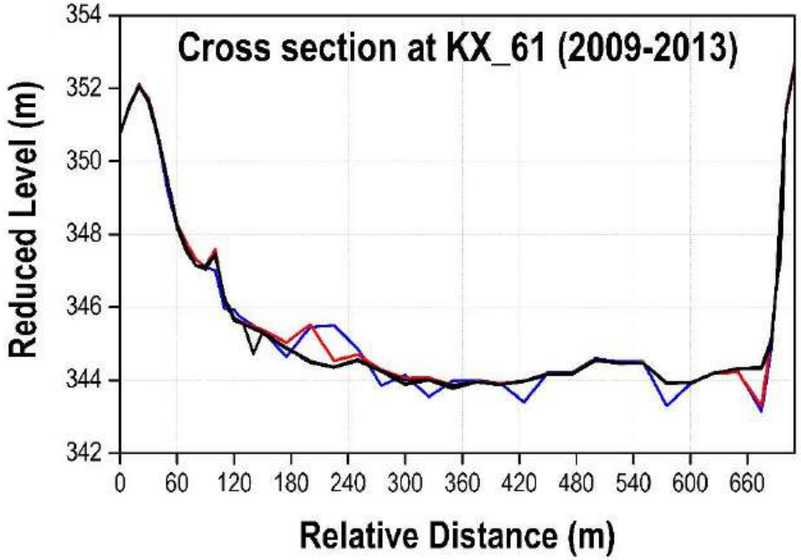
Cross section at KX_46 (2009-2013)
Reduced Level (m)
Relative Distance (m)

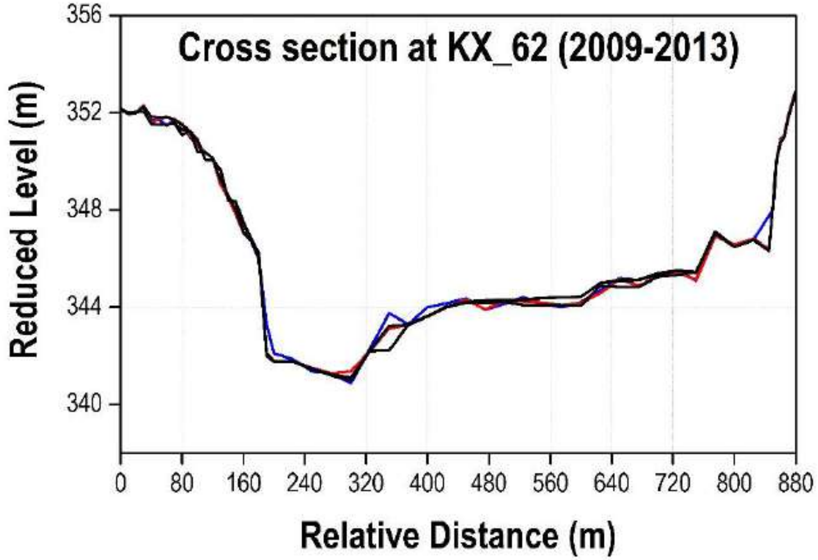


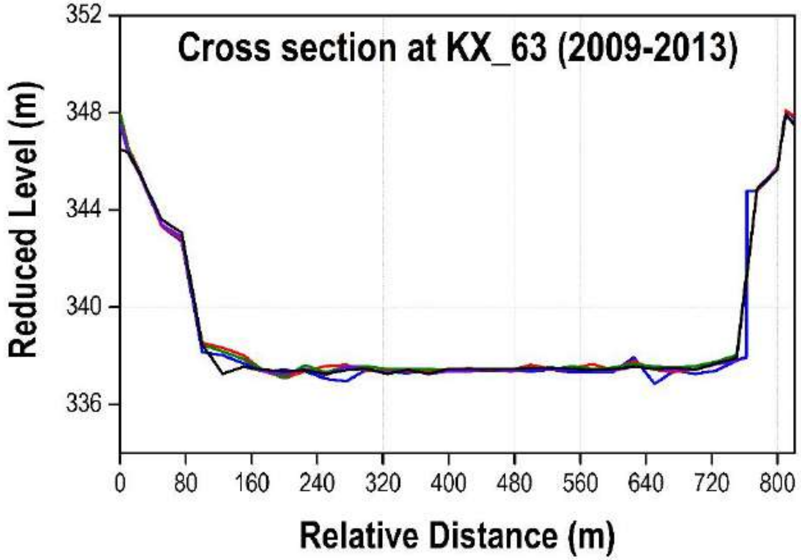
Cross section at KX_52 (2009-2013)
2009
2010
2011
2012
2013
Reduced Level (m)
Relative Distance (m)

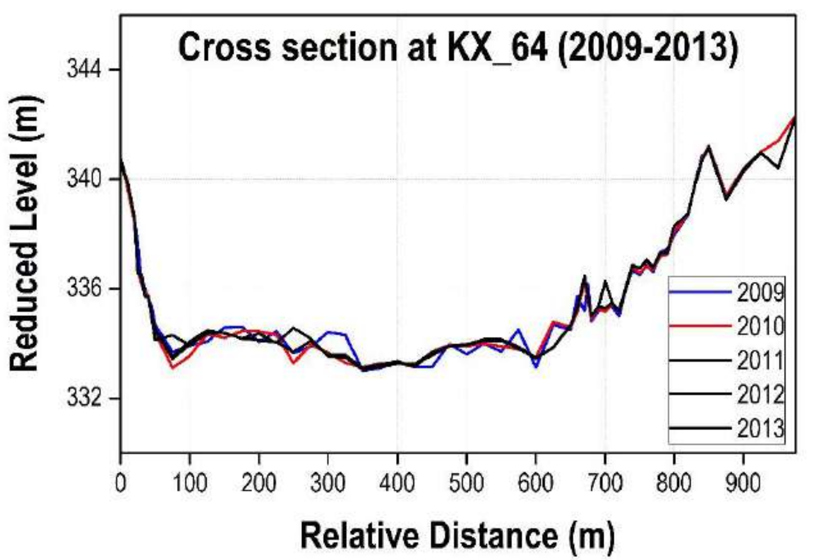

Cross section at KX_53 (2009-2013)
Reduced Level (m)
456
448
440
432
424
416
0
40
80
120
160
200
240
280
320
Relative Distance (m)
Cross section at KX_54 (2009-2013)
Reduced Level (m)
424
420
416
412
408
404
0
60
120
180
240
300
360
Relative Distance (m)
Cross section at KX_55 (2009-2013)
Reduced Level (m)
404
402
400
398
396
394
392
0
120
240
360
480
600
720
840
Relative Distance (m)
Cross section at KX_56 (2009-2013)
Reduced Level (m)
384
382
380
378
376
374
372
370
0
80
160
240
320
400
480
560
640
720
800
880
Relative Distance (m)
2009
2010
2011
2012
2013

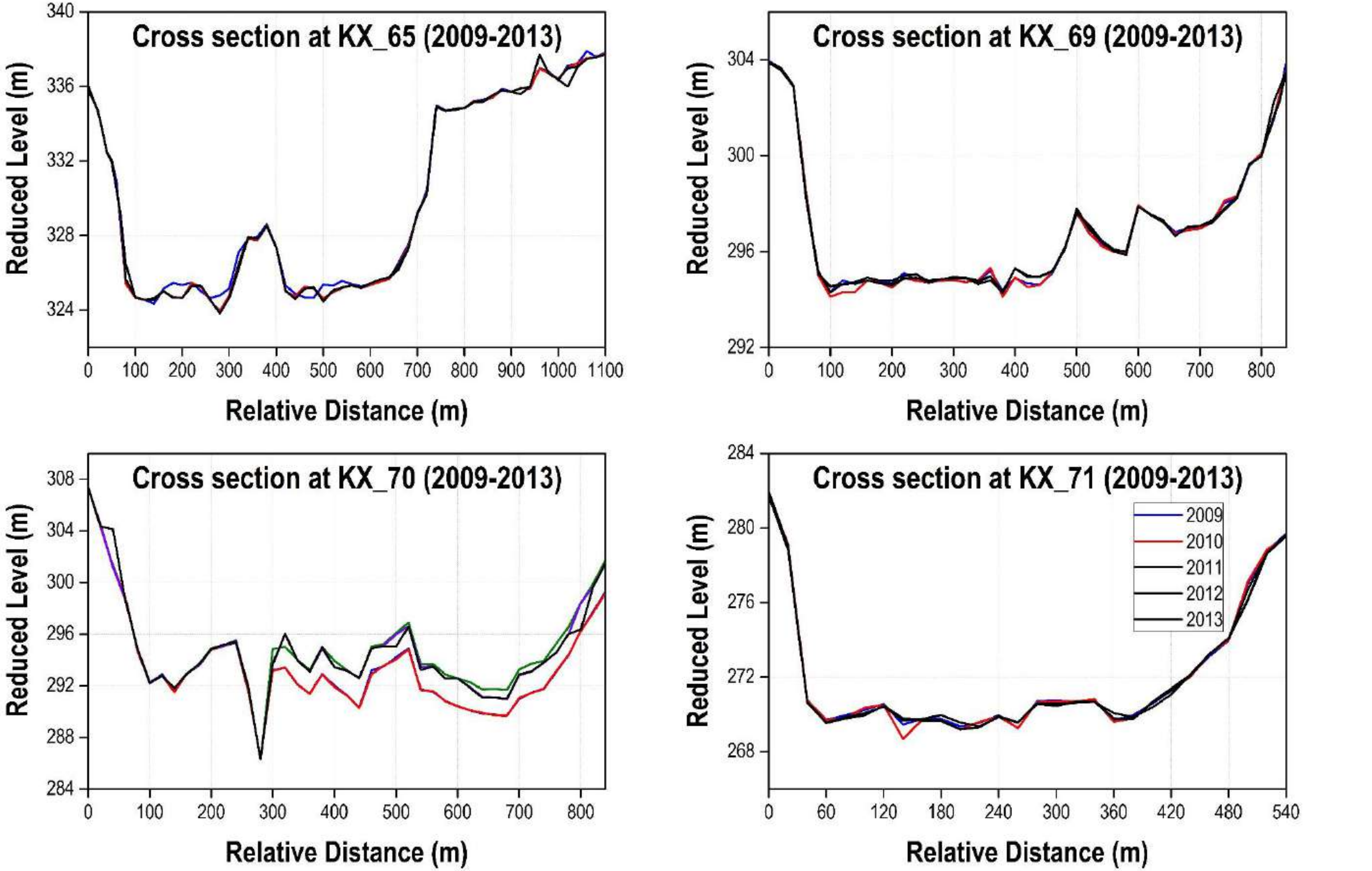

Cross section at KX_57 (2009-2013)
Reduced Level (m)
376
368
360
0
80
160
240
320
400
480
560
640
Relative Distance (m)
Cross section at KX_58 (2009-2013)
Reduced Level (m)
364
360
356
352
0
80
160
240
320
400
480
560
640
Relative Distance (m)
Cross section at KX_59 (2009-2013)
Reduced Level (m)
360
356
352
348
344
0
80
160
240
320
400
480
560
640
720
Relative Distance (m)
Cross section at KX_60 (2009-2013)
Reduced Level (m)
360
356
352
348
344
0
80
160
240
320
400
480
560
640
720
800
Relative Distance (m)
2009
2010
2011
2012
2013

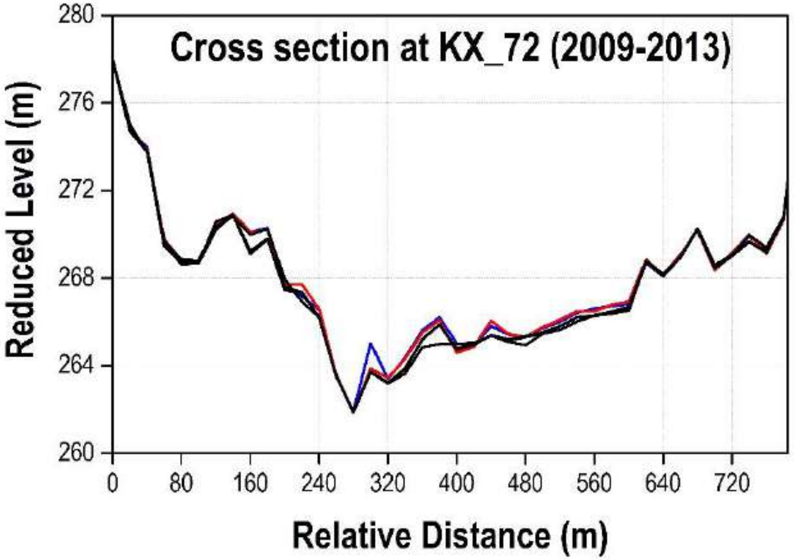

Cross section at KX_61 (2009-2013)
Reduced Level (m)
Relative Distance (m)
342
344
346
348
350
352
354
0
60
120
180
240
300
360
420
480
540
600
660

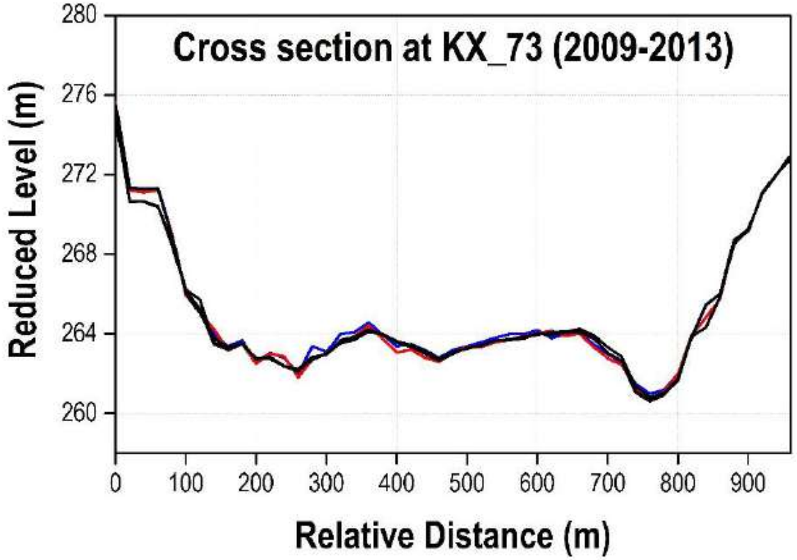

Cross section at KX_62 (2009-2013)
Reduced Level (m)
Relative Distance (m)
340
344
348
352
356
0
80
160
240
320
400
480
560
640
720
800
880

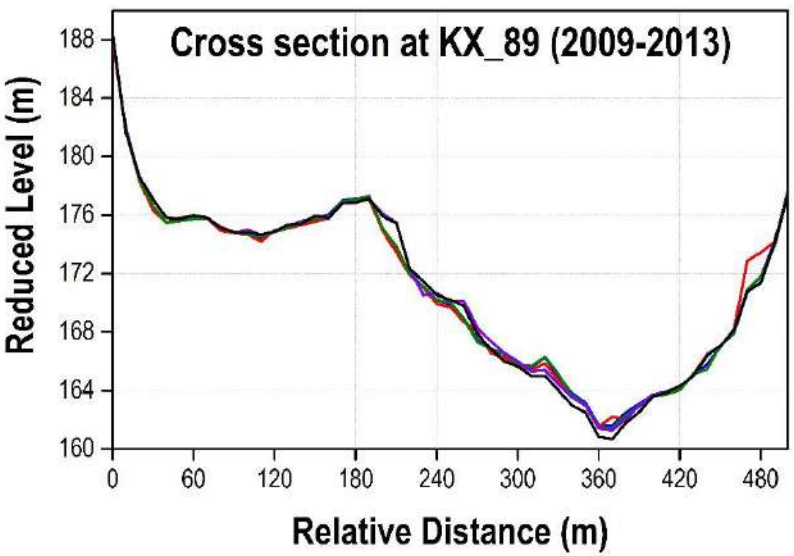

Cross section at KX_63 (2009-2013)
Reduced Level (m)
Relative Distance (m)
336
340
344
348
352
0
80
160
240
320
400
480
560
640
720
800

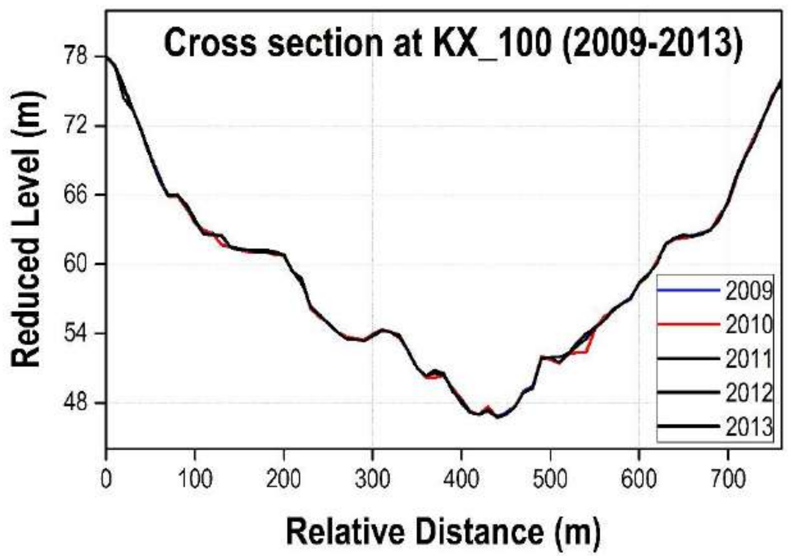

Cross section at KX_64 (2009-2013)
Reduced Level (m)
Relative Distance (m)
332
336
340
344
0
100
200
300
400
500
600
700
800
900
2009
2010
2011
2012
2013

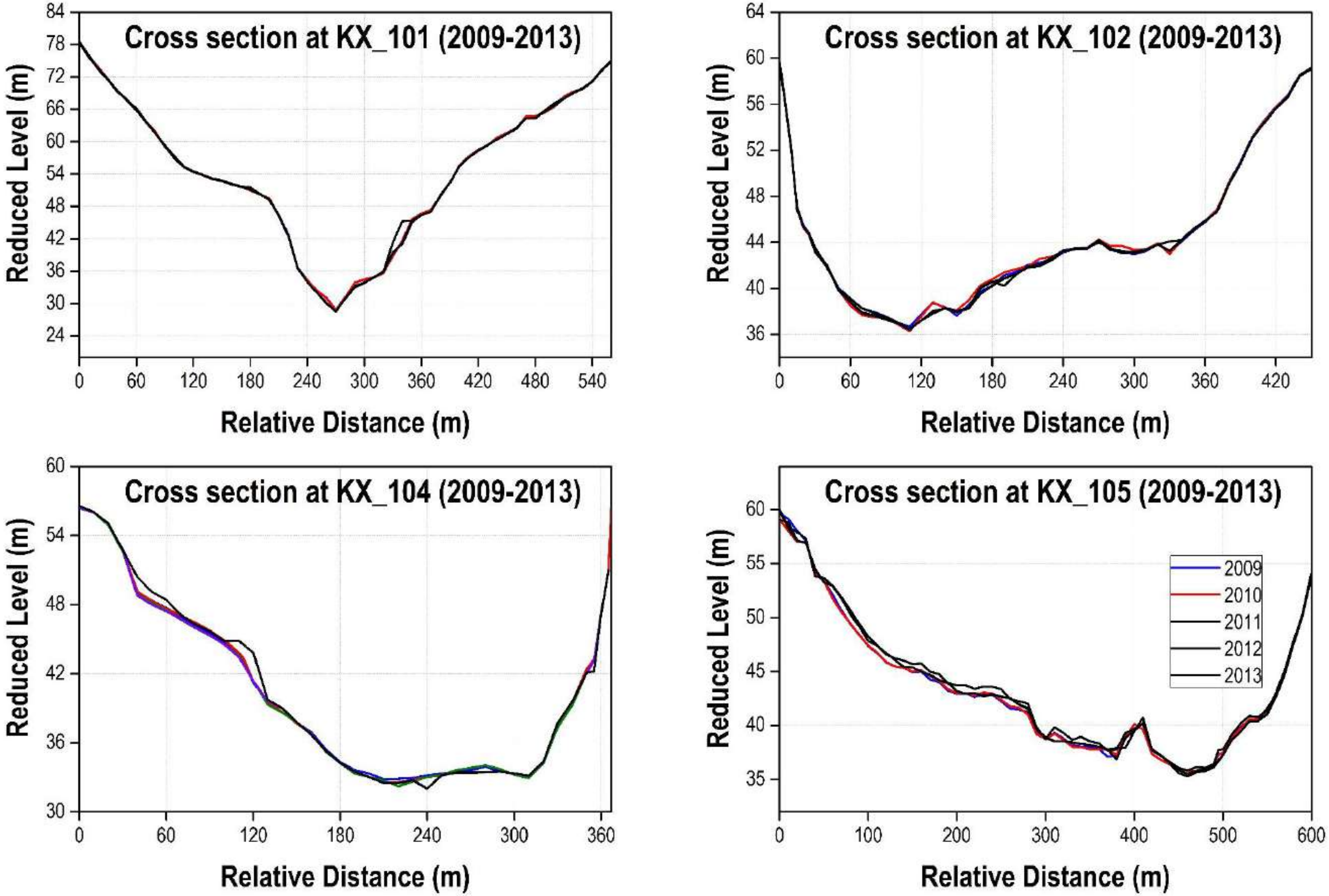

Cross section at KX_65 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_69 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_70 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_71 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013

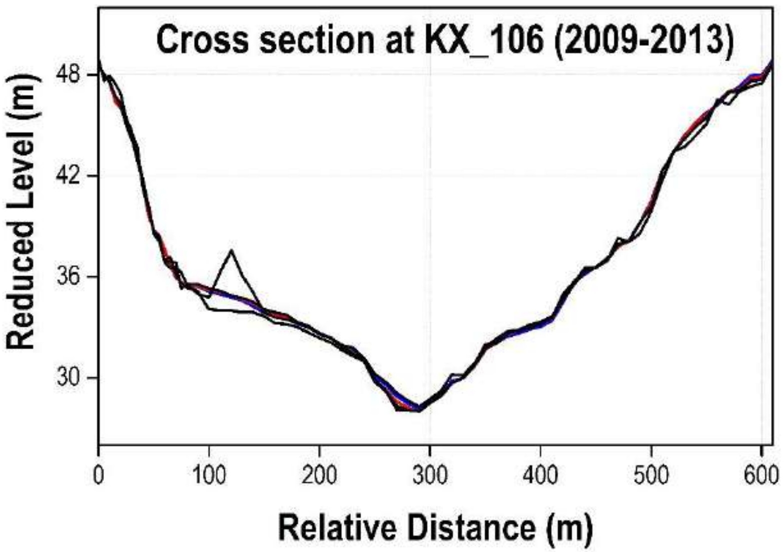

Cross section at KX_72 (2009-2013)
Reduced Level (m)
280
276
272
268
264
260
0
80
160
240
320
400
480
560
640
720
Relative Distance (m)

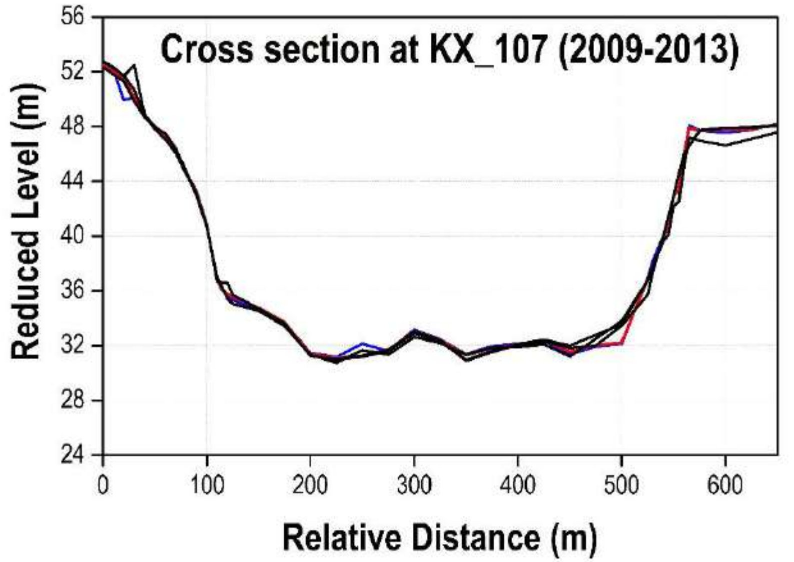

Cross section at KX_73 (2009-2013)
Reduced Level (m)
280
276
272
268
264
260
0
100
200
300
400
500
600
700
800
900
Relative Distance (m)

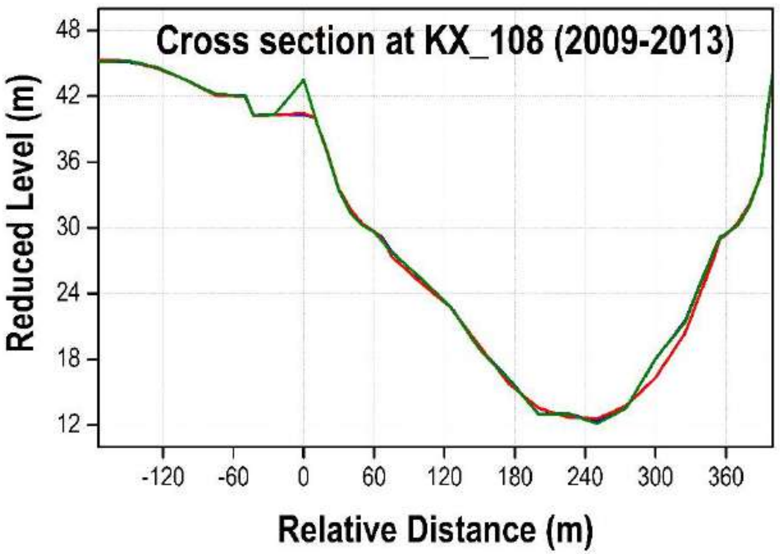

Cross section at KX_89 (2009-2013)
Reduced Level (m)
188
184
180
176
172
168
164
160
0
60
120
180
240
300
360
420
480
Relative Distance (m)

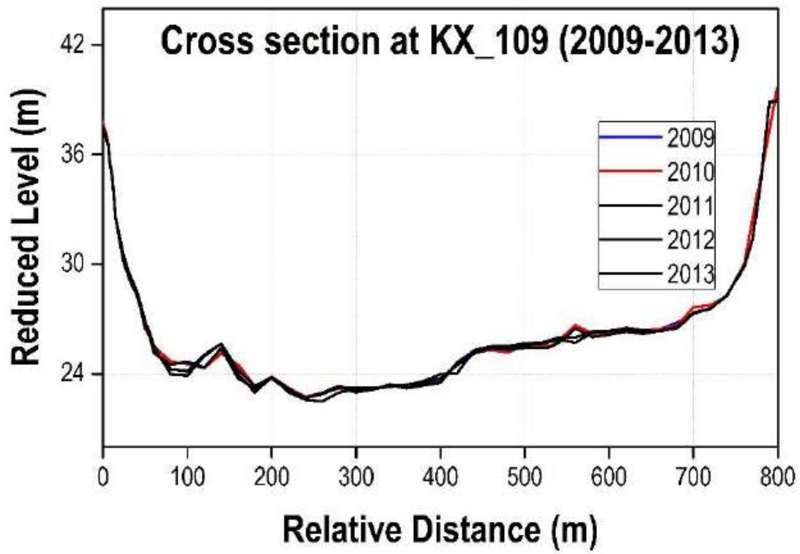

Cross section at KX_100 (2009-2013)
Reduced Level (m)
78
72
66
60
54
48
0
100
200
300
400
500
600
700
Relative Distance (m)
2009
2010
2011
2012
2013

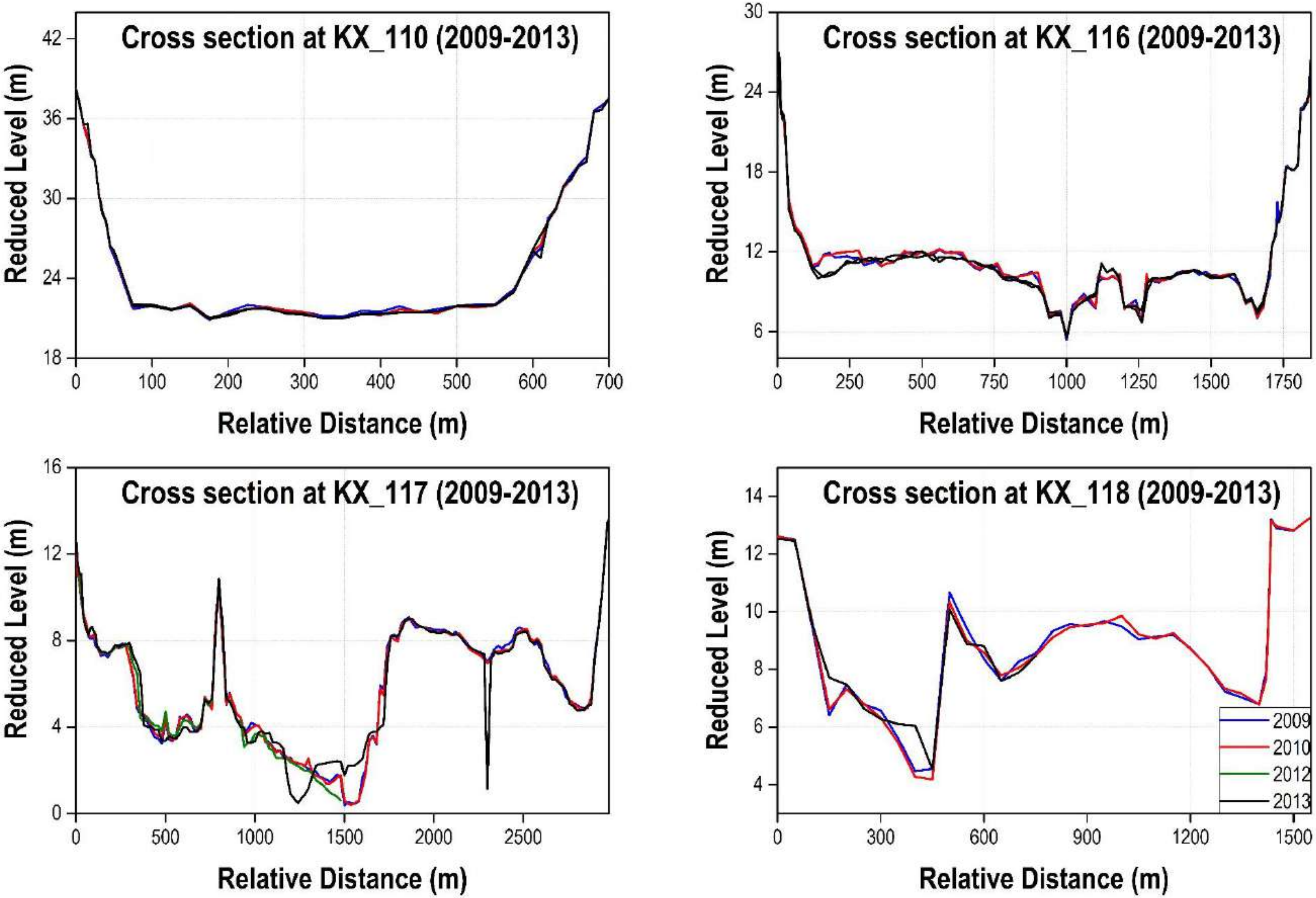

Cross section at KX_101 (2009-2013)
Cross section at KX_102 (2009-2013)
Cross section at KX_104 (2009-2013)
Cross section at KX_105 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013

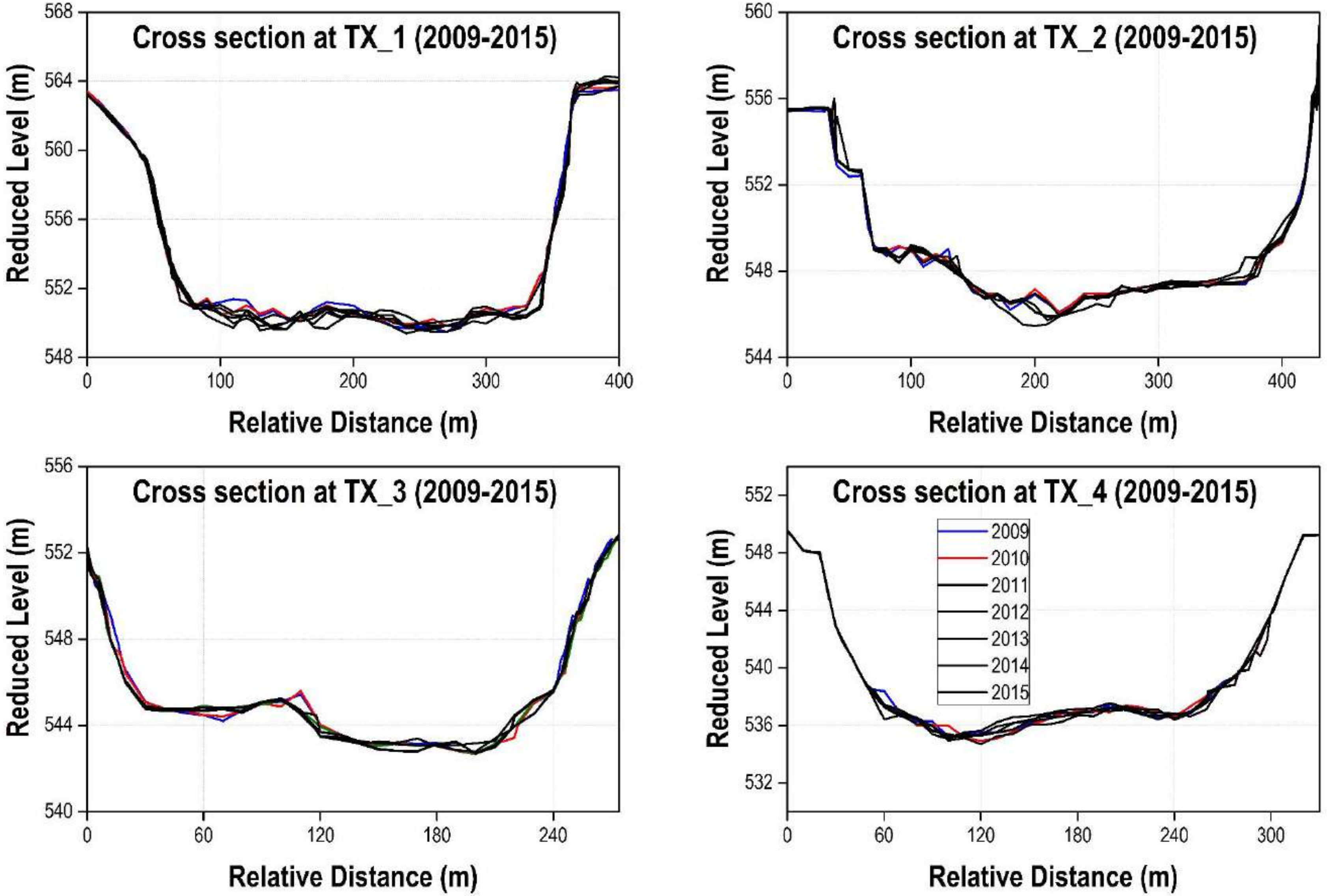

Cross section at KX_106 (2009-2013)
Reduced Level (m)
48
42
36
30
0
100
200
300
400
500
600
Relative Distance (m)

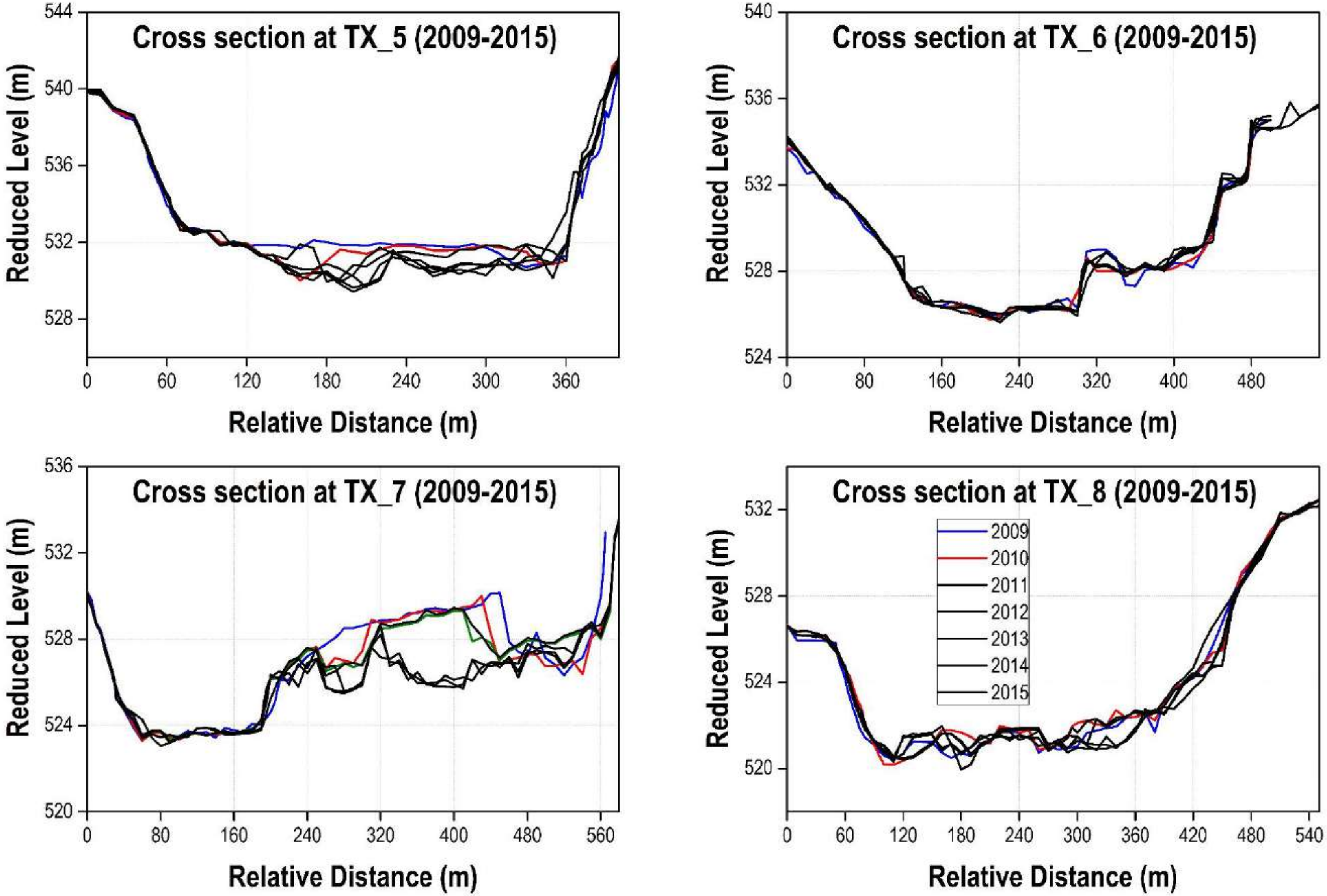

Cross section at KX_107 (2009-2013)
Reduced Level (m)
56
52
48
44
40
36
32
28
24
0
100
200
300
400
500
600
Relative Distance (m)

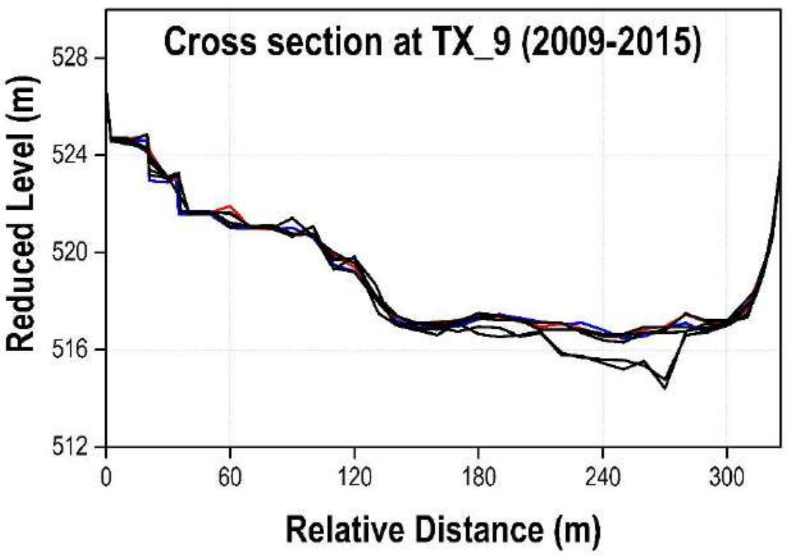

Cross section at KX_108 (2009-2013)
Reduced Level (m)
48
42
36
30
24
18
12
-120
-60
0
60
120
180
240
300
360
Relative Distance (m)

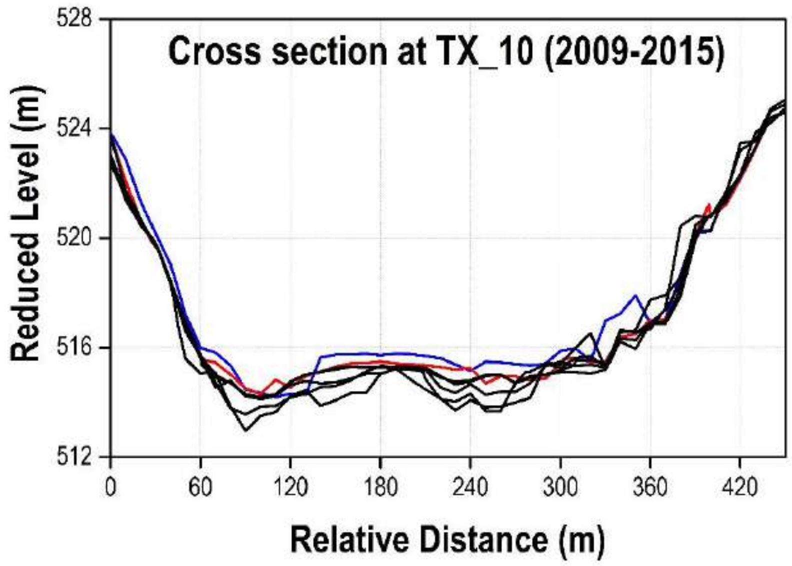

Cross section at KX_109 (2009-2013)
Reduced Level (m)
42
36
30
24
2009
2010
2011
2012
2013
0
100
200
300
400
500
600
700
800
Relative Distance (m)

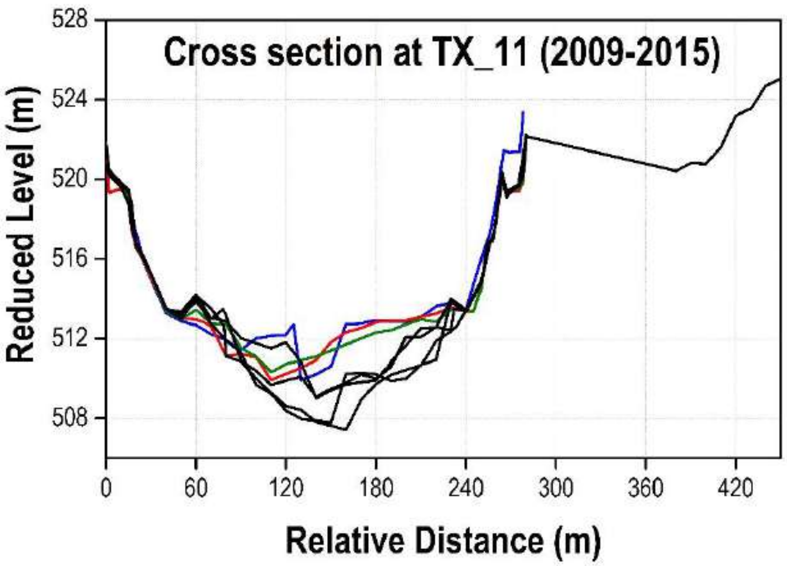

Cross section at KX_110 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_116 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_117 (2009-2013)
Reduced Level (m)
Relative Distance (m)
Cross section at KX_118 (2009-2013)
Reduced Level (m)
Relative Distance (m)
2009
2010
2012
2013

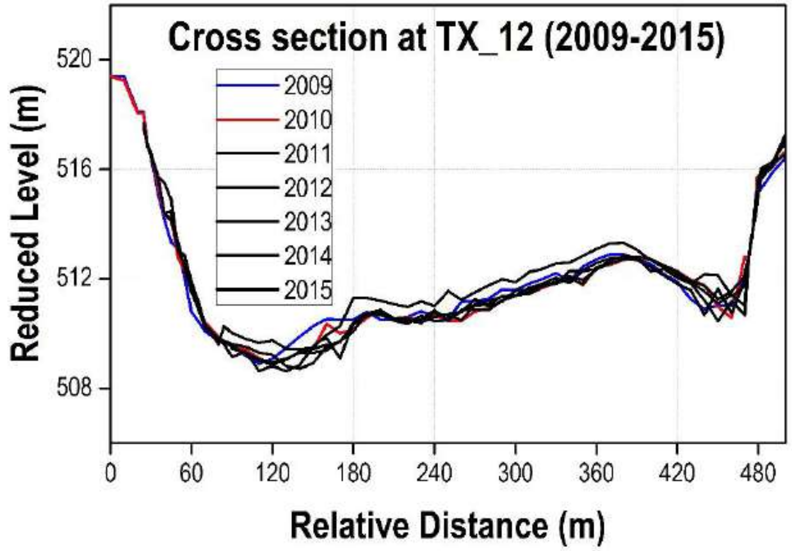

Cross section at TX_1 (2009-2015)
Reduced Level (m)
Relative Distance (m)
568
564
560
556
552
548
0
100
200
300
400
Cross section at TX_2 (2009-2015)
Reduced Level (m)
Relative Distance (m)
560
556
552
548
544
0
100
200
300
400
Cross section at TX_3 (2009-2015)
Reduced Level (m)
Relative Distance (m)
556
552
548
544
540
0
60
120
180
240
Cross section at TX_4 (2009-2015)
Reduced Level (m)
Relative Distance (m)
552
548
544
540
536
532
0
60
120
180
240
300
2009
2010
2011
2012
2013
2014
2015

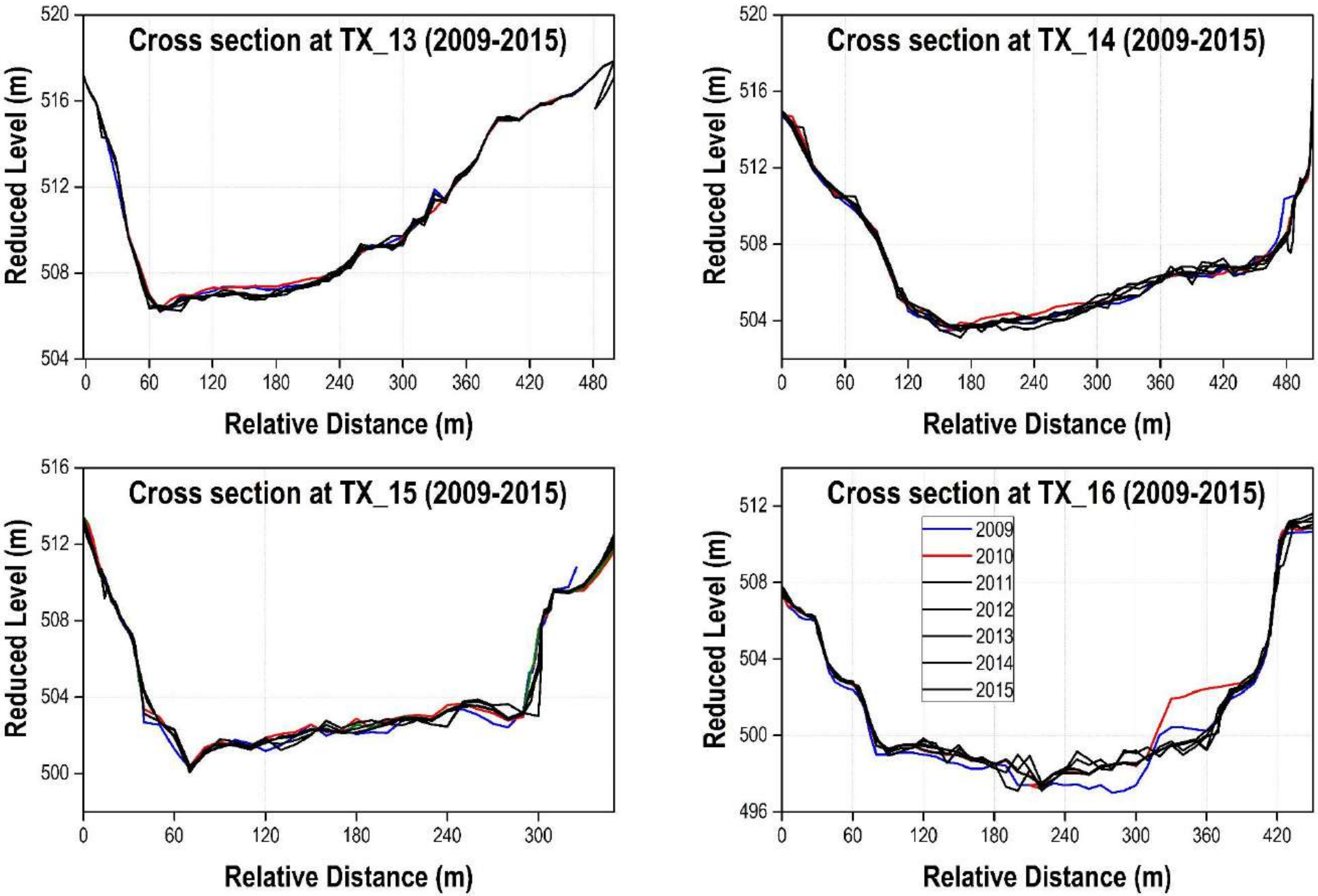

Cross section at TX_5 (2009-2015)
Cross section at TX_6 (2009-2015)
Cross section at TX_7 (2009-2015)
Cross section at TX_8 (2009-2015)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013
2014
2015


Cross section at TX_9 (2009-2015)
Reduced Level (m)
Relative Distance (m)
528
524
520
516
512
0
60
120
180
240
300

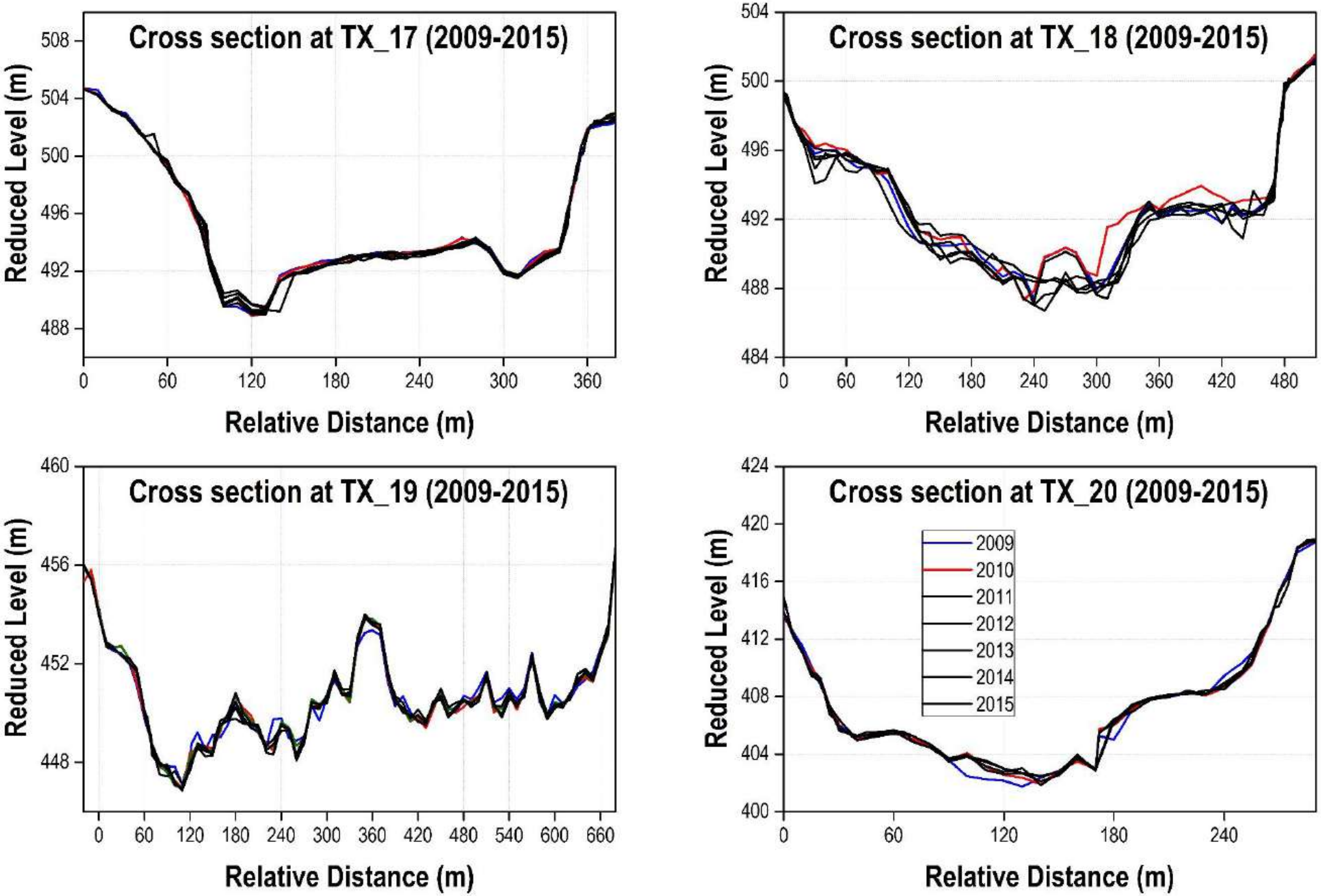

Cross section at TX_10 (2009-2015)
Reduced Level (m)
Relative Distance (m)
528
524
520
516
512
0
60
120
180
240
300
360
420

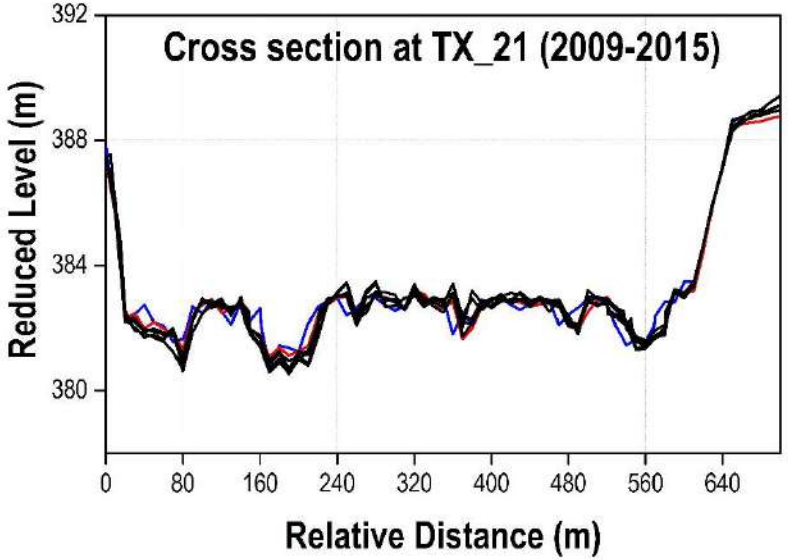

Cross section at TX_11 (2009-2015)
Reduced Level (m)
Relative Distance (m)
528
524
520
516
512
508
0
60
120
180
240
300
360
420


Cross section at TX_12 (2009-2015)
2009
2010
2011
2012
2013
2014
2015
Reduced Level (m)
Relative Distance (m)
520
516
512
508
0
60
120
180
240
300
360
420
480

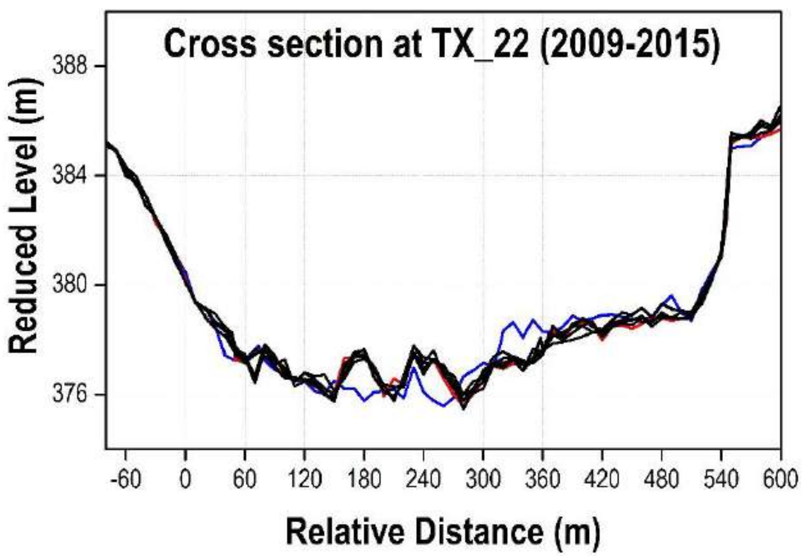


Cross section at TX_13 (2009-2015)
Reduced Level (m)
Relative Distance (m)
520
516
512
508
504
0
60
120
180
240
300
360
420
480
Cross section at TX_14 (2009-2015)
Reduced Level (m)
Relative Distance (m)
520
516
512
508
504
0
60
120
180
240
300
360
420
480
Cross section at TX_15 (2009-2015)
Reduced Level (m)
Relative Distance (m)
516
512
508
504
500
0
60
120
180
240
300
Cross section at TX_16 (2009-2015)
Reduced Level (m)
Relative Distance (m)
512
508
504
500
496
0
60
120
180
240
300
360
420
2009
2010
2011
2012
2013
2014
2015

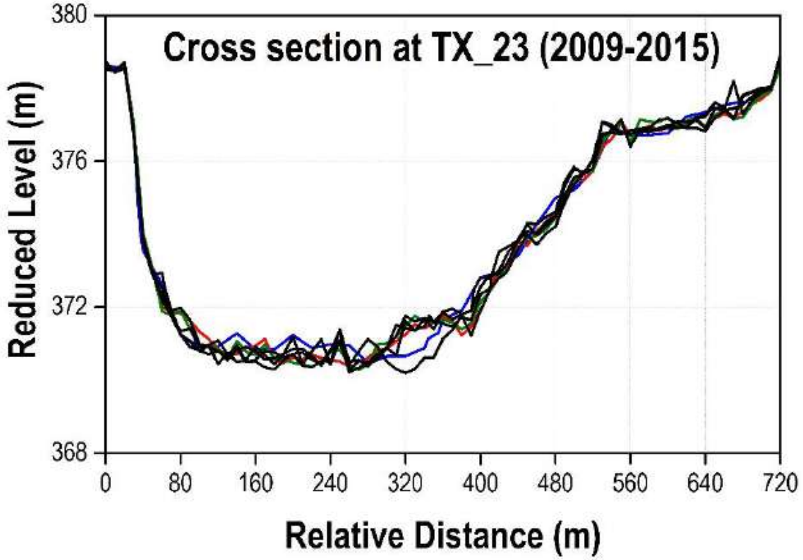

Cross section at TX_17 (2009-2015)
Reduced Level (m)
Relative Distance (m)
508
504
500
496
492
488
0
60
120
180
240
300
360
Cross section at TX_18 (2009-2015)
Reduced Level (m)
Relative Distance (m)
504
500
496
492
488
484
0
60
120
180
240
300
360
420
480
Cross section at TX_19 (2009-2015)
Reduced Level (m)
Relative Distance (m)
460
456
452
448
0
60
120
180
240
300
360
420
480
540
600
660
Cross section at TX_20 (2009-2015)
Reduced Level (m)
Relative Distance (m)
424
420
416
412
408
404
400
0
60
120
180
240
2009
2010
2011
2012
2013
2014
2015



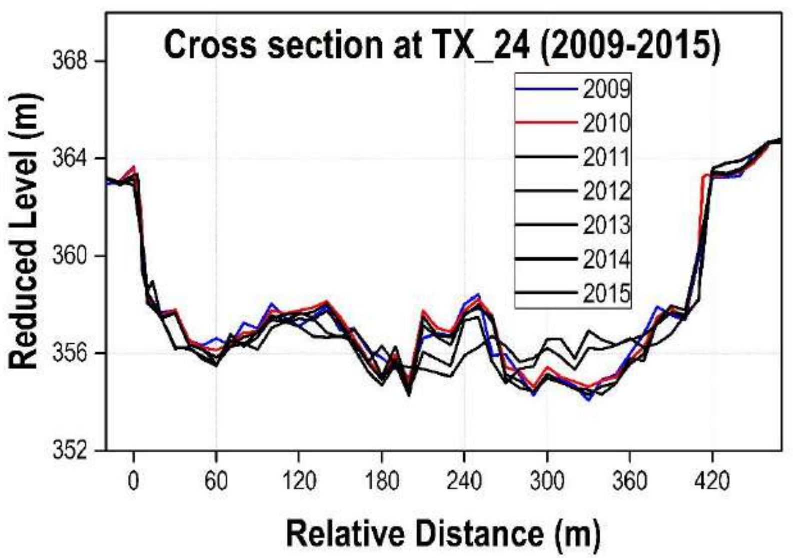
Cross section at TX_21 (2009-2015)
Reduced Level (m)
392
388
384
380
0
80
160
240
320
400
480
560
640
Relative Distance (m)



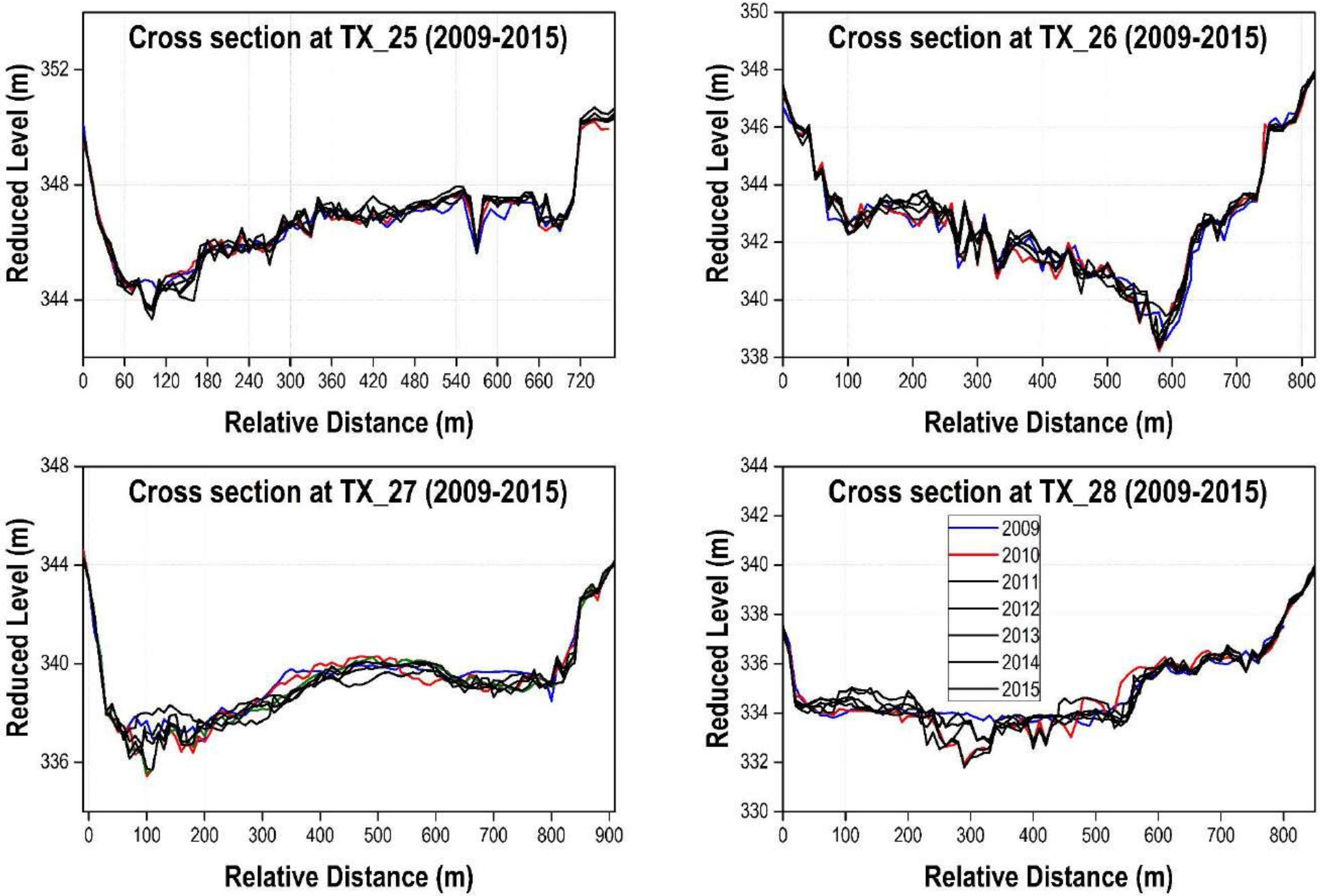
Cross section at TX_22 (2009-2015)
Reduced Level (m)
388
384
380
376
-60
0
60
120
180
240
300
360
420
480
540
600
Relative Distance (m)

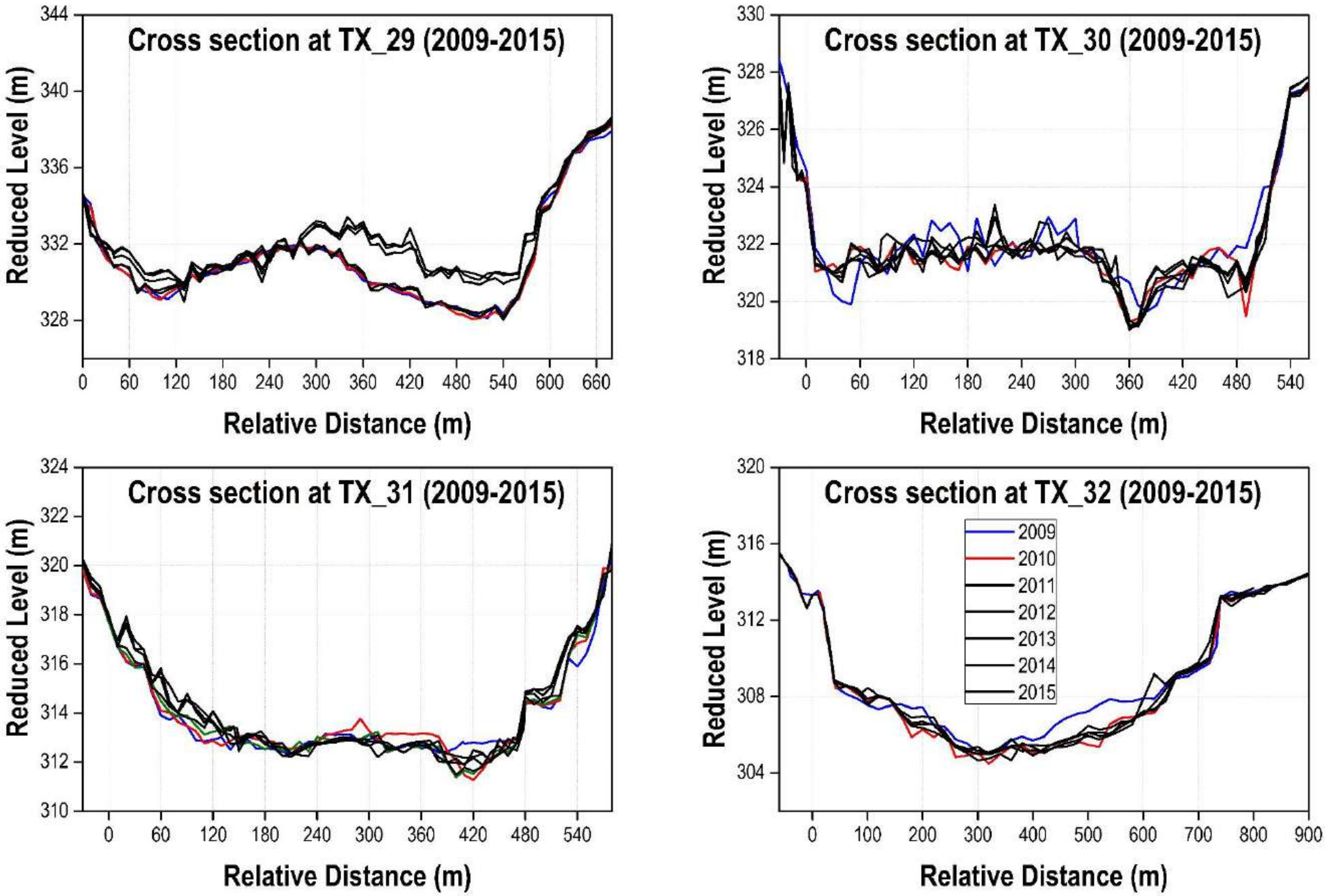


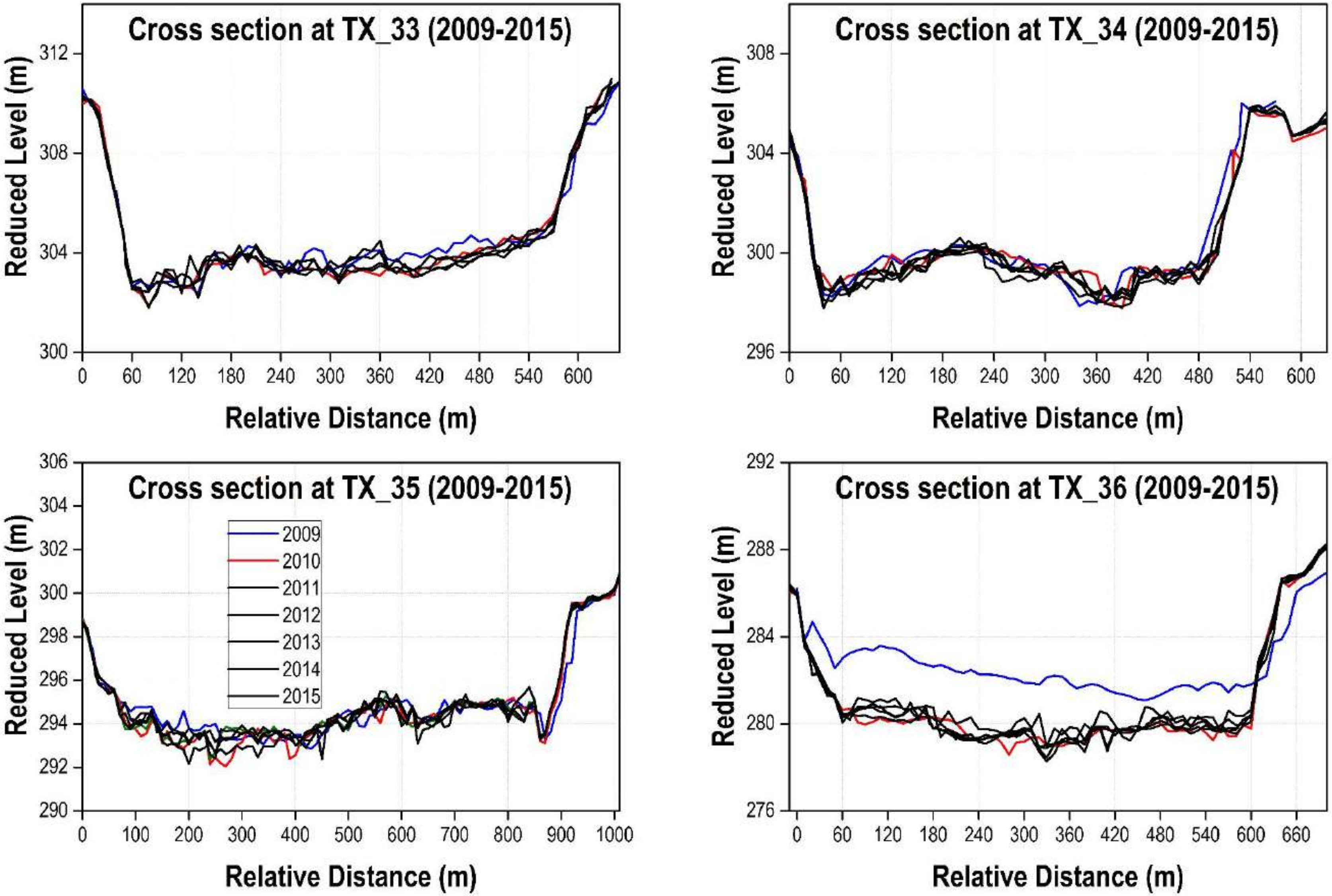
Cross section at TX_23 (2009-2015)
Reduced Level (m)
380
376
372
368
0
80
160
240
320
400
480
560
640
720
Relative Distance (m)

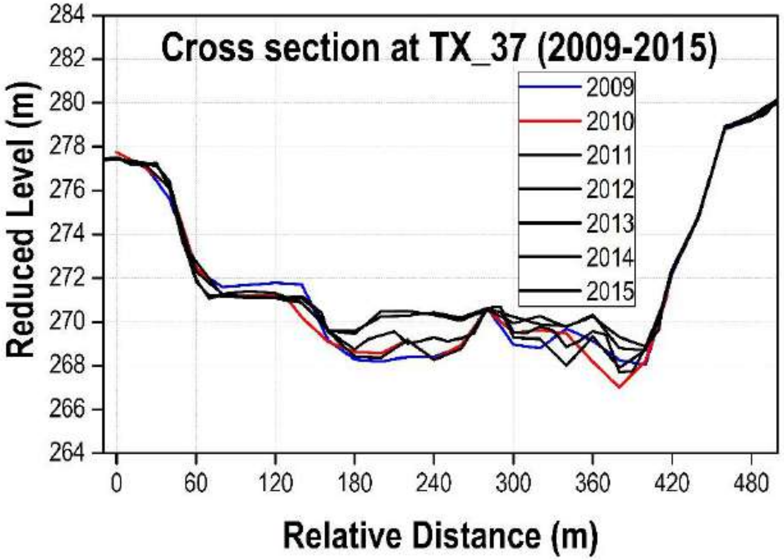


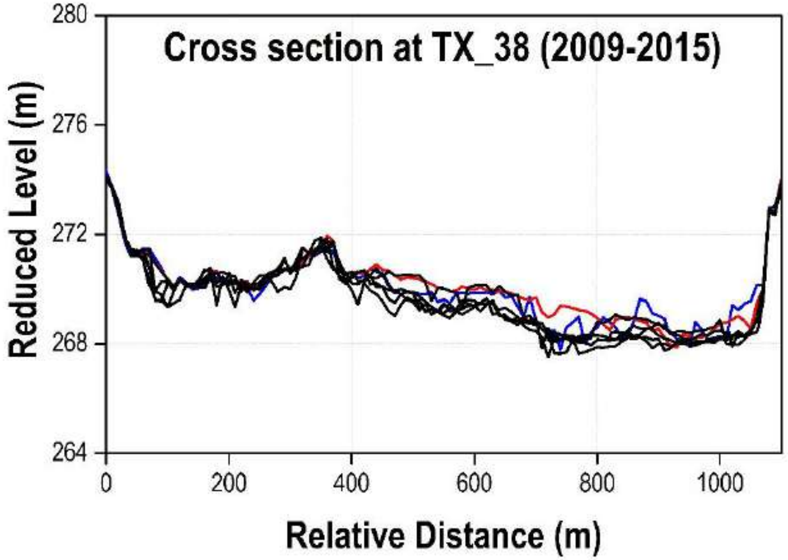
Cross section at TX_24 (2009-2015)
2009
2010
2011
2012
2013
2014
2015
Reduced Level (m)
368
364
360
356
352
0
60
120
180
240
300
360
420
Relative Distance (m)


Cross section at TX_25 (2009-2015)
Reduced Level (m)
Relative Distance (m)
352
348
344
0
60
120
180
240
300
360
420
480
540
600
660
720
Cross section at TX_26 (2009-2015)
Reduced Level (m)
Relative Distance (m)
350
348
346
344
342
340
338
0
100
200
300
400
500
600
700
800
Cross section at TX_27 (2009-2015)
Reduced Level (m)
Relative Distance (m)
348
344
340
336
0
100
200
300
400
500
600
700
800
900
Cross section at TX_28 (2009-2015)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013
2014
2015
344
342
340
338
336
334
332
330
0
100
200
300
400
500
600
700
800

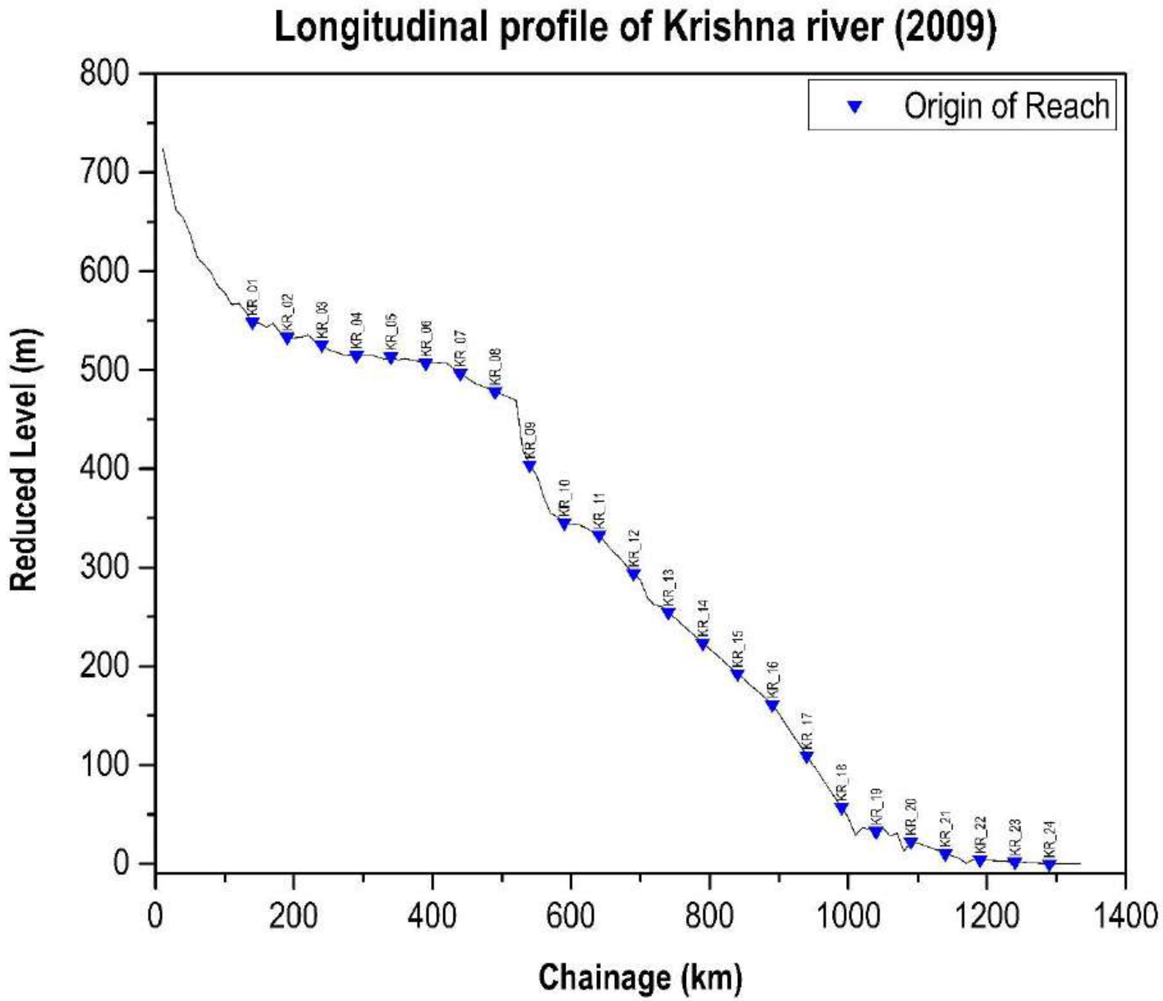

Cross section at TX_29 (2009-2015)
Reduced Level (m)
344
340
336
332
328
0
60
120
180
240
300
360
420
480
540
600
660
Relative Distance (m)
Cross section at TX_30 (2009-2015)
330
328
326
324
322
320
318
0
60
120
180
240
300
360
420
480
540
Cross section at TX_31 (2009-2015)
324
322
320
318
316
314
312
310
Cross section at TX_32 (2009-2015)
2009
2010
2011
2012
2013
2014
2015
320
316
312
308
304
0
100
200
300
400
500
600
700
800
900

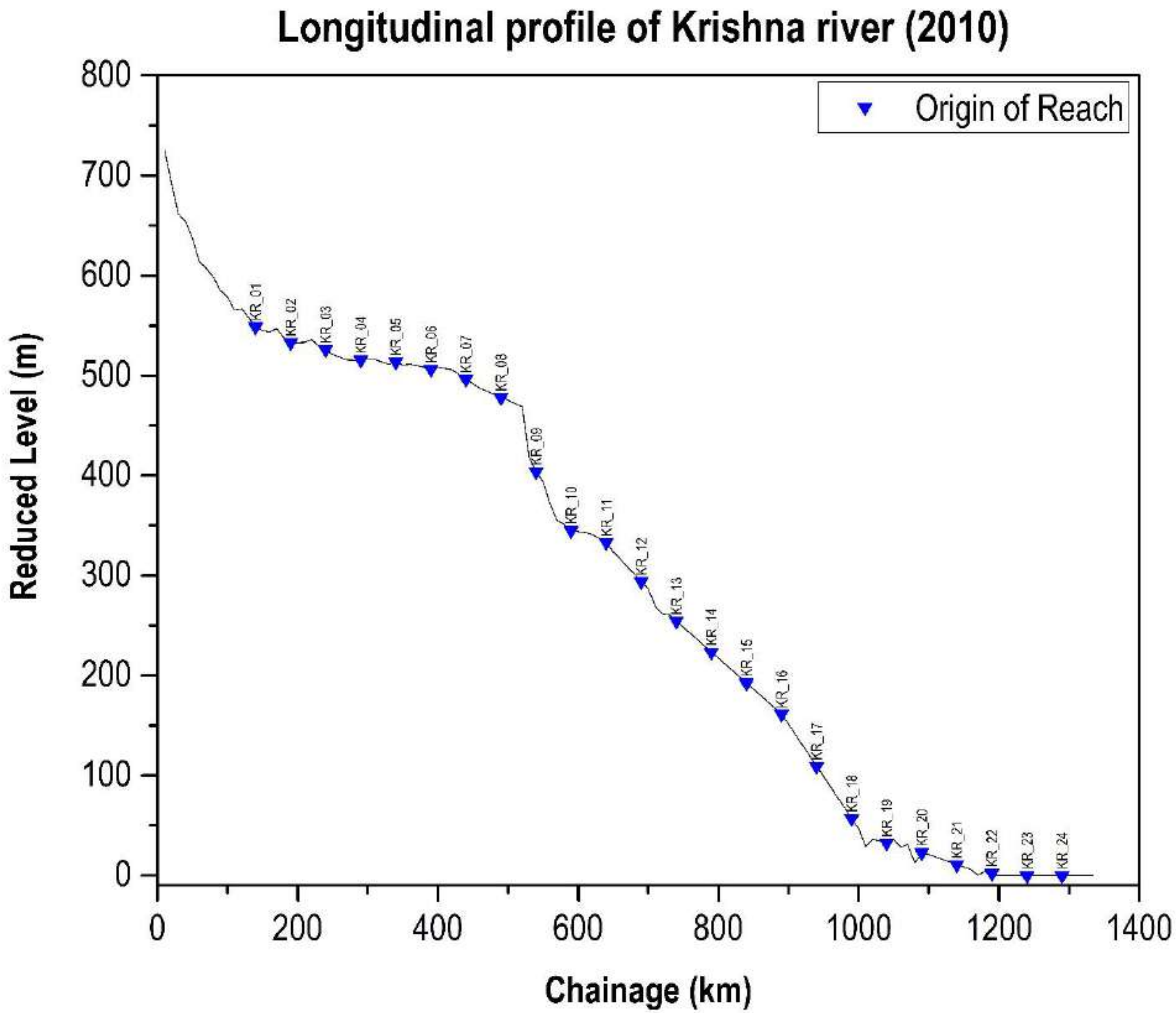

Cross section at TX_33 (2009-2015)
Cross section at TX_34 (2009-2015)
Cross section at TX_35 (2009-2015)
Cross section at TX_36 (2009-2015)
Reduced Level (m)
Relative Distance (m)
2009
2010
2011
2012
2013
2014
2015


Cross section at TX_37 (2009-2015)
2009
2010
2011
2012
2013
2014
2015
Reduced Level (m)
Relative Distance (m)
284
282
280
278
276
274
272
270
268
266
264
0
60
120
180
240
300
360
420
480

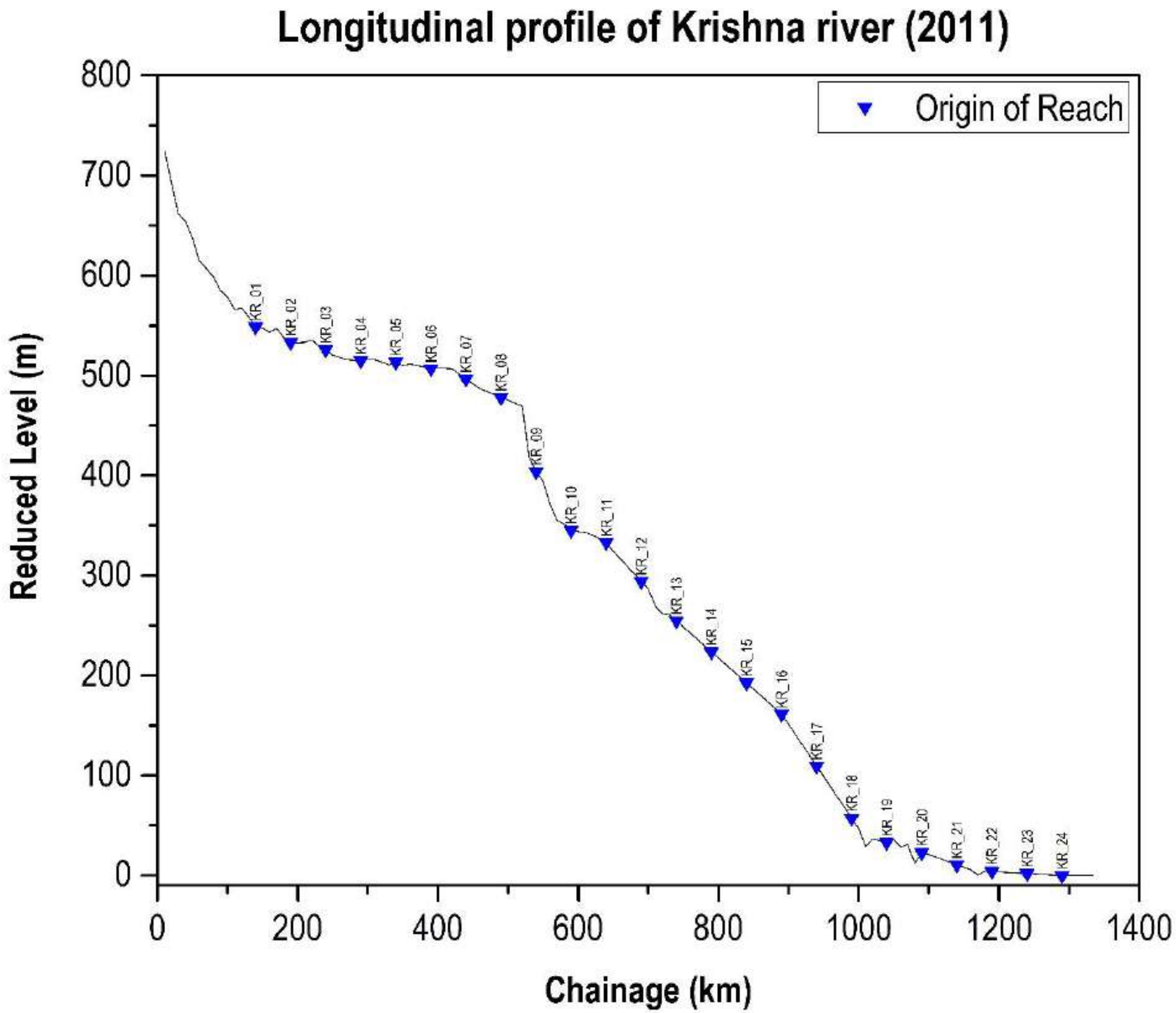

Cross section at TX_38 (2009-2015)
Reduced Level (m)
Relative Distance (m)
280
276
272
268
264
0
200
400
600
800
1000

Appendix XVII: Longitudinal profile of Krishna River during 2009 to 2012

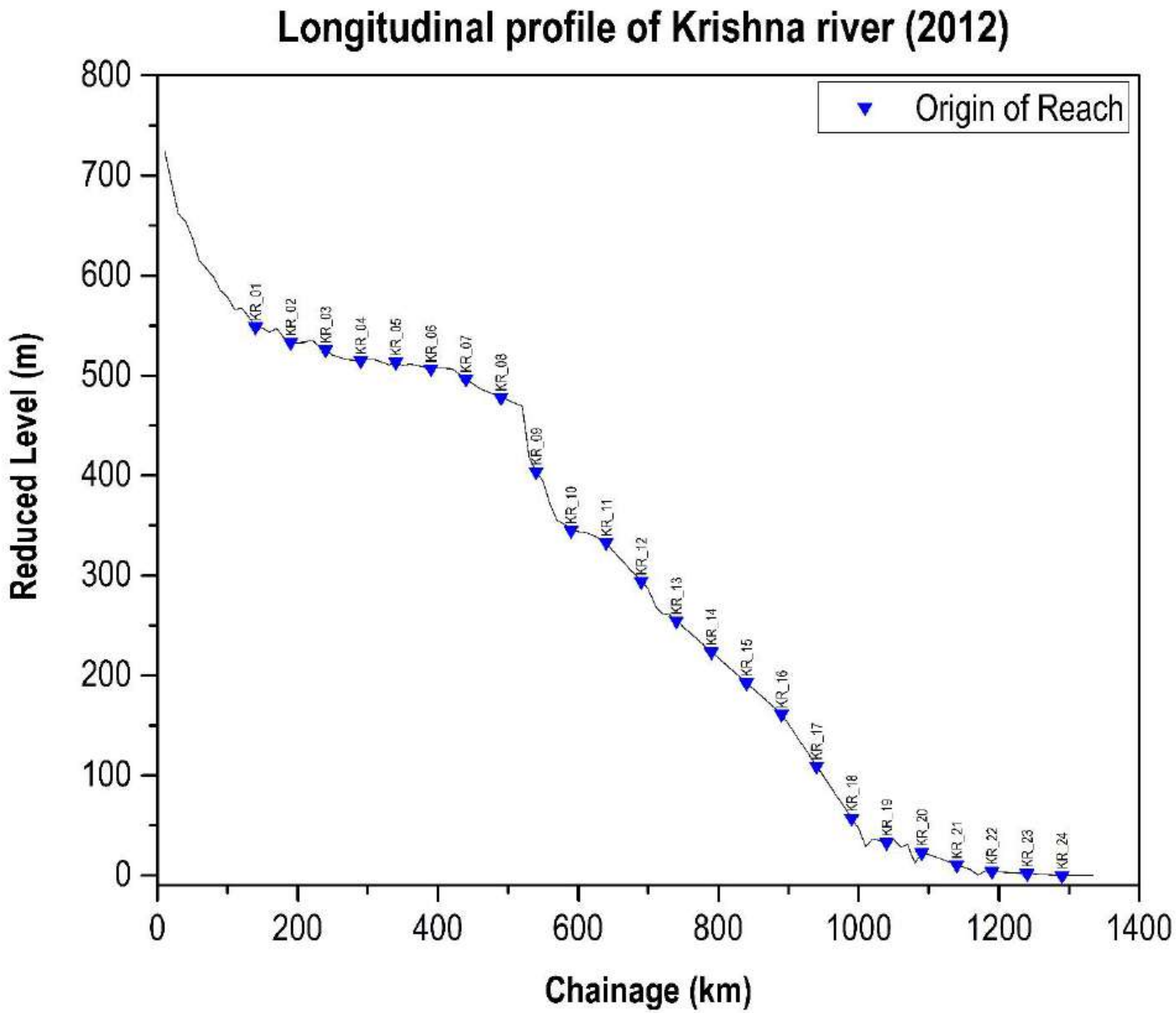




Longitudinal profile of Krishna river (2010)
Origin of Reach
Reduced Level (m)
Chainage (km)
0
100
200
300
400
500
600
700
800
0
200
400
600
800
1000
1200
1400
KR_01
KR_02
KR_03
KR_04
KR_05
KR_06
KR_07
KR_08
KR_09
KR_10
KR_11
KR_12
KR_13
KR_14
KR_15
KR_16
KR_17
KR_18
KR_19
KR_20
KR_21
KR_22
KR_23
KR_24

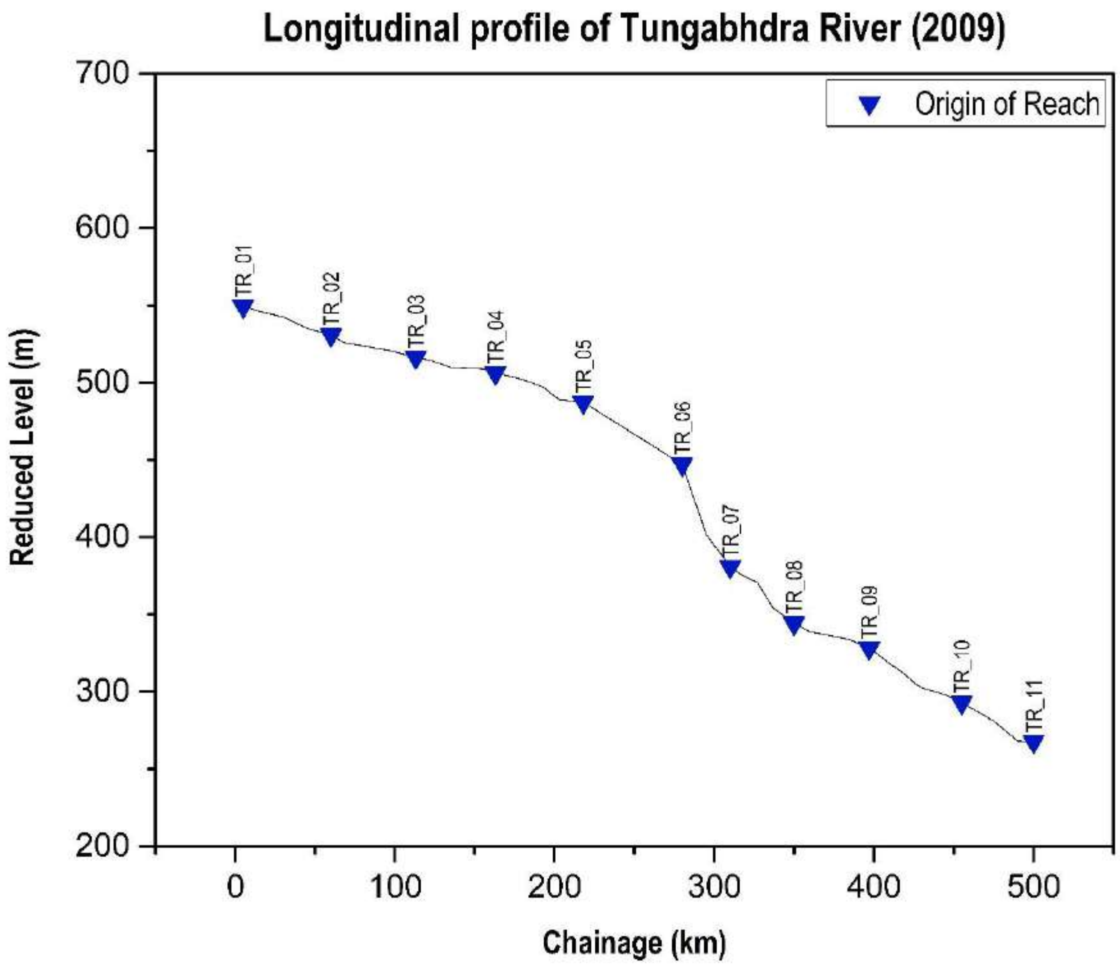


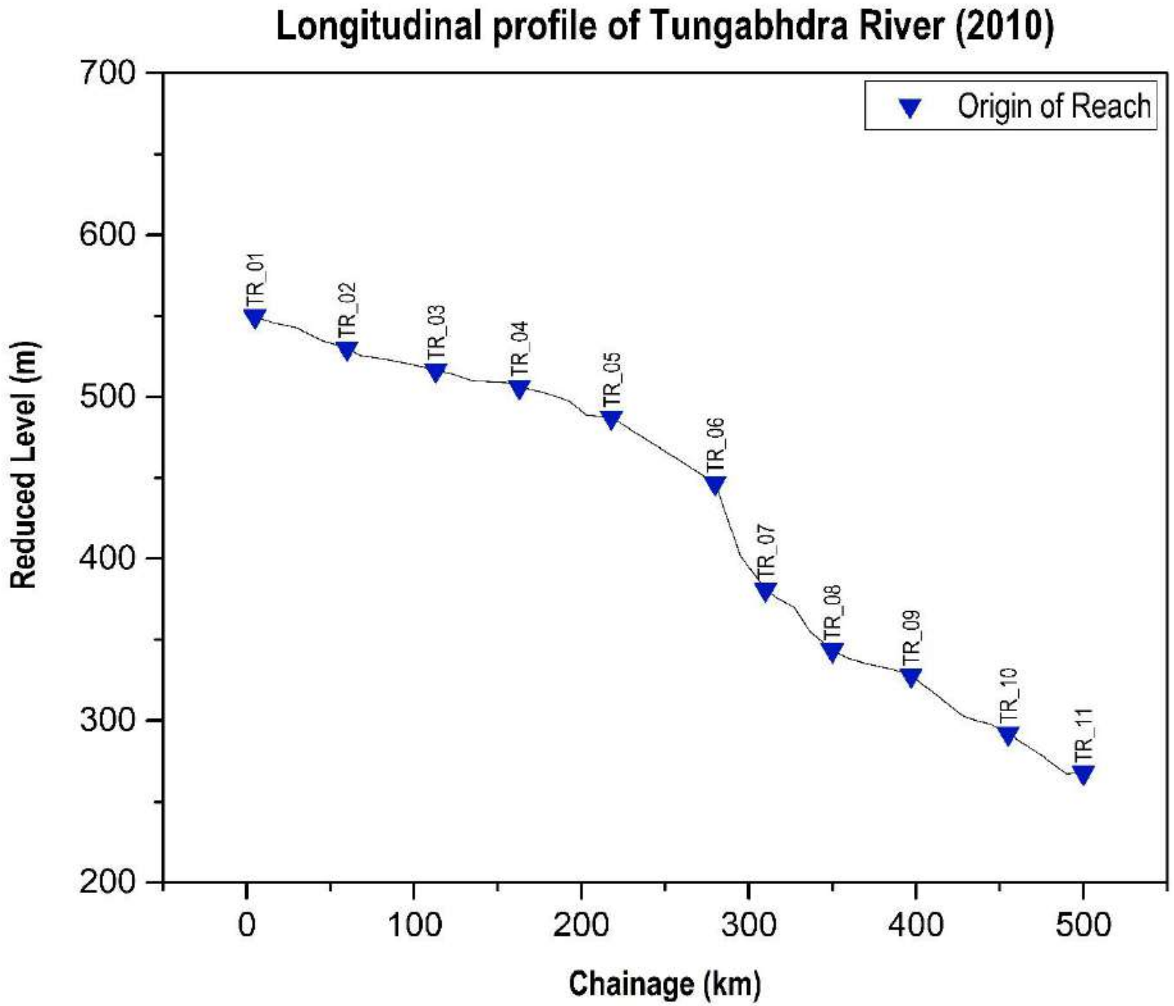
Longitudinal profile of Krishna river (2011)
Origin of Reach
Reduced Level (m)
Chainage (km)
0
100
200
300
400
500
600
700
800
0
200
400
600
800
1000
1200
1400
KR_01
KR_02
KR_03
KR_04
KR_05
KR_06
KR_07
KR_08
KR_09
KR_10
KR_11
KR_12
KR_13
KR_14
KR_15
KR_16
KR_17
KR_18
KR_19
KR_20
KR_21
KR_22
KR_23
KR_24

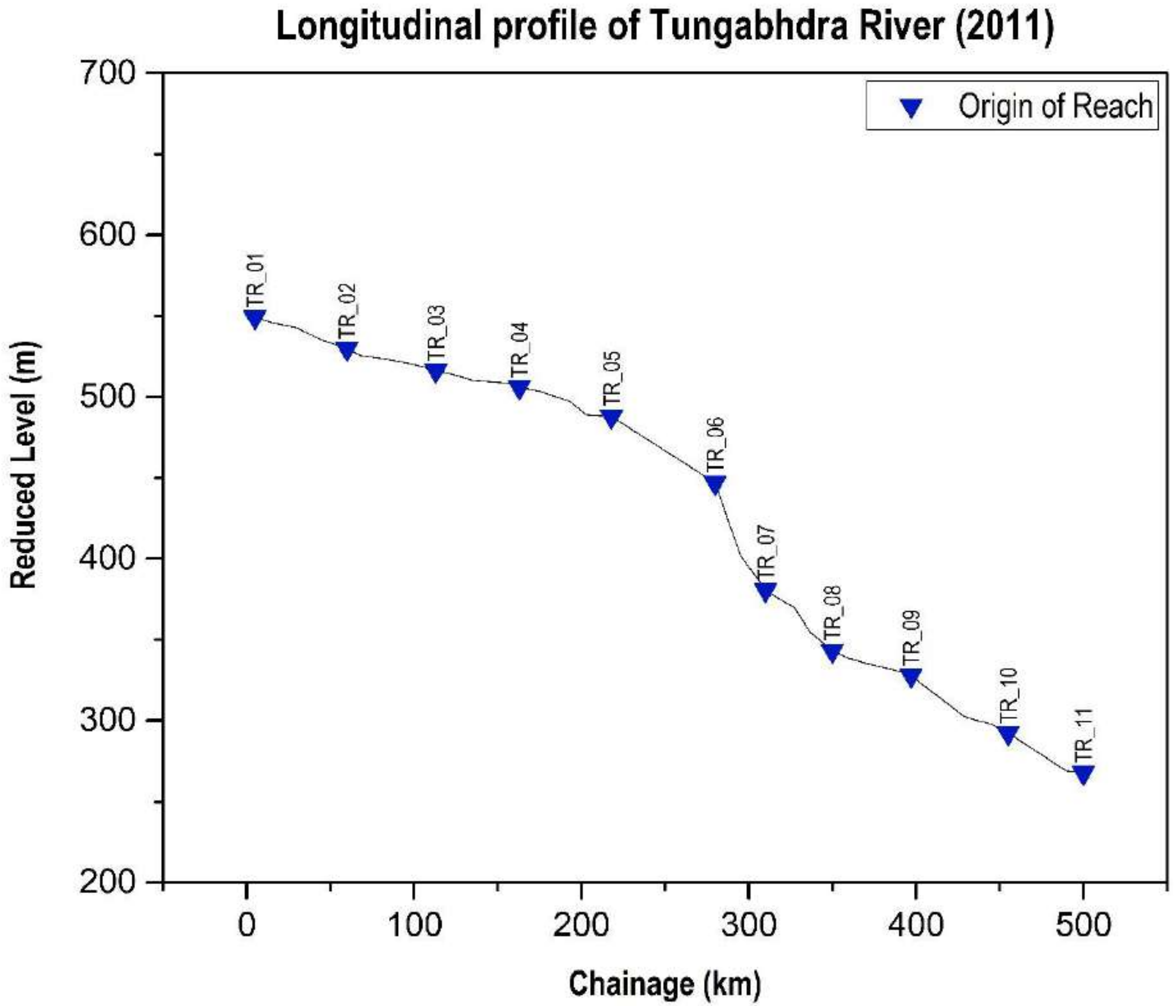


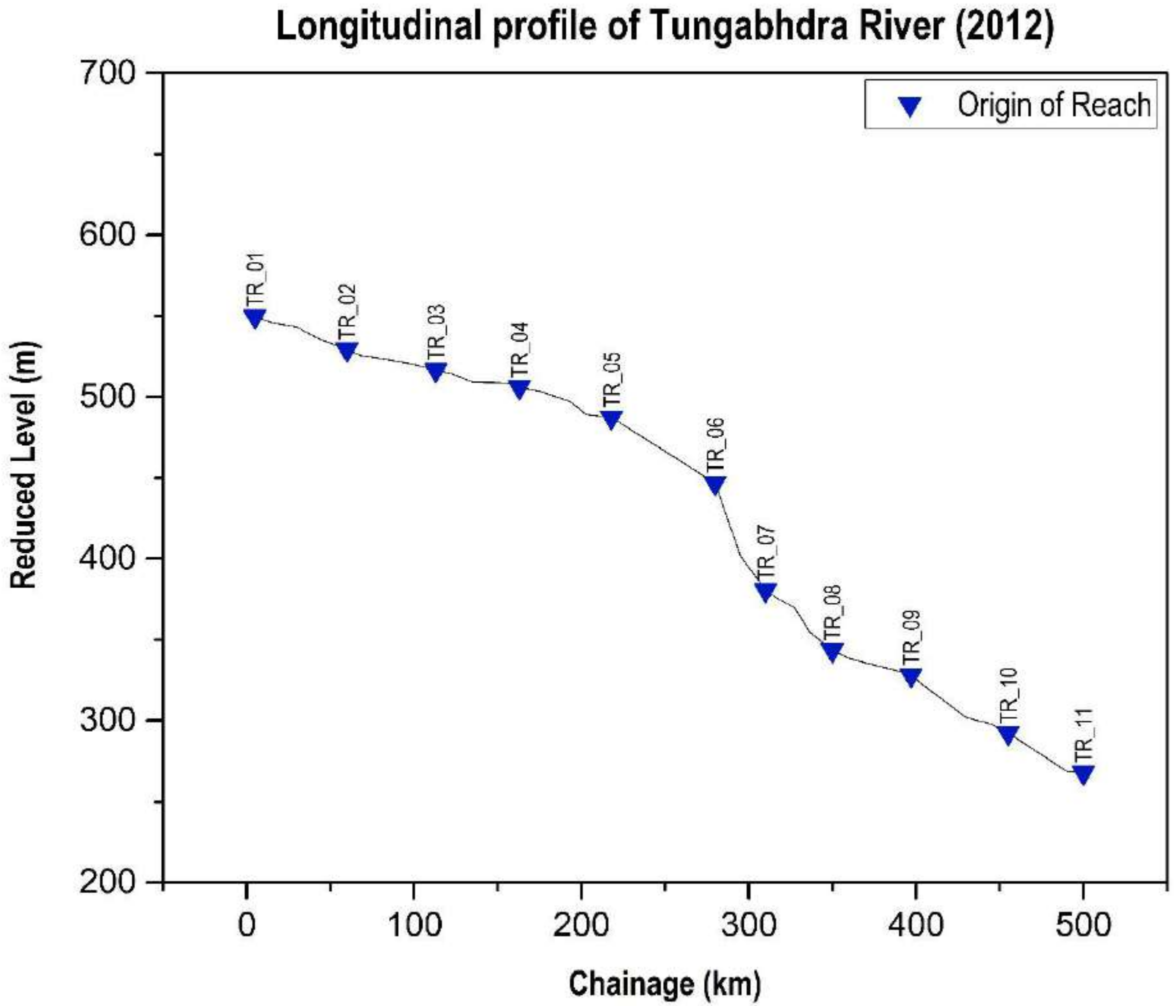
Longitudinal profile of Krishna river (2012)
Origin of Reach
Reduced Level (m)
Chainage (km)
KR_01
KR_02
KR_03
KR_04
KR_05
KR_06
KR_07
KR_08
KR_09
KR_10
KR_11
KR_12
KR_13
KR_14
KR_15
KR_16
KR_17
KR_18
KR_19
KR_20
KR_21
KR_22
KR_23
KR_24
0
100
200
300
400
500
600
700
800
1000
1200
1400

Appendix XVII: Longitudinal profile of Tungabhadra River during 2009 to 2015

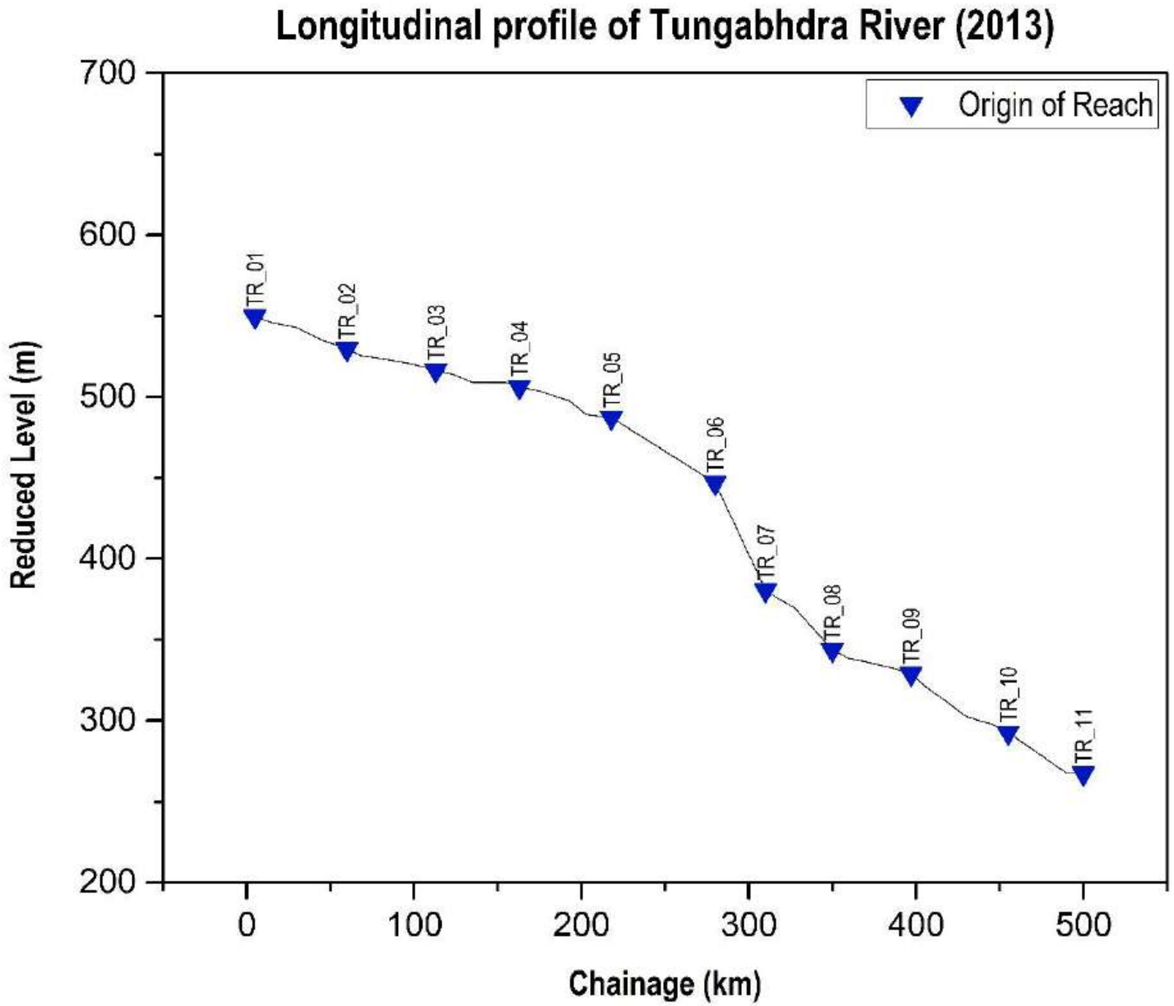



Longitudinal profile of Tungabhdra River (2010)
Origin of Reach
Reduced Level (m)
Chainage (km)
700
600
500
400
300
200
0
100
200
300
400
500
TR_01
TR_02
TR_03
TR_04
TR_05
TR_06
TR_07
TR_08
TR_09
TR_10
TR_11

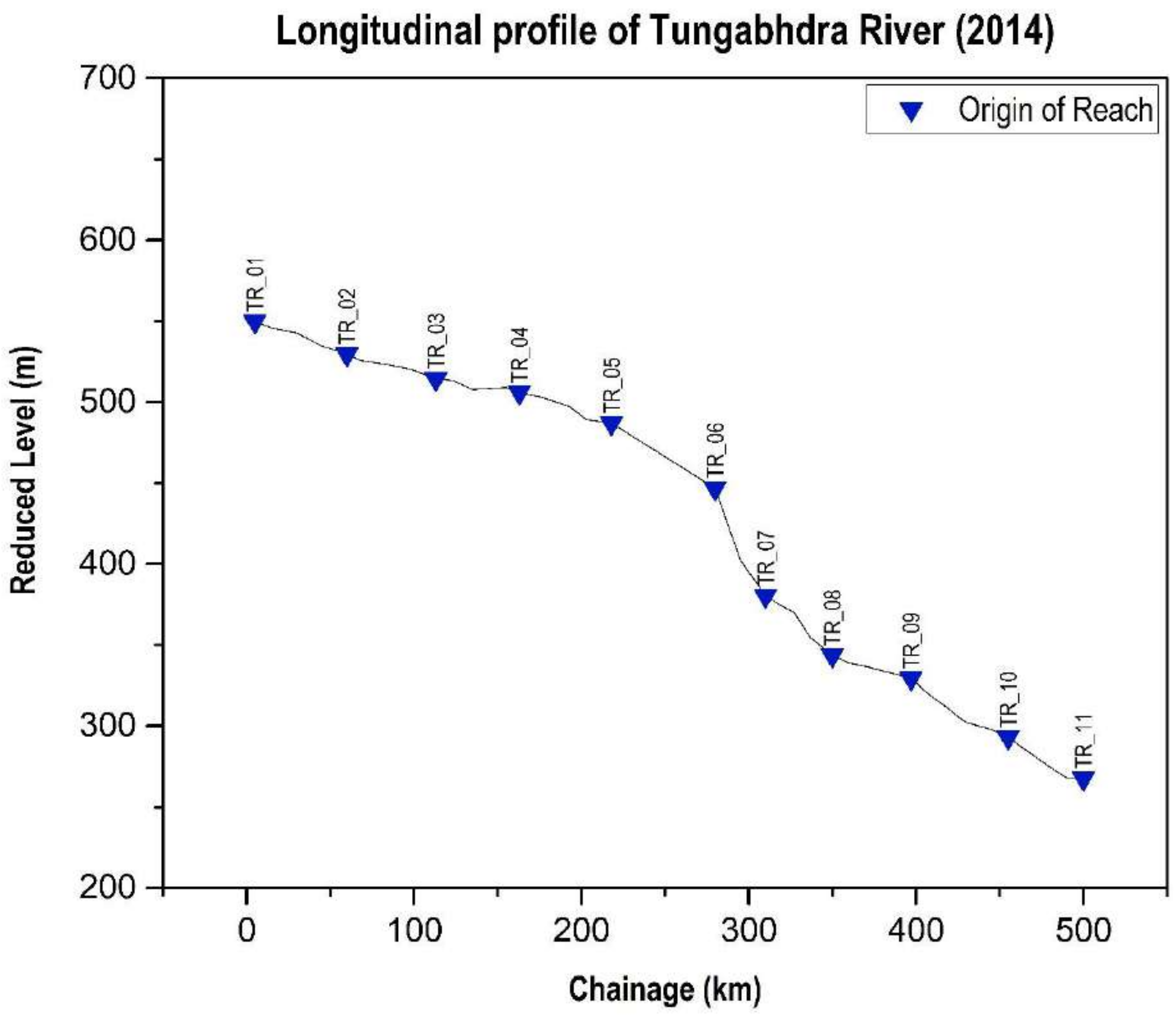

Longitudinal profile of Tungabhdra River (2011)
Origin of Reach
Reduced Level (m)
Chainage (km)
700
600
500
400
300
200
0
100
200
300
400
500
TR_01
TR_02
TR_03
TR_04
TR_05
TR_06
TR_07
TR_08
TR_09
TR_10
TR_11



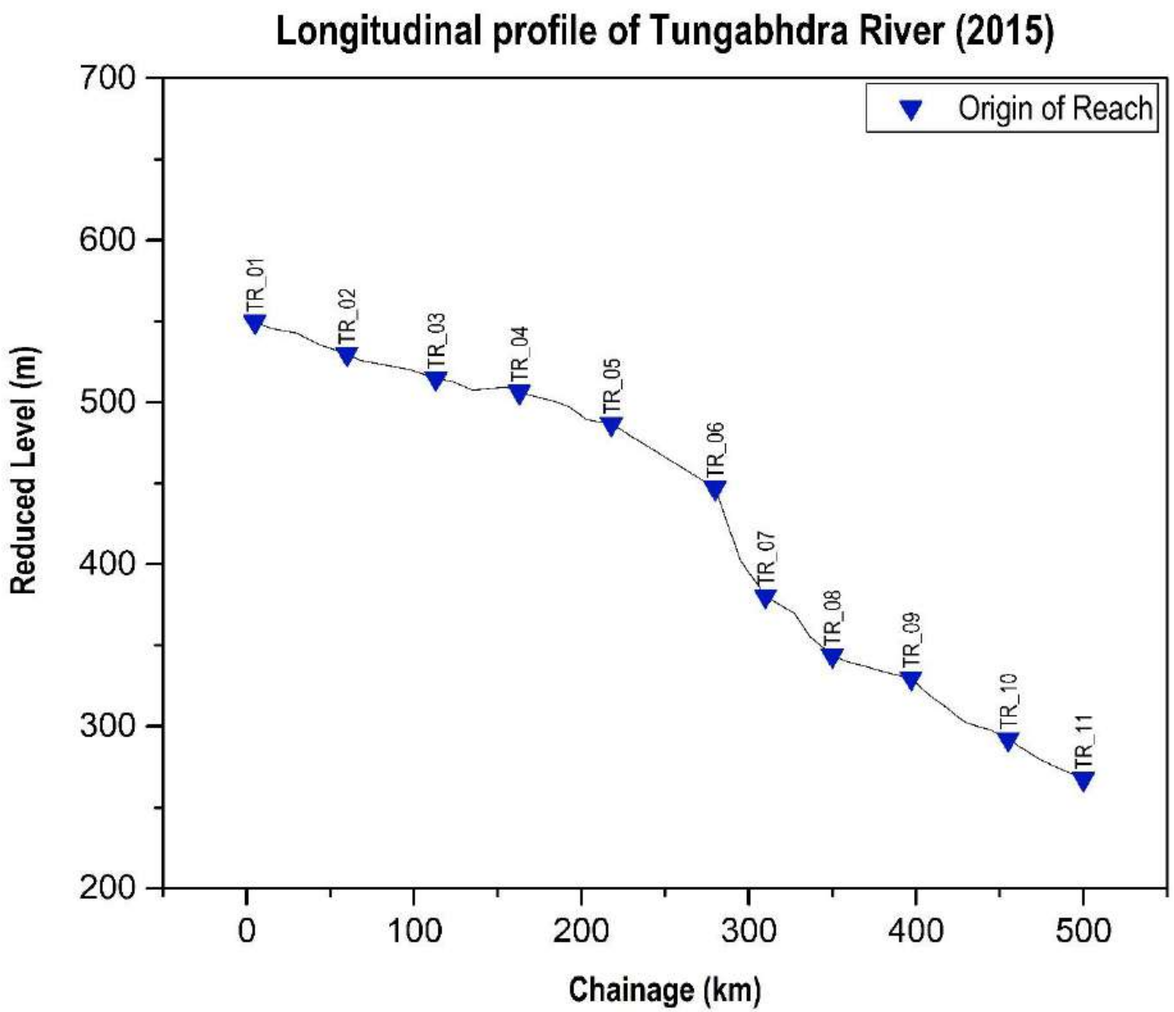
Longitudinal profile of Tungabhdra River (2012)
Origin of Reach
Reduced Level (m)
Chainage (km)
700
600
500
400
300
200
0
100
200
300
400
500
TR_01
TR_02
TR_03
TR_04
TR_05
TR_06
TR_07
TR_08
TR_09
TR_10
TR_11



Longitudinal profile of Tungabhdra River (2013)
Origin of Reach
Reduced Level (m)
Chainage (km)
700
600
500
400
300
200
0
100
200
300
400
500
TR_01
TR_02
TR_03
TR_04
TR_05
TR_06
TR_07
TR_08
TR_09
TR_10
TR_11



Longitudinal profile of Tungabhdra River (2014)
Origin of Reach
Reduced Level (m)
Chainage (km)
700
600
500
400
300
200
0
100
200
300
400
500
TR_01
TR_02
TR_03
TR_04
TR_05
TR_06
TR_07
TR_08
TR_09
TR_10
TR_11



Longitudinal profile of Tungabhdra River (2015)
Origin of Reach
Reduced Level (m)
Chainage (km)
700
600
500
400
300
200
0
100
200
300
400
500
TR_01
TR_02
TR_03
TR_04
TR_05
TR_06
TR_07
TR_08
TR_09
TR_10
TR_11