Assessment of Water Resources at Basin Scale using Space Inputs

A Pilot Study by

NRSC and CWC

Godavari and Brahmani - Baitarani Basins

Water Resources Division
WRG, RS & GIS Applications Area
National Remote Sensing Centre, ISRO
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16 **Abstract (with Keywords)**

The scope of this report is to submit the results of the pilot study on Water Resources Assessment using Space Inputs. Annual water resources during the period 1988-89 to 2007-08, mean annual water resources, water resources during the extreme rainfall conditions in the Godavari, and Brahmani - Baitarani Basins are presented. The project has been executed using the remote sensing data, other geo-spatial database, and field data through distributed hydrological modeling approach.

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Considering the importance of fresh reassessment of water resources availability in the country, National Remote Sensing Centre, ISRO, Hyderabad has initiated an R&D Project titled “Assessment of National Water Resources using Space Inputs” under EOAM funding by integrating space technology, geographical information tools, hydro-meteorological data and hydrological models. Subsequently, CWC has shown interest in joining the project. Series of discussions were held between NRSC and CWC, it was decided to take-up a joint pilot project in Godavari, Brahmani - Baitarani Basins to assess basin scale mean annual water resources using space inputs through hydrological modelling technique. This study emphasizes on quantifying basin scale water wealth by transformation from presently adapted basin terminal gauge site runoff aggregation to meteorological based water budgeting exercise through hydrological modelling approach.

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PROJECT TEAM

EXECUTIVE SUMMERY

The surface water and groundwater resources in India play a major role in agriculture, hydropower generation, livestock production, industrial activities, forestry, fisheries, navigation, recreational activities, etc. Potential impact of global climate change on water resources include enhanced evaporation due to warming, geographical changes in precipitation intensity, duration and frequency, together affecting the hydrological parameters such as, Runoff, Soil moisture, etc. Earlier, different commissions, agencies, researchers have estimated water resources of the country using different approaches. Among these, First Irrigation Commission (1902-03), Dr.A.N. Khosla (1949), Central Water and Power Commission (1954-66), Studu done by K L Rao, National Commission on Agriculture (1976), and Central Water Commission (1988) are very popular. Reassessment of Average Annual Water Resources Potential (1993) is the most recent and authentic study done by Central Water Commission. CWC's recent study was done for the period of 1967 to 1985 for many river basins.

All these studies are based on the observed flows at terminal sites and upstream abstractions for irrigation and domestic consumptions. Limitations of these studies are; limited field data on abstractions, lumped approach in estimation at terminal sites of the basins, no meteorological parameters (such as rainfall evapotranspiration) are taken into consideration, and no mechanism for cross validation. Considering the importance of fresh reassessment of water resources availability in the country, National Remote Sensing Centre, ISRO, Hyderabad has initiated an R&D Project titled "Assessment of National Water Resources using Space Inputs" under EOAM funding by integrating space technology, geographical information tools, hydro-meteorological data and hydrological models. In this context, a Brain-storming Session on Water Resources Assessment was also organized by NRSC at Hyderabad in which officers from IITs, IISc, RRSSC, CWC, NRSC participated and discussed various issues related to water resources assessment in the country. Subsequently, CWC has shown interest in joining the project. Series of discussions were held between NRSC and CWC, it was decided to take-up a joint pilot project in Godavari, and Brahmani - Baitarani Basins to assess basin scale mean annual water resources using space inputs through hydrological modelling technique.

This study emphasises on quantifying basin scale water wealth by transformation from presently adapted basin terminal gauge site runoff aggregation to meteorological based water budgeting exercise through hydrological modelling approach.

Daily rainfall data of 0.5 degree grids, daily temperature data of 1 degree grids were obtained for the last 20 years from the India Meteorological Department and converted into GIS format. Landuse grids of 1985, 1995, 2004, 2005, 2006, 2007, and 2008 prepared under NRC project using IRS-P6 AWiFS satellite data (56m resolution) were used. Soil textural map, landuse map, digital elevation map, and command area map were integrated to compute hydrological response grid of the basin. Different evapotranspiration methods were examined and Thortnthwaite method was adopted with suitable modifications after considering the availability of meteorological data at basin scale. Monthly evapotranspiration grids for the last 20 years were computed using the analysed meteorological data. In this study, a newer approach was adopted in computing monthly potential evapotranspiration grids by incorporating the landuse coefficients derived from the satellite data. All these grids were integrated in the modified Mather modelling framework to compute runoff. Observed discharges at various gauge stations were obtained from CWC and model was thoroughly calibrated and validated. Two years data was used for model calibration and 2 more years data for validation. It is found that computed runoff is very well matching with the field data with good accuracy. Different approach was adopted in computing runoff from irrigated agricultural lands. Irrigated agriculture area was identified using landuse and command area grids. Runoff in these HRUs are computed assuming sufficient irrigation supplies are provided to meet the actual avapotranspiration requirements and subsequently adjusted in runoff computations. Groundwater flux grids during these 20 years were computed using the groundwater level information obtained from Central Groundwater Board, India. Surface water flux was computed from the reservoir data obtained from the Central Water Commission (CWC), India. Domestic water consumption was computed as per the norms using the demographic data. These flux grids were integrated with computed runoff in assessing annual water resources availability in the basin. Mean annual water resources availability (WRA) during the 20 years period, WRA during dry year (minimum rainfall period) and wet year (maximum rainfall period) were computed. Rainfall of 35 years was analysed for identifying wet and dry years. Mean annual AET from the irrigated agriculture, irrigation supplies are also computed in the study.

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1.0 Introduction

Proper assessment of the availability of water resources is the cornerstone for proper planning, development and management. Precipitation, in the form of rain and snowfall, is a crucial component of the hydrological cycle that makes fresh water available on a renewable basis. The geographical area of the country is 329 million hectare (Mha), and the mean annual rainfall, taking the country as a whole is 1170 mm. This gives an annual precipitation of about 4,000 BCM. A significant part of this precipitation seeps into the ground and the balance flows through streams and rivers and collects in water bodies adding to the surface flow. A part of the water that seeps into the ground remains as soil moisture in the upper layers and the rest adds to the ground water resources. Subsequently, a major part of the water from surface flows, soil moisture and ground water sources, when put to various uses, returns to the atmosphere through evaporation and transpiration. Part of the water from surface flows may enter ground water and add to the ground water resources and part of the ground water again returns to streams and rivers. Thus the surface and the ground water sources are inter-linked, continuously inter-active and therefore very much part of a single entity.

Natural (virgin) flow in the river basin is reckoned as water resources of a basin. The mean flow of a basin is normally obtained on pro-rata basis from the average annual flow at the terminal site. However, at any point of time, the water resources in a river basin have already been developed and utilized to some extent through construction of major or medium storage dams and development of hydro-power, irrigation and other water supply systems. A large number of diversion schemes and pumped storage schemes may have also been in operation. Assessment of natural flow has, therefore, become complex in view of the upstream utilizations, reservoir storages, re-generated flows and return flows. The natural flow at the location of any site is obtained by summing up the observed flow, upstream utilization for irrigation, domestic and industrial uses both from surface and ground water sources, increase in storage of reservoirs (surface and sub-surface) and evaporation losses in reservoirs, and deducting return flows from different uses from surface and ground water sources.

2.0 Background of assessment of basin wise water resources potential in India

2.1 Work done in the past

2.1.1 First Irrigation Commission (1902-03)

The first ever attempt to assess the average annual flow of all the river systems in India was made by the Irrigation Commission of 1901-1903. The major constraint at that time was that while records in respect of rainfall were available, data in respect of river flows were not available even for many of the most important river systems. The Commission, therefore, resorted to estimation of river flows by adopting coefficients of runoff. The average annual flow of all the river systems in India was assessed as 1443 BCM.

2.1.2 Dr.A.N. Khosla (1949)

Dr. A.N Khosla developed an empirical relationship between mean temperature (as an expression for mean evaporation loss) and mean runoff based on his studies on the flows of Sutlej, Mahanadi and other river systems. While applying these relationships to the entire country, Dr. Khosla divided the country into six regions, viz (i) Rivers falling into Arabian Sea excluding Indus, (ii) Indus Basin within India, (iii) Rivers falling into Bay of Bengal other than the Ganga-Brahmaputra system, (iv) the Ganga, (v) the Brahmaputra, and (vi) Rajputana. According to these studies, the total annual flow of all the systems worked out to 1673 BCM.

2.1.3 Central Water and Power Commission (1954-66)

CWPC estimated the surface water resources of different basins during the period from 1952 to 1966. The study was mostly based on the statistical analysis of the flow data wherever available and rainfall-runoff relationships wherever data was meagre. The country was divided into 23 sub-basins / basins. Ganga was divided into as many as ten sub-systems. Other major peninsular river basins like Narmada, Tapi, Godavari, Krishna, Pennar and Cauvery were considered separately. Other river systems were combined together suitably into a few composite systems. According to these studies, the water resources of various basins amounted to 1881 BCM.

2.1.4 National Commission on Agriculture (1976)

NCA estimated total annual water resources of the country as 1850 BCM (1800 BCM available in an average year) based on water balance approach taking into account rainfall, percolation of water in soils, evaporation and evapo-transpiration.

2.1.5 Central Water Commission (1988)

As per the report 'Water Resources of India', the natural run-off of a basin could be computed by adding to the surface flow measured at the terminal site, the net export of the surface water out of the basin, the net increase of the surface water storage, additional evapotranspiration caused by use or storage of surface water, direct ground water flow from the river basin below or along the terminal site, the net export of ground water out of the basin, the net increase in ground water storage and soil moisture storage, and the additional evapotranspiration caused by use or storage of ground water. This is general water balance approach, applicable to any basin for any period. However, if averages over a long time period are taken, storage change would be zero or negligible. Also assuming a case of no export or import, and neglecting the ground water flow below or along the terminal site, a simplification is possible. With this simplification, the average annual natural flow can be computed by adding to the average annual surface flow measured at the terminal site, the average annual extra evaporation / evapotranspiration due to use or storage of surface water and the average annual extra evaporation / evapotranspiration due to storage or use of ground water.

Earlier, estimate of the natural runoff have been made by two approaches. The approach adopted by Dr. Khosla does not directly use the measured surface flow at terminal site but works out the natural runoff as the difference between precipitation received and estimated natural evapotranspiration. This approach would, thus require no correction for utilization of surface or ground water. The second approach utilizes the observed flow record and thus gives a more realistic estimate. In this approach the observed surface flow at the terminal site is corrected for extra evapotranspiration due to utilization of water. However, mostly the correction due to additional evapotranspiration due to storage or use of ground water was not done in actual working. This was now attempted.

District wise estimates of ground water draft i.e. withdrawal from ground water storage have already been worked out by Central Ground Water Board for the year 1983-84. 1983-84 district wise figures were converted into basin wise figures. The total draft for the country for the year 1983-84 was about 100 BCM / year.

Similar estimates for 1967-68 as available in Irrigation Commission report indicate that the draft for that year was about 58 BCM / year. Assuming linear variation, the annual draft for any year can be calculated. Basin wise figures for any other year can be estimated on the same proportion as the overall national figures. It is assumed that the consumptive use of ground water is 70% of the withdrawal. For each basin, where the natural run-off is being worked out from the observed terminal site flows, the period of data available has been considered for obtaining the average annual natural runoff. The correction for the consumptive use i.e. extra evaporation use to ground water is to be adjusted to the mid-point of the observed data period by the procedure stated above. Thus, depending upon the mid-point of the observed data period, different corrections were worked out. For basins such as Godavari and Krishna, where the mid-point fell around 1930, the required correction was negligible and was not done.

The basin wise average annual water resources were estimated as 1880 BCM following the above procedure. The above however excluded the groundwater which flows directly to the sea or to the neighbouring countries bypassing the terminal site. Studies, carried out elsewhere indicate that this quantum is not appreciable and would be around 5% of the runoff.

2.2 Latest Estimates

2.2.1 Reassessment of Average Annual Water Resources Potential (1993)

Basin wise reassessment of water resources potential in the country was carried out by Central Water Commission (CWC) in 1993 and given in the report entitled 'Reassessment of Water Resources Potential of India'. The water resources potential of the country was reassessed as 1869 BCM against an earlier assessment of 1880 BCM done by CWC in 1988.

While assessing the water resources of India, the country was divided into 20 river basins comprising 12 major basins and 8 composite river basins.

The twelve major basins are: (1) Indus; (2) Ganga-Brahmaputra-Meghna; (3) Godavari; (4) Krishna; (5) Cauvery; (6) Mahanadi; (7) Pennar; (8) Brahmani-Baitarni; (9) Sabarmati; (10) Mahi; (11) Narmada; and (12) Tapi.

The eight composite river basins are: (1) Subernarekha – combining Subernarekha and other small rivers between Subernarekha and Baitarni; (2) East flowing rivers between Mahanadi and Pennar; (3) East flowing rivers between Pennar and Kanyakumari; (4) Area of Inland Drainage in Rajasthan Desert; (5) West flowing rivers of Kutch and Saurashtra including Luni; (6) West flowing rivers from Tapi to Tadri; (7) West flowing rivers from Tadri to Kanyakumari; and (8) Minor rivers draining into Myanmar (Burma) and Bangladesh

Natural (virgin) flow in the river basin is reckoned as water resources of a basin. The mean annual flow of a basin is normally obtained on pro-rata basis from the mean annual flow at the terminal site. The natural flow at any location on a river is obtained by summing up the observed flow, upstream utilization for irrigation, domestic and industrial uses both from surface and ground water sources, increase in storage of reservoirs (both surface and sub-surface) and evaporation losses in reservoirs, and deducting return flows from different uses from surface and ground water sources.

The observed flows at terminal sites of the basins were corrected for upstream abstractions to arrive at the natural flows by adopting the following equation:

$$R_N = R_O + R_{IR} + R_D + R_{GW} - R_{RI} - R_{RD} - R_{RG} + S + E \qquad \text{Eq.1}$$

R_N is the natural flow

R_O is the observed flow

R_{IR} is the withdrawal for irrigation

R_D is the withdrawal for domestic and industrial requirement

R_{GW} is the ground water withdrawal

R_{RI} is the return flow from irrigated areas

R_{RD} is the return flow from domestic and industrial withdrawal

R_{RG} is the return flow from ground water withdrawal

S is the increase in storage of the reservoirs in the basin

E is the net evaporation from the reservoirs

Based on the above methodology, CWC assessed the average annual water resources potential of the country as 1869 BCM in the year 1993.

The data used for reassessment of water resources potential in the various river basins as detailed in the report 'Reassessment of Water Resources Potential of India' (March, 1993) are given below:

Basin	Flow data	Withdrawal data
Godavari	Observed river flow data for the period 1967-68 to 1984-85 at Polavaram which covers 98.4% of the total area of basin.	Data on abstractions for irrigation have been obtained from the records maintained by irrigation project authorities. Wherever such records are not available, the abstractions have been estimated from the area irrigated by adopting suitable delta. Area irrigated has been mostly obtained from the reports of the Bureau of Economics and Statistics. Withdrawals for domestic and industrial requirements have been estimated assuming per capita total requirement of 100 litre per day, using population figures as per 1981 census. Ground water draft for the basin has been worked out based on the estimates of total ground water draft for the country by Irrigation Commission in 1967-68 and Central Ground Water Board in 1983-84.
Brahmani-Baitarni	At Jenapur on the Brahmani, observed river flow data were available for the period 1964-65 to 1984-85. Jenapur covers about 90% of the	Withdrawal for irrigation was calculated based on the yearwise irrigation potential created assuming an average delta of 0.82m. Withdrawal for domestic use was based on the population statistics assuming requirement of 70 lpcd for rural population and 140 lpcd for urban

	Brahmani sub-basin area. At Biridi on Baitarni, observed river flow data available for the period 1964-65 to 1984-85. It covers nearly 97.8% of the sub-basin area.	population

Based on the above methodology (eq. 1), CWC assessed the average annual water resources potential of the country as 1869 BCM in the year 1993.

2.2.1.1 Limitations of the 1993 study

The broad limitations of the study are as follows:

(1) For working out the upstream abstractions, for various uses, assumptions had to be made depending upon the type of data that could be obtained for the abstractions. Uniform procedure could not naturally be adopted for all the river basins. Particularly for estimating withdrawals for irrigation which is the major consumer of water varying assumptions had to be made. In many cases while diversions from major and medium irrigation projects were available, those from minor schemes were seldom available.

(2) In most of the cases the year-wise withdrawal from ground water has been estimated approximately assuming linear variation between the state-wise draft given by the Irrigation Commission of 1972 for the year 1967-68 and by the Central Ground Water Board for the year 1983-84, and interpolating for other years.

(3) Return flows have been assumed to be 10% in the case of irrigation (major and medium) and 80% in the case of domestic and industrial supplies which are only approximate.

2.2.2 Assessment by National Commission for Integrated Water Resources Development (1999)

The National Commission for Water Resources Development (NCIWRD) while assessing the potential, agreed with the estimates of the Reassessment study carried out by CWC (1993) excepting the cases of Brahmaputra and Krishna basins. In case of Brahmaputra basin, the NCIWRD assessment included additional contribution of 91.81 BCM which was estimated to be the flow of the 9 tributaries joining Brahmaputra downstream of Joghighopa site. In the case of Krishna basin, the figure adopted by the NCIWRD was based on the mean flow of the yield series that is accepted by the KWDT Award. Taking into account the above two variations, the estimation of NCIWRD yielded that the average annual water resources potential of the country is 1953 BCM.

3.0 Genesis of the Pilot studies in Godavari and Brahmani-Baitarni river basins

3.1 Assessment of National Water Resources – R&D Programme under Earth Observation Application Mission (EOAM) Programme of NRSC, ISRO, Hyderabad

National Remote Sensing Centre, ISRO, Hyderabad initiated a R&D Project titled "Assessment of National Water Resources using Space Inputs" under EOAM funding for integrating space technology, geographical information tools, hydro-meteorological data and hydrological models. In this context, a Brain-storming Session on Water Resources Assessment was also organized by NRSC at Hyderabad on 24th March, 2009 in which officers from IITs, IISc, RRSSC, CWC, NRSC participated and discussed various issues related to water resources assessment in the country.

The need for reassessment of water resources in the country, methods, models, time scale, spatial scale, input data, quality of data, impact of climate change on water resources, and other key aspects were discussed during the sessions. During the session two Committees namely the Drafting Committee and Expert Committee were constituted to bring out a technical document (guide) for research and practice on water resources assessment in the country.

Based on the discussions held during the Brain-Storming Session, literature study and further discussion among the various authors, a technical guide for research and practice titled "Water Resources Assessment – The National Perspective" was brought out by NRSC, ISRO, Hyderabad in October, 2009. The technical guide includes: Water Resources Assessment – Indian Perspective containing hydrological setting of the country, need for water resources assessment at the national level, previous studies for assessment of water resources, international practices, etc; Methodology for Integrated Water Resources Assessment containing approach and models, review of available models and softwares, snowmelt runoff – methods and models, criteria and selection of model(s), model calibration and validation, etc; Data requirements containing spatial data, time series data, gauge and discharge data, meteorological data, groundwater data, topographic data, satellite based products of meteorological parameters, satellite based rainfall product sources, etc; Review of water availability estimates; Operational aspects; and Recommendations.

3.2 National Water Mission

With a view to address the climate change related issues, the National Action Plan on Climate Change (NAPCC) has been prepared by the Government of India. The NAPCC has laid down the principles and has identified the approach to be adopted to meet the challenges of impact of climate change through eight National Missions namely, (a) National Solar Mission, (b) National Mission for Enhanced Energy Efficiency, (c) National Mission on Sustainable Habitat, (d) National Water Mission, (e) National Mission for Sustaining the Himalayan Eco-system, (f) National Mission for a Green India, (g) National Mission for Sustainable Agriculture, and (h) National Mission on Strategic Knowledge for Climate Change.

One of the strategies identified for implementation under the Comprehensive Mission Document of National Water Mission was “Reassessment of basin wise water situation” under present scenario including water quality by using latest techniques, which inter-alia may include:

- Development or adoption of comprehensive water balance based model,
- Fitting models to basin using current data, and
- Assessment of likely future situation with changes in demands, land use, precipitation and evaporation.

The steps for implementation of the strategy as circulated in the document prepared by P&D Organisation (nodal organisation for Climate Change / National Water Mission activities in Central Water Commission), RM wing, envisaged coordination with NRSC for “Assessment of National Water Resources” using Remote Sensing, GIS based modelling.

3.3 Discussions of CWC with NRSC, Hyderabad for initiation of pilot studies in Godavari and Brahmani-Baitarni river basins

Subsequently, several meetings were held among the officers of CWC, NRSC, NIH, CGWB under the Chairmanship of Member (WP&P) wherein various issues such as methodology of the reassessment of water resources of the country, non-availability of utilization data uniformly throughout the country / river basins, various models available for indirect estimation of utilization data, selection of models, time and spatial scales, data requirements, budget requirement, etc were deliberated in detail.

Finally, during the meeting held on 27.01.10, it was decided that pilot studies on experimental basis can be initiated in the two selected river basins of Godavari and Brahmani-Baitarni. The project would be jointly executed by NRSC and CWC engineers. The highlights of the methodology include water balance approach; precipitation as primary resource (spatial interpolation); new technology tools i.e. satellite derived spatial data (land use, land cover, elevation, soil), GIS; semi-distributed modeling approach; concept of Hydrologic Response Unit (HRU) for water balance computation; calibration and validation using CWC observed discharge observations. Thus, the study will indirectly estimate the utilization of water by various sectors. Further, the modalities for procurement of various data such as landuse / landcover maps, digitizing soil texture maps, preparation of other spatial data, mean monthly rainfall and temperature data, monthly / daily discharge data, data pertaining to groundwater table, monthly reservoir water level data, census data, irrigated command area boundary maps, etc was also discussed. It was also decided that Budget requirement will be met by NRSC under Earth Observation Application Mission (EOAM) Programme.

3.4 Objectives of the pilot study

Considering the need and data availability in these river basins, the following main objectives were set for the pilot study:

- To assess the annual water resources potential in the Godavari Basin, Brahmani - Baitarani basins during 1988-89 to 2007-08 (20 years).
- To computed the mean annual water resources potential during the 20 years in these basins.
- To compute water resources during extreme dry and wet conditions (minimum and maximum rainfall scenarios) during the last 35 years (1973-74 to 2007-08) in the basins.

4.0 Approaches and Hydrological Models

Rainfall-runoff models can be classified in terms of the processes represented, the time & space scale used, and the methods of solution to equations are used. The main features for distinguishing the approaches are; the nature of basic algorithms (empirical, conceptual or process-based), whether a stochastic or deterministic approach is taken, and whether the spatial representation is lumped or distributed.

The first feature defines if the model is based on a simple mathematical link between input and output variables of the catchment or it includes the description, even if in a simplified way of the basic processes involved in the runoff formation and development. Generally, when the observations are reliable and adequate, extremely simple statistical or parametric models are used. They vary from the simple regression models to the more recent Artificial Neural Networks models. These models are strongly dependent on the data used for calibration and, ought to non-linear behavior of the rainfall-runoff process. Their reliability beyond the range of observations may be questionable. For this reason conceptual models are generally preferred. The term conceptual denotes also the fully distributed physically based models because, even if they use parameters which are related to physical characteristics of the catchment and operate in a distributed framework, they must use average variables and parameters at grid or element scales greater than the scale of variation of the processes modeled (NRSC, 2009).

Another basic distinction between models is whether stochastic or deterministic representations and inputs are to be used. Most models are deterministic so they generate a single set of output. On the basis of the spatial representation, the hydrological models can be classified into three main categories: lumped models, semi-distributed models, and distributed models. The semi-distributed and distributed models take an explicit account of spatial variability of processes, input, boundary conditions, and/or watershed characteristics. Of course, lack of data prevents such a general formulation of distributed models, that is these models cannot be considered fully distributed.

Finally, according to the hydrological processes, hydrological models can be further divided into event-driven models, continuous-process models, or models capable of simulating both short-term and continuous events, and monthly based models. The first are designed to simulate individual precipitation-runoff events and their emphasis is placed on infiltration and surface runoff. The major limit to the use of event type model is the problem of unknown initial soil moisture conditions that cannot be measured and may heavily condition the forecasts in real time. Continuous process models, on the other hand, take explicitly account of all runoff components with provision for soil moisture redistribution between storm events. The daily models are suitable where sufficient field data is available and the study area is not very big and the user is intend to estimate runoff for a particular duration (may be a hydrological year). Monthly models are realistic for long term estimates in river basins and it gives reasonable estimates when we do water resources assessment at national level. These monthly models are process based and takes care of all hydrological processes such as Potential Evapotranspiration, Actual Evapotranspiration, Soil Moisture, change in groundwater storage, etc.

Various models and its data requirements, scope, limitations are examined. These includes, Iinitial and constant rate model, Modified SCS Curve Number Loss Model, Continuous Soil-moisture Accounting (SMA) Model, Green and Ampt Loss Method, NAM Model (rainfall-runoff (RR) module of the MIKE11 river modeling system), TOPMODEL, VIC Model (Variable Infiltration Capacity Model), SWAT Model (uses SCS and Green Ampt models for runoff estimation), MIKE SHE, HEC-HMS, and other monthly water balance models.

Selection of a model mainly depends on the objectives of study, data available, spatial and temporal scale of the study. Each model requires different type of input data, when we are doing hydrological modelling at basin level one has to optimise the model considering the availability of input data. It is obvious that distributed or semi-distributed models are more accurate in runoff estimation compared to lumped models. Land use, soil texture, and digital elevation models are basic topographic input for any distributed hydrological modelling. Some models require extensive data on soil moisture, groundwater condition, etc.

For the country like India estimating daily runoff for many years is very cumbersome task both in quantity and in input data requirements. Monthly models can simulate the runoff nearer to the field reality that can give the overall picture on national water resources. Various monthly models like Thortnwaite and Mather (TM) model, Pitman model, Thomas abcd model, Roberts model, etc are widely used for runoff estimation. These models were used for estimating runoff at national level in various countries like China, Brazil, USA, Russia, and in other countries. Advantages of these monthly models are, each component of hydrological cycle can be computed separately and accurately. Different algorithms can be chosen for estimating individual components of the hydrological cycle also. Considering the need, and the availability of long-term hydro-meteorological data at national level, it is proposed to use monthly water balance model in the pilot study.

After examining various water balance models, Mather soil water balance model is chosen for the study as it uses distributed modelling approach and widely applied in various countries. This model is almost nearer to the process based approach in which, potential evapotranspiration, water loss and accumulated water loss in a month, water holding capacity of soils up to root depth are considered in calculating actual evapotranspiration and subsequently runoff. Since the evapotranspiration is the major component in the hydrological water balance, a suitable and practically feasible method has to be adopted at basin scale considering the data availability.

Various evapotranspiration methods, its merits and limitations have been examined and some of them are discussed below,

4.1 Review of PET Estimation Methods

Many methods have been proposed to estimate PET world wide of which some of the popular methods are discussed here (Jianbiao et al, 2005; McCabe and Markstrom, 2007; Papadopolou et al, 2003; Kerkides et al, 1996; Nata Tadesse, 2006).

4.1.1 Penman-Monteith Method

The most popular formula for evapotranspiration is the Penman-Monteith formula,

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\, 900\, u_2\, (e_s - e_a)/(T+273)}{\Delta + \gamma\,(1 + 0.34\, u_2)} \qquad \text{Eq. 2}$$

where,

ET_o reference evapotranspiration [mm day-1],

R_n net radiation at the crop surface [MJ m-2 day-1],

G soil heat flux density [MJ m-2 day-1],

T mean daily air temperature at 2 m height [°C],

u_2 wind speed at 2 m height [m s-1],

e_s saturation vapour pressure [kPa],

e_a actual vapour pressure [kPa],

$e_s - e_a$ saturation vapour pressure deficit [kPa],

Δ slope vapour pressure curve [kPa °C-1],

γ psychrometric constant [kPa °C-1].

The method is of quite good accuracy and is usually used for calculations of evapotranspiration from farmlands. This method requires lot of field data.

4.1.2 Thornthwaite's formula

This formula is based mainly on temperature with an adjustment being made for the number of daylight hours. An estimate of the potential evapotranspiration, calculated on a monthly basis, the model is discussed in the section 5.1.

4.1.3 Blaney-Criddle formula

This formula, based on another empirical model, requires only mean daily temperatures T (^{0}C) over each month. Then:

$$PE = a + b(p(0.46.T_{mean} + 8.13)) \quad \text{Eq. 3}$$

where a and b are calibrated parameters that are functions of minimum daily relative humidity, mean ratio of actual to possible sunshine hours, Variable *p* is the mean daily percentage (for the month) of total annual daytime hours.

4.1.4 Hargreaves Method

The Hargreaves formula is as follows:

$$ET_0 = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{HE} R_a \quad \text{Eq. 4}$$

where T_{mean} is daily mean air temperature (^{0}C), T_{max} is daily maximum air temperature (^{0}C), T_{min} is daily minimum air temperature (^{0}C) and R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}). The mean air temperature in the Hargreaves equation is calculated as an average of T_{max} and T_{min} and R_a is computed from information on latitude of the site and time of the year. Therefore air temperature is the only parameter that needs to be measured and usually HE=0.5 is used.

4.1.5 Priestley-Taylor Method

The Priestley-Taylor model (Priestley and Taylor, 1972) is a modification of Penman's more theoretical equation. An empirical approximation of the Penman combination equation is made by the Priestley-Taylor to eliminate the need for input data other than radiation. This method is for no or low advective conditions.

$$ET_0 = 0.408\alpha[\Delta(R_n-G)/(\Delta+\gamma)], \text{ in mm} \quad \text{Eq. 5}$$

Where,

α = Constant (1.26)

R_n = Net radiation at the crop surface (MJ m^{-2} per day)

G = Soil heat flux

Δ = Slope of the vapour pressure curve (KPa $^0C^{-1}$)

γ = Psychrometric constant (KPa $^0C^{-1}$)

Considering the merits and limitations of individual PET estimation methods, hydrological models and the spatial meteorological data availability at the required temporal resolution, Thornthwaite and Mather model has been selected as the modelling frame work for achieving the set objectives.

PET by Different Methods

Monthly surface meteorological data from IMD is available at 15 locations covering major portion of Brahmani-Baitarani river basins. Using the above data PET has been estimated for each of the 15 locations by Thornthwaite (T), Penman-Montieth (PM) and Hargreaves (HRG) methods. Using Nearest Neighbourhood spatial interpolation technique, the point data have been converted into spatial images of PET. Figure 1 provides the average PET for Anandpur sub-basin catchment for three selected years, namely, 1990-91, 2000-01 and 2004-05.

PET Method	1990-91	2000-01	2004-05
T	1864	1755	1879
PM	1671(-10.3%)	1751 (-0.2%)	1627 (-13.4%)
HRG	1621 (-13%)	1694 (-3.5%)	1682 (-10.5%)

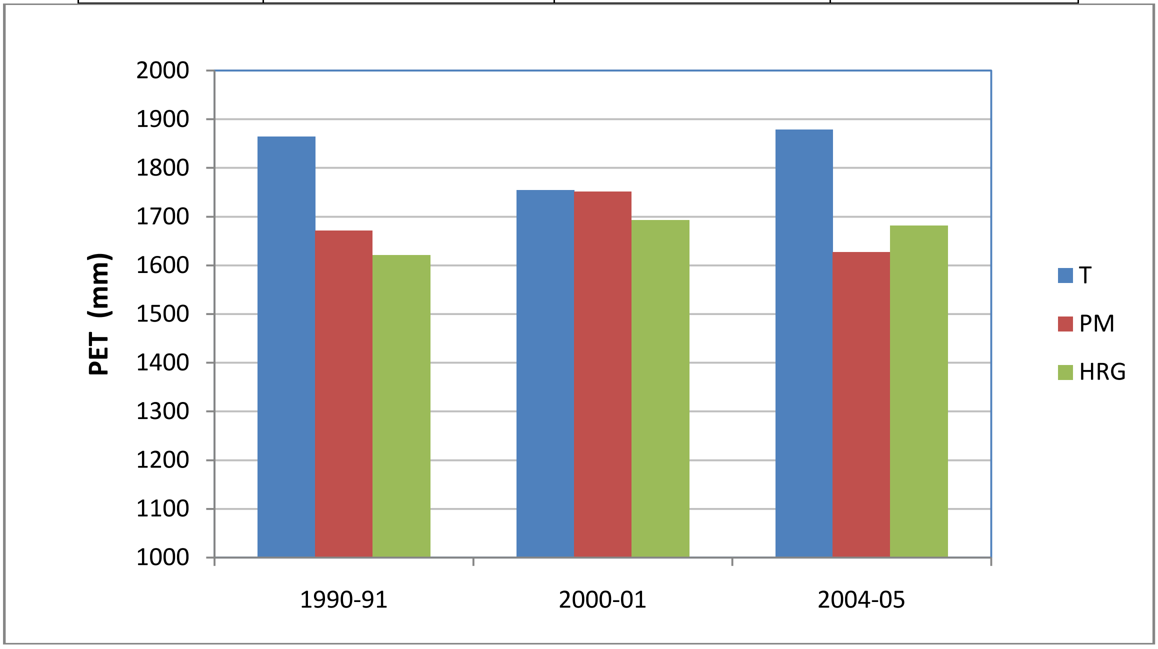


Fig.1 PET estimation by Different Methods in Anandpur Sub-basin

5.0 Modelling Framework

The modelling frame work for the present study (Figure 2) involves integration spatial data sets (DEM, LULC, soil texture, village census) with hydro-meteorological data sets (Rainfall, temperature, GW flux, reservoir flux, river discharge) in GIS environment to carry out water balance computations at hydrological response unit level. The model development and calibration was carried out using the four years data sets (2004-2008) and the calibrated model was extended for all the remaining years. The 20 years water balance outputs were averaged to arrive at Long-term Mean Annual Basin level Water Resources.

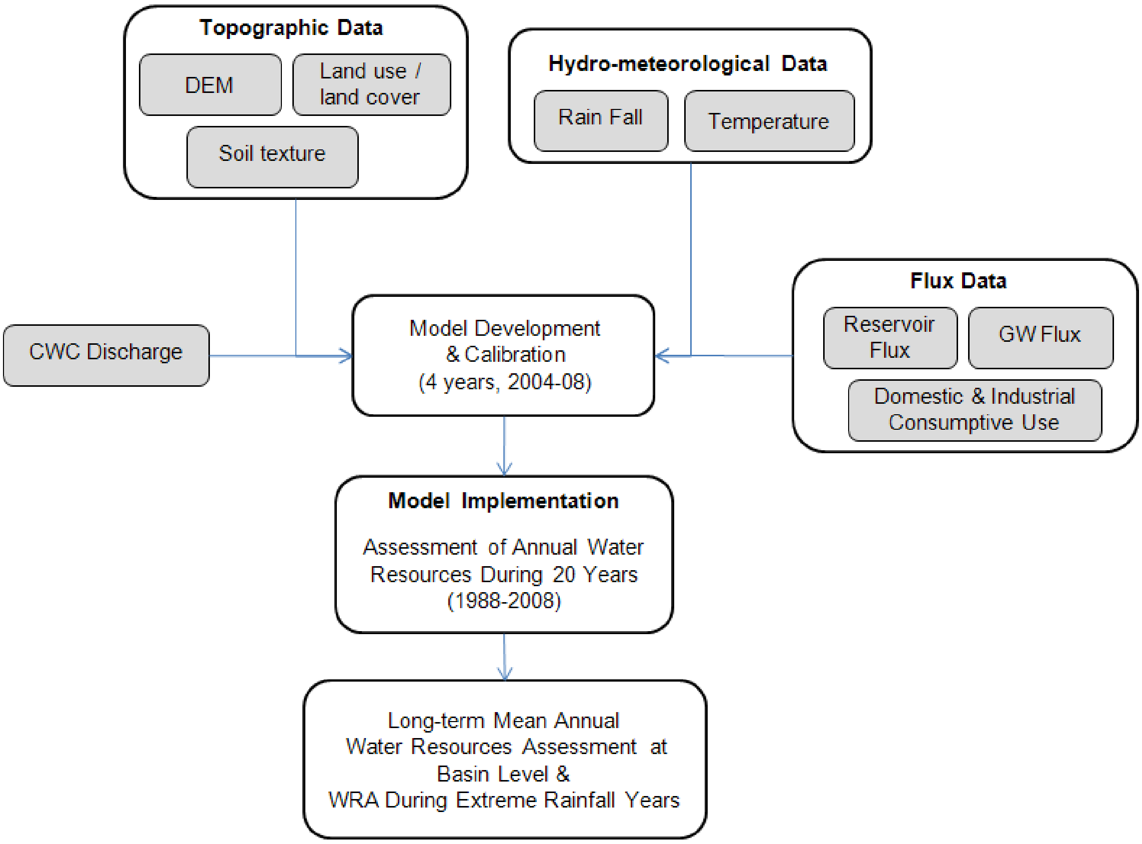


Fig.2 Modelling Framework

5.1 Thornthwaite & Mather Method

The water balance has been used for computing seasonal and geographic patterns of irrigation demand, the soil moisture stresses under which crop and natural vegetation can survive. Water table calculated for a single soil profile or for an entire catchment, refers to the balance between incoming of water by precipitation and outflow of water by evapotranspiration, ground water recharge and stream flow. Among the several possible methods of calculation, the one introduced by Thornthwait and Mather (1957) generally has been accepted. This technique uses long term average monthly rainfall, long term average potential evopotranspiration, and soil & vegetation characteristics. The last two factors are combined in the water capacity of the root zone.

Computation of ET in this method is mainly based on temperature data only. By using the eq.(6) a monthly heat index (**j**) is calculated employing the mean monthly temperatures.

$$j = \left(\frac{t_n}{5}\right)^{1.514} \qquad \text{Eq. 6}$$

Where, j = monthly heat index

t_n = monthly mean temperature, ^{0}c (where n= 1,2,3………12).

Annual heat index (J) is given by the equation (7) adding together twelve monthly heat indices.

$$J = \sum_1^{12} j \qquad \text{Eq. 7}$$

Then, monthly PET for any month is calculated by means of the following equation (8):

$$PET = 16f\left(\frac{10t_n}{J}\right)^a \qquad \text{Eq. 8}$$

Where, a is the cubic function of J

$$a = (675*10^{-9})J^3 – (771*10^{-7})J^2 + (179*10^{-4})J + 0.492 \qquad \text{Eq. 9}$$

f = factor, to correct for unequal day length between months.

It is necessary to adjust the value of unadjusted 30-day potential evapotranspiration and 12 hours of sunshine per day, modulating by factor (f). For other latitudes f value has to be interpolated from the following table.

North Lat.	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	0.97	0.98	1.01	1.03	1.05	1.06	1.05	1.03	1.08	0.99	0.98	0.96
20	0.93	0.96	1.00	1.05	1.09	1.11	1.10	1.07	1.03	0.98	0.93	0.91
30	0.87	0.93	1.00	1.08	1.14	1.18	1.16	1.10	1.03	0.96	0.88	0.85
40	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
50	0.72	0.84	0.98	1.15	1.28	1.37	1.33	1.21	1.06	0.90	0.76	0.68

Day length factor grid has been prepared in GIS environment. PET has been calculated using temperature grids and day length grids through spatial modelling technique. These spatial PET maps of country are prepared and subsequently PET grids of Godavari, Brahmani - Baitarani are extracted.

Vegetation Factors: The Thornthwaite method doesn't account for vegetative effect which is most useful parameter in water balance estimations (Peter E. Black). Monthly landuse factors have been derived for both the river basins using satellite remote sensing data and integrated with PET to account for vegetation effect on PET. The Thronthwaite method uses air temperature as an index of the energy available for evapotranspiration, assuming that air temperature is correlated with the integrated effects of net radiation and other controls of evapotranspiration, and that the available energy is shared in fixed proportion between heating the atmosphere and evapotranspiration. This method estimates PET only based on air temperature and do not the land cover and vegetation classes. But actually, the ET also depends on whether the soil is covered with or without vegetation and vegetation types. Hence, in this study it is proposed to consider the effect of vegetation cover and its type in estimating the PET using the Thronthwaite method by using vegetation coefficients.

$$PET_{revised} = PET * \text{vegetation factor} \qquad \text{Eq. 10}$$

The crop coefficient integrates the effect of characteristics that distinguish a typical field crop from the grass reference, which has a constant appearance and a complete ground cover. Consequently, different crops will have different K_c coefficients. The K_c values primarily depends on crop type, crop growth stage, soil evaporation.

Uniform vegetation coefficient during all the months has been considered for the vegetations like forest, scrub land etc. Whereas for agricultural lands, variable coefficients taken in different months according to the crop growth stage and type of crop. These vegetation coefficients are further calibrated using the field discharge data.

After the calculation of $PET_{revised}$, the dry and wet seasons should be identified. If the difference between P & $PET_{revised}$ is positive, it is considered as wet season, otherwise it is dry season.

The severity of the dry season increases during the sequence of months with excessive potential evapotranspiration. The accumulated potential water loss (La), which is the cumulative of negative values of ($P - PET_{revised}$) for the dry season only is calculated from the end of the wet season.

Next, the water storage capacity (SM), which depends upon the soil texture type, rooting depth of vegetation and land use, in the root zone of the soil must be determined. Then, from the readily available tables or graphs or by using the empirical formula for dry season months we can find how much water will be retained in the soil after various amounts of accumulated potential water loss. For the case of wet seasons, soil moisture values can be determined by adding the excess precipitation to the soil moisture value of the previous month until the total storage again reaches the water- holding capacity of the soil.

The soil moisture status for each month with evapotranspiration exceeding precipitation is calculated using the following eq. (11):

$$SM = W * e^{\left(\frac{-La}{W}\right)} \qquad \text{Eq. 11}$$

Where, SM = soil moisture, mm

La = accumulated potential water loss,

W = water holding capacity, which has been calculated for the different landuse class and soil texture, mm

The ability of soil to retain water depends upon the amount of silt and clay present; the higher the amount, the greater is the soil moisture content. Water holding capacity (W) of each HRU has been calculated based on the landuse, root depth, and soil textural information. SM in each month is calculated based on W and accumulated water loss in the month. ∆SM is the change in soil moisture in a month to its previous month.

Actual evapotranspiration (AET) represents the actual transfer of moisture from the soil and vegetation to the atmosphere. When P exceeds $PET_{revised}$, it is assumed that there is sufficient moisture to meet the climatic demands and

$$AET = PET_{revised} \qquad \text{Eq. 12}$$

Even if the soil moisture of root zone is not at its storage capacity but if $P > PET_{revised}$ it can be assumed that P will be sufficient to satisfy climatic moisture requirements, i.e. $AET = PET_{revised}$. When meteorological demand must be partially satisfied from the stored soil water (when $P < PET_{revised}$),

$$AET = P + |\Delta SM| \qquad \text{Eq. 13}$$

In irrigated agricultural land (canal and well irrigation), irrigation support (P- $PET_{revised}$) is added to rainfall to equate AET to $PET_{revised}$ and AET calculated accordingly. This assumption is made assuming full irrigation water requirements are being met. The added irrigation support has been subsequently adjusted while computing runoff. Then, we should identify that in which months occurs moisture deficit (D) that means there is not enough water to satisfy the vegetation needs. D that exists only in dry period when P< $PET_{revised}$, is calculated by the eq. (14)

$$D = PET_{revised} - AET \qquad \text{Eq. 14}$$

The amount of excess water that cannot be stored is termed as moisture surplus (S). When storage reaches its capacity, surplus is calculated using the eq. (15)

$$S = P - (AET + |\Delta SM|) \qquad \text{Eq. 15}$$

By definition, actual runoff equals to the available annual surplus. However due the lag between the time of precipitation and the time the water actually passes the gauging station, monthly computed surplus is not the same as monthly runoff (**RO**). As per Thornthwaite and Mather's suggestion it can be assumed that for large catchments approximately 50% of the surplus water that is available for runoff in any month runs off. The rest of the surplus is detained in the subsoil, groundwater, small lakes, and the channels of the basin and is available for runoff during the next month.

The complete basin has been divided into number of hydrological response units (HRU) based on the landuse, soil texture, root depth information, and command area grids and runoff in each hydrological response unit has been estimated. Meteorological data of the concerned HRU is used in runoff calculations.

5.2 Hydrological Response Units Generation

A Hydrological Response Unit (HRU) is an area within the basin having same soil type and land use, a basic computational unit assumed to be homogeneous in hydrologic response to land cover change. Depending on the number of soil textural classes and land cover classes, a number of HRU are derived within the basin. It is assumed that a particular soil textural class can have a particular water holding capacity and a certain vegetation type to have a maximum rooting depth. So a combination of soil textural class and vegetation type results in different HRUs.

In addition to the derived HRUs they are further categorised based on the irrigation command area boundaries. The HRUs within or outside the command boundary are assumed to meet all the AET demand considering the major crop season/seasons (i.e. Kharif, Rabi, Zaid and Double/Triple) in the basin. For Example, in Brahmani - Baitarani basin, Double/Triple crop assumed to satisfy all the AET demand (i.e. Actual ET = $PET_{revised}$) whether it is within or outside command boundary whereas in case of Kharif crop it is assumed to satisfy all the AET only if the crop is present only within the command boundary. In irrigated crop areas, both in canal irrigated and tube well irrigated the water requirements in excess of precipitation are supplemented through irrigation sources. In the present study, all the cropped area within irrigation canal jurisdiction and double/triple cropped area were considered as irrigated. In general, these irrigated cropped areas will meet their complete water requirements through precipitation and supplementary irrigation. But availability of records of irrigation supplies is difficult to collect because the irrigation sources may vary from surface storage from reservoirs, tanks and ground water sources such as open wells, deep bore wells. Hence, in the present study irrigation supplies are computed from the precipitation and $PET_{revised}$. It is assumed as under these cropped areas, actual evapotranspiration attains potential evapotranspiration, which means, whenever precipitation (P) falls short of $PET_{revised}$, the shortage (i.e., $PET_{revised}$ -P) is met with supplementary irrigation (Irrigation Support). To account for these irrigation supplies, the precipitation under the above mentioned cropped areas was revised as detailed under:

Precipitation (revised), $P_{revised} = P$ when Precipitation > $PET_{revised}$

$= P + (PET_{revised} - P)$, when Precipitation < $PET_{revised}$

(For double/triple cropped area and cropped area within irrigation command jurisdiction)

5.3 Estimation of Available Water Holding Capacity of Soil

As mentioned earlier, a particular soil textural class can have a particular water holding capacity and a certain vegetation type to have a maximum rooting depth. The water holding capacities for different soils are taken from available literature. Similarly, the root zone depths for each crop type are taken from available literature which also varies with soil type. The water available for vegetation is up to root zone depth and is computed as follows.

Available water capacity (mm) = Available water capacity (% volume) X Rooting depth (mm)

Model runoff calculations of particular HRU having water holding capacity as 90 mm is shown in the table 1 as an example.

	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	Total
Rainfall	75.7	459.7	520.1	146.0	10.0	1.3	0.1	0.0	20.3	1.8	0.0	3.7	1238.6
PET	294.7	156.9	138.8	166.9	134.0	87.0	53.4	46.4	76.3	142.6	285.5	373.6	1956.0
Vegetation Factor	1.1	1.2	1.1	0.9	1.1	1.2	1.1	0.9	0.5	0.8	1.1	0.7	
$PET_{revised}$	309.4	188.2	152.7	150.2	140.7	104.3	58.8	41.7	38.2	107.0	299.7	261.5	1852.5
$P_{revised}$	309.4	459.7	520.1	150.2	10.0	1.3	0.1	0.0	20.3	1.8	0.0	3.7	1476.5
$P_{revised}$ - $PET_{revised}$	0.0	271.4	367.5	0.0	-130.8	-103.1	-58.6	-41.7	-17.9	-105.2	-299.7	-257.8	
APWL	0.0	0.0	0.0	0.0	-130.8	-233.8	-292.5	-334.2	-352.1	-457.3	-757.0	-1014.9	
Soil Moisture	0.0	90.0	90.0	90.0	21.0	6.7	3.5	2.2	1.8	0.6	0.0	0.0	
Change SM	0.0	90.0	0.0	0.0	-69.0	-14.4	-3.2	-1.3	-0.4	-1.2	-0.5	0.0	
AET	309.4	188.2	152.7	150.2	78.9	15.6	3.3	1.3	20.7	3.0	0.5	3.7	927.6
Deficit	0.0	0.0	0.0	0.0	61.8	88.7	55.4	40.4	17.5	103.9	299.2	257.8	
Surplus	0.0	181.4	367.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	548.9
Tot.avl.for Runoff	0.0	181.4	458.2	229.1	114.5	57.3	28.6	14.3	7.2	3.6	1.8	0.9	
RO (Runoff)	0.0	90.7	229.1	114.5	57.3	28.6	14.3	7.2	3.6	1.8	0.9	0.4	548.5
Detention	0.0	90.7	229.1	114.5	57.3	28.6	14.3	7.2	3.6	1.8	0.9	0.4	

Water Holding Capacity of the soil up to root depth = 90 mm.

Table 1 Model Runoff Calculations

5.4 Model Calibration and Validation

If any unknown variable exists in the model, it can be calibrated using the observed/field data during the calibration process. The vegetation coefficients are the main variable to be calibrated. Basically the calibration process is a hit and train method. Vegetation coefficients need to be changed during the calibration process till the desired outputs are achieved. After calibrating the model, the runoff calculations have to be revised using the calibrated (revised) coefficients. The schematic diagram of the calibration procedure is shown in the figure 3. In the present study the model has been calibrated during 2004-05, and 2006-07 since these two are dry and wet years respectively.

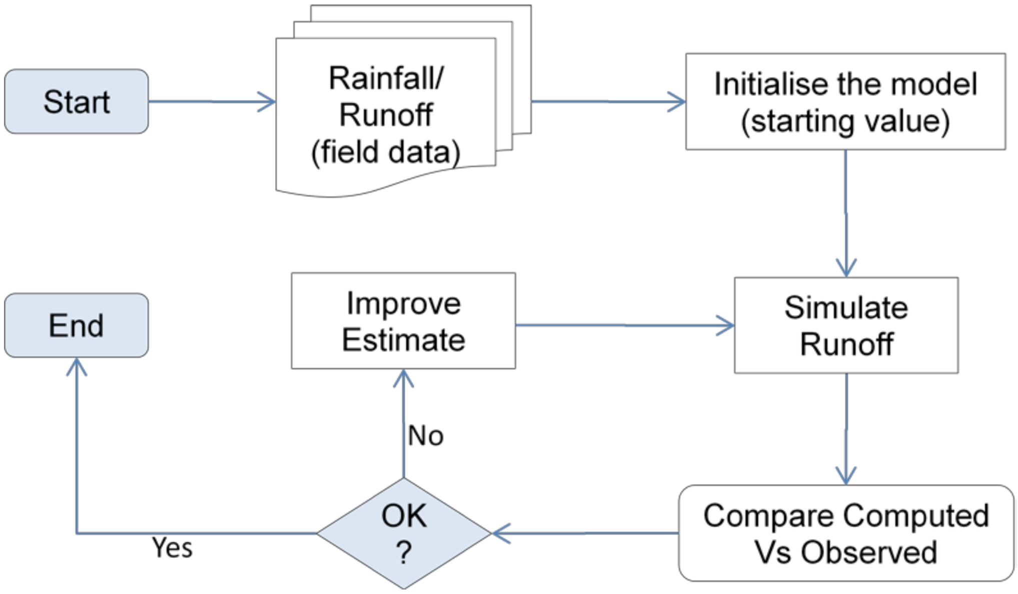


Fig. 3 Calibration Procedure

Once the model is calibrated perfectly, it has to be validated with other set of field observations to check the calibrated parameters. In the present study, model has been validated with the hydro-meteorological data of 2005-06 and 2007-08. The calibrated model has been validated with the data of all the remaining 18 years. From these results it can be inferred that the calibrated results are very well matching with the field observations. Calibration of the Model is done using the following equation (16).

$$R_{Calibrated/computed} = (R_{Model} - F_{GW} - F_{R} - F_{DI}) \approx R_{o} \qquad \text{Eq. 16}$$

$R_{Calibrated/computed}$ = Calibrated/computed runoff

R_{Model} = Model estimated runoff (output from Thornthwaite Mather Model)

F_R = Reservoir Flux (- ve sign for drawdown)

F_{GW} = Ground water Flux (- ve sign for drawdown)

F_{DI} = Domestic and Industrial consumption

R_0 = Observed runoff at gauge sites (CWC's observed data is taken)

In which, domestic and Industrial consumption is taken as 15% of its demand.

5.5 Water Resources Availability (WRA)

Water resources of the basin comprises of runoff in the river at final outlet, upstream effective utilisations for irrigation, domestic and Industrial, groundwater flux, and surface water flux. Thus, it can be expressed as;

$$WRA = R_{Calibrated/computed} + IS + E + F_{DI} + F_{GW} + F_R \qquad \text{Eq. 17}$$

Where,

E = evaporation from the reservoirs

IS = Irrigation Support Provided

Annual water resources availability during the 20 years (1988-89 to 2007-08) has been computed for both the study pilot basins. Mean annual water resources have been further calculated. Rainfall during the last 35 years has been analysed and the water resources availability during the extreme minimum and maximum rainfall years has been analysed further. It is noticed that these extreme events in both the basins are falling in the period 1988-89 to 2007-08.

6.0 Input Topographic Database

To achieve the objectives, various spatial and non-spatial data base have been created in GIS environment and used in this study. These databases include landuse/landcover, soil texture, digital elevation model, command area boundary, etc. The salient features of the geo-spatial databases are discussed below.

6.1 Land use/land cover

The rainfall-runoff relationship is one of the most complex hydrologic phenomena to comprehend due to the tremendous spatial and temporal variability of watershed characteristics, precipitation patterns, and the number of variables involved in the physical processes. Land use land cover is one of the main components that play a key role in hydrological process. Some important components in the hydrological cycle such as, evapotranspiration, recharge, and soil moisture depend on land use/land cover. Estimation of these parameters more accurately with space and time is very important in computing surface runoff of any basin. Satellite remote sensing data can provide valuable information on land use/land cover, soil moisture, determining watershed geometry, drainage network, and other map-type information for estimating surface runoff more accurately in spatial environment using distributed hydrologic modeling approach

National Remote Sensing Centre, has prepared different cycles land use/land cover maps of complete country using IRS-AWiFS satellite data under NRC project. Landuse/landcover maps of the basin of the period 2004-05, 2005-06, 2006-07, 2007-08 are used for runoff calculations in the study. In these landuse maps, agricultural area has been classified as Kharif only, Rabi only, Zaid only, and Double/triple crops. From the hydrological data analysis it is found that 2004-05 is a drought year and 2006-07 is a wet year. For runoff computation prior to 2004-05, landuse map of 2004-05 is used during the year in which the rainfall is less than 1000mm, and landuse map of 2006-07 is used when the annual rainfall is more than 1000mm. Landuse maps of 1995 and 1985 were also obtained (source: IGBP project: ISRO) and analysed. In these landuse grids, agricultural area has been classified as a single unit and number of classes also less than the recent landuse grids. Hence, these IGBP landuse maps are not used in the runoff computation. Landuse/landcover maps of the country prepared under NRSC project of NRSC of 2004-05, 2005-06, 2006-07, and 2007-08 are shown in the figure 4.

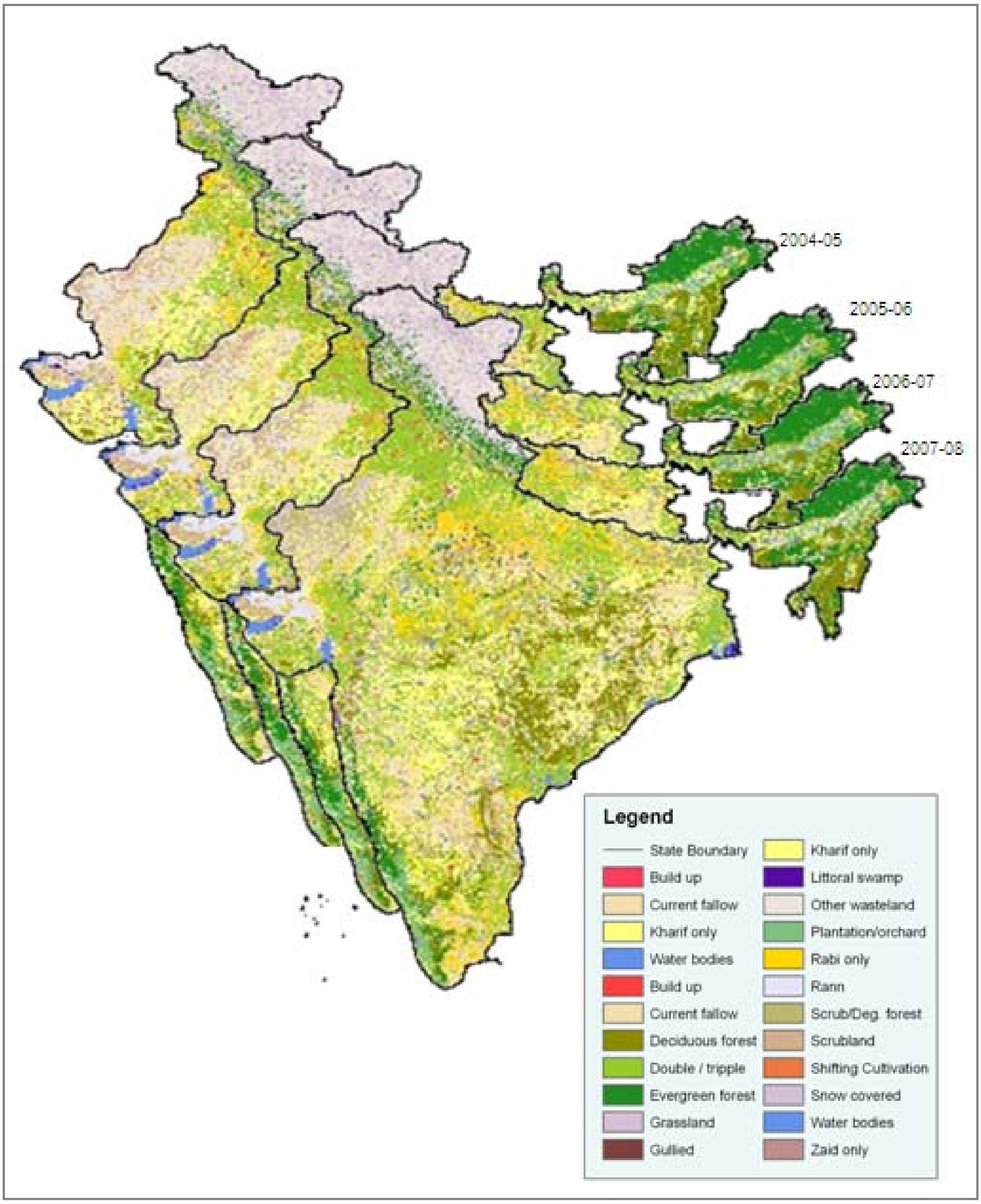


Fig. 4 Landuse/landcover map of the country derived from IRS P6 AWiFS data

6.2 Soil Texture

In the hydrological cycle, infiltration is a major component after the evapotranspiration. Infiltration at a given time depends upon the soil texture and the existing soil moisture at that point of time in any given study area. Soil texture in conjunction with the land use can derive various basin parameters for hydrological modelling. Soil textural information and soil depth are vital information in estimating soil moisture content and evapotraspiration components and subsequently for runoff estimation in any basin. Since the soil water balance is a physical process that takes place mainly vertically, abstractions can be analysed at a specific locations. Precipitation has strong interaction with the soil layers, which determine the amount of excess precipitation and subsequent runoff.

NBSS&LUP is the premier organisation in preparing soil maps of the country. Soil map (250K scale) prepared by NBSS&LUP has been obtained and reclassified into soil textural classification grid.

6.3 Digital Elevation Model

DEM is one of the main inputs for hydrological modelling studies. Basin boundaries and sub-basin boundaries mainly depends upon topography of the terrain. Flow direction and flow accumulation are the main basin parameters that divide the basin into sub-basins. In this study, Shuttle Radar Topographic Mission (SRTM) DEM of 90 m resolution and ASTER DEM of 30 m resolution are used to delineate the basin and sub-basin boundaries. SRTM DEM of the country is shown in the figure 5.

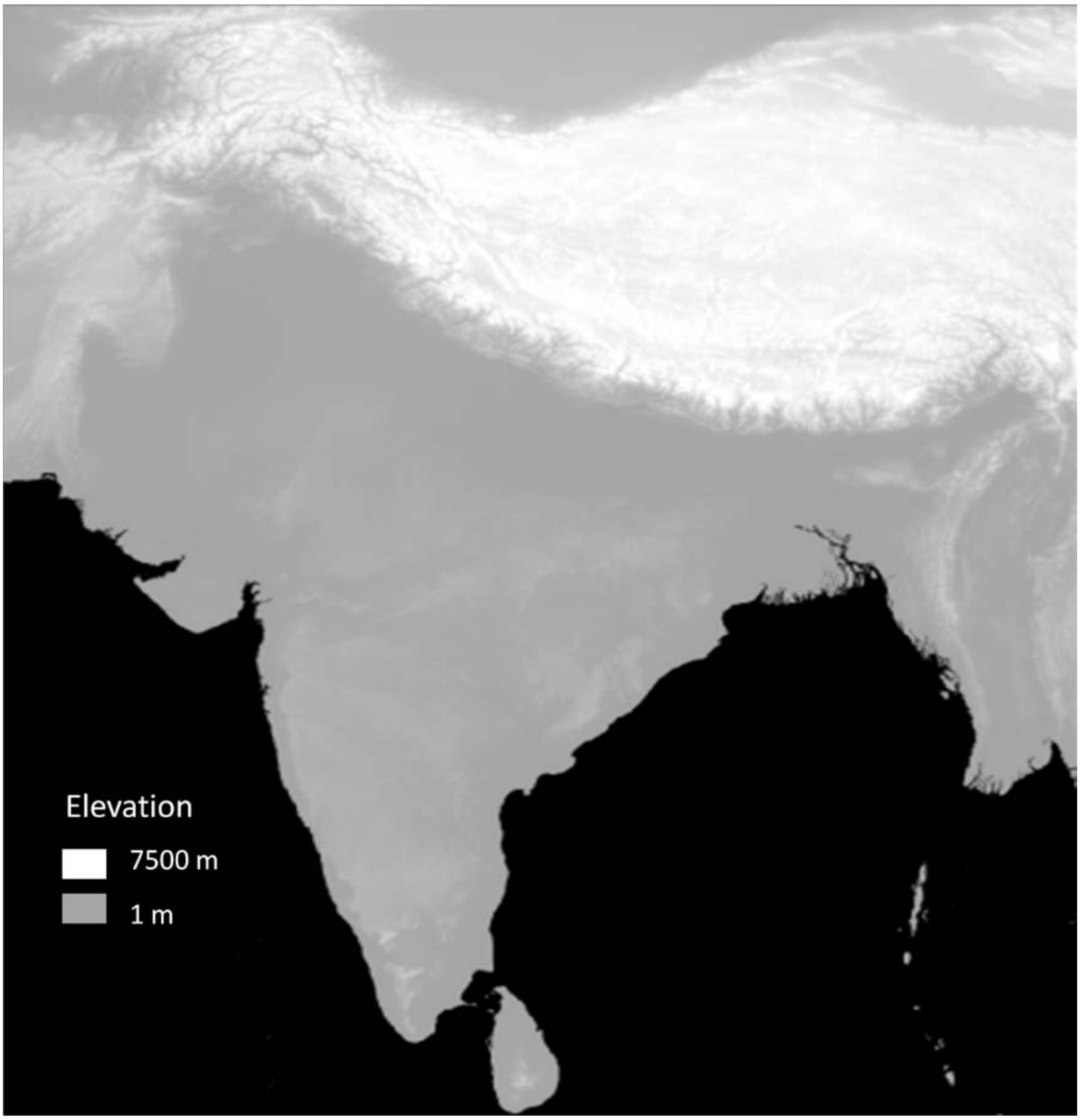


Fig. 5 Digital Elevation Model of the Country (source: SRTM DEM)

6.4 Basin & Sub-basin Boundaries

Basin and sub-basin boundaries have been delineated using the topographic maps, SRTM DEM (90m pixel size), and ASTER DEM of 30 m resolution. Drainage pattern and contour information were used in delineating the basin boundary and updated the satellite data. As the study area is very big it is divided into various sub-basins based on the drainage system and the modelling requirements. Sub-basin boundaries are extracted through automated process using the programmes available in GIS software. The said DEMs are used as a main input in extracting the sub-basins. Flow direction, flow accumulation grids were computed for sub-basin delineation. Keeping in view of the drainage pattern, and CWC's sub-basin classification, the Godavari basin has been sub divided into 23 sub-basins, Brahmini and Baitarani has been delineated into 8 sub-basins.

6.5 Command Area Grid

Estimation of actual evapotranspiration (AET) varies from irrigated area to rain-fed areas. It is assumed that irrigation supplies are provided for all the agricultural areas within the command boundaries. Kharif crop outside of the command area is considered as rain-fed crop and rest is assumed as irrigated with full irrigation water requirements are being met. Command area boundary maps of both the basins have been obtained from IndiaWRIS and used in the study.

7.0 Input Hydro-meteorological Database

The input hydro-meteorological data sets such as rainfall, temperature, river discharge, reservoir levels, depth to ground water level, etc., used in the study are described under the following sub- sections.

7.1 Rainfall Grids

India Meteorological Department (IMD) developed a high resolution 0.5^0 X 0.5^0 daily rainfall gridded data sets for entire India (Rajeevan, 2008). The rainfall records of 6,076 stations with varying periods are used in generation of the gridded data. The Fig.6 shows the rainfall on 01 June, 2004. The unit of rainfall was in 'mm'. All the rainfall data obtained from IMD was in binary 'grd' format and subsequently it has been converted in to ERDAS 'img' format for further GIS analysis. Monthly rainfall grids of all the years are computed using the daily rainfall grids. While calculating runoff, rainfall of the hydrological year (June – May) has been considered.

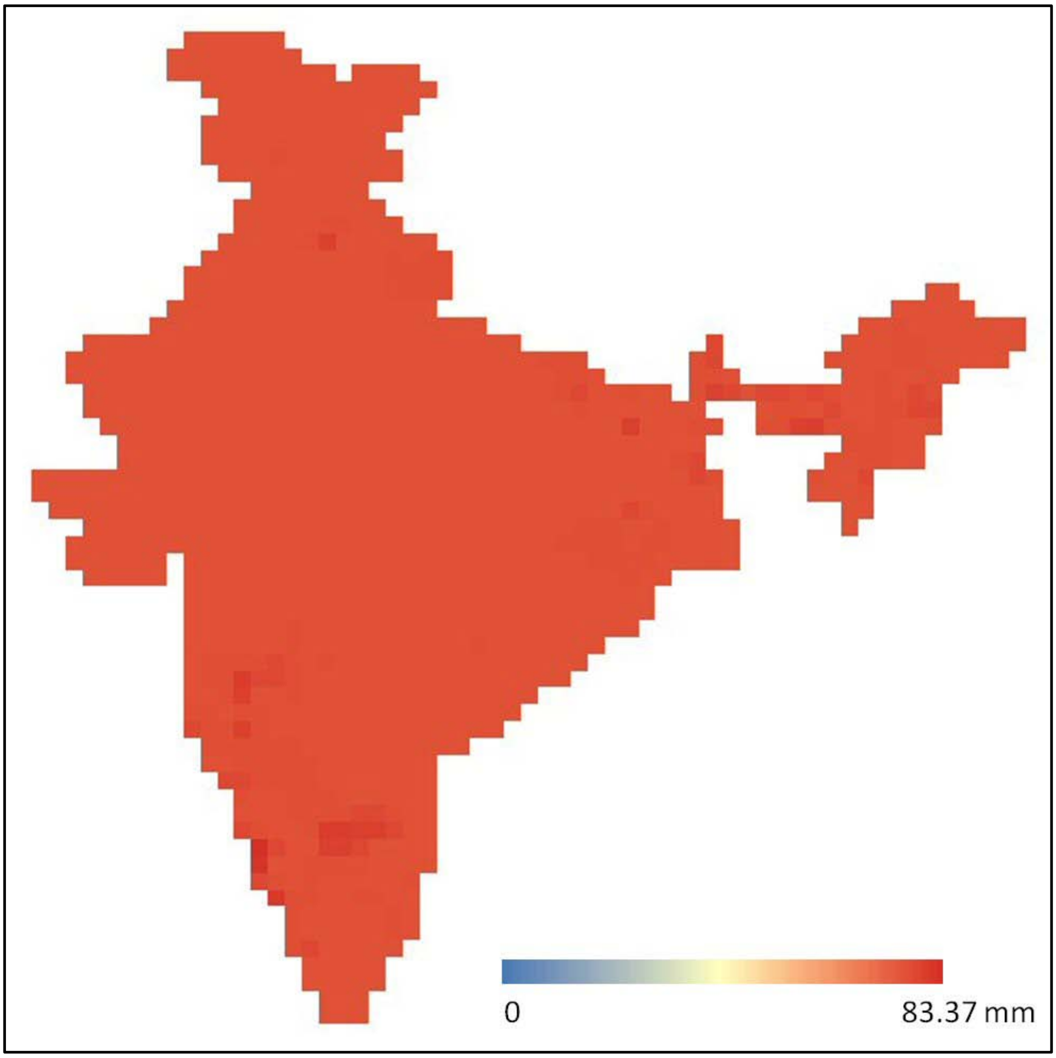


Fig.6 Rainfall grid of 01 June 2004 (source: IMD)

7.2 Temperature Grids

IMD also developed 1^0 X 1^0 daily temperature data sets for entire India. The daily maximum, minimum and mean temperature values of 395 quality controlled stations were used in generation of the gridded data (Srivastava, 2008). All the temperature data was in binary 'grd' format and was converted in to ERDAS 'img' format. The Fig.7 shows rainfall grid of 01 June 2004. The daily mean temperature data was converted into monthly mean temperature and used in runoff calculations.

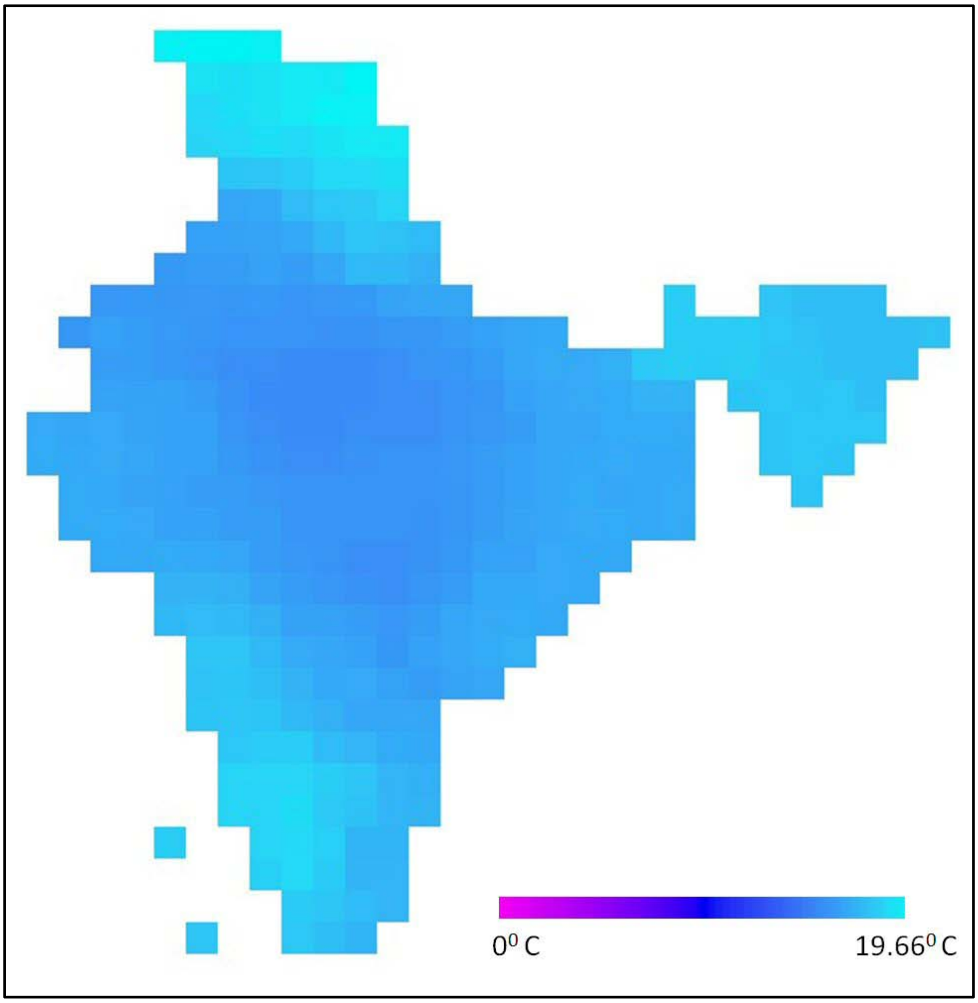


Fig.7 Temperature grid of 01 June 2004 (Source:IMD)

7.3 Reservoir Flux Data

Monthly reservoir level data were collected from Central Water Commission (CWC) for the two study basins. CWC monitors 11 major and medium reservoirs in Godavari basin and 2 major and medium reservoirs in Brahmani - Baitarani river basin. These include SriRamsagar, Lower Manair, Jyakwadi, Isapur, Mula, Yeldari, Pench, Balimela, Machkund, Upper Kolab and Upper Indravati, In Brahmani - Baitarani basin, 2 major reservoirs namely Rengali and Salandi data were used in the study. The reservoir level and corresponding volume data for the water year (June to May) was used in estimating the carryover of reservoir storage from one year to another year during the study period of 20 years. Reservoir flux is computed by subtracting the reservoir volume in May of succeeding year from current year as mentioned below.

Reservoir flux = Reservoir volume in Jun of current year - Reservoir volume in May of succeeding year

7.4 Groundwater Flux Data

Ground water recharge can be estimated using two methods, one using temporal ground water level fluctuation and specific yield and second is rainfall infiltration method (GEC report, 2009). Present study used first method estimating ground water draft at the catchment level.

Ground water level data were collected from Central Ground Water Board (CGWB) for the 2 basins. In Godavari and Brahmani - Baitarani basins, data of about 1,000 and 400 observational wells were used respectively . Ground water levels are expressed in 'meter below ground level' (MGBL). Annual ground water flux (recharge or withdrawal) for each observation site was arrived through arithmetical difference between April / May months observations (MGBL) of two succeeding years. The annual ground water flux data point observations were converted spatial maps of water-year-wise annual ground water flux using GIS techniques and spatial interpolation (Nearest neighbourhood) techniques. Specific yield map of the Godavari was obtained from Central Groundwater Board and used in groundwater volume computations after converting into GIS format. There are no available records of specific yield map of Brahmani - Baitarani river basins and hence a uniform 3% specific yield was assumed for the entire basin.

Change in annual ground water storage = $h \times S_y \times A$ (in m^3)

h = rise or fall in ground water level from one year to succeeding year (m)

S_y = specific yield;

A = basin area (m^2)

Using the above formula sub-basin wise annual ground water recharge/withdrawal was estimated and used in the subsequent analysis. Broad methodology showing the groundwater flux estimation is shown in the figure 8. Groundwater well locations in the Godavari, Brahmani - Baitarani Basins are shown in the figures 9 and 10 respectively.

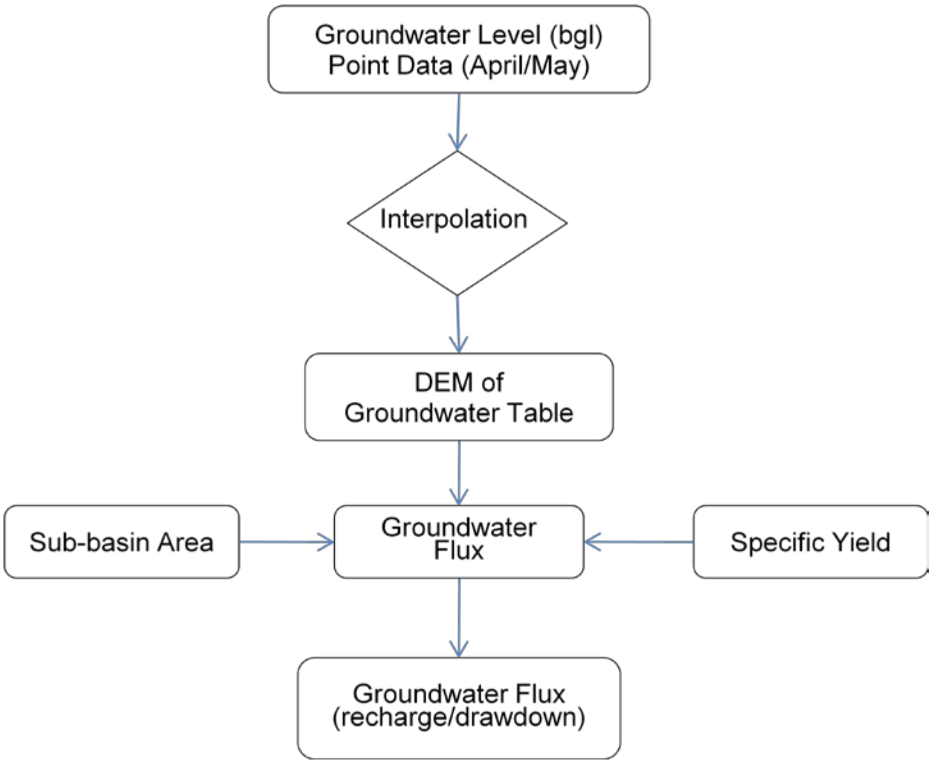


Fig.8 Flowchart of Methodology for estimation of Ground water flux

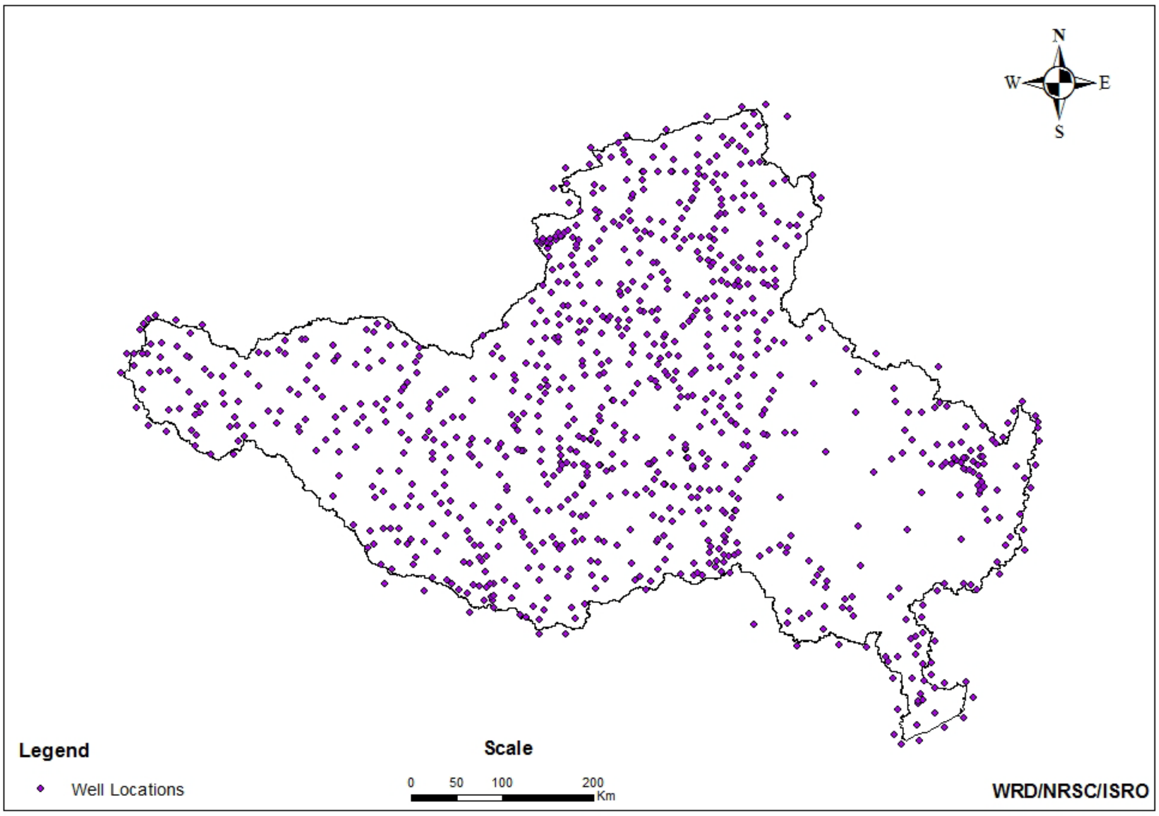


Fig.9 Well Locations in the Godavari Basin (Source: CGWB)

Fig.10 Well Locations in the Brahmani - Baitarani Basin (Source: CGWB)

7.5 Domestic and Industrial Water Use

Census data of 2001 was used for estimating domestic and industrial water use. Survey of India village administrative boundary map along with population attribute data was integrated with basin/sub-basin of the two river basins. The spatial village administrative boundary map was converted into point format and population of all the village locations falling within each of sub-basin were aggregated to arrive at sub-basin wise population as on 2001.

Census-India (www.Censusindia.gov.in) provided state-wise population projections for the year 2002 to 2008 taking 2001 as base year. The sub-basin wise population for the years 2002 to 2008 were estimated using the corresponding state growth rates, considering census of 2001 as base year. Similarly, 1981 & 1991 census data were used to arrive at sub-basin wise population statistics for the years 1988 to 2000.

For domestic requirement, it was assumed as 70 litres per capita per day (lpcd) for rural population and 140 lpcd in case of urban population. The data on industries established year-wise during the study period was not available. Hence, 50% of domestic demand was assumed as industrial demand for each year respectively. The livestock demand for water was also considered in estimating the total water requirements for this sector.

7.6 River Discharge Data

Daily/Monthly observed river discharge data was collected from Central Water Commission (CWC) for the two basins.

In Brahmani - Baitarani basin, 7 discharge sites data were used in the study viz. Tilga, Jaraikela, Panposh, Gomlai, Jenapur, Anandpur and Champua. Discharge data was available at all the sites for the study period of 20 years except for Panposh and Champua, where in the data was available only from 1990 to 1996 The daily/monthly discharge data were aggregated to annual scale and were used for calibration and validation of model computed runoff at sub-basin level.

Discharge data of nearly 55 gauge sites in the Godavari Basin was collected from CWC. Considering the drainage pattern, spatial distribution of these sites, 5 stations data was chosen for model calibration and validation.

8.0 WATER RESOURCES ASSESSMENT IN THE GODAVARI BASIN

8.1 **Geographic and Hydrologic Setting of the Godavari Basin**

Godavari Basin extends over an area of 312,800 km^2, which is nearly 9.5% of the total geographical area of the country. The basin lies in the states of Maharashtra (48.5 %), Andhra Pradesh (23.3 %), Chattisgarh (12.5 %), Madhya Pradesh (8.6 %), Orissa(5.7 %), and Karnataka (1.4 %). The Godavari, which is a perennial and the Second largest river draining in India. Godavari River originates near Trayambak near Nasik, northeast of Mumbai in the state of Maharashtra at an elevation of 1067 m and flows for a length of about 1465 km (910 miles) before joining the Bay of Bengal. It flows through the Eastern Ghats and emerges out at Polavaram into the plains. At Dhawaleswaram the river divides into two branches, the Gautami and Vasishta. Between the two lies the Godavari Central Delta. Pranahita, Manjeera, Sabari, and Indravati are the main tributaries of the Godavari River. The Godavari basin receives major part of its rainfall during the Southwest monsoon period. The other rainy seasons are not so well defined and well spread as the South-West monsoon season. Floods are the regular phenomenon in the basin. Badrachalam, Kunavaram, and Deltaic portion of the river are more flood-prone. The geographical setting of the basin is shown in the figure 11.

Rainfall : As discussed earlier, daily rainfall data of the last 35 years collected from IMD has been converted into GIS format. Monthly and annual rainfall in the basin has been analysed. From this data, it is found that rainfall varies temporally and spatially across the basin. More than 85% of the rainfall takes place during July to September months. Annual rainfall of the basin varies from 881 mm to 1395mm and average annual rainfall of these 35 years is found to be 1110 mm. When spatial variations are considered, some areas receive 600mm and some other areas receive 3000mm annual rainfall. Central part of the basin receives less rainfall, Indravari, Pranahita, and Sabari receives more rainfall that causes floods in the basin. Many times basin receives high rainfall in less duration causing floods in those years. Annual variations in the rainfall during last 35 years is shown in the figure 12.

During the last 35 years (1973-74 to 2007-08) maximum rainfall was recorded as 1393 mm in 1994-95 and minimum as 881 mm in 2002-03. Hence these two are considered as meteorologically wet and dry periods respectively during these 35 years span.

Temperature: Temperature varies from 20^{o}C to 35^{o}C in a year which causes lot of monthly variations in the potential evapotranspiration in the basin. Minimum potential evapotranspiration in the basin is 30 to 100 mm during Jan/Feb and maximum goes up to 400mm to 450mm during Apr/May months.

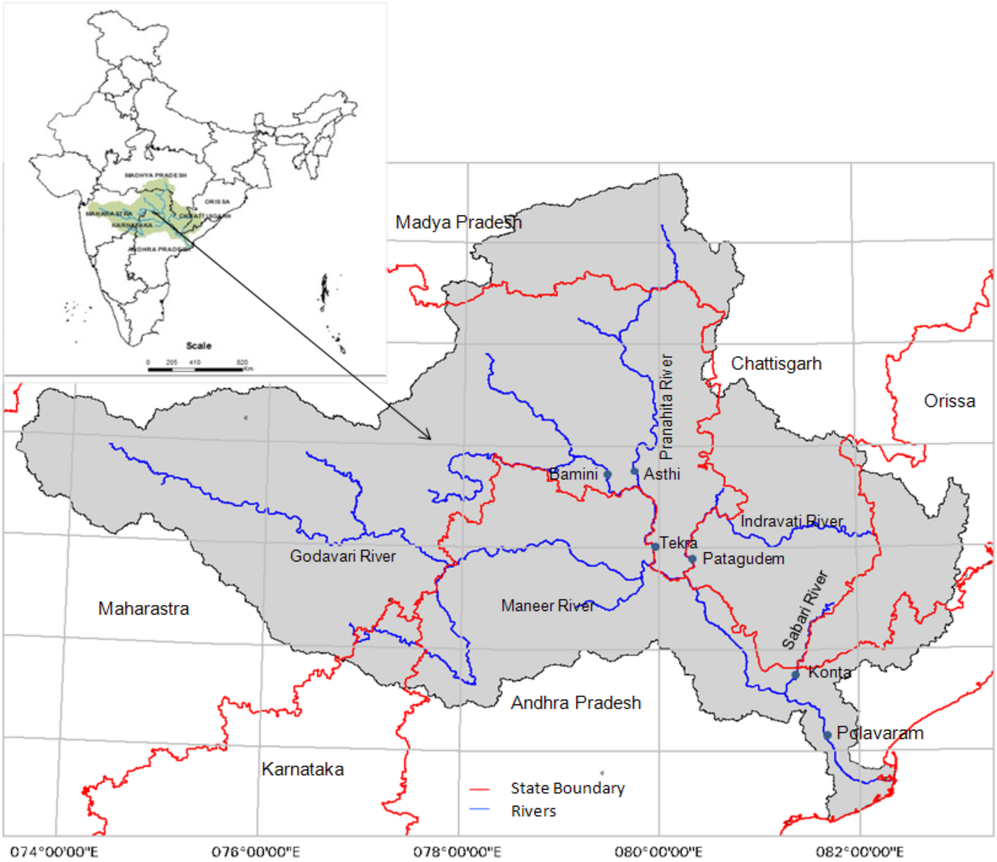


Fig. 11 Geographical Setting of the Basin

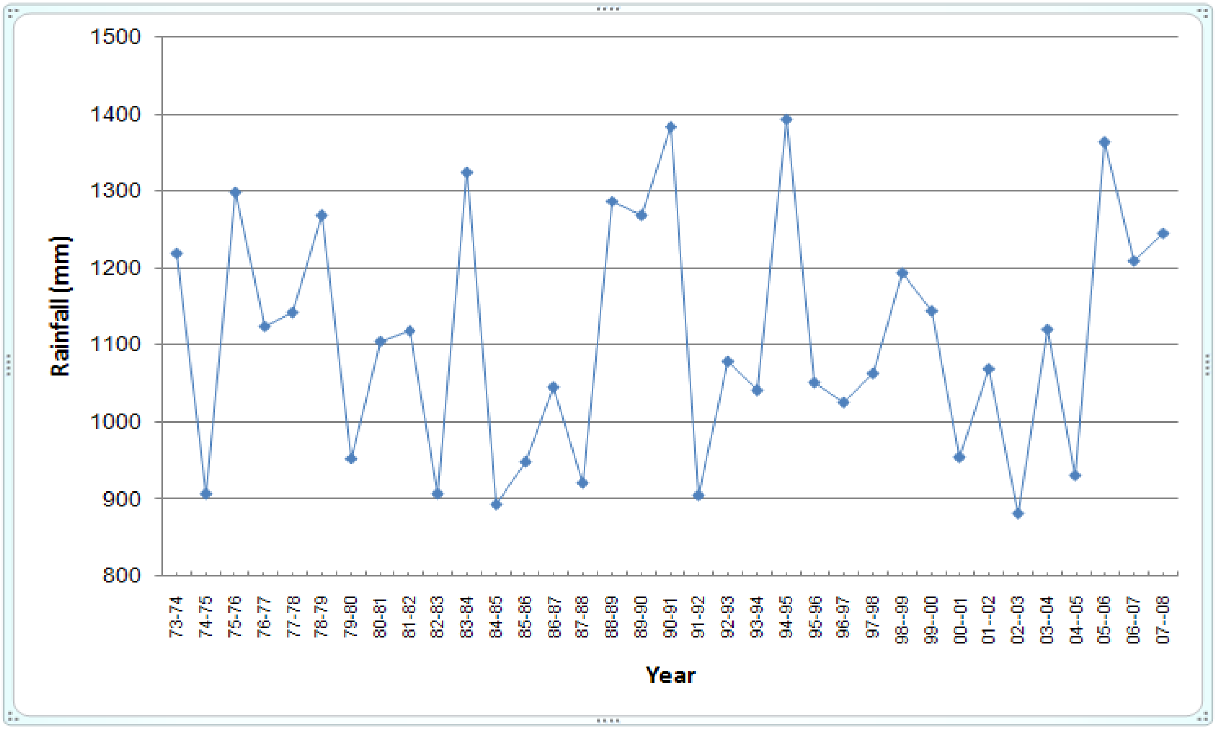


Fig. 12 Annual Vatiations in the Rainfall of the Godavari Basin

As mentioned earlier, daily rainfall and temperature grids of the mentioned 20 years obtained from IMD have been converted into GIS format. Rainfall and temperature spatial variations during July 2004 are shown in the figures 13 and 14 as an example.

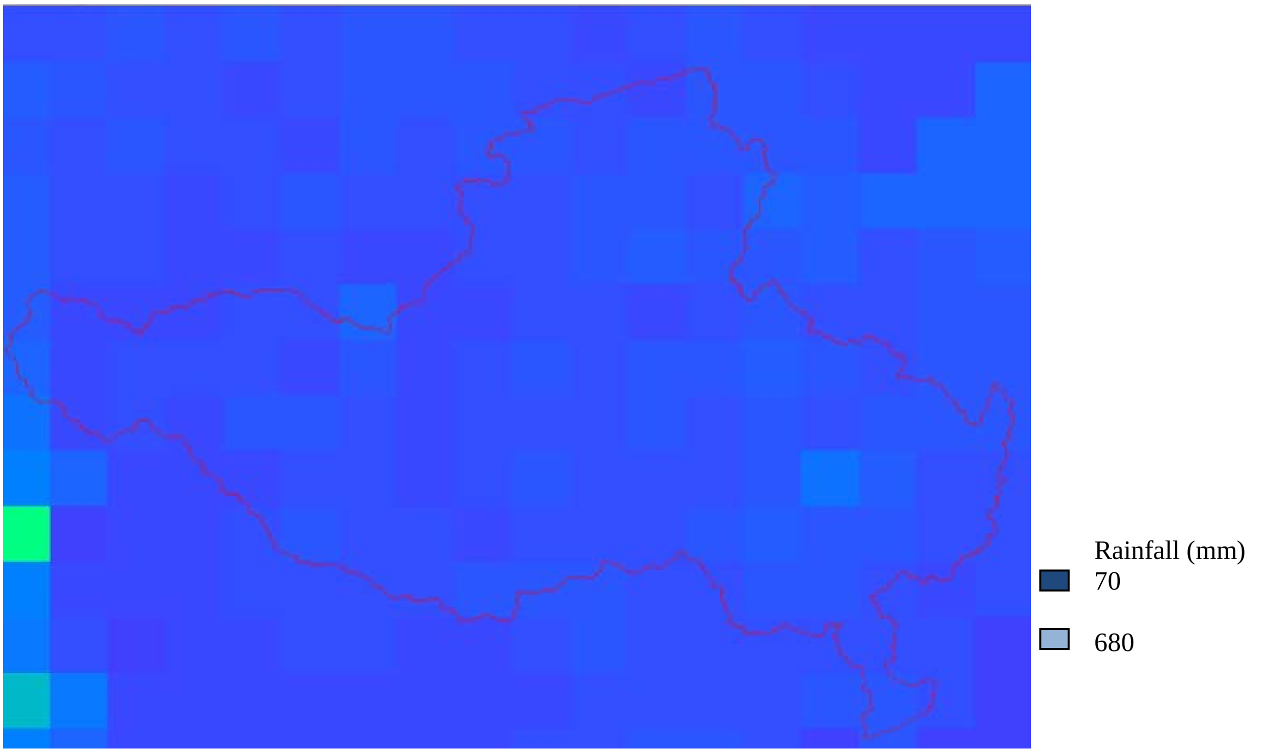


Fig. 13 Accumulated Rainfall of July 2004 (Raw Data Source:IMD)

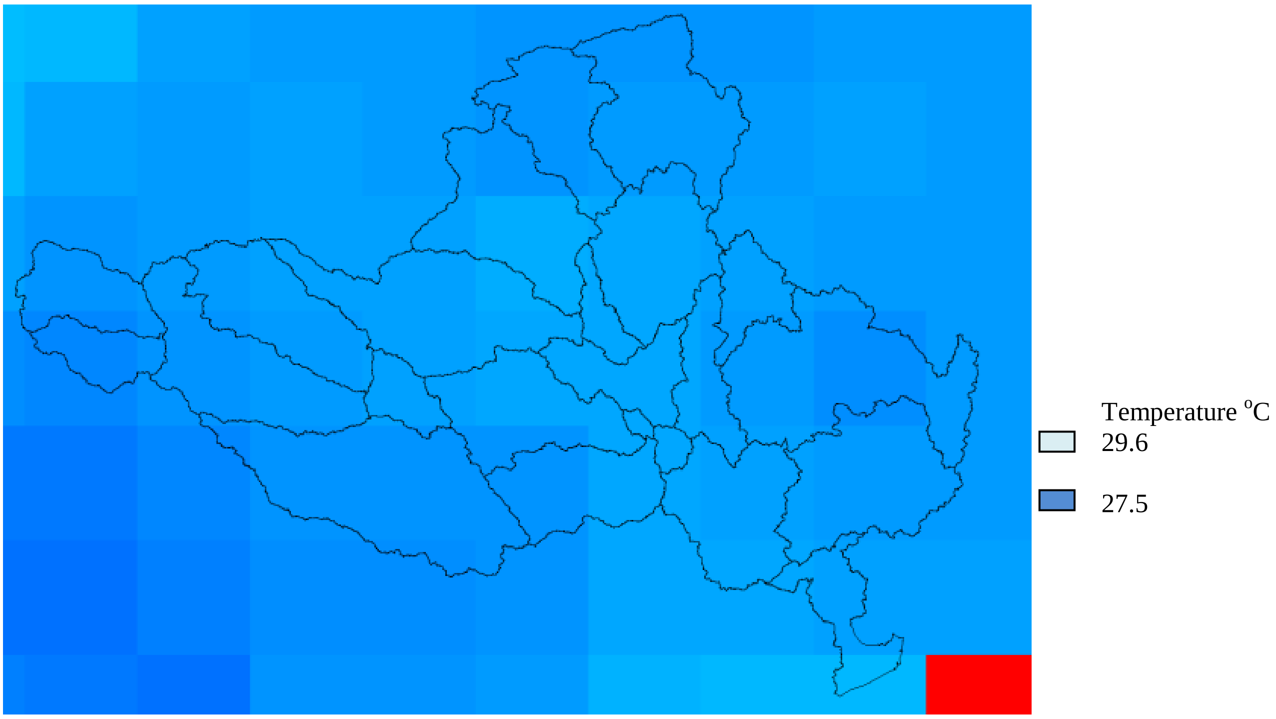


Fig. 14 Mean Temperature of July 2004 (Raw Data Source: IMD)

8.1.1 Landuse/landcover Pattern

As mentioned earlier, landuse/landcover maps of the basin for the period 2004-05, 2005-06, 2006-07, 2007-08 are used for runoff calculations in the study. For runoff computation prior to 2004-05, landuse map of 2004-05 is used during the year in which rainfall is less than 1000mm, and landuse map of 2006-07 is used when the annual rainfall is more than 1000mm. Landuse maps of 1995 and 1985 were also obtained (source: IGBP project: ISRO) and analysed. In these landuse grids, agricultural area has been classified as a single unit and number of classes also less than the recent landuse grids. When 1995 landuse map is compared with the 2004-05 landuse map, it is noticed that approximately 1.4 % and 3.3% change is noticed in the agricultural land and forest land respectively. Land use land cover derived from IRS P6 – AWiFS data of the year 2004-05 is shown in the figure 15.

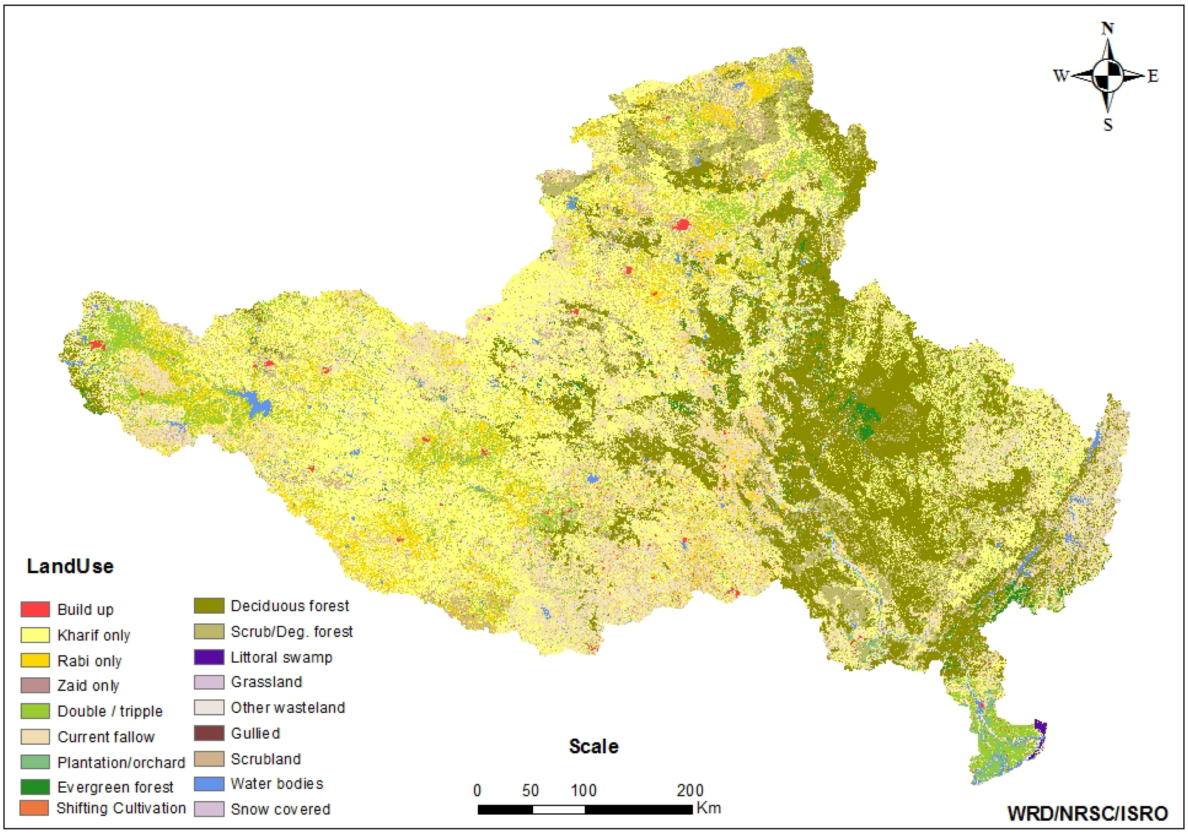


Fig.15 Landuse/landcover of Godavari Basin derived from IRS P6-AWiFS (2004-05)
(Courtesy: NRC Project, NRSC)

From the landuse/landcover map it is found that nearly 16 landuse classes exist in the study area. Agriculture land is the predominant landuse in the Godavari Basin accounting for more than 50% (including current fallow) of the basin area. This extent varies slightly from year to year. Next dominating class in the study area is forest land. These two landuse patterns contribute maximum evapotranspiration in the basin. Paddy, cotton, pulses are the main crops in the basin. Distribution of landuse/landcover pattern in the Godavari Basin during 2004-05 is given in the figure 16.

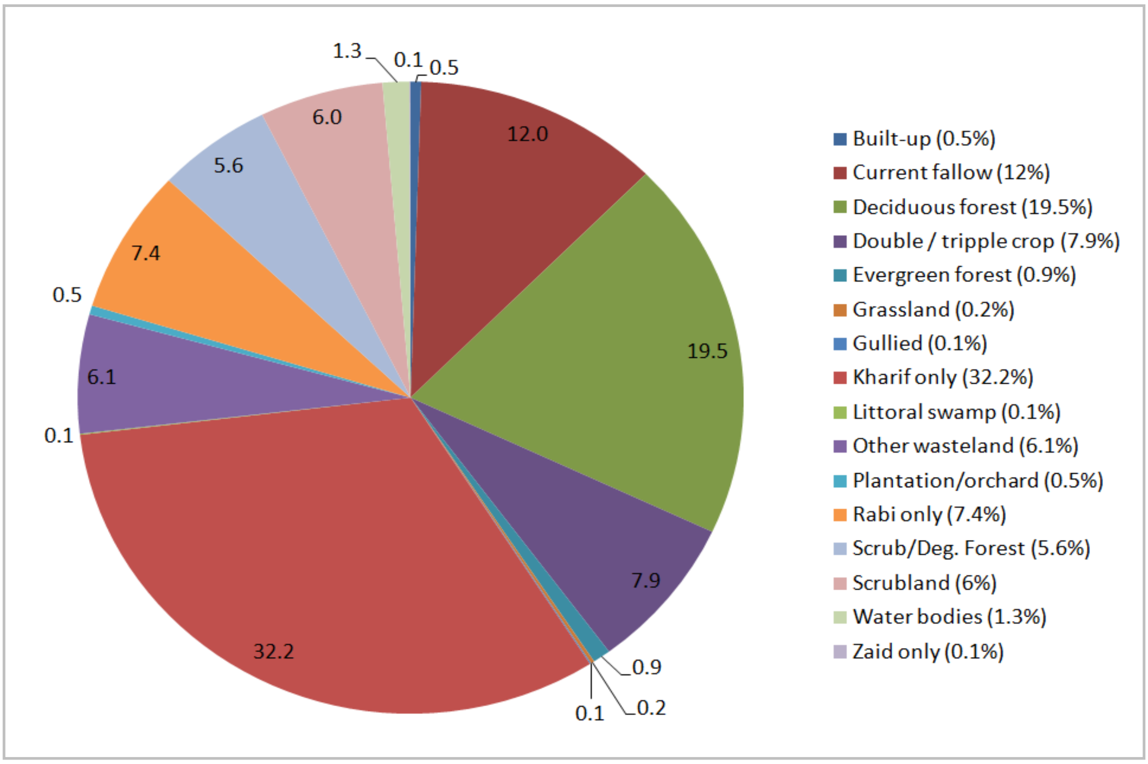


Fig. 16 Distribution of landuse/landcover pattern in the Godavari Basin (2004-05)

8.1.2 Soil Textural Classes

Clayey, loamy, loamy skeletal, clayey skeletal, sandy, rocky outcrop are the main soil textural classes in the study basin. Predominant soil textures in the study area are clayey and loamy that accounts for low infiltration rate and more runoff in the basin. Soil textural classes in the study area are shown in the figure 17.

8.1.3 Topography

From the DEM it is noticed that the elevation ranges from 1665 m to 0 m (near coast). Basin is very rugged in the North-eastern part and flat towards downstream side. Slopes in the floodplains are very flat (0 to 3 %) that is causing inundation in the floodplains. Digital elevation model (SRTM DEM) of the Godavari Basin is shown in the figure 18.

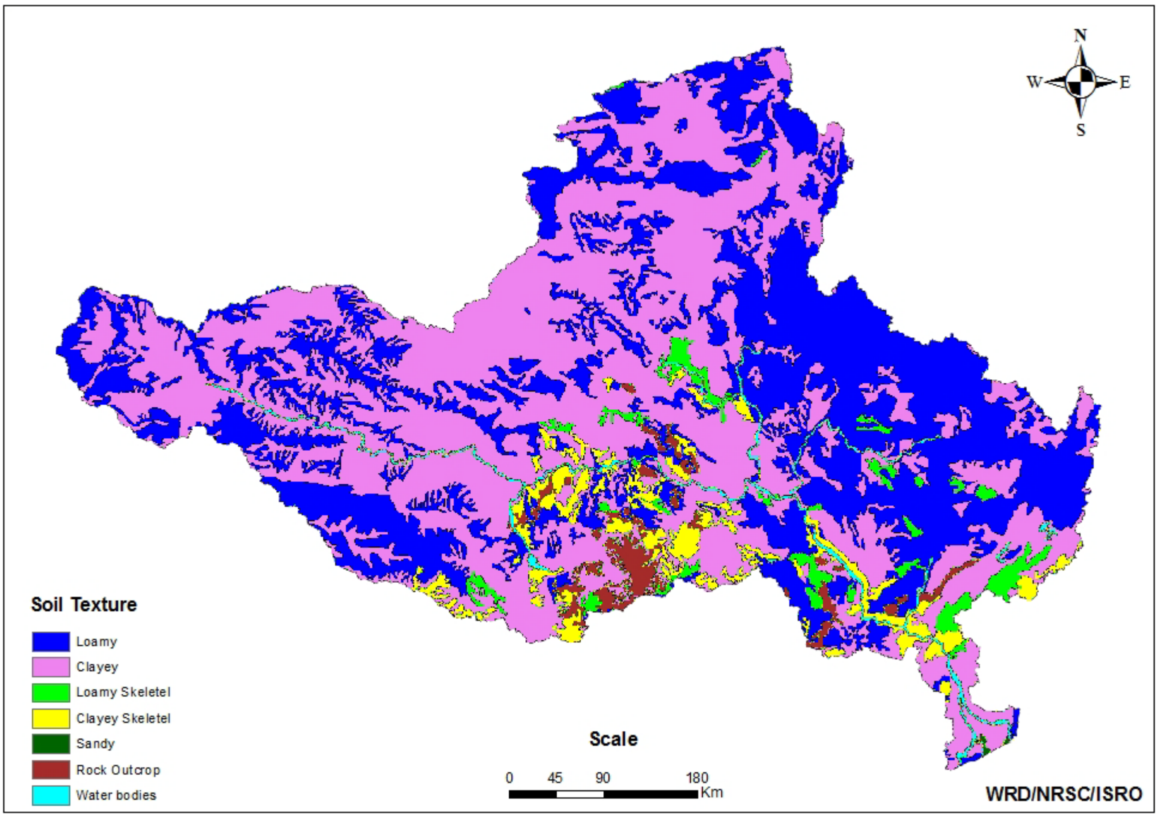


Fig. 17 Soil Textural Classes in the Godavari Basin (Source: NBSS&LUP)

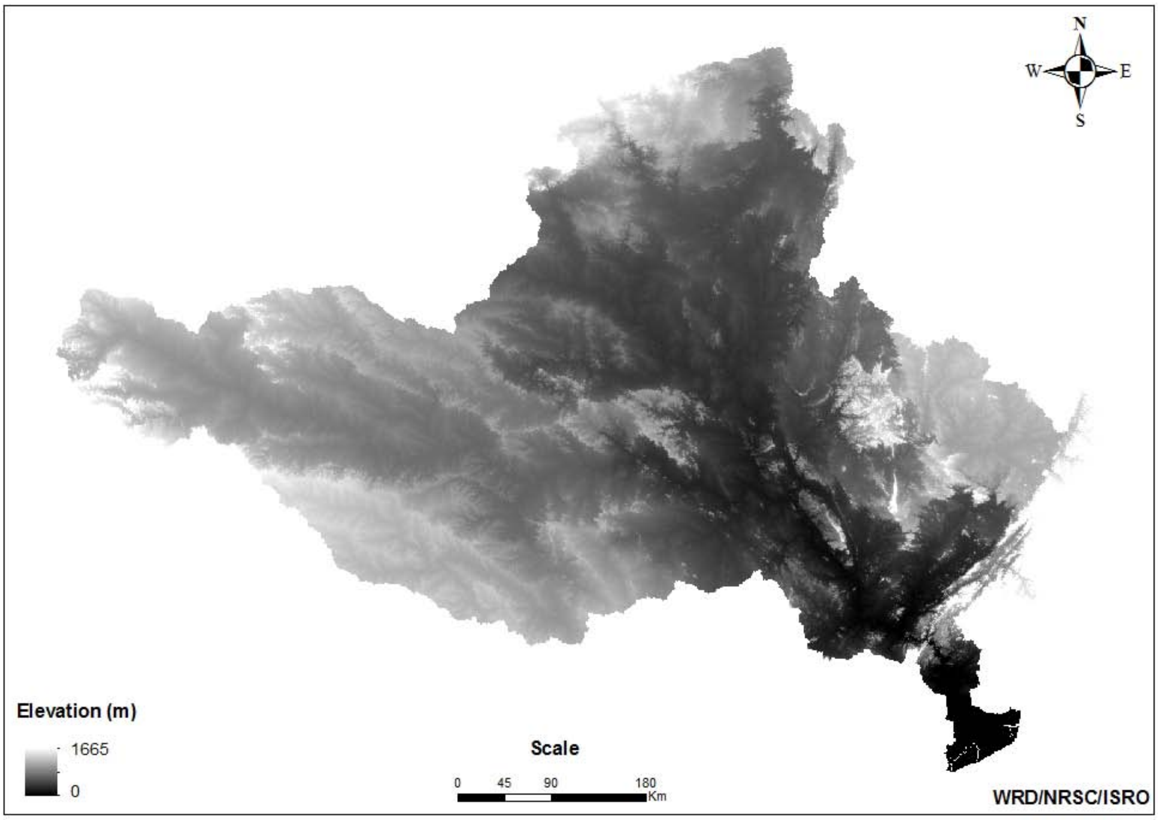


Fig. 18 Digital Elevation Model of the Godavari Basin (SRTM DEM)

8.1.4 Basin and Sub-basin delineation

The most common method used for watershed delineation is called the D8 or eight direction pour point model. Using this model, the flow direction for each cell is assigned based on the direction of the steepest slope from among the eight possible directions to the adjacent cells. Based on the flow direction, flow is accumulated towards the outlet of the watershed. In this process, one of the most sensitive parameters is the threshold area used to define the beginning of a stream channel. Choosing a small threshold area will result in high drainage density with more number of sub-basins and stream channels whereas choosing a large threshold area will result in delineation with less drainage density with only few sub-basins. Most often the threshold area chosen for delineation is very subjective and depends on the level of detail needed.

SRTM DEM of 90 m resolution is used to delineate the watershed and sub-watershed boundaries of the Godavari Basin. Flow direction and flow accumulation grids are computed using the DEM subsequently basin and sub-basin boundaries are delineated. Complete basin has been divided into 23 sub-basins based on the drainage pattern. While delineating the sub-basins CWC's sub-basins are retained. These delineated boundaries are corrected with the satellite data. The Godavari Basin boundary has been ratified by the Krishna Godavari Basin Organisation (KGBO), CWC, Hyderabad after having thorough discussions. Sub-basins of the Godavari is shown in the figure 19.

8.1.5 Groundwater of the Basin

Groundwater plays a major role in the water resources assessment. Large extent of the agricultural area depends on well irrigation also. Groundwater being exploited to meet the domestic and industrial needs as well in the urban areas of the basin. Annual groundwater flux in the basin varies from + 10m to -10m. Some pockets these fluctuations are more. Annual groundwater table data of 1990-91 to 2007-08 (only 18 years data is available) have been obtained from Central Groundwater Board and analysed. Wells having abnormal fluctuations compared to the surrounding wells are ignored. In total nearly 1000 wells have been identified and mapped in GIS environment and shown in the figure 9. It is found that wells data is not dense in Chattisgharh area (Sabari & Indravari Sub-basins). Annual groundwater flux grids during the mentioned period has been computed using the Inverse Distance Weight interpolation method. These interpolated grids are validated randomly. Annual groundwater flux grid of 2004-05 is shown in the figure 20.

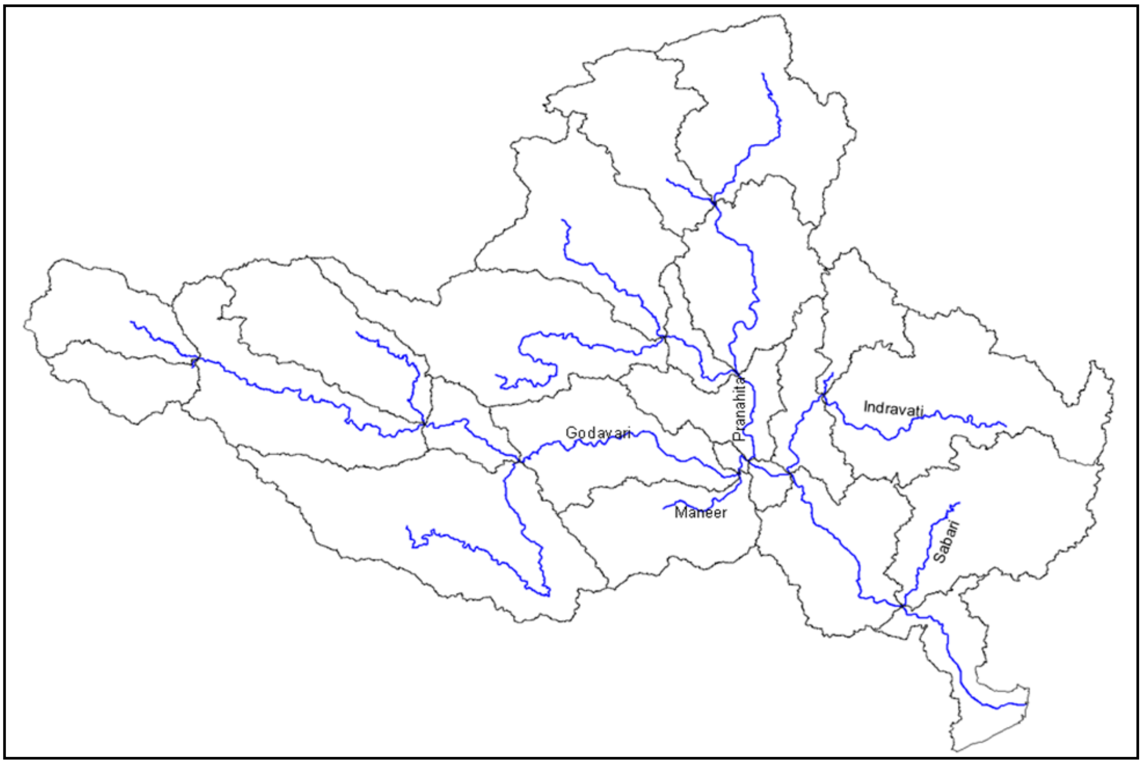


Fig. 19 Sub-basins of the Godavari Basin

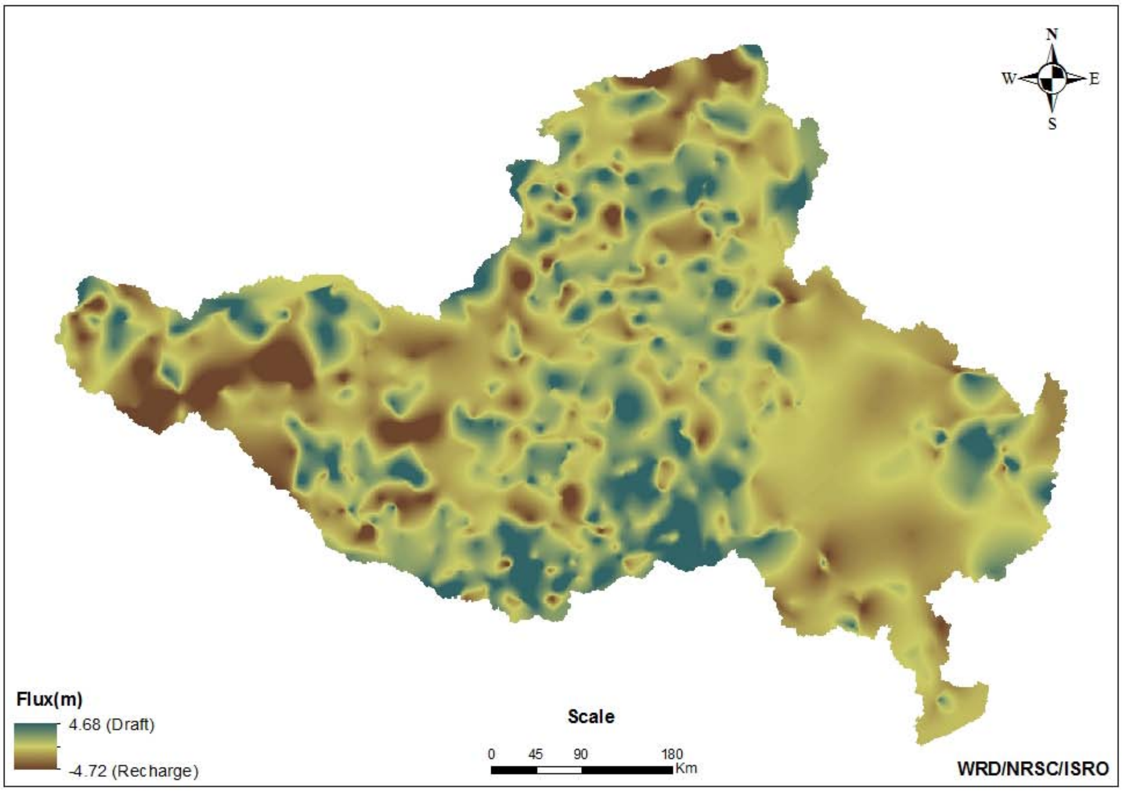


Fig. 20 Groundwater in the Godavari Basin Flux During 2004-05

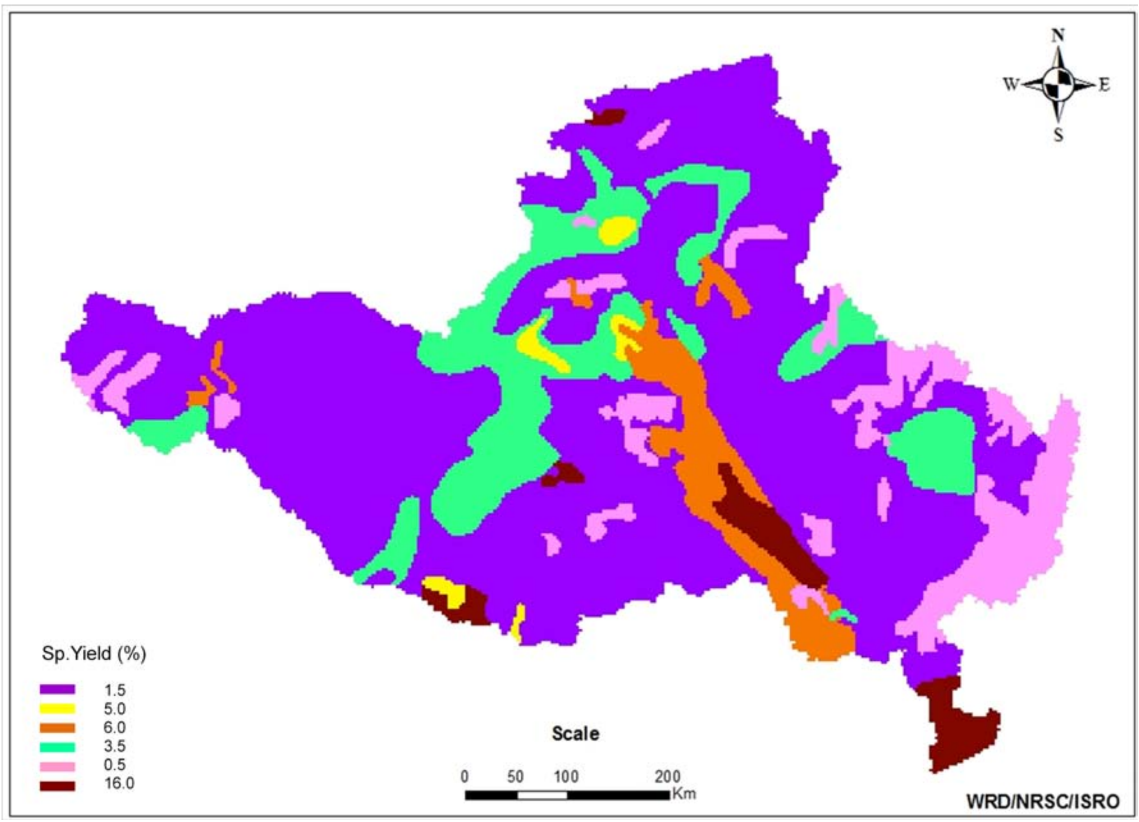


Fig.21 Specific Yield of the Godavari Basin (Source: CGWB)

Specific yield data is obtained from the CGWB, New Delhi and the spatial specific yield grid map is prepared in GIS domine as shown in the figure 21. Groundwater flux grids and specific yield grids are integrated to compute the change in groundwater volume in spatial environment for all the said years. Groundwater volume flux in each year have been extracted for all sub-basins and integrated with the runoff computed to estimate annual water resources in the basin during the mentioned period. The mean annual groundwater flux from 1990-91 to 2007-08 is estimated at 0.67 BCM (drawdown).

8.1.6 Reservoir Flux

Reservoirs are the main artificial depressions on the terrain used to store the water during excess period and to use during the lean period for irrigation, domestic and industrial use. Reservoir plays major role in water resources planning and management of any basin. Reservoir flux data from 11 major and medium reservoirs have been obtained from CWC and converted into GIS format. Annual flux during all the 20 years is calculated and used in the assessment of water resources of Godavari Basin. Reservoirs in individual sub-basins are aggregated to compute water resources in that concerned basin. From the data, it is noticed that in many reservoirs annual balance is maintained more or less (less annual flux). Reservoir locations in the basin are shown in the figure22. The mean annual reservoir flux of all the 11 major and medium reservoirs from 1990-91 to 2007-08 is estimated at 0.011 BCM (drawdown). *As the groundwater data is available for the period of 1990-91 to 2007-08, mean of all variables are computed considering these years data only*.

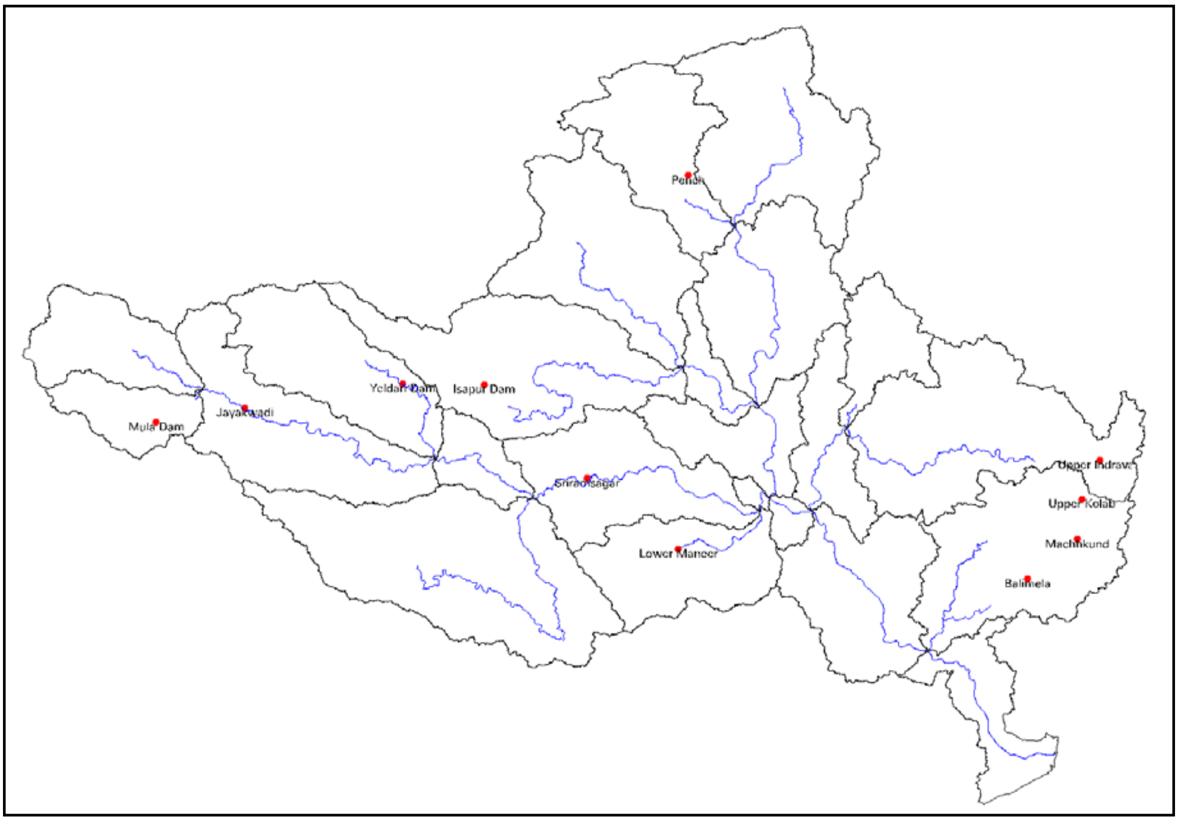


Fig. 22 Major and Medium Reservoirs in the Basin (Source: CWC)

8.1.7 Command Area

As mentioned earlier, water resources assessment in the irrigated agriculture has been computed separately. Kharif crop outside of the command boundary is only considered as rain-fed agriculture and the rest is irrigated agriculture (both canal and well irrigated). Command area boundaries of major and medium irrigation projects has been obtained from CWC and used in further analysis. Aerial extent of the command area is found to be approximately 69,000 sq.km. Agricultural area within this command area is roughly 45,000 sq.km. AET from irrigated agriculture and rain-fed agriculture are computed separately. Command area map of the basin is shown in the figure23.

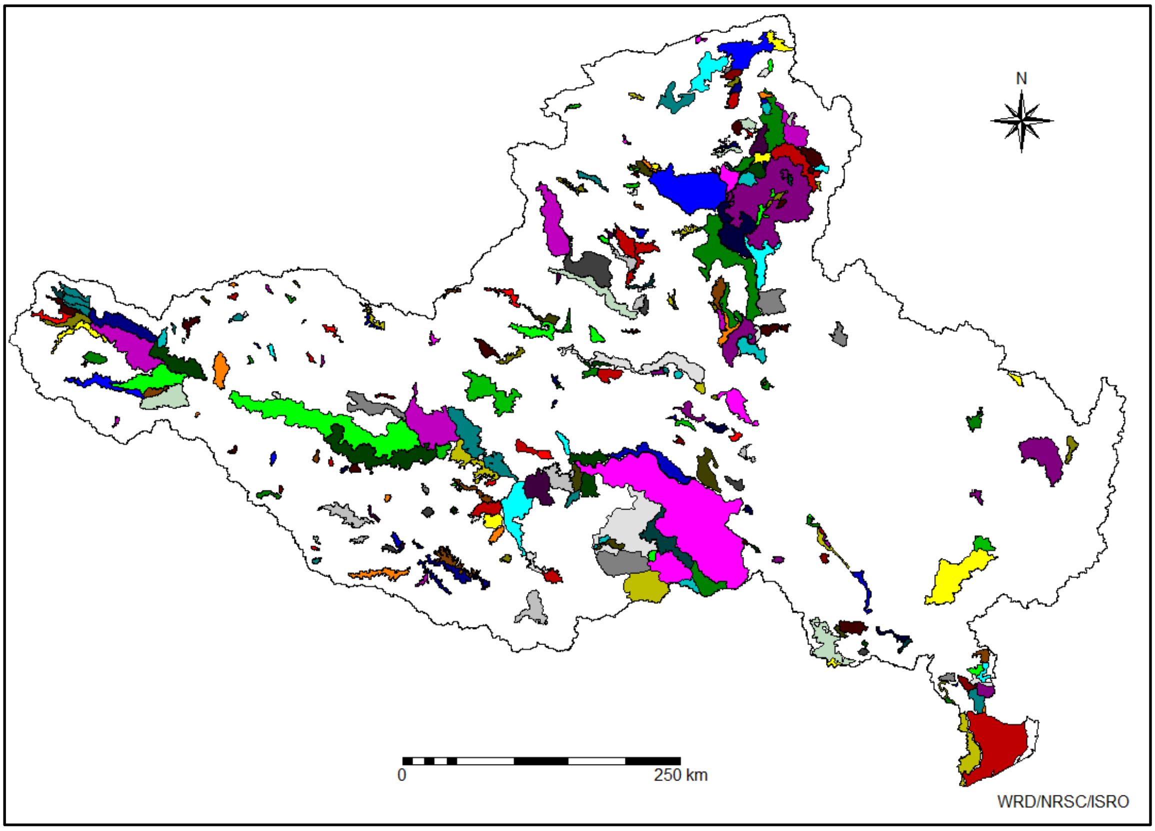


Fig. 23 Command Area Boundary of Major and Medium Irrigation Projects

8.1.8 Domestic and Industrial Consumption

Consumptive use for drinking and industrial needs are varying with population and development. Consumptive use for domestic needs has been estimated by assuming the rate of demand as 140 lpcd and 70 lpcd in urban and rural areas respectively. Census data of 2001 and 1991 is used in the study for estimating the domestic demands. Industrial demands are assumed as 50 % to the total domestic demand. Effective consumptive use is assumed as 15% of the demand. The mean annual domestic and industrial consumption flux is estimated at 0.33 BCM in the basin.

8.2 Previous Water Resources Assessments in the Godavari Basin (CWC, 1999).

Water potential of Godavari River system has been assessed at different times by different authorities. The very first estimation was made by the First Irrigation Commission based on the past records of flow in the River. The commission estimated annual surface flow in the basin as 116.76 BCM. In 1949, annual runoff of the Godavari Basin was estimated using the Khosla's formula as 125.519 BCM.

In 1960 irrigation potential studies of the country were compiled by the Central Water and Power Commission. Runoff of the Godavari River system was assessed at 115.33 BCM.
In 1962 Krishna-Godavari Commission setup by the Government of India gave a figure of 117.99 BCM as the total yield from the catchment.
Water resources assessment of the Godavari Basin was carried out by CWC in 1993 using the observed flow at Polavaram of 1967-68 to 1984-85. Extending the flow records by rainfall-runoff regression analysis was not considered in this case (CWC, 1999). The assumptions in this study are;

1. Abstractions for irrigation have been obtained from the records maintained by irrigation project authorities. Whereever such data was not available, the abstractions have been estimated from the area irrigated by adopting suitable Deltas.
2. Withdrawals for domestic and industrial requirements have been estimated assuming per capita consumption as 100 lt/day and 1981 population census data.
3. For estimating groundwater draft in the Godavari Basin, national average groundwater draft figures were used.
4. Evaporation from the major reservoirs only used while computing the water resources of the basin. For the remaining reservoirs the loss has been assumed as 20% of the annual utilisation.
5. Return flows from the irrigation use was assumed as 10% and from the groundwater was neglected. Return flows from the domestic use was assumed to be 80% of the consumption.
6. Change in annual reservoir storage is assumed as zero.

The estimation of year-wise water availability is indicated in the table 2 the average flow in the Godavari Basin works out to be 110.54 BCM.

Year	Observed flow at Polavaram,	withdrawals			Return flows		Evap. loss	Natural flow
	Ro	Rir	Rd	Rgw	Rri	Rrd	E	Rn
1967 - 68	95652	7957	2006	3546	796	1605	1827	108587
1968 - 69	68347	8098	2006	3704	810	1605	1810	81550
1969 - 70	95463	7706	2006	3870	771	1605	1841	108510
1970 - 71	103920	9076	2006	4028	908	1605	2245	118762
1971 - 72	56307	9037	2484	4187	904	1987	2103	71227
1972 - 73	48567	9338	2484	4346	934	1987	2082	63896
1973 - 74	110898	12467	2484	4511	1247	1987	2910	130036
1974 - 75	41776	14028	2484	4670	1403	1987	2937	62505
1975 - 76	130726	13539	2484	4829	1354	1987	3034	151271
1976 - 77	112566	15128	2484	4988	1513	1987	3229	134895
1977 -78	87160	14928	2484	5153	1493	1987	3154	109399
1978 - 79	120648	16127	2484	5312	1613	1987	352	144494
1979 - 80	66342	14393	2484	5471	1439	1987	299	88261
1980 - 81	102514	15703	2484	5630	1570	1987	326	126041
1981 - 82	103879	13715	3134	5795	1372	2507	281	125457
1982 - 83	56955	14357	3134	5948	1436	2507	290	79352
1993 - 84	152266	13921	3134	6113	1392	2507	303	174566
1984 - 85	55161	15560	3134	6113	1556	2507	306	78971

Table 2. Estimation of Water Resources Potential in the Godavari Basin (CWC:1993)

Average annual flow at Polavaram = 108. 766 BCM

Average annual flow of the complete basin = 108766*(312800/307800) = 110.54 BCM

8.3 Landuse Coefficients

As discussed in the section 5.1, landuse coefficients are used to correct the PET computed from the Thornthwaite Method. Cropping pattern and its statistics of major command areas have been obtained. Predominant crops in each sub-basin during each cropping season (Kharif, Rabi, Zaid) are identified from the statistics. Monthly crop coefficients for all sub-basins are arrived at using FAO and ICAR crop coefficients information. Crop coefficients for other landuse patterns such as forest area, scrub land etc, in the Godavari basin are taken from various literatures cited. Coefficients for these landuse classes are assumed as uniform during all the months. These coefficients are different within command area and outside command area wherever different crop type exists during the same crop season.

Landuse factors are kept as variable parameter in the runoff calculations. These coefficients are calibrated with the observed runoff at 5 stations in the basin during two years. Subsequent to calibration, landuse coefficients are validated with another set of two years data at the same 5 stations. All the landuse coefficients are tuned till the computed runoff matched with the observed runoff. In the Godavari Basin land use coefficients are freezed after 4 trails/iterations. Final coefficients are shown in the table 3.

and Use			Crop coeff.									
Agriculture			D/T,K ,R,Z									
Scrubland/Scrub/Deg. forest			0.65									
Plantation/orchard			0.85									
Other wasteland			0.55									
Littoral swamp			1									
Grassland			0.7									
Evergreen forest /Deciduous forest			0.9									
Current fallow /Gullied/Build Up			0.5									
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Subwat No. 12,14,15,17,18,20,21,22,23												
D/T crop (within command)	1.05	1.20	1.10	0.90	1.05	1.20	1.10	0.90	0.50	0.75	1.05	0.70
D/T (outside command)	1.05	1.20	1.10	0.90	0.50	0.71	0.62	0.50	0.50	0.50	0.50	0.50
Kharif only (within command)	1.05	1.20	1.10	0.90	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Kharif only (outside command)	1.05	1.20	1.10	0.90	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Rabi only (within command)	0.50	0.50	0.50	0.50	1.05	1.20	1.10	0.90	0.50	0.50	0.50	0.50
Rabi only (outside command)	0.50	0.50	0.50	0.50	0.50	0.71	0.62	0.50	0.50	0.50	0.50	0.50
Zaid (all places)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.75	1.05	0.70
Subwat No. 3,4,6,7,8,9,10,11,13,16,19												
D/T crop (within command)	1.05	1.20	1.10	0.90	1.05	1.20	1.10	0.90	0.50	0.75	1.05	0.70
D/T (outside command)	1.05	1.20	1.10	0.90	0.50	0.75	1.05	0.70	0.50	0.50	0.50	0.50
Kharif only (within command)	1.05	1.20	1.10	0.90	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Kharif only (outside command)	0.50	0.71	0.62	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Rabi only (within command)	0.50	0.50	0.50	0.50	0.50	0.71	0.62	0.50	0.50	0.50	0.50	0.50
Rabi only (outside command)	0.50	0.50	0.50	0.50	0.50	0.71	0.62	0.50	0.50	0.50	0.50	0.50
Zaid (all places)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.75	1.05	0.70
Subwat No. 1,2,5												
D/T crop (within command)	1.05	1.20	1.10	0.90	0.50	1.36	1.24	0.50	0.50	0.75	1.05	0.70
D/T (outside command)	1.05	1.20	1.10	0.90	0.50	0.80	1.10	0.50	0.50	0.50	0.50	0.50
Kharif only (within command)	1.05	1.20	1.10	0.90	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Kharif only (outside command)	0.50	0.80	1.10	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Rabi only (within command)	0.50	0.50	0.50	0.50	0.50	0.71	0.62	0.50	0.50	0.50	0.50	0.50
Rabi only (outside command)	0.50	0.50	0.50	0.50	0.50	0.80	1.10	0.50	0.50	0.50	0.50	0.50
Zaid (all places)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.75	1.05	0.70

Table 3 Landuse coefficients of Godavari Basin

8.4 Runoff Estimation

Landuse, soil texture, command area grids were overlaid and hydrological response unit (HRU) grid has been prepared. More than 160 HRU combinations are observed in the HRU grid. Runoff has been computed for each HRU unit by using the corresponding sub-watershed meteorological data in which the HRU falls. In total more than 2000 such combinations were found in 23 sub-basins.

Runoff has been estimated for all the 20 years (1988-89 to 2007-08) using the Thornthwaite and Mather Model as discussed in the section 5.1. Rainfall and temperature grids of the corresponding years were used while computing the runoff. Landuse coefficients given in the table 3 are used for final runoff computation. Runoff in each sub-basin during all the years has been aggregated separately. Computed runoff and observed runoff has been validated and calibrated at 5 prominent CWC gauge stations namely; Polavaram, Asthi, Bamini, Patagudem, and Tekra. Runoff has been further aggregated at these sites during all the years. Polavaram is the final gauge station in the Godavari Basin that represents the hydrology of the complete Basin. Cachment area at Polavaram is approximately 3,07,800 Sq.Km. out of the total basin area of 3,12,800 Sq.Km. it is found that at Polavaram computed runoff is very well matching with the observed runoff.

After computing runoff in each HRU a spatial runoff maps have been prepared. Map showing the spatial variations in runoff during 2006-07 is given in the figure 24

Maximum computed runoff is found to be 188.51 BCM during 1990-91 and minimum is found to be 44.71 BCM in 2004-05. Mean runoff of the complete basin is found to be 95.45 BCM against the observed runoff of 90.13 BCM. Average ratio of runoff to rainfall at Polavaram is found to be 0.274 (during normal rainfall year) hence this can be treated as runoff coefficient of the basin. This coefficient is approximately 0.2 during low rainfall year and nearly 0.3 during high rainfall year. It is also noticed that runoff percentage with rainfall depends upon rainfall distribution in that year. As per rainfall, highest rainfall was noticed in 1994-95 but the highest runoff was found in 1990-91. Similarly, minimum rainfall was noticed in 2002-03 where as minimum runoff was noticed in 2004-05, this may be due to variation in monthly distribution of rainfall during these years. *As the groundwater data is available for the period of 1990-91 to 2007-08, mean of all variables are computed considering these years data only*.

Observed and computed runoff during the study years at Polavaram gauge site is shown in the figure 25. Table 4 shows the variation of runoff during the study period and comparison with the observed runoff.

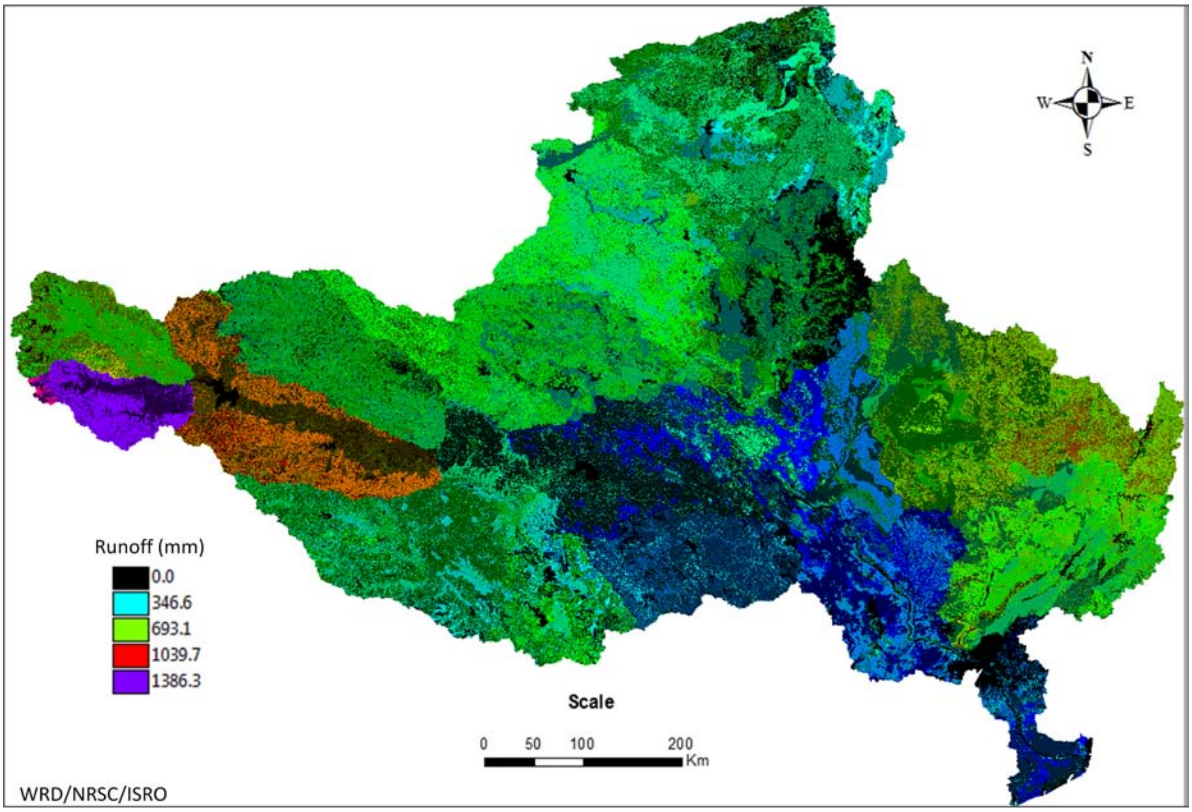


Fig. 24 Spatial Variations of Runoff in the Godavari Basin in 2006-07

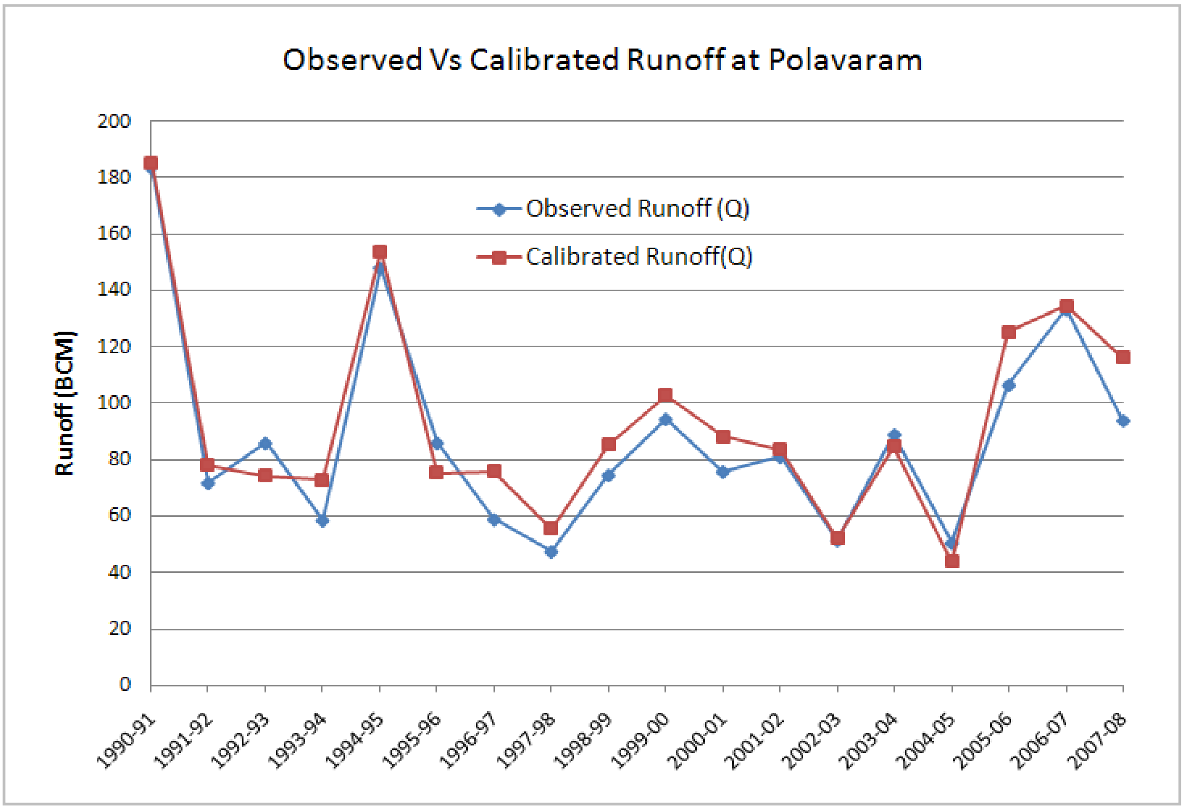


Fig. 25 Observed and Calibrated Runoff at Polavaram (1990-91 to 2007-08)

Polavaram (Catchment Area = 3,07,800 Sq.Km.)					
	Observed Runoff (Q) at Polavaram, BCM	Calibrated Runoff(Q) at Polavaram, BCM	Rainfall upto Polavaram, BCM	% of Obs.Q/Rainfall	100*(Obs.-Cali.)/Obs
1988-89	Not Available	122.16***	396.18		
1989-90	95.11	117.18***	390.38	24.36	-22.90
1990-91	183.76	185.50	425.52	43.18	-0.95
1991-92	71.72	78.20	278.42	25.76	-9.03
1992-93	85.88	74.50	332.24	25.85	13.25
1993-94	58.48	72.96	320.41	18.25	-24.76
1994-95	148.05	154.14	428.91	34.52	-4.12
1995-96	85.88	75.65	323.76	26.53	11.92
1996-97	58.79	75.95	315.62	18.63	-29.20
1997-98	47.4	55.45	326.95	14.50	-16.99
1998-99	74.49	85.40	367.05	20.29	-14.65
1999-00	94.37	103.07	351.92	26.82	-9.22
2000-01	75.72	88.39	293.52	25.80	-16.73
2001-02	80.95	83.87	329.05	24.60	-3.61
2002-03	51.4	52.47	271.1	18.96	-2.07
2003-04	88.95	84.73	344.65	25.81	4.75
2004-05	50.48	43.99	286.38	17.63	12.85
2005-06	106.5	125.32	419.32	25.40	-17.67
2006-07	133.28	134.66	371.98	35.83	-1.03
2007-08	93.88	116.31	383.31	24.49	-23.89
Average**	**88.33**	**93.92**	**342.78**	**25.16**	**-5.90**
Complete Basin Runoff					
	90.13*	**95.45**	**348.35**		

*Observed runoff of complete basin = Runoff at Polavaram * 312800/307800

** Average of 1990-91 to 2007-08 (as groundwater data of 88-89 and 89-90 is not available)

*** Calibrated runoff without groundwater flux

Table 4 Variations in Runoff and Rainfall at Polavaram

Mean computed runoff at Asthi gauge station is found to be very well matching with the observed runoff. Runoff and rainfall ratio is found to be 0.35, this is more than basin mean runoff coefficient it may be due to high rainfall zone.

Computed/calibrated runoff is very well matching with the observed runoff at Bamini and Tekra Also. Runoff and rainfall ratio at these two sites are 0.25 and 0.31 respectively. Compared to other stations, error at Patagudem (Indravati River) is high. Match between observed and computed runoff is found to be 81% at Patagudem. Rainfall runoff ratio at Pathagudem is found to be 0.37, in general this is on higherside. Rainfall of this sub-basin needs re-examination. Since its catchment area (40,000 Sq.Km) is less compared to the total basin area its contribution in the total error is minimum.

Observed and computed runoff during the 20 years at Asthi, Bamini, Tekra, and Patagudem are shown in the figures, 26, 27, 28, and 29 respectively. Tables 5, 6, 7, and 8 shows the variation of runoff during all the 20 years and comparison with rainfall at these stations respectively.

In the following tables, average values are computed using the data/results of 1990-91 to 2007-08 only as the groundwater data is not available for 1988-89 and 1989-90.

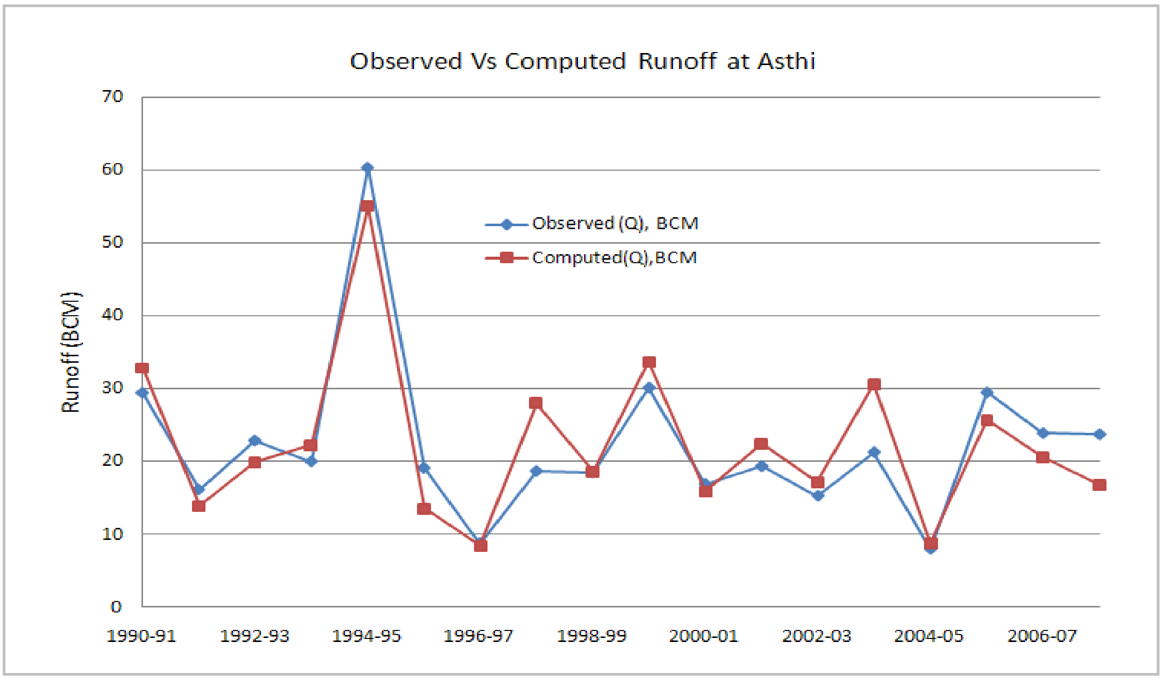


Fig. 26 Observed and Calibrated Runoff at Asthi

Asthi (Catchment Area = 50,990 Sq.Km.)					
	Observed Runoff (Q) BCM	Calibrated Runoff(Q) BCM	Rainfall BCM	% of Obs.Q/Rainfall	100*(Obs.-Cali.)/Obs
1988-89		17.3	62.7		
1989-90	9.3	11.9	54.2	17.1	-27.8
1990-91	29.4	32.8	71.7	41.0	-11.5
1991-92	16.1	13.8	46.9	34.3	14.3
1992-93	22.8	19.9	57.6	39.7	13.1
1993-94	20.0	22.2	64.6	31.0	-11.2
1994-95	60.4	55.0	98.7	61.2	8.9
1995-96	19.1	13.5	56.6	33.7	29.0
1996-97	8.8	8.4	46.6	18.8	4.0
1997-98	18.7	27.9	76.5	24.4	-49.7
1998-99	18.5	18.6	63.4	29.1	-0.5
1999-00	30.1	33.7	73.1	41.2	-11.7
2000-01	16.9	15.9	49.5	34.1	6.0
2001-02	19.3	22.4	61.8	31.3	-16.1
2002-03	15.2	17.2	58.5	26.1	-12.7
2003-04	21.3	30.6	71.0	30.0	-43.8
2004-05	8.0	8.7	50.0	15.9	-9.4
2005-06	29.5	25.7	73.8	39.9	12.8
2006-07	23.9	20.6	56.2	42.4	13.6
2007-08	23.7	16.8	58.7	40.4	29.0
Average	**22.3**	**22.4**	**63.1**	**34.14**	**-0.5**

Table 5 Variations in Runoff and Rainfall at Asthi

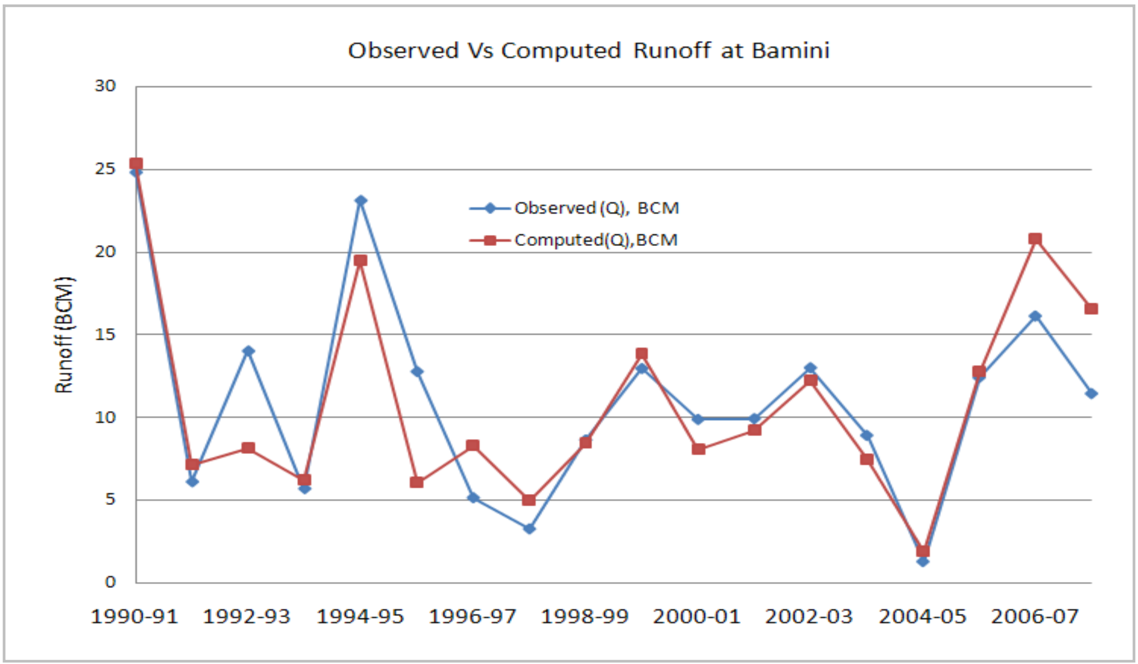


Fig. 27 Observed and Calibrated Runoff at Bamini

Bamini (Catchment Area = 46,020 Sq.Km.)					
	Observed Runoff (Q) BCM	Calibrated Runoff(Q) BCM	Rainfall BCM	% of Obs.Q/Rainfall	100*(Obs.-Cali.)/Obs
1988-89		15.4	54.5		
1989-90	10.2	10.8	45.3	22.5	-6.3
1990-91	24.9	25.4	56.8	43.8	-2.1
1991-92	6.1	7.2	30.9	19.8	-16.9
1992-93	14.0	8.1	44.3	31.7	42.1
1993-94	5.7	6.2	40.5	14.1	-9.1
1994-95	23.1	19.5	56.4	41.1	15.7
1995-96	12.8	6.0	39.5	32.4	52.7
1996-97	5.2	8.3	37.6	13.7	-61.4
1997-98	3.3	4.9	44.1	7.4	-51.2
1998-99	8.7	8.5	48.4	17.9	2.1
1999-00	13.0	13.9	49.9	26.0	-7.0
2000-01	9.9	8.0	32.7	30.2	18.8
2001-02	9.9	9.2	42.0	23.7	7.2
2002-03	13.0	12.2	42.9	30.4	6.2
2003-04	8.9	7.4	41.6	21.5	16.6
2004-05	1.3	1.9	33.9	3.8	-45.5
2005-06	12.4	12.8	53.0	23.4	-3.0
2006-07	16.2	20.8	52.2	30.9	-28.7
2007-08	11.5	16.6	49.6	23.1	-44.4
Average	**11.1**	**10.9**	**44.2**	**24.1**	**1.4**

Table 6 Variations in Runoff and Rainfall at Bamini

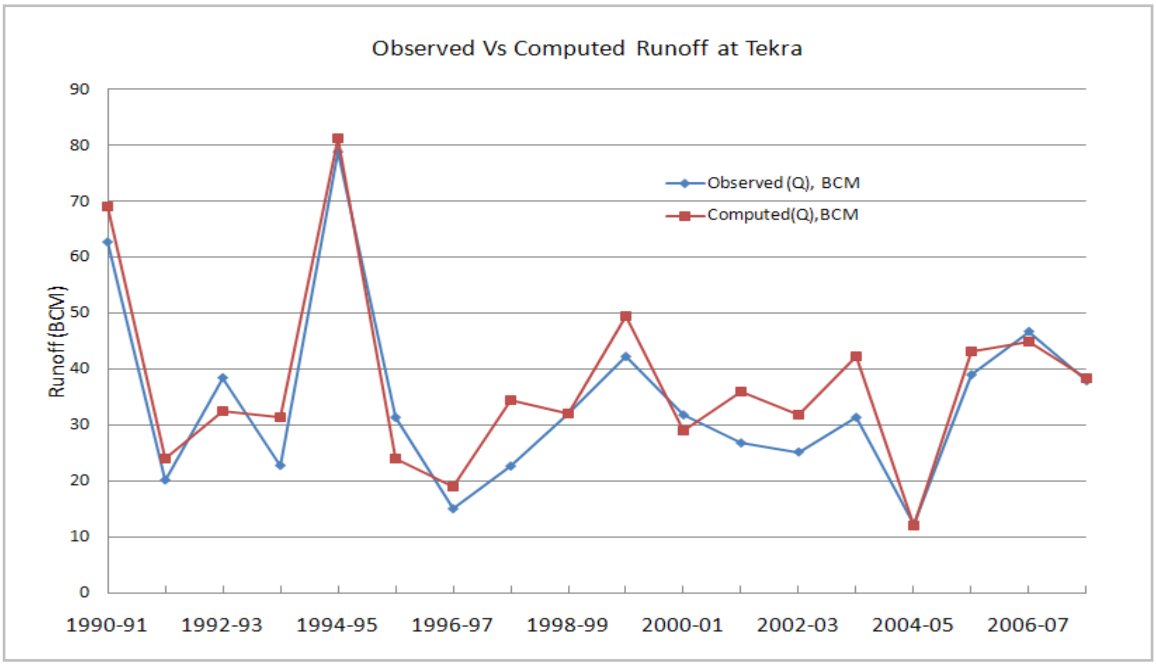


Fig. 28 Observed and Calibrated Runoff at Tekra

Tekra (Catchment Area = 1,08,780 Sq.Km.)					
	Observed Runoff (Q) BCM	Calibrated Runoff(Q) BCM	Rainfall BCM	% of Obs.Q/Rainfall	100*(Obs.-Cali.)/Obs
1988-89		39.4	134.9	0.0	
1989-90	27.6	27.3	114.8	24.1	1.2
1990-91	62.8	69.0	149.1	42.1	-9.9
1991-92	20.2	23.9	88.4	22.9	-18.2
1992-93	38.5	32.5	117.3	32.8	15.5
1993-94	22.8	31.4	117.8	19.4	-37.6
1994-95	78.9	81.2	173.3	45.5	-3.0
1995-96	31.4	23.9	110.4	28.5	24.0
1996-97	15.1	19.0	95.8	15.8	-25.9
1997-98	22.7	34.4	133.2	17.1	-51.2
1998-99	32.1	32.0	128.5	25.0	0.4
1999-00	42.3	49.4	135.0	31.3	-16.8
2000-01	31.9	28.9	94.9	33.6	9.2
2001-02	26.9	35.9	117.5	22.9	-33.6
2002-03	25.2	31.7	112.0	22.5	-25.8
2003-04	31.4	42.3	127.3	24.7	-34.5
2004-05	12.3	12.0	94.6	13.0	2.1
2005-06	39.1	43.1	141.6	27.6	-10.4
2006-07	46.8	44.9	120.5	38.8	4.0
2007-08	38.0	38.4	123.6	30.7	-1.2
Average	**34.4**	**37.5**	**121.2**	**27.45**	**-9.0**

Table 7 Variations in Runoff and Rainfall at Tekra

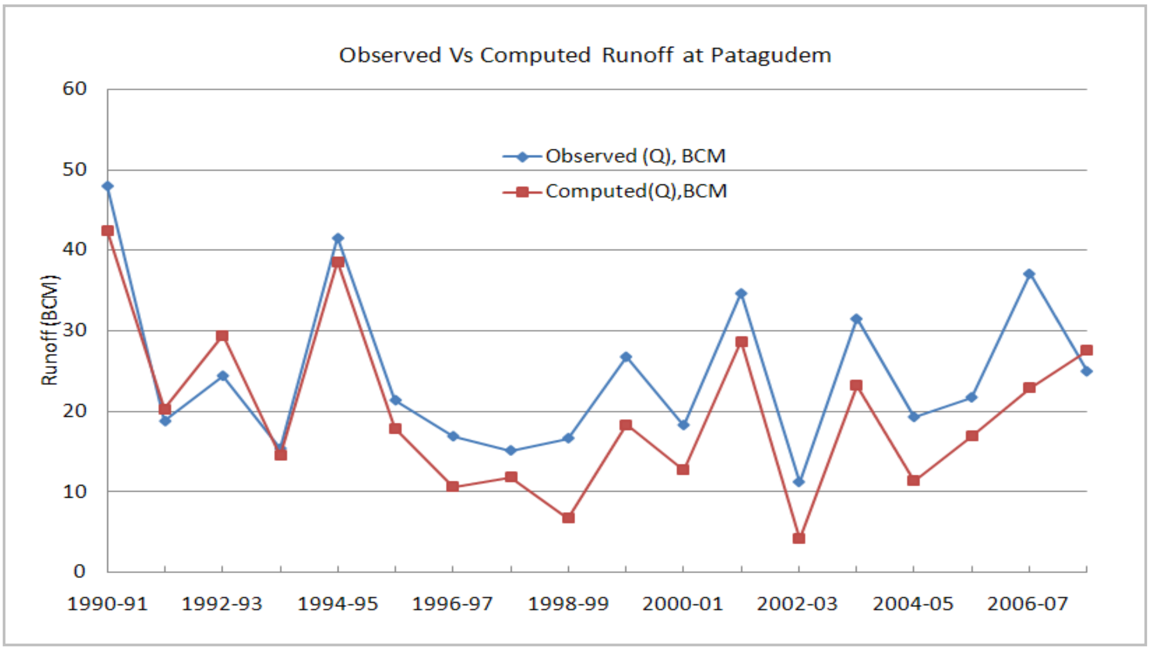
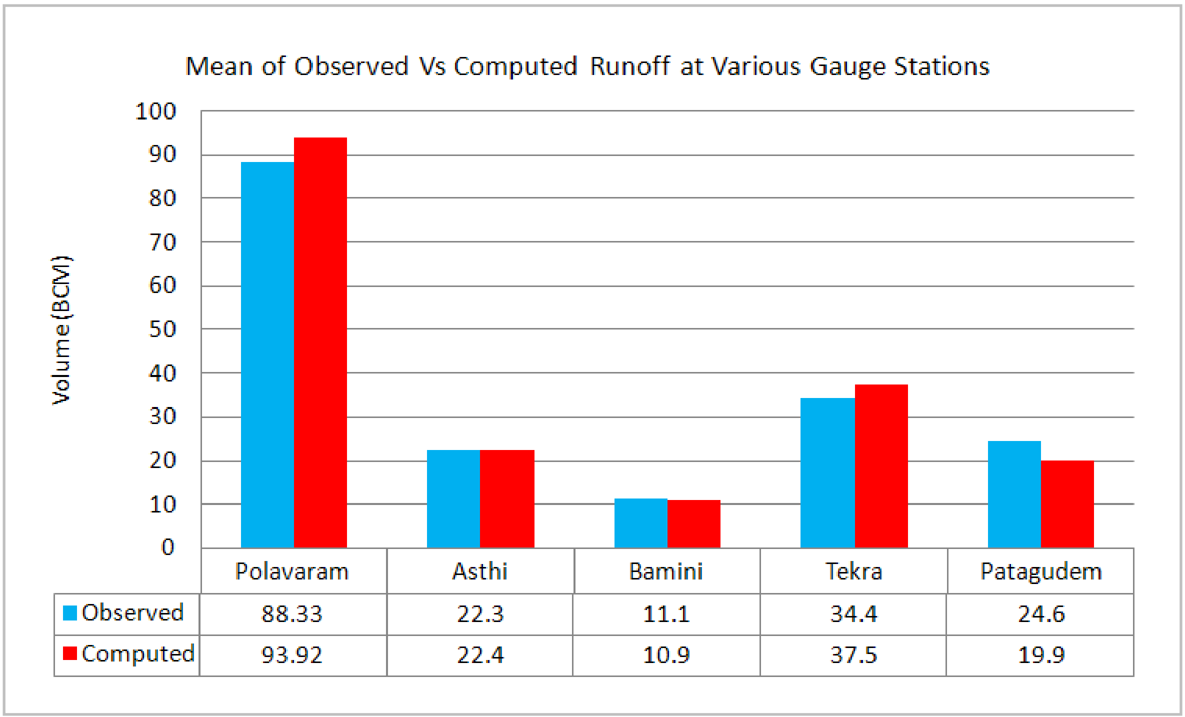


Fig. 29 Observed and Calibrated Runoff at Patagudem

Patagudem (Catchment Area = 40,000 Sq.Km.)					
	Observed Runoff (Q) BCM	Calibrated Runoff(Q) BCM	Rainfall BCM	% of Obs.Q/Rainfall	100*(Obs.-Cali.)/Obs
1988-89		14.6	52.1	0.0	
1989-90	20.0	17.9	56.2	35.6	10.6
1990-91	48.0	42.5	76.5	62.7	11.6
1991-92	18.8	20.3	53.0	35.4	-8.1
1992-93	24.4	29.4	64.1	38.1	-20.6
1993-94	15.4	14.6	50.0	30.7	5.3
1994-95	41.5	38.5	77.3	53.7	7.3
1995-96	21.4	17.9	53.1	40.2	16.2
1996-97	16.9	10.6	45.9	36.7	37.1
1997-98	15.1	11.8	47.4	31.9	21.9
1998-99	16.6	6.8	43.7	38.1	59.4
1999-00	26.8	18.3	51.9	51.6	31.4
2000-01	18.3	12.7	45.3	40.3	30.3
2001-02	34.6	28.7	62.2	55.7	17.2
2002-03	11.2	4.2	33.8	33.1	62.6
2003-04	31.5	23.2	58.9	53.5	26.2
2004-05	19.3	11.3	50.1	38.4	41.3
2005-06	21.7	17.0	57.8	37.6	21.9
2006-07	37.1	22.9	53.1	69.8	38.3
2007-08	25.0	27.6	66.6	37.5	-10.5
Average	**24.6**	**19.9**	**53.0**	**43.6**	**19.2**

Table 8 Variations in Runoff and Rainfall at Patagudem

Mean of the computed and observed runoff of the mentioned five gauge stations are shown in the figure 30.



	Polavaram	Asthi	Bamini	Tekra	Patagudem
Observed	88.33	22.3	11.1	34.4	24.6
Computed	93.92	22.4	10.9	37.5	19.9

Fig. 30 Observed and Calibrated Runoff (Mean) at Various Gauge Stations

8.5 Water Resources Assessment of the Basin

Water resources availability (WRA) in a basin comprises the model runoff, irrigation support (excess water in addition to rainfall), and evaporation from reservoirs.

Water Resources Availability = Calibrated Runoff + Irrigation Support + Evaporation from Reservoirs + D&I Consumption + GW Flux + Reservoir Flux

= 95.45 + 16.45 + 1.52+ 0.33 + (-0.67) + 0.011 (BCM)

= 113.09 BCM (mean of 1990-91 to 2007-08)

Water resources availability during the study period has been computed and presented in the table 9. Mean water resources of the basin during the these years (1990-91 to 2007-08) is found to be 113.09 BCM. In this, evaporation from only 11 reservoirs (data provided by CWC) is only considered.

Annual water resources availability and the mean are shown in the table 9. Distribution of rainfall into various hydrological components such as AET, runoff, etc is also shown in the table 9. Mean water resources availability and its components are shown in the figure 31.

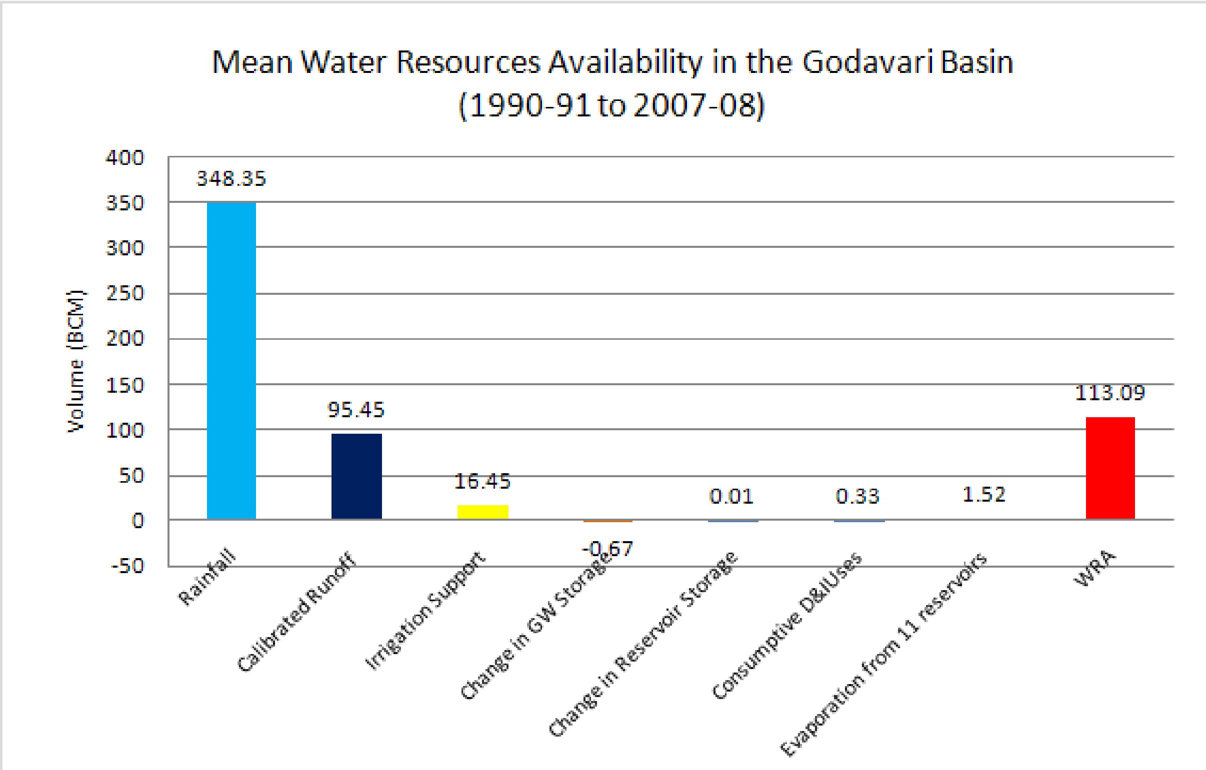


Fig. 31 Water Resources Availability in the Godavari Basin (1990-91 to 2007-08)

Year	Rainfall	Calibrated Runoff	AET Irrigated (including irrigation support)	Irrigation Support	Change in Groundwater Storage	Change in Reservoir Storage	Consumptive Domestic and Industrial Uses	Evaporation from 11 reservoirs (Major & Medium)	WRA
88--89	402.61	124.15*	65.4	16.96	Not Available	2.23	0.27	1.52	145.13**
89--90	396.72	119.09*	66.64	14.65	Not Available	0.43	0.27	1.38	135.82**
90--91	432.43	188.52	58.71	12.09	-2.18	0.42	0.28	1.48	200.60
91--92	282.94	79.47	46.59	15.47	-8.43	-3.78	0.28	1.48	84.49
92--93	337.63	75.72	69.45	23.52	-0.58	1.11	0.29	1.59	101.65
93--94	325.62	74.15	50.39	12.53	0.80	0.33	0.3	1.58	89.69
94--95	435.88	156.65	61.22	13.43	4.71	2.25	0.3	1.36	178.70
95--96	329.02	76.87	53.5	16.99	-3.06	-0.59	0.31	1.63	92.15
96--97	320.75	77.19	50.12	13.89	0.21	0.74	0.31	1.44	93.78
97--98	332.27	56.35	70.55	19.75	-1.73	-0.66	0.32	1.65	75.68
98--99	373.01	86.79	69.73	14.24	-1.73	2.35	0.33	1.57	103.54
99--00	357.64	104.74	62.89	14.24	0.29	-0.68	0.33	1.43	120.35
00--01	298.28	89.82	46.91	15.26	-3.89	-1.66	0.34	1.52	101.39
01--02	334.40	85.23	63	18.2	-1.73	-0.11	0.34	1.58	103.51
02--03	275.50	53.32	50.47	19.87	-2.71	0.15	0.35	1.66	72.63
03--04	350.25	86.11	67.23	21.47	4.82	0.13	0.35	1.54	114.41
04--05	291.04	44.71	48.81	14.09	-3.90	0.12	0.36	1.5	56.87
05--06	426.13	127.35	66.88	14.8	8.07	0.93	0.37	1.36	152.88
06--07	378.00	136.85	66.3	21.42	-0.73	0.44	0.37	1.49	159.84
07--08	389.56	118.19	70.39	14.88	-0.22	-1.28	0.38	1.43	133.39
Average ***	**348.35**	**95.45**	**59.62**	**16.45**	**-0.67**	**0.01**	**0.33**	**1.52**	**113.09**

* Runoff without groundwater flux taken into consideration ** WRA without groundwater flux taken into consideration

*** Average of 1990-91 to 2007-08

Note: All units are in BCM; Groundwater and reservoir storage +ve indicates recharge

Table 9 Water Resources Assessment of the Godavari Basin

As mentioned earlier, mean water resources of the basin assessed by CWC in 1993 based on the data from 1967-68 to 1984-85, is 110.54 BCM.

Since the IMD rainfall data is available since 1973-74, rainfall of the basin has been extracted for all the years. It is found that nearly 8 BCM of rainfall has been increased from the period 1973-85 to 1988-2008, this may be one of the reason for increase in the WRA of the basin during 1988-89 to 2007-08.

8.5.1 Water Resources Availability During Extreme Rainfall Conditions

Rainfall data from 1973 to 2008 (35 years data) has been analysed, it is found that 1994-95 and 2002-03 was maximum and minimum rainfall years respectively during this period. Hence, WRA during these two years has been analysed separately. It is found that WRA during maximum dry period is 72.63 BCM and during maximum wet period is 178.70 BCM. Variations in rainfall, runoff during maximum and minimum rainfall periods is shown in the table 10.

Condition	Year of Occurrence	Rainfall (BCM)	Water Resources Availability (BCM)
Minimum Rainfall	2002-03	275.50	72.63
Maximum Rainfall	1994-95	435.88	178.70
Mean Condition	Mean of 1990-91 to 2007-08	348.35	113.09

Table 10 Water Resources Availability During Extreme Rainfall Conditions in the Godavari Basin

Water resources availability and its distribution during extreme dry (minimum rainfall) and wet (maximum rainfall) conditions are shown in the figures 32 and 33 respectively.

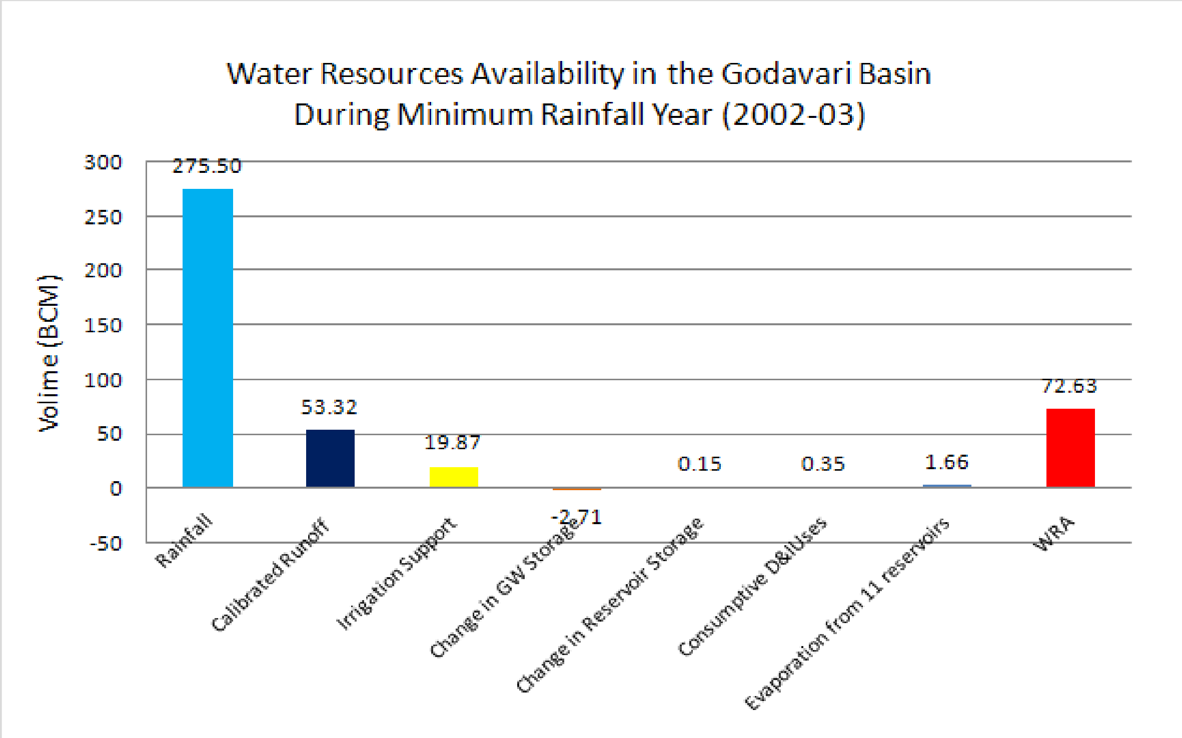


Fig. 32 Water Resources Availability During Minimum Rainfall Year (Extreme Dry Year)

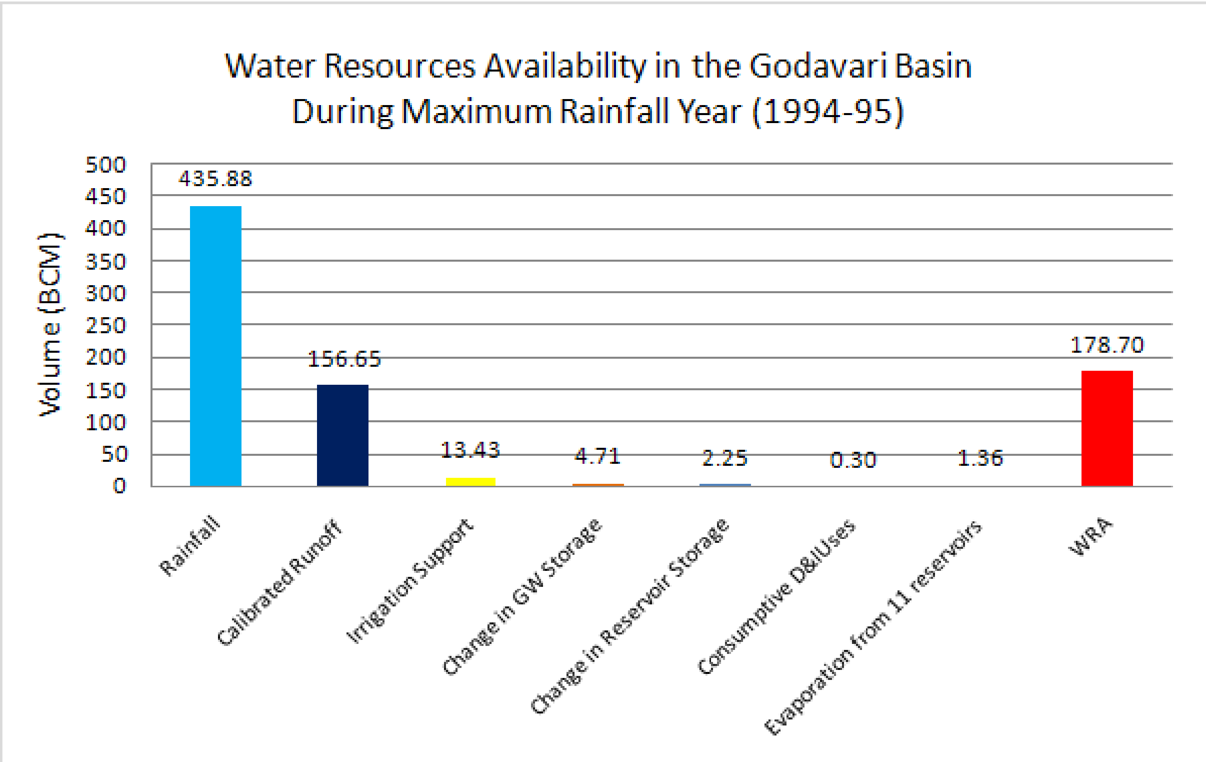


Fig. 33 Water Resources Availability During Maximum Rainfall Year (Extreme Wet Year)

8.5.2 Distribution of Actual Evapotranspiration

Since, the AET from agricultural land is very important component, it has been analyzed further. AET from irrigated agricultural and rain-fed agriculture are aggregated separately. As discussed earlier, AET from agricultural land made it equal to PET $_{revised}$ by adding irrigation supplies to the rainfall of an amount equalant to (PET $_{revised}$ -Rainfall). Hence, these irrigation supplies are also aggregated separately to account in water resources assessment of the basin. AET from irrigated area, rain-fed area, irrigation support, total AET from all landuses during all the study period is shown in the table 11. Mean of these components are shown in the figure 34.

Year	AET Irrigated (BCM)	AET Rainfed (BCM)	AET of total Agriculture (BCM)	Irrigation Support (BCM)
88--89	65.4	33.95	99.35	16.96
89--90	66.64	32.42	99.06	14.65
90--91	58.71	29.79	88.50	12.09
91--92	46.59	31.23	77.82	15.47
92--93	69.45	34.53	103.98	23.52
93--94	50.39	32.96	83.35	12.53
94--95	61.22	30.54	91.76	13.43
95--96	53.5	35.86	89.36	16.99
96--97	50.12	30.04	80.16	13.89
97--98	70.55	32.13	102.68	19.75
98--99	69.73	35.82	105.55	14.24
99--00	62.89	31.79	94.68	14.24
00--01	46.91	30.70	77.61	15.26
01--02	63	31.07	94.07	18.2
02--03	50.47	28.98	79.45	19.87
03--04	67.23	31.63	98.86	21.47
04--05	48.81	32.13	80.94	14.09
05--06	66.88	30.52	97.40	14.8
06--07	66.3	29.51	95.81	21.42
07--08	70.39	34.42	104.81	14.88
Average*	**59.62**	**31.87**	**91.49**	**16.45**

*Average of 1990-91 to 2007-08

Table 11 AET from Irrigated and Rain-fed Area

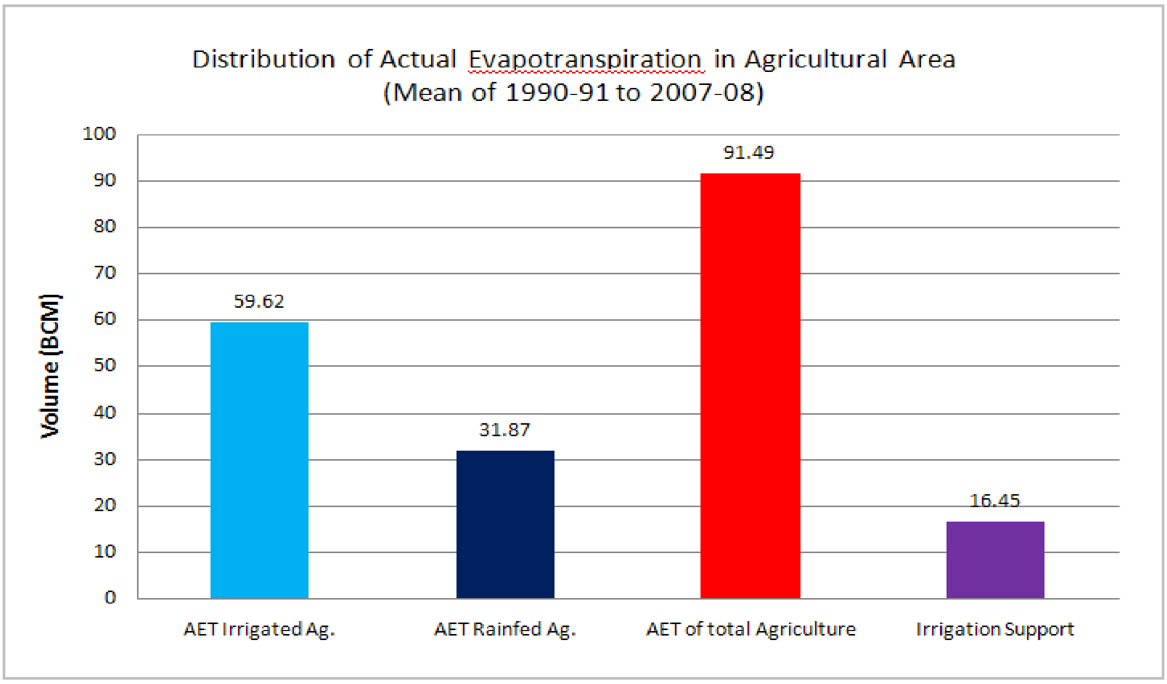


Fig. 34 Distribution of Actual Evapotranspiration

9.0 Water Resources Assessment in Brahmani-Baitarani Basin

9.1 Geographic and Hydrologic Setting of the Basin

The combined Brahmani-Baitarani river basin extends over a geographical area of 50,768 sq.km and the basin is bounded on the north by the Chhotanagpur Plateau, on the west and south by the ridge separating it from Mahanadi basin and on the east by the Bay of Bengal. Through intersection of state administrative boundaries and basin boundary (derived for the present study) state-wise drainage areas are computed. The drainage area of the basin lies in the States of Orissa (33,923 sq.km.), Jharkhand (15,479 sq.km.) and Chhattisgarh (1,367 sq.km.). Out of the total basin area, major part of 66.82% is covered in Orissa State, 30.49% of area is in Jharkhand State and 2.69% of area falls in Chhattisgarh State. The basin is bounded by 20^0 29' 00" N to 23^0 37' 47" N latitude and 83^0 53' 49" E to 87^0 1' 27" E longitude. Fig.35 shows the location map of the basin.

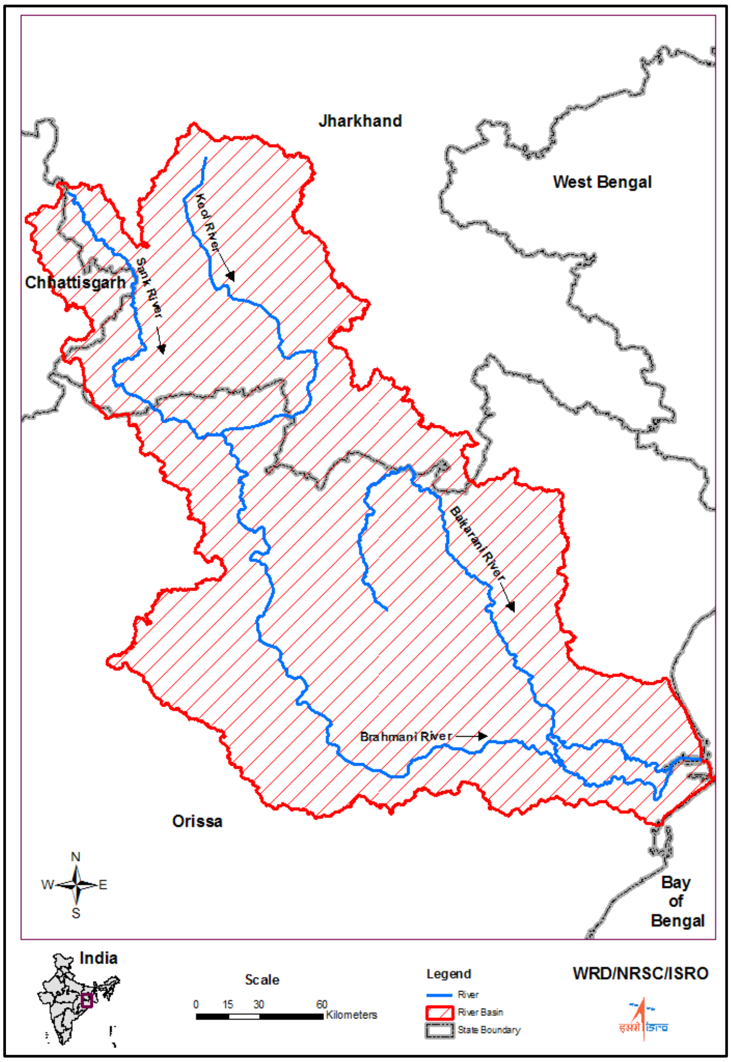


Fig.35 Location Map of Brahmani-Baitarani basin

9.1.1 Rainfall

Rainfall varies both spatially and temporally in the Brahmani-Baitarani basin. Fig.36 shows gridded monthly rainfall of Brahmani-Baitarani basin for the water year 2004-05. Fig.37 shows the annual rainfall for 37 years (1971-72 to 2007-08) of Brahmani-Baitarani basin. Among these 37 years, the lowest annual rainfall is 802 mm (2004-05) and highest annual rainfall is 2022 mm (1994-95). The analysis of rainfall during the study period of 1988-89 to 2007-08 (20 years) indicated the average annual rainfall is 1467 mm. Both the lowest annual rainfall of 802 mm and highest annual rainfall of 2022 mm among 37 years falls within the study period of 20 years and represents the extreme dry and wet rainfall conditions. Of the 20 years, 11 years annual rainfall is higher the mean annual rainfall and remaining 9 years lower than the mean annual rainfall. Fig.38 shows mean monthly variations of rainfall of the basin during the 20 years (1988-89 to 2007-08). The highest rainfall occurs in the month of August (348 mm), followed by July (331 mm), followed by June and September months. The South-West monsoon rainfall (1278 mm) amounts to 87% of total annual rainfall.

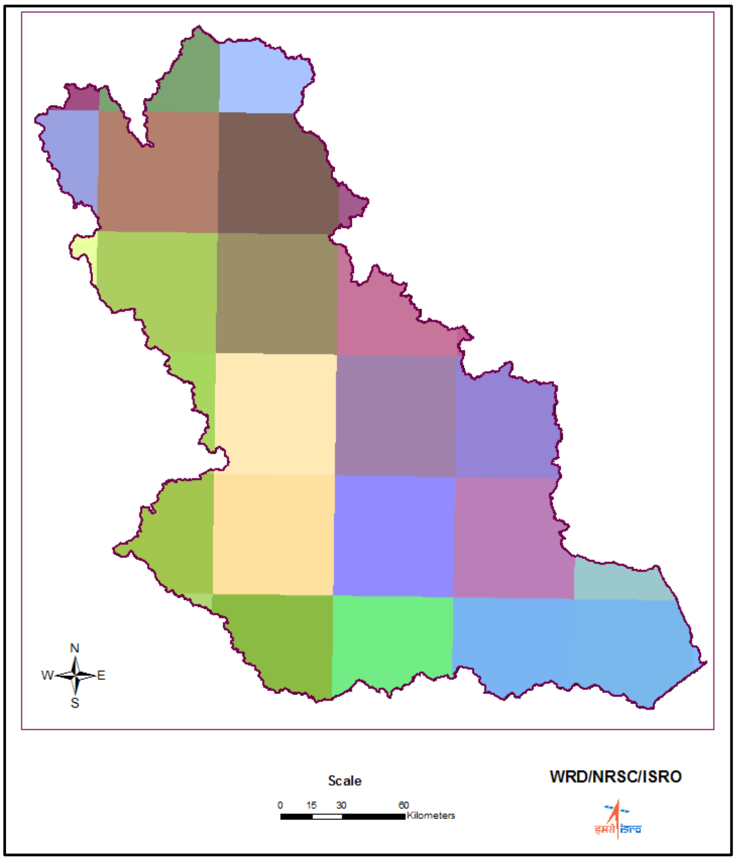


Fig.36 Rainfall Image of Brahmani-Baitarani basin

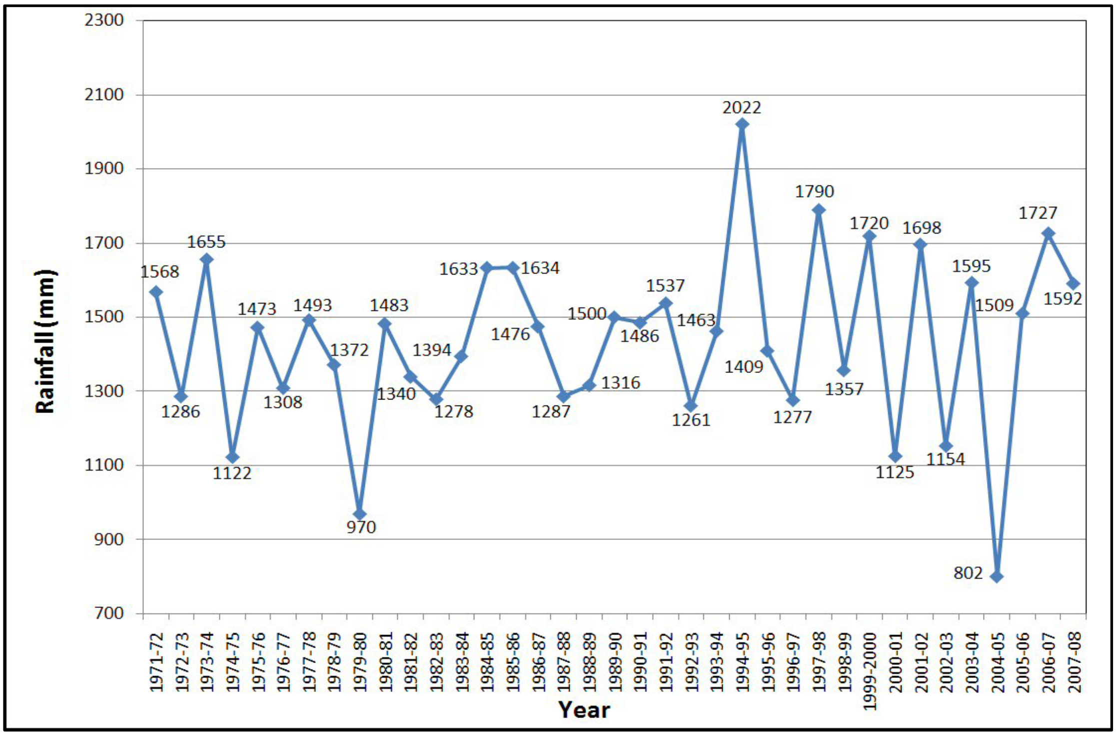


Fig. 37 Annual Rainfall of Brahmani-Baitarani basin for 1971-72 to 2007-08 (37 years)

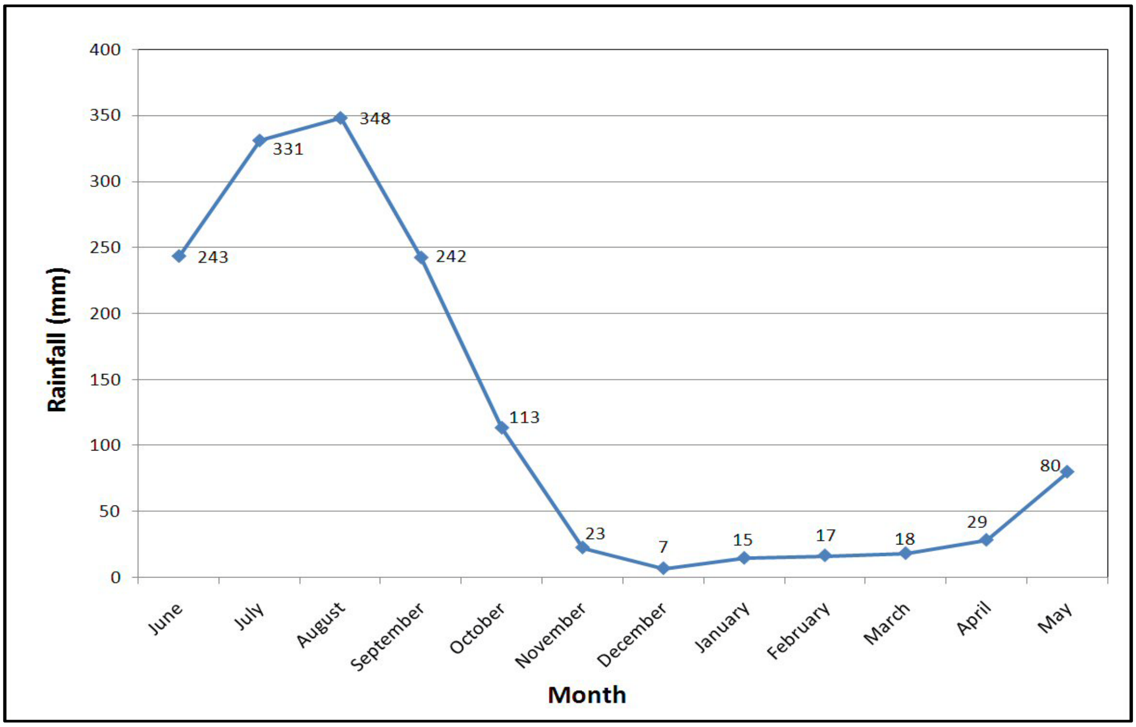


Fig. 38 Mean Monthly Rainfall of Brahmani-Baitarani basin (1988-89 to 2007-08)

9.1.2 Climate

In Brahmani basin, maximum temperature rises to 47° C during summer while the minimum during winter may be as low as 4°C. Temperatures in the coastal region are moderate but humidity is higher. In Baitarni basin the maximum recorded temperature of Keonjhar District in summer is 48.5°C and minimum in winter is 6° C. Fig.39 shows mean monthly temperatures for 2004-05 of Brahmani-Baitarani basin. The highest mean monthly temperature is observed in May which is about 32^0 C and lowest mean monthly temperature is about 19^0 C in January.

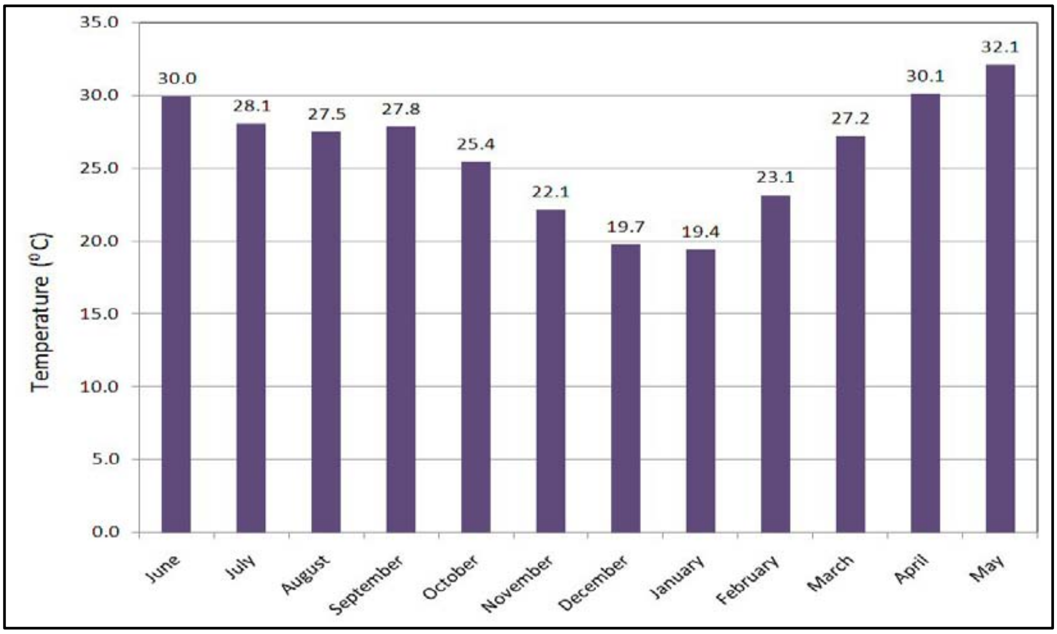


Fig. 39 Mean Monthly Temperature during 2004-05

9.1.3 Land Use/Land Cover Pattern

The land use / land cover of the basin is shown in Fig.40. The image corresponds to the 2004-05 year and consists of 17 different classes. Forest cover forms as the major constituent (31.9%), followed by crop area (29.15%) and current fallow (28.25%). The remaining 10.7% of basin area is covered by built up land, plantation, littoral swamp, grassland, gullied land, scrubland, other waste land and water bodies (Fig.41). The crop area is further categorised as Kharif only (23.64%), Rabi only (0.9%), Zaid only (0.26%) and Double/Triple (4.35%) classes.

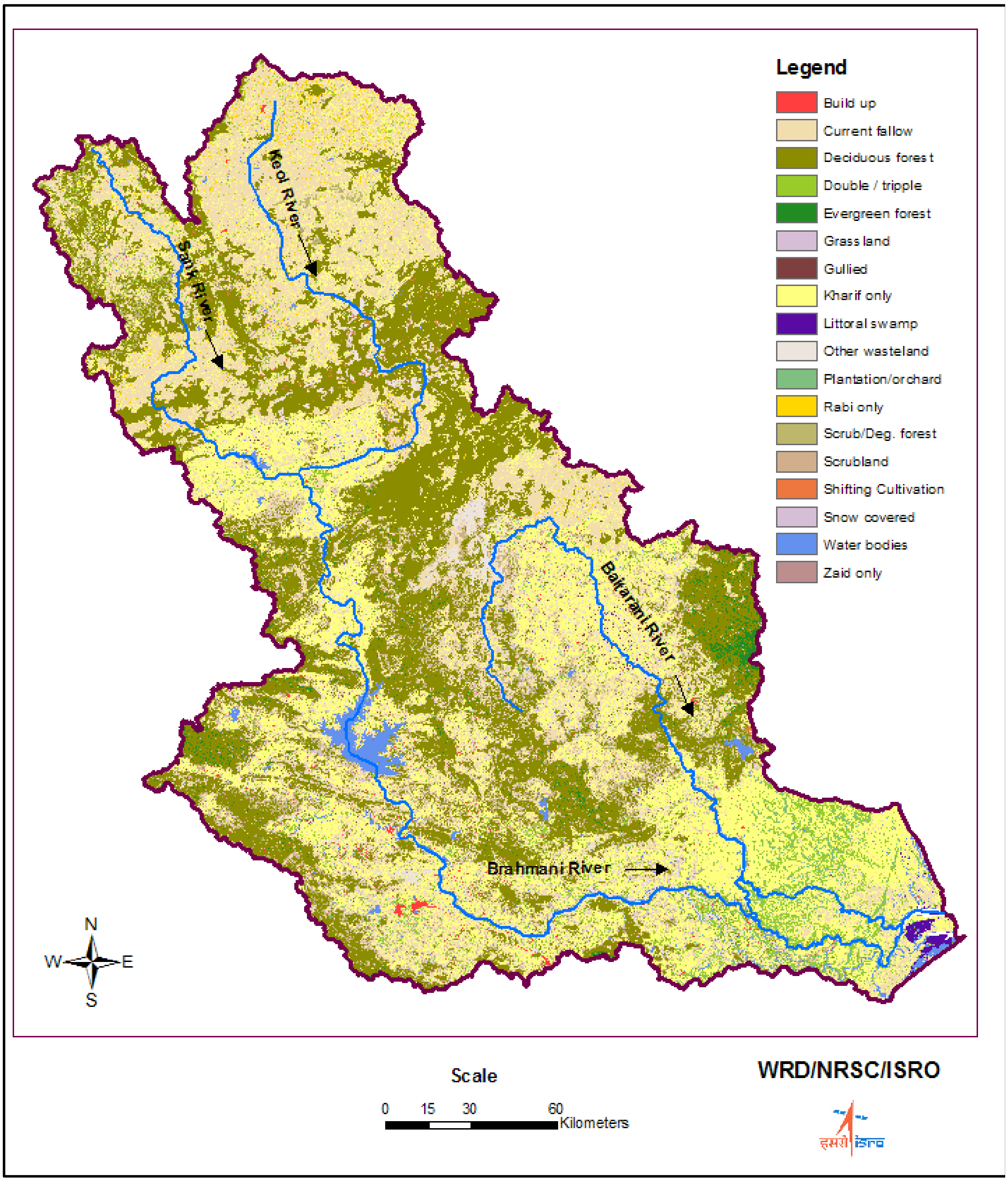


Fig. 40 Land Use / Land cover Map of Brahmani-Baitarani basin (2004-05)

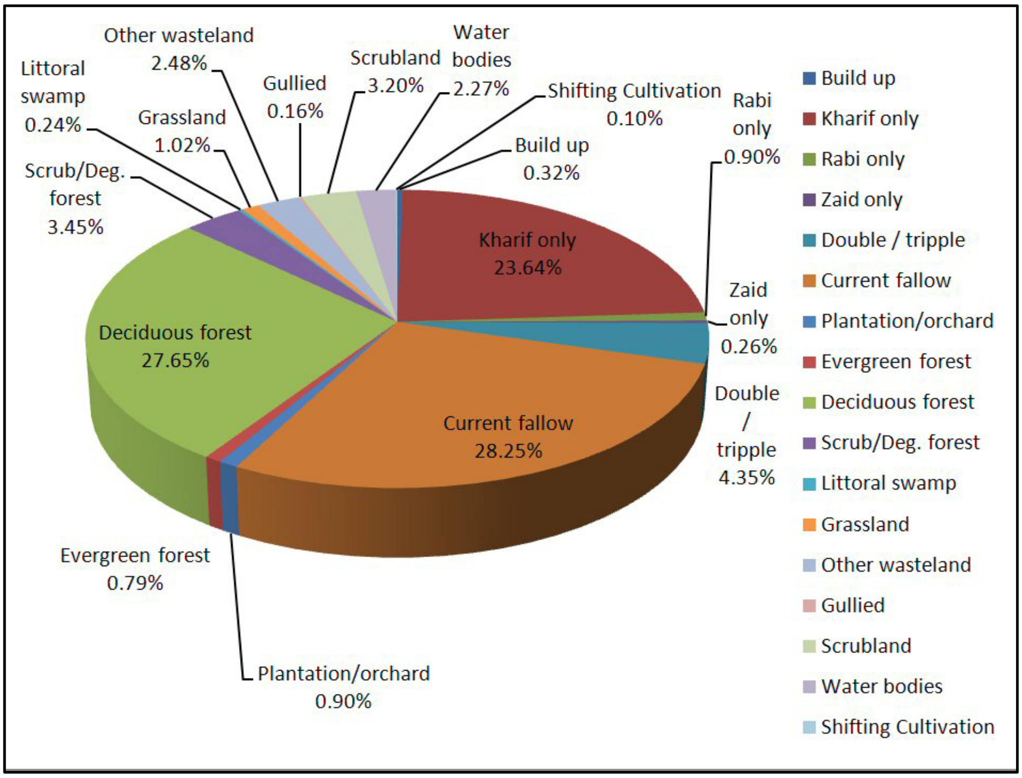


Fig. 41 Distribution of Land Use / Land cover for 2004-05 year

9.1.4 Soils

The main soil types found in the basin are red and yellow soils, red sandy and loamy soils, mixed red and black soils and coastal alluvium. The coastal plains consist of fertile delta area highly suited for intensive cultivation. The Fig.42 shows various categories of soils in the basin. The soils are classified based on the soil textural information as sandy, loamy, clayey, loamy skeletal, clay skeletal.

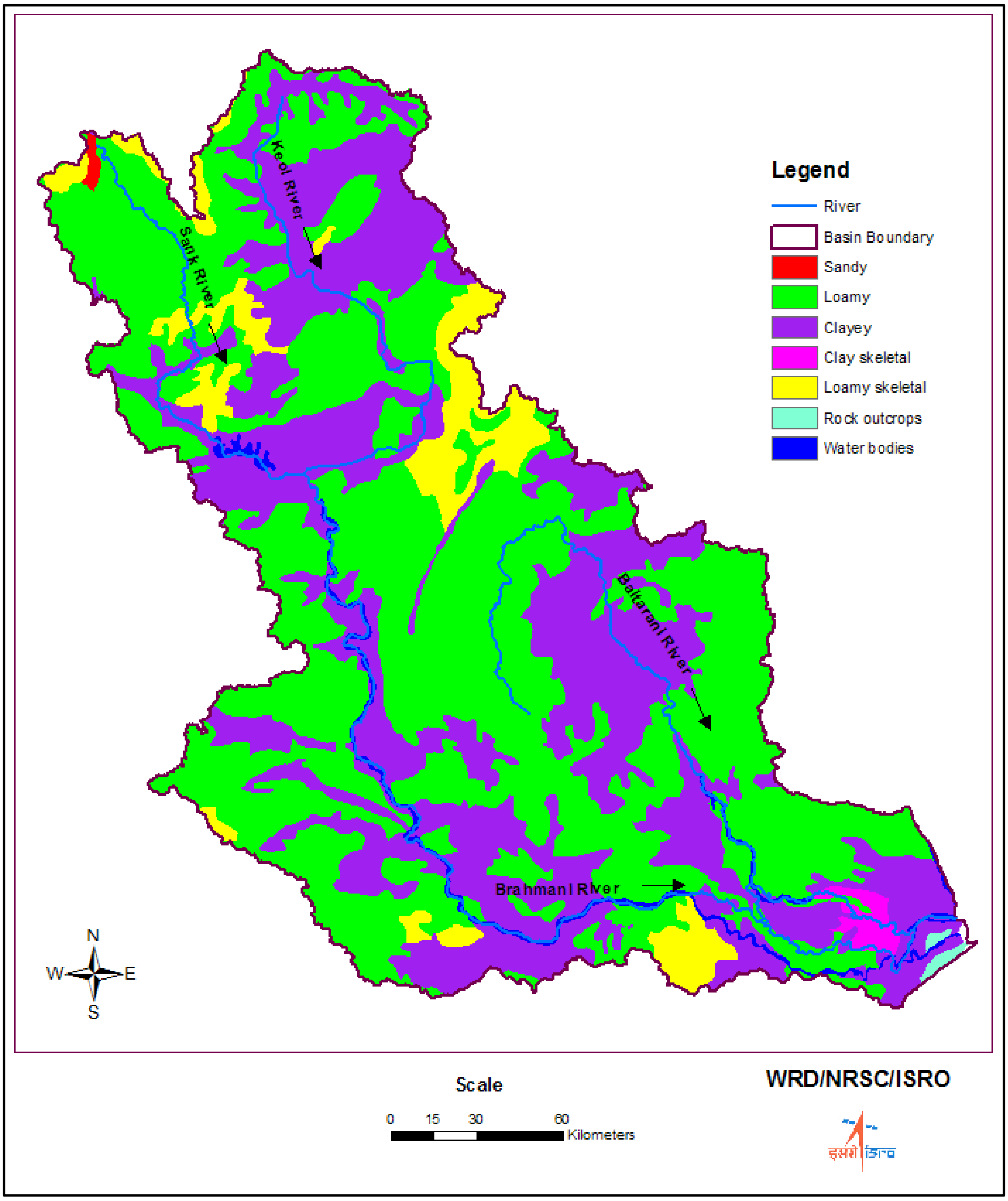


Fig. 42 Soil Map of Brahmani-Baitarani basin

9.1.5 Topography

The topography of the basin consists of ghat areas, northern plateau, central table land and the coastal plains. The upper regions of the basin are mostly hilly and forested. The lower region of the basin is deltaic plains. The elevation values ranges from a minimum of 1m to a maximum of 1176 m. The average elevation is about 341 m in the basin. The Fig.43 shows ASTER DEM of the basin.

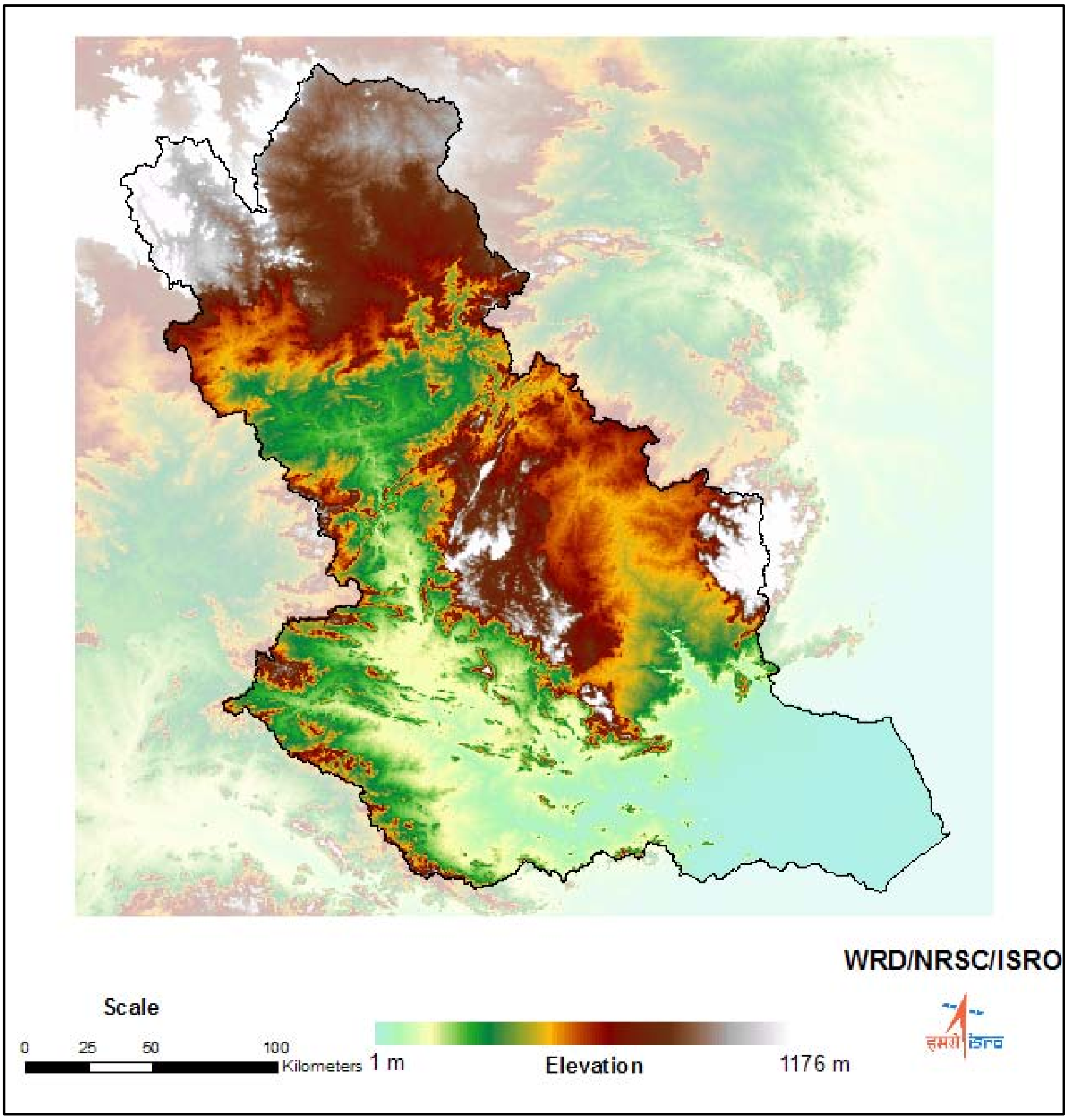


Fig. 43 ASTER DEM of Brahmani-Baitarani basin

9.1.6 Rivers and Discharge

The Brahmani river rises near Nagri village in Jharkhand State at an elevation of about 600 m and has a total length of 799 km. The major tributaries of Brahmani are the Keol, the Tirka and the Sankh Rivers. After the confluence of Sankh river and Keol River, the river is called as Brahmani River. The Baitarani river rises in the Guptaganga hill ranges of Keonjhar district of Orissa at an elevation of about 900m and has a length of about 355 km. The important tributaries of Baitarani are the Salandi and the Matai. Both river systems outfall into the Bay of Bengal forming a common delta area. Before out falling into the Bay of Bengal both Brahmani-Baitarani join and interleave in the delta region forming multiple outlets. The Fig.44 shows the location of 7 CWC discharge sites namely Tilga, Jaraikela, Panposh, Gomlai, Jenapur on Brahmani and its tributaries and Champua and Anandpur on Baitarani River.

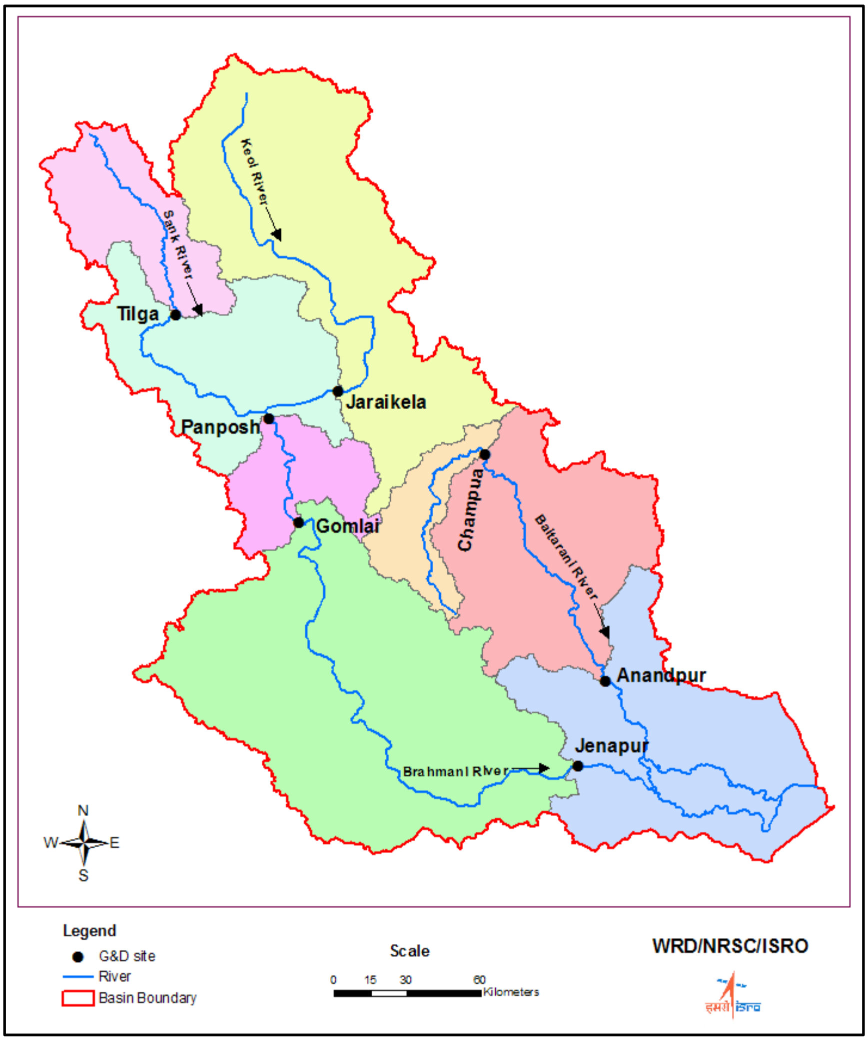


Fig. 44 Location of 7 CWC discharge sites in Brahmani-Baitarani basin

9.1.7 Reservoirs

Fig.45 shows the location of 3 main reservoirs in Brahmani-Baitarani basin. One, the Mandira dam is constructed on Sankh river, a tributary of Brahmani river during 1957 - 1959. The dam is exclusively meant for the purposed of storing water for supply to the Rourkela Steel Plant located about 24 km downstream along the river course. Two, the Rengali dam constructed across Brahmani river during 1974 - 1985. This is a multipurpose reservoir for flood control, irrigation and power generation. The gross capacity and live storage capacity of reservoir at Full Reservoir Level (FRL) is 4,400 MCM and 3,452 MCM correspondingly (Dam safety Report, 2007). Three, the Salandi Dam built across Salandi river, a tributary of Baitarani river with main purpose of irrigation.

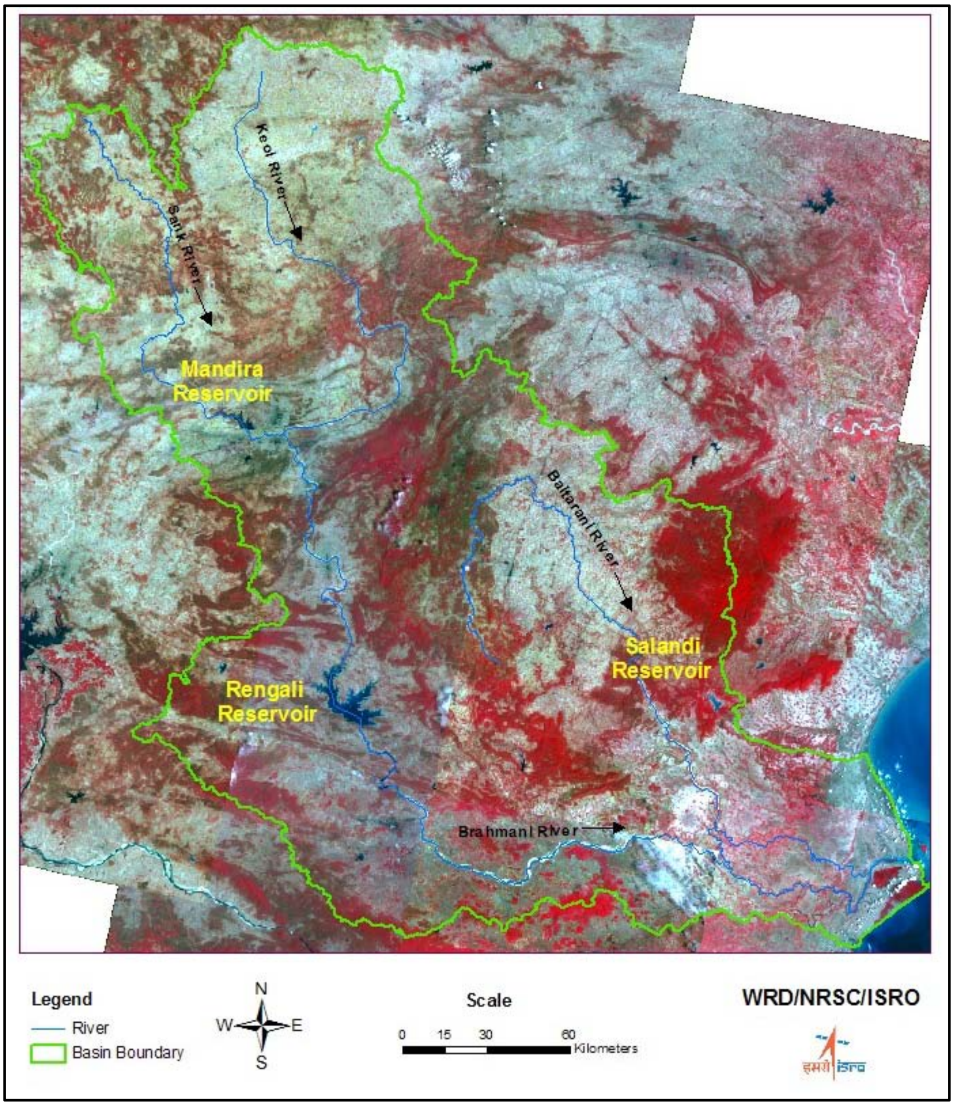


Fig.45 Major Reservoirs in Brahmani-Baitarani basin

9.1.8 Ground Water Usage

Ground water forms the important component in water resources of the basin. As mentioned in the earlier section ground water levels are converted from point data to spatial data for 20 years. The spatial annual ground water levels are used in estimating the ground water flux (Fig.46). For Brahmani-Baitarani basin no information was available on specific yield and hence, a uniform specific yield of 3% is assumed for entire basin. The ground water recharge or withdrawal for the basin is computed using the annul ground water flux and specific yield for 20 years.

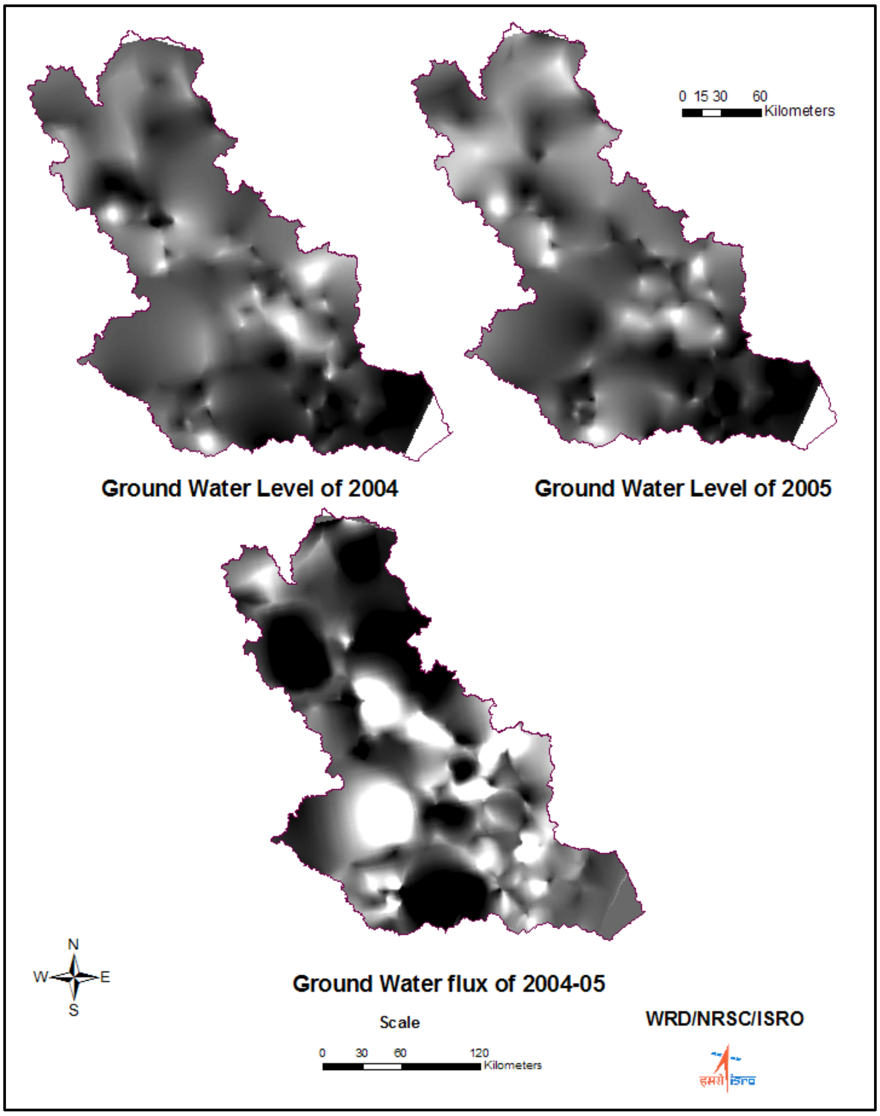


Fig.46 Ground water flux (spatial data) estimated during 2004-05

9.2 Previous Estimations

In 1949, using Khosla's empirical formula basin-wise water resources assessment of the Brahmani-Baitarani basin was estimated as 39,225 Mm^3. In 1960, the Central Water and Power Commission, while conducting irrigation potential studies, assessed the total annual runoff of the basin as 28,691 Mm^3 on the basis of Strange's rainfall-runoff coefficients.

In 1988, CWC reported 36,227 Mm^3 as average water resources of the Brahmani-Baitarani basin using Khosla's formula.

In 1993, CWC has undertaken reassessment of water resources potential of India. The Brahmani-Baitarani basin has a total catchment area of 51,822 sq.km. For the Brahmani portion of the basin, flow data at Jenapur (CWC discharge station with catchment area of 36,300 sq.km.) available for the period 1964-65 to 1984-85 (Table.xx). For the Baitarani portion of the basin, flow data at Biridi (catchment area of 10,120 sq.km.) available for the period 1964-65 to 1984-85 (Table.12) were used. The discharge flows were proportionately taken based on the areas with respect to Jenapur to the total Brahmani basin (catchment area of 39,030 sq.km.) and Biridi to the total Baitarani basin (catchment area of 10,982 sq.km.). Withdrawal for irrigation has been calculated based on the year-wise irrigation potential created assuming an average delta of 0.82 m. Withdrawal for domestic use has been based on population statistics assuming requirement of 70 lpcd for rural population and 140 lpcd for urban population. the change in storage in the reservoirs in the basin is neglected. The total water resources available was estimated as 28,477 Mm^3 in the basin.

Year	Observed flow at Jenapur (MCM)	Withdrawals (MCM)		Return Flows (MCM)		Evaporation Losses (MCM)	Natural Flow (MCM)
		Irrigation	Domestic & Industrial	Irrigation	Domestic & Industrial		
1964-65	25,714	650	301	65	241	0	26,259
1965-66	7,434	666	320	67	256	0	8,097
1966-76	15,338	683	340	68	272	0	16,021
1967-68	20,664	699	360	70	288	0	21,305
1968-69	15,258	716	380	72	304	0	15,978
1969-70	11,438	732	398	73	318	0	12,177
1970-71	24,709	749	419	75	335	0	25,467
1971-72	40,523	765	440	77	352	0	41,299
1972-73	19,266	787	459	79	367	0	20,066
1973-74	44,228	798	479	80	383	0	45,052
1974-75	12,212	815	501	82	401	0	13,045
1975-76	21,531	831	520	83	416	0	22,383
1976-77	14,362	848	542	85	434	0	15,233
1977-78	24,248	864	562	86	450	0	25,138
1978-79	21,869	881	582	88	466	8	22,786
1979-80	7,320	897	604	90	483	21	8,269
1980-81	18,972	914	624	91	499	21	19,941
1981-82	14,945	931	645	93	516	21	15,933
1982-83	10,018	947	666	95	533	21	11,024
1983-84	16,993	964	684	96	547	21	17,961
1984-85	23,580	980	707	98	566	21	24,624
Average	19,553	815	502	82	401	6	20,384

Table 12 CWC 1993 Estimation of Water Resources Potential of Brahmani Basin

Average annual flow at Jenapur = 20,384

Average annual flow for the whole Brahmani basin = 20,384X 39,033/36,300

= 21,919 MCM

year	Observed flow at Biridi (MCM)	Withdrawals (MCM)		Return Flows (MCM)		Evaporation Losses (MCM)	Natural Flow (MCM)
		Irrigation	Domestic & Industrial	Irrigation	Domestic & Industrial		
1964-65	7,169	207	38	21	30	0	7,363
1965-66	3,442	234	39	23	32	0	3,660
1966-76	4,276	260	40	26	32	0	4,518
1967-68	5,744	286	41	29	33	0	6,009
1968-69	6,145	312	44	31	35	0	6,435
1969-70	6,941	339	44	34	35	0	7,255
1970-71	5,611	355	44	36	35	0	5,939
1971-72	12,228	391	46	39	37	0	12,589
1972-73	5,371	418	46	42	37	0	5,756
1973-74	10,781	444	48	44	38	0	11,191
1974-75	4,483	470	49	47	39	0	4,916
1975-76	6,710	496	50	50	40	0	7,166
1976-77	3,551	523	51	52	41	0	4,032
1977-78	4,937	550	53	55	42	0	5,443
1978-79	2,606	575	53	58	43	0	3,133
1979-80	2,665	602	54	60	43	0	3,217
1980-81	4,980	628	55	63	44	0	5,556
1981-82	4,905	654	57	65	45	0	5,506
1982-83	4,510	680	58	68	46	0	5,134
1983-84	7,022	707	59	71	47	0	7,670
1984-85	3,731	733	60	73	48	14	4,417
Average	5,610	470	49	47	39	1	6,043

Table 13 CWC 1993 Estimation of Water Resources Potential of Baitarani Basin

Average annual flow at Biridi = 6,043

Average annual flow for the whole Baitarani basin = 6,043 X 10,982/10,120

= 6,558 MCM

Average annual flow for Brahmani-Baitarani basin = 21,919 + 6,558 = 28,477 MCM

9.3 Sub-basins of Brahmani-Baitarani

The Brahmani-Baitarani basin is divided in to 8 sub-basins (Fig. 47) viz. Tilga, Jaraikela, Panposh, Gomlai and Jenapur in Brahmani basin and Champua and Anandpur in Baitarani basin and combined delta region as one sub-basin. The following Table 14 gives details of each sub-basin. The sub-basins are divided in such a way that the location of CWC discharge sites is taken as sub-basin outlet. The drainage area given in the table indicates entire area draining up to the outlet of the sub-basin.

S. No.	Sub-basin	River	Drainage Area (sq.km)
1	Tilga	Sank	3,060
2	Jarikela	Koel	10,201
3	Panposh	Brahmani	18,589
4	Gomlai	Brahmani	20,819
5	Jenapur	Brahmani	34,574
6	Champua	Baitarani	1,735
7	Anandpur	Baitarani	8,307
8	Delta	Brahmani-Baitarani	50,768

Table 14 Sub-basinwise details Brahmani-Baitarani basin

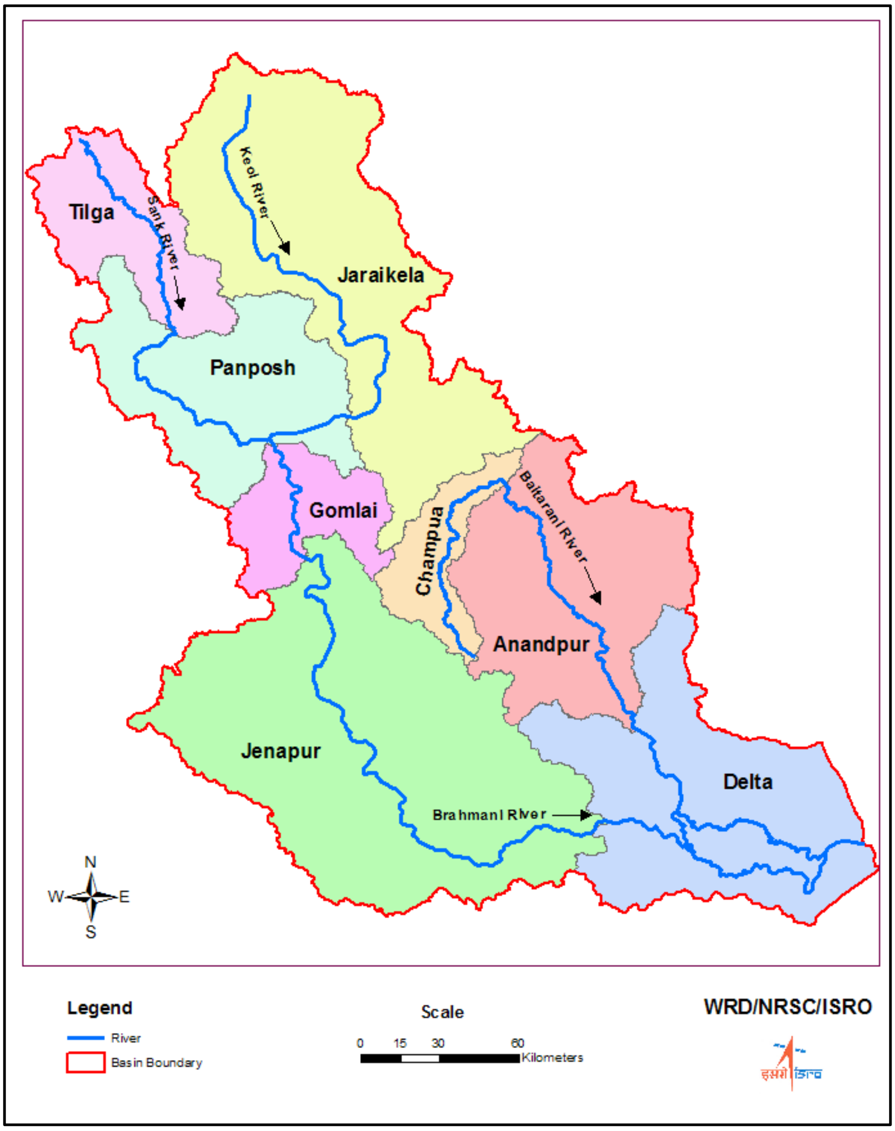


Fig.47 Sub-basins of Brahmani-Baitarani basin

9.4 Landuse Coefficients

The landuse coefficients used in different land use categories are of two types. First, a constant value throughout the year for classes such as built-up (0.25), plantation (0.85), evergreen and deciduous forest (0.85), degraded forest (0.4), littoral swamp and water bodies(1.0), grassland (0.7), other wasteland(0.3), gullied (0.25) and scrub land(0.4). Second, value varying for each month depending on the crop season, type and its growth (Table. 15).

Based on the district-wise crop area statistics for the past few years in the basin, major crops for each crop season were identified. Rice in Kharif only season, saflower in Rabi only season, Groundnut in Zaid only season and Rice in double/tripe season are considered as principle crops grown correspondingly and hence, only these are assumed to be representing the entire area of that particular land use. On examining the cropping pattern within the basin, crop growing seasons are decided as Kharif only crop during 4 months (July to October), Rabi only crop during 4 months (November to February), Zaid only crop during 4 months (February to May), double/triple crop during 8 months (July to October and January to April) and shifting cultivation during 4 months (July to October). Considering all the above factors land use coefficients are taken based on the earlier studies carried out in the basin (Mohan et al, 1996).

	Kharif only	**Rabi only**	**Zaid only**	**Double/Triple**	**Shifting cultivation**
June	0.2	0.35	0.35	0.2	0.2
July	1.15	0.4	0.4	1.15	0.35
August	1.23	0.4	0.4	1.23	0.91
September	1.14	0.4	0.4	1.14	1.17
October	1.02	0.4	0.4	1.02	0.28
November	0.5	0.35	0.35	0.5	0.2
December	0.2	0.35	0.2	0.2	0.2
January	0.2	0.91	0.2	1.15	0.2
February	0.2	1.17	0.45	1.23	0.2
March	0.2	0.28	0.75	1.14	0.2
April	0.2	0.2	1.05	1.02	0.2
May	0.2	0.2	0.7	0.5	0.2

Table 15 Land use coefficients for various land cover types

These land use coefficients are used in estimating the PET values for each month by multiplying PET computed from Thronthwaite formula.

9.5 Available Water Holding Capacity

As mentioned earlier, a particular soil textural class can have a particular water holding capacity and a certain vegetation type to have a maximum rooting depth. The water holding capacities for different soils are taken from available literature as shown below.

Soil Type	Available water capacity (% volume)
Sand	90
Loamy skeletal	120
Loam	150
Clayey skeletal	160
Clay	200

Similarly, the root zone depths for each crop type are taken from available literature which also varies with soil type (Table.16).

Vegetation Type	Soil Type	Rooting Depth (mm)
Kharif only (Rice) Double/tripe (Rice) Degraded forest	Sand	600
	Loamy skeletal	559
	Loam	518
	Clayey skeletal	505
	Clay	450
Rabi only (Saflower)	Sand	1600
	Loamy skeletal	1491
	Loam	1382
	Clayey skeletal	1345
	Clay	1200

Zaid only (Groundnut)	Sand	600
	Loamy skeletal	559
	Loam	518
	Clayey skeletal	505
	Clay	450
Plantation Evergreen and deciduous forest	Sand	1500
	Loamy skeletal	1398
	Loam	1295
	Clayey skeletal	1261
	Clay	1125
Grass Shifting cultivation	Sand	700
	Loamy skeletal	652
	Loam	605
	Clayey skeletal	589
	Clay	525
Scrub	Sand	250
	Loamy skeletal	233
	Loam	216
	Clayey skeletal	210
	Clay	188
Current fallow Other waste land Gullied	Sand	150
	Loamy skeletal	140
	Loam	130
	Clayey skeletal	126
	Clay	113

Table 16 Rooting depths of different types of vegetation

The water available for vegetation is up to root zone depth and is computed as follows.
Available water capacity (mm) = Available water capacity(% volume) X Rooting depth (mm)

9.6 Irrigation Command Area

The HRUs are further classified based on their location within or outside command boundary. In case of Kharif only crop, irrigation support(Actual ET= PET) is provided only crop area located within command boundary and if located outside command no irrigation support is provided. For double/triple crop, irrigation support is provided whether crop is located within or outside command boundary. The areal extent under crop categories, namely, Rabi only and Zaid only is less and also scattered all over the basin with insignificant area under command jurisdiction. The field statistical data also indicates cultivation of Gram/Pulses crops during this period which are less water intensive and area mostly cultivated with residual soil moisture. therefore, irrigation support is not considered for these crop categories. Fig.48 shows location of irrigation command boundaries in Brahmani-Baitarani basin. The annual irrigation supplies were computed for the period of 20 years based on the procedure mentioned in modelling framework.

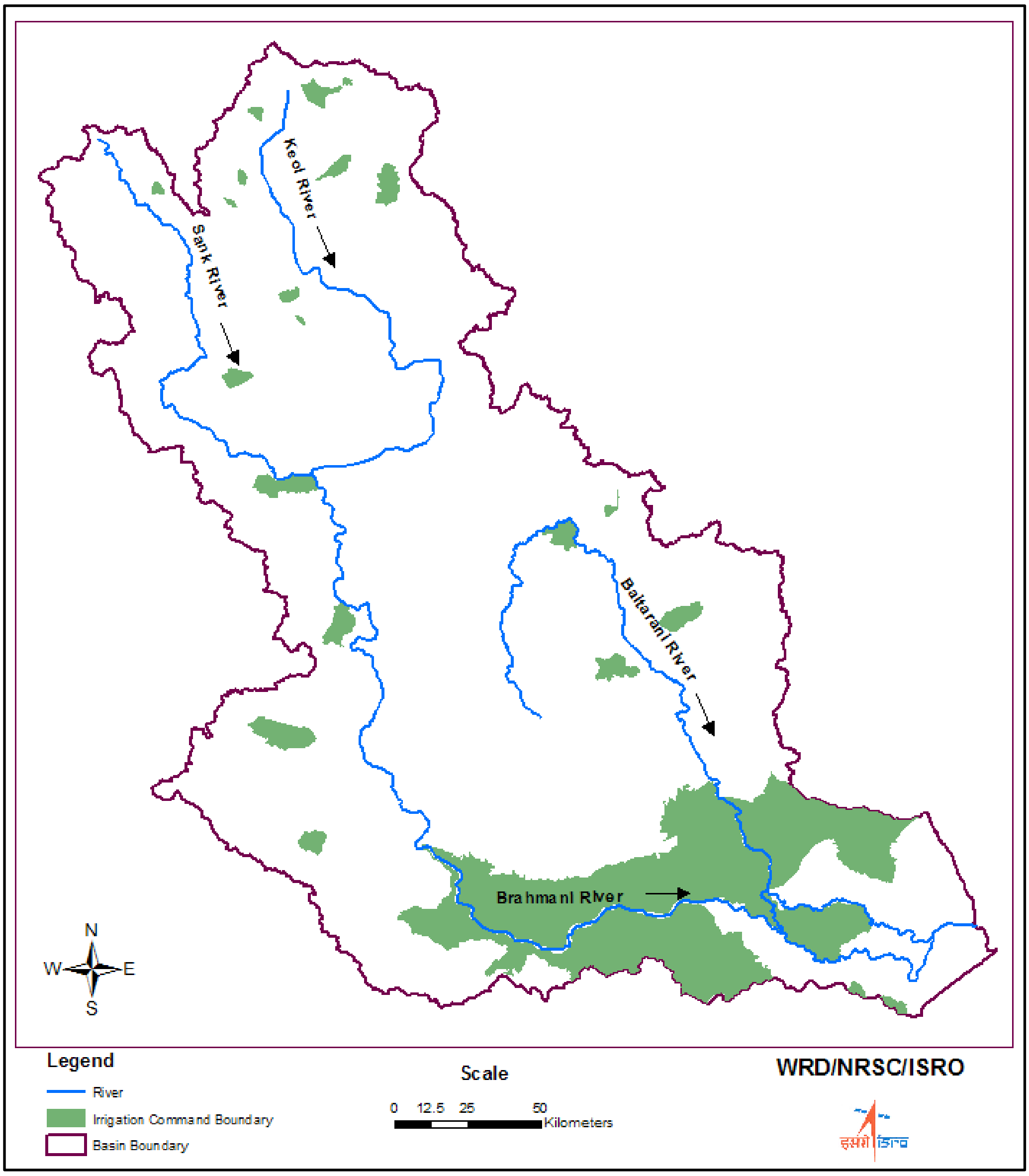


Fig.48 Irrigation Command Boundaries of Brahmani-Baitarani basin

9.7 Domestic and Industrial Demand

Fig.49 shows village boundaries layer of Brahmani-Baitarani basin. The population of each village (2001 census) is provided as an attribute in the layer. The domestic demand is estimated as described in the modelling frame work chapter. Industrial demand statistics were not available, it is assumed as 50% of the domestic demand for each year. The total domestic and Industrial consumption is taken as 15% of demand and remaining 85% is considered as return flows

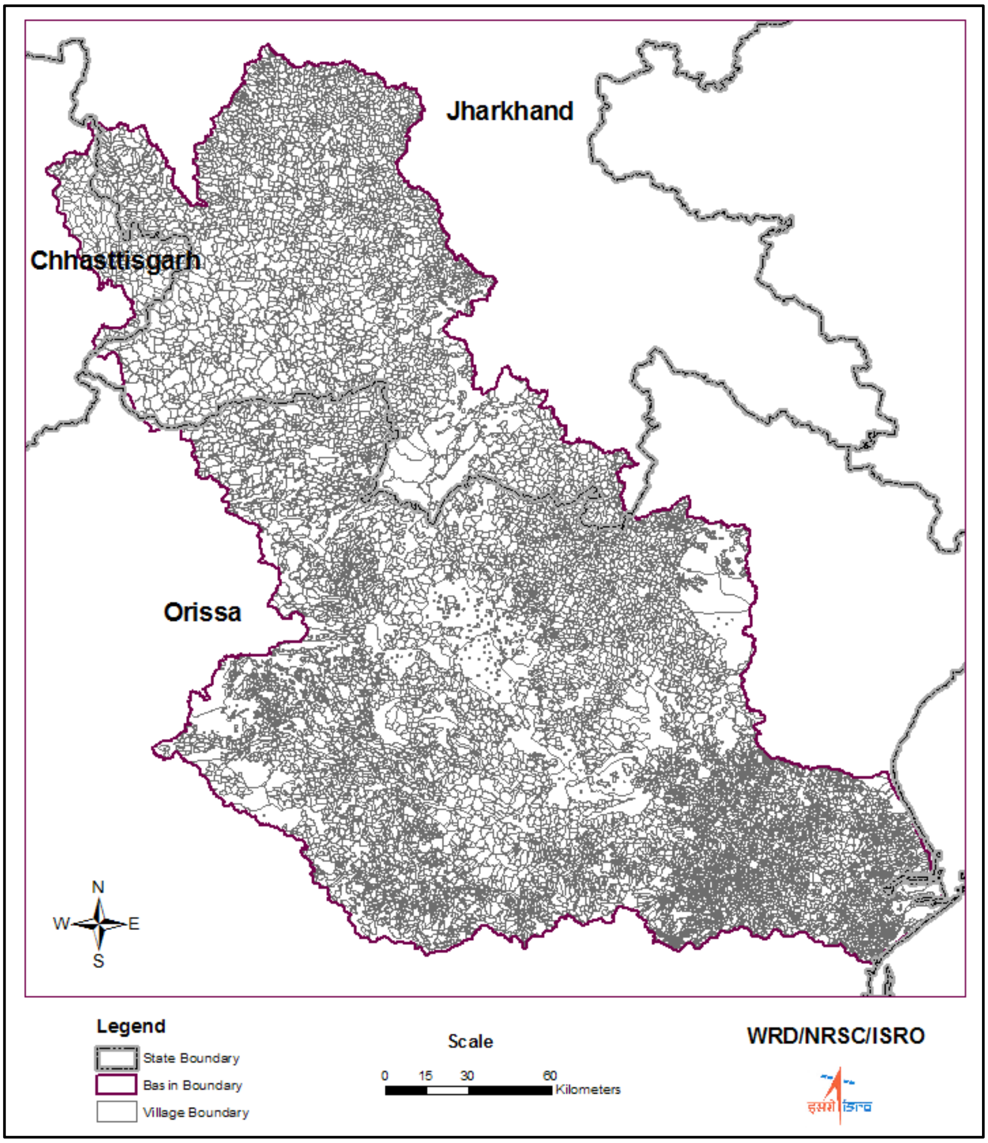


Fig.49 Village Boundaries of Brahmani-Baitarani basin

9.8 Evaporation from Major/Medium Reservoirs

Mandira and Rengali reservoirs on Brahmani river and Salandi reservoir on Salandi river are the main sources of evaporation losses from surface storage. The following Table 17 provides annual evaporation values from each of the reservoir for the period of 1988-89 to 2007-08 (20 years). The average annual evaporation volume for Mandira, Rengali and Salandi reservoirs is about 42 MCM, 530 MCM and 50 MCM respectively. The three reservoirs combined average total evaporation amounts to about 622 MCM annually. These evaporation quantities are derived from the maximum water spread area of the reservoir. Generally, the water spread area of the reservoir decreases from maximum at October / November to minimum at May. In order to account the variations in water spread and hence evaporative losses, 70% of estimated evaporation values are taken as the annual evaporation losses.

Year	Model Estimated Evaporation Volume from Reservoirs (MCM)			
	Mandira	Rengali	Salandi	Total
1988-1989	44.8	552.7	52.3	649.8
1989-1990	42.0	502.7	47.8	592.4
1990-1991	44.7	540.0	51.0	635.7
1991-1992	40.9	495.4	48.6	584.9
1992-1993	43.1	514.6	47.4	605.1
1993-1994	42.7	520.3	48.5	611.5
1994-1995	34.9	486.3	46.5	567.7
1995-1996	45.2	547.4	51.3	643.8
1996-1997	41.0	502.8	47.3	591.1
1997-1998	38.2	526.0	48.1	612.4
1998-1999	47.9	585.0	55.2	688.1
1999-2000	38.5	528.7	48.1	615.2
2000-2001	41.7	520.1	50.3	612.2
2001-2002	38.5	532.6	49.8	620.9
2002-2003	44.5	546.6	53.1	644.3
2003-2004	44.5	528.6	52.2	625.2
2004-2005	53.5	603.0	57.5	714.0
2005-2006	45.3	474.9	53.4	573.6
2006-2007	37.6	466.9	48.3	552.9
2007-2008	32.0	618.7	52.1	702.8

Table 17 Evaporation in the Reservoirs in BB Basin

9.9 Runoff Estimation

The runoff is estimated using the procedure as mentioned previously in Modelling Frame work chapter. The runoff that is estimated from each HRU is aggregated within each sub-basin. The estimated runoff for each sub-basin is calibrated with observed discharge. Calibrated runoff is estimated as as discussed earlier for each of the sub-basin.

While estimating ground water flux using ground water level fluctuation and specific yield method, the specific yield is taken as 3% for the entire basin. The ground water flux computed is negative indicates withdrawal of water from the current year ground water storage and if it is positive indicates increase in ground water recharge from the current year.

On Brahmani River Tilga, Jaraikela, Panposh, Gomlai and Jenapur discharge sites are located and the model estimated runoff is calibrated against the observed discharge at all the locations. Similarly, on Baitarani River, Champua and Anandpur discharge sites are located and the model estimated runoff is calibrated against the observed discharge at these 2 locations. For the combined Brahmani-Baitarani deltaic region observed discharge data is not available. Hence, for entire Brahmani-Baitarani basin, runoff is computed by adding model estimated runoff at Jenapur(entire upstream), Anandpur (entire upstream) and Delta region(exclusive) and computing calibrated runoff as mentioned above. The following Tables. 18 to 24 give calibrated discharge along with observed discharge during 20 years for the 7 discharge stations. The Figs.52 to 56 show comparative graphs of calibrated runoff and observed discharge at Tilga on Sank river, Jariakela on Keol River, Panposh, Gomali and Jenapur on Brahmani River and Champua & Anandpur on Baitarani River.

Tilga (Catchment Area = 3,060 sq.km.)						
S.No	Year	Observed Discharge (MCM)	Calibrated Runoff (MCM)	Rainfall (MCM)	% of Obs.Q/Rainfall	100*(Obs-Comp)/Obs
1	1988-1989	1,998	2,228	4,086	48.9	-11
2	1989-1990	1,240	1,259	3,604	34.4	-1
3	1990-1991	1,867	2,118	4,287	43.5	-13
4	1991-1992	2,150	2,613	4,570	47.1	-22
5	1992-1993	988	1,137	3,089	32.0	-15
6	1993-1994	1,881	2,152	4,270	44.1	-14
7	1994-1995	3,428	4,015	6,176	55.5	-17
8	1995-1996	1,831	2,202	4,400	41.6	-20
9	1996-1997	2,638	3,083	4,969	53.1	-17
10	1997-1998	2,789	3,275	5,816	48.0	-17
11	1998-1999	2,455	2,584	4,966	49.4	-5
12	1999-2000	2,776	2,724	4,759	58.3	2
13	2000-2001	1,195	1,531	3,340	35.8	-28
14	2001-2002	2,590	1,772	3,772	68.7	32
15	2002-2003	1,556	1,264	3,460	45.0	19
16	2003-2004	2,236	3,022	5,218	42.8	-35
17	2004-2005	1,684	991	2,524	66.7	41
18	2005-2006	1,768	1,780	4,133	42.8	-1
19	2006-2007	1,588	2,870	5,049	31.4	-81
20	2007-2008	1,864	1,651	3,830	48.7	11

Table 18 Calibrated runoff along with observed discharge at Tilga

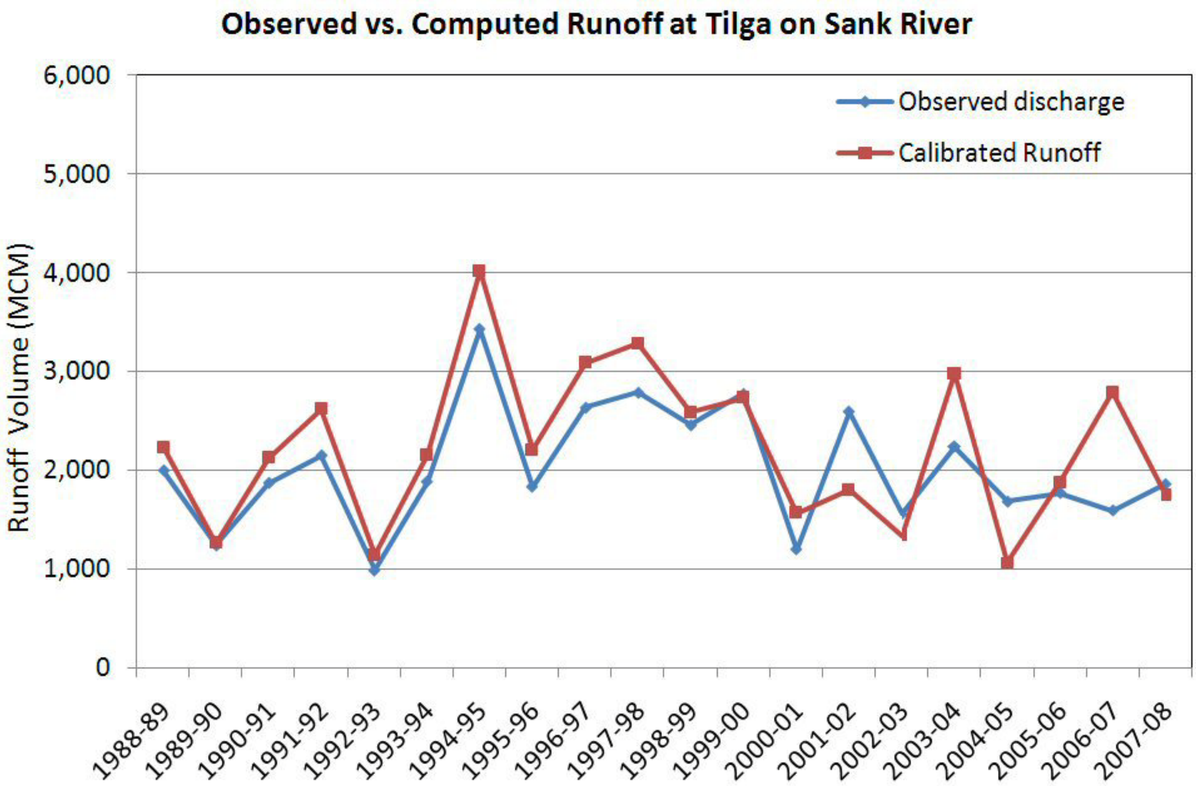


Fig.50 Calibrated runoff at Tilga on Sank River

Jaraikela (Catchment Area = 10,201 sq.km.)						
S.No	Year	Observed Discharge (MCM)	Calibrated Runoff (MCM)	Rainfall (MCM)	% of Obs.Q/Rainfall	100*(Obs-Comp)/Obs
1	1988-1989	4,925	5,505	11,954	41.2	-12
2	1989-1990	3,665	6,132	14,016	26.2	-67
3	1990-1991	5,748	6,433	14,080	40.8	-12
4	1991-1992	4,515	5,932	12,987	34.8	-31
5	1992-1993	1,903	3,232	9,949	19.1	-70
6	1993-1994	3,777	5,491	12,899	29.3	-45
7	1994-1995	7,992	11,979	19,158	41.7	-50
8	1995-1996	4,749	5,334	12,699	37.4	-12
9	1996-1997	6,867	5,516	11,588	59.3	20
10	1997-1998	7,692	9,259	17,587	43.7	-20
11	1998-1999	4,279	4,961	12,246	34.9	-16
12	1999-2000	6,228	8,300	15,992	38.9	-33
13	2000-2001	3,729	6,169	12,375	30.1	-65
14	2001-2002	5,397	5,921	12,161	44.4	-10
15	2002-2003	3,075	3,969	11,234	27.4	-29
16	2003-2004	4,239	5,447	13,191	32.1	-28
17	2004-2005	3,540	3,784	8,627	41.0	-7
18	2005-2006	2,592	3,953	11,303	22.9	-52
19	2006-2007	4,347	7,388	15,224	28.6	-70
20	2007-2008	5,801	7,806	15,029	38.6	-35

Table 19 Calibrated runoff along with observed discharge at Jaraikela

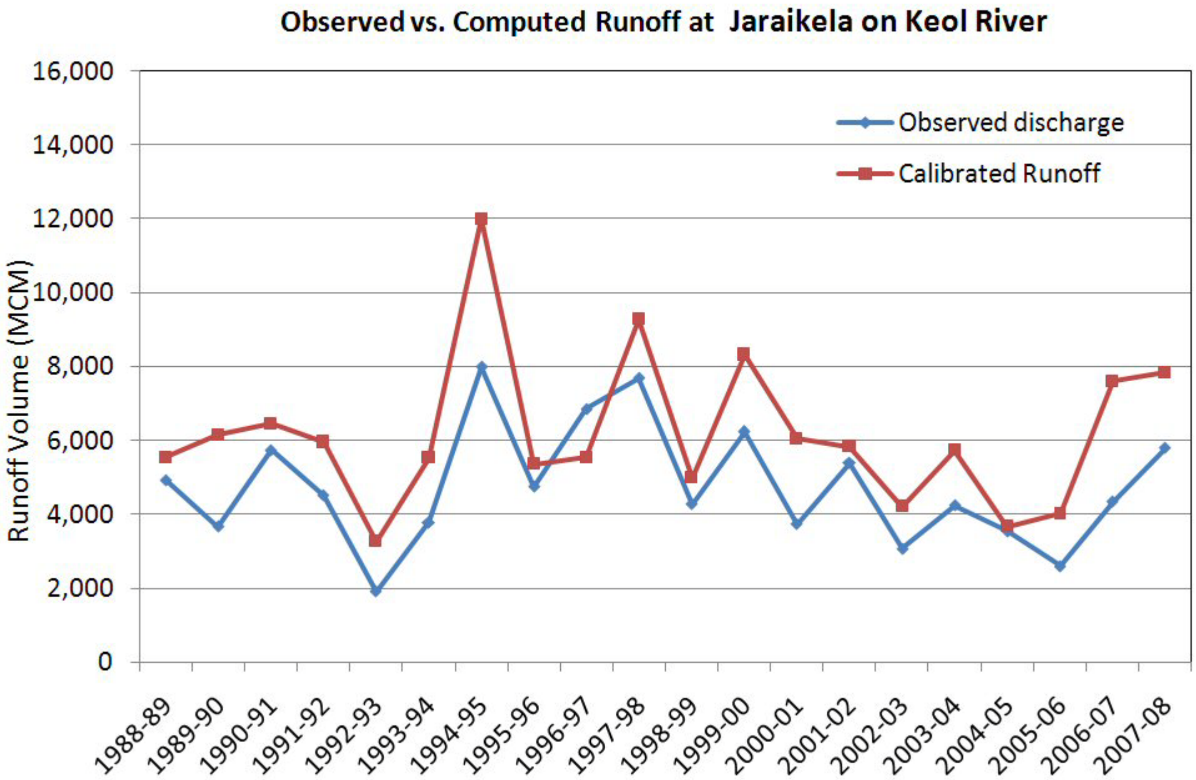


Fig.51 Calibrated runoff at Jaraikela on Keol River

Panposh (Catchment Area = 18,589 sq.km.)						
S.No	Year	Observed Discharge (MCM)	Calibrated Runoff (MCM)	Rainfall (MCM)	% of Obs.Q/Rainfall	100*(Obs-Comp)/Obs
1	1988-1989	-	13,738	25,401	-	-
2	1989-1990	-	11,394	25,812	-	-
3	1990-1991	-	13,709	27,434	-	-
4	1991-1992	-	13,252	25,927	-	-
5	1992-1993	-	7,804	19,882	-	-
6	1993-1994	-	12,621	25,849	-	-
7	1994-1995	-	25,635	38,838	-	-
8	1995-1996	-	10,407	23,713	-	-
9	1996-1997	12,968	12,630	23,721	54.7	3
10	1997-1998	14,251	17,166	32,339	44.1	-20
11	1998-1999	11,260	10,835	24,704	45.6	4
12	1999-2000	13,123	15,671	28,987	45.3	-19
13	2000-2001	6,700	9,654	20,817	32.2	-44
14	2001-2002	13,621	12,915	24,510	55.6	5
15	2002-2003	7,804	7,980	21,291	36.7	-2
16	2003-2004	9,519	11,396	25,438	37.4	-20
17	2004-2005	7,598	6,337	15,343	49.5	17
18	2005-2006	7,083	9,474	23,224	30.5	-34
19	2006-2007	9,879	14,964	28,985	34.1	-51
20	2007-2008	13,580	14,068	27,158	50.0	-4

Table 20 Calibrated runoff along with observed discharge at Panposh

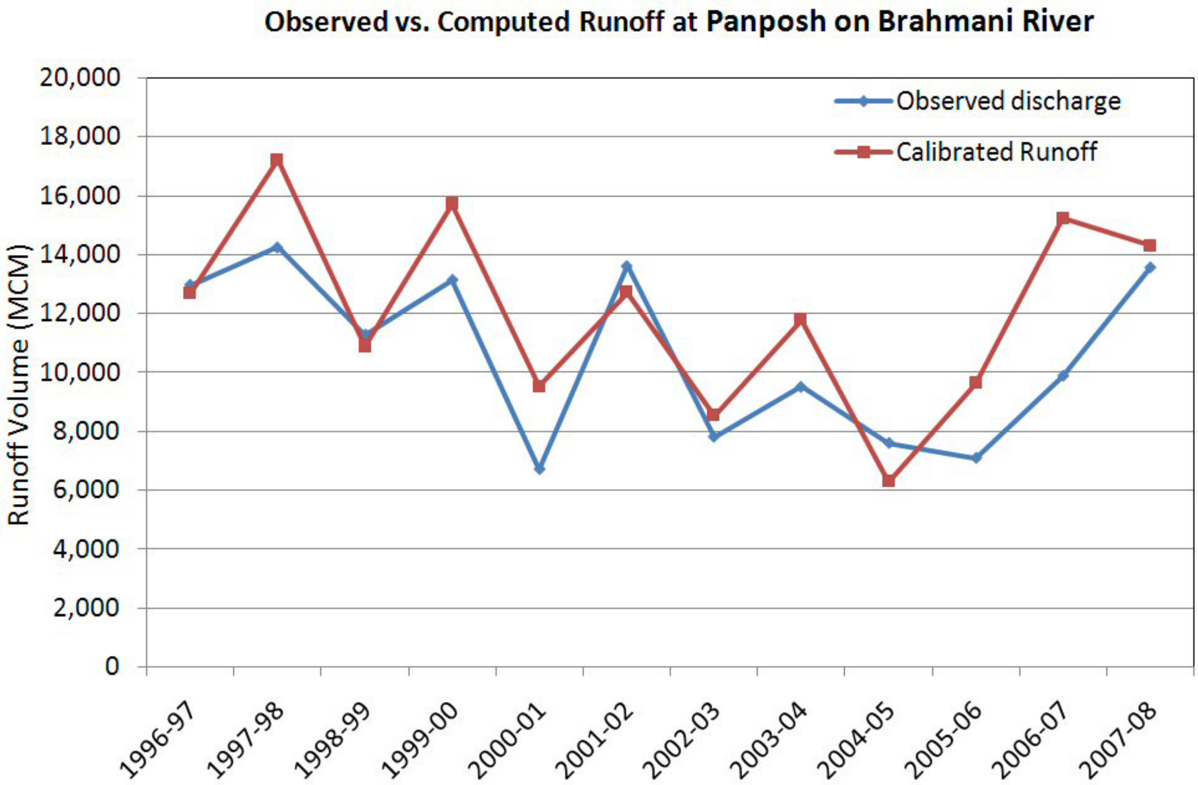


Fig.52 Calibrated runoff at Panposh on Brahmani River

Gomlai (Catchment Area = 20,819 sq.km.)						
S.No	Year	Observed Discharge (MCM)	Calibrated Runoff (MCM)	Rainfall (MCM)	% of Obs.Q/Rainfall	100*(Obs-Comp)/Obs
1	1988-1989	11,583	14,971	28,235	41.0	-29
2	1989-1990	8,879	12,724	29,078	30.5	-43
3	1990-1991	12,862	14,747	30,375	42.3	-15
4	1991-1992	12,051	14,510	28,809	41.8	-20
5	1992-1993	5,056	8,459	22,192	22.8	-67
6	1993-1994	9,088	13,840	28,930	31.4	-52
7	1994-1995	22,967	28,878	44,032	52.2	-26
8	1995-1996	10,170	11,571	26,699	38.1	-14
9	1996-1997	13,291	13,933	26,581	50.0	-5
10	1997-1998	14,502	18,508	35,986	40.3	-28
11	1998-1999	10,155	11,886	27,796	36.5	-17
12	1999-2000	14,735	17,498	32,659	45.1	-19
13	2000-2001	7,227	10,569	23,327	31.0	-46
14	2001-2002	16,006	15,486	28,688	55.8	3
15	2002-2003	7,735	8,588	23,723	32.6	-11
16	2003-2004	10,306	12,152	28,215	36.5	-18
17	2004-2005	8,169	7,149	17,423	46.9	12
18	2005-2006	6,821	10,791	26,576	25.7	-58
19	2006-2007	10,788	17,611	33,572	32.1	-63
20	2007-2008	16,113	15,930	30,932	52.1	1

Table 21 Calibrated runoff along with observed discharge at Gomlai

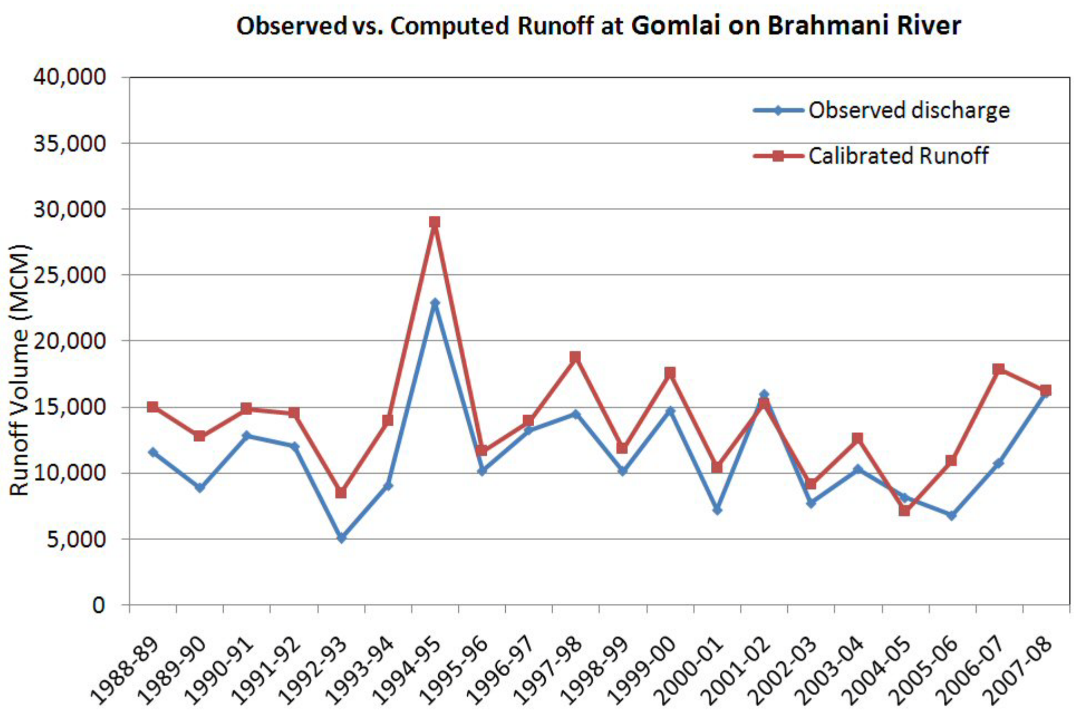


Fig.53 Calibrated runoff at Gomlai on Brahmani River

Jenapur (Catchment Area = 34,574 sq.km.)						
S.No	**Year**	**Observed Discharge** (MCM)	**Calibrated Runoff** (MCM)	**Rainfall** (MCM)	**% of Obs.Q/Rainfall**	**100*(Obs-Comp)/Obs**
1	1988-1989	17,178	22,313	46,779	36.7	-30
2	1989-1990	15,111	22,786	52,439	28.8	-51
3	1990-1991	19,798	24,963	53,518	37.0	-26
4	1991-1992	21,669	27,195	52,819	41.0	-26
5	1992-1993	11,136	15,969	41,482	26.8	-43
6	1993-1994	16,382	21,857	48,873	33.5	-33
7	1994-1995	30,991	43,509	71,104	43.6	-40
8	1995-1996	15,709	18,797	46,159	34.0	-20
9	1996-1997	16,685	19,000	43,650	38.2	-14
10	1997-1998	20,606	27,069	58,361	35.3	-31
11	1998-1999	15,226	17,566	46,849	32.5	-15
12	1999-2000	22,755	28,934	56,832	40.0	-27
13	2000-2001	10,608	13,994	38,101	27.8	-32
14	2001-2002	28,461	30,447	55,629	51.2	-7
15	2002-2003	10,785	11,337	39,074	27.6	-5
16	2003-2004	21,413	22,550	51,299	41.7	-5
17	2004-2005	12,544	9,883	28,848	43.5	21
18	2005-2006	16,546	19,520	48,688	34.0	-18
19	2006-2007	14,810	29,120	57,252	25.9	-97
20	2007-2008	22,536	26,766	52,881	42.6	-19

Table 22 Calibrated runoff along with observed discharge at Jenapur

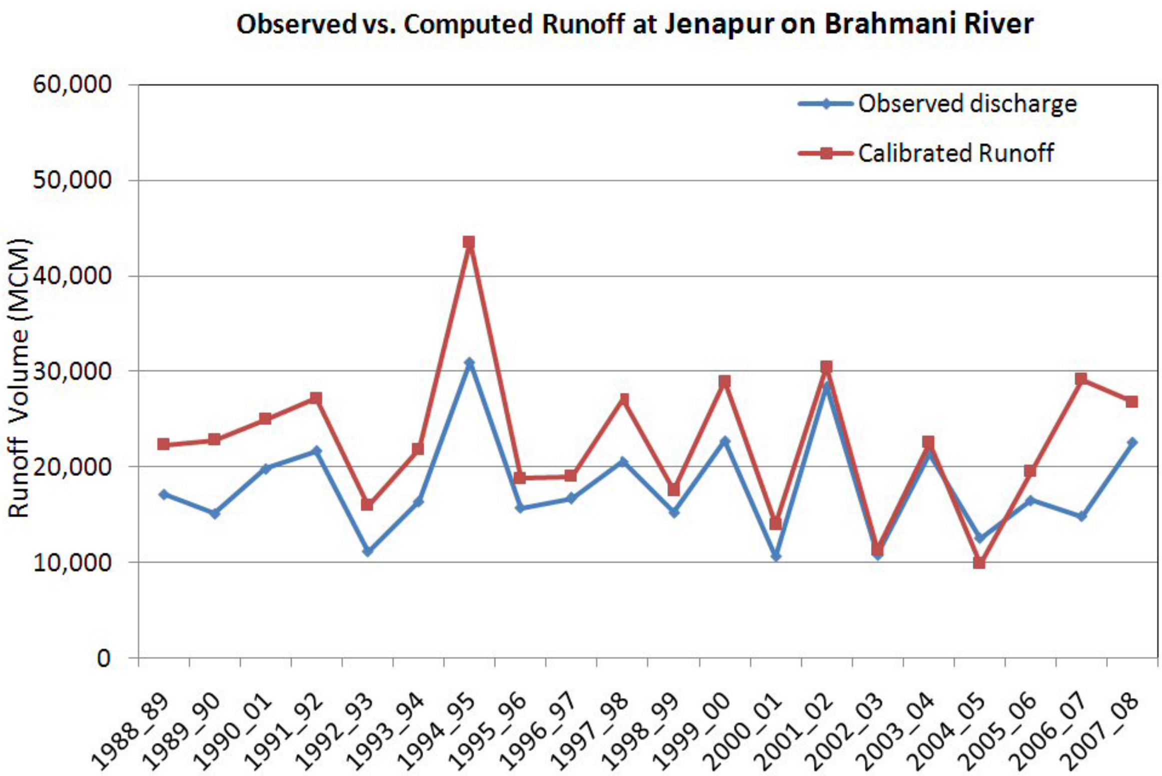


Fig.54 Calibrated runoff at Jenapur on Brahmani River

Champua (Catchment Area = 1,735 sq.km.)						
S.No	Year	**Observed Discharge** (MCM)	**Calibrated Runoff** (MCM)	**Rainfall** (MCM)	**% of Obs.Q/Rainfall**	**100*(Obs-Comp)/Obs**
1	1988-1989	-	741	2,149	-	-
2	1989-1990	-	1,288	2,680	-	-
3	1990-1991	1,191	1,204	2,621	45.5	-1
4	1991-1992	1,116	1,050	2,331	47.9	6
5	1992-1993	420	686	2,020	20.8	-63
6	1993-1994	976	883	2,208	44.2	9
7	1994-1995	1,672	1,752	3,093	54.1	-5
8	1995-1996	886	1,085	2,444	36.3	-22
9	1996-1997	1,004	1,313	2,622	38.3	-31
10	1997-1998	1,170	1,379	3,063	38.2	-18
11	1998-1999	772	971	2,426	31.8	-26
12	1999-2000	1,951	1,626	3,065	63.7	17
13	2000-2001	770	1,437	2,694	28.6	-87
14	2001-2002	1,302	1,394	2,619	49.7	-7
15	2002-2003	478	641	1,948	24.5	-34
16	2003-2004	930	786	2,197	42.3	15
17	2004-2005	891	540	1,519	58.7	39
18	2005-2006	1,144	1,277	2,614	43.8	-12
19	2006-2007	1,179	1,678	2,966	39.7	-42
20	2007-2008	1,730	1,648	2,994	57.8	5

Table 23 Calibrated runoff along with observed discharge at Champua

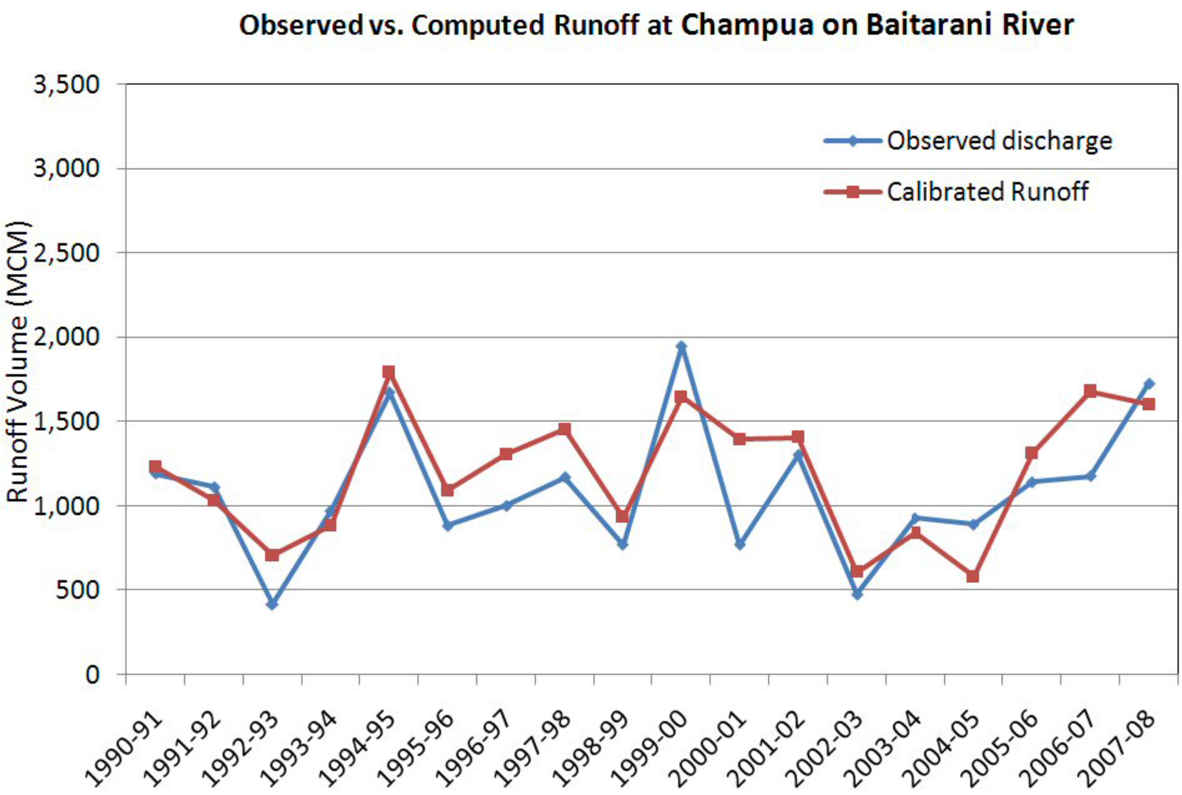


Fig.55 Calibrated runoff at Champua on Baitarani River

Anandpur (Catchment Area = 8,307 sq.km.)						
S.No	**Year**	**Observed Discharge** (MCM)	**Calibrated Runoff** (MCM)	**Rainfall** (MCM)	**% of Obs.Q/Rainfall**	**100*(Obs-Comp)/Obs**
1	1988-1989	4,263	4,397	11,056	38.6	-3
2	1989-1990	6,091	6,035	13,916	43.8	1
3	1990-1991	6,521	6,330	13,885	47.0	3
4	1991-1992	6,002	6,323	13,199	45.5	-5
5	1992-1993	2,732	3,557	10,704	25.5	-30
6	1993-1994	4,593	4,761	12,005	38.3	-4
7	1994-1995	7,920	8,295	15,332	51.7	-5
8	1995-1996	5,253	4,707	11,898	44.2	10
9	1996-1997	4,683	4,310	11,474	40.8	8
10	1997-1998	6,342	7,029	15,351	41.3	-11
11	1998-1999	2,942	3,178	10,542	27.9	-8
12	1999-2000	9,599	6,707	14,413	66.6	30
13	2000-2001	3,500	4,530	11,143	31.4	-29
14	2001-2002	4,885	6,692	13,355	36.6	-37
15	2002-2003	1,923	2,392	9,293	20.7	-24
16	2003-2004	4,693	4,474	12,169	38.6	5
17	2004-2005	3,446	1,757	6,927	49.8	49
18	2005-2006	5,288	5,452	13,012	40.6	-3
19	2006-2007	5,474	7,911	14,600	37.5	-45
20	2007-2008	8,601	8,515	15,592	55.2	1

Table 24 Calibrated runoff along with observed discharge at Anandpur

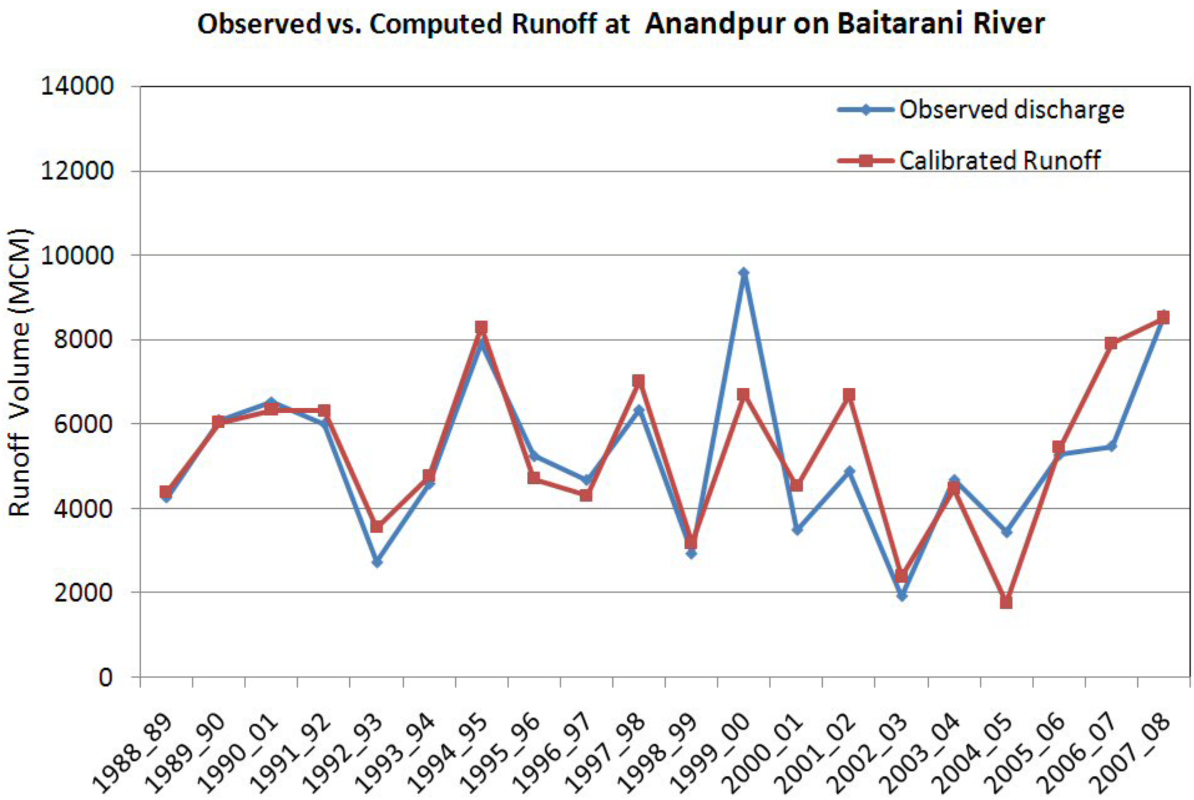


Fig.56 Calibrated runoff at Anandpur on Baitarani River

Table 25 gives calibrated runoff of Brahmani-Baitarani basin for 20 years. The average calibrated runoff is about 33,469 MCM annually. The maximum annual calibrated runoff is 60,429 MCM during 1994-95 which is wettest year in the 20 years. The minimum annual calibrated runoff is 12,003 MCM during 2004-05 which is the driest year in the 20 years. The average irrigation supplies is about 1,146 MCM annually. The maximum annual irrigation supplies is about 2,591 MCM during 2004-05 which is driest year in the 20 years. The minimum annual irrigation supplies is about 610 MCM.

S.No	Year	Model Runoff (MCM)	Reservoir Flux (MCM)	Ground water Flux (MCM)	Domestic & Industrial consumption (MCM)	Calibrated Runoff (MCM)
1	1988-1989	30,804	35	-1039	46	31,762
2	1989-1990	35,032	297	959	47	33,729
3	1990-1991	36,923	-84	74	48	36,885
4	1991-1992	39,714	-223	-610	49	40,498
5	1992-1993	24,288	-107	297	50	24,048
6	1993-1994	33,565	-24	58	50	33,481
7	1994-1995	60,913	245	188	51	60,429
8	1995-1996	28,401	187	463	52	27,699
9	1996-1997	26,102	98	-298	53	26,249
10	1997-1998	41,528	308	402	53	40,765
11	1998-1999	23,677	-550	-536	54	24,709
12	1999-2000	44,458	14	297	55	44,092
13	2000-2001	19,525	-56	-594	56	20,119
14	2001-2002	44,074	179	-365	57	44,203
15	2002-2003	16,209	196	364	58	15,591
16	2003-2004	34,926	72	402	58	34,394
17	2004-2005	11,330	-412	-320	59	12,003
18	2005-2006	33,046	118	563	60	32,305
19	2006-2007	46,511	585	91	61	45,774
20	2007-2008	39,915	-659	-120	62	40,632

Table 25 Water balance components of Brahmani-Baitarani basin

9.10 Water Resources Assessment of the Basin

Water resources of the basin comprises of flow in the river at final outlet, upstream effective utilisations for irrigation, domestic and Industrial, change in storage of groundwater, change in storage of reservoirs and evaporation from reservoirs.

9.10.1 Annual Water Resources Availability of the Basin

Table 26 shows the different components that are required to estimate the basin level water resources of Brahmani-Baitarani for 20 years. The maximum annual water resources is 62,417 MCM during 1994-95 which is wettest year in the 20 years. The minimum annual water resources is 14,421 MCM during 2004-05 which is the driest year in the 20 years. The wettest and driest years are identified based on the amount of annual rainfall volume within the 20 years. The average annual available basin water resources is 35,129 MCM. The average available water resources of Brahmani-Baitarani basin accounts about 47% of mean annual rainfall.

Year	Rainfall (MCM)	Calibrated Runoff (MCM)	Irrigation Supplies (MCM)	Domestic & Industrial Consumption (MCM)	Reservoir Evaporati on Losses (MCM)	Change in Reservoir Storage (MCM)	Change in Ground water Storage (MCM)	Basin level Water Resources (MCM)	Water Resources % out of Rainfall
1988-89	70,218	31,762	1,218	46	455	35	-1,039	32,477	46
1989-90	79,260	33,729	1,202	47	415	297	959	36,649	46
1990-01	80,656	36,885	842	48	445	-84	74	38,210	47
1991-92	80,198	40,498	610	49	409	-223	-610	40,733	51
1992-93	63,897	24,048	717	50	424	-107	297	25,429	40
1993-94	75,360	33,481	937	50	428	-24	58	34,930	46
1994-95	1,01,932	60,429	1,107	51	397	245	188	62,417	61
1995-96	70,034	27,699	811	52	451	187	463	29,663	42
1996-97	64,910	26,249	1,785	53	414	98	-298	28,301	44
1997-98	88,128	40,765	1,018	53	429	308	402	42,975	49
1998-99	69,101	24,709	1,259	54	482	-550	-536	25,418	37
1999-00	87,433	44,092	922	55	431	14	297	45,811	52
2000-01	57,755	20,119	1,740	56	429	-56	-594	21,694	38
2001-02	83,555	44,203	809	57	435	179	-365	45,318	54
2002-03	57,352	15,591	1,668	58	451	196	364	18,328	32
2003-04	79,086	34,394	626	58	438	72	402	35,990	46
2004-05	42,599	12,003	2,591	59	500	-412	-320	14,421	34
2005-06	76,713	32,305	1,043	60	401	118	563	34,490	45
2006-07	87,765	45,774	798	61	387	585	91	47,696	54
2007-08	81,892	40,632	1,220	62	492	-659	-120	41,627	51

Table 26 Water Resources Availability in the Brahmani & Baitarani Basins

9.10.2 Annual Water Resources of the Basin during Extreme Rainfall Conditions

Year	Rainfall (MCM)	Calibrated Runoff (MCM)	Irrigation Supplies (MCM)	Domestic & Industrial Consumption (MCM)	Reservoir Evaporation Losses (MCM)	Change in Reservoir Storage (MCM)	Change in Ground water Storage (MCM)	Basin level Water Resource (MCM)	Water Resources % out of Rainfall
1994-95	1,01,932	60,429	1,107	51	397	245	188	62,417	61
2004-05	42,599	12,003	2,591	59	500	-412	-320	14,421	34

Table 27 Water Resources Availability in the Brahmani & Baitarani Basins During Extreme Rainfall Conditions

Out of the total 37 years of meteorological data base available, during the years 1994_95 and 2004_05, extreme wet and dry rainfall conditions occurred in Brahmani-Baitarani river basins. The annual water resources of Brahmani-Baitarani basin during these two extreme rainfall conditions are 62,417 MCM and 14,421 MCM, respectively. The water balance components during these are presented in the Figures 57 and 58.

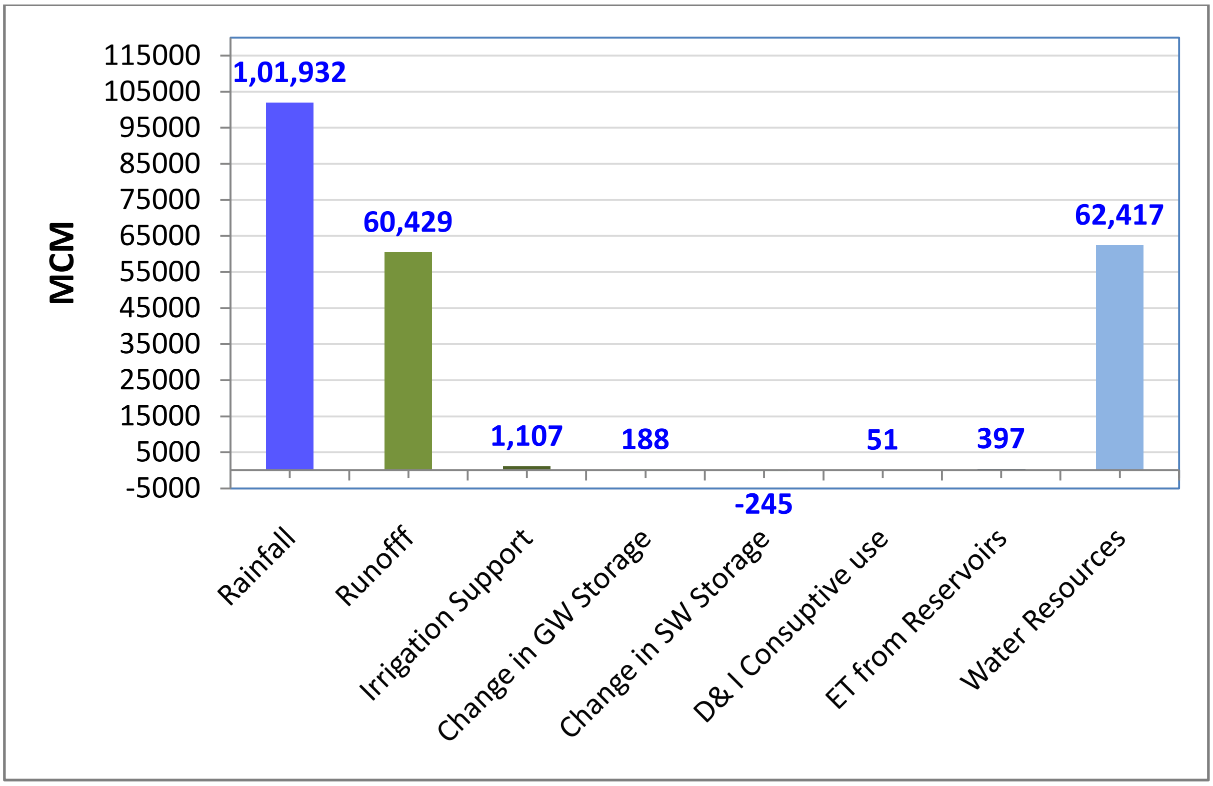


Fig.57 Water Balance components of Brahmani-Baitarani basin during extreme high rainfall (1994-95) year

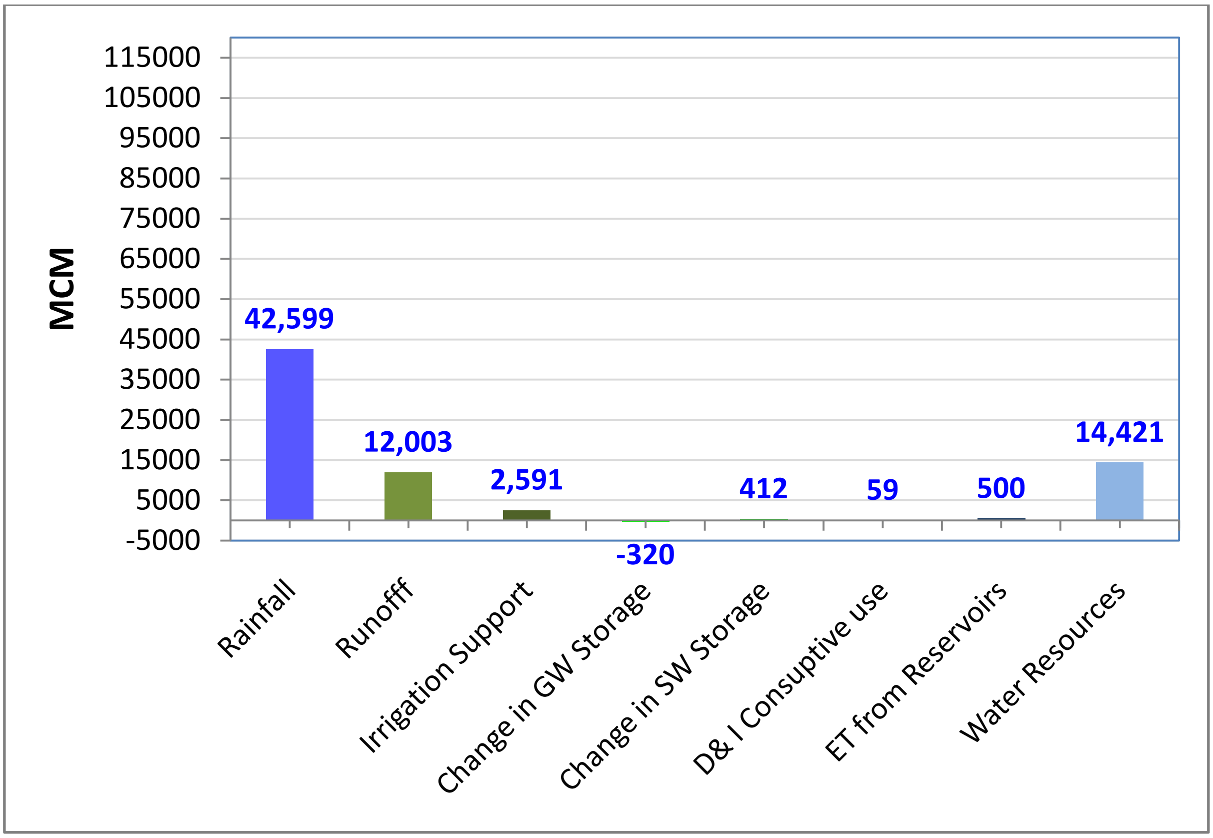


Fig. 58 Water Balance components of Brahmani-Baitarani basin during extreme low rainfall (2004-05) year

9.10.3 Mean Water Resources of the Basin

The mean water resources of the basin is computed by taking mean of the 20 years water balance components such as flow in the river at final outlet, upstream effective utilisations for irrigation, domestic and Industrial, change in storage of groundwater, change in storage of reservoirs and evaporation from reservoirs.

Mean water resources = Mean of (Calibrated Runoff + Irrigation supplies + D&I consumption + Change in groundwater storage + change in storage of reservoirs + Evaporation)

= 33,469+1,146+53+14+11+436 = 35,129 MCM

The mean available annual water resources of the Brahmani-Baitarani basin is 35,129 MCM. Fig.59 shows the various water balance components averaged over a period of 20 years during 1988-89 to 2007-08. The previous CWC (1993)estimate of available water resources of the basin is 28,477 MCM.

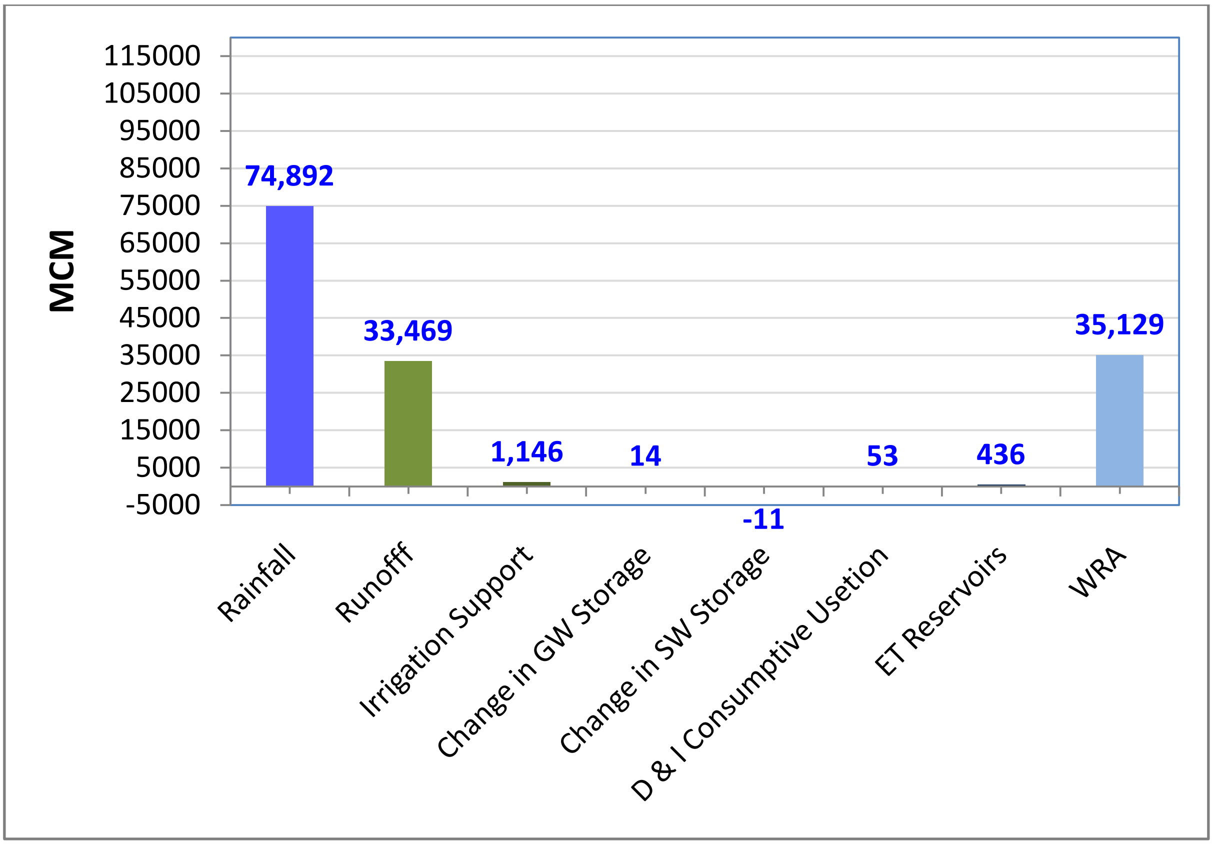


Fig.59 Water Balance components of Brahmani-Baitarani basin (mean of 20 years)

The following points need to be considered while comparing the present estimate with previous estimate of CWC:

- The mean annual rainfall during 1988-2008 is 6.6% more than the mean annual rainfall during the period 1971-85 which was considered for 1993 estimate.
- In 1993 estimate, the river discharge data was available only at Jenapur on Brahmani river and at Birdi on Baitarani river. Discharge data at the outlet of the composite basin was not available. Hence, area proportionate approach was adopted to estimate composite delta water resources. While using this approach, the composite delta area was estimated as 3,595* sq.km as against the delta area estimated from present study is 7,887 sq.km (which is based on geo-spatial data sets). As a result of this, the water resources estimate of composite delta was 2,050 MCM during 1993 as against present estimate of 4,780 MCM.
- In 1949, using Khosla's empirical formula basin-wise water resources assessment of the Brahmani-Baitarani basin was estimated as 39,225 MCM.
- In 1960, the Central Water and Power Commission, while conducting irrigation potential studies, assessed the total annual runoff of the basin as 28,691 MCM on the basis of Strange's rainfall-runoff coefficients.

- In 1988, CWC reported 36,227 MCM as average water resources of the Brahmani-Baitarani basin using Khosla's formula.
- 1993 CWC estimate considered only irrigation supplies for assessing basin level water resources while not making any mention of ground water irrigation, as it has been done in other river basin studies.

* *As per 1993 estimate, the total Brahmani-Baitarani basin area was 50,015 sq.km which is the sum of Brahmani basin area (39,023 sq.km) and Baitarani basin area (10,982 sq. km). The sum of independent basin areas of Brahmani up to Jenapur (36,300 sq.km) and for Baitarani up to Bridi (10,120 sq.km) was 46,420 sq.km. The difference between 50,015 sq.km and 46,420 sq.km is 3,595 sq.km which is the composite delta area.*

10.0 Limitations of the Study

The assumptions and limitations of the study in Godavari, Brahmani-Baitarani Basins are;

- The model is setup at annual time-step, monthly calibrations are not carried out.
- Kharif crop outside of the command area boundary is assumed as rain-fed and rest is assumed as irrigated agriculture.
- In irrigated agriculture land AET is calculated by assuming 100% water requirements are met from the rainfall and irrigation supplies together (AET=PET condition).
- landuse/landcover maps of the period 2004-05, 2005-06, 2006-07, 2007-08 are used for runoff calculations in the study. For runoff computations prior to 2004-05, landuse map of 2004-05 is used during the year in which rainfall is less than 1000mm, and landuse map of 2006-07 is used when the annual rainfall is more than 1000mm. Landuse maps of 1995 and 1985 were also obtained (source: IGBP project: ISRO) and analysed. In these landuse grids, agricultural area has been classified as a single unit and number of classes also less than the recent landuse grids hence these landuse maps are not used in runoff computation.
- Considering the availability of meteorological data in spatial environment, Thornthwaite method with suitable landuse coefficients is considered for PET calculations
- As the specific yield map of the Brahmani-Baitarani is not available, uniform yield is assumed in groundwater flux computations.
- The water utilization due to irrigation has been indirectly estimated through the help of Thornwaite & Mather method and other available literature in absence of the withdrawal data uniformly throughout the basin.

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ANNEXURE

Study on impact of cropping patterns information on sub-basin level water resources assessment

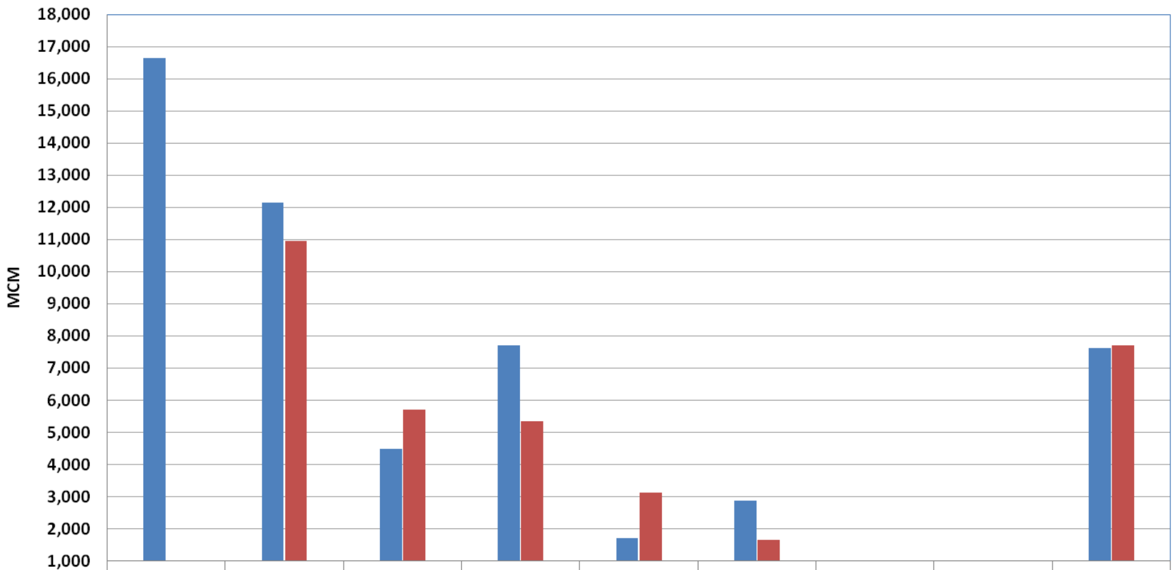
Manair sub-basin under Godavari basin was chosen for studying the influence of multiple crop type information on sub-basin scale water balance components and water resources estimates. The study was carried out for the year 2007-08.

In the first approach, water balance computations were carried out using NRC LULC data wherein agricultural classess are presented as season specfic classes, namely, kharif only, rabi only, zaid only and double/triple crops. In the second approach, water balance computations were carried out using detailed agricultural classes along with other classes of NRC LULC.

The total PET was lower by 7.7% when detailed agricultural crop classes were adopted when compared with NRC LULC based approach and similarly AET was lower by 9.9%. The differences in PET and AET resulted in changes water balance components. The runoff estimate using detailed agricultural classes was 5,707 MCM, while it was 4,497 MCM when NRC LULC was used, indicating 1,210 MCM (at 26.9%) increase in runoff when detailed agricultural classes were considered. However, the Basin level Water Resources (BWR) did not show significant deviation between the two approaches with a difference of 1.1%.

Table Comparison of Water Balance components of two approaches in Manair sub-basin

Water Balance Components	NRC LULC (MCM)	LULC with Detailed Agriculture classes (MCM)	% of variation of WBC
Rain Fall	16,656		
PET	14,001	12,924	7.7
Total AET	12,159	10,949	10.0
Irrigation Support	2,878	1,642	43.0
Crop AET	8029	7018	12.6
Runoff	4,497	5,707	-26.9
D&I Consumption	21	21	0.0
ET Reservoirs	216	216	0.0
BWR	7,626	7,703	-1.0



	Rain Fall	Total AET	Runoff	AET Irrigated	AET Rainfed	Irrigation Suport	D&I Consumption	ET Reservoirs	BWR
LuLc	16,656	12,159	4,497	7705	1720	2,878	21	216	7,626
LuLc_ Agri		10,949	5,707	5333	3121	1,642	21	216	7,703

Figure Comparison of Water Balance components of two approaches