Transforming to hydrological modelling approach for long-term water resources assessment under climate change scenario – a case study of the Godavari Basin, India

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This communication discusses quantifying basin-scale water wealth by transformation from the presently adapted basin terminal gauge site run-off aggregation to distributed hydrological modelling approach. In this study, an attempt was made to propose modifications to simple monthly water balance model using time-series land-use grids derived from the temporal remote sensing satellite data to compute run-off at basin scale. This approach will help in studying run-off and water resources availability with limited meteorological parameters. The study was aimed at computing mean annual water resources in the Godavari Basin, India during the last 18 years (1990–91 to 2007–08) using the proposed approach and to compute availability of water resources during extreme wet and dry rainfall conditions in the basin. The land-use grids were integrated with soil textural, digital elevation and command area grids to compute hydrological response unit grids. Groundwater, reservoir flux, domestic and livestock water consumption and industrial water consumptive use were computed using the spatial data and integrated in the model environment to compute run-off. The model was calibrated and validated using observed discharge data at various prominent gauge stations in the basin. Long-term water resources availability in the basin was computed using the developed methodology.

Keywords: Climate change, hydrological modelling, remote sensing, water resources availability.

PROPER assessment of water resources availability in a basin is the cornerstone for strategic planning, development and management. Availability of water resources greatly varies spatially and temporally, but the demand for water is ever increasing with population growth. Potential impact of climate change on water resources is greatly affecting the water resources in the basin. Hence, there is need for scientific assessment of water resources for optimum planning and management to cater to the future demands.

Among the first estimates, the Irrigation Commission (1901–03) estimated the average annual flow of all river systems of undivided India (excluding Assam, Burma and East Bengal) as 1443 cubic kilometers[1]. In these studies, run-off coefficients were used in the absence of field discharge data in estimating river flows. Rao[2] had initially made some rough estimates of India's water resources in 1973, based on the available field data. The National Commission on Agriculture (1976) estimated the total average annual water resource of the country at 1850 km^3. This was done based on water balance approach by taking rainfall, infiltration and evapotranspiration into account. Central Water Commission (CWC) has estimated the total water resources of the country in 1993 at 1870 km^3 (ref. 3).

Most recent and authentic estimates in the Godavari Basin were done by CWC for the period 1967–68 to 1984–85. Natural (virgin) flow in the river basin was reckoned as water resource of a basin. The mean flow of a basin was computed by averaging annual flow at the terminal site using a long time data. The natural flow in the basin was estimated by summing up the observed flow, upstream utilization for irrigation, domestic and industrial uses, change in reservoirs storage, evaporation losses in reservoirs and deducting return flows from different uses from surface and groundwater sources[1].

The major limitation of the previous water resources assessment studies is that these were done based on field discharge observations and with some rough estimation on the utilization part. Rainfall and other meteorological parameters were not considered in these estimations. Simple lumped approach was used in these studies, which does not represent any spatial variations. Absence of cross-check mechanism was also a drawback of those studies. Over a period of time, these estimates has to be updated due to several reasons such as change in land-use and land-cover, water utilization and global climatic change, etc.[4].

Thus, assessment of water resources in a scientific way is an important aspect in water resources development and management. The water balance is useful for predicting some of the human impacts on the hydrologic cycle. Remote satellite data may be used extensively in studying the land-use dynamics and its effect on hydrology. Keeping these in view, a joint research project has been executed by National Remote Sensing Centre (NRSC) and CWC for re-assessment of water resources in the Godavari Basin. The main objectives of the study are to compute water resources in the basin during the last 18 years (1990–91 to 2007–08), mean annual water resources and the availability of water resources under extreme wet and dry rainfall conditions through distributed hydrological modelling approach using space inputs.

Godavari Basin extends over an area of 312,800 km^2, covering nearly 9.5% of the total geographical area of India. The Godavari River is perennial and also the second largest river in India and joins the Bay of Bengal after flowing through a distance of 1470 km (ref. 1). It flows through the Eastern Ghats and emerges into the plains

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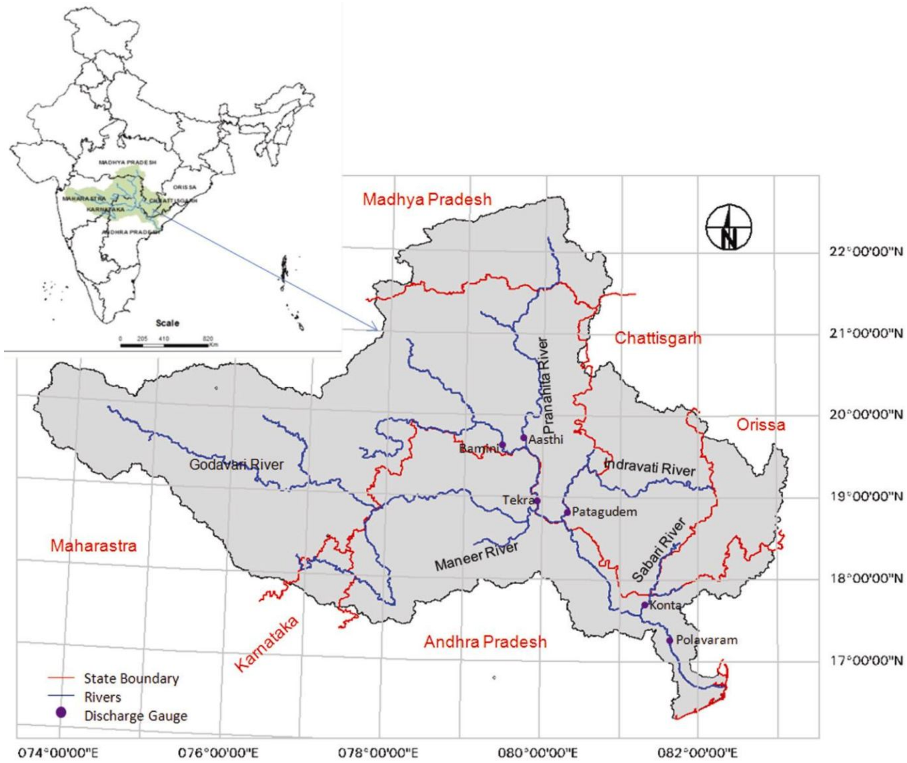

Figure 1. Geographic setting of the Godavari Basin.

after passing through Polavaram. Pranahita, Sabari and Indravati are the main tributaries of the Godavari River. The basin receives the major part of its rainfall during the southwest monsoon period. More than 85% of the rainfall takes place from July to September. Annual rainfall of the basin varies from 880 to 1395 mm and the average annual rainfall is 1110 mm. Geographic setting and prominent discharge measuring stations of the basin are shown in the Figure 1.

Digital Elevation Model (DEM) is one of the main inputs for hydrological modelling studies. CARTO DEM of 30 m resolution was used to delineate the watershed and sub-watershed boundaries of the Godavari Basin. The most common method used for watershed delineation is called eight direction pour point model. Using this model, flow direction for each cell was 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 accumulation towards the outlet of the watershed was calculated. The complete basin was divided into 23 sub-basins based on the drainage pattern and corrected with the satellite data. These sub-basins are used in aggregating the final results at the identified gauge sites.

In a hydrological cycle, infiltration is another major component after evapotranspiration. Infiltration at a given time depends upon the soil texture and the existing soil moisture. Soil maps (1 : 250,000 scale) of the National Bureau of Soil Survey and Land Use Planning (NBSS& LUP), India were used in the study. These soil maps were reclassified into soil textural grids and used in computing-monthly soil moisture availability.

The rainfall–run-off 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. Rate of evapotranspiration mainly depends upon the land-use/land-cover pattern. Land-use/land-cover maps (1 : 250,000 scale) of the years 2004–05, 2005–06, 2006–07 and 2007–08 prepared using AWiFS sensor data of IRS-P6 satellite (source, Natural Resources Census project, Indian Space Research Organisation) and land-use maps of 1985 and 1995 (source: ISRO Geosphere–Biosphere Programme) were used for computing land-use coefficients and subsequently for run-off calculations in the study.

Estimation of actual evapotranspiration (AET) varies from irrigated area to rainfed areas. It was assumed that the irrigation supplies are provided for all the agricultural areas within the command boundaries. Kharif crop outside of the command area was considered as rainfed crop and the rest was assumed as irrigated with full irrigation water requirements being met. Command area map of the basin was obtained and used in the evapotranspiration and run-off computations after integrating with land-use map.

Daily rainfall grids at 0.5° and temperature grids at 1° resolution of the mentioned period 18 years were obtained from the India Meteorological Department (IMD)[5] and used in the model for run-off computations after converting them into monthly grids in Geographic Information System (GIS) domain. Data from more than 250 meteorological stations from the Godavari Basin area were used by IMD in preparing the rainfall and temperature grids. Monthly observed river discharge data for 18 years of various gauge stations spread across the basin were collected from CWC and used in the model calibration and validation.

Groundwater-level data of nearly 1000 wells spread across the basin and the specific yield map were collected from the Central Ground Water Board (CGWB), India. Annual groundwater flux (recharge or withdrawal) for each observation was arrived at using arithmetical difference between June/May observations of the two consecutive years. A point map was created and spatial interpolation was done in GIS environment to create groundwater flux grids. Annual groundwater recharge or withdrawal in each year was computed by integrating groundwater flux grids with specific yield grid. This groundwater flux was attributed to the net effect of recharge and irrigation withdrawal in the basin.

CWC monitors 11 major and medium reservoirs in Godavari Basin; monthly reservoir-level data of all the 18 years were collected from CWC. The reservoir level and corresponding volume data for the water year (June to May) were used in estimating the carryover of reservoir storage from one year to another during the study period of 18 years. This reservoir flux was attributed to the net effect of evaporation from the reservoirs, inflow and irrigation withdrawal in the basin.

Census data of 1991, 2001 and 2011 (www.Census-india.gov.in) were used for estimating domestic and industrial water use. Survey of India village administrative information was integrated with population attribute data to prepare spatial population maps for each year by interpolating the above census data. For domestic requirement, it was assumed as 70 litre 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 were not available. Domestic consumptive use was considered as 15% of the demand[3]. Hence, the industrial demand has been assumed as equivalent to the domestic demand in each year. Industrial consumptive use is considered as 50% of its demand[3].

The livestock demand for water was also considered in estimating the total water requirements for this sector. According to the 18th livestock census data of the National Dairy Development Board, it was estimated that livestock population in the country is about 50% (529 million according to 2007 data) of the human population. According to National Commission of Integrated Water Resources Development (NCIWRD), India, average water requirement by livestock is about 30 litre/livestock/day, out of which 15% is consumptive use. Accordingly, livestock consumptive use was also computed and considered in water resources assessment.

Various hydrological models, their data requirements, scope and limitations were examined. These include initial and constant rate method, modified SCS curve number method, continuous soil-moisture accounting (SMA) model, green and ampt loss method, HEC-HMS[6], NAM model, SWAT (soil and water assessment tool) model, monthly water balance models, etc. Selection of a model mainly depends on the objectives of the study, data available and spatial and temporal scale of the study. To compute mean annual water resources at basin scale, monthly water balance models were examined further. Advantage of these monthly models is that each component of the hydrological cycle can be computed separately and accurately[7–9]. Various monthly models like Thornthwaite and Mather (TM) model, Pitman model, Thomas abcd model, Roberts model, etc. are widely used for run-off estimation[4,10]. After examining various water balance models, Mather soil water balance model was chosen for the study as it uses distributed modelling approach and is widely applied and accepted in various countries. This model is almost nearer to the process-based approach since it considers potential evapotranspiration, water loss and accumulated water loss in a month and water-holding capacity of soils up to root depth in calculating actual evapotranspiration and run-off.

As the potential evapotranspiration (PET) is a major component in the hydrological water balance, a suitable and practically feasible method has to be adopted at basin scale considering the availability of hydro-meteorological data. Various evapotranspiration methods, their merits and limitations were examined. Some of them are: Penman–Monteith formula, Thornthwaite's formula, Hargreaves method and Priestley–Taylor method[11]. From the initial computations in a selected sub-basin where the data are available, it is found that the variation in PET estimations using the said models is roughly 2–8%. Scope of the remote sensing-based methods for ET estimation was also examined[12]. Hence there is a need to have a simple monthly hydrological model to compute run-off more accurately with limited meteorological parameters to suit Indian conditions. In this study, a newer approach was adopted for computing PET by considering the merits and limitations of individual ET estimation methods and the availability of meteorological data at the required spatial and temporal resolution. Monthly PET computed through Thornthwaite method was corrected using the land-use coefficients derived from the satellite data. The modelling framework of the present study involves integration of spatial datasets (DEM, LULC, soil texture, village census) with hydro-meteorological datasets (rainfall, temperature, groundwater flux, reservoir flux and river discharge) in GIS environment in computing water-balance components.

TM model uses monthly rainfall, PET, and soil and vegetation characteristics. The last two factors are combined in computing water-holding capacity of the root zone. Computation of PET in this method is mainly based on temperature data and day-length factors[13]. The Thornthwaite method does not account for vegetative effect which is the most useful parameter in water-balance estimations[14]. But ET also depends on whether the soil is covered with vegetation and vegetation types or not. Monthly land-use factors were derived using satellite remote sensing data and integrated with PET to account for vegetation effect on PET. Monthly PET grids were computed using temperature and day-length grids through spatial modelling technique. $PET_{revised}$ was calculated using

$$PET_{revised} = PET * \text{vegetation factor}, \quad (1)$$

Uniform vegetation coefficients during all the months were taken for vegetations like forest, scrub land, etc.[15,16]. Whereas for agricultural lands, variable coefficients were taken for different months according to the crop type and crop growth stage[17–19]. Crop-type statistics was obtained from the irrigation command area reports of the basin and used in computing initial land-use coefficients. These vegetation coefficients were further calibrated by trail and hit method using field discharge data.

Hydrological response unit (HRU) concept was adopted in run-off computation, which is a function of land-use, soil texture and command area boundary. Spatial meteorological data were used in run-off calculations. After calculation of monthly $PET_{revised}$, dry and wet months were identified. If the difference between rainfall (P) $PET_{revised}$ is positive, it is considered as wet season; otherwise it is a dry season. The severity of dry season increases during the sequence of months with excessive PET. The accumulated potential water loss (La), which is the cumulative of negative values of ($P - PET_{revised}$) for the dry season was calculated. The water holding capacity (W) of each HRU unit was calculated based on soil texture, vegetation type and its rooting depth[13,20]. Soil moisture (SM) during wet month is limited to water-holding capacity. SM during the dry months (when $PET_{revised} > P$) was calculated based on eq. (2). Root depth of the vegetation was considered in estimating the SM.

$$SM = W * e^{(-La/W)}, \quad (2)$$

where SM is the soil moisture up to root depth (mm), La, accumulated potential water loss (mm) and W is the water-holding capacity (mm).

The ability of soil to retain water depends upon the amount of silt and clay present; the higher the amount of silt and clay, the greater is the SM content. Water-holding capacity of each HRU was calculated based on land-use, root depth and soil textural information. SM in each month was calculated based on W and accumulated water loss in the month. ΔSM 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 sufficient moisture exists in the soil within the root depth to meet the climatic demands, in such a case AET will be equal to $PET_{revised}$. In the condition when $P < PET_{revised}$, AET demand will be met from P and change in SM. In irrigated agricultural land (canal and well irrigation), it is assumed that full irrigation support is provided to meet the AET requirements. Irrigation support ($P - PET_{revised}$) is added to rainfall to make AET equal to $PET_{revised}$. Kharif crop outside the command area boundaries is considered as rainfed and the rest considered as irrigated either by canal or well irrigation system. The added irrigation support was subsequently adjusted while computing run-off. Monthly moisture surplus and deficit and run-off were calculated based on P, $PET_{revised}$, AET and SM. These monthly run-off calculations were aggregated to annual time-step for further analysis and for computation of water resources availability.

If any unknown variable exists in the model, it has to be calibrated using the observed/field data during the calibration process as given in eq. (3). Basically the calibration process is a hit and trial method. Spatial and temporal (monthly) vegetation coefficients were calibrated till the computed run-off fits best with the field observed run-off. After calibrating the model, the run-off calculations have to be revised using the calibrated (revised) coefficients. In the present study, the model was calibrated using hydro-meteorological data of 4 years and land-use grids (2004–05, 2005–06, 2006–07 and 2007–08). Once the model is calibrated perfectly, it has to be validated with another set of field observations to check the calibrated parameters. In this study the model was validated for all the remaining 14 years.

$$R_{Calibrated/computed} = (R_{Model} - F_{GW} - F_R - F_{DIL}) \approx R_0, \quad (3)$$

where $R_{Calibrated/computed}$ is the calibrated/computed run-off, R_{Model} the model estimated run-off (output from TM model), F_R the reservoir flux (negative sign for drawdown, CWC reservoir data were used), F_{GW} the groundwater flux (negative sign for drawdown, CGWB data were used), F_{DIL} the domestic, industrial and livestock consumption and R_0 is the observed run-off at gauge sites (observed data from CWCs were taken).

Domestic and livestock consumptive use was taken as 15% of its demand, and industrial consumptive use was taken as 50% of the demand[3]. Industrial requirements were considered being equivalent to domestic requirements.

Water resources of the basin comprise of run-off in the river at the final outlet, upstream effective utilization for irrigation, domestic and industrial purposes, groundwater flux and surface water flux[1]. Thus, water resources assessment (WRA) can be expressed as

$$WRA = R_{Calibrated/computed} + IS + E + F_{DIL} + F_{GW} + F_R, \quad (4)$$

where E is the evaporation from the reservoirs (computed) and IS is the estimated consumptive irrigation input provided (computed).

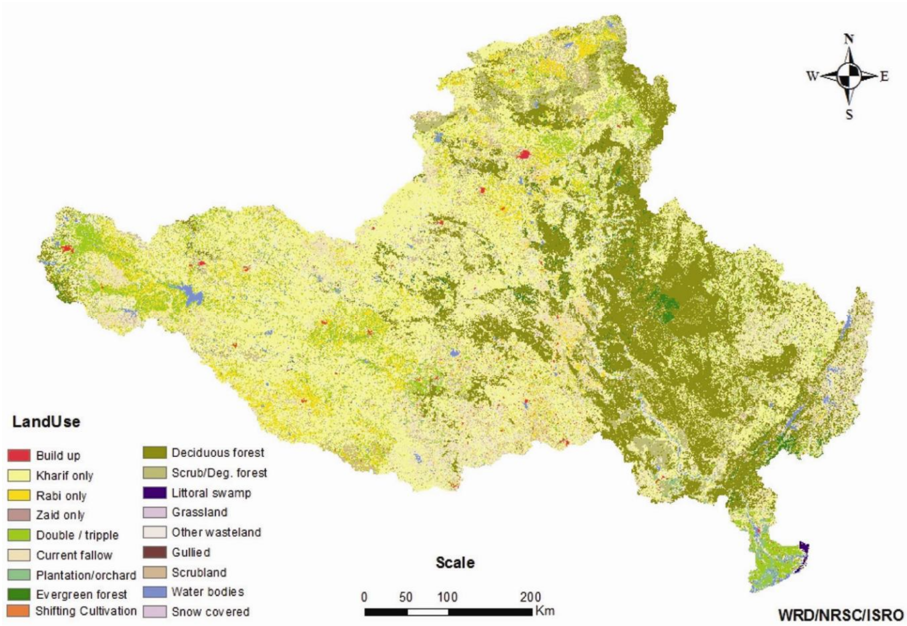

Figure 2. Annual variations in the rainfall of the Godavari Basin.

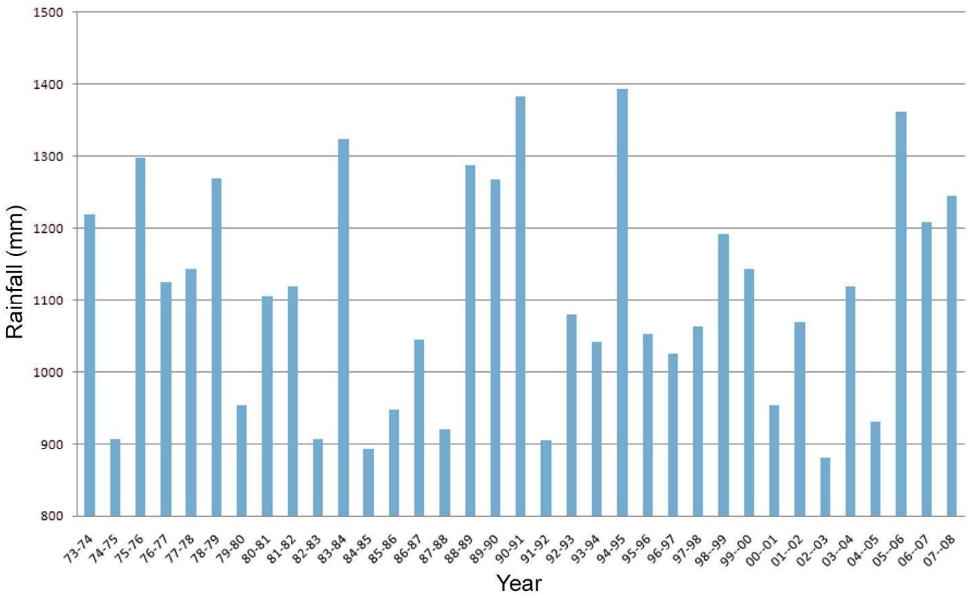

Figure 3. Land-use/land-cover of Godavari Basin derived from IRS P6-AWiFS (2004–05) (courtesy: NRC Project, NRSC).

Annual water resources availability during the 18 years (1990–91 to 2007–08) was computed in the Godavari Basin and mean annual water resources were further calculated. Rainfall during the last 35 years (1973–74 to 2007–08) was analysed and water resources availability during the extreme minimum and maximum rainfall years during these 35 years was also computed.

From the land-use/land-cover grids analysed in this study, it is found that agriculture land is the predominant land-use class in the Godavari Basin, having more than 50% (including current fallow) of the basin area; this extent varies slightly from year to year. The next principal class in the study area is forest cover. These two land-use patterns contribute maximum ET in the basin. Paddy, cotton and pulses are the main crops in the study area. When the 1995 land-use grid was compared with the 2004–05 grid, approximately 1.4% and 3.3% change in the agricultural and forest land respectively, was found. Land-use/land-cover derived from IRS P6 data of the year 2004–05 is shown in Figure 2 as an example.

Average monthly temperature was found to vary from 20°C to 35°C in a year, which causes monthly variation in PET in the basin. Minimum PET in the basin varies from 30 to 100 mm during January/February and maximum goes up to 400–450 mm during April/May. From the analysis of rainfall data, it is found that during the last 35 years (1973–74 to 2007–08) maximum rainfall (1393 mm) was recorded in the Godavari Basin in 1994–95 and minimum (881 mm) in 2002–03, as shown in Figure 3. Hence these two are considered as meteorologically extreme wet and dry periods respectively, during the time-period. Incidentally, these two extreme years fall in the present study period only (1990–91 to 2007–08).

Loamy, clayey, clayey skeletal, loamy skeletal, sandy and rocky outcrop are found to be core soil textural classes in the study basin. Among these, clayey and loamy are dominating classes which have the property of low infiltration rate and more run-off. Annual groundwater flux in the basin is found to vary from –10 m to +10 m. In some pockets these fluctuations are more; otherwise sustainable flux is noticed. Specific yield of the basin varies from 1.5% to 16%, with maximum part of the basin having specific yield of 1.5%. The mean annual groundwater flux in the basin during the 18 years is estimated at 0.67 BCM (drawdown). Reservoir fluxes in individual sub-basins are aggregated; it is noticed that many reservoirs maintain sustainable flux (less annual flux). The mean annual reservoir flux of all the 11 major and medium reservoirs is estimated at 0.01 BCM (drawdown). The mean annual domestic, livestock and industrial consumption flux is estimated at 0.99 BCM in the basin. Land-use coefficients calibrated through trial and process are found to range from 0.5 for bare soil to 1.2 for paddy during peak crop stage. Land-use factors for scrubland, grassland and forest lands are found to be 0.65, 0.7 and 0.9 respectively.

Run-off in each sub-basin during all the 18 years was aggregated separately. Computed run-off and observed run-off were calibrated and validated at five prominent CWC gauge stations, viz. Polavaram, Asthi, Bamini, Patagudem and Tekra. Polavaram is the final gauge station in the Godavari Basin that represents the hydrology of the complete basin. Catchment area at Polavaram is approximately 307,800 sq. km, out of the total basin area of 312,800 sq. km. It is found that at Polavaram computed run-off matches well with the observed run-off. Maximum computed run-off at Polavaram is found to be 187.95 BCM during 1990–91 and minimum is found to be 43.97 BCM during 2004–05. Mean run-off of 20 years for the complete basin is 94.78 BCM, against the observed run-off of 90.13 BCM. Average ratio of run-off to rainfall at Polavaram is found to be 0.272 (during normal rainfall year). Hence this can be treated as run-off coefficient of the basin. This coefficient is approximately 0.2 during low rainfall year and nearly 0.35 during high rainfall year. It is also noticed that run-off percentage with rainfall depends upon rainfall distribution in that year. Highest rainfall was noticed in 1994–95, but the highest run-off was found in 1990–91. Similarly, minimum rainfall was noticed in 2002–03, whereas minimum run-off was noticed in 2004–05, this may be due to variation in monthly distribution of rainfall during these years. Deviation between average computed run-off and average observed run-off for 18 years is found to be only 5.58%. Observed and computed run-off during the 18 years at Polavaram gauge site is shown in Figure 4.

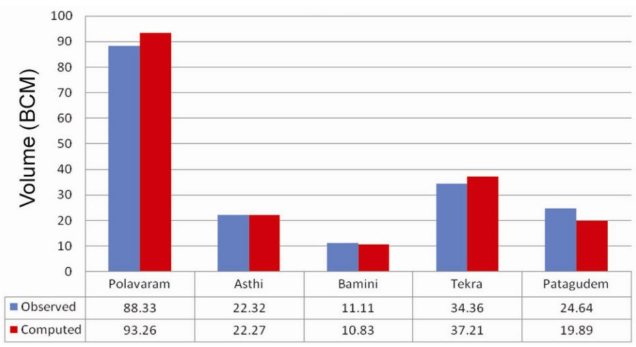

Figure 5. Observed and calibrated run-off (mean of 18 years) at various gauge stations.

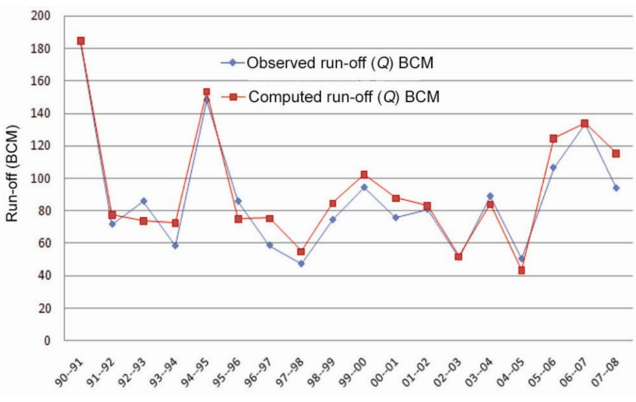

Figure 4. Observed and calibrated run-off at Polavaram during 18 years (1990–91 to 2007–08).

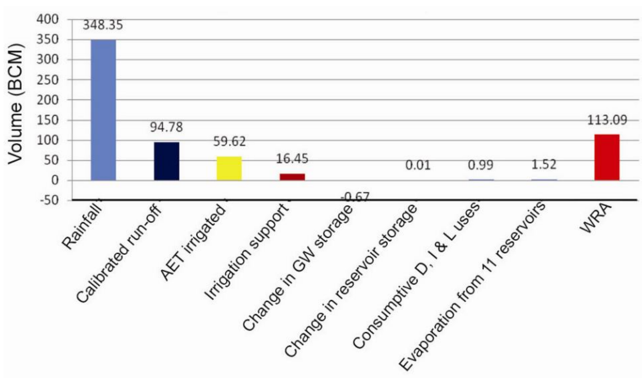

Figure 6. Water resources availability in the Godavari Basin (mean of 18 years).

It is found that annual mean of the computed and observed run-off for 18 years at the five gauge stations matches, as shown in Figure 5. Mean of the annual water resources (blue water) of the complete basin during the 18 years (1990–91 to 2007–08) computed using eq. (4) is found to be 113.09 BCM. Mean water resources availability (for 18 years) and its components are shown in Figure 6.

Mean water resources of the basin during 1967–68 to 1984–85 as assessed by CWC was 110.54 BCM against the present assessment of 113.09 BCM. From the rainfall data analysis, it is found that there is an increase of nearly 8 BCM of rainfall from the period 1973–1985 to 1988–2008. This may be one of the reasons for increase in water resources availability of the basin during the present study period. From the rainfall data of 1973–2008 (35 years), it has been inferred that 1994–95 and 2002–03 were maximum and minimum rainfall years having rainfall of 435.1 and 275.3 BCM respectively. Hence, water resources availability during these two years was analysed separately. The water resources availability in extreme maximum and minimum rainfall years during the last 35 years was found to be 178.7 and 72.63 BCM respectively. Percentage ratio of these two extreme climatic conditions was 246. This is challenging task for water resources planners to manage the available water resources during the dry periods.

The present study discusses quantifying basin-scale water wealth by transformation from the presently adapted basin terminal gauge site run-off aggregation by CWC to distributed hydrological modelling approach. In this study, a procedure was developed for realistic assessment of water resources at basin scale using a simple monthly water balance model by incorporating land-use coefficients derived from remote sensing data. This approach requires limited meteorological parameters and can be used for water resources assessment in any basin. The spatial modelling approach can help in quantifying water resources availability in any major tributary of the basin also. This simple modelling approach can help in studying the impact of future climate change in water resources of the basin. Different components in the water balance such as evapotranspiration from agriculture, forest area and other land uses can be computed in spatial environment using this spatial modelling approach. Ratio of water resources availability during the extreme climatic conditions during the last 35 years in the basin is a matter of serious concern to the water resources planners to manage the water resources during the dry periods.

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