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Original Research Paper

Hydrologic Modelling of Mahanadi River Basin in India Using Rainfall-Runoff Model

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ABSTRACT

The present study highlights on the application of an Integrated Water Resources Management (IWRM) tool, Water Evaluation and Planning (WEAP) system model for hydrologic simulation of Mahanadi river basin in India. A monthly time step hydrologic model was developed using rainfall-runoff method incorporated in WEAP with an aim to address the challenge of water resources estimation in Mahanadi basin. The model was set-up without taking into account effects of development and it was calibrated against measured flow data available at six gauging stations. A good agreement was observed between simulated and measured flow after calibration. Crop coefficient (Kc) and effective precipitation are the parameters changed during calibration. The range of calibrated parameters was found as ± 5 % and ± 1 % for Kc and effective precipitation respectively for different catchments. The simulation of stream flow using calibrated values revealed that, in most cases, the variation between measured and simulated stream flow values is less than 10%. This shows the good agreement with measured data by using calibrated parameters. The calibrated and validated model can be applied for runoff simulations in other basins with similar hydro-meteorological conditions. The results of the study demonstrate the potential of using WEAP model for water resource management and assessment of future resource development in the basin.

INTRODUCTION

The need for water is universal and without water, life, as we know it, will simply cease to exist. Water is the most precious and replenishable resource. Earth's water is constantly in motion, passing from one state to another and from one location to another, which makes its rational planning and management a very complex and difficult task under the best of circumstances (Turner et al. 2004). The availability and use of water is therefore mainly constrained by its spatial quantity and quality distribution. So, its development and management is of prime concern for any country or region. With the fast growing economic scenario, change in life styles, industrialization, urbanization and for other requirements such as ecology, the competing demand for water has increased many fold. Available supplies are under great duress as a result of high population growth, unsustainable consumption patterns, poor management practices, inadequate investment in infrastructure, lack of maintenance of systems and low efficiency in water use. Apart from quantity, quality of utilizable water is also deteriorating in the absence of adequate policy initiatives and constraints in implementation.

Orissa is one of the states endowed with ample surface and groundwater resources in its river systems, and the Mahanadi river basin contributes a large share of it. Hirakud is a major project of India started and commissioned in 1957 and has served the aspirations of the people effectively and efficiently over the last fifty years. At the time of its completion, Hirakud Dam was the longest earthen dam in the world; it remains the largest reservoir in Asia with a surface area of 746 km^2, and a live storage capacity of $5.37 \times 10^9 m^3$. Though irrigation achieved its full development within a short period, industrial development lagged behind in spite of the basin being rich in natural resources. However, industrialization has picked up momentum and a number of industries are coming up now in the Ib and bheden sub-basins close to the Hirakud reservoir, requiring water from the storage. Though this demand was anticipated in the project planning stage itself, no specific allocation was made for various uses. Flood control remained as the main purpose during monsoon, and the reservoir is filled by 1st October every year, for meeting demands for irrigation, power generation, industrial needs, municipal water supply and ecological requirements during the post monsoon period (Report of HLTC 2007). Water resources planning, once an exercise based primarily on engineering considerations, increasingly occurs as part of a complex, multi-disciplinary investigation that bring together a wide array of individuals and organizations with varied interests, technical expertise and priorities. In this multi-disciplinary setting, successful planning requires effective IWRM models that can clarify the complex issues that can arise (Loucks 1995). IWRM is viewed as a systematic process for the sustainable development, allocation and monitoring of water resources use in the context of social, economic and environmental objective. The decision problems regarding water resources such as water use and allocation, development, conservation, sustainability and sustenance of fragile ecosystems can be confusing and a DSS tool may bring about clarity.

WEAP21 introduces major advances including a modern Graphic User Interface (GUI), a robust solution algorithm to solve the water allocation problem, and the integration of hydrologic sub-modules that include a conceptual rainfall runoff, an alluvial groundwater model, and a stream water quality model (Rosenzweiga et al. 2004). Water allocation models are being widely used in order to assess the impacts of future development trends, water management strategies, climate change, etc. on the availability of water resources (Wurbs 2005). WEAP21 model attempts to address the gap between water management and watershed hydrology and the requirements that an effective IWMR be useful, easy to-use, affordable, and readily available to the broad water resource community (Yates et al. 2005). This model was used in Ghana to simulate the impact of small reservoirs in the Upper Volta (Hagan 2007). The model performed well. Arranz & McCartney (2007) have also applied the model to the Olifants catchment in South Africa. In their analysis, the model performed well in doing quick analysis of current and future water demands. Other investigators (Alfarra 2004, Levite et al. 2003) have applied the model to various catchments around the Globe with success. It is a priority driven software, that employs priority based optimization algorithm as an alternative to hierarchial rule based logic that uses a concept of Equity Group to allocate water in time of inefficient supply (Mounir et al. 2011).

For any model, calibration and validation are critical and necessary steps before its application. For most watershed models, calibration is the process of modifying the input parameters to a model until the output from the model matches an observed set of data. Model validation is generally an extension of the calibration process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations for periods separate from the calibration effort. Hydrologists are concerned with developing a proper relationship between the rainfall over a catchment and the resulting runoff at the catchment outlet. The link between rainfall and runoff has inspired many research workers and the evaluation of river flow from rainfall has stimulated the imagination and ingenuity of engineers. In this study, Water Evaluation and Planning Version 21 model was applied for rainfall-runoff simulation in middle reach of Mahanadi river basin. The model is preferred to others because of its robustness and ease of use depending on data availability (Mugatsia 2010). The model can perform both lumped to distributed catchment hydrological simulation. It can handle aggregated to disaggregated water management demands of various sectors. The system is therefore appropriate for studying catchments with minimum to moderate data availability.

STUDY AREA

The Mahanadi river basin is divided into three parts. Upper drainage basin of the Mahanadi which is centred on the Chhattisgarh Plain, middle reach which is started from Hirakud to Munduli and the delta region which is the lower part of basin where floods may damage the crops. The study area to carry out present research work is middle reach region of Mahanadi river basin. The Mahanadi River flows to

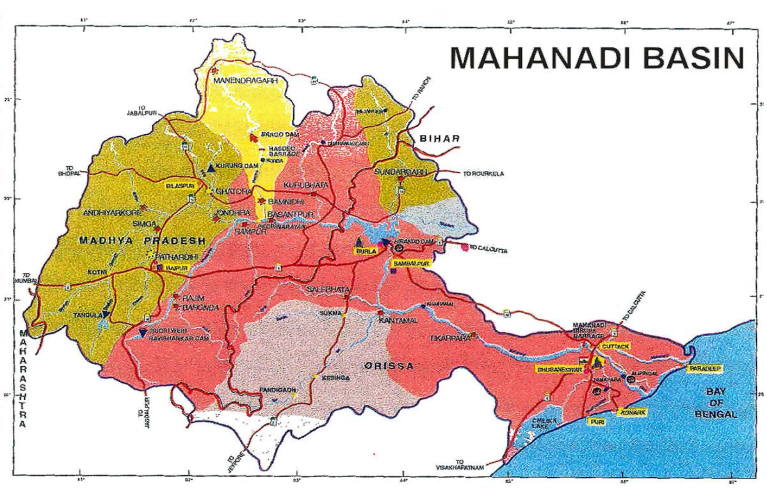

Fig. 1: Mahanadi river basin.

Table 1: Area of sub catchments in study area.

Sub Catchment	Area, sq. km	Sub Catchment	Area, sq. km
Jira	1839.08	Rana	10033.29
Ong	5058.66	Legara	1439.63
Mahanadi	6292.86	Sondur	2802.05
Jonk	2340.62	Gurubella	1404.59
Sagara	1370.81	Ib	2074.30
Pillasalunki	1673.21	Tel	2345.85
Lanth	1581.86	daya	4177.56
Kalia pata	969.77	Pairi	1587.05

the Bay of Bengal in east-central India; it drains an area of 141,589 km^2 and has a length of 851 km. The average elevation of the drainage basin is 426 m with a maximum of 877 m and a minimum of 193 m. About 53% of the basin is in the state of Chhatisgarh, about 46% is in the coastal state of Orissa, and the remainder of the basin is in the states of Jharkhand and Maharashtra. Numerous dams, irrigation projects, and barrages are present in the Mahanadi River basin (Fig. 1), the most prominent of which is Hirakud Dam. Approximately 65% of the basin is upstream from the dam. The average annual discharge is 1,895 m^3/s, with a maximum of 6,352 m^3/s during the summer monsoon. Minimum discharge is 759 m^3/s and occurs during the months October through June. Near the city of Cuttack and approximately 114 km from the Bay of Bengal, the Mahanadi River splits into at least six major distributaries and numerous smaller channels. Almost all of the distributaries are channelled in embankments designed to contain a discharge of about 25,500 m^3/s. The river passes through tropical zone and is subjected to cyclonic storms and seasonal rainfall. In the winter the mean daily minimum temperature varies from 4°C to 12°C. The month of May is the hottest month, in which the mean daily maximum temperature varies from 42°C to 45.5°C.

METHODOLOGY

The basic data required to run WEAP model are precipitation (monthly/daily), temperature (monthly average temperature), relative humidity, reference potential evaporation, groundwater, runoff, soil groups and land use categories. The water demand side data of domestic purpose, industrial uses, agricultural and allied sectors are required to carry out demand and supply analysis. There are three methods presented in WEAP21 for simulating catchment processes. These are (1) Irrigation Demands Only versions of the FAO Crop Requirements Approach, (2) the Rainfall Runoff and (3) the Soil Moisture Method. The FAO rainfall-runoff method was used to simulate stream flow of basin in this study. The rainfall-runoff method also determines evapotranspiration for irrigated and rainfed crops using crop coefficients. The remainder of rainfall not consumed by evapotranspiration is simulated as runoff to a river, or can be proportioned among runoff to a river and flow to groundwater via catchment links. The various types of data required to perform rainfall-runoff simulation using this method are: (i) Land use (area, crop coefficients Kc, effective precipitation), (ii) Climate (precipitation and reference crop evapotranspiration ETo). Rainfall data and temperature data were obtained from the India Meteorological Department (IMD) Bhubaneswar. The effective precipitation was determined using Smith (1992) effective rainfall method (equation 1).

$$P_{eff} = P\frac{(125 - 0.2P)}{125}\ for\ P \leq 250\ mm/m \qquad ...(1)$$
$$P_{eff} = 125 + 0.1\ P\ for\ P > 250\ mm/m$$

The mean monthly precipitation and effective precipitation for all sub catchments in the study area are shown in Figs. 2 and 3 respectively. The crop co efficient (kc) values were used from previous studies carried out by Tyagi et al. (2000) and Mohan & Arumugam (1994). The Evapotranspiration (ETo) was calculated by DSS-ET software using Hargreave method. The Monthly reference crop evapotranspiration is shown in Fig. 4.

Satellite images of the study area were downloaded from the GLCF site (www.glcf.umd.edu) and ASTER DEM (30m × 30m) from Earth Remote Sensing Data Analysis Centre (ERSDAC) site (www.gdem.aster.ersdac.or.jp). Stream network was delineated from downloaded DEM. The catchment was delineated into sixteen sub-catchments in ArcGIS 9.3 using DEM. There was a fair distribution of rainfall stations in the whole catchment. The daily data for all stations were obtained for the period of study from IMD Bhubaneswar. Runoff data for all six gauging stations were collected from Central Water Commission (CWC) Bhubaneswar. Soil map of the study area was digitized to get different soil groups. Land use land cover map was prepared by supervised classification of downloaded satellite images in ERDAS 9.1.

For calibration of stream flow in study area using WEAP model, six gauging stations were taken into account. The daily stream flow data for year 2000-2009 at these stations were collected from CWC. Further, for stream flow simulation, study area was divided into 16 sub catchments. The area of these sub catchments is given in Table 1. For each sub catchment, monthly rainfall time-series were derived by calculating an area-weighted rainfall average from the corresponding rainfall zones.

WEAP21 Model: The WEAP model was developed by the Stockholm Environment Institute (SEI) in 1988. The first major application of WEAP was in the Aral Sea region in 1989 with the sponsorship of the newly formed Stockholm Environment Institute (SEI). WEAP was conceived by Paul

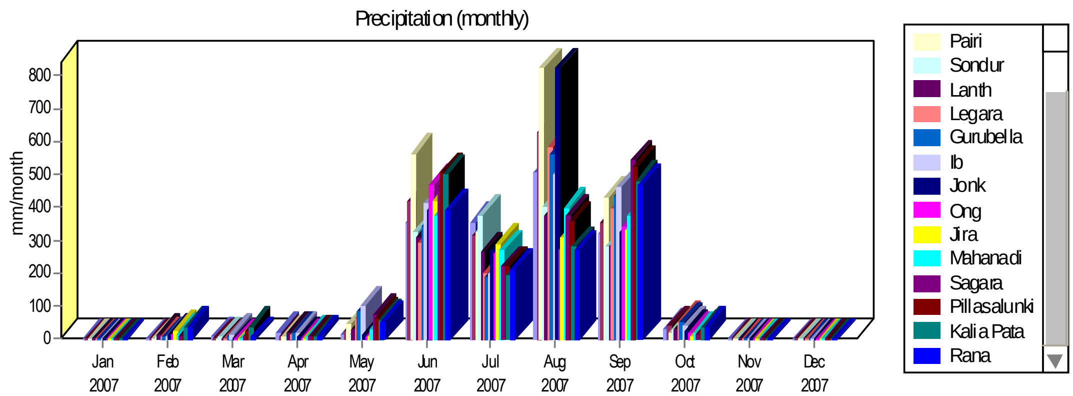

Fig. 2: Mean monthly precipitation for sub catchments in different months.

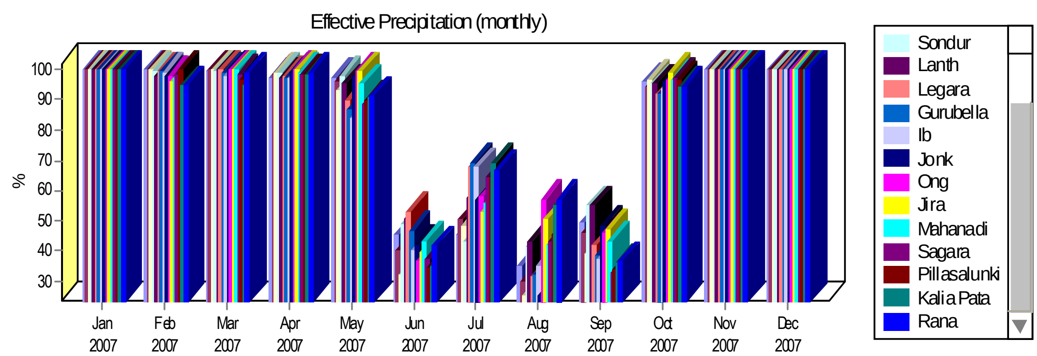

Fig. 3: Mean monthly effective precipitation in different months.

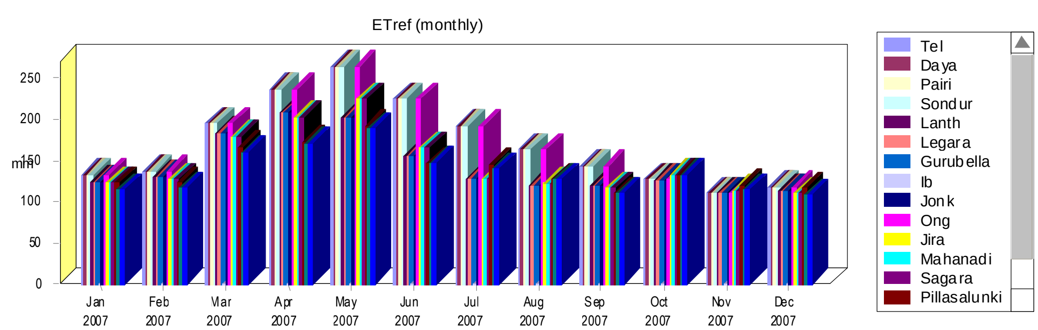

Fig. 4: Monthly reference crop evapotranspiration ETo.

Raskin, President of Tellus Institute, and developed under his supervision until 2001. This new version of WEAP is called as WEAP21. WEAP21 operates on the basic principle of a water balance and can be applied to agricultural systems in a single watershed or complex transboundary river basin systems.

WEAP21 is a general multipurpose, multi-reservoir simulation program which determines the optimal allocation of water for each time-step according to demand priorities and supply preference. It operates at a monthly time step on the basic principle of water balance accounting. The model can represent any water resource system incorporating natural inflows, precipitation, evaporation, and evapotran-spiration as input data. Operational features that can be represented include storage and release of water by reservoirs, physical discharge controls at reservoirs outlets, water flow in channels, consumptive demands and hydropower releases. These operational features can be specified as steady-state or time-varying. In addition, WEAP21 allows users to develop their own set of variables and equa-

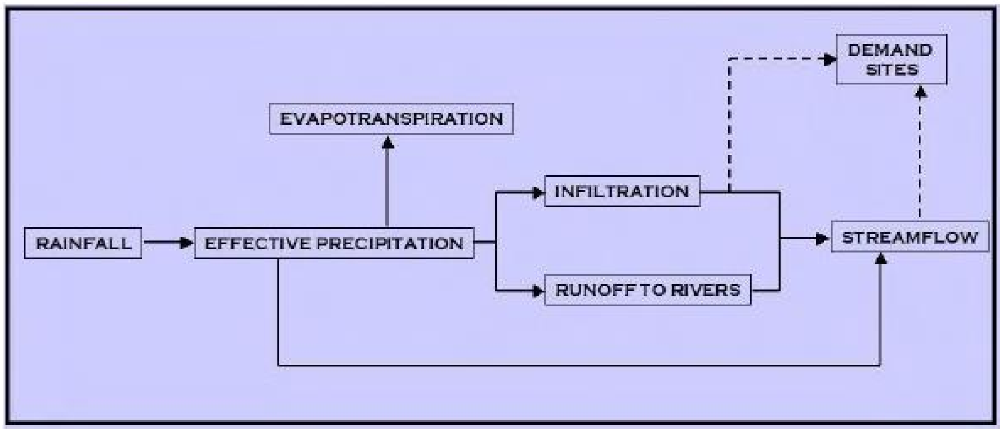

Fig. 5: Schematic of WEAP rainfall-runoff component.

tions to further refine and adapt the analysis to local constraints and conditions with possible data exchange with other software such as Excel (SEI 2005).

In the current study, the primary objective was to test WEAP's ability to simulate the rainfall-runoff process of the basin. Therefore, the FAO crop requirements rainfall runoff method was selected for this study. The schematic of WEAP rainfall-runoff component is shown in Fig. 5. Hydrological processes occurring in the catchment were modelled and stream flow, simulated on a monthly time-step, were compared to the measured flow series available six catchments. This was done because in this catchment, measured flow records from gauging stations are affected by human water abstractions and do not represent the flow originally from the rainfall-runoff process. The model was calibrated for year 2007 using two parameters at different steps (Table 2). The three basic views of WEAP model are schematic, data and result view (Fig. 6).

Once the model is simulating the measured flow series satisfactorily, water demand sites can be added and WEAP can be run in its water allocation mode using the rainfall-runoff parameters determined from the first phase.

The amount of rainfall that is not evapotranspired is available for infiltration and runoff. Independently of the rainfall intensity, the amount of rainfall going to runoff (or groundwater) is specified as a percentage (fixed for the whole simulation) of the amount of water still available after evapotranspiration has occurred.

RESULTS AND DISCUSSION

The rainfall runoff method was used to simulate river flows; this was constrained by the type of data available (rainfall, evaporation and crop data). The following types of data are required to perform rainfall-runoff simulation using this method:

Table 2: Parameter initial values and steps used for calibration.

Parameter	Initial value	Step
Crop coefficient (Kc)	0-1.59	± 5 %
Effective precipitation	100 %	± 1 %

Table 3: Flow measured at different gauging stations in year 2007.

Catchment	Mundali	Tikarapara	Kheirmal	Salebhata	Kesinga	Kantamal
Jan	40.12	33.90	32.60	1.55	54.39	67.24
Feb	305.44	244.36	241.69	2.67	56.04	60.48
Mar	283.90	227.12	225.40	1.73	42.71	48.83
Apr	33.01	27.41	26.35	1.13	55.62	56.75
May	50.22	40.37	40.95	1.30	93.03	10.34
Jun	1212.59	970.07	879.01	91.06	419.52	343.59
Jul	5284.45	4227.56	4053.87	173.69	790.75	908.72
Aug	6157.13	4925.70	4827.77	97.94	1620.85	2239.80
Sep	6794.10	5435.28	5214.23	221.06	819.02	1570.63
Oct	2846.76	2277.41	2214.10	63.30	399.50	554.85
Nov	13.88	10.30	10.65	6.66	140.54	17.84
Dec	78.61	62.49	62.24	2.24	130.34	16.15

Table 4: Monthly simulated flows before parameter calibration.

Catchment	Mundali	Tikarapara	Kheirmal	Salebhata	Kesinga	Kantamal
Jan	0.00	0.00	0.00	0.00	67.24	0.00
Feb	17.15	8.71	8.71	0.52	60.48	6.19
Mar	13.48	12.62	12.08	0.00	48.83	12.00
Apr	0.00	0.00	0.00	0.00	56.75	0.00
May	0.00	0.00	0.00	0.00	103.34	0.00
Jun	4436.19	3433.92	3220.24	583.00	343.59	1787.70
Jul	2069.01	1789.21	1740.60	203.83	908.72	1120.00
Aug	4635.61	4158.70	4037.76	217.12	2239.80	3063.91
Sep	4341.74	3042.39	2810.81	359.05	1570.63	1612.97
Oct	55.21	47.08	46.47	1.30	554.85	43.15
Nov	0.00	0.00	0.00	0.00	170.84	0.00
Dec	0.00	0.00	0.00	0.00	165.15	0.00

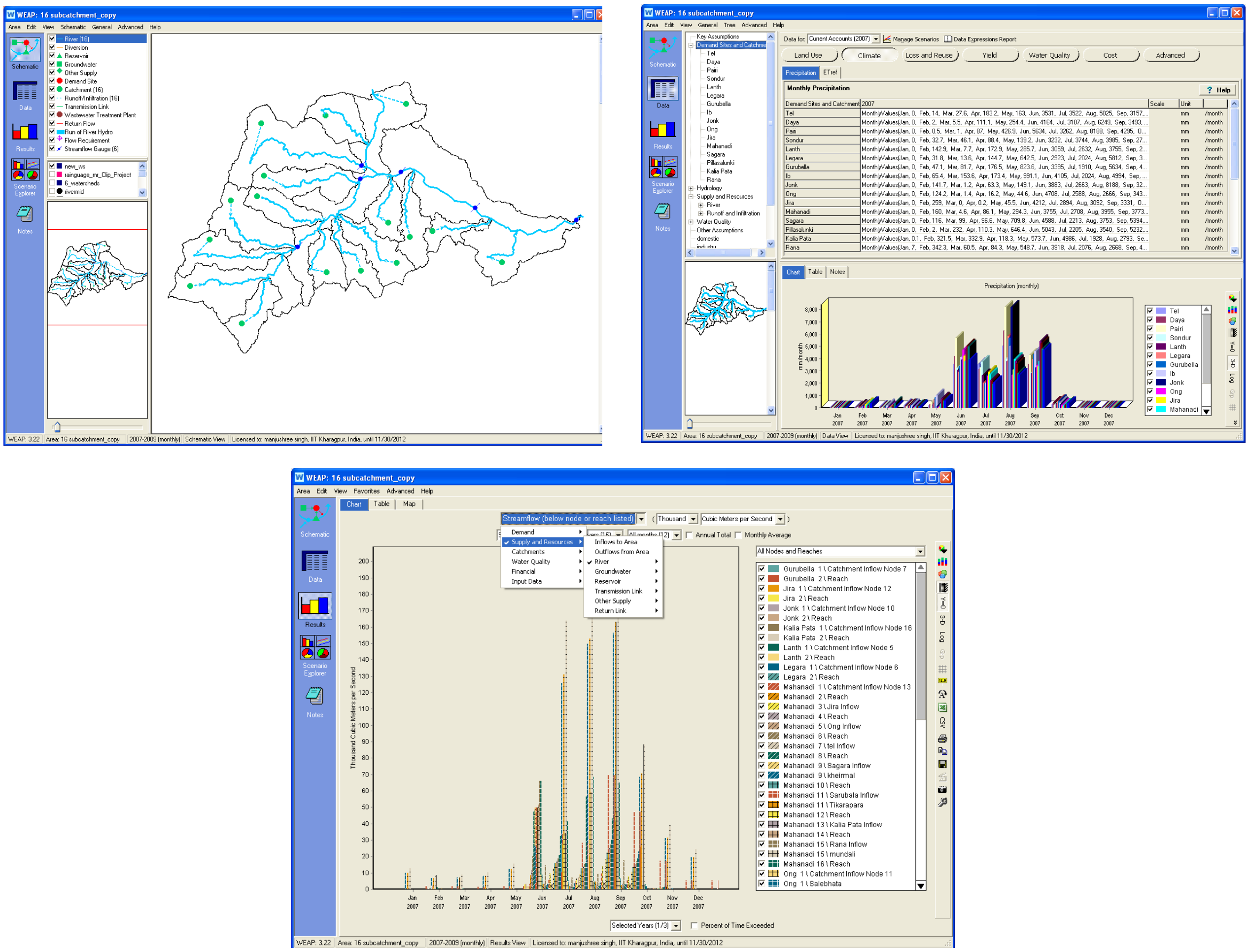

Fig. 6: Schematic, Data and Results view of WEAP model

Table 5: Results of parameter calibration.

Parameter/ Catchment	Kc	Effective precipitation	Parameter/Catchment	Kc	Effective precipitation
Kesinga	5 %	0.5 %	Kheirmal	-1 %	-0.5 %
Kantamal	-5 %	0.5 %	Tikarapara	1%	1 %
Salebhata	5 %	-1%	Mundali	-5%	1 %

i. Land use (area, Kc, effective precipitation)

ii. Climate (precipitation and ETo)

Where Kc is crop coefficients and ETo is the reference crop evapotranspiration.

Initially, the WEAP model was run without calibration of parameters. There was huge variation in measured and simulated stream flow. At some points these values differ by almost twice. The measured flow at six gauging station is given in Table 3. The results of simulation of stream flow at these six locations before calibration are given in Table 4.

The WEAP model was calibrated using rainfall runoff component for year 2007. Calibration included changing the model parameters to better simulate historic patterns. WEAP has no automatic calibration routine; therefore, the changes implemented were tested manually by comparing the simulated and observed time series. The results of parameter calibration are presented in Table 5. The calibrated parameters of each catchment were again used for simulation in WEAP model. These simulation results are presented in Fig. 7.

After these simulations, the results were compared for the percent variation between measured and simulated values (Fig. 8). It was found that most of the simulated values are falling in the range of 10% of measured stream flow.

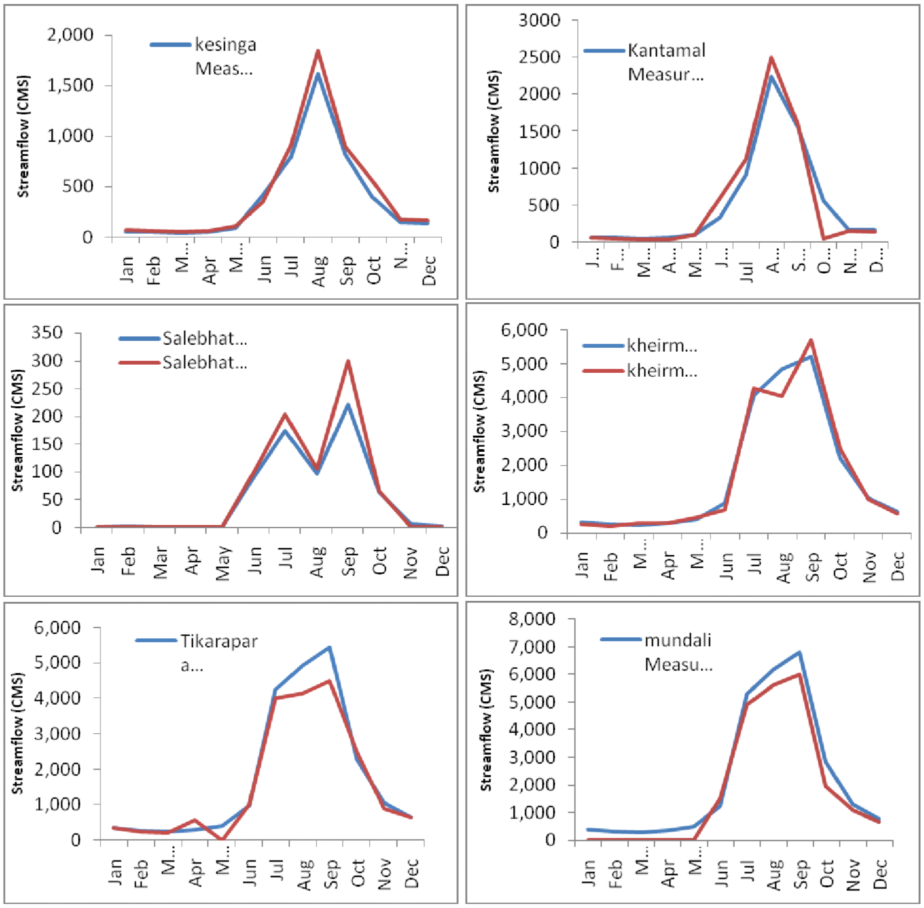

Fig. 7: Simulated flows in different catchments after calibration of parameters.

WEAP model was performing satisfactorily for simulation of runoff using rainfall and other required data for Mahanadi river basin using calibrated parameters. Therefore, this calibrated model can also be applied to other river basins in India with similar hydro-meteorological conditions.

CONCLUSION

Modelling the hydrological processes and response of a 47,000 km² catchment is a complex task and the results of such a simulation have to be treated with caution. Errors are likely to be introduced from the structure of the model itself as well as from the sets of data that were used to run it. Instead of trying to model each hydrological component (e.g. evapotranspiration, runoff, infiltration) with accuracy, it was decided to use a system that relied on simplified equations and to run it at a much larger scale than it is usually done; the average sub catchment area in the study was approximately 3,000 km². There were two main reasons for adopting this approach. Firstly, because the aim of the study was to assess water resources in the whole catchment, it was not practical to set the model up using a finer spatial resolution. Secondly, most of the data required for the aquifer design are not available and it was easier to estimate them at a larger scale.

WEAP was chosen because it operates in a simple manner. The purpose was not to describe accurately the hydrological process of the Mahanadi river basin, but to be able to simulate the water resources of the basin with limited data and using a small number of parameters. The work conducted the tested WEAP's ability to simulate the rainfall runoff process in the basin and assessed the impact of development on water resources. The study revealed that WEAP was able to simulate well the measured flow time-series from six catchments. This constituted a good test of its ability to model the rainfall-runoff response of the catchment. There are very few studies that deal with water resource assessment and impact of development at the scale undertaken in the current study. However, this seems to be a critical step as water management (especially with the establishment of water management agencies) will have to be achieved at this scale.

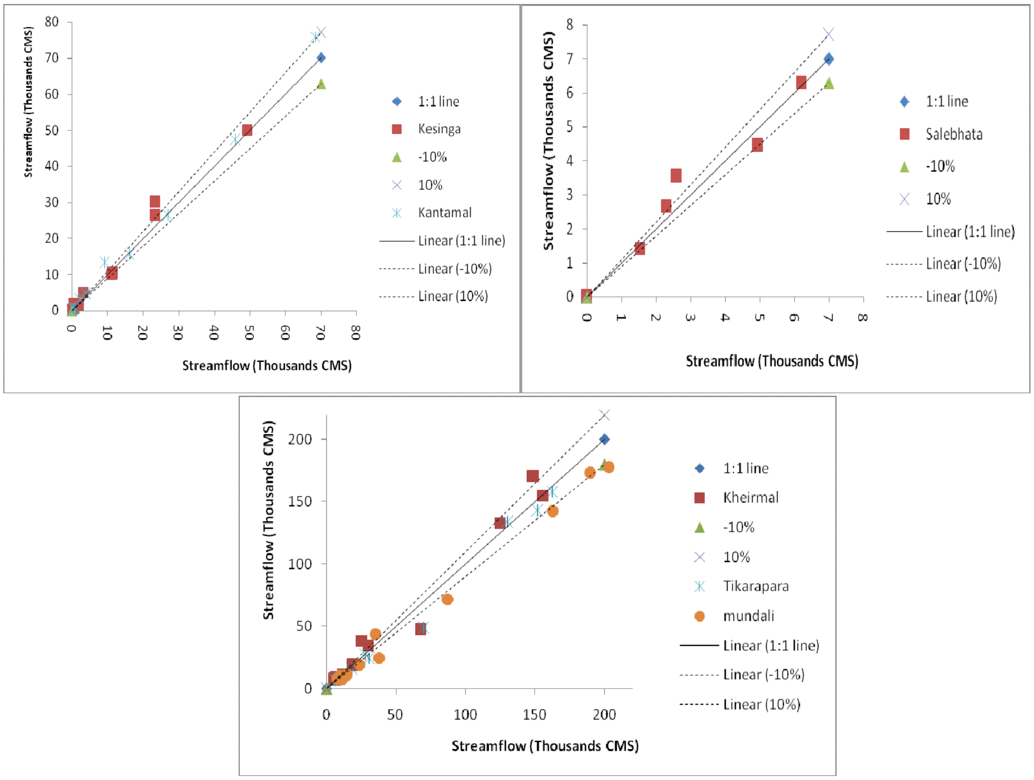

Fig. 8: Percent variation between measured and simulated stream flow values after calibration.

In that perspective, WEAP could be a useful planning and management tool, not only in the Mahanadi basin or in India, but also in other areas.

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