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Estimation of Water Yield under Various Climate Scenarios at a River Basin Scale in the Manimala River, Kerala, India

VENKATESH B, CHANDRAMOHAN T, JOSE M K, PURANDARA B K AND VARADARAJU S

Regional Centre, National Institute of Hydrology, Hanuman Nagar, Belagavi, Karnataka, INDIA

College of Fisheries, Hoize Bazar, Mangalore, Karnataka, INDIA

Email: *bvenki30@yahoo.com, cmohant@yahoo.com, mathewkjose@gmail.com, purandarabk@yahoo.com, svraju1103@rediffmail.com*

Abstract: *In the present study, a distributed hydrological model namely soil water analysis tool (SWAT) has been employed for Manimala River Basin in Kerala, India. The entire basin has been divided into 7 major sub-basin to predict the water balance components and their variability under changing climatic conditions. The calibration of the model using the observed data indicated the model parameters such as SOL_AWC, ESCO, GW_REVAP and CN are the sensitive parameters. The estimates of water balance component at basin and sub-basin level show that irrespective of land covers, the runoff generation is as high as 47% (runoff coefficient Q/P) and groundwater recharge is 36%. The estimate of ET is comparatively low.*

Keywords: *Water Yield, Climate Change, GCM, SWAT, Manimala*

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) states that the availability and distribution of freshwater resources will be greatly affected by climate change and the vulnerability to water scarcity that populations currently experience could increase [8]. Studies relating climate change and hydrology are becoming prevalent [10], but few published studies focus on changes in groundwater and the population dependent upon it. The IPCC calls for expanded research on local impacts of climate change and finer-resolution assessments of changes in surface and groundwater systems.

Climate change continues, and with it our ability to predict changes is refined, but there is a need to develop simple tools that empower water resource managers to use the predictions to better understand and manage water sources. Complex models that generate outputs on continental scales are of little use for decision makers who are trying to allocate resources to alleviate local water scarcity. Rather, decision makers require readily applicable tools that can use climate predictions to accurately forecast local hydrologic changes.

Water balance models have been used to accurately simulate historical basin discharges [11], forecast changes in discharges based on climate changes [4], [1], [6], and are relatively straightforward to apply. Thus, water balance models could be an empowering tool for water resource managers to prepare for and mitigate the effects of regional climate change on their local hydrologic resources. There are a number of integrated physically based distributed models. Among them, researchers have identified SWAT as the most promising and computationally efficient. Hence, in this study, an attempt has been made to identify the most sensitive parameters, calibrate, validate the SWAT model and to determine the important hydrologic components of a river basin with focus on water conservation and management.

2. SWAT Rainfall-Runoff Model

The SWAT model is a long-term, continuous simulation watershed model. It operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields. The model is physically based, computationally efficient, and capable of simulating a high level of spatial detail by allowing the division of watersheds into smaller sub watersheds. SWAT models water flow, sediment transport, crop/vegetation growth, and nutrient cycling [7]. The model allows users to model watersheds with less monitoring data and to assess predictive scenarios using alternative input data such as climate, land-use practices, and land cover on water movement, nutrient cycling, water quality, and other outputs. Major model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management. Several model components have been previously validated for a variety of watersheds.

In SWAT, a watershed is divided into multiple sub watersheds, which are then further subdivided into Hydrologic Response Units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the sub watershed area and are not identified spatially within a SWAT simulation. The water balance of each HRU in the watershed is represented by four storage volumes: rain, soil profile (0–2 meters), shallow aquifer (typically 2–20 meters), and deep aquifer

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(more than 20 meters). The soil profile can be subdivided into multiple layers. Soil water processes include infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. Flow, sediment, nutrient, and pesticide loadings from each HRU in a sub watershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Detailed descriptions of the model and model components can be found in Arnold et al. [2].

SWAT Input Data: The model requires land use, soil, and topography data for simulating runoff from the watershed. The land use data were obtained from FAO and the soil information from NBSS&LUP. Topographic information were derived using Digital Elevation Model (DEM) data (the SRTM DEM have been used). The DEM data were used to generate variations in sub-watershed configurations such as sub-watershed delineation, stream network delineation, and slope and slope lengths using the ArcView interface for the SWAT model. Land-use categories provided in FAO land use files are relatively simplistic, including all categories such as forest and its variants, agricultural land, barren land and etc. In the present case, many of the watersheds considered for the analysis are covered by 100% Broad leave natural forest, forest plantation and rubber plantation. The soil data available in NBSS&LUP, which contains soil maps at a 1:250,000 scale. Each map unit is linked to the Soil Interpretations Record attribute database that provides the proportionate extent of the component soils and soil layer properties. The soil map units and associated layer data were used to characterize the simulated soils for the SWAT analyses.

3. Study Area

Manimala river originates from Tatamala hills in Idukki district at an elevation of 1156m above msl and drains through the highland, midland and the lowland physiographic provinces of Kerala. It empties into the Vembanad Lake, after merging with the Pamba at Muttar in Alappuzha District. Owing to the steep topography, the stream network of the Manimala basin is very dense. The present analysis considers the river basin upto the gauge-discharge site at Thondara which covers a geographical area of 780 km^2. The location of the study area is shown in Figure 1.

Manimala River basin receives major portion of rainfall during south-west monsoon period (June – September). The south-west monsoon forms around 80 per cent of annual rainfall. The north-east monsoon (October-November) supplies the remaining portion of the rainfall. The average annual rainfall of the basin is around 2600 mm.

The major soil type found in the basin is gravelly clayey with good drainage characteristic. The basin is predominantly used for rubber plantation within the midland regions and part of high land and low land regions. The low lands are covered by paddy and other short term crops and vegetables and shrubs. High land regions are having forest areas (disturbed, semi-evergreen and evergreen) and forest plantations.

3.1 Data Availability

Data from Rainfall observation stations maintained by the State Irrigation department is collected and used for the project. In this study, the data of station such as Boyce estate (1990-2008) and Changanacherry (2000-2008) are used. The State Irrigation Department maintains gauge-discharge sites at three locations along the whole river stretch. The flow characteristics of high land reaches of the basin is measured at Mundakkayam, the Manimala gauge station represents the flow upto midland region and the overall discharge till low land area is measured at Thondara.

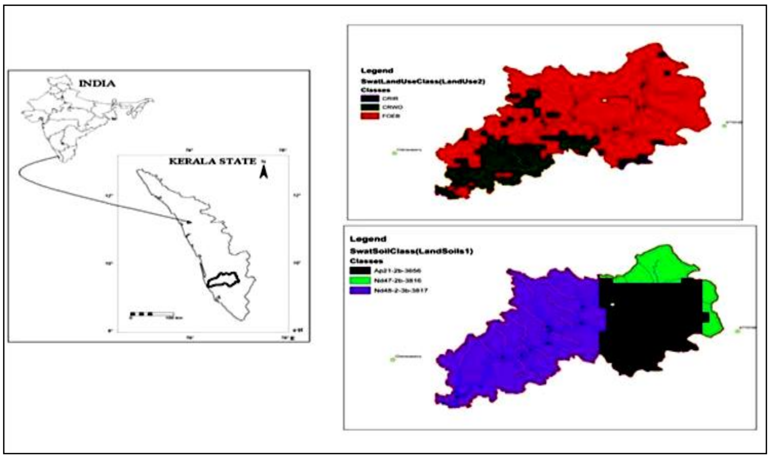

Figure 1: *Index map of Manimala basin with land use and soil maps*

GCM Data: In order to understand the impact of climate change on the water balance component of the basin, one needs data on future climate variables, such as rainfall (P), and temperature (T), which in the current study were obtained from Canadian Centre for Climate Change and Analysis (CCCma) for baseline period starting from 1961 to 2000. Since there are not observed data available during the period (1961-2000), the IMD gridded data was also used in the study to test the SWAT simulations using the projected climate data of CCCma.

4. Results and Discussion

The SWAT modes was set-up for the Manimala basin using the observed daily data on rainfall at Boyce Estate and Changanacherry and discharge data at Thondara which is maintained by state Irrigation Department. The data for these stations were collected for a period of 8 years starting from 2000 to 2007. The SWAT model was set-up with 7 sub-basins cover the entire basin area. Further, each of the sub-basin were divided into number of Hydrologic Responsive Unit (HRU's)'s to evaluate the effect of changing climate on the hydrological processes. Figure 2 and Figure 3 show Digital Elevation Model (DEM) used in the study and the sub-basins

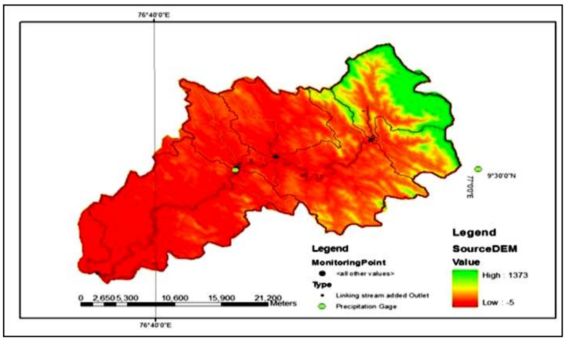

Figure 2: *Digital Elevation Model (DEM) used for the study and location of Raingauge*

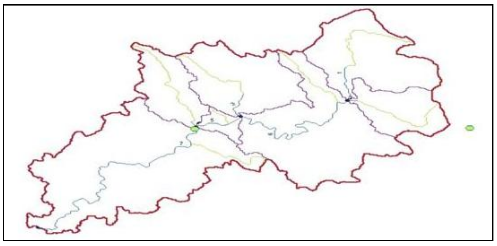

Figure 3: *Demarcation of sub-basins in Maninala for SWAT analysis*

The SWAT model was calibrated using the data for 2000 to 2005 and validated for a 2 year period (2006-2007). Calibration of the model was done by adopting the manual calibration procedure. Santhi et al. [9] suggested a generalized manual calibration procedure, indicating the most sensitive input parameters, acceptable model evaluation results and sensible ranges of parameters uncertainty. As few of the model parameters are not possible to measure in the field and are need to be calibrated against the observed discharge. Therefore, during the calibration period, the model parameters were varied within the physically allowed range and more realistic to the natural condition of the basin. As recommended by Coffey et al. [3] to use the R^2 and modelling efficiency objective functions to evaluate the performance of the model. The following modelling evaluation indices were used in this study:

The root mean square error (RMSE) and the normalized objective function (NOF) were computed based on the following equation

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - Q_i)^2}{N}} \quad (1)$$

$$NOF = \frac{RMSE}{\bar{Q}} \quad (2)$$

Where, Pi is model predicted values, Qi are the observed values for the N observations, and $\bar{Q}$is the mean of observed values. According to Kornecki et al. (1999), the ideal value of NOF is 0.0.However, a model is acceptable for NOF values in the range from 0.0to 1.0 when site-specific data are available for calibration. In that case, the model can be used to test scenarios associated with management practices. The optimized values of the model parameters are tabulate in Table 1.

Table 1. *The optimized values of the model parameters*

Model Parameters	Variable Name	Range	Model Value
Curve Number	CN	69-85	78
Soil Evaporation Compensation Factor	ESCO	0.75-0.95	0.85
Plant uptake compensation factor	EPSO	0.01-1.0	0.55
Soil available water capacity (mm)	SOL_AWC	0- 50	22
Baseflow alpha factor	ALPHA-BF	0.05-0.8	0.048
Groundwater revap Coefficient	GW_REVAP	0.02-0.2	0.02
Groundwater delay time (days)	GW DELAY	0-100	31
Deep aquifer Percolation fraction	RECHARGE_DP	0-1	0.05

Table 2: *Performance indicators*

Performance Indicator	Calibration	Validation
Root Mean Square Error (RMSE)	86.29	85.35
Normalised Objective Function (NOF)	0.88	0.68

The optimized Curve number for the catchment is reported to be 78, which is indicative of generating higher runoff. As reported in the earlier paragraphs, the natural forest and plantations are the major land use of the basin (Figure 1), which is further supported by the lower values of ESCO, as its value is close to the defaulted of 0.95. As this parameter (ESCO) adjusts the depth distribution for evaporation from the soil to account for the effect of capillary action. The higher values of ESCO causes lower soil evapo-transpiration as entire soil layers is at the saturation and need not to compensate for a water deficit in upper layers, which in turn increases both surface runoff and baseflow. ESCO was found to have a higher impact on baseflow than surface runoff.

The other most sensitive parameter as reported elsewhere is Base flow alpha factor (ALPHA–BF) [5], any increase in the value will result in simulating steeper hydrograph recession. The GW_REVAP coefficient controls the amount of water that moves from the shallow aquifer to the root zone. This parameter was increased to allow more movement of water from shallow aquifer to the unsaturated zone. This parameter was used to adjust summer base flow.

GW_DELAY was modified to improve model predictions groundwater and summer low flow.

The model evaluation statistics obtained for both calibration and validation period are tabulated in Table 2. The Table 2 revealed that, the RMSE values for calibration and validation are lower and are indicative of the higher efficiency of the model in simulating the flow. Similarly the lower values were obtained for other evaluating parameter NOF.

4.1 Assessment of Impact of Climate Change on Water Balance Components

The calibrated and Validated SWAT model was used to simulate the water balance component of the basin using 0.25 degree IMD data and CCCma data for the period 1961-2000 (A1B scenario). The third generation Couple Global Climate Model (CGCM3) projected data were used in this study. The simulated average monthly water balance component for entire basin and at sub-basin level are tabulated in Table 3, and for the sub-basins used in the study Table 4.

From the Table 3, it is observed that, the majority of the runoff occurs during the south-west and north-east monsoon on the year amounting to 45% with the IMD data, whereas, the simulation using the CGCM3 data show that 51%. However, the ET estimates show a very low amount using the IMD temperature data and almost double the amount with CGCM3 data.

Table 3. *Simulated average monthly water balance component for entire basin and at sub-basin level*

Month	0.25 degree IMD data					CGCM3 data				
	Rainfall (mm)	Surface runoff (mm)	Lateral flow (mm)	Water Yield (mm)	ET (mm)	Rainfall (mm)	Surface runoff (mm)	Lateral flow (mm)	Water Yield (mm)	ET (mm)
January	14.69	1.43	1.39	57.23	71.08	34.84	8.19	1.2	23.38	47.24
February	26.61	0.78	0.85	19.43	46.03	51.69	6.62	1.37	14.32	48.83
March	39.32	0.62	1.09	6.71	33.69	142.69	48.17	3.28	56.21	53.55
April	123.32	9.03	2.21	14.25	48.44	157.66	77.52	3.88	92.95	45.06
May	200.13	52.84	4.11	67.22	62.99	516.51	332.36	8.24	362.11	58.1
June	594.08	282.9	9.27	334.66	44.91	379.98	217.43	9.56	267.92	60.13
July	674.19	359.64	14.59	500.34	44	373.89	219.64	9.18	290.1	68.56
August	452.93	210.17	12.15	406.92	53.74	261.34	117.74	7.92	194.02	70.67
September	313.61	118.24	7.9	302.5	58.36	282.15	141.17	8.25	216.34	59.51
October	365.04	139.96	9.73	308.33	63.34	211.8	96.85	6.61	174.8	68.81
November	197.23	71.46	8.09	220.82	54.24	56.27	15.21	3.09	73.9	39.52
December	50.59	9.14	3.52	118.29	39.53	24.14	4.69	1.45	38.56	21.2

This could be due to fact that, the IMD data is grid averaged data generated using measured data and CGMA is obtained through simulations. The hydrological simulations at sub-basin show a (Table 4 and Table 5) different picture. As shown in the Table 4, the sub-basins 3-7 is contributed to the runoff whereas the other two sub-basins have minimal contribution. A similar pattern is noticed for groundwater flow component. However, ET estimates are consistent across all the sub-basins. Further, it is observed that, the sub-basins covered by the evergreen forest have contributed more to the groundwater recharge than that of the crop/woodland mosaic (Table 5). The runoff simulated using CGCM3 data, yield very high runoff (>47%) irrespective of land cover. A lower groundwater recharge is observed under the CGCM3 simulation compared to that of the IMD data.

Table 4: *The sub-basin wise annual average water balance component in Manimala basin*

Sub-Basin	Area (Km^2)	0.25 degree IMD data				CGCM3 data			
		Rain (mm)	Surface Runoff (mm)	Ground Water flow (mm)	ET (mm)	Rain (mm)	Surface Runoff (mm)	Ground Water flow (mm)	ET (mm)
1	42.5	1964.23	521.23	729.6	679.25	2567.37	1265.99	571.74	696.15
2	62.3	1964.23	393.9	843.15	687.09	2567.37	1101.07	715.95	709.61
3	53.5	1964.23	525.78	723.94	679.4	2567.37	1272.33	563.14	697.52
4	93.4	3356.64	1384.94	1189.39	707.66	2567.37	1230.27	547.81	741.35
5	53.9	3356.64	1384.92	1194.79	707.61	2567.37	1230.25	550.32	741.33
6	13.2	3356.64	1384.89	1187.3	707.48	2567.37	1230.23	546.76	741.29
7	163.0	3356.64	1432.54	1170.1	695.09	2431.55	1297.23	408.99	692.09
7	130.0	3356.64	1722.48	1303.69	262.38	2431.55	1510.69	571.9	303.78

***Table 5**: Spatial variation of various hydrological processes and their contribution*

Sub-Basin	Area (Km^2)	Land use	0.25 degree IMD data			CGCM3 data		
			Runoff Coeff.	ET (% Rain)	GW (% Rain)	Runoff Coeffi.	ET(% Rain)	GW (% Rain)
1	42.5	Evergreen Broadleaf Forest	26.54	34.58	37.14	49.31	27.12	22.27
2	62.3	Evergreen Broadleaf Forest	20.05	34.98	42.93	42.89	27.64	27.89
3	53.5	Evergreen Broadleaf Forest	26.77	34.59	36.86	49.56	27.17	21.93
4	93.4	Forest Plantation	41.26	21.08	35.43	47.92	28.88	21.34
5	53.9	Forest/Plantation	41.26	21.08	35.59	47.92	28.88	21.44
6	13.2	Forest/Plantation	41.26	21.08	35.37	47.92	28.87	21.30
7	163.0	Crop/Plantation	42.68	20.71	34.86	53.35	28.46	16.82
8	130.0	Disturbed Forest	51.32	7.82	38.84	62.13	12.49	23.52

5. Conclusions

This study assessed and identified hydrologic parameters of the SWAT model by the application to the forested catchment located in Kerala India. The model was calibrated and validated using the observed runoff. This model has been used to simulate the impact of climate change on the water balance component. The results indicate that, there are noticeable changes reported for the CGCM projected data against the IMD grid data. However, keeping in view of the results obtained, following conclusions can be drawn

1. The sub-basin level analysis of water balance enables us to spatially identify the dominant hydrologic process.
2. The parameters such as CN, ESCO, GW_REVAPand SOL_AWC are the most sensitive parameters for the basin.

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