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Distributed rainfall runoff modeling over Krishna river basin

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Abstract: Floods can have catastrophic consequences and can have effects on the economy, environment and people. It initiates comprehensive assessment and forecasting of possible flooding events, which is typically carried out using hydrological models. Thus, the main objective of this study was to present a distributed hydrological model, namely Variable Infiltration Capacity (VIC) model for simulating the hydrological variables over Krishna River Basin, India and evaluating its performance by comparing with observed datasets. The main advantages of the VIC model compared to other physically based hydrological models, are the variable infiltration curve, which implements a nonlinear function of the fractional grid cell area to scale the maximum infiltration for enabling runoff calculations for sub grid-scale areas and the parameterization of baseflow using a nonlinear recession curve. Meteorological forcings at 0.5 degree by 0.5 degree spatial resolution from 1980 to 2005 over the basin were used to run the model at a daily time step. The model showed an acceptable performance during calibration and validation with Nash-Sutcliffe efficiency (NSE) = 0.34 and coefficient of determination (R^2) = 0.60 for calibration and NSE = 0.42 and R^2 = 0.68 for validation periods. The results from VIC model shows that it can handle large-scale variability. However, it has a tendency to overestimate the streamflow in the downstream portion possibly due to not considering the effect of storage structures in the present model.

Key words: Hydrological model, VIC, Streamflow

1. INTRODUCTION

Water is vital for agricultural, industrial, domiciliary and ecological purposes. Although the earth is made up of 71% of water, the amount of freshwater available for human use is very less. Water resources management requires a system approach, which includes all of the hydrological components, its linkage and interactions amongst all the components. Understanding the hydrology of a watershed is crucial for managing hydrological extremes (floods and droughts), through proper forecasting of hydrological variables.

The Krishna river basin is one of the major river basins in India. It ranks fourth considering annual discharge, and it is regarded as the fifth largest basin in terms of surface area in India. The Krishna River is flowing over the states of Maharashtra, Karnataka, Telangana and Andhra Pradesh, and providing freshwater (75% dependable water) of 58.3 km^3 (Sathish 2012). However, the hydrology of this river basin is changing rapidly due to human interventions on the environment, including land use and land cover change, irrigation, flow regulation etc. (Biggs *et al*. 2007). In last few decades, the Krishna River Basin has also witnessed high rainfall and consequent floods during monsoon. Hydrological models were developed and applied to look at these consequences on water resources by a large number of researchers (Bergstorm *et al*. 1998; Kite *et al*. 1999; Arnell 1999). Some of the past studies have noted that advanced basin scale hydrological models can contribute for better water resource management (Smakhtin 2006; Biggs *et al*. 2007), which is also very relevant to Krishna river basin.

In this paper, in order to represent the spatial variability of important land surface characteristics in River Basin, the VIC (3L) model, a distributed hydrological model, which is used widely by different researchers, is presented to simulate the runoff and other hydrological processes in Krishna River Basin. The VIC model was developed by Wood *et al*. (1992) and upgraded to the VIC-2L model by enhancing the water and energy balance algorithms by Liang *et al*. (1994). In the VIC-3L model, the spatial distribution of rainfall is also considered, and the parameterization of soil moisture and land surface thermal fluxes are integrated for simulating runoff and hydrographs precisely. In a recent study, Reddy *et al*. (2016) studied the effect of climate change impacts on crop water balance in lower Krishna River Basin of South India by VIC-3L model.

One of the crucial tasks for hydrologist is to estimate the various hydrologic variables for water policy making, flood regulations, hydropower plants and in various other watershed management works that utilize rainfall-runoff models to produce synthetic flood flows from rainfall data. Therefore, the goal of this study is to develop a general framework to perform hydrologic simulation by the application of a distributed hydrological modeling over Krishna River basin.

2. DESCRIPTION OF VIC HYDROLOGICAL MODEL

VIC is a semi-distributed land surface hydrologic model that considers the interaction of atmosphere, vegetation and soil, the dynamic change of water and energy flux. One distinguishing characteristic of the model is that it represents vegetation heterogeneity using multiple vegetation tiles in a single grid cell, multiple soil layers with variable infiltration, and non-linear drainage from a lower soil moisture zone (base flow) (Wood *et al*. 1992; Liang *et al*. 1994). For vegetation tiles, evapotranspiration is calculated according to the Penman–Monteith equation (Liang *et al*. 1994), adding the canopy layer evaporation and vegetation transpiration. The Horton infiltration curve is employed to account for the sub-grid variability of soil infiltration functionality under various soil types land covers.

As the VIC-3L model generates the runoff depth in each grid cell, a standalone routing scheme is required for routing of the model simulated runoff via channel network to the outlet of the basin. The routing scheme that was presented by Nijssen *et al*. (1997) is used in the study. This routing model transports the grid cell surface runoff simulated by means of the VIC-3L model inside every grid cell to the outlet of that grid cell and then into the river network. The routing within a grid cell makes use of a Unit Hydrograph theory, and the channel routing makes use of the linearized Saint-Venant equations.

3. MODEL APPLICATION

3.1 Study area and data used

The Krishna River Basin, located in southern India, lies between 73°15′ to 81°20′ E and 13°5′ to 19°20′ N (Fig. 1) with a total basin area of 258,912 km^2. The river originates in the Western Ghats at an elevation of about 1337 m, just north of a town called Mahabaleshwar at about 64 Km from the Arabian Sea, and flows for about 1400 km before reaching the Bay of Bengal. The average annual rainfall is 850 mm (spatially varying 500–2000 mm); the maximum temperature varies between 20° C and 42°C and the minimum temperature between 8° and 30°C.

The VIC model requires various forcing files, which includes meteorological, soil parameter, vegetation parameter and vegetation library files. This vegetation parameter and vegetation library data is used to differentiate between various land cover types. This vegetation datasets are collected from Hydro Group at University of Washington (Weedon *et al*. 2011) at a one-kilometer spatial resolution and consists of 11 different land cover classes. Soil data is based on soil textures of FAO (1995) and obtained from the same source. For gridded weather data, this study uses the dataset prepared for VIC at $0.5^o \times 0.5^o$ spatial resolution for the period 1980 to 2005 by the University of Washington Climate Impacts Group (Maurer *et al*. 2002). Daily observed streamflow of the Krishna River at Wadenapally station was taken from the WRIS-India for model calibration.

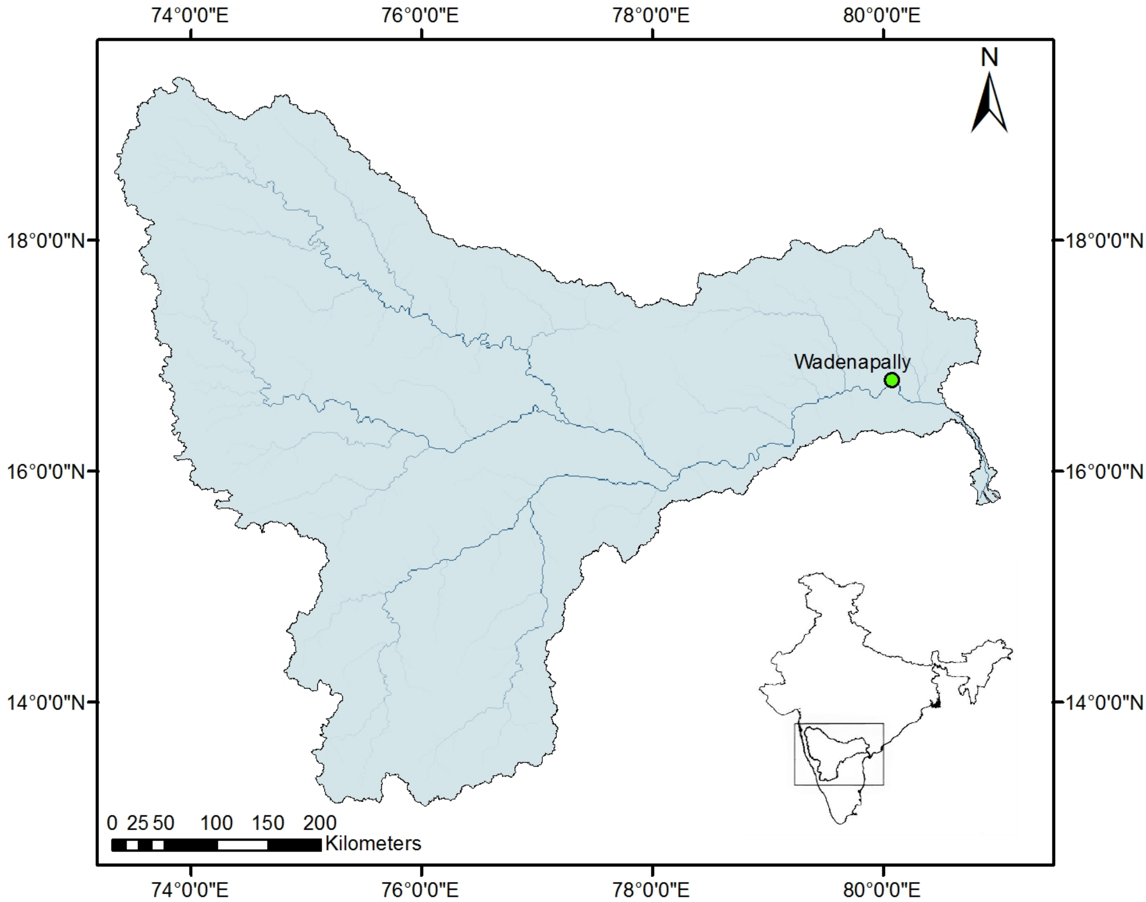

Figure 1. Krishna River Basin

3.2 Model implementation

Data are collected from the mentioned sources and extracted for the study area. Both the VIC model and the standalone routing model are run on Linux platform. All hydrological simulations were performed at daily time step in water balance mode. Routing model was assigned to compute the daily series of the streamflow at Wadenapally station of the Krishna River Basin. Streamflow is an effective measure of hydrologic response in the river basin. Hence, observed streamflows are considered as the most important parameters for comparison of the model and understanding the model capabilities. Given that, the size of the modelled study area is large, monthly averages were used to compare simulated and observed streamflow. The observed discharges of Wadenapally hydrological station are used in model calibration.

3.3 Model calibration and validation

Physically based VIC hydrological model has several parameters that need to be adjusted. Generally, six parameters are approached for calibration (Lohmann *et al*. 1998): i) the infiltration parameter (b_{inflt}), that regulates the separation of rainfall into direct runoff and infiltration (a lower b_i offers higher infiltration and yields less surface runoff); ii) d_2 and d_3, that are the thickness of second and third soil layer and have an effect on the available water for transpiration and baseflow respectively (thinner soil depths have faster runoff reaction); iii) W_s, D_s and D_{smax} are the parameters for baseflow and also are finalized via calibration. W_s represents the fraction of most soil moisture content of the third soil layer at which non-linear baseflow occurs, D_s represents the fraction of largest baseflow speed, and D_{smax} represents the highest baseflow speed. These three baseflow parameters decide how fast the stored water in the third soil layer is departed as baseflow (Liang *et al.*1994). The calibration procedure here involves manual adjustment of these six parameters values to achieve best-fit results. During model validation, calibrated parameters were taken as input along with other known parameters and the performance of the VIC model were evaluated using Coefficient of determination (R^2) and Nash–Sutcliffe efficiency (NSE) by the following equations:

$$R^2 = \frac{\left(\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(S_i - \overline{S}\right)\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 \times \sum_{i=1}^{n}\left(S_i - \overline{S}\right)} \tag{1}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \tag{2}$$

where O_i and S_i are the observed and simulated values, n is the total number of paired values, $\overline{O}$ is the mean observed value.

4. RESULTS AND DISCUSSION

The VIC model using the Lohman routing scheme was applied to the Krishna river basin to simulate the streamflow during the period of 1980 to 2005. The meteorological forcing series was divided into two part (i.e., 1980-1884 and 1995-2005) for evaluating the streamflow before and after the rapid irrigation project expansion and dam construction**.** The calibration period was chosen from 1/1/1980 to 31/12/1989, in which the model was manually calibrated using standard calibration measures. Calibration was performed for the monthly mean streamflow. During calibration, value of the coefficient of determination was 0.604, and the value of Nash Sutcliffe model Efficiency (NSE) was obtained as 0.34. A yearly average simulated flow of 968 m^3/s vs a yearly average observed flow of 756 m^3/s were also obtained during calibration. So, there is clearly some overestimation in model simulated flow values. For simulated and observed flows, the standard deviations were obtained as 1008 m^3/s and 1259 m^3/s respectively. It indicates the averaging out of extreme flow values in VIC model. Details of the calibrated parameter values and their range used for calibration are given in the Table 1. Comparison of the monthly average runoff between calibrated simulated streamflow and observed streamflow is shown in the Figure 2a.

Table 1. Details of the calibrated parameter values

Parameter	units	Range	Calibrated value
b_{infilt}	index	0.00001–0.4	0.01
D_s	fraction	0.0–1.0	0.2
D_{smax}	mm/day	1-40	5
W_s	fraction	0.0–1.0	0.99
d_2	meters	0.3-2.5	0.7
d_3	Meters	0.2-4.5	2.1

After model calibration, next five years (1990-1994) were chosen for model validation. Comparison of monthly average runoff for validation period is shown in the Fig. 2b. During validation, values of coefficient of determination and NSE were estimated as 0.68 and 0.42 respectively. Mean and standard deviation of simulated flows were 963 and 1187 m^3/s, while for observed flow they were 1019 and 1353 m^3/s for the validation time. From the results presented in Fig. 2b, is can be noticed that the model is performing quite well during validation period.

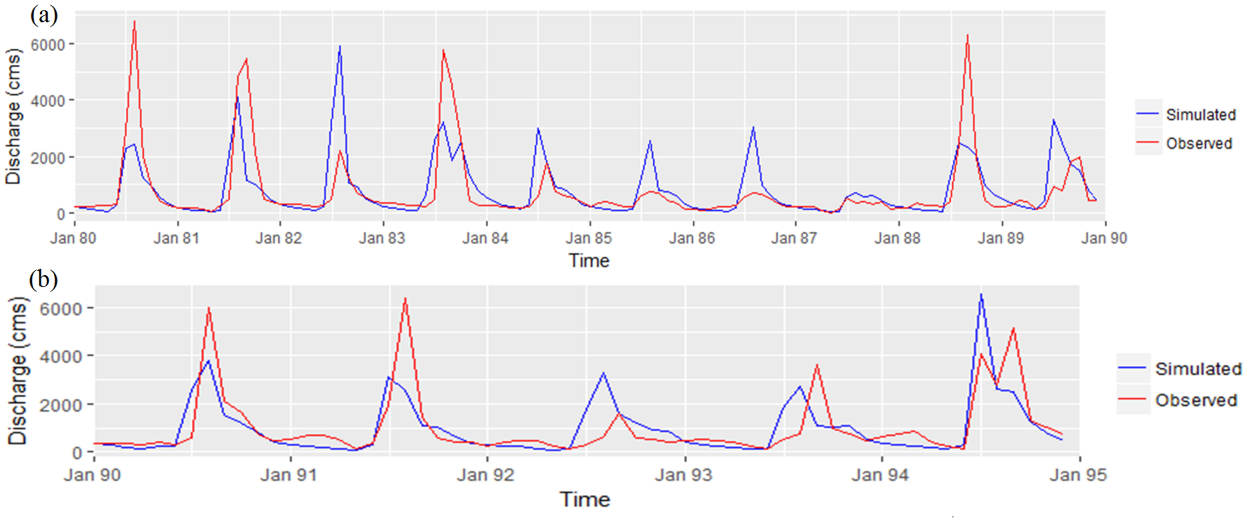

Figure 2. Comparison of VIC generated streamflow with observed streamflow during (a) calibration (1980-1989) and (b) validation (1990-1994)

According to CWC report (1999), Krishna river basin's mean annual runoff was found to be 57 km^3 (29% of rainfall) or 1807 m^3/s for 1901-1990, which is around twice of the simulated average annual runoff for the basin (968 m^3/s). It has been reported that rapid dam construction and irrigation project expansion resulted 54.5 km^3 of total live reservoir storage by the twenty century, which is also nearly equal to annual discharge of Krishna river basin (Biggs *et al*. 2007). Even in the present study, when the calibrated model was operated for 1995 to 2005, it showed a poor performance with coefficient of determination and NSE as 0.5 and -4.2 respectively. It can be shown (Fig.3) that, after 1995 most of year were having significantly less discharges, even in the monsoon periods. The annual average of simulated flow during this period was 1129 m^3/s, while the observed annual flow decreased to 460 m^3/s. Without significant changes in rainfall, discharges were reduced due to the effect of various storage structures. This might attribute to the degradation of model performance due to not considering this storage structures effects within the model.

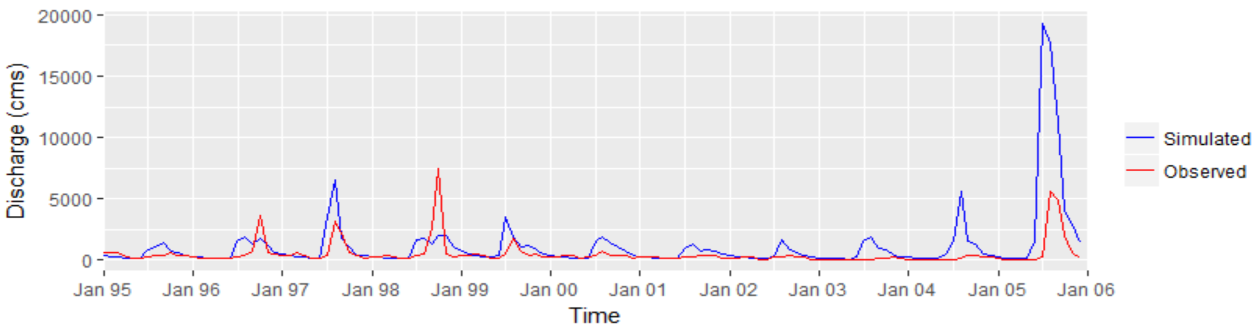

Figure 3. Comparison of VIC generated streamflow with observed streamflow during 1995-2005

4. CONCLUSION

In this study, a framework for applying the VIC-3L model to conduct hydrological simulations over the Krishna River Basins is described. Daily forcing data for the period of 1980 to 2005 are prepared grid-wise at $0.5^o \times 0.5^o$ spatial resolution along with the vegetation and soil dataset, and then the VIC-3L model is applied to each of the 93 grids of Krishna river basin. Comparison of monthly streamflow at Wadenapally in the Krishna River Basin shows a moderate agreement between model simulated and observed flows.

However, it is also found that in the Krishna river basin, the large number of storage structures (i.e., total 660 dams) is effecting the natural stream and play an important role in altering the flow hydrographs. These storage structures are also found to be responsible for minimization of peak annual flood, which leads to a reduction in flood damages. However, it is expected that in order to obtain a better hydrologic simulation in Krishna river basin using VIC hydrologic model, the effect of storage structure should be incorporated in the model.

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