SIMULATING HYDROLOGICAL ALTERATIONS IN THE CONDITIONS OF LIMITED DATA: LESSONS FROM THE WALAWE RIVER BASIN IN SRI LANKA

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ABSTRACT

The paper examines the performance of two modeling methods of varying complexity in the conditions of limited observed data, using the example of Rakwana Oya catchment - a tributary of Walawe river basin in the Southern Sri Lanka. The first method is a distributed physically based SWAT model. The second is the non-linear spatial interpolation method which deals exclusively with observed records. The SWAT model was calibrated and subsequently applied to assess the impacts of land use change on river flows with different land use scenarios for years 1956, 1985 and 1999. While the model is useful for assessing such impacts on flow, its intensive data requirements suggest that its application to bigger catchment (e.g. the entire Walawe basin) is not feasible. It is shown that less data intensive, spatial interpolation method can also perform satisfactorily and may be used to simulate non-regulated river flows in small and big basins.

INTRODUCTION

The quantification of hydrological processes under natural and modified conditions in study river basins is a constant need for the variety of social, environmental and engineering applications. In developing countries such quantification is often complicated by limited quantity and poor quality of available observed data and other pertinent information. A typical example is the Walawe River basin which spreads across the semi-arid zone of southern Sri Lanka. A number of dams, irrigation tanks and conveyance structures have impounded, over the years, the flow in Walawe River and its tributaries, leading to adverse social and environmental consequences, while measuring network in the basin has remained inappropriate. The purpose of the current study was three-fold: to investigate the performance of existing modeling methods of varying complexity in the conditions of limited observed data, to establish the hydrological reference condition against which the impacts of land-use change and water-resources development in the basin over the last 50 years could be assessed, and to quantify these impacts.

BASIN DESCRIPTION

Walawe is the largest river basin (2442 km^2) in the southern part of Sri Lanka, spreading over four administrative districts. The river originates in the southern part of the central uplands at the altitude of 2395 masl and travels 84.9 km southwards before it flows into the Indian Ocean near Ambalantota town (Fig.1). A characteristic feature of the basin is two wet seasons - from the North-East and South-West monsoons with peaks in April and November. The average annual precipitation is 2050 mm with uneven spatial distribution. Despite high precipitation, droughts occur every 3-5 years and some parts of the basin experience water scarcity problems during February-March and July-October in almost every year. About 40% of the catchment area is under irrigated land and 20% under rain fed agriculture. Natural and planted forests constitute another 20% and the balance area is home gardens, wetlands and degraded lands.

Irrigation development has been the major strategy for livelihood enhancement of the people in the basin. Two major reservoirs for irrigation and hydropower generation are constructed on the main river. The two major reservoirs, Samanalawewa (upstream, in 1993) and Udawalawe (middle reaches, in 1967) with a total capacity of 486 MCM, supply water for hydropower and irrigation schemes (Fig.1). The land-use of the basin has also undergone significant changes over the past few decades. The attempt to assess these changes was first made using the limited data from the only gauged tributary of Walawe – Rakwana Oya at Thimbolketiya (this sub-basin is drained, effectively, by two almost similarly sized streams Rakwana Oya and Andolu Oya - Fig. 2). The drainage area of the catchment is 232 km^2, which is about one tenth of the total Walawe catchment. This sub-catchment was selected for the initial application of modeling approaches, because it has 9 years of measured daily flow data and no major flow control structures upstream. The major land-use categories identified within the basin include: forest, scrubland, paddy, and cropland. Built-up land, homesteads, pasture, chena, marshes and water bodies are also present to a lesser extent. These land-uses are typical to the entire Walawe River basin.

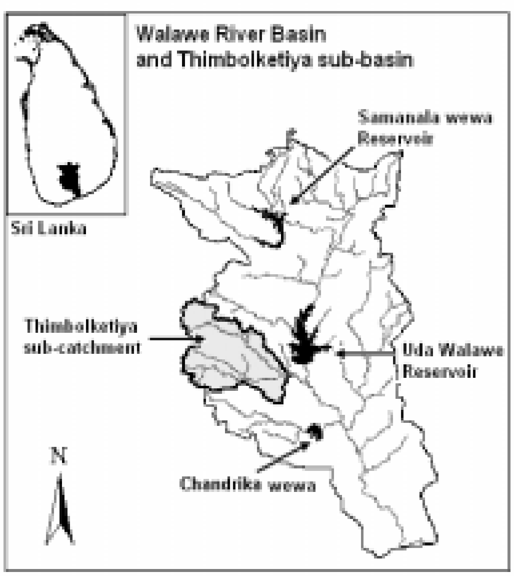

Fig. 1: A schematic map of the Walawe river basin

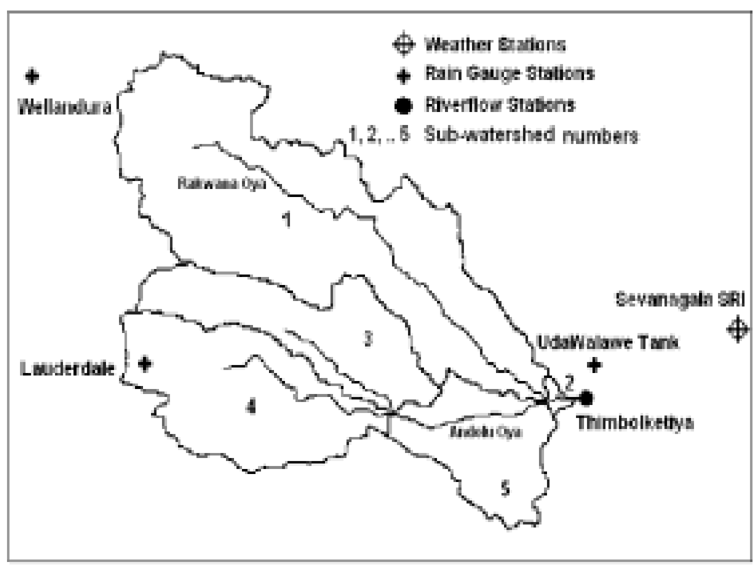

Fig.2: The five sub-watersheds of the Thimbolketiya catchment and locations of measuring stations

SWAT MODEL APPLICATION

Model description

The Soil and Water Assessment Tool (SWAT) of Environmental Protection Agency (EPA) USA, is a physically based catchment model operating with a daily time step (Arnold et al., 1993).SWAT uses the topography, land use/cover conditions, soil and meteorological time series as inputs, and simulates the hydrologic cycle with the following water balance equation

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_i - Q_{surf,\,i} - E_i - W_{seep,\,i} - Q_{gw,\,i}) \qquad (1)$$

where SW_t is soil water content (mm) on day t, SW_0 is the initial soil water content (mm), R_i is the amount of precipitation on day *i* (mm), Q_{surf} is the amount of surface runoff on day *i* (mm), E_i is the amount of evapotranspiration on day *i* (mm), $W_{seep,i}$ is the amount of water entering the vadose zone from the soil profile(percolation) on day *i* (mm), and $Q_{gw,i}$ is the amount of return flow on day *i* (mm).

Precipitation may be intercepted or fall to the soil surface. Water on the surface infiltrates into the soil profile or flows as runoff. Infiltration is calculated with SCS method.

Surface runoff moves towards a stream channel and contributes to short-term catchment response. SWAT simulates surface runoff volumes and peak runoff rates for each Hydrologic Response Unit (HRU). A HRU is a calculation unit that consists of a single land use and soil type. Runoff volume is computed using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972). The curve number varies non-linearly with moisture content of the soil.

The model computes evaporation from soils and plants separately. Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index (Ritchie 1972). Actual soil water evaporation is estimated using exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index. Potential evapotranspiration is estimated by Hargreaves formula (Hargreaves and Samani, 1985).

The redistribution component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Percolation occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is determined by the saturated hydraulic conductivity of the soil layer. Lateral subsurface flow in the soil profile (0-2m) is calculated simultaneously with redistribution using kinematic storage model. The model accounts for variation in conductivity, slope and soil water content. It also allows for flow upward to an adjacent layer or to the surface.

Return flow (base flow) is the stream flow originating from groundwater. SWAT allows the simulations to be made separately for two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the basin and a deep, confined aquifer which contributes return flow to streams outside the basin (Arnold et al., 1993). Water percolating below the root zone is partitioned into two fractions which constitute recharges to these aquifers. In addition to return flow, water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions or be directly removed by plant uptake. SWAT models the movement of water (from shallow aquifer) into overlaying unsaturated layers as a function of water demand for evapotranspiration.The maximum amount of water that will be removed from the aquifer via this (‘*revap*’) process, is determined by the REVAP coefficient. Water in the shallow aquifer may also seep into the deep aquifer or be removed by pumping. Water in the deep aquifer may be removed by pumping.

Catchment subdivision

For simulation purposes, Thimbolketiya catchment was further sub-divided into five smaller sub-watersheds. The boundaries of these drainage units are shown in Figure 2. For each sub-watershed land use and soil data were supplied. In the given area, 10 land use/cover types and 4 soil groups were identified. Three rainfall gauging stations (Wellandura, Lauderdale and Udawalawe) with measured daily rainfall records, are located in the vicinity of the catchment (Fig. 2). However, the detailed analysis of rainfall data revealed that only Wellandura station is usable. Other climatic time series data for the region are obtained from the Sevanagala Sugar Research Institute's meteorological station.

The daily flow data from the Thimbolketiya gauging station (maintained by Irrigation Department of Sri Lanka) from 1990 to 1994 (5 yrs.) were used for model calibration. Daily data from 1995 to 1997 (3 yrs.) were used for model validation.

Model calibration

Model calibration is carried out for two sets of parameters: parameters related to surface runoff and parameters related to soil (unsaturated zone) and groundwater. The calibration parameters are listed in Table 1.

The single calibration parameter directly related to surface runoff is the SCS curve number. Each land use type in the watershed is assigned a runoff SCS curve number (CN). SWAT further reclassifies this information to assign each HRU with a curve number. During model calibration the CN values for each land use category was adjusted within acceptable limits, to achieve the required peak flow values.

Most of the soil and groundwater parameter measurements were not available. Therefore in the calibration process the most sensitive ground water parameters were identified. The plant available water capacity in soil(SOL_AWC) and the soil conductivity (SOL_K) parameter was adjusted within the limits allowed for given soil (Dingman 1994).The Revap coefficient(GW_REVAP), and the threshold depth of the shallow aquifer for base flow to occur (GWQ_MN), governing the ground water flow were also adjusted. A threshold depth GWQ_MN should be exceeded in the shallow aquifer for Revap to occur. Also these two parameters are highly correlated. Adjustments to the parameter values were made keeping this fact in mind. Base flow recession constant (ALPHA_BF) which is a direct index of groundwater flow response to changes in recharge of the shallow aquifer was also adjusted to achieve the required baseflow values in the outflow hydrograph.

Table 1. Calibrated model parameter values

Parameter description	**Units**	**Value**
Curve Number (CN)	-	39-60†
REVAPMN (threshold depth of shallow aquifer)	mm	100
GW_REVAP (groundwater revap coefficient)	-	0.10
GWQMN (shallow aquifer depth for revap)	mm	200
ALPHA_BF (baseflow Alfa coefficient)	days	1.0

† curve numbers range for major land use types

Table 2. Fit statistics at Thimbolketiya for the two simulation approaches

	SWAT		**Spatial Interpolation**
	Calibration	**Validation**	**Validation**
	1990 - 1994	1995 – 1997	1990– 1998
R^2	0.77	0.57	0.42
CE	0.24	0.39	0.38

The example hydrograph for the year 1995 from the validation period is shown in Figure 3. The statistics in Table 2 are the best which could be achieved given the quality of the available input data. The inaccuracies may partially be attributed to the lack of good quality rainfall data (which does not allow spatial variability of rainfall over the catchment to be properly reproduced on a daily time scale), partially – to inherent inaccuracies in observed flow data and partially – to catchment approximation for simulation. While limited improvement may, perhaps, be achieved with a different approximation, the first two problems will remain. In addition, the model was run for the latter period (validation) with the "static" land-use of 1985, which may have also impacted the quality of simulations.

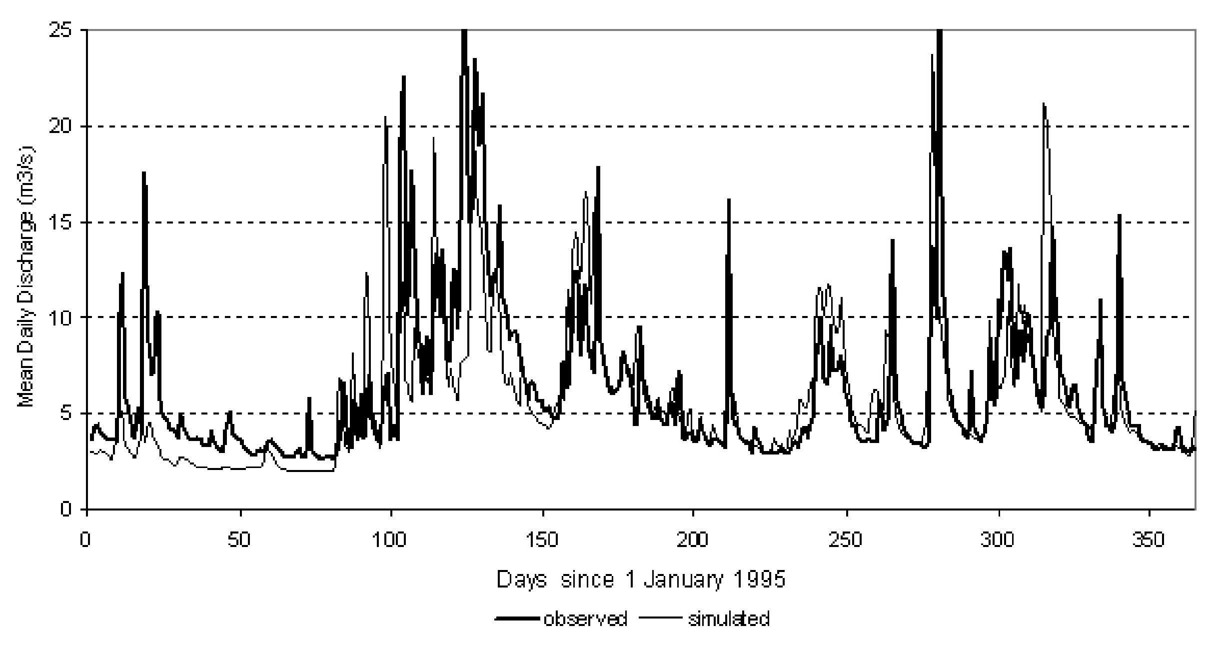

Fig. 3 : Observed and simulated hydrographs at Thimbolketiya, 1995

Simulating land use changes

The calibrated model can be used to evaluate the effects of land use/land cover change on the basin hydrology. A land use/land cover map in SWAT is linked to a database with parameter values for each land use type featured in that map. For the selected years (1956, 1985 and 1999) three separate land use maps are prepared (Fig. 4) and linked to the database. The change of land use over the time is represented in these maps by the varying areal extent of different land use/land cover types. Rainfall time series for the period of 1990 to 1997 were used with three different land use scenarios to generate corresponding catchment responses. Figure 5 shows the extracts from the hydrographs simulated at these scenarios with the same rainfall input.

Statistical analysis of the two land use maps show that during the 43 years from1956 to 1999, the coconut cultivation area has increased by 10.4 % and gardens and built-up areas has increased by 5 %. Scrub jungle area has decreased by almost 10 %. Tea cultivated area has decreased by 3.78 %. Rubber and Paddy cultivation areas have decreased each by 1.5 %. Areas under other plantations have increased. The effect of these individual changes on catchment response is varied. The least variable flows (low peaks and high low flows) have been simulated with the land-use scenario of 1985, which was characterized by least scrub area and increased coconut plantation compared to 1956. The decrease in forest area from 1985 to 1999 by almost 20% and corresponding increase in gardens lead to a slight increase in peaks and reduced low flows in 1999 scenario (Fig. 5). Overall, over the last 43 years the expansion of agricultural area and the population has increased the water use and hence, reduced the total runoff at the catchment outlet.

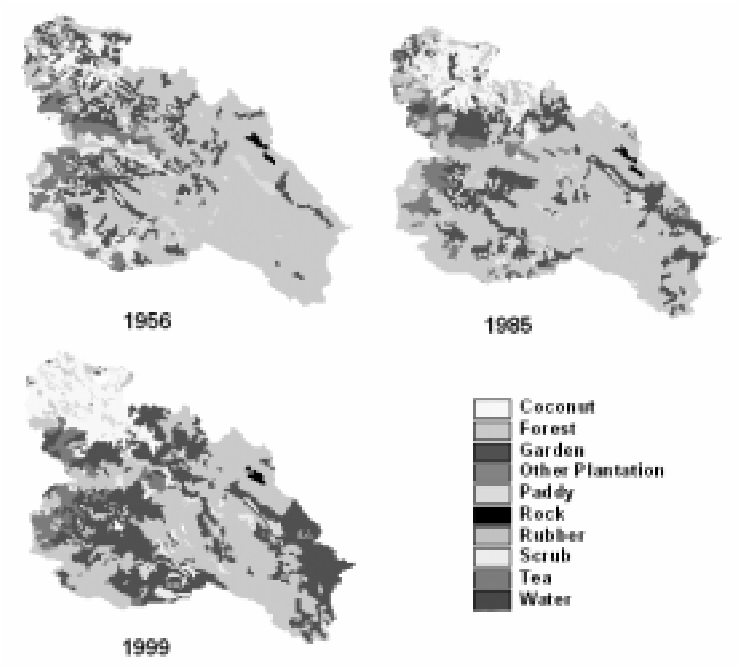

Fig. 4 : Land use / Land cover maps of Thimbolketiya catchment for 1956, 1985 and 1999.

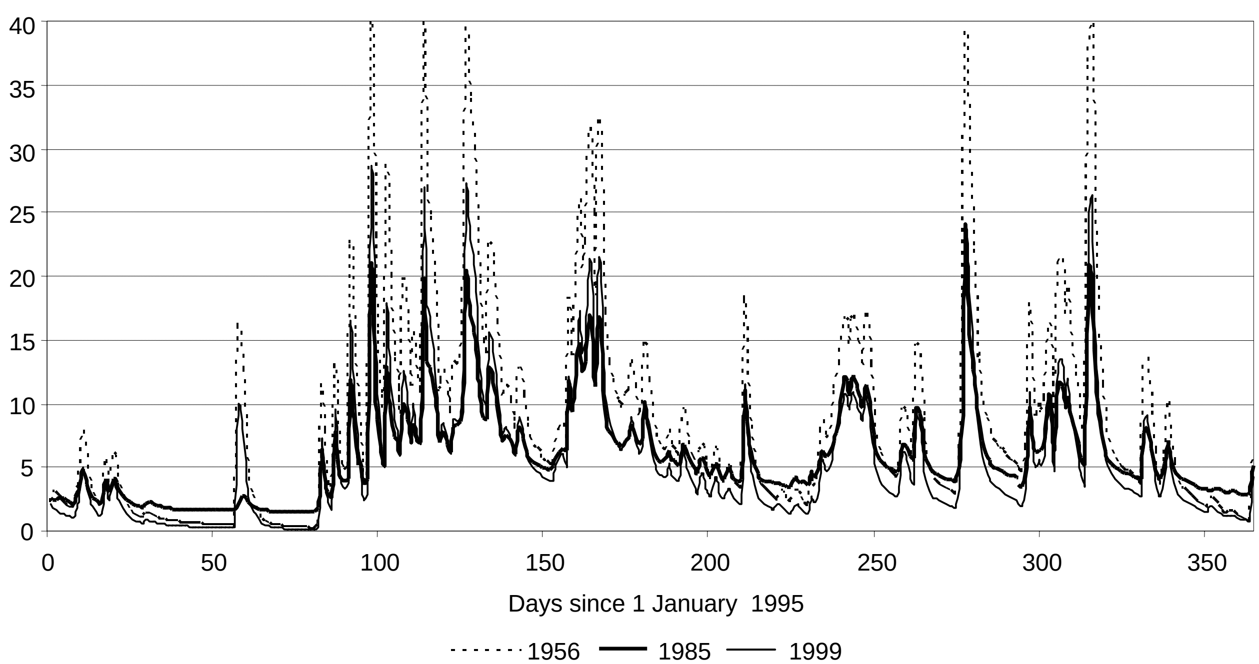

Fig. 5 : Simulated hydrographs for land use /land cover scenarios of 1956, 1985 and 1999

APPLICATION OF SPATIAL INTERPOLATION METHOD

The application of information consuming modeling methods, such as SWAT, may not always be appropriate in data poor regions, like Walawe basin. The use of more pragmatic techniques may be more justified, much less resource intensive and equally successful. The alternative technique used to simulate flows at Rakwana Oya is known as "spatial interpolation" of observed flow records (Hughes and Smakhtin [1996]). This technique makes an intensive use of flow duration curves. A flow duration curve (FDC) is a cumulative distribution of river flows: a relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded. It is normally calculated from available observed or simulated flow time series. But because the shape of the curve is determined by rainfall pattern, catchment size and physiographic characteristics, land-use type and the state of water resources development, the primary assumption of this approach is that the effects of all these factors may be built into a FDC *prior* to the simulation of the actual flow time series. The components of this approach therefore include i) technique(s) by which to establish representative FDCs for different types of ungauged river catchments and ii) technique(s) by which the established FDCs may be transformed into actual continuous flow time series for any further analysis.

Estimating flow duration curves

For ungauged river basins, FDCs may be constructed by means of hydrological regionalization (e.g. Smakhtin et al [2004]). If a graphical approach is used, for example, the FDCs from available gauged catchments in a physiographically homogeneous region may be standardized by some "index" flow (e.g. long-term mean discharge) and plotted on one graph. Each FDC is represented by several flows at fixed percentage points to cover the entire range of probabilities. By averaging the standardized ordinates of all curves for each of the fixed percentage points, the average regional curve may be calculated. To establish the actual FDC at the ungauged site, the regional curve must be made dimensional by multiplying its standardized flows by the estimate of a long-term mean (or other index flow used). Long-term means may be calculated using national hydrological databases, relevant regional regression models or other established national practices. A special case of this approach is when the FDC at the ungauged site is established by using the curve from the nearest gauged site either in the same or in the adjacent catchment. The "gauged" curve is adjusted by the ratio of index flows or catchment areas of ungauged and gauged basins.

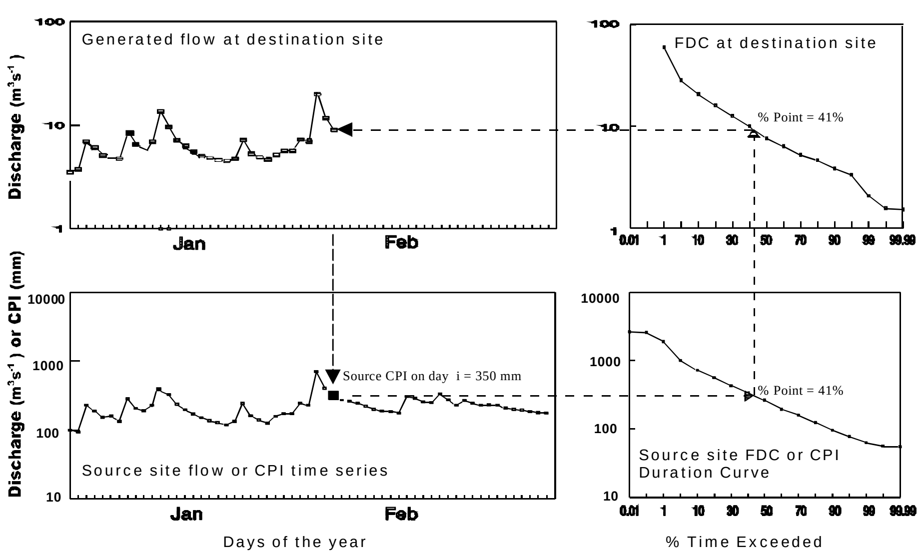

Fig. 6 : Illustration of the spatial interpolation procedure.

Generating Continuous Streamflow Time Series

Once a FDC is established it may be converted into actual continuous flow time series by a non-linear spatial interpolation algorithm developed by Hughes and Smakhtin (1996). The method uses the data from one or more "source" (gauged) sites and transfers these data through the FDCs to the "destination" site, where the flow time series is required. The main assumption of the algorithm in its original form is that flows occurring simultaneously at sites in a reasonably close proximity to each other correspond to similar percentage points on their respective FDCs. For each selected source and destination sites, tables of discharge values are generated for each month of the year for the 17 fixed percentage points on the corresponding FDC (from 0.01% to 99.99%). The core of the computational procedure includes the estimation of the percentage point for each day's flow at the source site and the identification of flow for the equivalent percentage point from the destination site's FDC (Fig. 6). The discharge tables are used to "locate" the flows on corresponding curves and log-interpolation is used between fixed percentage points. If several source sites are used, the procedure is repeated for each of them and the final destination discharge value on that day is calculated as a weighted average of values obtained using individual source sites.

The selection of source site(s) is usually subjective. The general rule is to select the nearest unregulated gauge at the same stream as the destination site, or to select gauges in the nearest adjacent catchments(s). In both cases, the assumption is that if there is some overlap in catchment area and/or if the adjacent catchment areas are likely to experience similar rainfall pattern, then both source and destination sites will have similar hydrological responses. It has to be noted that the choice of source data is almost always limited and/or obvious, considering the scarcity of gauged records in data poor regions. If no suitable source flow gauge(s) with observed records can be identified in the vicinity of the destination site, the use may be made of more readily available rainfall records. In this case, both source flow time series and source FDC (bottom two graphs in Fig. 6) are replaced by corresponding rainfall-related functions, reflecting the status of catchment wetness. One example of such function is Current Precipitation Index, which reflects daily precipitation input and an exponential depletion of catchment moisture during days with no rainfall (Smakhtin and Masse [2000]).

$$CPI_t = CPI_{t-1} K + R_t \tag{2}$$

where CPI_t is a Current Precipitation Index (mm) for day t, R_t is the catchment precipitation for day t and K is the recession coefficient, which was found to vary in a small range of 0.8 to 0.95 and has limited impact on the resultant time series. Continuous daily CPI time series may be generated for any rainfall station in a catchment and consequently, the required CPI duration curves may also be established. They are then used as substitutes for the source flows. The major assumption of the algorithm in this case becomes that both the CPIs occurring at rainfall sites in a reasonably close proximity to the destination site, and the destination site's flows themselves correspond to similar percentage points on their respective duration curves. The layout of the computational procedure remains the same (Fig. 6).

Simulating daily flows for Rakwana Oya

The Rakwana Oya at Thimbolketiya is a tributary of Walawe, which, in turn, is part of a group of catchments collectively known as Ruhuna drainage area. The total drainage area of Ruhuna basins is over 5500 km^2. Only five flow gauges in the entire Ruhuna area were identified, for which daily flow data were available. Only three of these were found to be reasonably accurate. The average observation period for these datasets was 22 years. These data sets were used to calculate the regional FDC standardized by the long-term mean daily discharge using the simple averaging procedure described above.

As was already mentioned, the Rakwana Oya at Thimbolketiya is also gauged and the daily flow data are available for the period from 1990 to 1998. For the purpose of the study, this catchment was however considered to be ungauged and the available flow record was only used to assess the quality of simulations. To establish the actual FDC at the "ungauged" Thimbolketiya site, the estimate of a mean flow was obtained using the "basin-rainfall" method, which assumes that in two adjacent basins, flow varies proportionally to their areas and areal rainfall amounts (Dharmasena [1999]). The calculated long-term mean flow at Thimbolketiya was then used to calculate the destination FDC.

No suitable flow gauges with daily data in the vicinity of Thimbolketiya catchment were identified. It was therefore necessary to use the rainfall data from the nearest three rain gauges. The CPI time series were calculated by (1) for each rain gauge and used as source time series in the spatial interpolation procedure described in the text above and illustrated by Figure 6. Arbitrarily selected extracts from the simulated and observed daily flow time series are presented in Figure 7. The lack of suitable source records leaves almost no options for "calibration" or improvement of the results. The R^2 and Coefficient of Efficiency do not exceed 0.42 and 0.38 respectively, but are only slightly worse compared to those obtained for the same site using SWAT model.

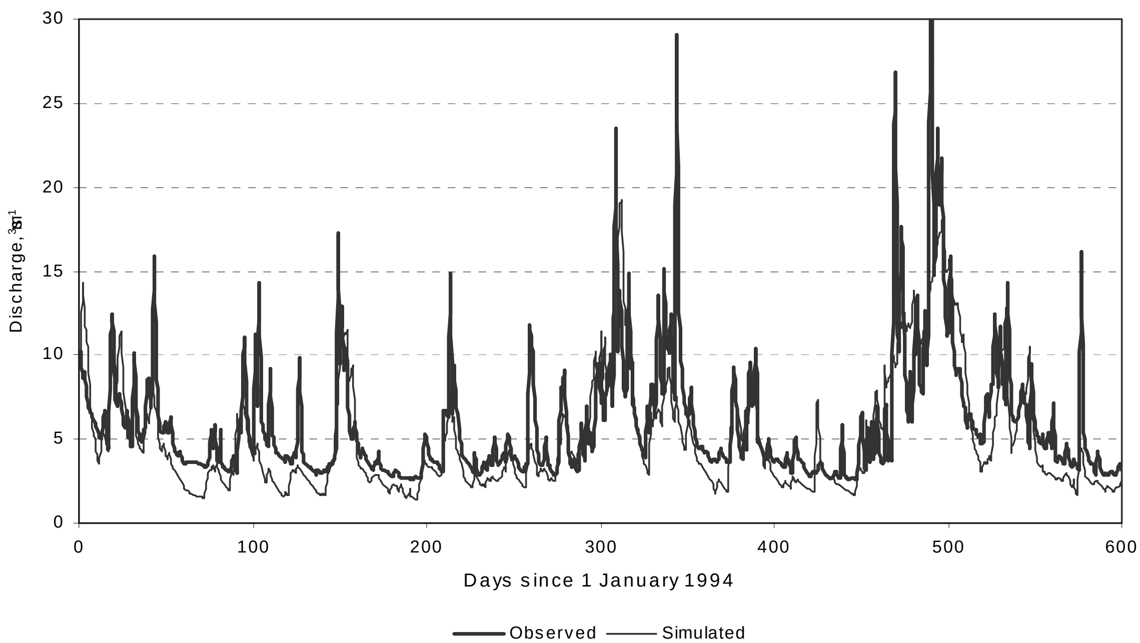

Fig. 7 : The extracts from observed and simulated by FDC method daily flow time series for Rakwana Oya at Thimbolketiya.

CONCLUSIONS

The results of the study show that simpler modeling methods, which use much less input data (when compared to deterministic physically based distributed models), can produce comparable results with less effort.

At the same time, in data poor regions with the high uncertainty associated with available model input (particularly, rainfall) the achievable accuracy of the results is limited regardless of the simulation method used.

The application of the physically-based models like SWAT remains a feasible option for assessing the impacts of land-use changes and water-resources developments, because, as was illustrated in the study, the effects of these changes may be incorporated into model parameter values. Simplified simulation approaches, like spatial interpolation, lack this capability.

Simulating *daily* streamflow hydrology of river basins is a particularly difficult case (compared with monthly modeling, for example), due to the complexity of hydrological processes at this scale and associated with it increased data requirements. At the same time, it is daily flow analysis which will be more needed for the future as the demands to accuracy increase and as new tasks will be on the agenda for water resources management. The example is the assessment and maintenance of environmental flow requirement of rivers and wetlands, which have become the accepted concept in several countries in the world and are slowly emerging in Sri Lanka. Such assessment methods use primarily daily flow data.

In the context of the above, simplified methods constitute a useful option for simulation of past, unregulated and un-impacted river flows (hydrological reference conditions), against which to assess the subsequent flow changes. Once the regional flow duration curves, based on unregulated (even limited) observed flow records are established for a region or a basin, they can be used to "restore" the natural flow pattern in river basins from that region. The spatial interpolation method is now being applied for such restoration at different sites along the main stream of Walawe River, where the assessment of environmental flow requirements will follow.

If long-term hydro-meteorological data collection programs are not established and maintained and if already collected data are not managed/conserved properly, lack of available data, for application of hydrological models will remain a major problem.

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