HYDROLOGICAL PROCESSES
Hydrol. Process. **28**, 628–639 (2014)
DOI: 10.1002/hyp.9615

Modelling the impact of extensive irrigation on the groundwater resources

T. V. Reshmidevi[1] and D. Nagesh Kumar[2]*

[1] *Department of Civil Engineering, Indian Institute of Science, Bangalore, 560012, India*
[2] *Also with Center for Earth Sciences, Indian Institute of Science, Bangalore, 560012, India*

Abstract:

Drastic groundwater resource depletion due to excessive extraction for irrigation is a major concern in many parts of India. In this study, an attempt was made to simulate the groundwater scenario of the catchment using ArcSWAT. Due to the restriction on the maximum initial storage, the deep aquifer component in ArcSWAT was found to be insufficient to represent the excessive groundwater depletion scenario. Hence, a separate water balance model was used for simulating the deep aquifer water table. This approach is demonstrated through a case study for the Malaprabha catchment in India. Multi-site rainfall data was used to represent the spatial variation in the catchment climatology. Model parameters were calibrated using observed monthly stream flow data. Groundwater table simulation was validated using the qualitative information available from the field. The stream flow was found to be well simulated in the model. The simulated groundwater table fluctuation is also matching reasonably well with the field observations. From the model simulations, deep aquifer water table fluctuation was found very severe in the semi-arid lower parts of the catchment, with some areas showing around 60 m depletion over a period of eight years. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS ArcSWAT; groundwater; irrigation; water balance

Received 4 May 2012; Accepted 8 October 2012

INTRODUCTION

With fast depleting fresh water resources and increasing demand for food grains, agricultural growth and water resources sustainability are becoming two critically conflicting issues. Several studies were conducted in the past on fresh water resource depletion resulting from the excessive irrigation (Sophocleous and Perkins, 2000; Changming *et al.*, 2001; Xu *et al.*, 2005). The scenario is very severe especially in the semi-arid and arid regions of India. Cultivation of highly water intensive crops and multiple cropping increase the water demand, making irrigation inevitable. Due to the institutional benefits and the availability of water near the demand point, groundwater resources are widely tapped to meet the irrigation demand. In India, groundwater irrigated area is increasing at a faster rate compared to the surface water irrigated area, resulting in a drastic water table depletion in many areas. With the water table depletion, open wells tapping the shallow aquifer have become less reliable, causing a widespread increase in the number of deep bore wells to tap the deeper aquifer, further aggravating the groundwater resource depletion problem. One of the earlier studies has reported more than 30 m depletion in the groundwater table in a period of three decades in some parts of India (Santosh *et al.*, 2011).

An integrated model capable of simulating the surface and sub-surface hydrologic processes is required for modeling and analyzing the impact of excessive irrigation on the groundwater resources. SWAT (Arnold *et al.*, 1998), MIKE-SHE (Refsgaard and Storm, 1995), SLURP (Kite, 1995) and SWAP (Kroes and van Dam, 2003) are some of the hydrological models capable of simulating the hydrological processes in various vertical layers starting from the surface to the saturated zone. Soil and Water Assessment Tool (SWAT) is a simple, yet robust model, readily available in the public domain. Several studies conducted in the past have established the applicability of the SWAT to a wide range of flow and solute transport problems (Sun and Cornish, 2005; Ficklin *et al.*, 2009; Ghaffari *et al.*, 2010; Setegn *et al.*, 2010; Dessu and Melesse, 2012, Güngör and Göncü, 2012). The model is capable of simulating various agricultural activities at the catchment level (Holvoet *et al.*, 2005; Arabi *et al.*, 2008; Garg *et al.*, 2012). Integration of SWAT with a user interface in a Geographic Information System (GIS) environment provided the facility to input spatially referenced data and thereby enhanced its capability to represent spatial heterogeneity. In this study, ArcSWAT (v.2009), which is the SWAT integrated with ArcGIS (Winchell *et al.*, 2007), was used to study the impact of excessive groundwater withdrawal for irrigation on the sub-surface water resources in a semi-arid catchment in India.

SWAT is a catchment-scale conceptual model, which is originally developed from the Simulator for Water Resources in Rural Basins (Williams *et al.*, 1985; Arnold

---

*Correspondence to: D. Nagesh Kumar, Department of Civil Engineering, Indian Institute of Science, India.
Email: nagesh@civil.iisc.ernet.in

et al., 1993). In SWAT, the land phase is vertically divided into four different control volumes viz., surface, root zone, shallow aquifer and deep aquifer (Arnold *et al.*, 1993). Using different approaches and approximations, the precipitation is partitioned into surface flow, evapotranspiration (AET), lateral flow, percolation, return flow and deep aquifer recharge, and water balance is achieved in these four control volumes.

SWAT represents the groundwater component in two control volumes: the shallow aquifer and the deep aquifer. The groundwater component was developed compatible with the surface components, requiring only the readily available inputs from the field (Arnold *et al.*, 1993). Variation in the shallow and deep aquifer storages is estimated by using a lumped model, and this has been reported as the main drawback of the SWAT groundwater component (Sophocleous *et al.*, 1999). Integration of SWAT with a fully distributed groundwater model MODFLOW was attempted in a few studies to simulate the spatially varying recharge, evaporation from the aquifer and the groundwater table (Sophocleous *et al.*, 1999, Kim *et al.*, 2008). In the SWAT-MODLFOW integration, SWAT model is split before the groundwater module, and the MODFLOW is added to simulate the shallow and deep aquifer components. This increases the model complexity, first, due to the difference in the spatial disaggregation approaches adopted in SWAT and MODFLOW. SWAT uses virtual areas called HRUs, which have unique soil-vegetation-slope combination, but no spatial reference within the sub-basin (Kim *et al.*, 2008). On the other hand, MODFLOW uses the concept of pixels with a unique spatial reference. Therefore, SWAT-MODFLOW integration requires the transfer of the HRU information to the corresponding pixels. Also, when SWAT is split before the groundwater module, the interaction between various layers (e.g. Revap, stream–aquifer interaction) needs to be represented carefully. Second, such integrated models are not associated with the GIS-integrated versions like ArcSWAT. In ArcSWAT, the entire program is run in a single stretch, and hence the component processes cannot be separated and replaced with other programs like MODFLOW. Hence, in this study the ArcSWAT (v.2009), which is readily available in the public domain, was used for the analysis assuming that the groundwater processes incorporated in the model are satisfactory for the current level of analysis.

Malaprabha catchment in India was selected as the case study area. It is an agricultural watershed located in a semi-arid region. Majority of the agricultural land in the catchment is supported by irrigation, mostly from the groundwater. Excessive groundwater extraction for irrigation has resulted in drastic groundwater table depletion in many parts of the catchment. Qualitative information from the field shows that while drilling bore wells, the depth at which water appeared has increased by around 100 m in certain areas over a period of three decades. In this study, an attempt was made to simulate the impact of excessive groundwater pumping for irrigation on the sub-surface water resources of the catchment using ArcSWAT. This paper presents the problem identified when the ArcSWAT was applied to the study area. In ArcSWAT, the shallow aquifer and the deep aquifer are of undefined depths. However, the initial storage in these layers is limited to 1000 mm and 3000 m, respectively. These initial storage values were found to be insufficient to explain the high rate of groundwater extraction occurring in the study area. Therefore in this study, a separate water balance component was used, taking deep aquifer recharge and irrigation requirement from the SWAT simulation. Integrated use of this model and its application to simulate the impact of excessive irrigation on the groundwater resources in the study area are described in detail in this paper.

STUDY AREA

Malaprabha River originates from the Western Ghats in the Belgaum District in North Karnataka, India. The area drained by the Malaprabha River and its tributaries up to the Malaprabha dam is selected as the present study area. Total catchment area is 2564 sq.km. Location map of the catchment is shown in Figure 1. Important towns (Khanapur, Belgaum, Bailhongal and Hubli) in and around the catchment and National Highway-4 passing through the catchment are also shown in the figure. The boundaries shown in the figure are with reference to the maps published by the Survey of India. Geological information shows that the area is underlain by greywacke/argillite of the Chitradurga group, pink granite of the Closepet group and basalt in a small area. The argillite and the granite of the Achaean period hold water in the weathered zones and in the fractures and joints. In the Chitradurga group, fractures and joints are reported to be present up to a depth of 100 m. Similarly, granites of the Closepet group bear fractures up to 40 to 50 m and in some cases up to 90 m (Subhash Chandra, 1994). Climatology of the area varies from tropical humid (with average annual rainfall more than 3000 mm) in the upper catchment to semi-arid (with average annual rainfall close to 500 mm) in the lower catchment. Much of this rainfall is received during the monsoon period (June–September). Soil data of the catchment shows that gravelly soil and cracking clay are predominant in the upper catchment whereas clayey soils are found in most of the other areas.

The area is an agricultural watershed with paddy, sugarcane, oilseeds, cereals and pulses as the major crops. In addition to the cultivation of the water-intensive crops, many areas are cultivated more than once in a year with the help of irrigation. The large irrigation requirement of the area is mainly met from the groundwater resources. According to the statistics of the Directorate of Economics and Statistics, the net irrigated area and also the groundwater irrigated area in the study region have almost doubled in the last three decades. This has resulted in severe groundwater table depletion in many parts of the catchment. The climatology and the soil characteristics together make the upper catchment as the main recharge

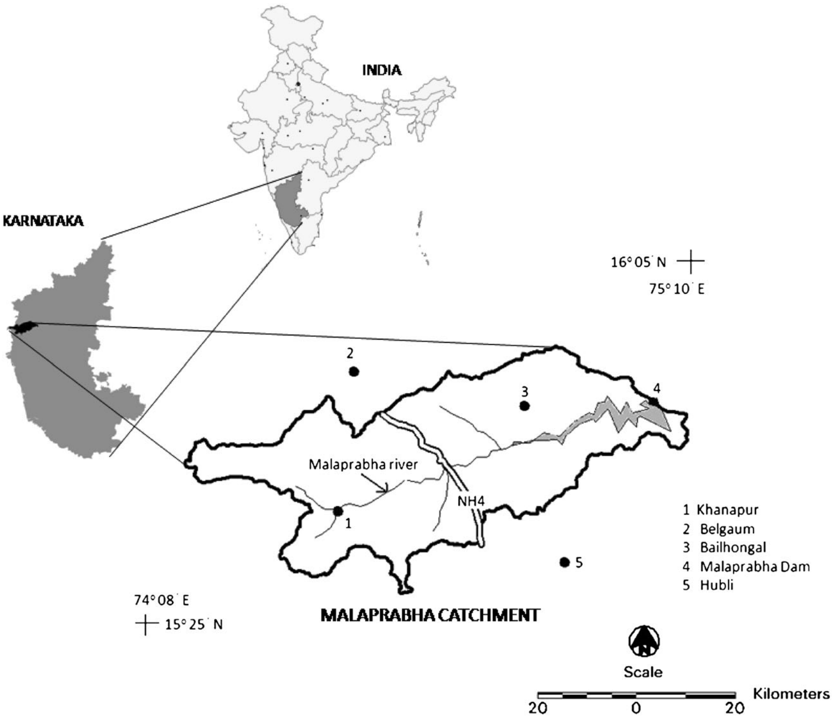

Figure 1. Location map of the Malaprabha catchment in India

area in the catchment. Less rainfall and the extensive irrigation activities result in extensive extraction and poor groundwater recharge in the lower reaches.

DESCRIPTION OF THE ArcSWAT

ArcSWAT (v.2009)

In this study, ArcSWAT (v.2009), SWAT integrated with ArcGIS (Winchell *et al*., 2007), was used to simulate the hydrologic processes in the catchment. SWAT is a conceptual model that simulates hydrologic processes at two different phases viz., land phase and the channel phase. The land phase is divided into various sub-basins, which are further disaggregated into spatially homogeneous HRUs. Each HRU is vertically divided into the surface layer, root zone, shallow aquifer and the deep aquifer layers as shown in Figure 2. Precipitation, after interception at the canopy layer, reaches the soil surface, and a part of it becomes surface runoff. The remaining part infiltrates into the soil layer and adds to the soil moisture storage. After making due allowance for the AET, water balance is achieved between the lateral flow and the percolation components. A kinematic flow equation involving the saturated hydraulic conductivity of the soil layer, slope, drainable porosity and the drainable volume of water present in the layer is used to simulate the lateral flow (Neitsch *et al*., 2005). Percolation from the soil layer is computed as a function of the drainable volume of water present in the layer. This percolation is added to the shallow and deep groundwater storages.

Water balance in the shallow aquifer is achieved between percolation, deep aquifer recharge, revap (which is the movement of water from the shallow aquifer to the root zone) and groundwater flow. The model also considers the withdrawal from the shallow aquifer. Groundwater flow from each HRU is estimated as a function of the rate of change of water table height and is added to the channel reach at the sub-basin outlet. Recharge to the deep aquifer is estimated as a fraction of the total percolation reaching the shallow aquifer. The deep aquifer is defined in such a way that the flow from this layer meets the channel only outside the basin. Therefore, the groundwater flow from the deep aquifer is not modeled in ArcSWAT. It merely considers the balance between the recharge and the extraction in the deep aquifer.

In ArcSWAT, various crop management operations like ploughing, sowing, irrigation (both timing and source), harvesting, etc., can be defined for each HRU. The model assumes irrigation when the plant water stress exceeds the user-specified threshold.

ArcSWAT with additional water balance component for the deep aquifer

In ArcSWAT, deep aquifer water balance considers the percolation from the shallow aquifer (or recharge to the deep aquifer, R_i) and the withdrawal (which in this case is the groundwater extraction for irrigation, Irr_i). The water balance for the deep aquifer can be represented as given in Equation 1.

$$S_{Deep,\ i} = S_{Deep,\ i-1} + R_i - Irr_i \tag{1}$$

Where $S_{Deep,i-1}$ and $S_{Deep,i}$ are the storages in the deep aquifer in the previous and the current time steps,

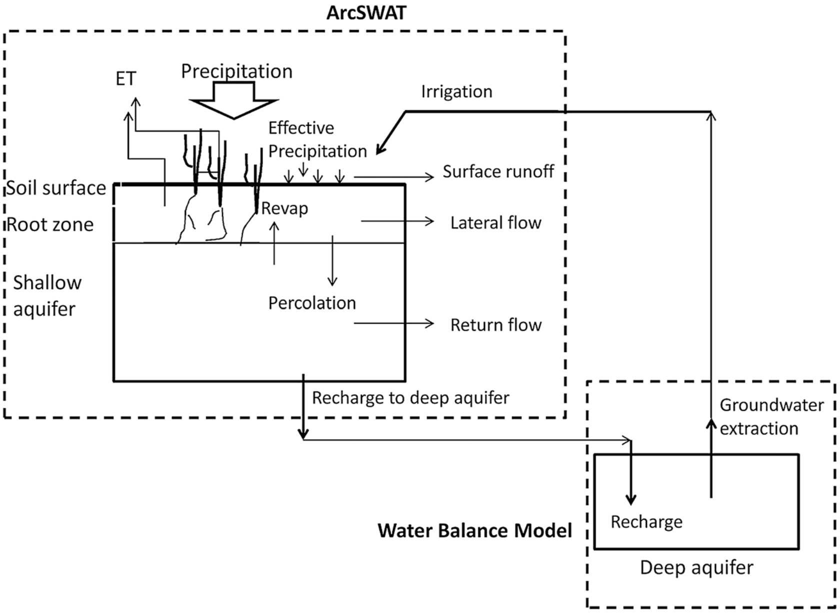

Figure 2. Schematic representation of the ArcSWAT integrated with the deep aquifer water balance model

respectively. In the current version of ArcSWAT, the maximum value that can be assigned to the initial deep aquifer storage is limited to 3000 mm. Therefore, when the deep aquifer is selected as the source for irrigation, the initial water availability for irrigation is limited to 3000 mm. This was found to be insufficient to represent the high rate of irrigation and the corresponding groundwater extraction happening in the study area. Therefore, in this study, the ArcSWAT was combined with a separate water balance model for the deep aquifer. Schematic representation of the integration of the water balance model with ArcSWAT is shown in Figure 2. In ArcSWAT, hydrologic components in the surface, root zone and the shallow aquifer control volumes are interrelated to each other and also connected with the channel phase. On the other hand, the deep aquifer has the minimum interference with the other layers and takes only the withdrawal and the recharge information from the other control volumes.

In this study, ArcSWAT and the water balance models were run separately. While running ArcSWAT, the in-built deep aquifer component was retained, and recharge to the deep aquifer was estimated. In ArcSWAT, recharge to the deep aquifer is calculated as a fraction of the percolation to the shallow aquifer, and it is independent of the storage level in the shallow and deep aquifer. On the other hand, necessary modifications were made in ArcSWAT to stop the model from taking feedback (which is the withdrawal for irrigation in this case) from the deep aquifer. The withdrawal is directly controlled by the irrigation demand and the water availability in the deep aquifer for pumping. Therefore, in order to assure unlimited water supply for irrigation, in the combined model, irrigation was assumed to be from an unlimited source outside the catchment, and the actual irrigation demand was estimated. The deep aquifer recharge and the irrigation demand thus estimated at each HRU were given as inputs to the water balance model. In the water balance model, HRUs in each sub-basin were identified first, and the net recharge and irrigation requirement was estimated at the sub-basin level. Difference in the deep aquifer storage was calculated at sub-basin level using Equation 2.

$$\nabla WT = \frac{\sum R_i.A_i - \sum Irr_i.A_i.\varepsilon_i}{s.\sum A_i} \tag{2}$$

Where, ε_i is the irrigation efficiency and A_i is the area of the i^{th} HRU in the selected sub-basin. Specific yield of the aquifer in the sub-basin is represented by s.

MODEL SETUP AND INPUT DATA

Basic input required for the model includes the Digital Elevation Model (DEM), soil map, land use/land cover map and hydro-meteorological data such as rainfall, temperature, relative humidity and wind speed. Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global DEM (GDEM) released by the Japan's Ministry of Economy, Trade and Industry (METI) and NASA, at a spatial resolution of 30 m (Figure 3.a), was used to delineate the catchment boundary and to extract the topographic characteristics related to hydrology. Land use/land cover (LU/LC) map (Figure 3.b) was generated from multi-season Landsat-7 ETM + imageries. Seven main LU/LC classes viz., water, agricultural land, barren/fallow land, rocky area, forest, settlement and grass land were extracted in the first step. Based on the field information and the district statistical information about the crop production, the agricultural area was further classified into various crop classes. Each of the LU/LC classes was assigned to a corresponding SWAT class. Soil map of the area generated by NBSS & LUP was used in this

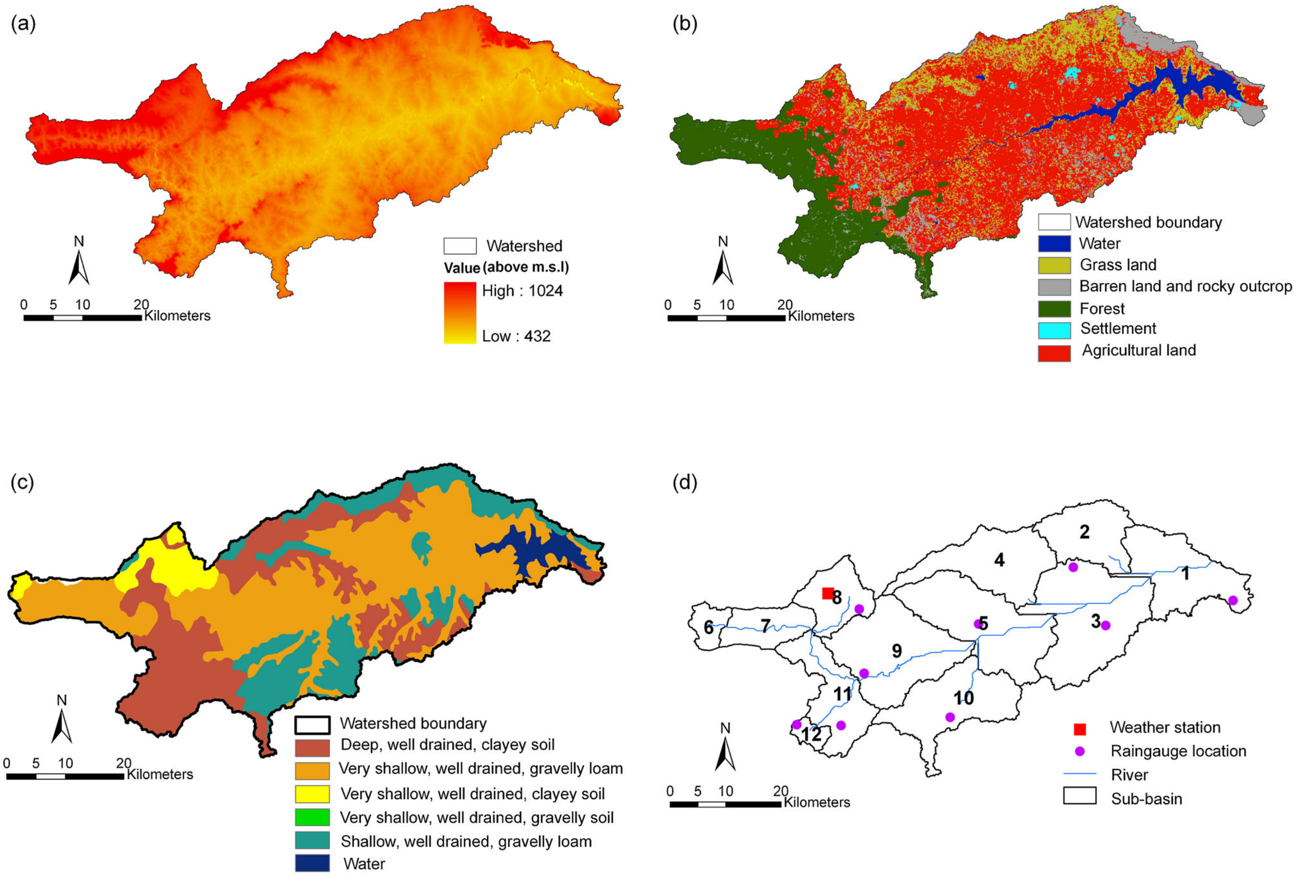

Figure 3. Spatial data of Malaprabha catchment used in the ArcSWAT (a) Digital Elevation Model (b) Land use/land cover map (c) Soil map and (d) Sub-basins of the catchment and the locations of weather stations and rain gauge stations

study (Figure 3.c). Details of each of the soil classes were obtained from an earlier study (Reshmi *et al*., 2008). To incorporate the large spatial variation in rainfall in the study area, data from nine rain gauge stations in the catchment, obtained from the Directorate of Economics and Statistics, Bangalore, were used in the model. Location of these rain gauge stations is shown in Figure 3.d. Observed data of daily maximum and minimum temperature, relative humidity and wind speed from a single observatory in the catchment were also given as input to the model.

Using the flow information, the catchment was divided into 12 sub-basins as shown in Figure 3.d. Land use/land cover, soil and slope information were used to define HRUs in each sub-basins. Crop management practices viz., beginning and end of the cropping period, irrigation application, etc., were manually defined for each HRU, based on field observations. From the ArcSWAT interface, the modified Curve Number method (USDA-SCS, 1972) and the Hargreaves methods (Hargreaves and Samani, 1985) were selected for estimation of the surface runoff and the potential AET, respectively. The model simulates

Table I. ArcSWAT parameter sensitivity ranks for the Malaprabha catchment

Sl. No	Parameter	Parameter description	Rank
1	ALPHA_BF	Base flow recession coefficient	13
2	CH_K2	Channel hydraulic conductivity	12
3	CH_N2	Manning’s roughness coefficient for the channel	14
4	CN2	Curve number	3
5	EPCO	Plant uptake compensation factor	2
6	ESCO	Soil evaporation compensation factor	4
7	GW_delay	Delay time for aquifer recharge	10
8	GW_revap	Revap coefficient	6
9	GWQMN	Threshold water level in the shallow aquifer for base flow	7
10	RCHRG_DP	Deep aquifer percolation coefficient	1
11	REVAPMN	Threshold water level in the shallow aquifer for revap	11
12	SOL_AWC	Available water capacity of the soil	5
13	SOL_K	Saturated hydraulic conductivity of the soil	8
14	SURLAG	Surface runoff lag coefficient	9

various hydrologic processes in the root zone and the shallow aquifer and calculates the recharge to the deep aquifer at each time step, at the HRU level. In the ArcSWAT simulation, the irrigated crops were identified, and the irrigation was assumed when the plant stress reaches the threshold value of 0.95.

The recharge and the irrigation requirement at the HRU level were taken as input to the water balance model and the deep aquifer water table was simulated. Following the recommendations of the Central Ground Water Board, specific yield of the rock formations in the area was assumed as 3% (R&D Advisory Committee on Groundwater Estimation, 2009). Assuming flood irrigation method, the average irrigation efficiency of 0.4 was assumed for the area (Narayanamoorthy, 2006). Monthly inflow to the Malaprabha Reservoir for a period 1992–2003 was obtained from the Water Resources Development Organization, Bangalore. The ArcSWAT clubbed with the water balance model was calibrated using the observed stream flow data.

CALIBRATION AND SENSITIVITY ANALYSIS

In ArcSWAT, sensitivity analysis can be done automatically by using the Latin Hypercube (LH) and One-factor-At-a-Time method. The LH sampling method is used to divide the feasible parameter range into different sub-ranges, and the parameter sensitivity is estimated by running the model for different combinations of the input parameters by changing only one parameter at a time.

ParaSol method (Van Griensven and Meixner, 2006) is incorporated in ArcSWAT for the parameter calibration and uncertainty analysis. In ParaSol, sum of the squares of the residuals between the simulated series and the observed data series is used as the objective function. In cases where observed data for more than one parameter is available, requiring the use of a multiple objective function, a global optimization criterion is derived by using the objective functions. Further, the Shuffled Complex Evolution Algorithm is used for the optimization (Van Griensven, 2005). In ArcSWAT, the hydrologic processes can be calibrated only with respect to the flow at the sub-basin outlets. Based on the model efficiency to simulate the flow, the other components are assumed to be reasonably well simulated in the model. Since the flow at the sub-basin outlet does not include the flow from the deep aquifer, the calibration using the flow data is less reliable to evaluate the accuracy of the deep aquifer simulation. Often, excess water from the other control volumes is transferred to the deep aquifer in a process to attain a good simulation of the flow at the sub-basin outlet. In the present study, since the flow as well as the deep aquifer water level needs to be simultaneously considered, the sensitive parameters were manually calibrated with respect to the monthly stream flow at the catchment outlet, and the deep aquifer water levels were verified with respect to the qualitative information from the field. The indices used for the manual calibration were the correlation coefficient, root mean square error (RMSE), normalized mean square error (NMSE) and

Table II. Manually calibrated model parameters for the Malaprabha catchment

Serial number	1	2	3	4	5	6	7	8	9
Parameter	RCHRG_DP	EPCO	ESCO	CN2	CH_N2	CH_K2	ALPHA_BF	SOL_AWC	GW_REVAP
Best range of parameters for various sub-basins	0.01–0.8	1	0.1	40–98	0.03	5.0	0.01	0–3 times	0.2–0.5

Nash–Sutcliffe efficiency (NSE). Monthly stream flow data for the eight year period 1992–1999 was used for calibration, and four year period 2000–2003 was used for model validation.

RESULTS AND DISCUSSIONS

Sensitivity, calibration and uncertainty analysis of parameters in ArcSWAT

In this study, relative sensitivity of 14 parameters that control the surface flow and groundwater flow for simulations were analyzed. Parameters and their descriptions are shown in Table I. From the analysis, the deep aquifer recharge (RCHRG_DP) was identified as the most sensitive parameter followed by the plant uptake compensation factor (EPCO) and the curve number (CN2). Sensitivity ranks of the selected parameters are shown in Table I. RCHRG_DP is the fraction of the percolation to the shallow aquifer, which recharges the deep aquifer. It affects the groundwater storages in both the shallow and deep aquifers. Since the groundwater contribution to the stream flow is controlled by the water storage in the shallow aquifer, it has significant effect on the total flow.

Further, the sensitive parameters were manually calibrated. Deep aquifer recharge was adjusted for each sub-basin to match the simulated groundwater table fluctuation with the qualitative information available from the field. In the downstream catchment, where large water table depletion was observed, the flow was assumed to be mainly vertical, and hence higher values were assumed for RCHRG_DP. On the other hand, due to the shallow groundwater table in the upper catchment, the fluctuation in the deep aquifer was assumed to be negligible, and hence lower values were assigned to RCHRG_DP. In the upper catchment, the recharge and the discharge were happening mainly from the shallow aquifer, which was well represented in the ArcSWAT.

During calibration, higher values of EPCO and lower values of ESCO were found to be giving better results for the catchment, with a minimum restriction to the evaporation. Another important parameter calibrated was the curve number. Curve number values for various land cover types were adjusted manually to make the simulated flow values match with the observed data. Parameters SOL_AWC and GW_REVAP were also calibrated to improve the flow simulation. Values of the parameters ALPHA_BF, channel hydraulic conductivity (CH_K2) and the channel roughness coefficient (CH_N2) were adjusted to a physically meaningful range. For the study area, CH_K2 was selected 5 mm/h. For firm bedded channels, the range for the channel roughness coefficient is 0.025–0.032 (Arcement and Schneider, 1989) and for the study area, after calibration CH_N2 was selected as 0.03. Calibrated parameters and their best values are shown in Table II. Parameters EPCO, ESCO CH_N2, CH_k2 and ALPHA_BF are assumed to be uniform for all the sub-basins. On the other hand, RCHRG_DP, SOL_AWC and GW_revap are calibrated for each sub-basins separately, and hence the range of values adopted for various sub-basins are shown in Table II. Parameter CN2 varies for each HRU with respect to the land cover and soil type, and hence the range of CN2 values for the catchment is shown in the table. The statistical evaluation indices for the calibration and validation periods are given in Table III. The model performance is found to be satisfactory in terms of correlation coefficient, RMSE, NMSE and NSE. Further, the stream flow simulation from the current model was found to be perfectly matching with that obtained using the original ArcSWAT with the same set of calibrated parameters. The model was then validated for the period 2000–2003.

Monthly stream flow simulated using the current model and the observed data for the calibration and validation periods are compared in Figure 4. Flow–duration curve was generated using the simulated monthly stream flow

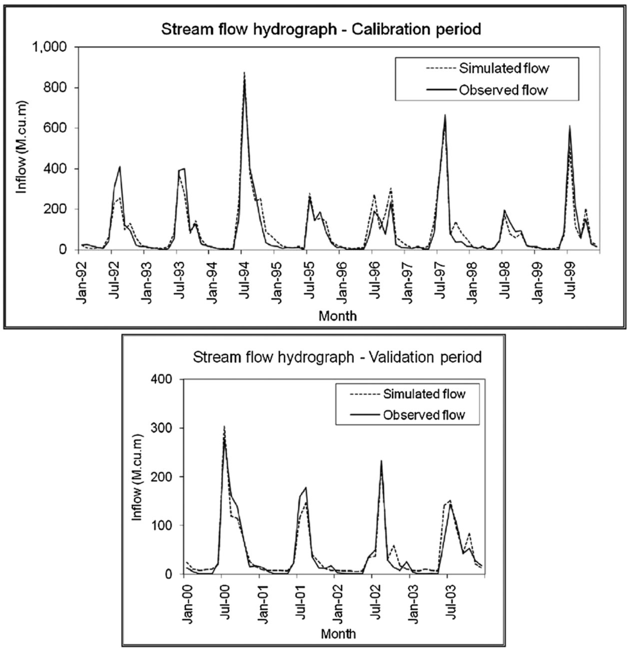

Figure 4. Stream flow hydrographs for the calibration and validation periods obtained using the ArcSWAT integrated with the water balance model

Table III. Model performance indices for the Malaprabha catchment

Statistical index	Correlation coefficient	RMSE (M.cu.m)	NMSE	NSE
Calibration period	0.963	41.34	0.074	0.925
Validation period	0.961	18.10	0.075	0.923

values and was compared with that of observed flow in Figure 5. The monthly stream flow hydrograph and the flow–duration curve of the simulated flow match reasonably well with those of the observed flow. Using the flow–duration curve, 10%, 25% and 75% dependable monthly flows were identified from both the observed and simulated monthly stream flow data series. From the model simulations, 10%, 25% and 75% dependable monthly flows were estimated to be 270.5 M.cu.m, 136.9 M.cu.m and 10.9 M.cu.m, respectively. These are found to be within a close range of the corresponding values for the observed data which are 278.3 M.cu.m, 119.2 M.cu.m and 8.2 M.cu.m, respectively.

Using the calibrated model, parameter uncertainty analysis was carried out using the ParaSol method inbuilt in ArcSWAT, for the 14 parameters related to the stream flow and groundwater. The feasible range of the parameters and the range for good simulations are given in Table IV. For most of the selected parameters, the good simulation covers more than 90% of the feasible range.

Water budget components

Rainfall (P) and withdrawal for irrigation (Irr) are the main input for the overall water budget of the catchment. Other major water budget components are actual AET surface runoff (Sur_Q), lateral flow from the root zone (Lat_Q), groundwater flow or return flow from the shallow aquifer (GWQ), percolation from the root zone (Perc) and soil moisture content (SMC). Annual average values of these water budget components for all the sub-basins, for the study period 1992–2003, are given Table V. Sub-basin indexing is shown in Figure 3.d. Annual average rainfall in the catchment varies from more than 3500 mm in upper catchment to less than 500 mm in the lower catchment. Percolation to the groundwater zones was found to be high in the upper catchment, whereas irrigation was found to be the maximum in the lower catchment.

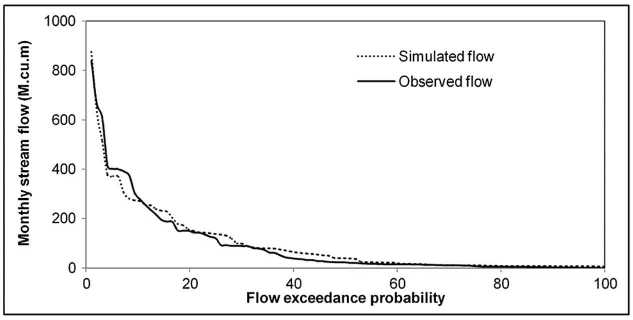

Figure 5. Flow–duration curve for the Malaprabha catchment during the calibration period

Original ArcSWAT was run for the catchment with the same set of calibrated parameters, for the same period. The initial storage in the deep aquifer was set as 3000 mm, which was the maximum value that ArcSWAT can take. Source of irrigation was specified as the deep aquifer of the corresponding sub-basin. Simulated water budget components are shown in Table V. All the components, except AET, Irr and SMC of sub-basin 3, were found to be matching with those obtained using the current model. The difference in Irr is due to the lack of water available at the source, which is the deep aquifer in this case. Percolation to the ground water layers is less in the lower catchment whereas, irrigation demand is the maximum. The excess demand is met from the initial storage available at the sub-basin. Irrigation demand was the highest in sub-basin 3, which was more than the maximum initial storage that ArcSWAT can assign to the deep aquifer. The resulted moisture deficiency was reflected as the difference in AET and SMC in sub-basin 3. On the other hand, in other sub-basins irrigation demand was less which was sufficiently met from the deep aquifer, and hence no difference was observed in the water budget components simulated using the current model and the original ArcSWAT. While running ArcSWAT, due to the cumulative withdrawal, in excess of the recharge, water storage was gradually diminishing to a stage when the water available was not sufficient to meet the demand. The disparity between the irrigation

Table IV. ArcSWAT parameter range for good simulations

Sl No	Parameter	Feasible range	Range for good simulations	% Range
1	ALPHA_BF	0–1	0.01 – 0.9	91.05
2	CH_K2	0–5	0 – 4.75	95.02
3	CH_N2	0–0.03	0 – 0.029	97.51
4	CN2	−25% to 25%	−20.6 to 24.2[a]	89.72
5	EPCO	0–1	0 – 0.888	88.82
6	ESCO	0–1	0 – 0.9951	99.51
7	GW_DELAY	0–50	0 – 46.34	92.67
8	GW_REVAP	0–0.5	0 – 0.495	99.06
9	GWQMN	0–1000	0 – 979.2	97.93
10	RCHRG_DP	0–1	0 – 0.8216	82.162
11	REVAPMN	0–100	0 – 99.43	99.427
12	SOL_AWC	−25% to 25%	−24.955 to 24.36(%)[a]	98.60
13	SOL_K	−25% to 25%	−23.6 to 22.5 (%)[a]	92.31
14	SURLAG	0–10	0.056 – 9.98	99.21

[a] Parameter changes are with respect to the calibrated values

Table V. Annual average water balance components for the Malaprabha catchment for the current rainfall scenario

ArcSWAT with the water balance model									
Sub-basins	Rainfall	PET	AET	Perc	Sur_Q	GWQ	Lat_Q	Irr	SMC
	mm	mm	mm	mm	mm	mm	mm	mm	mm
1	544.9	1874.8	853.2	20.8	96.7	2.8	19.7	61.1	95.7
2	528.6	1595.6	530.3	17.6	41.8	8.8	2.6	51.4	66.5
3	467.4	1685.7	653.9	5.9	34.3	0.8	0.5	112.7	69.8
4	731.4	1595.8	634.6	52.1	83.0	26.1	6.8	39.2	104.3
5	731.4	1612.3	706.3	18.2	83.8	10.3	2.3	53.3	83.5
6	3562.4	1530.5	782.7	833.5	1680.9	541.7	377.1	0.0	160.2
7	1139.7	1547.3	714.5	122.3	271.4	59.6	67.3	1.9	177.8
8	1176.1	1596.3	593.4	227.0	383.2	143.8	2.0	0.0	74.7
9	1802.9	1596.9	816.8	407.6	605.0	274.7	84.4	31.0	289.5
10	1057.1	1597.4	693.8	65.9	374.4	36.1	1.9	25.3	253.4
11	1656.3	1597.9	911.6	229.6	510.2	116.3	37.3	5.3	307.1
12	3716.2	1597.8	846.2	1215.8	1577.9	884.3	116.3	0.0	215.0
ArcSWAT									
1	544.9	1874.8	853.2	20.8	96.7	2.8	19.7	61.1	95.7
2	528.6	1595.6	530.3	17.6	41.8	8.8	2.6	51.4	66.5
3	467.4	1685.7	646.2	5.9	34.3	0.8	0.5	103.1	69.4
4	731.4	1595.8	634.6	52.1	83.0	26.1	6.8	39.2	104.3
5	731.4	1612.3	706.3	18.2	83.8	10.3	2.3	53.3	83.5
6	3562.4	1530.5	782.7	833.5	1680.9	541.7	377.1	0.0	160.2
7	1139.7	1547.3	714.5	122.3	271.4	59.6	67.3	1.9	177.8
8	1176.1	1596.3	593.4	227.0	383.2	143.8	2.0	0.0	74.7
9	1802.9	1596.9	816.8	407.6	605.0	274.7	84.4	31.0	289.5
10	1057.1	1597.4	693.8	65.9	374.4	36.1	1.9	25.3	253.4
11	1656.3	1597.9	911.6	229.6	510.2	116.3	37.3	5.3	307.1
12	3716.2	1597.8	846.2	1215.8	1577.9	884.3	116.3	0.0	215.0

Table VI. Annual average water balance components for the Malaprabha catchment for the hypothetical scenario of 50% rainfall deficit

ArcSWAT with the water balance model									
Sub-basins	Rainfall	PET	AET	Perc	Sur_Q	GWQ	Lat_Q	Irr	SMC
	mm	mm	mm	mm	mm	mm	mm	mm	mm
1	272.8	1874.8	746.0	2.1	11.0	0.3	9.2	102.7	52.7
2	265.1	1595.6	361.4	0.0	2.1	0.1	0.9	97.7	24.0
3	233.8	1685.7	542.7	0.7	2.3	0.1	0.3	190.1	42.7
4	366.3	1595.8	503.6	0.0	4.1	0.2	2.8	140.5	42.9
5	366.3	1612.3	561.0	1.5	3.9	0.9	1.0	176.2	36.2
6	1781.3	1530.5	717.6	421.6	466.6	219.8	220.1	0.0	139.3
7	570.1	1547.3	517.5	16.8	29.8	7.9	25.7	3.7	94.1
8	588.3	1596.3	451.1	70.3	76.5	37.5	1.0	0.0	39.3
9	903.6	1596.9	701.1	131.1	113.0	75.9	32.6	47.3	227.8
10	529.0	1597.4	543.3	14.8	42.9	8.5	1.2	52.4	134.2
11	830.5	1597.9	738.9	42.7	57.5	20.4	15.3	6.4	186.4
12	1858.2	1597.8	792.9	604.2	413.5	359.5	65.8	0.0	188.5
ArcSWAT									
1	272.8	1874.8	745.1	2.1	11.0	0.3	9.2	100.9	52.5
2	265.1	1595.6	361.4	0.0	2.1	0.1	0.9	97.7	24.0
3	233.8	1685.7	455.7	0.5	2.2	0.1	0.2	101.1	38.2
4	366.3	1595.8	467.9	0.0	4.1	0.2	2.8	101.4	40.7
5	366.3	1612.3	489.4	1.2	3.7	0.7	1.0	100.2	31.0
6	1781.3	1530.5	717.6	421.6	466.6	219.8	220.1	0.0	139.3
7	570.1	1547.3	517.5	16.8	29.8	7.9	25.7	3.7	94.1
8	588.3	1596.3	451.1	70.3	76.5	37.5	1.0	0.0	39.3
9	903.6	1596.9	701.1	131.1	113.0	75.9	32.6	47.3	227.8
10	529.0	1597.4	543.3	14.8	42.9	8.5	1.2	52.4	134.2
11	830.5	1597.9	738.9	42.7	57.5	20.4	15.3	6.4	186.4
12	1858.2	1597.8	792.9	604.2	413.5	359.5	65.8	0.0	188.5

demand and the water availability further increases with time. To highlight the difficulty in applying the ArcSWAT to groundwater problem in a high groundwater extraction area, a hypothetical scenario was developed, wherein 50% deficit from the current rainfall was assumed for a period of 12 years. Comparison of the water budget components simulated by the current model and the ArcSWAT is shown in Table VI. With 50% deficit in rainfall, the irrigation requirement was higher than the current scenario. Consequently, in ArcSWAT the water deficiency was expanded to sub-basins 1, 4 and 5 in the lower catchment.

Graphical comparison of the water budget components simulated using the current model and ArcSWAT is shown in Figure 6. Though, the variation in AET, SMC and Irr was insignificant while taking annual average values for the current scenario, the discrepancy was found to increase with further increase in the irrigation demand, which may be due to deficit in the rainfall (as presented in the hypothetical scenario) or a change in the climate or cropping pattern.

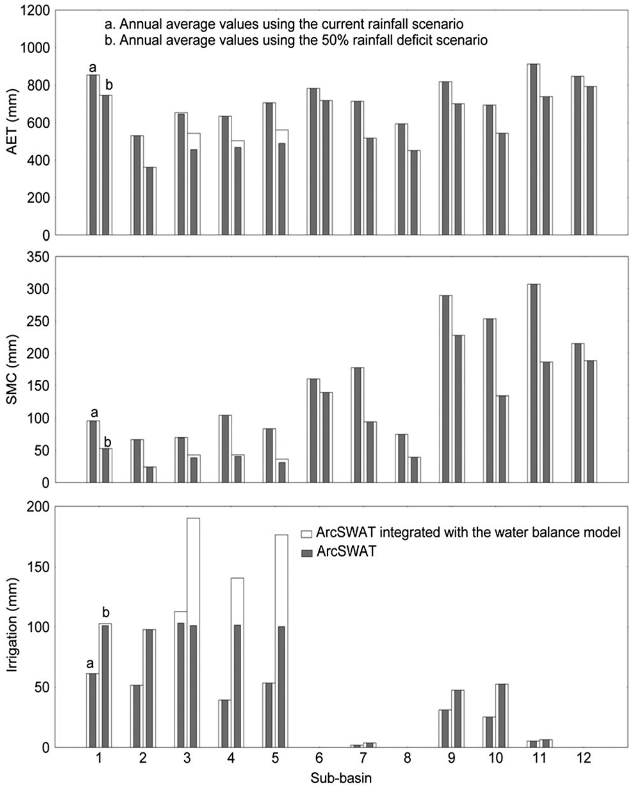

Figure 6. Simulated water budget components for various sub-basins in the Malaprabha catchment

Groundwater scenario of the catchment

Irrigation requirement and the deep aquifer recharge from the calibrated model were used in the water balance model, and the water table fluctuation at each sub-basin was calculated for the calibration period, which is shown in Figure 7. The numbers show the sub-basin indices and the values in the bracket show the corresponding changes in the groundwater table (in meters). Negative values indicate groundwater table depletion. Model simulation shows that the deep aquifer water table fluctuation varies from the minimum in the upper catchment to the maximum in the lower catchment. The upper catchment is mainly forested land and is characterized by high annual rainfall. Extraction from the deep aquifer is very less, and hence the water table fluctuation is also insignificant in the upper catchment. On the other hand, less rainfall combined with the extensive irrigation activities in the lower catchment results in large irrigation demand, which is met mainly from the deep aquifer. Consequently, drastic water table depletion was observed for the sub-basins in the lower catchment.

The deep aquifer water table fluctuation simulated using the model was compared with the qualitative information available from the field. While drilling bore wells, the depth at which water appeared was taken as the indicator of the groundwater table depth. Field-based information shows that the water table has depleted 10–15 m at various villages in sub-basin 9 during the calibration period, which is very well matching with the simulated 14 m depletion. The 63 m depletion in sub-basin 3 simulated by the model is also in the close range of 70 m reported in the field. In sub-basin 5, the water table depletion of 23 m simulated by the model is less when compared with the 20–40 m depletion observed in the field. In sub-basin 4,

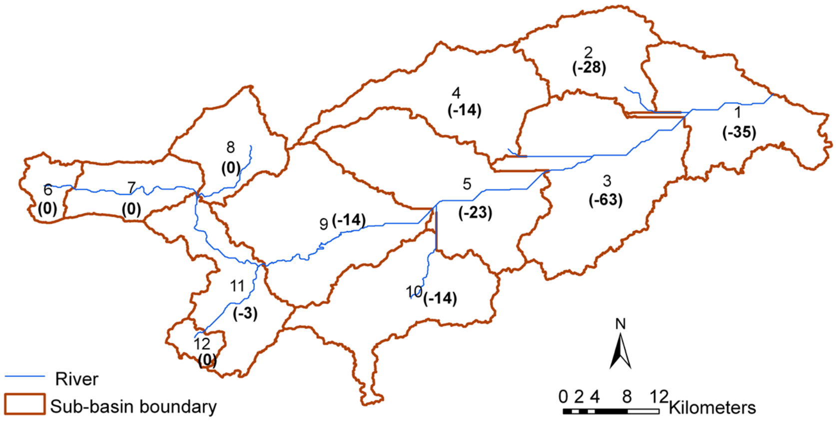

Figure 7. Change in the groundwater table in the sub-basins of the Malaprabha catchment (in meters)

simulation result shows 14 m depletion in the groundwater table, whereas the field observations show around 25 m depletion.

The water balance model considers only the recharge and extraction components, ignoring the lateral movement of groundwater from the upper reaches to the lower reaches. Omission of this groundwater re-distribution component may be the reason for the differences between the observed and the simulated water table fluctuation.

CONCLUSIONS

The ArcSWAT was used to study the impact of extensive irrigation on the groundwater resources. A water balance model was clubbed with the ArcSWAT to overcome the limitation of the model while simulating the large-scale groundwater table depletion. Taking Malaprabha catchment as the case study area, the model parameters were calibrated with respect to the observed monthly stream flow data and the qualitative information about the groundwater table depletion in the area. The stream flow was found to be well simulated in the model with Nash–Sutcliffe efficiency greater than 0.92 for both the calibration and validation periods. Model simulated values of the 10%, 25% and 75% dependable monthly flow were also found to be matching reasonably well with the observed values. Withdrawal for irrigation was found to be very high in the lower catchment whereas, percolation to the groundwater was the minimum. The irrigation demand is met from the groundwater resources, which has resulted in the drastic depletion of groundwater table in the lower catchment. The groundwater table simulation shows that in the semi-arid parts of the catchment, the water table has depleted 30–40 m, and in some areas up to 70 m depletion was observed. With the maximum initial storage in the deep aquifer limited to 3000 mm, the original ArcSWAT when applied to the case study area was found to be under-simulating the irrigation due to the water deficiency in this layer. This has also resulted in the under-simulation of AET and soil moisture content. The scenario may be further critical in case of an increase in the irrigation demand or a decrease in the rainfall. On the other hand, when clubbed with an additional water balance model, the constraint on the storage was removed, and the model was performing satisfactory even in the areas of large groundwater extraction. The ArcSWAT together with the water balance model is thus found to be helpful to get a general picture of the groundwater scenario in the area.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance from the Department of Science and Technology, Government of India for providing the financial support for this research project under the SERC Fast Track Fellowship Scheme (SR/FTP/ETA-037). This work is partially supported by the Department of Science and Technology, Govt. of India, through AISRF project no. DST/INT/AUS/P-27/2009 and Ministry of Earth Sciences, Govt. of India, through project no. MoES/ATMOS/PP-IX/09. The authors also acknowledge the help of METI and NASA in providing the ASTER GDEM data used in this study.

REFERENCES

Arabi M, Frankenberger JR, Engel BA, Arnold JG. 2008. Representation of agricultural conservation practices with SWAT. *Hydrological Processes* **22**: 3042–3055. DOI: 10.1002/hyp.6890

Arcement GJ, Schneider VR. 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains. *United States Geological Survey Water Supply Paper 2339 (Metric Version).*

Arnold JG, Allen PM, Bernhardt G. 1993. A comprehensive surface-groundwater flow model. *Journal of Hydrology* **142**: 47–69.

Arnold JG, Srinivasan R, Muttiah RS, Williams JR. 1998. Large area hydrologic modeling and assessment- Part I: model development. *Journal of the American Water Resources Association* **34**(1): 73–89.

Changming L, Jingjie Y, Eloise K. 2001. Groundwater exploitation and its impact on the environment in the North China Plain. *Water International* **26**(2): 265–275.

Dessu SB, Melesse AM. 2012. Modelling the rainfall–runoff process of the Mara River basin using the Soil and Water Assessment Tool. *Hydrological Processes*. DOI: 10.1002/hyp.9205

Ficklin DL, Luo Y, Luedeling E, Zhang M. 2009. Climate change sensitivity assessment of a highly agricultural watershed using SWAT. *Journal of Hydrology* **374**: 16–29. DOI:10.1016/j.jhydrol.2009.05.016

Garg KK, Karlberg L, Barron J, Wani SP, Rockstorm J. 2012. Assessing impacts of agricultural water interventions in the Kothapally watershed, Southern India. *Hydrological Processes*. DOI: 10.1002/hyp.8138

Ghaffari G, Keesstra S, Ghodousi J, Ahmadi H. 2010. SWAT-simulated hydrological impact of land-use change in the Zanjanrood Basin, Northwest Iran. *Hydrological Processes*. DOI:10.1002/hyp.7530

Güngör Ö, Göncü S. 2012. Application of the soil and water assessment tool model on the Lower Porsuk Stream Watershed. *Hydrological Processes*. DOI: 10.1002/hyp.9228

Hargreaves GH, Samani ZA. 1985. Reference crop evapotranspiration from temperature. *Transactions of ASAE*. **1**(2): 96–99.

Holvoet K, van Griensven A, Seuntjens P, Vanrolleghem PA. 2005. Sensitivity analysis for hydrology and pesticide supply towards the river in SWAT. *Physics and Chemistry of the Earth* **30**: 518–526. DOI:10.1016/j.pce.2005.07.006

Kim NM, Chung IM, Won YS, Arnold JG. 2008. Development and application of the integrated SWAT-MODFLOW model. *Journal of Hydrology* **356**(1–2): 1–16.

Kite GW. 1995. *Manual for the SLURP Hydrological Model*. NHRI: Saskatoon, Canada.

Kroes JG, van Dam JC. 2003. *Reference manual SWAP version 3.03*. Alterra Rep. 773: Alterra, Wageningen, the Netherlands.

Narayanamoorthy A. 2006. Potential for drip and sprinkler irrigation in India. *Draft, IWMI-CPWF Project on Strategic Analysis of India's National River Linking Project*. International Water Management Institute: Colombo, Sri Lanka.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR. 2005. *Soil and Water Assessment Tool theoretical documentation*. SWAT technical manual: Texas.

R&D Advisory Committee on Groundwater Estimation. 2009. Status report on review of groundwater resources estimation methodology. Central Ground Water Board: Faridabad.

Refsgaard JC, Storm B. 1995. MIKE SHE. In *Computer Models of Watershed Hydrology*, Singh VP (ed). Water Resour.Publ.: Highlands Ranch, Colorado; 809–846.

Reshmi TV, Christiansen AB, Badiger S, Barton DN. 2008. Hydrology and water allocation: comprehensive database and integrated hydro-economic model for selected water services in the Malaprabha River Basin. *Report SNO 5695–2008*, Norwegian Institute for Water Research: Oslo, Norway.

Santosh DT, Satishkumar U, Shashidhara N, Ravikumar H, Chayadevi K. 2011. Watershed Management of Unkal Watershed, Dharwad District, Karnataka to Enhance Groundwater Resource-A Case Study. *International Journal of Agriculture, Environment and Biotechnology* **4**(2): 175–180.

Setegn SG, Srinivasan R, Melesse A, Dargahi B. 2010. SWAT model application and prediction uncertainty analysis in the Lake Tana Basin, Ethiopia. *Hydrological Processes* **24**: 357–367. DOI: 10.1002/hyp.7457

Sophocleous MA, Koelliker JK, Govindaraju RS, Birdie T, Ramireddygari SR, Perkins SP. 1999. Integrated numerical modeling for basin-wide water management: The case of the Rattlesnake Creek Basin in south-central Kansas. *Journal of Hydrology* **214**(1–4): 179–196.

Sophocleous M, Perkins SP. 2000. Methodology and application of combined watershed and ground-water models in Kansas. *Journal of Hydrology* **236**(3–4): 185–201.

Subhash Chandra KC. 1994. Occurrence of groundwater and aquifer characteristics of hard rocks in Karnataka. In *Geo Karnataka*, Mining and Geology Department (MGD) Centenary Volume. Bangalore, India; 337–359.

Sun H, Cornish PS. 2005. Estimating shallow groundwater recharge in the headwaters of the Liverpool plains using SWAT. *Hydrological Processes* **19**: 795–807. DOI: 10.1002/hyp.5617

USDA-SCS. 1972. *National Engineering Handbook*, Hydrology Section 4. U.S. Department of Agriculture: Washington, D.C.

van Griensven A. 2005. Sensitivity, auto-calibration, uncertainty and model evaluation in SWAT2005. Unpublished report.

van Griensven A, Meixner T. 2006. Methods to quantify and identify the sources of uncertainty for river basin water quality models. *Water Science and Technology*, **53**(1): 51–59.

Williams JR, Nicks AD, Arnold JG. 1985. SWRRB, Simulator for water resources in rural basins. *Journal of Hydrologic Engineering*. ASCE **111**(6): 970–986.

Winchell M, Srinivasan R, Di Luzio M, Arnold J. 2007. ArcSWAT Interface for SWAT2005: User's Guide. Blackland Research Center, Texas Agricultural Experiment Station, Texas and Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service: Texas.

Xu Y, Mo X, Cai Y, Li X. 2005. Analysis on groundwater table drawdown by land use and the quest for sustainable water use in the Hebei Plain in China. *Agricultural Water Management* **75**(1): 38–53.