TECHNICAL NOTE:

HYDROLOGICAL MODELING WITH SWAT IN A MONSOON-DRIVEN ENVIRONMENT: EXPERIENCE FROM THE WESTERN GHATS, INDIA

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ABSTRACT. *Monsoon regions are characterized by a pronounced seasonality of rainfall. Model-based analysis of water resources in such an environment has to take account of the specific natural conditions and the associated water management. Especially, plant phenology, which is predominately water driven, and water management, which aims at reducing water shortage, are of primary importance. The aim of this study is to utilize the Soil and Water Assessment Tool (SWAT) in a monsoon-driven region in the Indian Western Ghats by using mainly generally available input data and to evaluate the model performance under these conditions. The test site analyzed in this study is the meso-scale catchment of the Mula and Mutha Rivers (2036 km^2) upstream of the city of Pune, India. Most input data were derived from remote sensing products or from international archives. Forest growth in SWAT was modified to account for the seasonal limitation of water availability. Moreover, a dam management scheme was derived by combining general dam management rules with reservoir storage capacity and estimated monthly outflow rates from river discharge. With these model adaptations, SWAT produced reasonable results when compared to mean daily discharge measured in three of four subcatchments during the rainy season (Nash-Sutcliffe efficiencies 0.58, 0.63, and 0.68). The weakest performance was found at the gauge downstream of four dams, where the simple dam management scheme failed to match the combined management effects of the four dams on river discharge (Nash-Sutcliffe efficiency 0.10). Water yield was underestimated by the model, especially in the smallest (headwater) subcatchment (99 km^2). Due to the absence of rain gauges in these headwater areas, the extrapolation errors of rainfall estimates based on measurements at lower elevations are expected to be large. Moreover, there is some indication that evapotranspiration might be underestimated. Nevertheless, it can be concluded that using generally available data in SWAT model studies of monsoon-driven catchments provides reasonable results, if key characteristics of monsoon regions are accounted for and processes are parameterized accordingly.*

Keywords. *Data-scarce environment, India, Monsoon, SWAT, Water management.*

Monsoon regions are characterized by a pronounced seasonality of water and energy fluxes. This seasonality has a strong impact upon the environment. The varying water availability governs the phenological development of natural and agricultural vegetation (Goldsworthy and Fisher, 1984) and is a major motivation for the construction of large reservoirs to secure year-round water supply (Jain et al., 2007). Seasonal disparity of the natural water supply is often met by an increasing water demand due to rapid population growth and industrial development as well as changes in land use patterns and land management procedures (Pangare et al., 2006). Under such conditions, hydrologic models are essential tools for a sustainable current and future water resources management (Ajami et al., 2008).

A huge number of hydrologic models is available for different aspects of water resources management, such as flood forecasting, water supply and demand analysis, and water quality evaluation. These modeling approaches vary in conception and complexity from physically based (e.g., MIKE SHE; Refsgaard and Storm, 1995; Im et al., 2009) to more conceptual models (e.g., TOPMODEL; Beven and Kirkby, 1979; Vincendon et al., 2010). In monsoon regions, model application is often restricted by limited data availability or outdated data due to the rapid socio-economic development. Therefore, modeling approaches that balance data requirements and process representations are essential for water resources analysis and management in these regions. Among others, the Soil and Water Assessment Tool (SWAT; Arnold et al., 1998) has proven its capability to model water fluxes in regions with limited data availability (Ndomba et al., 2008;

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Stehr et al., 2008) and has already been utilized in larger-scale studies in India (Dhar and Mazumdar, 2009; Gosain et al., 2006; Immerzeel and Droogers, 2008; Immerzeel et al., 2008). Hence, SWAT is a suitable tool for hydrological modeling of a meso-scale catchment in the Indian Western Ghats.

The main objective of this study is to utilize SWAT in a monsoon-driven meso-scale catchment by using mainly generally available input data and evaluate the model's potential for water resources management under these conditions. Successful implementation of this methodological approach provides a transferable method for the assessment of water resources in a monsoon-driven, data-scarce environment.

Materials and Methods

Study Area

The Western Ghats catchment of the Mula and Mutha Rivers (2036 km^2, fig. 1) is a sub-basin and source area of the Krishna River, which drains towards the east and into the Bay of Bengal. It has a tropical wet and dry climate characterized by seasonal monsoon rainfall from June to October and low annual temperature variation, with an annual mean of 25°C at the catchment outlet in Pune (18.53° N, 73.85° E). There is a pronounced west (approximately 3500 mm) to east (750 mm) decline of annual precipitation in the catchment (Gadgil, 2002; Gunnell, 1997); likewise, the relief declines from 1300 m on the top ridges in the Western Ghats to 550 m at Pune.

About two-thirds of the study area consists of grassland, shrubland and (semi-evergreen) deciduous forest (table 1). The agricultural areas are characterized by small fields (<1 ha). Typically, two crops per year are harvested. A rainfed crop is grown from June to October, and an irrigated crop is cultivated after the end of the monsoon season (November to March). In a few locations, where irrigation water supply is sufficient, a third crop is grown in April and May.

Water resources are highly managed by maintenance of six large dams in the catchment, which serve various purposes, such as power generation, irrigation, and municipal water supply for the city of Pune. Within the catchment, four gauged subcatchments that are defined by the locations of the gauges (G1, G2, G3, and G4) are used for model validation (table 1).

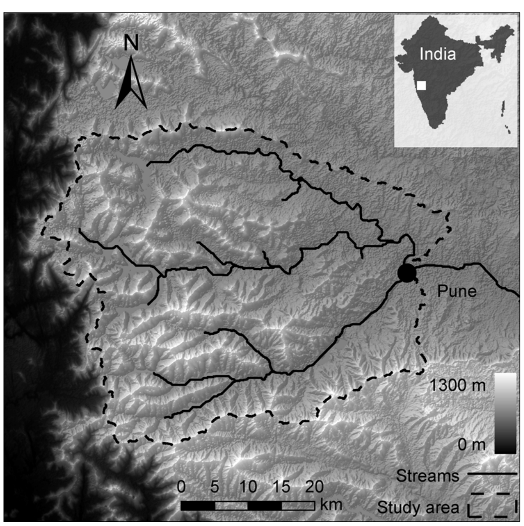

Figure 1. Location and elevation of the Mula-Mutha catchment.

Table 1. Main characteristics of the Mula-Mutha catchment and of four subcatchments, defined by gauge locations G1 to G4.

Catchment	Mula-Mutha	G1	G2	G3	G4
Area (km^2)	2036	498	331	680	99
Mean elevation (m)	676	634	694	729	803
Mean slope (%)	17	12	21	22	26
Forest (%)	20.6	10.5	34.2	31.3	45.1
Shrubland (%)	26.6	19.8	30.1	34.1	33.5
Grassland (%)	22.8	31.0	17.5	17.1	15.9
Cropland (%)	11.2	17.3	4.4	4.6	3.2
Water (%)	5.8	5.5	12.6	6.6	1.6
Urban (%)	13.0	16.0	1.3	6.2	0.7

Digital Elevation Model

A suitable digital elevation model (DEM) is an essential prerequisite for hydrological model studies. We used a DEM based on ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite data with a spatial resolution of 30 m (fig. 1). Four readily processed DEMs, calculated from stereo images of the near-infrared band, were acquired from the U.S. Geological Survey (USGS, 2009). To cover the entire study area, these four ASTER DEMs were merged. However, water surfaces are poorly represented in DEMs derived from optical satellite data. To determine water surfaces, a Landsat 7 ETM+ scene was used, and the water levels were derived from the ASTER elevations of the reservoir banks.

Compared to the 90 m × 90 m SRTM DEM (Jarvis et al., 2008), the ASTER DEM has a mean offset in elevation of 13.6 m. After correcting for this offset, the mean absolute error, which indicates the mean deviation from the SRTM DEM, is 8.8 m and the root mean square error is 15.3 m. The most pronounced differences can be observed in the mountain ranges, which typically result from the different spatial resolutions. The major advantage of the higher spatial resolution is a more accurate representation of slopes and the possibility to derive a more detailed stream network. Visual comparison to the drainage maps acquired from the Groundwater Department of Pune confirms the accuracy of the calculated stream network.

Soil Map

The spatial distribution of the soils was derived from the *Digital Soil Map of the World* (FAO, 2003). Major parts (92.5%) of the study area consist of a sandy clay loam (Hh11-2bc, Haplic Phaeozem). Minor parts (7.5%) are covered by a clay (Vc43-3ab, Chromic Vertisol). The two-layer soil parameterization used for modeling (table 2) was partly taken from a macro-scale modeling study of the region by Immerzeel et al. (2008).

Weather Data

Daily weather data (temperature, precipitation, humidity, solar radiation, and wind speed) from the Indian Meteorological Department (IMD) weather station in Pune (ID 430630, 18.533° N, 73.85° E, 559 m) were used as model input. In addition, three daily rainfall measurement stations that are maintained during the monsoon season by Tahasil (subdistrict administrative division) offices supplemented the record of precipitation in the catchment. Weather data is incorporated into the model at the SWAT sub-basin level. Due to the strong elevation gradient and the resulting east-to-west rainfall gradient (Gadgil, 2002; Gunnell, 1997), the SWAT stan-

Table 2. Parameterization for the two soils in the catchment adapted from Immerzeel et al. (2008); bulk density and organic carbon content taken from FAO (2003).

FAO Soil Code	Layer	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Sat. Hydraulic Conductivity (mm h^{-1})	Available Water Capacity (mm mm^{-1})	Bulk Density (g cm^{-3})	Organic Carbon Content (%)
Hh11-2bc	Topsoil	0-30	28.0	26.2	45.8	0.17	0.22	1.27	1.81
	Subsoil	30-137	28.3	23.1	48.6	0.14	0.07	1.35	0.70
Vc43-3ab	Topsoil	0-30	51.7	23.7	24.6	0.11	0.05	1.65	0.76
	Subsoil	30-143	54.6	22.9	22.5	0.16	0.01	1.75	0.46

dard method of using the nearest measurement station to represent precipitation in the sub-basin is not a suitable approach in the Mula-Mutha catchment. Therefore, a virtual weather station was generated in the center of each of the 27 sub-basins generated by SWAT. The precipitation for these virtual stations was estimated from the measurements of the four weather stations using an approach by Mauser and Bach (2009) that is based upon combining a regression technique with an inverse distance interpolation scheme. Firstly, a linear regression of elevation and mean daily measured rainfall amount was calculated ($R^2 = 0.8$, $p = 0.10$). Secondly, the regression equation and the mean elevation of the respective sub-basin were used to estimate the mean daily rainfall amounts for each sub-basin. Thirdly, the residual of daily rainfall (daily rainfall - mean daily rainfall) was calculated for every wet day and every measurement station. These residuals were interpolated to the center of each sub-basin using an inverse distance weighting scheme. Finally, by adding the interpolated residuals to the mean daily rainfall values calculated from the regression equation, a complete precipitation record was produced for every sub-basin.

To account for temperature differences in the catchment, temperature values were adjusted for every sub-basin using adiabatic temperature gradients of 0.98°C per 100 m on a dry day (no precipitation) and 0.44°C per 100 m on a wet day (Weischet, 1995). Using the sub-basin specific temperature records and the specific humidity measured at the weather station in Pune, relative humidity was calculated for each sub-basin. Solar radiation and wind speed data are only available in Pune and were therefore used for the whole catchment. In the two sub-basins that include a weather station or a rain gauge, the measurements from these stations were used as model input instead of the interpolated sub-basin specific data.

Land Use Map

A land use map (fig. 2) was derived from a satellite image taken on 30 November 2009 by the Linear Imaging Self-Scanning Sensor III (LISS-III) on the Indian satellite IRS-P6. LISS-III is a medium-resolution (23.5 m) multi-spectral sensor with two bands in the visible region, one band in the near-infrared region, and one band in the shortwave infrared region. All four of these bands were used for the classification. A stratified knowledge-based classification approach, using a maximum likelihood classifier, was applied as follows: thresholds of elevation (<800 m) and slope (<10%) were set for agricultural land use. In the study area, agriculture depends on the proximity to rivers and is therefore located in the valleys, which typically meet the 800 m elevation criterion. Pixels classified as agriculture in areas exceeding these thresholds were assumed to be grassland.

Finally, a majority analysis was applied on a moving 3 × 3 raster window to remove misclassified, spatially singular pixels within areas covered by one homogeneous class. Ground truth mapped at three test sites between 20 September and 9 October 2009 was used for calibration and validation. The time gap between ground truth and satellite imagery resulted from the need for a cloud-free image. This time lag has an influence on the classification of agricultural classes, as rice fields and some sugarcane fields had been harvested in between. Hence, the good quality of the classification (overall accuracy of 79%) decreases when rice and sugarcane are distinguished from other agricultural land use types (overall accuracy of 65%). The user's accuracy, which expresses the quality of the land use classification from the user's perspective (Story and Congalton, 1986), ranges from low accuracy for mixed cropland (27%), bare soil (41%), shrubland (45%) and grassland (69%) to high accuracy for forest (79%), rice (86%), urban (89%), and sugarcane (92%). Evidence of the quality of the land use classification is also derived from comparison with the most recent (cropping year 2007-2008) agricultural statistics available from the Department of Agriculture in Pune.

The land use classification indicates the dominance of semi-natural vegetation (table 1) in the catchment, with forest covering the higher elevations in the west, and grassland and shrubland dominating the lower elevations (fig. 2). Agricultural land mainly located in proximity to rivers and dams accounts for only 10.6% of the catchment (4.7% rice, 0.7% sugarcane, and 5.3% mixed cropland). The eastern part of the catchment is dominated by the city of Pune and its surrounding settlements (1.9% high-density and 11.1% medium-density urban area).

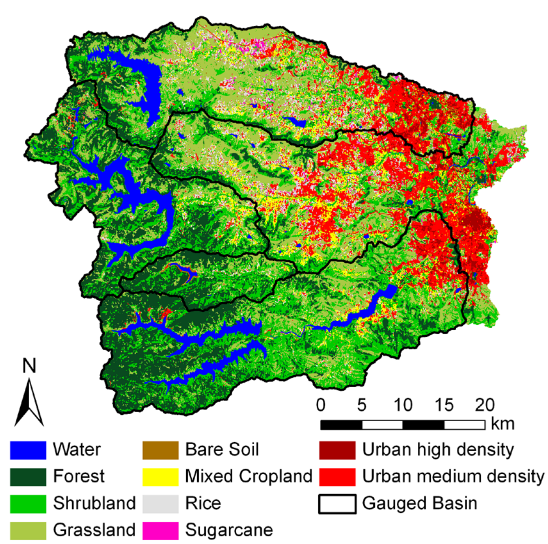

Figure 2. Land use map of the study area derived from LISS-III satellite data.

Table 3. Model setup for the vegetation land use classes.

Land Use	SWAT Land Use Code (Neitsch et al., 2010)	Management Details
Forest	FRSD	Original forest modified for the final model run
Grassland	BERM	Two growth cycles in rainy season, one in dry season
Shrubland	BERM, FRSD	Combination of 70% grassland and 30% forest
Bare soil	BERM, AGRL	Combination of 50% grassland and 50% mixed cropland
Mixed cropland	AGRR, AGRL	50% per class, grown as Kharif and Rabi crop, including auto irrigation and fertilization
Rice	RICE, SWHT	Rice as Kharif crop, wheat as Rabi crop, including auto irrigation and fertilization
Sugarcane	SUGC	18-month period of growth, including auto irrigation and fertilization

Model Setup

The catchment was divided into 27 sub-basins, which were defined by stream confluences and reservoir outlets. These sub-basins were subdivided into 922 hydrological response units (HRUs), representing homogenous slope (0% to 5%, 5% to 10%, 10% to 15%, and above 15%), soil, and land use classes. Surface runoff is generated using the SCS curve number method (Mockus, 1972). For channel routing according to a kinematic wave approach, a default value for Manning's roughness coefficient of 0.014 s $m^{-1/3}$ was used. Potential evapotranspiration was calculated using the Penman-Monteith equation (Monteith, 1965). The chosen model plant types and management of the vegetation land use classes are given in table 3. Shrubland was modeled as a mixture of forest and grassland to account for the percentage of trees. Two of the general crop classes in SWAT (AGRL, AGRR; Neitsch et al., 2010) contribute equally to the modeling of mixed cropland. The bare soil class was split between agriculture and grassland, as some fields were harvested and bare when the satellite image was taken. For the rice fields, the typical crop rotation of growing rice in the Kharif season (June to October) and wheat in the Rabi season (November to March) was implemented. This rotation was the only crop rotation pattern that was clearly observable from the field surveys. A growing period of 18 month was realized for the modeling of sugarcane. Heat units to bring a plant to maturity were calculated and adjusted to the growing periods of the local crops. For all crops, auto-irrigation was initialized. The irrigation procedure is based on plant water demand, triggering irrigation when plant growth falls below 95% of potential plant growth (Neitsch et al., 2010). In sub-basins with reservoirs, water for irrigation is taken from the reservoirs. In the other sub-basins, irrigation water is supplied by the rivers. A fraction of two-thirds of river discharge is allowed to be used for irrigation purposes, which is in agreement with the percentage of surface water used for irrigation in Pune Division (districts of Pune, Sangli, Satara, Solapur, and Kolhapur; Bhagwat, 2006). Apart from rivers and reservoirs, wells are also used as water sources for irrigation in the study area (Bhagwat, 2006). A model run performed without any water limitation did not indicate remarkable differences in the growth of irrigated crops. Hence, we assume that the implemented irrigation management supplies a sufficient amount of water. On an annual average, this irrigation setup resulted in a supply of 764 mm to sugarcane, 292 mm to the rotation of rice and wheat, and 275 mm to mixed cropland. For auto-fertilization, elemental nitrogen was used. The model (SWAT 2009) was run for eight years from 2000 to 2007. Only seven years (2001-2007) of the simulation period were analyzed, allowing for a one-year model spin-up phase.

Adaptation of Forest Growth

The SWAT model provides a land use and crop database with plant parameters for the respective land use type. Basically, three types of forests are supported: deciduous, coniferous, and mixed forests. The forest in the Western Ghats consists of deciduous trees. The annual growth cycle starts with the beginning of the monsoon in June and ends in the dry season, when leaves are dropped due to water and temperature stress. Most forests can be classified as tropical semi-evergreen forests, whereas evergreen forests are very limited in extent (Dikshit, 2002). Plant growth of deciduous trees in SWAT incorporates a dormancy period. The phenology model in SWAT predicts dormancy as a function of latitude and day length (Neitsch et al., 2005). The shortest day of the year triggers the beginning of tree dormancy in the model. However, in our region, dormancy is related to water and temperature stress. The methodology used by SWAT, which was developed for regions of the temperate zone, is not suitable for monsoon-driven or tropical climates. Consequentially, we modified this SWAT subroutine by shifting the dormancy period to the dry season, starting at the beginning of April and lasting until mid-May. Additionally, the maximum LAI for deciduous forests was modified (BLAI = 6) based on the LISS-III satellite image and using a relationship of normalized differenced vegetation index (NDVI) and LAI observed by Madugundu et al. (2008). Due to the unusually wet November in 2009, the LAI derived for 30 November is a suitable estimate for maximum LAI. Heat units were calculated (4500 heat units to maturity) to allow for a maximum of ten months of growth. Throughout this period, forest growth is primarily driven by water availability (fig. 3). The course of the annual LAI development of the modified forest growth model from mid-May to the end of March agrees significantly better with the phenology of the mainly semi-evergreen forests in the region (Dikshit, 2002) than the original model does.

Dam Management

The hydrology in the Mula-Mutha catchment is largely affected by six large dams (fig. 4), which are maintained to mitigate the effects of the pronounced seasonality in rainfall. Hence, it is essential for any successful model application to implement dam management. However, the available information regarding the dams is limited to maximum target storage and remotely sensed surface area. Maximum target storage for the reservoirs was made available by the Government of Maharashtra (2010), and the surface area of the reservoirs, corresponding to maximum target storage, was derived from satellite data (LISS-III image, 30 November 2009), which is assumed to be a valid estimate due to the wet November in 2009. On this basis, a simple dam management scheme was developed.

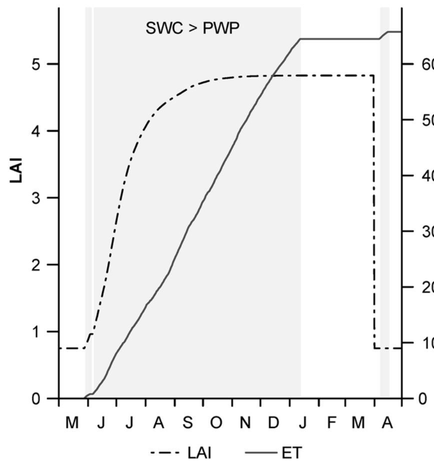

Figure 3. Modified forest growth allows for soil water limited evapotranspiration (ET): total (green and brown) leave area index (LAI), cumulative evapotranspiration (ET), and periods (gray shaded) when soil water content (SWC) is above permanent wilting point (PWP) of an exemplary forest HRU from May 2001 to April 2002.

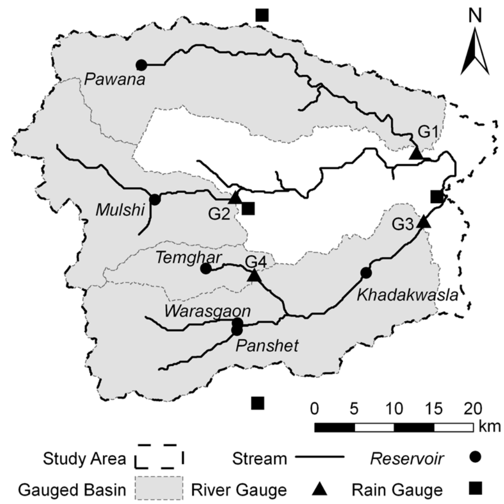

Figure 4. Location of river gauges, reservoirs, and rain gauges in the Mula-Mutha catchment.

Table 4. Reservoir characteristics acquired from the Government of Maharashtra (2010) and derived from LISS-III satellite data; dam outflow rates estimated by combining general management rules with river discharge observations at downstream gauges.

Dam	Maximum Target Storage (10^6 m^3)	Surface Area (km^2)	Dry Season Maximum Outflow (m^3 s^{-1})	Rainy Season Minimum Outflow (m^3 s^{-1})
Pawana	241	23.5	8	2
Mulshi	523	40.0	15	6
Khadakwasla	56	10.0	31.5	2
Panshet	298	13.7	12	2
Warasgaon	362	19.2	15	3
Temghar	70	1.6	2.5	2.2

The dam management in SWAT is controlled by monthly target storage and monthly minimum and maximum flow rates that were estimated from discharge observations at the river gauges. From June to October, the target storage is equal to the maximum target storage of the dam (table 4). From November on, the target storage is decreased every month, so that the water is released from the dams at a linear rate that is limited by the dry season maximum flow rate (table 4). This setup secures the water supply until a potentially late onset of monsoon in mid-July. A constant minimum flow rate during monsoon season was specified (table 4). If the mean annual amount of precipitation occurs, then the minimum flow rate allows the dam to fill up to the maximum target storage. When the target storage is reached, additional water is stored in flood storage. No flood storage information was available; therefore, flood storage was assumed to account for 10% of the maximum target storage. The flood storage is decreased at a dam-specific constant maximum flow rate. Table 4 presents the derived parameterization for each reservoir. Dam storage information, which is supplied online by the Government of Maharashtra (2010) and is updated on a daily basis, was logged for the rainy season of 2010 and provides evidence for the adequacy of the assumed dam management.

River Gauging Stations

The Government of India implemented a Hydrological Information System within the World Bank supported Hydrology Project, through which the river discharge data were provided by the Water Resources Department of Nashik. In the catchment, four river gauging stations are available that define four gauged subcatchments (table 1). All gauges are located downstream of a managed reservoir (fig. 4); consequently, no record of unmanaged river discharge is available. The runoff record only provides data for the monsoon seasons of the years 2001 to 2007. Some data gaps are also observable in the rainy season. On average, 70 to 100 daily measurements per year were available at gauges G1, G2, and G4. The record for gauge G3 consists of only 127 measured values for the entire observation period.

Model Calibration and Validation

Although the SWAT model does not require much calibration (Gosain et al., 2005; Gosain et al., 2006), the model was not calibrated with ground-based measurements in this study. Site-specific model calibration often results in significant improvements of the model output. However, achieving good agreement between model results and independent measurements, such as river runoff, through model calibration does not imply that the underlying processes and parameterization are correctly described. Thus, our study does not primarily aim at achieving the best match between model and measurements through model calibration, but rather at analyzing processes and setting model parameters based on process understanding and regional knowledge, in order to learn from discrepancies between models and observations and thereby gain a better understanding of the system. It is assumed that proper process understanding and model parameterization build a solid and transferable basis to apply models in data-scarce regions or under conditions of environmental change resulting from land use or climate change or from alternative management decisions (Kirchner, 2006).

The model was validated with respect to simulated discharge and water balance. To evaluate the capability of the model to reproduce measured discharge at the four subcatchment gauges, a set of commonly used goodness-of-fit indicators was calculated: the coefficient of determination (R^2), the Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970), and the ratio of root mean square error and standard deviation of the observations (RSR; Moriasi et al., 2007). Direct validation of the simulated water balance is only possible for the periods for which measured data are available. Hence, water yield can only be validated in monsoon time. Additionally, supplementary information from regional studies regarding runoff coefficient and evapotranspiration (ET) was used to evaluate the simulated water balance.

Results and Discussion

River Discharge

Comparing modeled and measured discharge for the four gauged subcatchments indicates a reasonable performance of the model (table 5). Except for gauge G3, where the smallest number of validation values (127 days) is available, more than 60% of the variability in discharge is explained by the model, and the NSE (0.58 to 0.68) and RSR (0.57 to 0.65) values suggest satisfactory to good performance. Exemplary hydrographs for the years 2003 and 2005 (lowest and highest discharge rates) at gauge G1 (best model performance, table 5) show the capability of the model to simulate runoff dynamics accurately (fig. 5).

The importance of an appropriate dam management is indicated by the substantially lower goodness-of-fit indicators in a simulation without dams (table 5). The most notable increase in model performance was achieved at G2, which is located downstream of the largest reservoir (Mulshi dam) in the catchment. Although the model performance at G3 was improved by implementation of dam management, it is still unsatisfactory. This might result from its position downstream of four dams (Khadakwasla, Panshet, Warasgaon, and Temghar), which are operated by the same agency that potentially applies more complex, interrelated management rules for these dams. Two gauges (G1 and G4) show satisfactory results even without implementation of dam management rules. Hence, it can be concluded that management of these dams is less important for river discharge at these gauges. In the case of G4, this is probably due to the smaller size of the upstream Temghar dam (table 4), while at G1 the longer distance between gauge and dam (49.4 km, fig. 4) mitigates the impact of the Pawana dam on river discharge. The satisfactory model performance at these two gauges, where the impact of dam management is less important, shows that natural hydrology was generally modeled with acceptable accuracy.

Although effects should be smallest at gauge G1, the implementation of dam management helps to simulate runoff peaks more accurately, as shown in figure 4 for the peaks on 30 June, 3 July, and 26 July 2005. Model results without dam management clearly overestimated discharge peaks, whereas the implemented dam management reproduced the dampening effect of the reservoir. Nevertheless, it should be noted that the relatively simple, knowledge-based management scheme does not allow for more complex dam operations; for example, the higher observed discharge between the peaks on 26 July and 2 August 2005 was not matched by the simulation.

Table 5. Model performance at the river gauges based on daily discharge during rainy season; results without incorporation of dam management are given in parentheses.

Gauge	R^2	NSE	RSR	No. of Validation Values	Validation Period
G1	0.71 (0.70)	0.68 (0.55)	0.57 (0.67)	655	2001-2007
G2	0.63 (0.51)	0.63 (-0.17)	0.61 (1.08)	586	2001-2007
G3	0.34 (0.33)	0.10 (-0.38)	0.94 (1.17)	127	2002, 2004-2007
G4	0.70 (0.60)	0.58 (0.53)	0.65 (0.69)	689	2001-2006

Water Balance

For long-term water resources management, changes in the catchment water balance are of special interest and possibly more important than discharge rates during the monsoon season. However, a direct validation of simulated long-term water balance components (ET = 679 mm, Q = 1172 mm, and P = 1860 mm) calculated for the period from 2001 to 2007

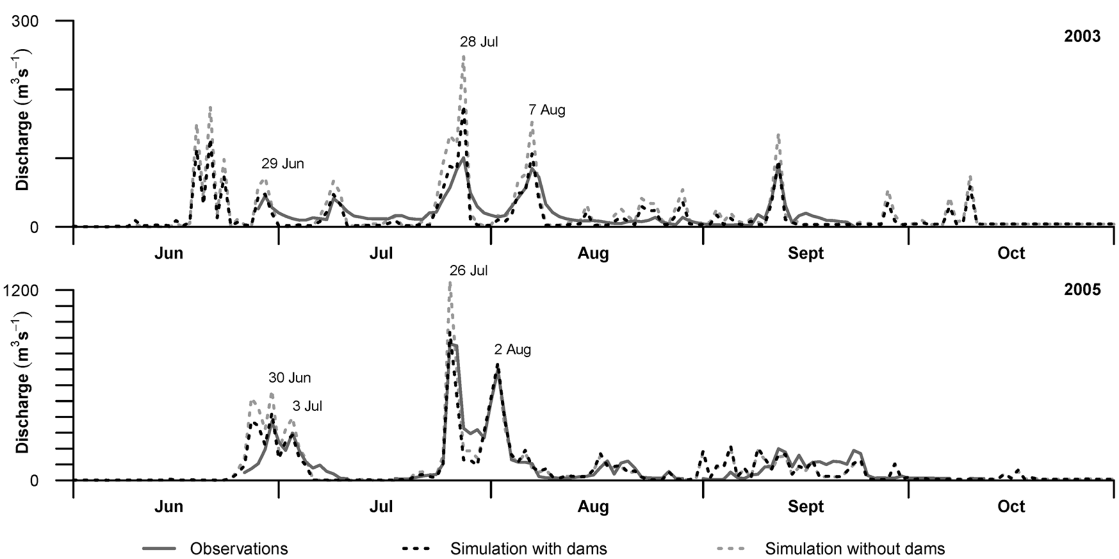

Figure 5. Observed and modeled discharge at gauge G1 with and without dam management for low-flow (2003) and high-flow (2005) years.

is not possible, as measured ET data are missing, Q is only available during the monsoon season, and measurements of P are spatially limited to four rain gauges. Comparison of the modeled runoff coefficient (Q/P) of the Mula-Mutha catchment (0.63) to a comparable catchment in the Western Ghats region (upper Krishna: 0.68; Biggs et al., 2007) gives some confidence in the modeled water balance. The available average water yield measured during the monsoon periods from 2001 to 2007 are 878 mm for the catchment upstream of G1, 796 mm for G2, 1006 mm for G3, and 2432 mm for G4. Due to some data gaps, these cumulative values underestimate the total monsoon discharge by approximately 10% to 25%, as estimated from the ratio of the modeled amount of discharge during validation to the entire monsoon period. For those periods for which measurements are available, the model underestimated water yields by 12.8%, 11.1%, 9.5%, and 44.7% at gauges G1, G2, G3, and G4, respectively. This underestimation may have resulted from one or more of the following reasons: (1) modeled ET is too large; (2) during monsoon season, water is stored and hence baseflow is underestimated by the model; or (3) precipitation is underestimated, especially in the headwater subcatchments.

The mean annual ET (2001-2007) in the catchment is 679 mm. Implementation of the modified forest phenology model increased forest ET by 18.6%, which corresponds to an increase of 5.3% at the catchment scale. Figure 3 shows that this increase is mainly due to ET in the dry months from November to January, as the modified model allows for ET until soil water content is decreased to the wilting point. As irrigation is only applied on 11.2% of the catchment area and only a small areal percentage is irrigated in the summer months (sugarcane 0.7%), irrigation does not have a major impact on ET (13.2% on the catchment scale). Despite the increase of forest ET, especially in the dry season, overall ET seemed to be low compared to the results of other studies that include the Mula-Mutha catchment (Immerzeel and Droogers, 2008; Immerzeel et al., 2008). In the region of our study, Immerzeel and Droogers (2008) calculated ET values between 500 and 700 mm for the period from October 2004 to May 2005. For the same period, ET amounts to 370 mm in our model. Although the comparison of a short period of time with macro-scale studies that are based on coarser land use maps is questionable, it may be concluded that ET during the dry season tends to be underestimated by the model; therefore, it seems highly unlikely that the low water yield results from an overestimation of ET.

The second potential reason for the underestimation of water yield during the monsoon season might be an overestimation of modeled groundwater recharge and storage. However, as declining simulated hydrographs do not show a prolonged baseflow effect (e.g., 29 June, 28 July, and 7 August 2003; fig. 5), groundwater storage seems to have an unimportant effect on modeled water yield.

Underestimation of precipitation is the most likely error source for the underestimation of water yield, especially in the case of headwater subcatchments. In G4 (fig. 4, table 1), where measured water yield (2432 mm) is almost as large as modeled annual precipitation (2606 mm), the precipitation interpolation seems to fail. This failure probably originates from the small number of input rainfall stations (four) that do not sufficiently represent horizontal and vertical characteristics of rainfall in the catchment (e.g., the highest station is 694 m, whereas mean elevation of G4 is 803 m). Hence, the applied dependency between elevation and precipitation is extrapolated and more uncertain for high altitudes. Additionally, spatial distribution of rainfall may also be influenced by factors other than elevation, e.g., by the dominant southwest wind direction during monsoon. This underlines the importance of appropriate precipitation data. To improve precipitation input, additional data from the region may be used to derive large-scale dependencies that are also applicable in the Mula-Mutha catchment. Remote sensing products such as those from the Tropical Rainfall Measuring Mission (TRMM) may be used to reduce errors in the spatial distribution of rainfall. However, coarse spatial resolution or incomplete timely resolution of the available TRMM products does not allow for a direct integration of the data into the model. Nevertheless, development and application of a more sophisticated rainfall interpolation scheme using auxiliary variables (Verworn and Haberlandt, 2011) like wind direction or TRMM rainfall patterns could improve our model results.

Summary and Conclusions

In this study, the SWAT model was used to simulate river discharge and water balance in the catchment of the Mula and Mutha Rivers. The catchment hydrology is dominated by a pronounced seasonality of rainfall due to the yearly monsoon, which governs vegetation growth and leads to strong management of water resources (e.g., irrigation measures and management of large reservoirs). Despite the limited availability of model input data, which were mainly derived from remote sensing and other freely available data sources, it was possible to reproduce the measured discharge accurately in three of four subcatchments by applying an expert-based model parameterization. A relatively simple dam management scheme was derived from reservoir volumes, remote sensing, and local expert knowledge. In addition, the forest growth model in SWAT was modified to take into account water-limited plant growth during the dry season. However, modeled evapotranspiration during the dry season was small compared to results from macro-scale modeling studies. Moreover, precipitation input was especially underestimated in headwater catchments, and therefore water yield was underestimated, too. The determination of spatial patterns and amounts of precipitation remains a source of error that must be addressed in further studies.

In general, the quality of the model output, which was achieved by using mainly freely available and at times very coarse input data, is very promising. The methodology can be transferred to other monsoon-driven, data-scarce environments and may be adopted for predictions in ungauged catchments.

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