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SPATIAL MAPPING OF AGRICULTURAL WATER PRODUCTIVITY USING THE SWAT MODEL IN UPPER BHIMA CATCHMENT, INDIA[†]

KAUSHAL K. GARG[1]*, LUNA BHARATI[2], ANJU GAUR[3], BIJU GEORGE[4], SREEDHAR ACHARYA[5], KIRAN JELLA[5] AND B. NARASIMHAN[6]

[1]*International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India*
[2]*International Water Management Institute-Nepal, Jawalakhel, Lalitpur, Nepal*
[3]*The World Bank, New Delhi, India*
[4]*Department of Civil and Environmental Engineering, University of Melbourne, Australia*
[5]*International Water Management Institute-Patancheru, Patancheru, India*
[6]*Indian Institute of Technology, Chennai, India*

ABSTRACT

The Upper Bhima River Basin is facing both episodic and chronic water shortages due to intensive irrigation development. The main objective of this study was to characterize the hydrologic processes of the Upper Bhima River Basin and assess crop water productivity using the distributed hydrologic model, SWAT. Rainfall within the basin varies from 450 to 5000 mm in a period of 3–4 months. The basin has an average rainfall of 711 mm (32 400 Mm^3 (million cubic metres)) in a normal year, of which 12.8% (4150 Mm^3) and 21% (6800 Mm^3) are captured by the reservoirs and groundwater reserves, respectively, 7% (2260 Mm^3) exported as runoff out of the basin and the rest (63%) used in evapotranspiration. Agricultural water productivity for sugarcane, sorghum and millet were estimated as 2.90, 0.51 and 0.30 kg m^{-3}, respectively, which were significantly lower than the potential and global maximum in the basin and warrant further improvement. Various scenarios involving different cropping patterns were tested with the goal of increasing economic water productivity values in the Ujjani Irrigation Scheme. Analysis suggests that maximization of the area by provision of supplemental irrigation to rainfed areas as well as better on-farm water management practices can provide opportunities for improving water productivity. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: hydrological modelling; SWAT; crop water productivity; water balance; Upper Bhima; Ujjani Irrigation Scheme

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RÉSUMÉ

Le bassin versant du Haut-Bhima est confronté aux pénuries d'eau épisodiques et chroniques à cause de développement de l'irrigation intensive. L'objectif principal de cette étude est de caractériser les processus hydrologiques de ce bassin versant du Haut-Bhima et d'évaluer la productivité en eau des cultures en utilisant SWAT, le modèle hydrologique distribué. Les précipitations dans le bassin versant varient de 450 mm/an à 5000 mm/an et sont réparties inégalement dans le temps et dans l'espace. Le bassin a une pluviométrie moyenne de 711 mm (32 400 Mm^3) dans une année normale, dont 12.8% (4150 Mm^3) et 21% (6800 Mm^3) remplissent ou rechargent les réservoirs ou les nappes phréatiques, 7% (2260 Mm^3) ruissellent, et le reste (63%) est prélevé pour l'évapotranspiration. La productivité de l'eau agricole dans le bassin pour la canne à sucre, le sorgho et le mil ont été estimés à 2.90, 0.51 et 0.30 kg m^{-3}, ce qui est significativement plus faible que le potentiel maximal habituellement rencontré dans le monde. Il y a donc des marges de progrès qu'il convient d'explorer. Différents scénarios impliquant différents itinéraires techniques ont été testés dans le but d'accroître la valeur économique de la productivité de l'eau dans le système d'irrigation d'Ujjani. L'analyse suggère que la maximisation de la superficie grâce à la fourniture d'irrigation d'appoint pour les zones pluviales, ainsi que le recours à des pratiques agricoles de gestion plus économes en eau, peuvent offrir des possibilités pour améliorer la productivité de l'eau. Copyright © 2011 John Wiley & Sons, Ltd.

MOTS CLÉS: modélisation hydrologique; SWAT; productivité en eau des cultures; gestion équilibrée de l'eau; bassin du Haut-Bhima; système d'irrigation d'Ujjani

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* Correspondence to: Kaushal K. Garg, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) - GT-AES. Patancheru-502324 Andhra Pradesh Hyderabad Andhra Pradesh 502324, India. Tel.: +91 40 30713464. E-mail: k.garg@cgiar.org

[†] Cartographie de la productivité de l'eau en utilisant le modèle SWAT dans le bassin versant du Haut-Bhima, en Inde.

INTRODUCTION

The impact of climate change presents extraordinary challenges for users and managers of water resources. This is particularly true in basins that are already facing water scarcity. Water scarcity is particularly acute in many developing countries, which have to cope with rapidly expanding populations, and the need to eradicate poverty and improve people's quality of life. The Upper Bhima River Basin in the state of Maharashtra in India is an example basin that is facing both episodic and chronic water shortages. The shortages are mainly due to water resources development following the rapid expansion of irrigated agriculture. Due to upstream basin development and increased diversion to meet growing demand, the water released from the Upper Bhima River Basin has declined by 59% from an average of 8820 Mm^3 in 1970–1980 to 3620 Mm^3 during 1994–2000 (Gaur *et al.*, 2007). The challenge is to find ways to meet growing demand and also to achieve positive environmental and economic outcomes.

The water resources in the basin are used to meet the growing intersectoral demands of the basin, including hydropower, agriculture, industry and drinking water supplies. Agriculture is the largest consumer of water in the Bhima Basin. Therefore, any appropriate strategies for water savings and more efficient use of water in agriculture would help to manage water scarcity issues in the basin. The production of more food under a water-scarce situation can be achieved by maximizing crop yield per unit of water consumed (Kijne *et al.*, 2003; Bouman, 2007), which is termed "crop water productivity" (WP) (Molden, 1997; Kijne *et al.*, 2003). The framework of WP is a useful means to evaluate the performance of agricultural production systems and recommend management practices at any scale, ranging from field to river basin (Molden and Sakthivadivel, 1999; Loeve *et al.*, 2004). The Upper Bhima River Basin is very complex with highly spatial and temporal variability in climate, water availability, land use and irrigation practices, and soil type coupled with a series of multipurpose reservoirs. There is a need for analytical tools or models that can simulate the basin hydrology, land use and provide site-specific interventions. The Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998; Srinivasan *et al.*, 1998) is a process-based continuous hydrological model that can predict the impact of land management practices spatio-temporally on water and agricultural yields in complex watersheds with varying soils, land use and management conditions. SWAT is a proven tool for hydrological modelling to assess water quantity and quality (Kannan *et al.*, 2007; Geza and McCray, 2008; Bosch, 2008; Yang *et al.*, 2009; Ullrich and Volk, 2009) at different spatial scales, from small watersheds (Kang *et al.*, 2006; Green and Griensven, 2008) to larger river basins (Luo *et al.*, 2008) or to continental scale (Schuol *et al.*, 2008). Several researchers mentioned above have successfully used the model for hydrological and water resources assessment, WP mapping and simultaneously testing scenarios for various water- and land-based interventions. In particular Immerzeel *et al.* (2008) have used SWAT to map WP in the Upper Bhima Basin which was calibrated by using remotely sensed evapotranspiration based on the SEBAL algorithm (Bastiaanssen *et al.*, 1998a, b, 2005). The model was set up at macro scale for the basin and lacked detailed field verification, therefore it was not possible to simulate for project-specific water management scenarios. The present study aims at mapping agricultural WP within the basin using actual observations (flows and crop yields) for calibration and simultaneously to understand the impact of various water management scenarios on physical and economic WP in agriculture.

METHODOLOGY

Site description: Upper Bhima

The Upper Bhima (Figure 1) is one of the main tributaries of the Krishna River with a basin area of 46 066 km^2 (National Water Development Agency, 2003). The major portion of this sub-basin lies in the state of Maharashtra (98.4%) with a small portion in Karnataka (1.6%). The major area of the basin is relatively flat and about 95% lies below 800 m elevation. Elevation in the Western Ghat mountains reaches up to 1458 m from 414 m in the eastern part of the basin. The climate of the Upper Bhima River Basin is highly diverse, caused by the interaction between the monsoon and the Western Ghat mountain range (Gunnel, 1997). The mean annual rainfall of the basin is 653 mm, with an uneven distribution in space and time (National Water Development Agency, 2003). The Western Ghats zone is covered with thick forest and receives heavy rainfall reaching a maximum of 5000 mm yr^{-1}. Rainfall decreases rapidly towards the eastern slopes and plateau areas where it is less than 500 mm yr^{-1}. It again increases towards the east; therefore, the central part of the Upper Bhima receives the lowest rainfall. The mean maximum temperature varies from 38 to 40 °C in May and minimum temperature varies from 11 to 16 °C in January. The average annual reference evapotranspiration (ETo) of the basin is 1838, mm ranging from 263 mm in May to 113 mm in December. The Upper Bhima River Basin lies on granite, zeonite and basalt rocks, that all contain considerable stocks of groundwater. Total replenishable groundwater is 5363 Mm^3 (Ground Water Resources of India, 1995). Soil in the basin is broadly divided into five groups: coarser shallow black soil, medium black soil, reddish brown soils, laterite and lateritic soils, and deep black soils. The alluvial plains are predominantly characterized by vertisols, while the Western Ghats and steep slopes are luvisols (National Water

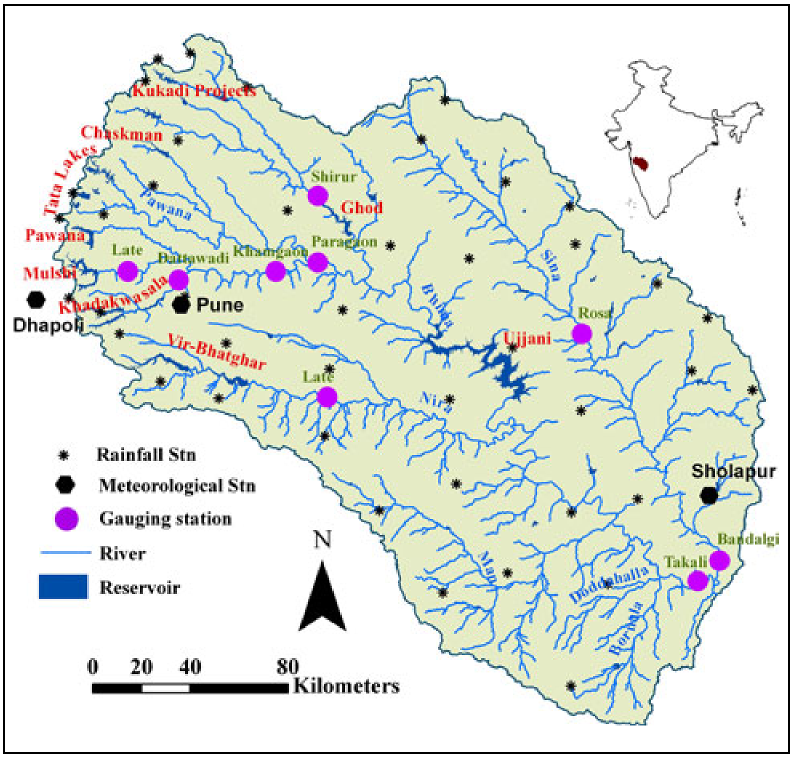

Figure 1. Location of major reservoirs, stream network, discharge gauge, rainfall and meteorological stations in Upper Bhima Basin. This figure is available online at wileyonlinelibrary.com/journal/ird

Development Agency, 2003; National Bureau of Soil Survey and Land Use Planning (Challa *et al.*, 1999), Nagpur, India).

The basin serves a population of 15 million (Government of India, 2001) of which 6 million live in urban areas. It is an important basin in the context of serving intersectoral demands including urban, irrigation (4025 km^2) and hydropower generation (371 MWH). The basin is highly regulated, with 6 major and more than 30 medium reservoirs with a gross storage capacity of 7900 Mm^3 and live storage capacity of 5700 Mm^3. The salient features of the important reservoir projects are listed in Table I. The reservoirs are operated in an integrated manner while serving as a flood

Table I. The salient features of major projects in the Upper Bhima River Basin

Scheme	Purpose	Live storage (Mm^3)[a]	Gross storage (Mm^3)	Power potential (MWH)[b]
Bhima (Ujjani)	Irrigation and hydropower	1518	3320	12
Ghod	Irrigation	155	216	–
Khadakwasla series	Irrigation, drinking and hydropower	740	841	16
Pawana	Irrigation and hydropower	274	318	10
Vir-Bhatghar	Irrigation and hydropower	931	951	25
Kukadi projects				–
Chaskaman	Irrigation and hydropower	214	241	3
Yedgaon	Irrigation	79	93	–
Dimbhe	Irrigation and hydropower	355	382	5
Manikdoh	Irrigation and hydropower	288	308	6
Wadaj	Irrigation	33	36	–
Hydropower schemes (westward diversion)				
Mulshi	Hydropower	523	554	150
Andhra	Hydropower	353	353	72
Tatalakes	Hydropower	265	274	72
Total		5728	7887	371

[a] Mm^3: million cubic metres.
[b] MWH: megawatt-hours.

cushion and water source for various water users in the basin. The downstream storages primarily depend on the releases from upstream storages in the Western Ghats. Inflow takes place during the monsoon (June–October) season and the stored water is supplied for irrigation and non-irrigation uses throughout the year depending upon the water availability in a reservoir. In general, live storages are depleted during the year and the reservoirs are left with dead storages by April or May. The projects in the basin were designed for protective irrigation for seasonal dry crops. But the cropping pattern later shifted to water-intensive perennial crops such as sugarcane. Increased population growth and economic development have placed immense stress on the water resources of this basin. Intersectoral demands have changed, especially with increasing needs for the urban and industrial sectors accounting for 22% of total water use.

The land use consists of rainfed and irrigated area, forest, urban, rangeland and water bodies (Figure 2 and Table II). About 70% of total land is under agriculture, with 40% rainfed area. The major crops grown in this basin are sugarcane, sorghum, wheat, corn, millet, groundnut, fodder grass, and a variety of horticultural crops (Neena, 1998). The irrigated crops such as sugarcane and sorghum account for 25% of the total geographical area in the *kharif* and *rabi* seasons. The major sources of irrigation are canals (30% of irrigated area) and groundwater (70%) (Agricultural Census, Government of Maharashtra).

The Ujjani Reservoir (Figure 1) is the largest reservoir in the Upper Bhima River Basin and has a basin area of 14 712 km^2. The project is designed to irrigate an area of 2595 km^2 or 259 500 ha. Gross and live storage capacities of this reservoir are 3320 and 1517 Mm^3, respectively. The dead storage capacity of the reservoir is higher than the live storage capacity due to the flat topography of its location. As a result, approximately 580 Mm^3 yr^{-1} of storage (17% of gross storage) is lost by evaporation and seepage. Inflow to the Ujjani Reservoir is dependent on upstream water use and releases from upstream reservoirs. The situation becomes critical especially during dry years (+25% inflow to normal is considered a wet year and −25% inflow of normal is a dry year). For example in 2003, the Ujjani Reservoir did not fill even to the dead storage level at the end of the monsoon due to low inflows. Farmers solely dependent on canal releases ended up dealing with crop

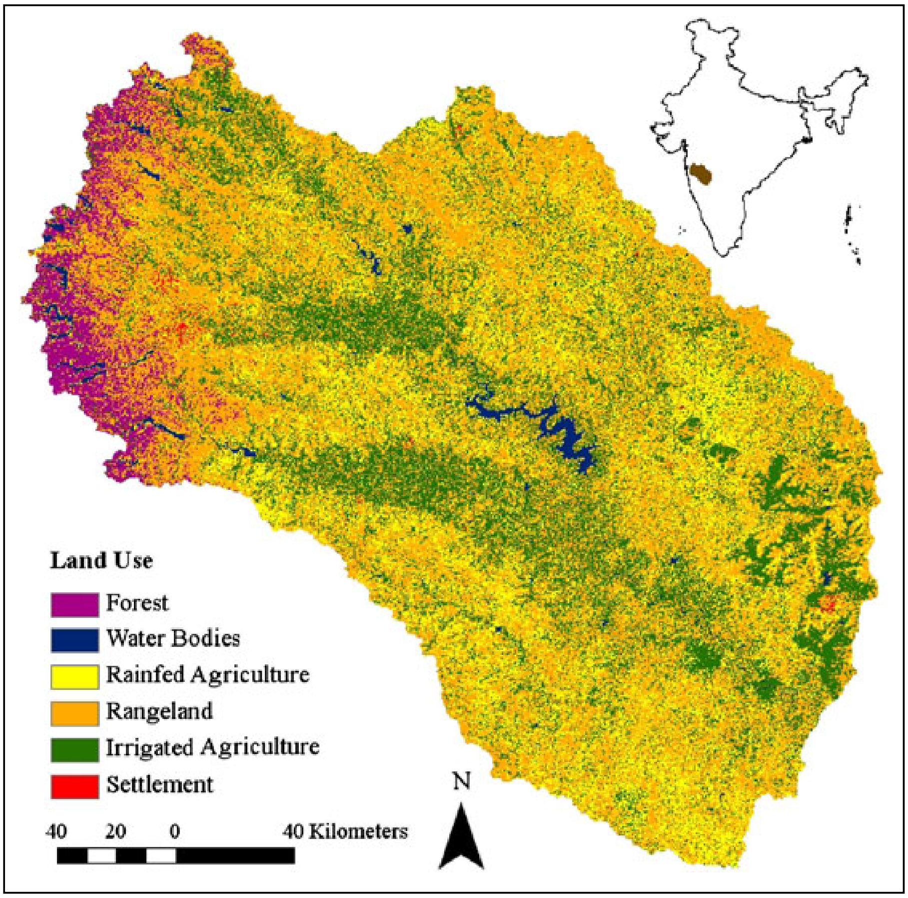

Figure 2. Major land use classes in Upper Bhima Basin. This figure is available online at wileyonlinelibrary.com/journal/ird

Table II. Land use classes in the Upper Bhima River Basin

Land use classes	Crop grown in SWAT HRUs	Growing season	Crop period	Area (km^2)	Area (%)
Rainfed area	Sorghum	*Kharif*	15 Jun–2 Nov	2 520	5.5
	Millet	*Kharif*	15 Jun–2 Nov	18 986	41.7
Irrigated area	Sorghum	*Kharif*	15 Jun–2 Nov	9 930	21.8
	Sugarcane	Perennial	5 Jan–20 Dec	1 612	3.5
	Sorghum	*Rabi*	15 Nov–2 Mar	9 930	21.8[a]
Urban land				119	0.3
Forest land				1 907	4.2
Range land				9 826	21.6
Water bodies				660	1.5

[a] Second crop grown in irrigated area.

failure. Despite water scarcity in this region, a substantial area is being cultivated under sugarcane, which requires high, intensive, year-round irrigation. The cropping pattern in the Ujjani command is characterized by a variety of food and commercial crops like sorghum, maize, groundnut, wheat, oilseed, millet, cotton and sugarcane. Sugarcane is, however, the predominant perennial crop (20–40% of the total cultivable area).

SWAT model set-up

The Soil and Water Assessment Tool (SWAT) is a process-based continuous hydrological model and the main components of the model include: climate, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, channel and reservoir routing. The public domain model ArcSWAT2005 (version 2.4.1a) working with the ArcGIS9.2 interface was selected for this study as it considers spatial variability of soil, land use, climate and also captures human-induced land and water management practices which is particularly important in a complex basin like the Upper Bhima.

The model divides the watershed into multiple sub-basins, which are then further sub-divided into hydrological response units (HRUs) which consist of homogeneous land use, management and soil characteristics. SWAT divides rainfall into different components which include evaporation, surface runoff, infiltration, plant uptake, lateral flow and groundwater recharge. Surface runoff from daily rainfall is estimated with a modification of the SCS curve number method from the United States Department of Agriculture Soil Conservation Service (USDA SCS) and peak runoff rates using a modified rational method (Neitsch *et al.*, 2005). The model estimates plant growth under optimal conditions, and then computes the actual growth under stresses inferred by water and nutrient deficiency. Detailed descriptions of the model can be found in Arnold *et al.* (1998), Srinivasan *et al.* (1998), Gassman *et al.* (2007) and Williams *et al.* (2008).

SWAT requires three basic files for delineating the basin into sub-basins and HRUs: a digital elevation model (DEM), soil map and land use/land cover (LULC) map. A 90 m spatial resolution shuttle radar topographic mission (SRTM) DEM was used in this analysis (Rabus *et al.*, 2003). A soil map of Maharashtra state was collected from the National Bureau of Soil Survey and Land Use Planning (Challa *et al.*, 1999), Nagpur, India. Land use/land cover were derived for the year 2004–2005 using Indian remote sensing satellites (IRS) P6 (Resourcesat 1), linear imaging self-scanner (LISS) III remote sensing images of October 2004 and February 2005 with a spatial resolution of 23.5 m. Initially, unsupervised classification with a large number of classes (150) was performed. Later, these classes were attributed to the six main classes (Figure 2) using normalized difference vegetation index (NDVI) patterns, verifying ground truth surveys and Google earth images.

Daily rainfall data from 44 rain gauge stations (Figure 1), which are spatially spread across the entire basin, were collected from the Indian Meteorological Department (http://www.imdpune.gov.in/), Pune, India. Further records of meteorological parameters such as daily maximum and minimum temperatures, wind speed, solar radiation and relative humidity were obtained from the meteorological stations in Pune, Sholapur and Dhapoli (Figure 1). Daily discharge data from eight stations were collected from the Hydrology Data Centre Nasik, Maharashtra, for model calibration and validation purposes. Similarly, daily inflow and outflow data of different reservoirs were collected from the Irrigation Project and Water Resources Investigation Circle (http://www.pipcpune.in/index.html), Pune, India. The sub-district-level data for cropping pattern and crop yield data were collected from the Agricultural Statistics Department of Maharashtra for the entire basin. Actual data for crop yield and total production under various crops for the Ujjani command were collected from the Ujjani Command Area Development Authority (CADA), Sholapur (http://www.solapurcada.org/). Canal water releases for agriculture in different seasons were also collected from CADA, Sholapur.

A total of 105 sub-basins and 968 HRUs were delineated in the Upper Bhima River Basin and further parameterized. SWAT attributes soil, management, hydrological and water quality parameters for each HRU based on the spatial input data. Reservoirs play an important role in the hydrology of the Upper Bhima River Basin. Therefore 11 reservoirs were built into the model to represent the total storage in the basin. Only major reservoirs having storage capacity of more than 85 Mm^3 were taken into consideration. Out of the 11, 3 reservoirs divert water outside the basin for power generation (Mulshi, Andhra and Tata lakes) and the rest are multipurpose reservoirs with irrigation as the major water user (Table I). Irrigation command areas for each reservoir were delineated separately and overlaid on the SWAT project to identify the source of irrigation in the model-generated sub-basins.

There are three types of cropping systems in the Upper Bhima River Basin: (1) rainfed agriculture in which crops are grown in the monsoon season (June–October) and no irrigation is supplied; (2) irrigated short duration crop in which 100–120-day duration crops are grown with complete or partial irrigation; and (3) irrigated long duration crop in which fully irrigated two-seasonal or perennial crops are grown. Although the cropping pattern in Upper Bhima consists of many food grain and commercial crops, the three most dominant crops, i.e. sorghum, millet and sugarcane, were considered in the simulation (Table II). The first season crop, millet, was grown in 41.7% of total basin land under rainfed area; and sorghum in 27.3% of total basin land under both rainfed and irrigated areas during the *kharif* (monsoon) season. The second-season crop, sorghum, was grown in 21.8% of total basin land under irrigated area during the *rabi* (post-monsoon) period. Sugarcane was grown in 3.5% of total basin land under irrigated area for the entire 12-month period.

Parameters concerned with management operations like tillage, plantation, fertilization, irrigation and harvesting were also provided as input to the model. The irrigation supply was specified by crop water requirements (based on ET calculations). During the growing season, reservoirs were considered as the source of irrigation in command areas, whereas groundwater was considered as the source of irrigation outside the command areas. Considering reuse of return flows and seepage by farmers within the command area, the overall efficiency of the major irrigation conveyance system was assumed as 70%. The command areas of different reservoir projects were delineated first. Sub-basin HRUs belonging to distinct command areas were identified and assigned the corresponding reservoir as the source of irrigation. For the sorghum crop, during the *kharif* season supplemental irrigation of 75 mm was assigned three times and in the *rabi* season 75 mm was assigned every 10 days throughout the crop growth period. For the sugarcane crop, 75 mm of supplemental irrigation was applied 20 times during the whole season. In general canal water is applied as flood irrigation in the majority of command areas. In the model, water diverted for agriculture was adjusted based on actual canal releases from each reservoir.

Model calibration and validation

The data from January 1998 to December 2001 were used for model calibration, and data from January 2002 to October 2005 for model validation. In the calibration phase, runoff was simulated at a daily time step and was compared with observed discharge data from 8 gauging stations together with measured inflow data of 11 reservoir locations (Figure 3). Calibration is performed at various steps, starting from upstream to downstream parts of the basin. A series of reservoirs located near the Western Ghats receive virgin flows and the hydrological responses of these stations are directly subjected to climatic variations. The inflow into the downstream reservoirs consisted of spills, releases from the upstream reservoirs and runoff contributed by its own basin. In addition, water stored in various reservoirs and irrigation releases were compared with SWAT simulated values to parameterize local management of various command areas during the calibration process.

As it is not feasible to include all parameters in the calibration procedure, sensitivity analysis was performed for a few selected locations. Parameter sensitivity was obtained applying a combination of Latin hypercube and one-factor-at-a-time sampling techniques (Van Griensven *et al.*, 2006). Table III has a list of the most sensitive parameters and their initial and final values before and after calibration. Performance evaluation of the model was assessed based on the Nash–Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970), the correlation coefficient (r) as well as visual comparison of hydrographs. Moreover, crop growth parameters for different crops were adjusted by comparing simulated and measured crop yield in rainfed and irrigated locations.

Estimation of crop water productivity

Crop WP is the amount of grain yield obtained per unit of water used (Tuong and Bouman, 2003). Depending on the type of water sources considered, WP is expressed as grain yield per unit water evapotranspired (WP_{ET}) or grain yield per unit total water input (irrigation plus rainfall) (WP_{IP}). In this study, technical WP was calculated using simulated values of evapotranspiration (ET_a) and yield values of different crops over the entire basin area. Moreover, economic water productivity, EWP (US\$ m^{-3} of water)

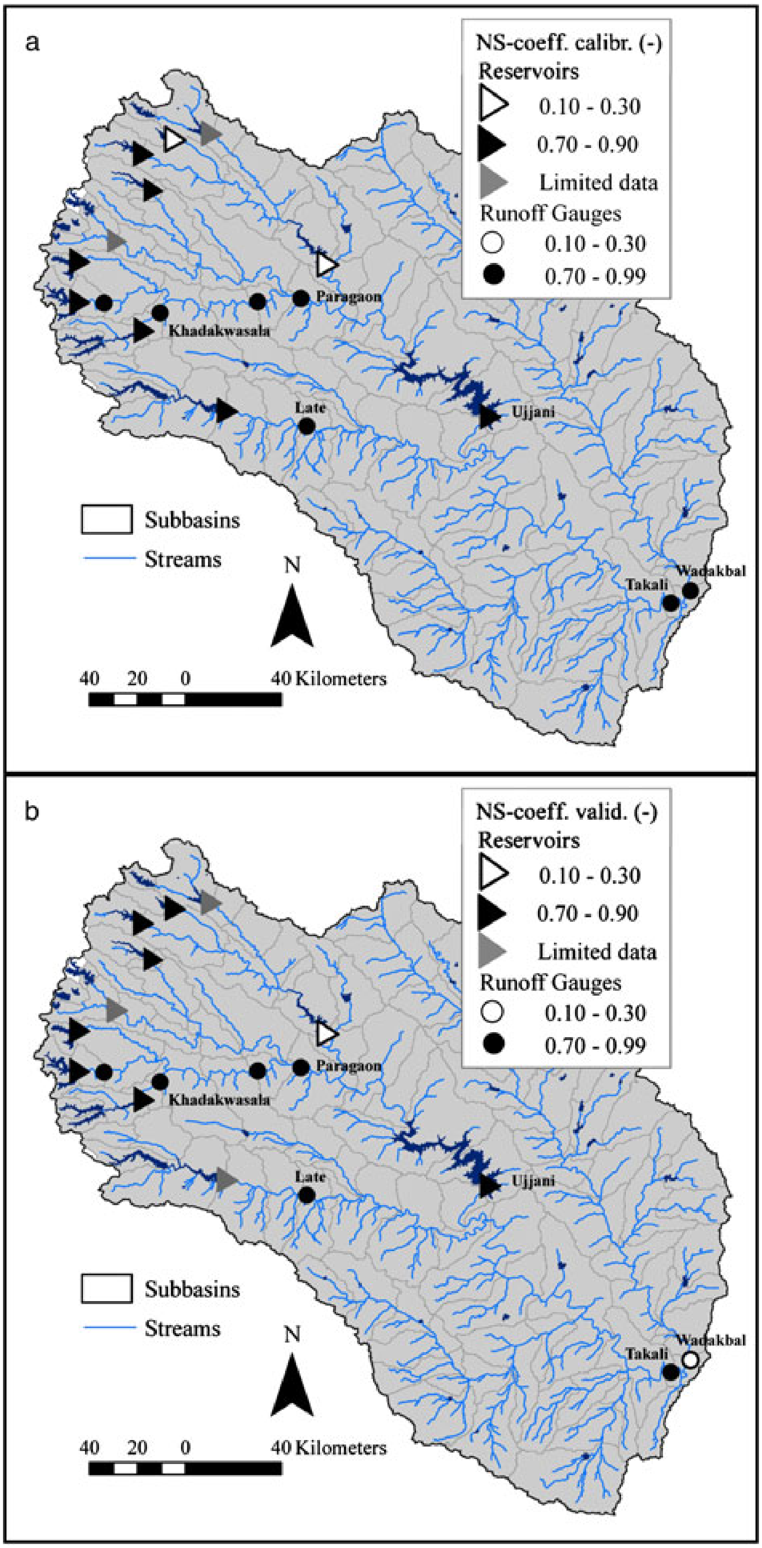

Figure 3. Model performance at different gauging stations and reservoir locations: (a) NSE coefficient during model calibration; (b) NSE coefficient during model validation. This figure is available online at wileyonlinelibrary.com/journal/ird

Table III. The most sensitive parameters and their initial and final ranges before and after calibration

Parameter name	Definition	Sensitivity result	Calibration results	
		Sensitivity rank included observed values	Initial parameter range	Final parameter range
RCHRG_DP	Deep aquifer percolation factor (–)	1	0.0–1.0	0.01–0.9
CN2	SCS runoff curve number (–)	2	35–85	40–85
ALPHA_BF	Base flow alpha factor (days)	3	0.0–1.0	0.2–0.8
ESCO	Soil evaporation compensation factor (–)	4	0.0–1.0	0.20–0.87
SOL_AWC[a]	Soil available water storage capacity (mm H_2O/mm soil)	5	0.10–0.28	0.10–0.28
SOL_Z[a]	Soil depth (cm)	6	50–430	50–430
GW_DELAY	Groundwater delay time (days)	7	0–100	10–31
GW_REVAP[b]	Groundwater revap coefficient (–)	8	0.02–0.20	0.05–0.19
SURLAG	Surface runoff lag coefficient (days)	9	0.0–10.0	1–3
REVAP_MN	Threshold depth of water for revap in shallow aquifer (mm H_2O)	10	0–500	1–10

[a] These parameters were not considered for calibration.
[b] Water in shallow aquifer returning to root zone (mm H_2O).

was calculated for the Ujjani command using the following equations:

$$\mathrm{EWP}_{(\mathrm{IP})}(\$\mathrm{US\ m^{-3}}) = \frac{\sum_{i=1}^{n}\text{Gross Income generated (\$US)} - \text{Cost of cultivation (\$US)}}{\text{Total water irrigated } (\mathrm{m}^3) + \text{Effective rainfall } (\mathrm{m}^3)} \tag{1}$$

$$\mathrm{EWP}_{(\mathrm{ET})}(\$\mathrm{US\ m^{-3}}) = \frac{\sum_{i=1}^{n}\text{Gross Income generated (\$US)} - \text{Cost of cultivation (\$US)}}{\text{Evapotranspiration } (\mathrm{m}^3)} \tag{2}$$

The cost of cultivation for major crops was collected from the Directorate of Economics and Statistics, Planning Department, Government of Maharashtra, (http://mahades.maharashtra.gov.in). The support prices for the year 2003–2004 were used to estimate gross income. Finally net income was estimated by subtracting cost of cultivation from gross income. The conversion rate for Indian rupees (22 November 2010) to US$ was adopted as US$1 = 45.31 INR.

Scenario analysis

The Ujjani command area in the Upper Bhima sub-basin was selected for detailed assessment of the impact of crop management scenarios on EWP. The scenarios primarily focused on diversifying crops with an aim to improve EWP. These new crops were grown under a limited amount of supplemental irrigation. In the model, the major cropping pattern diversification included groundnut in the monsoon (*kharif*) and wheat in the post-monsoon (*rabi*) season. The amount and frequency of irrigation water diverted from the reservoir during both seasons were similar to current irrigation practice, which is four times during *kharif* and six times during *rabi*. A detailed crop calendar is given in Table IV. Four scenarios were developed to understand the impact on WP:

- Scenario 1 aimed at replacing sorghum and millet with a high-value crop such as wheat and groundnut. The sugarcane crop was maintained with prioritization for irrigation followed by wheat and groundnut;
- Scenario 2 targeted expansion of the command area by diversifying to short-duration high-value crops such as groundnut and wheat and also more stress-tolerant crops like millet and sorghum in place of long-duration high-water-requiring sugarcane, while the application of water was limited to a certain number of irrigations;
- Scenario 3 included maximization of the irrigated area by complete diversification to wheat and groundnut under a limited water supply;

Table IV. Details of simulation scenarios in the Ujjani command

Scenarios	Crop	Crop growing period												No. of irrigations
		J	J	A	S	O	N	D	J	F	M	A	M	
Scenario 1	Groundnut	░	░	░	░									4
	Wheat					▓	▓	▓	▓	▓				6
	Sugarcane	█	█	█	█	█	█	█	█	█	█	█	█	High priority
Scenario 2	Groundnut	░	░	░	░									4
	Millet	░	░	░	░									4
	Wheat					▓	▓	▓	▓	▓				6
	Sorghum					▓	▓	▓	▓	▓				6
Scenario 3	Groundnut	░	░	░	░									4
	Wheat					▓	▓	▓	▓	▓				6
Scenario 4	Groundnut	░	░	░	░									No water stress
	Wheat					▓	▓	▓	▓	▓				No water stress

- Scenario 4 described the impact if the crops under Scenario 3 were grown under an environment free of water stress. Irrigation was applied based on water requirements. Auto-irrigation (where the model will automatically assign irrigation based on soil moisture status) was assigned to avoid a water-stress situation during the crop growth period.

All the scenarios were simulated to map crop water productivity for wet, normal and dry rainfall years.

RESULTS AND DISCUSSION

Model performance

Performance evaluation of the model was assessed based on the Nash–Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe, 1970), the correlation coefficient (r) as well as visual comparison of hydrographs. Positive values of NSE indicated that the calibrated model was a better predictor than the mean values of the observed discharge. NSE values greater than 0.60 are generally considered "satisfactory" and values greater than 0.8 are considered "good" (Chiew *et al.*, 2002). The coefficients were calculated based on observed data from 14 stations on a monthly basis. For the calibration period, NSE coefficients were found in the range of 0.70−0.99 for 12 stations and less than 0.3 for the remaining 2 stations (Figure 3a). Similarly, NSE coefficients for the validation period were found in the range of 0.70−0.90 for 12 stations and between 0.10 and 0.30 for 2 stations (Figure 3b). The poor performance for some stations can be attributed to interaction among various reservoirs, unaccounted minor regulation structures (weirs and minor storages) and other land and water management practices that were probably not accounted for in detail. The poorly performing stations were not similar during the calibration and validation periods and the trend probably varied due to different rainfall patterns during the calibration and validation periods. The calibration period with rainfall of 845 mm was comparatively wetter than the validation period (746 mm). The difference in rainfall pattern must have contributed to a difference in reservoir filling and release pattern and hence in the performance of the model. During dry years, even the dead storages were used for domestic purposes.

Overall, the hydrograph with simulated and actual values demonstrated good performance of the model as shown in Figure 4. The coefficient of correlation was estimated between 0.73 and 0.86 during calibration on a daily timescale. During validation, the coefficient of correlation except at one location was estimated between 0.69 and 0.97. Comparison of observed and simulated discharges at four gauging locations is presented in Figure 4 (a–d). From Figure 4 it is clear that the model performed well in both low- and high-flow periods. Similar results were also found at other monitoring locations.

The model was also tested by comparing the simulated and observed values of water released for agricultural use and reservoir storage. The water release pattern and reservoir storage simulated by the model and those measured were found to match very well. There was clear evidence of unfilled storage during dry years when reservoirs filled up to only 70% of live storage. These findings additionally supported the model performance and management strategy (e.g. cropping pattern and irrigation scheduling) assigned in the model set-up.

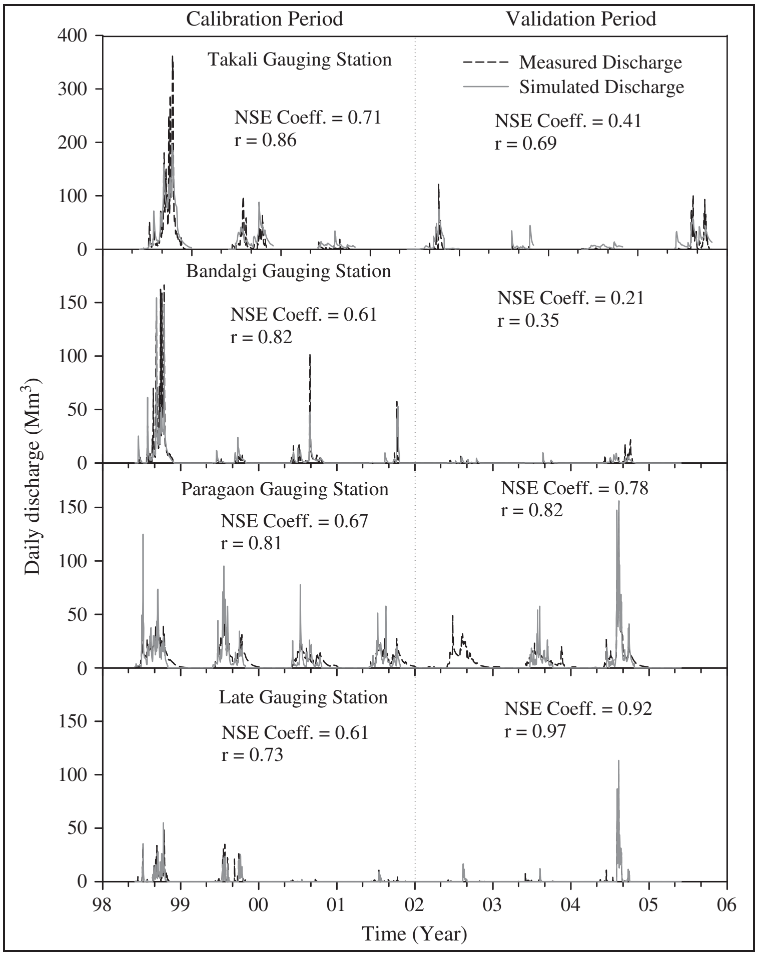

Figure 4. (a–d). Measured and simulated discharge at selected four gauging stations in Upper Bhima Basin

Water balance

SWAT calculates the water balance at HRU (hydrological response unit) and sub-basin levels on a daily/monthly timescale. The water balance results of the Upper Bhima River Basin from 1999 to 2004 are presented in Figure 5(a), which consisted of five hydrological components: rainfall, evapotranspiration (ET_a), change in reservoir storage, discharge from outlet and balance closure. The term "balance closure" comprised groundwater recharge, change in soil moisture storage in the vadose zone, westward export from the basin for hydropower (1207 Mm^3) and model inaccuracies. Positive values of rainfall in the upper panel in Figure 5 indicated the source of water and negative values in the bottom panel represented different sink terms. Annual rainfall during a normal year (2000–01) was estimated at 711 mm (32 400 Mm^3) which resulted in a surface runoff of 148 mm (20.8%). In the monsoon season of a normal year (2000–01), 12.8% (92 mm) and 21% (156 mm) of rainfall were captured in reservoirs and groundwater storages, respectively, while 7% (45 mm) was discharged as runoff out of the basin. These reserves were diverted for irrigation during monsoon and during non-monsoon seasons and subsequently depleted the system as ET_a. The runoff coefficient in dry and wet years ranged from 0.12 to 0.25. During dry years, the majority of runoff was captured by reservoirs. Approximately 20% of water stored in the reservoirs was diverted out of the basin in the Western Ghats for hydropower generation. Change in reservoir storage was found to be negligible on an annual timescale, which suggests that there was no carryover storage in the system. The positive value of change in reservoir storage in 2002 was because of the depletion of water from the dead storage level to meet drinking water demands.

The major sink annual ET_a was in the range of 60% of rainfall, the majority of which occurred in the monsoon season (40%). The ET_a comprised evaporation and transpiration from rainfed and irrigated areas as well as from other parts of the basin. The fraction of ET_a was low (55%) during a wet year (1999), while during a dry rainfall year (2003) it accounted for almost 70% of total rainfall with

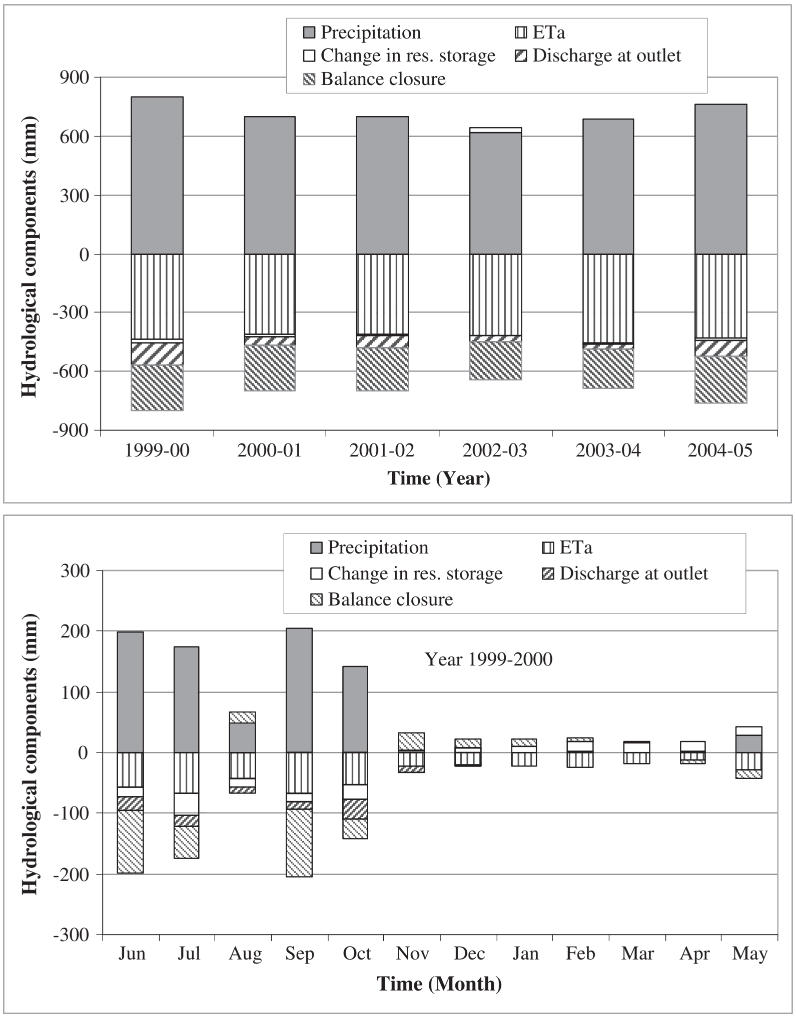

Figure 5. (a) Annual water balance from 1999–2000 to 2004–05 of Upper Bhima Basin; (b) monthly water balance from June 1999 to May 2000 of Upper Bhima Basin

significantly low runoff out of the basin. Discharges at the basin outlet were found to be 5130 Mm^3 (112 mm) in 1999 (wet year) and 1070 Mm^3 (22 mm) in 2003 (dry year). Average discharge (1999–2004) at the basin outlet was estimated as 2270 Mm^3 (7% of average annual rainfall). The annual average groundwater recharge coefficient was in therange of 13–19% of total rainfall, which resulted in 87–135 mm (3980–6190 Mm^3) of annual water reserve in the ground during the study period (1999–2004) with an average value of 117 mm (5370 Mm^3). This replenishable groundwater is available for domestic, industrial and agricultural uses. The groundwater potential is 13% more than the surface storage in the basin but accounts for almost 70% of the irrigated area in the basin, demonstrating double the irrigation efficiency in the groundwater-irrigated area.

The monthly water balance from June 1999 to May 2000 is presented in Figure 5(b). It is seen from the figure that 95% of total precipitation (802 mm) falls from June to October. ET_a was highest in the months of July and September (67 mm in each month) and lowest in April (12 mm). During the monsoon and non-monsoon seasons ET_a was estimated as 287 mm (35.8% of total rainfall) and 148 mm (18.5% of total rainfall), respectively. Of the total rainfall, 103 mm (12.8%) was captured in different reservoirs during the monsoon period (4700 Mm^3). About 99 mm of water was transferred outside the basin (4500 Mm^3) during the monsoon period.

Spatial pattern of water balance components

Spatial distribution of rainfall runoff, groundwater recharge and ET_a were further analysed and are presented in Figure 6 (a–d). Average annual data for a normal year (2000–01) were used to generate Figure 6. A substantial amount of runoff (water yield) was generated in the upstream regions (Ghats) due to high rainfall and the steep

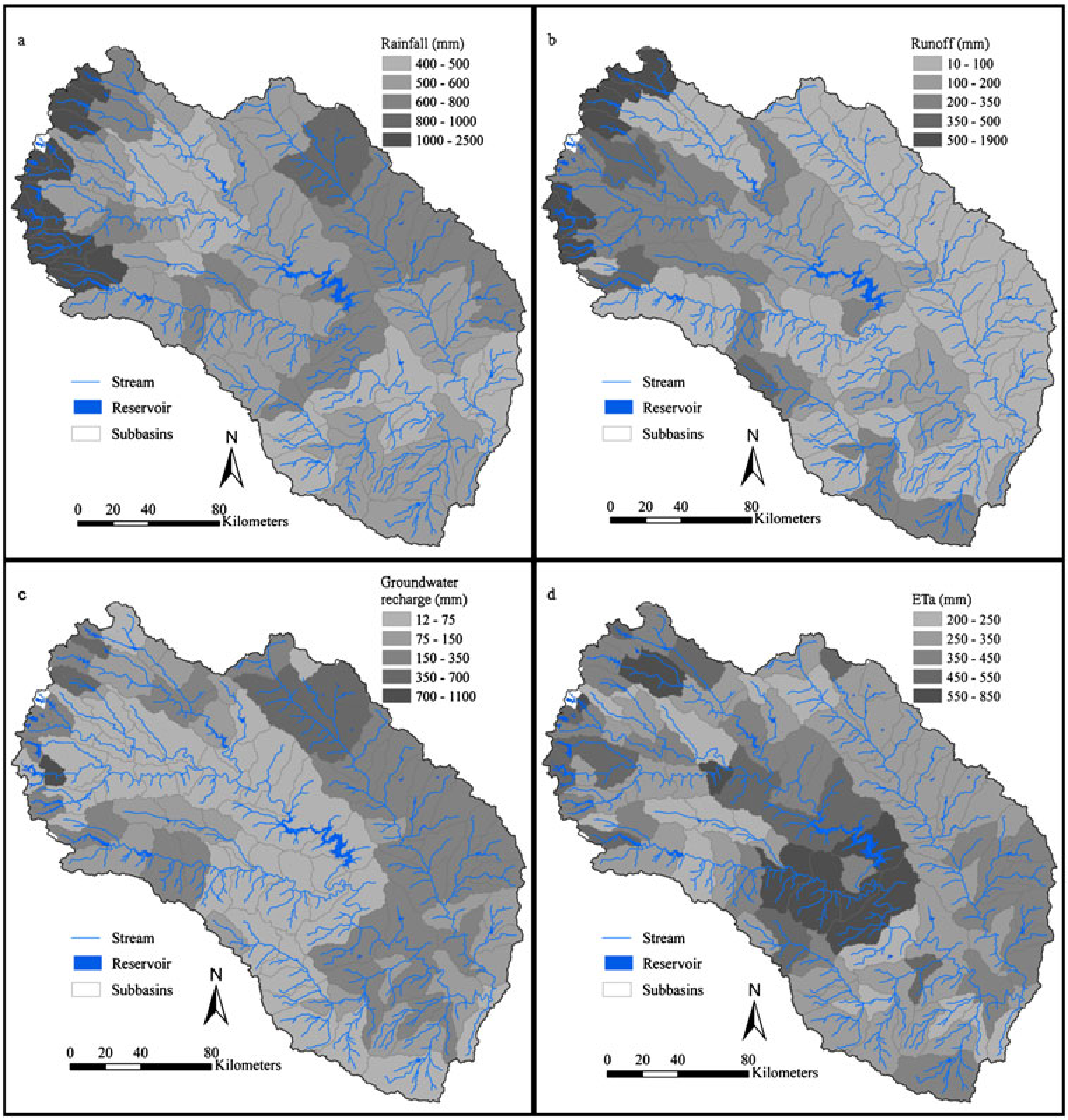

Figure 6. (a–d). Spatial variability of different hydrological components: rainfall, runoff, groundwater recharge and evapotranspiration in Upper Bhima Basin during a normal year, 2000–01. This figure is available online at wileyonlinelibrary.com/journal/ird

topography of this landscape. The runoff coefficient in the Ghat regions (upstream) was very high, ranging from 0.60 to 0.80 which declined to between 0.02 and 0.15 in the downstream regions. Similarly, groundwater recharge varied spatially, ranging from 12 to 1100 mm. The recharge was found to be largest (1100 mm) around reservoirs, followed by the Western Ghats and the major irrigation command areas (350–700 mm) (Figure 6c). The majority of the basin had groundwater recharge in the range of 12–75 mm or 150–350 mm. Annual average ET_a of normal year (2000–01) is presented in Figure 6(d). Out of total ET_a of 411 mm from the basin, the majority was used by rainfed (33%) and irrigated agriculture (45.5%) while forest and rangelands accounted for 2.9 and 12%; and losses (evaporation) from urban areas and water bodies were confined as 0.2 and 6.4%, respectively. The actual ET_a was found to be low (200–350 mm) from rainfed agriculture in low rainfall zones due to the limited availability of moisture in the soil. As expected, the ET_a values in irrigated command areas, particularly Ujjani and Vir Bhatghar, were found to be in the highest range of 550–850 mm (Figure 6d). ET_a in the upstream Western Ghats was found in the middle ranges (400–600 mm) due to a combination of soil and land cover factors. The depth of soil in the Western Ghats is shallow and water-holding capacity low compared to other parts of the basin. As a result, the potential for ET_a is less in the Ghats during the non-monsoon period. A large portion of the Ghat area is covered by forests, where water can be extracted from subsurface layers to contribute to ET_a. Overall 79% of ET_a was used by agricultural crops, while 15% was used by forest or rangelands and 6% lost (through evaporation) from urban areas and water bodies. In other words, 46% of rainfall was used by agricultural crops.

Crop water productivity

Crop yield and WP were mapped spatially on a sub-basin scale and are presented in Figures 7 and 8 for sorghum and sugarcane during wet (1999) and dry (2003) years respectively. Crop productivity in different sub-basins was estimated based on yield and ET_a from SWAT-simulated outputs. The top two panels of Figure 7 show sorghum yield and crop WP for 1999 and the lower panel yield and WP for 2003. In a similar manner, results are presented for sugarcane in Figure 8.

The crop yields simulated by the model were found comparable with the actual yield obtained from the Department of Agriculture, Government of Maharashtra (http://www.mahaagri.gov.in) for different years. During a normal year (2000–01), the average simulated yields (σ, standard deviation) of sugarcane, sorghum and millet crops were found as 40 (±19.1), 1.4 (±1.0) and 0.75 (±0.5) t ha^{-1}, respectively. Actual average yield (Department of Agriculture, Government of Maharashtra, India) were reported as 90 (±13), 1.3 (±0.3), 1.1 (±0.4) t ha^{-1}, for sugarcane, sorghum and millet crops respectively. The model was set with a large acreage under sugarcane crop compared to the actual area in 2000–01 (land use classification was based on 2004–05). Water availability for the sugarcane crop (modelled area) was not adequate which resulted in a lower crop yield (simulated) particularly outside the command area. Crop yields varied significantly at both temporal and spatial scales.

Variations in yield were found to be very high for sorghum, as it ranged from 0.01 to 5.8 t ha^{-1} yr^{-1} at different locations in different rainfall years. During a wet year, the majority of the basin demonstrated yield in the range of 1–3 t ha^{-1}, while the yield peaked in some irrigation projects at 3–5.8 t ha^{-1}. During the dry year in 2003, crop yield declined to 0.5–1 t ha^{-1} or less.

Sorghum WP in 1999 (wet year) varied from 0.01 to 1.8 kg m^{-3}, with the majority of the area between 0.5 and 0.9 kg m^{-3}. WP declined significantly during the dry year (2003) and the majority of the area had a WP below 0.5 kg m^{-3} with 70% of the basin below 0.2 kg m^{-3}. Sorghum yield was found to be high in irrigated command areas, particularly in middle reaches and in the downstream part of the basin possibly due to rainfall pattern, water availability in the soil and access to irrigation from canals or groundwater. Despite high rainfall in the Western Ghats WP was found to be poor, probably due to comparatively fewer number of rainy days, low soil water availability as well as soil nutrient stress in agricultural fields.

The sugarcane yields within different sub-basins showed that the yields in irrigated command areas were as high as 45–90 t ha^{-1} during 1999 (wet year). Crop yields outside the irrigated command were, however, estimated to be very low (10–45 t ha^{-1}). During a dry year (2003), the range of crop yields reduced to 45–60 t ha^{-1} in the irrigated command and below 20 t ha^{-1} outside the command areas. During 2003, releases for irrigation from some major reservoirs (particularly Ujjani) were curtailed significantly when some reservoirs ended up using dead storage for domestic needs. During 1999, WP for the sugarcane crop was found in the range of 4–12 kg m^{-3} in the majority of the basin, with 8–12 kg m^{-3} in canal-irrigated commands. During 2003, the majority of the area had a WP of 1–4 kg m^{-3}, while some irrigated command areas or areas around reservoirs demonstrated WP in the range of 4–8 kg m^{-3}.

The average water productivities were found as 2.9 (±2.0) kg m^{-3} for sugarcane, 0.51 (±0.3) kg m^{-3} for sorghum and 0.30 (±0.1) kg m^{-3} for millet crops. The optimum values of WP for sugarcane, sorghum and millet crops were found when ET_a was in the range of 1100–1200, 300−400 and 400–500 mm respectively. Immerzeel *et al.* (2008) reported similar WP for sugarcane in the Upper Bhima but larger values (1.3 kg m^{-3}) for sorghum crops. The values for sorghum were comparable with the optimum WP, which indicates that Immerzeel *et al.* (2008) must have estimated potential WP under no water or nutrient stress. Similar values for sorghum WP have been reported by Doorenbos and Kassam (1979) (0.60–1.0) and Mu *et al.* (2008) (0.65 kg m^{-3}) for China. In the case of pearl millet, Klaij and Vachaud (1992) reported a slightly higher range (0.5–1.1 kg m^{-3}) in Nigar (Rockstrom, 1995). Wheat has been reported to be more productive when compared with other crops within India and elsewhere. For instance Mu *et al.* (2008) reported 1.31 kg m^{-3} in China which was twice that of sorghum. In India, various values for wheat WP were reported as 0.86–1.31 kg m^{-3} in Pantnagar (Mishra *et al.*, 1995); 1.11–1.29 kg m^{-3} in West Bengal (Bandyopadhyay and Mallick, 2003); 0.48–0.71 in Uttar Pradesh (Sharma *et al.*, 2001); and 0.27–0.82 in Karnal (Sharma *et al.*, 1990). A large gap among estimated and potential (Immerzeel *et al.*, 2008) and global water productivities clearly shows considerable scope for improvement which could be obtained through appropriate land and

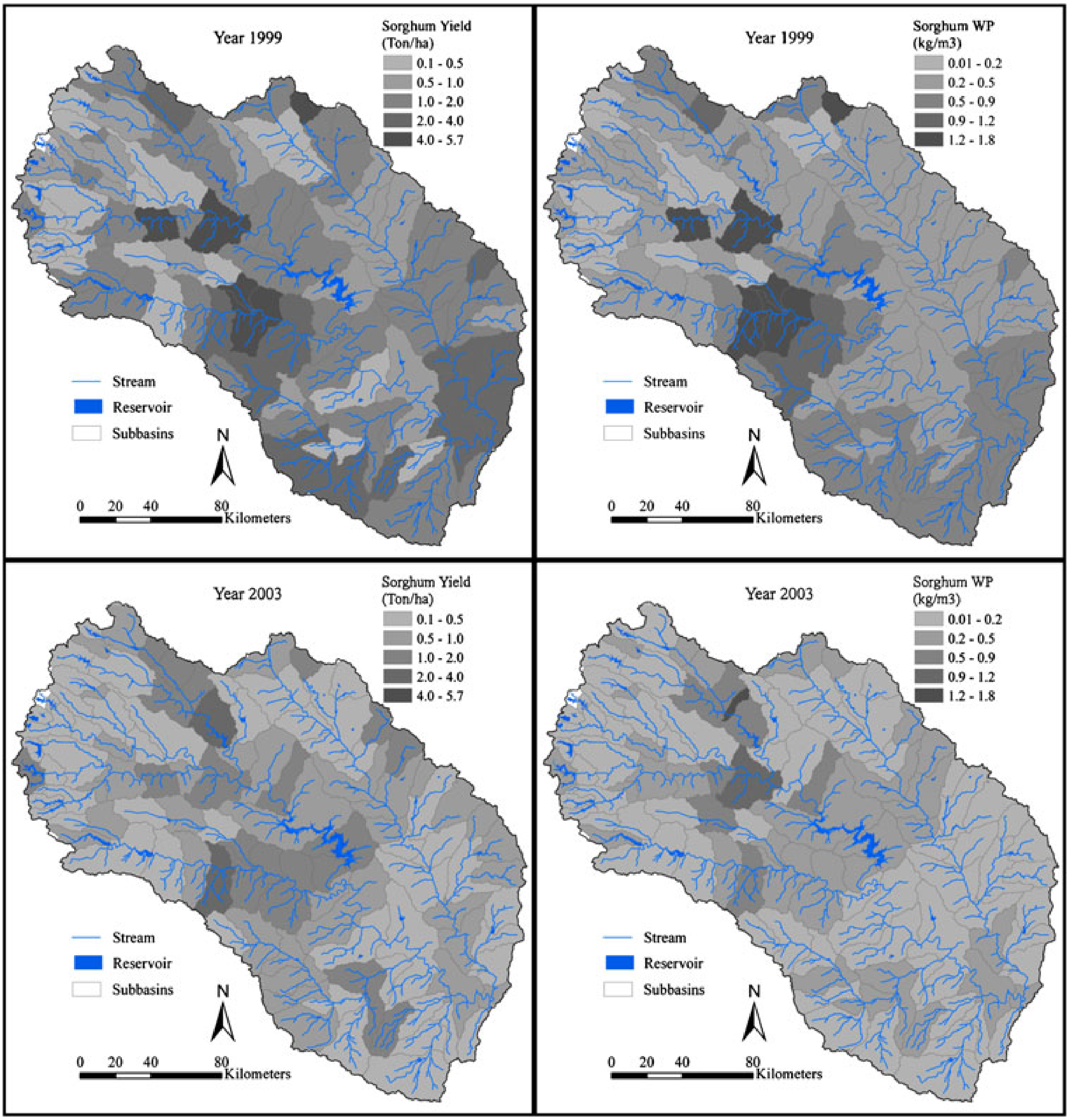

Figure 7. Yield and water productivity of sorghum crop in 1999 (wet year) and 2003 (dry year). This figure is available online at wileyonlinelibrary.com/journal/ird

water management practices, improved and drought-tolerant crop varieties, supplementary irrigation in rainfed areas, irrigation scheduling and improvement in irrigation efficiency and precision farming in irrigated lands.

Economic water productivity

The economic water productivity (EWP) is a function of net income and water used (Equations 1 and 2). The EWP was determined for the Ujjani canal irrigated command, which is one of the largest and most important projects in the basin. The irrigated area in the command varied from 759 to 1005 km^2 which accounted for 33–44% of irrigation potential in the command. The sugarcane area accounted for an area similar to the irrigated area in the command.

In general, the net income from sugarcane (US\$1394 ha^{-1}) was tenfold that of millet (US\$129 ha^{-1}) and twentyfold of sorghum (US\$67 ha^{-1}) (Table V). The water requirement of sugarcane was four times that of sorghum and millet. However, the water requirements of wheat and groundnut were not significantly different from sorghum and millet, and the net incomes were comparable with millet and

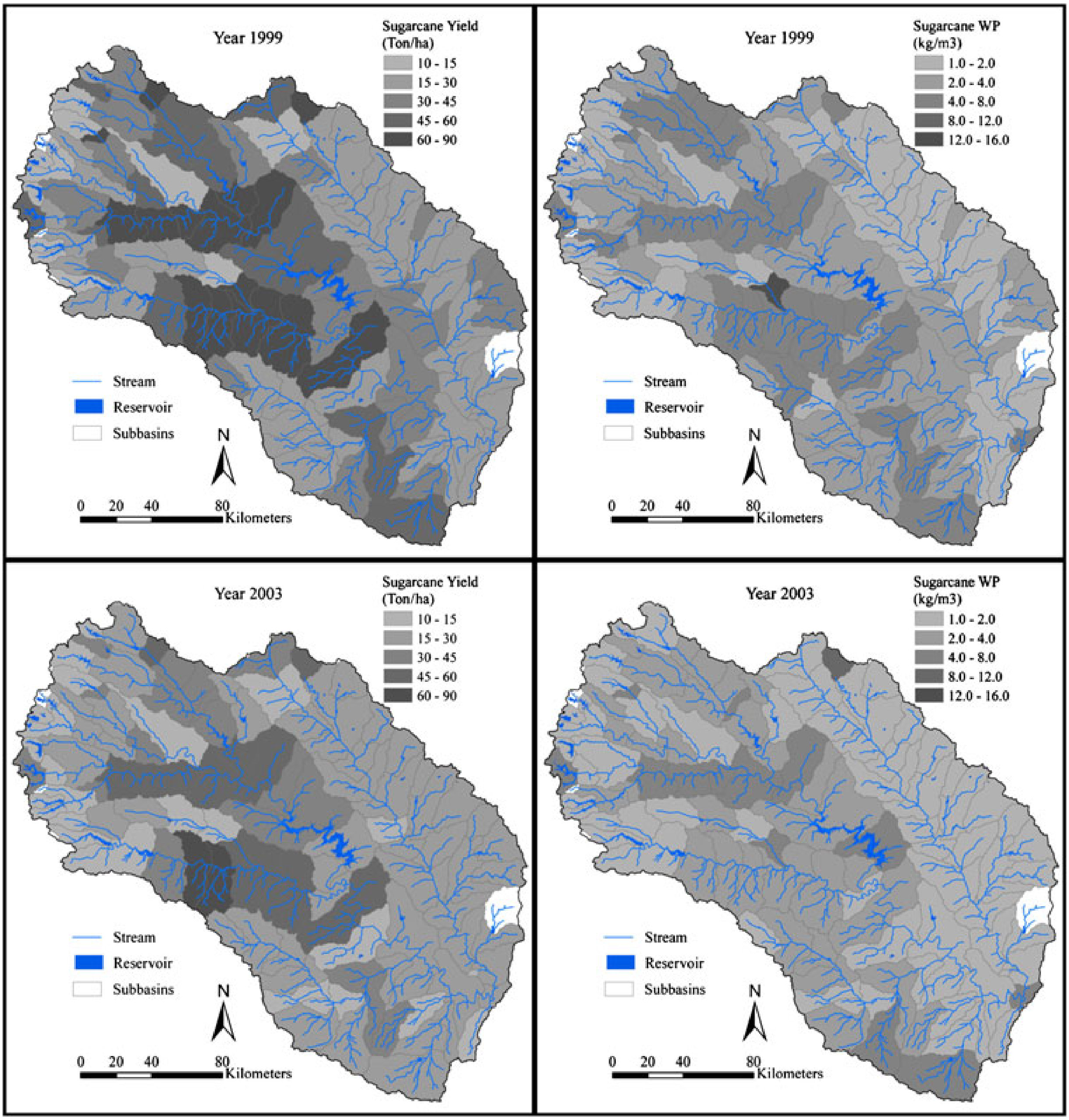

Figure 8. Yield and water productivity of sugarcane crop in 1999 (wet year) and 2003 (dry year). This figure is available online at wileyonlinelibrary.com/journal/ird

sugarcane, respectively. When compared for EWP_{ET}, groundnut was found the most productive, followed by sugarcane, wheat and millet.

Net income from the basin ranged from US\$40.6 million in a wet year to US\$31.3 million in a dry year (Table VI). The EWP of the basin was estimated with respect to actual water input (EWP_{IP}) and ranged between US\$0.022 m^{-3} in a wet year to US\$0.036 m^{-3} in a dry year (Table VI). The EWP_{IP} was maximal during a dry year because of significantly less water input (irrigation and effective rainfall) than in a wet year. However, the water input during a wet year was three times the total water available for the crop in a dry year, and the net income was found to be only 30% higher in a wet year than in a dry year. It means the WP was more determined by water input during a year. The water input increased productivity to a certain extent and water in excess affected the crop yield adversely. Vaidyanathan and Sivasubramaniyan (2004) also reported similar ranges of EWP in irrigated and rainfed areas between US\$0.018–0.027 and 0.012–0.032 m^{-3}, respectively, for major river basins in India during 1991–1993. EWP in irrigated areas is found to be lower than for rainfed crops at larger percentage area due to

Table V. Evapotranspiration (year 2000–01) and net value of major crops in the Ujjani command

Crop grown	Crop growing season	Crop yield ($t\ ha^{-1}$)	ET_a (mm)	ET_a under no stress condition (mm)	Water stress factor[a]	Income (US$ ha^{-1})
Millet	*Kharif*	1.7	398	306	0.0	129
Sorghum	*Rabi*	1.2	237	353	0.33	67
Sugarcane	Perennial	110	1418	1348	0.0	1394
Groundnut	*Kharif*	3.1	382	394	0.03	890
Wheat	*Rabi*	1.5	205	347	0.41	137

[a] Stress factors 0 and 1 represent no stress and maximum stress situation during crop growth, respectively.

Table VI. VIEconomic water productivity in the Ujjani command (base line)

Year		1999–2000	2000–2001	2001–2002	2002–2003
Canal water released for irrigation (Mm^3)		1530	848	519	697
Effective rainfall (mm)		620	507	531	390
Gross area cultivated (km^2)	Actual	1005	844	759	983
	Modelled	4664	2618	1313	1755
Net income generated (US$ million)	Actual	40.7	36.5	32.0	31.4
	Modelled	78.4	43.8	23.5	17.9
EWP_{IP} (US$ m^{-3})	Actual	0.022	0.033	0.044	0.036
	Modelled	0.026	0.029	0.027	0.017

over-irrigation and high conveyance and application losses (especially in canal command areas). Aggarwal *et al.* (2001) reported similar EWP (US\$0.025–0.063 m^{-3}) for paddy, wheat, mustard and cotton crops in *kharif* and larger EWP (US\$0.10–0.13 m^{-3}) in *rabi* under a surface irrigation system in Sirsa district, Haryana, India.

Scenario analysis in the Ujjani command area

In order to understand the impact of various scenarios, the net income and EWP of major crops were used as indicators. Considering socio-economic aspects, four scenarios (Table VII) focusing on various crop diversification options were evaluated for the Ujjani command. The indicators for impact assessment were irrigable area, crop yields and the EWP (with respect to actual water input) which were compared with the baseline, i.e. actual values during a year. All the indicators with respect to each scenario during wet (1999–2000), normal (2000–01) and dry (2001–02 and 2002–03) years are shown in Table VII.

Scenario 1 included diversification from millet and sorghum to groundnut and wheat. The actual water requirements were not significantly different from the baseline except that the sugarcane was prioritized even during dry years which resulted in no irrigation to wheat and groundnut during dry years or probably stressed during normal years. The level of stress was evidenced by low crop yields during normal and dry years than wet years. The area irrigated during a normal year was quite close to the baseline, while net income increased to US\$60 million as opposed to US\$36.4 million for current practices. During a wet year, net income almost quadrupled but during a dry year, it matched the baseline. The EWP_{IP} were similar during wet and normal years (US\$0.058 m^{-3}) and almost twice the baseline. During a dry year, the EWP_{IP} (US\$0.040 m^{-3}) was comparable with the baseline.

Scenario 2 aimed at maximizing irrigation intensity by diversifying the sugarcane area into groundnut and wheat while maintaining sorghum and millet crops. The irrigation potential was substantially higher than the baseline areas which can be attributed to some limitations in the model. Although attempts were made to account for spatial variability in various parameters, the model was unable to incorporate the actual spatial pattern of land use, irrigation efficiencies and water stress over the command. The model prioritizes irrigation by limiting the area or stress to a defined limit while in practice the stress varies from field to field. Groundwater use in the model was limited to a shallow aquifer while in practice the groundwater is exploited from a deep aquifer. This limitation might have led to underestimation of irrigation potential during dry years. The net income under this scenario (US\$116 million) was almost three times the baseline during wet and normal years. During a dry year, it declined to US\$45 million which is 25% higher than the baseline. As opposed to Scenario 1, this scenario improved the EWP_{IP} significantly during normal and dry years and ranged from US\$0.035 m^{-3} (wet year) to US\$0.066 m^{-3} (normal year).

Table VII. Comparison of various indicators under various scenarios in the Ujjani command

Parameters		Scenarios				
		Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Year 1999–2000 (wet year)						
Kharif crops Area km^2 (yield t ha^{-1})	Millet	2260 (2.0)	–	1364 (0.7)	–	–
	Groundnut	–	1491 (1.9)	1364 (2.1)	2827 (2.2)	1435 (2.6)
Rabi crops Area km^2 (yield t ha^{-1})	Sorghum	2260 (1.7)	–	2267 (0.8)	–	–
	Wheat	–	1491 (1.1)	2217 (1.3)	3896 (1.3)	3107 (1.4)
Perennial Area km^2 (yield t ha^{-1})	Sugarcane	145 (82)	413 (127)	–	–	–
Total area (km^2)		4665	3395	7182	6723	4542
Net income (US$ million)		78.4	155	111	213	142
Water used (Mm^3)	IP	3021	2711	3203	3283	2419
	ET	1640	1328	1865	1369	1459
Economic water productivity (US$ m^{-3})	EWP$_{(IP)}$	0.026	0.057	0.035	0.065	0.059
	EWP$_{(ET)}$	0.048	0.117	0.059	0.155	0.097
Year 2000–2001 (normal year)						
Kharif crops Area km^2 (yield t ha^{-1})	Millet	1269 (2.5)	–	899 (1.7)	–	–
	Groundnut		0	879 (3.2)	1883 (3.3)	1207 (4.0)
Rabi crops Area km^2 (yield t ha^{-1})	Sorghum	1269 (1.3)	–	1292 (1.2)	–	–
	Wheat		317 (1.3)	1264 (1.5)	2280 (1.5)	1853 (1.6)
Perennial Area km^2 (yield t ha^{-1})	Sugarcane	81 (73)	413 (73)	–	–	–
Total area (km^2)		2619	731	4334	4163	3060
Net income (US$ million)		43.8	61	116	204	163
Water used (Mm^3)	IP	1532	1057	1748	1802	1459
	ET	944	642	1187	999	1061
Stress factor (–)		0.14	0.19	0.22	0.37	0.0
Economic water productivity (US$ m^{-3})	EWP$_{(IP)}$	0.029	0.058	0.066	0.113	0.112
	EWP$_{(ET)}$	0.046	0.095	0.097	0.204	0.154
Year 2001–2002 (dry year)						
Kharif crops Area km^2 (yield t ha^{-1})	Millet	636 (2.7)	–	321 (1.4)	–	–
	Groundnut	–	0	314 (2.7)	674 (2.8)	399 (3.0)
Rabi crops Area km^2 (yield t ha^{-1})	Sorghum	636 (1.4)	–	901 (1.1)	–	–
	Wheat	–	0	881 (1.6)	1612 (1.6)	1321 (1.9)
Perennial Area km^2 (yield t ha^{-1})	Sugarcane	41 (66)	251 (99)	–	–	–
Total area (km^2)		1313	251	2417	2286	1720
Net income (US$ million)		23.5	30	45	77	58
Water used (Mm^3)	IP	879	652	856	877	731
	ET	501	361	598	464	520
Stress factor (–)		0.17	0.03	0.32	0.45	0.12
Economic water productivity (US$ m^{-3})	EWP$_{(IP)}$	0.027	0.046	0.052	0.087	0.079
	EWP$_{(ET)}$	0.047	0.084	0.075	0.165	0.112
Year 2002–2003 (dry year)						
Kharif crops Area km^2 (yield t ha^{-1})	Millet	850 (1.4)	–	321 (1.4)	–	–
	Groundnut	–	0	313 (3.0)	660 (3.0)	416 (3.2)
Rabi crops Area km^2 (yield t ha^{-1})	Sorghum	850 (1.3)	–	1093 (1.3)	–	–
	Wheat	–	0	1070 (1.6)	1894 (1.7)	1543 (2.0)
Perennial Area km^2 (yield t ha^{-1})	Sugarcane	55 (60)	296 (93)	–	–	–
Total area (km^2)		1755	296	2797	2554	1959
Net income (US$ million)		17.9	32	54	85	69
Water used (Mm^3)	IP	1050	812	944	954	859
	ET	675	441	736	441	660
Stress factor (–)		0.15	0.11	0.31	0.44	0.0
Economic water productivity (US$ m^{-3})	EWP$_{(IP)}$	0.017	0.040	0.057	0.089	0.081
	EWP$_{(ET)}$	0.026	0.073	0.073	0.193	0.105

In Scenario 3, the irrigated area was maximized by replacing existing crops with groundnut and wheat. This scenario enhanced irrigation intensity (ratio of area irrigated to command area) to 300% during a wet year and to 200% during a normal year. Simultaneously, the range of net income was enhanced between US$77 million (dry year) to

US\$213 million (wet and normal years) which was almost two to six times the baseline WP. The EWP_{IP} increase varied from US\$0.065 m^{-3} (wet year) to US\$0.113 m^{-3} (normal year), demonstrating a threefold increase in productivity under this scenario.

Under Scenario 4, irrigation was optimized to provide a stress-free environment for the crops adopted in Scenario 3 in order to maximize returns per unit of land. As a result, irrigation intensity declined by 100% when compared with Scenario 3. The net income (US\$58–162 million) was also found to be significantly less than the income under Scenario 3, yet it was two to four times the baseline income. Since the water used was less than under Scenario 3, the EWP_{IP} was comparable with Scenario 3.

All the scenarios led to improvement in irrigation intensity, net income and economic WP over baseline. Scenario 3 demonstrated the largest irrigation intensity, net income and EWP followed by Scenarios 4, 2 and 1. It means that the groundnut and wheat crops with limited irrigation supplies of four and six irrigations, respectively, were the best option out of the alternatives assessed in the present study. The water-stress-free environment for these crops improved the yield but it led to a reduction in irrigation intensity and net income as in Scenario 4. The priority given to sugarcane in Scenario 1 led to a substantial reduction in WP by ignoring irrigation supplies to wheat and groundnut during dry years. However, as Scenario 2 contained mixed cultivation of millet or sorghum along with high-value crops targeting a more diverse and resilient cropping system. Sorghum and millet are both low-value crops but have high tolerance to water-stress situations. Therefore, although the WP values are lower, the scenario is good during water-stress years. The EWP based on evapotranspiration was 1.5–2.4 times the EWP based on actual water utilized, suggesting that the potential for EWP in the basin during a normal year was US\$0.204 m^{-3}, leading to a total net income of US \$204 million. It may be noted that the study considered support prices. The actual value of crops may vary according to market conditions, which is predominantly controlled by supply and demand characteristics and several other externalities.

SUMMARY AND CONCLUSIONS

The Upper Bhima River Basin is facing both episodic and chronic water shortages due to intensive development in domestic, industrial and irrigation water needs. With a shrinking allocation to irrigation, there is a need to introduce water management interventions with optimum returns. In this study, the hydrological processes of the Upper Bhima River Basin were modelled using the distributed hydrologic model, SWAT. The spatial pattern of WP of major crops was analysed with the aim of improving the economic efficiency of water use in the irrigated area. The key findings of this study are:

- rainfall in the basin ranged from 450 to 5000 mm, the majority of which occurred in the Western Ghats within 3–4 months. During a normal year, out of average rainfall of 32 400 Mm^3 (711 mm), 12.8 and 21% were stored in surface and ground reserves, respectively, and 7% resulted in surface runoff out of the basin;
- evapotranspiration is the major sink component in the hydrological balance (60%), where 46% was used by agricultural crops;
- the WP of major crops, sugarcane, sorghum and millet, was found to be 2.9, 0.51 and 0.30 kg m^{-3}, respectively. Crop productivity in the basin was found in the lower range when compared with potential and global values. The findings suggested that there was a potential to improve further;
- during a normal year, the net returns and EWP of the Ujjani Irrigation Scheme were found to be US \$36.6 million and US\$0.033 m^{-3}, respectively, which could be further improved to US\$204 million and US \$0.204 m^{-3}, by diversifying existing crops (sorghum, millet and sugarcane) to groundnut and wheat crops.

Physical water scarcity was, however, not the only factor for poor WP in the basin. High nutrient losses in upstream locations due to heavy runoff and inefficient water utilization in water-rich command areas are other important factors. There is potential to increase the WP of different crops in the basin as the productivity of cereal crops was very low. Better on-farm water management practices, crop diversification, supplemental irrigation to rainfed areas and other technological innovations could be implemented.

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