Prediction of sediment erosion pattern in Upper Tapi Basin, India

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Physics-based distributed models are useful in identification of critical erosion-prone areas and planning soil conservation measures in the catchment. In this study, soil and water assessment tool (SWAT), a semi-distributed hydrological model, is utilized for modelling sediment yield in Upper Tapi Basin, India. Twelve years of observed runoff and sediment yield data are used for calibration and validation of the aforesaid model. The performance indicators, viz. Nash–Sutcliffe efficiency and ratio of root-mean-squared error to standard deviation showed good performance of calibrated model in prediction of sediment yield for independent datasets. The two adjoining sub-catchments in the basin have shown contrasting behaviour with reference to sediment yield due to differences in their topography, land use–land cover, soil and climatic conditions. Also, simulated erosions at hydrological response units levels, enabled the investigators to demarcate the critical erosion-prone areas in the catchment. The SWAT model has further been used to assess the performance of various soil conservation measures, such as providing filter strips and stone bunds, in the critical erosion prone areas in reducing the sediment yield. Both soil conservations measures, being applied on equal areas, yielded comparative performance in controlling erosion from the catchment.

Keywords: Best management practices, distributed models, sediment yield, soil conservation measures, Upper Tapi Basin.

PREDICTION of sediment yield from a river basin is essentially required in planning of soil conservation measures, modelling of reservoir sedimentation and predictions of morphological changes in alluvial rivers. Conventional methods such as universal soil loss equation (USLE)[1], modified universal soil loss equation (MUSLE)[2] and revised universal soil loss equation (RUSLE)[3] are frequently used to estimate sediment yield and surface erosion from the catchments[4–6]. The soil erosion rates are found to have large spatial variability due to variation in rainfall, topography, land-use and land-cover and soil conditions in the catchment. Such variability had prompted the earlier investigators to use data-intensive physics-based distributed models in prediction of sediment yield, wherein a catchment is discretized into sub-areas each having similar characteristics and uniform distribution of rainfall[7,8]. The application of geographical information system (GIS) is useful in quantification of the heterogeneity of catchments in terms of their drainage and topographic features[9,10]. Some spatially distributed models are CREAMS (chemicals run-off and erosion from agricultural management systems)[11], SEDIMOT[12], AGNPS[7], ANSWERS[13] and WEPP[14].

The soil and water assessment tool (SWAT), a physics-based semi-distributed hydrological model, developed at Texas agricultural experiment station, is used to estimate the runoffs and sediment yields at daily time scales in the catchment[15]. The development of SWAT is an outcome of USDA Agricultural Research Service (ARS) modelling experience for over a period of 30 years. The present form of SWAT model comprises fundamental modules obtained from USDA-ARS models, and models such as groundwater loading effects of agricultural management systems (GLEAMS)[16], CREAMS[17] and the Environmental Policy Integrated Climate model[18]. Successful estimation of the stream flow and sediment yield in the Texas Gulf basin for the watershed areas ranging from 2,253 to 304,260 sq. km was reported by Arnold and Allen[19], wherein the stream flow data of approximately 1,000 stream gauging stations during 1960 to 1989, were used to calibrate and validate the SWAT model. Hao *et al.*[20] and Jha *et al.*[21] presented the application of SWAT model in prediction of sediment yield in watersheds of different scales. Few successful applications of SWAT in the sediment yield modelling (including calibration and validation) are due to Betrie *et al.*[22] for Upper Blue Nile at Diem; Jeong *et al.*[23] at Riesel (Texas); Park *et al.*[24] at Chunju Dam (Korea); Chandra *et al.*[25] for Burhanpur subcatchment of Upper Tapi Basin, India and Bieger *et al.*[26] for the Xiangxi catchment in the Three Gorges region, China. Prabhanjan *et al.*[27] used SWAT for estimation of sediment yield and spatial erosion pattern in ungauged Indian watersheds using both default parameters and the parameters derived from the process of regionalization. The SWAT-2009 code incorporates

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pre- and post-processing software tools, including the widely used ArcGIS SWAT (ArcSWAT) interface[28]. A key strength of SWAT model is the flexible framework which allows the simulation of wide varieties of conservation and best management practices (BMPs) including fertilizer/manure application rates and timings, filter strips, grassed waterways and wetlands. The SWAT model was applied in the past to simulate pollutant reduction using BMPs[29], effects of riparian buffer zone for reduction of non-point sources pollutants[30] and effect of agricultural management practices[31–35]. Tuppad *et al.*[36] applied SWAT model using BMP options in hydrological response units (HRUs) at sub-basin and basin scales. Vache *et al.*[35] modelled grassed waterways, field borders, riparian buffers and filter strips after modifying the channel erodibility and channel cover factors in the SWAT to simulate the erosion resistance and cover density of the chosen management alternatives. White and Arnold[37] developed improved versions of routines to model vegetative filter strips; and Arabi *et al.*[29] suggested suitable parameterization of input parameters to implement structural management practices. Narsimhan *et al.*[38] indicated that sediment loads can be reduced by 15% with the implementation of an in-stream BMP, such as stream bank stabilization, at Cedar Creek watershed outlet in north-central Texas. Silva-Hidalgo *et al.*[39] reviewed the application of simulation models in integrated management of water resources.

The significant reduction in reservoir capacity due to reservoir sedimentation, as reported by Ladhe *et al.*[40] for Hathnur reservoir, located in Upper catchment of Tapi Basin, India, is a matter of concern for the stakeholders. The identification of critical erosion-prone areas in the catchment; and their subsequent treatment may help in reducing the sediment yield and enhancing the useful life of the reservoir. The main objectives of the present study are as follows:

- Calibration and validation of SWAT model using water and sediment discharge data of the two subcatchments of Hathnur reservoir.
- Identification of critical erosion-prone areas in subcatchments by analysing sediment yield at HRU scales.
- Application of BMPs in soil erosion-prone areas and assess their effects in reduction of the sediment yield.

Study area and data used

Study area

The Tapi River is the second largest west flowing interstate river in India passing through the Madhya Pradesh, Maharashtra and Gujarat states. Total length of the river from its origin to its outfall into the Arabian Sea is 724 km. The Tapi Basin is the northern-most basin of the Deccan plateau, and it lies approximately between 72°33′ to 78°17′E long. and 20°N to 22°N lat. The Tapi River drains an area of 65,145 sq. km out of which nearly 80% lies in Maharashtra. The basin cover consists of deep black and coastal alluvium soils. Major part of the Tapi Basin lies in the Western plateau and Hilly agro-climatic zone. The major reservoirs located in the Tapi Basin are Hathnur, Girna and Ukai reservoirs located in Upper, Middle and Lower basins respectively (Figure 1).

The present study area includes a part of the Tapi Basin up to Hathnur reservoir, also called Upper Tapi Basin (Figure 2) with a total catchment area of 29,430 sq. km. The area is located in Maharashtra and Madhya Pradesh between 20°09′N to 22°3′N lat. and 75°56′E to 78°17′E long. in subtropical to temperate climatic conditions, and has altitude variations from 752 m near the origin of Tapi River at Multai to about 200 m near the Hathnur dam. The Satpura range is on the north of Upper Tapi catchment while Ajanta range is in the south. The Purna is a major left bank tributary of the Tapi River and meets the latter just 8 km upstream of Hathnur dam site. The Hathnur reservoir receives sediments mainly from the main Tapi River and its tributary Purna river; and it has been observed that reservoir is losing its capacity annually at an alarming rate of about 330 t/ sq. km (ref. 40). The subcatchments of Tapi river at Burhanpur, viz. Burhanpur subcatchment (area of 8,487 sq. km), and that of Purna river at Yerli, viz. Yerli subcatchment (area of 16,517 sq. km), make up almost 85% of the total catchment area of Upper Tapi Basin.

Data used

In the study area, i.e. Upper Tapi Basin, the mean minimum and mean maximum temperature range from 11.1°C to 14.4°C and 38°C to 42°C respectively. The temperature data of Amraovati and Jalgaon stations have been used for development of the sediment yield model of Upper Tapi Basin. The daily rainfall data for a period of 30 years of six rain gauge stations in Burhanpur subcatchment and 18 rain gauge stations in the Yerli subcatchment, collected from India Meteorological Department (IMD), have been used in this study. The location of aforesaid rain gauge stations is included in Figure 2. The maximum and minimum relative humidity values in the study area are 89% and 32% respectively. On average, maximum and minimum daily wind speeds in the study area are 12.33 and 4.3 km/h in June and December respectively. The suspended sediment and river discharge data, on daily time scale, collected from Central Water Commission (CWC), Government of India, at two stream gauging stations, viz. Burhanpur and Yerli (Figure 2) during 1993–2004, have been used for calibration and validation of the SWAT model. The satellite imagery LISS

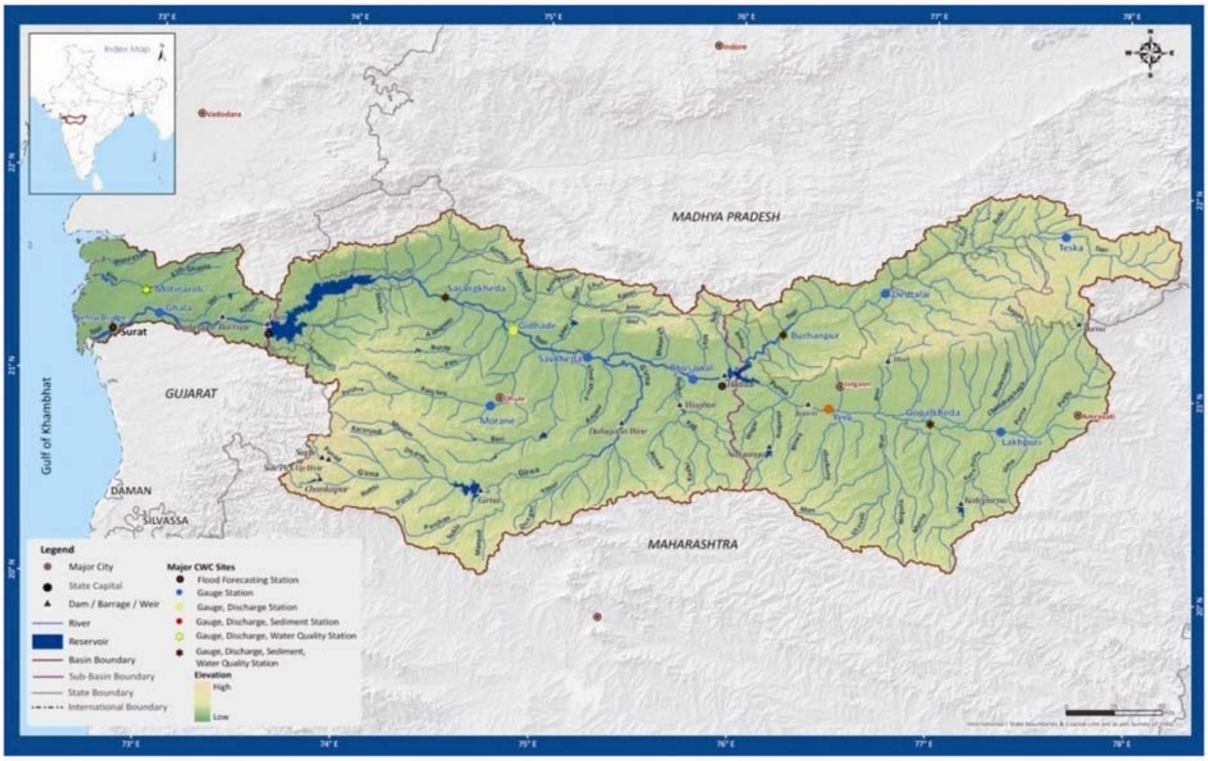

Figure 1. Catchment of Tapi River (source: www.india-wris.nrsc[70]).

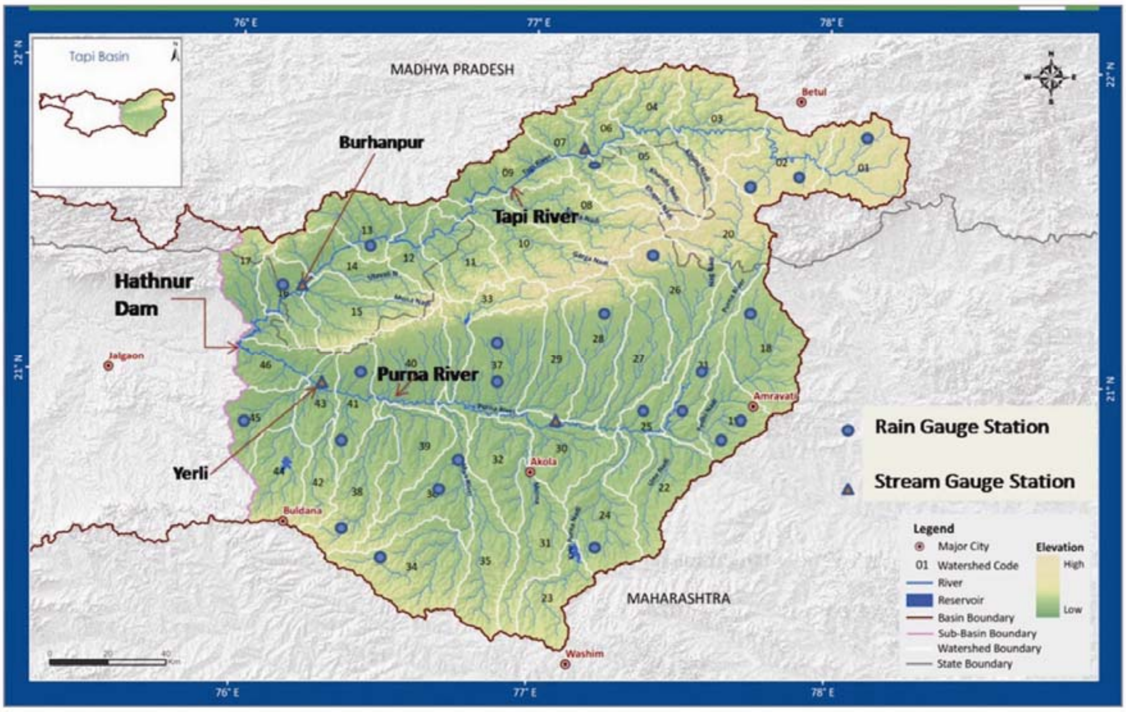

Figure 2. Upper Tapi Basin (source: www.india-wris.nrsc[69]).

III (row-57, path-96), IRS-1D was obtained for 17 January 1999 from National Remote Sensing Centre (NRSC), Hyderabad for preparation of land-use–land-cover maps of the study area. The Survey of India (SOI) Toposheet Nos 55c, 55d, 55g, 55h, 55k and 56a (scale – 1 : 250,000) have been used for preparation of digital elevation model (DEM) and for georeferencing the satellite imagery. The soil analogue maps (scale – 1 : 500,000) obtained from

Table 1. Statistical properties of observed annual rainfall and sediment yield

Hydrological data	Period	Precipitation over the subcatchment			Sediment yield at the outlet of subcatchment		
Subcatchment	Calibration (1993–1998) Validation (1999–2004)	Mean (mm)	Standard deviation	Skewness	Mean (t/ha)	Standard deviation	Skewness
Burhanpur	Calibration	999.40	129.90	–0.33	13.41	6.99	–0.27
	Validation	873.39	162.51	–0.23	4.31	3.02	0.69
Yerli	Calibration	679.44	67.77	0.31	0.73	0.41	–0.18
	Validation	631.08	96.58	0.083	1	1.96	2.43

National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, India, have been utilized for classification of soil groups in the study area. The statistical properties of the observed annual rainfall and sediment yield (at subcatchment outlets) for the data being used in the present study are included in Table 1.

Methodology

SWAT model

The SWAT is a physics-based model used for simulation of continuous-time landscape processes at basin scale[41,42]. The basin is further divided into HRUs on the basis of land use, soil type and slope classes for allowing a high level of spatial and detailed simulations. The hydrology of each HRU is predicted in the model while including water balance of daily precipitation, runoff, evapotranspiration, percolation and return flows. The SWAT model estimates surface runoff using two options, i.e. Natural Resources Conservation Service Curve Number (CN) method[43] and Green and Ampt method[44]. The percolation through soil layers is estimated using storage routing techniques in conjunction with crack-flow model[15]. The model estimates evapotranspiration (ET) using three options, viz. Priestley–Taylor[45], Penman–Monteith[46] and Hargreaves[47] methods. The combination of CN method for surface runoff and Hargreaves method for ET has been used, as recommended by Kannan *et al.*[48]. The variable storage coefficient method[49] or Muskingum method[50] are used for flow routing in the channel. In the present study, variable storage method has been used for flood routing in the channel. The SWAT model employs MUSLE for computation of soil erosion at HRU levels. The MUSLE uses runoff energy to erode and transport the sediments in the overland[51]. Sediment routing in the channel consists of degradation and deposition processes, which are prescribed using the concepts of stream power[52] and fall velocity respectively.

BMPs in watershed management are accounted for by modifying parameters suitably in the SWAT modelling[32]. However, selection of BMPs and their parameters is site-specific, and should reflect the physical processes in study area. Filter strips, being used as a soil conservation measure, are vegetated areas that are situated between the surface water bodies and cropland. The width of edge-of-filter strips FILTERW (*.mgt) is defined in HRUs[53] depending upon the requirement of soil conservation measures therein. The sediment, pesticide, nutrient and bacterial loads are arrested as the surface runoff passes through the filter strip. Stone bunds are temporary barriers designed to limit the flow of silt and sediment from sites of disturbed soil[53]. The effects of stone bunds in the SWAT model are represented using parameters such as CN2, average slope length (SLSUBBSN) and the USLE support practice factor (USLE_P). Terracing is used to decrease the peak flow, soil surface erosion, maintaining soil moisture and water quality improvement[54]. The SWAT model parameters affected by terracing include Curve Number 2 (CN2), SLSUBASIN (sub-basin average slope length) and USLE_P[32]. The contouring is the tillage practice for planting crops aligned to terrain contours. It enhances surface detention, reduces erosion and runoff. The SWAT simulates contouring operation by altering CN2 to increase the surface storage and USLE_P to decrease soil surface erosion[55]. Strip cropping is a band arrangement of crops which is mainly used on steep slopes. It is incorporated in SWAT model by adjusting STRIP_N (manning coefficient for overland flow), CN2 and STRIP_C (USLE cropping factor). The grade stabilization structure (GSS) is addressed through the structures to reduce streams and waterways slopes in natural or artificial water courses. It reduces the water velocity to store runoff and stabilize the grade to trap the sediments. The GSS is accounted in SWAT modelling while modifying the calibration parameters such as ‘main channel slopes (CH-S2) and factors of channel erodibility (CH-EROD)[56].

Preparation of thematic layers

The information on land use and land cover in SWAT were derived using satellite imagery (IRS 1D–LISS III sensor). Necessary model inputs for the SWAT model were obtained by combining the thematic data with observed climatic parameters such as precipitation, temperature and topographic parameters such as elevation, slope and stream network. Thematic maps for the

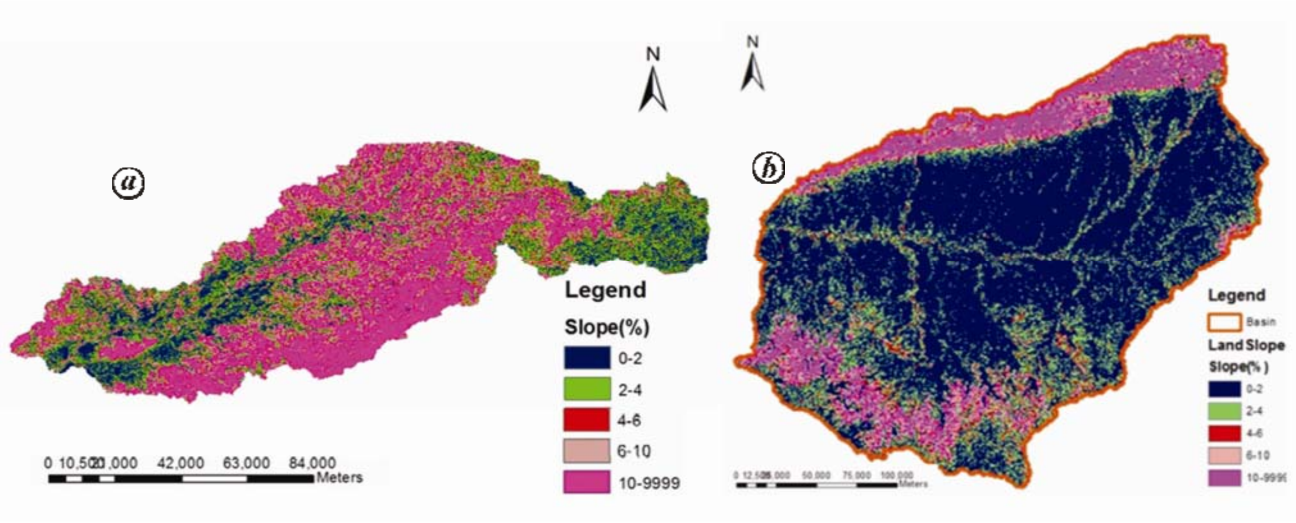

Figure 3. Slope maps of Upper Tapi Basin: ***a***, Burhanpur; ***b***, Yerli subcatchments.

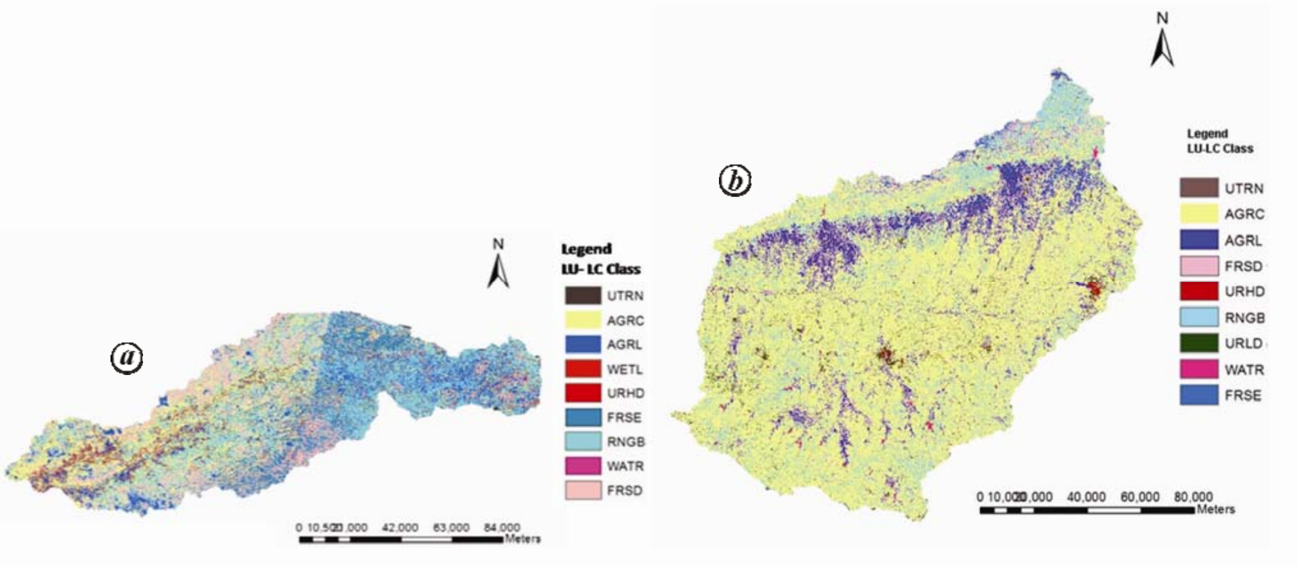

Figure 4. Land-use–land-cover maps of Upper Tapi Basin: ***a***, Burhanpur; ***b***, Yerli subcatchments.

subcatchments of Tapi and Purna rivers at Burhanpur and Yerli stations respectively, were prepared by extracting the necessary information from the relevant satellite imagery, toposheets and soil maps. Watershed parameterization and model inputs are derived using the Arc SWAT interface[57]. The derived slope maps of the Burhanpur and Yerli subcatchments are shown in Figure 3. In Burhanpur subcatchment, slopes greater than 10% occupy about 30% and slopes between 6% and 10% occupy about 16% of the watershed areas; whereas in the Yerli subcatchment, slopes between 0% and 2% occupy approximately 64% of the watershed area. The classification norms of US Geographical Survey (USGS) have been utilized to obtain 10 land-use–land-cover classes after recoding the classified images. The views of the land-use and land-cover maps for the subcatchments of the Burhanpur and Yerli, used in SWAT modeling in this study, are shown in Figure 4. The land-use–land-cover nomenclatures depicted in Figure 4 *a* and *b* are: AGRL – Agricultural land – Generic; AGRC – Agricultural land – Crops; FRST – Forest – Mixed; FRSD – Forest – Deciduous; WATR – Water; URML – Urban residential medium/low density; UTRN – Urban transportation; RNGB – Range land – Brush; RNGE – Range land – Grasses, and WETF – Wetland – Forested. All the polygons of the soil analogue map were converted into digital form, and each polygon was classified among different hydrological soil groups namely, A, B, C and D as per their infiltration and textural characteristics. Soil group A has a low runoff potential while group D has the highest runoff potential with group B being the soil with

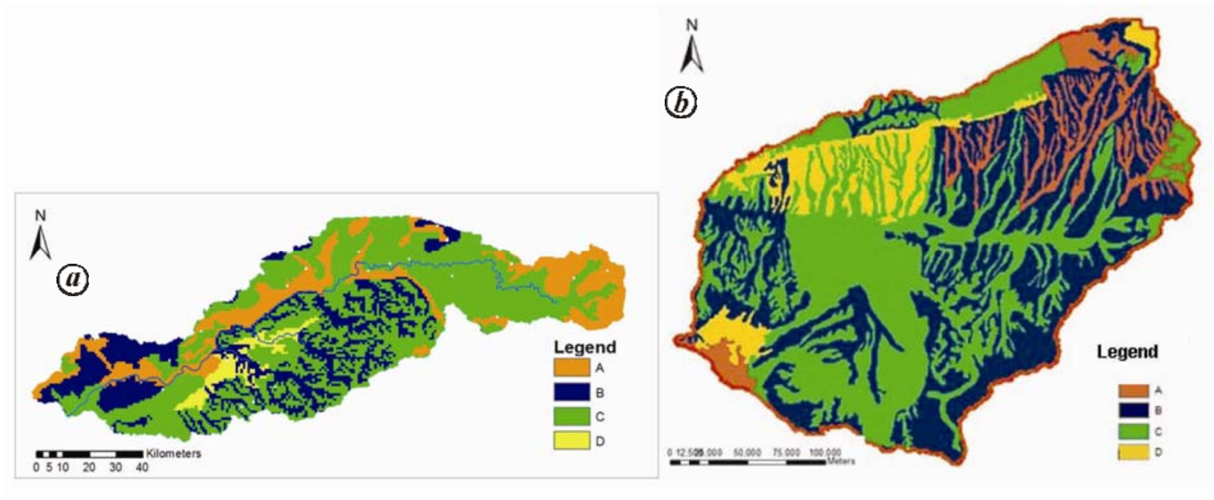

Figure 5. Soil maps of Upper Tapi Basin: ***a***, Burhanpur; ***b***, Yerli subcatchments.

Table 2. Composition of land-use–land-cover and soil group in study area

	Land-use–land-cover (% /area in sq. km)				Soil group classification (%/area in sq. km)			
Subcatchment	Agriculture	Forest	Rangeland	Others	A	B	C	D
Burhanpur	38.09/3232.68	44.72/3795.39	15.89/1349.43	1.30/109.50	16.95/1438.55	22.29/1892.51	56.91/4829.95	3.84/325.90
Yerli	74.41/12290.30	12.74/2104.26	9.49/1567.46	3.36/554.98	9.77/1613.71	39.00/6441.63	42.22/6973.48	9.01/1488.18

moderate infiltration characteristics[25]. The soil maps of the Burhanpur and Yerli subcatchments are shown in Figure 5.

Table 2 shows the broad areas covered in Burhanpur and Yerli subcatchments under different land-use–land-cover and soil groups as being used in the SWAT model. In the Purna river subcatchment, the agricultural crop area which is helpful in arresting soil erosion is about eight times than that existing in the subcatchment of Tapi at Burhanpur. The area under soil group B with moderate infiltration rates is significantly more in the Yerli subcatchment than in the adjoining Burhanpur subcatchment. In the Burhanpur subcatchment, the area covered under steep slopes is about twice more than that in the Yerli subcatchment. The land-use–land-cover, soil and slope class maps were overlain to derive 549 unique HRUs and 20 subbasins in the Burhanpur subcatchment; and 489 HRUs and 26 sub-basins in the Yerli subcatchment.

Calibration and validation of SWAT model

Previous studies[58,59] recommended that stream flow, sediment and nutrient transport be calibrated sequentially due to interdependencies of shared processes among them. Sometimes, due to the existence of large number of parameters, the model parameterization and calibration become very complex. Van Griensven and Bauwens[60] developed an auto calibration method that reduces multiple objective functions into a single global criterion which helps in overcoming aforesaid calibration issues. An automatic sensitivity analysis tool, One-factor-at-a-time (LH-OAT) Latin hypercube sampling, is used for sensitivity analysis of the model parameters[61], and accordingly, the rankings are established. Abbaspour *et al.*[62] developed SWAT-CUP, a multi-site, SUFI-2 (semi-automated inverse modelling routine sequential uncertainty fitting)[62,63] is used for calibration and uncertainty analyses in the SWAT. The SUFI-2 lends itself easily to parallelization, and is capable of analysing a large number of parameters and measured data simultaneously[64,65]. It is common practice in hydrological studies to divide the measured data either temporally or spatially for calibration and validation of the selected model[59]. In this study, SWAT model has been calibrated using SUFI-2 algorithm for 24 sensitive parameters. The statistical performance indicators, viz. Nash–Sutcliffe efficiency (NSE)[66] and ratio of root-mean-squared error (RMSE) to the standard deviation of observed data (RSR) have been used to assess the performance of calibrated model.

The NSE and RSR are defined using eqs (1) and (2) as

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{\mathrm{obs}} - Y_i^{\mathrm{sim}})^2}{\sum_{i=1}^{n} (Y_i^{\mathrm{obs}} - Y^{\mathrm{mean}})^2} \right] \qquad (1)$$

$$\mathrm{RSR} = \frac{\mathrm{RMSE}}{\mathrm{STDEV_{obs}}} = \left[\frac{\sqrt{\sum_{i=1}^{n} (Y_i^{\mathrm{obs}} - Y_i^{\mathrm{sim}})^2}}{\sqrt{\sum_{i=1}^{n} (Y_i^{\mathrm{obs}} - Y^{\mathrm{mean}})^2}} \right]. \quad (2)$$

Here, Y_i^{obs} and Y_i^{sim} are respectively, the observed and simulated values of *i*th observation; Y^{mean} the mean of observed data of the parameter under consideration, and *n* is the total number of observations.

The NSE has limits from $-\infty$ to 1.0 with NSE = 1 as the optimal value. A value of NSE exceeding 0.50 is considered satisfactory for hydrological applications[67]. The RSR denotes the zero as the optimal value, and, therefore, perfect performance of model simulation. During the calibration, model parameters are adjusted such that the computed values are closer to the observed values. Calibration and validation periods for the observed data, in this study, were divided into two parts, i.e. calibration period (1993–1998) and validation period (1999–2004), for the data available at Burhanpur and Yerli stream gauging stations, and it was observed that both the periods include dry and wet years.

Results and discussion

Sensitivity of the model parameters, validation of the calibrated model, identification of erosion prone areas and effect of BMPs in arresting the soil erosion, are described as follows.

Calibration and sensitivity of model parameters

Optimal values of the calibrated parameters and their range for Burhanpur and Yerli subcatchments are shown in Table 3. For Burhanpur subcatchment, average NSE and RSR values for the calibration period have been estimated to be 0.85 and 0.21 respectively, for the monthly runoff. For the same catchment, corresponding values for sediment yield have been found to be 0.82 and 0.35 respectively. In the Yerli subcatchment, average NSE and RSR values during the calibration period have been computed to be 0.79 and 0.26 respectively, for monthly runoff; while corresponding values for monthly sediment yield have been found to be 0.72 and 0.38 respectively. Figure 6 shows comparison of the observed and simulated values of the sediment yield for the calibration period along the line of perfect agreement for Burhanpur and Yerli subcatchments.

Out of the 24 parameters identified for calibration of SWAT model in Burhanpur and Yerli subcatchments, sensitivity analysis has been performed to identify the most sensitive parameters of SWAT model in prediction of sediment yield. The analysis indicated that for 100% variation in the model parameters, percentage variation in the sediment yield for the five most sensitive parameters

Table 3. Calibration parameters of SWAT model for upper Tapi Basin

Parameters	Lower bound	Upper bound	Optimal value Burhanpur subcatchment	Optimal value Yerli subcatchment
Alpha_bf, Base flow alpha factor	0	1	0.4	0.58
Canmax, Maximum canopy storage for land-use pasture	0	10	3.52	6.32
Ch_K2, Effective hydraulic conductivity in main channel	0	150	78	76
Manning's *n* value for the main channel	0	0.3	0.14	0.14
CN2, SCS runoff curve number for moisture condition II	25	90	82	65
Epco, Plant uptake compensation factor	0	1	0.36	0.32
Esco, Soil evaporation compensation factor	0	1	0.41	0.42
Gw_Delay, Groundwater delay time	1	100	36	32
Gw_Revap, Groundwater revap. coefficient	0.05	0.5	0.082	0.083
Gwqmn, Threshold depth of water in the shallow aquifer required for return flow to occur	0	1000	153	125
Revapmn, Threshold depth of water in the shallow aquifer for 'revap' to occur	0	100	29	24
Sol_Alb, Moist soil albedo	0.1	0.5	0.25	0.24
Sol_Awc, Soil available water storage capacity	0	0.8	0.36	0.37
Sol_K, Soil conductivity	1	25	7	6.8
Sol_Z, Depth from soil surface to bottom of layer	25	400	270	195
Surlag, Surface runoff lag time	0	10	5.4	7.2
Rchrg_Dp, Deep aquifer percolation fraction	0.01	1	0.42	0.58
Lat_Time, Lateral flow travel time	1	4	2.2	1.9
Manning's *n* value for overland flow	0.2	0.6	0.44	0.22
Sol_Bd, Bulk density	–0.5	1.5	0.72	0.76
Spcon, Linear coefficient for sediment routing in channel	0	0.4	0.21	0.19
Ch_Erod, Channel erodibility factor	0.01	0.35	0.20	0.10
USLE_P, USLE equation support practice factor	0.1	1	0.51	0.32
USLE_C, USLE equation crop practice factor	0.001	0.5	0.43	0.19

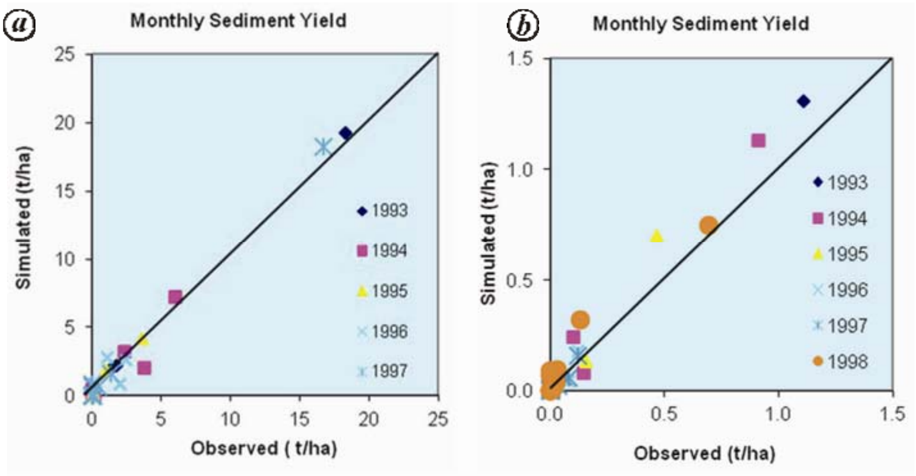

Figure 6. Observed versus simulated values of sediment yield during calibration period (1993–1998) for (***a***) Burhanpur and (***b***) Yerli subcatchments.

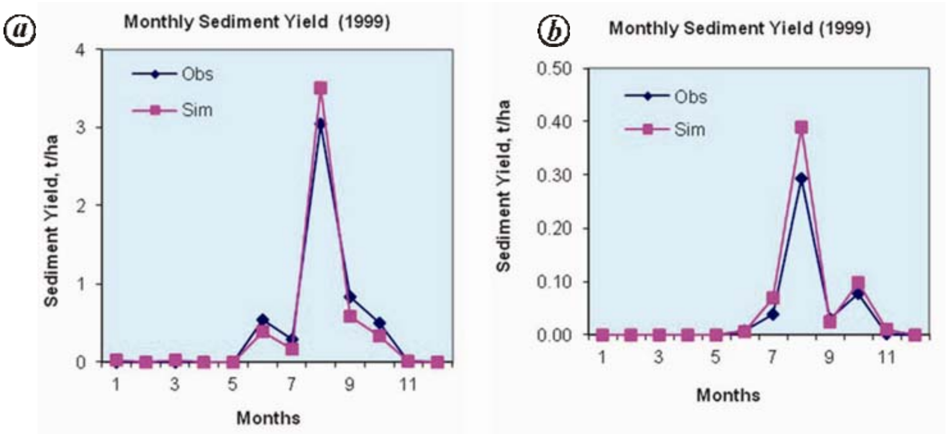

Figure 7. Observed and simulated sedimentographs under validation for year 1999 of (***a***) Burhanpur (***b***) Yerli subcatchments.

are (indicated in brackets): (i) Surlag SURLAG (–150), (ii) Curve number CN2 (102), (iii) USLE-P (100), (iv) USLE_C (100) and (v) Mannings *n* overland (65). The analysis also indicated that the remaining input parameters are less sensitive in prediction of sediment yield, and even their 100% variations could cause variation in sediment yield by less than 5%. The other SWAT parameters contribute largely to the ground and soil water flows, evapotranspiration, etc. and do not significantly affect the sediment yield. Sensitive analysis of model parameters helps in identifying appropriate BMPs (soil conservation measures), affecting the most sensitive parameters and, hence, be effective in arresting the soil erosion.

Validation

The independent datasets, during 1999–2004, have been used for validation of the calibrated model. Sedimentographs for a typical year (1999) obtained from simulated results and observed data are shown in Figure 7. Average values of NSE and RSR for prediction of sediment yield for the validation period have been found to be 0.82 and 0.41 respectively, for the Burhanpur subcatchment. The corresponding values of NSE and RSR for the Yerli subcatchment have been found to be 0.71 and 0.51 respectively. From Figure 6, it is observed that simulated values are invariably higher (≈13–15%) than observed values, which may be attributed to the fact that simulated values include the total load while observed values, available at the stream gauging sites, pertain to the suspended load only. In general, the calibrated model performs better for higher sediment yield conditions vis-à-vis low sediment yield due to representation of high percentage of bed load at low flow conditions, and non-accounting of the same in the observed data. Table 4 shows the average hydrological balance of Burhanpur and Yerli subcatchments during the study period 1993–2004 as per the SWAT model results. In Table 4, it is seen that the average run-off coefficient for Burhanpur subcatchment is about 0.50 which is more than twice the run-off coefficient of the Yerli subcatchment. Also, the error component in water balance, as expressed by Jain[68], was derived for Burhanpur and Yerli subcatchments, and its respective values are 1.58% and 2.39% (in terms of precipitation). However,

Table 4. Average hydrological balance of Burhanpur and Yerli subcatchments

Subcatchment	Precipitation (mm)	Surface run-off (mm)	Base flow (mm)	Lateral flow (mm)	Soil percolation (mm)	ET (mm)	Water yield (mm)	PET (mm)
Burhanpur	936.40	457.72	127.54	107.72	36.22	228.61	692.98	593.78
Yerli	655.27	143.99	149.83	107.31	45.67	238.47	401.13	949.99

ET, Evapotranspiration; PET, Potential evapotranspiration.

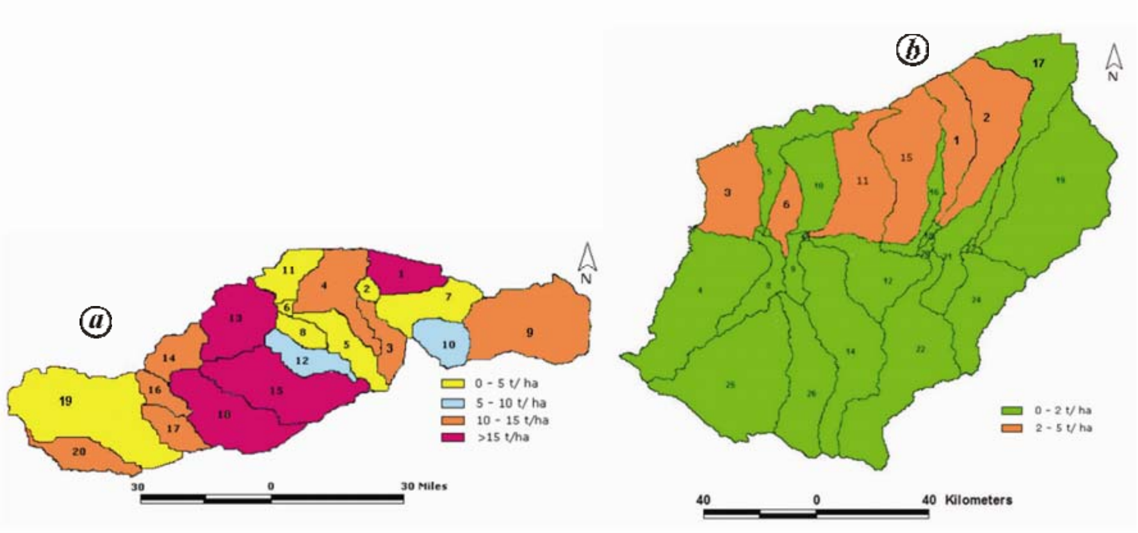

Figure 8. Sub-division of catchment with reference to sediment yield in (***a***) Burhanpur and (***b***) Yerli subcatchments.

the value of ET for Burhanpur subcatchment seems to be lower while comparing the values for Indian river basins as recommended by Jain[68]. Such low value of ET requires further studies such as transboundary effects. Also, average rainfall in the Yerli subcatchment is about 30% less than that of the Burhanpur subcatchment. During the study period 1993–2004, the average annual sediment yield of Burhanpur subcatchment is 10.1 t/ha, which is much higher than that of the Yeri subcatchment (0.78 t/ha). This is mainly due to the existing topography, land-use–land-cover and climatic patterns prevailing in the subcatchments as discussed earlier.

Identification of erosion-prone areas

The SWAT model, developed for the Upper Tapi Basin, also helped in identifying the sediment yield prone areas in both Burhanpur and Yerli subcatchments. Zoning of the areas with reference to annual sediment yield rates in Burhanpur and Yerli subcatchments is shown in Figure 8. Analysis of sediment yield data during 1993–2004 at HRU level indicates that sub-zones 1, 15, 18 and 13 are highly prone to erosion (>15 t/ha/year) followed by the sub-zones 20, 14, 16, 17, 4, 3 and 9; wherein the annual erosion rate is between 10 and 15 t/ha. Identification of highly sediment yield prone areas in Burhanpur subcatchment through foregoing analysis indicated that such areas are mostly dominated by agricultural barren lands with topography having ground slope greater than 8%. The sediment yield prone areas require soil conservation practices such as vegetative filter and stone bunds, which are appropriate for application in erosion-prone areas of the Burhanpur subcatchment. For the Yerli subcatchment, Figure 8 *b* shows that six sub-basins of Yerli subcatchment exhibit annual sediment yield 2 and 5 t/ha; while others exhibit magnitude between 0 and 2 t/ha. Overall, Figure 8 indicates that Burhanpur subcatchment is more erosion-prone vis-à-vis Yerli subcatchment and requires extensive soil conservation measures in the catchment.

Sedimentation in Hathnur reservoir

Analysis of data for 1993–2004 indicated that nearly 80% of the annual sedimentation in Hathnur reservoir occurs due to the sediments brought in by the Tapi River subcatchment at Burhanpur, which occupies nearly half the area than the adjoining Yerli subcatchment. The annual sediment yield in the Hathnur reservoir (on the basis of study period 1993–2004) as simulated from the SWAT model has been found to be 11.66 MT (10.1 MT from Tapi River and 1.56 MT from the Purna river). Considering the catchment area and gross storage capacity of Hathnur reservoir, the primary trap efficiency factor, as per Brown[69] has been estimated to be 0.79. Thus, total simulated reservoir sedimentation is 9.21 MT, which is equivalent to 313 t/sq. km/year. The simulated reservoir sedimentation rate (313 t/sq. km/year) matches closely the average annual observed sedimentation rate of 330t/sq. km/year (ref. 40).

Table 5. Scenarios description and SWAT parameters used to represent BMPs

		SWAT parameter used			
Scenarios	Description	Parameter name (input file)		Calibration value	Modified value*
Scenario-0	Baseline	–			
Scenario-1	Filter strip	FILTERW (.hru)**		0	1 (m)
Scenario-2	Stone bund	SLSUBBSN (.hru)	0–10% slope	60 (m)	10 (m)
			10–20% slope	23 (m)	10 (m)
			>20% slope	9.1m	9.1 (m)
		CN2 (.mgt)		82	59
		USLE_P (.mgt)		0.51	0.32

*As per calibrated values (Table 3). **The extensions, .hru and .mgt are input files, where parameter values were edited.

Table 6. Reduction in sediment yield under different scenarios in Burhanpur subcatchment

Scenarios	Description	Area of application (sq. km)	Sediment yield	% reduction wrt to base line
Scenario-0	Baseline/current conditions	2500	15.6 t/ha	–
Scenario-1	Filter strip	2500	12.8 t/ha	18%
Scenario-2	Stone bund	2500	13.1 t/ha	16%

Best management practice scenarios

Critical erosion prone-areas in Burhanpur subcatchment have been identified using calibrated SWAT model for the same catchment, as discussed earlier. In view of the higher sediment yield from Burhanpur sub-catchment, BMPs with appropriate options, viz. filter strips and stone bunds, considering their suitability for application in the study area, were used to reduce the erosion rates in the subcatchment and hence reduction of reservoir sedimentation. The BMPs in the SWAT model are represented by modifying SWAT parameters to reflect the effect of the practices in controlling erosion in the catchment[32]. The modified values of calibrated parameters under BMP scenario for different options are included in Table 5 (ref. 42).

In scenario 0, the existing conditions of the basin, i.e., baseline scenario is considered. In Scenario 1, the filter strips were placed in all agricultural HRUs that are combination of dry cropland, all soil types and slope classes covering an area of about 2500 sq. km in the Burhanpur subcatchment, having sediment yield rates greater than 15 t/ha. The filter strip filters the runoff and traps the sediment in agricultural plots itself[32]. FILTERW value of 1 m has been adopted for simulation of its impact on trapping of the sediments. The value of FILTERW has been modified by editing the HRU (.hru) input table of the SWAT model. In scenario 2, the stone bunds were placed on agricultural HRUs in a similar manner as the filter strips. The stone bunds reduce overland flow, prevent sheet erosion and reduce slope length[32]. SLSSUBSN values were modified by editing the input table of HRU (.hru), while the values of USLE_P and CN2 were revised by editing the Management (.mgt) input table. The SLSUBBSN parameter value was assigned on basis of the slope classes. The assigned values of SLSUBBSN for foregoing BMP option in the SWAT model for slope classes 0–10%, 10–20% and over 20% were 10, 10 and 9.1 m respectively. The modified values of USLE_P and CN2 have been taken as 0.32 and 59 respectively. The SLSUBBSN represents the spacing between successive stone bunds in the field. The USLE_P and CN2 values were modified as per SWAT user's manual version 2005 (ref. 42).

The SWAT model was run with aforesaid BMP scenarios in the Burhanpur subcatchment and their effects on reduction of erosion are indicated in Table 6. The filter strips scenario reduces the total sediment yield by 18% from the original conditions of the sub-catchment. On the other hand, the stone bunds scenario reduces the total sediment yield by 16% from the existing condition. The filter strips scenario showed marginally higher reduction in sediments than the stone bunds scenario, for implementation in an equal area. 'Filter strips' and 'stone bunds' have limited application in Burhanpur subcatchment as about 2500 sq. km is covered by agricultural fields. This study demonstrated that SWAT modelling approach could be helpful to decision makers for evaluating effectiveness of a particular BMP measure in controlling sediment yield from a selected catchment.

Conclusions

The following key conclusions can be summarized from the investigations reported in this study.

- Parameters of the SWAT model have been calibrated for prediction of sediment yield at Burhanpur and Yerli gauging stations on Tapi and Purna rivers respectively, for the period 1993–1998. The calibrated model has been found to predict sediment yield satisfactorily at aforesaid gauging stations during the validation period 1999–2004 (see Figures 6 and 7).

- Sensitivity analysis of SWAT parameters showed that five parameters, namely, Surlag SURLAG, curve number CN2, USLE_P, USLE_C and Mannings *n* overland, are most sensitive in prediction of the sediment yield.
- The SWAT simulation results including land-use–land-cover maps developed using GIS and remote sensing data, helped to identify highly erosion-prone areas of Burhanpur subcatchment.
- Simulated results from SWAT model indicated that Burhanpur subcatchment at Tapi River is much more erosion-prone than the adjoining Yerli subcatchment at Purna river, and contributes nearly 80% of sedimentation in Hathnur reservoir.
- BMPs, viz. vegetative filter strip and stone bunds in the most erosion-prone areas in the Burhanpur subcatchment, have been simulated to reduce the sediment yield by 16% and 18% respectively. Processes such as deterioration of the BMPs, concentration of flow in filter strips and lack of model parameterization in BMPS at sub-basin scale are not well-simulated in the SWAT.

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