Water Supply

Water Supply Vol 22 No 3, 3342 doi: 10.2166/ws.2021.399

Integrated watershed development plan for a sub-basin, central India

Saranya C. Nair [a,*] and A. B. Mirajkar [b]

[a] Water Resource Engineering VNIT, Nagpur 440010, India
[b] Department of Civil Engineering VNIT, Nagpur, 440010, India
*Corresponding author. E-mail: saranyawre@gmail.com

SCN, 0000-0003-3994-4992; ABM, 0000-0001-6146-8326

ABSTRACT

The present study aims to propose an integrated watershed development plan for the Wainganga basin situated in Maharashtra, India. Also, the study involves evaluating the performance and applicability of SWAT (Soil and Water Assessment Tool) as a runoff model along with the trend analysis of rainfall for the above mentioned study area. The decadal land-use/land-cover (LULC) variation from 1985 to 2005 has been studied using data procured from Goddard Earth Sciences Data and Information Services Center (GES-DISC) and the groundwater table level of the study area was monitored using dug/bore well data collected from the Central Ground Water Board (CGWB). Rainfall trend analysis for a period of 101 years using historic rainfall data procured from the India Meteorological Department (IMD) has been analyzed to foresee the future scenario. It was observed that the rainfall-runoff relationship of the area is getting affected by the LULC variation and is thereby affecting the groundwater regime. There is a significant deterioration in the forest cover and water bodies which is alarming. The study devises the importance of an immediate master plan to be implemented in the basin to avoid any future crisis. Also, the study emphasizes the advancement of remote sensing in the use of hydrologic models like SWAT more realistically.

Key words: flood, LU/LC, rainfall-runoff, SWAT, trend analysis, Wainganga basin, watershed

HIGHLIGHTS

- The present study incorporates an integrated approach for watershed planning.
- Rainfall runoff relationships were identified.
- Land use-land cover anomalies and rainfall trend characteristics were analyzed.

1. INTRODUCTION

Rainfall can be considered as the key element of the hydrologic cycle as it replenishes water and nurtures the ecosystem. India being an agrarian country mostly depends on rain-fed agriculture and the economy is directly connected with the monsoon system (Karcher *et al.* 2013; Pan *et al.* 2017). Rainfall characteristics like seasonality, intensity, and return period largely affect the cropping pattern and hence need close monitoring. The current scenarios of climate change and rainfall variations have made the life of farmers miserable and an unusual trend of farmer suicides started hitting the headlines in the recent past (Mishra 2006). Upon this, the population status of India is expecting to reach 1.6 billion by 2050 which is a demanding situation (Bloom 2011; Jha 2020). However, the availability of resources and demands are not doable to rig the current situation causing exploitation.

Integrating the natural as well as human elements of a watershed to optimize the resources and to curb the adverse human activities is called watershed management (Zoltay *et al.* 2010). A watershed is a catchment area that drains the benefits of rainfall to a river or an outlet point (Himanshu *et al.* 2018). Excessive rainfall can make the river flood and inundate the catchment causing damage and erosion (Khazaei *et al.* 2012; Simin *et al.* 2012; Ozturk *et al.* 2013). Hence it is primarily important to model the rainfall-runoff relation of the area to channel out the excess water before flooding (Rao *et al.* 2010; Alfa *et al.* 2011). SWAT is a physically-based runoff model capable of discretising large watersheds where simulation at ground scale is difficult to execute (Fadil *et al.* 2011; Arnold *et al.* 2012; Shi *et al.* 2013).

The recent replacements in the land-cover structures with impervious land-use surfaces have appended the situation of excessive runoff generation which in turn is perverse to the groundwater recharge (Varalakshmi *et al.* 2014; Goswami & Rabha 2020; Resmi *et al.* 2020; Nair & Mirajkar 2021). Unlike surface water bodies, groundwater levels are elusive in nature and require close monitoring. The ever-increasing demands and rainfall irregularities have intensified the abstraction rate and caused an imbalance between aquifer recharge and pumping (Shin 2007; Van der Gun & Lipponen 2010; Zamani *et al.* 2017; Prasad *et al.* 2020). Hence the idea of runoff management through land-cover restoration along with aquifer recharge can help the watershed planning program to a greater extend (Thomas *et al.* 2009; Singh & Katpatal 2017).

Here the study aims to include all the possible parameters of a watershed (runoff, rainfall, groundwater, land use-land cover) and details the current scenario of each. The study area, Wainganga basin, is in the assured rainfall zone is facing rainfall variabilities and unusual patterns of flood and drought. The effect of disparate rainfall scenarios was often studied but the other parameters like land, groundwater, runoff, etc were ignored or concerned with individual studies. The present analysis tries to integrate the current scenario of each parameter and its impacts on the area.

2. STUDY AREA

Wainganga River originates from Madhya Pradesh and encompasses a total basin area of 50,000 km^2 and extends from 19° 30′N to 22°30′N latitude and 79°00′ E to 80°30′E longitude. Wainganga basin has peculiar topography with valleys and ridges and it possesses the highest forest cover in Maharashtra state (Patil *et al.* 2010; Madhurima & Banerjee 2013). The location map of the Wainganga basin is shown in Figure 1. A major part of the rainfall is from the southwest monsoon and the area lies in the moderate rainfall zone with an average annual rainfall of 1400 mm. Wainganga basin is particular with its contrasting climate characteristics when compared to other regions of Maharashtra.

3. MATERIALS AND METHODOLOGY

The objective of watershed management can be proposed only after a detailed and integrated study. Here in this study, rainfall, runoff, land-use/land-cover, and groundwater were used as the primary parameters for modeling. The runoff

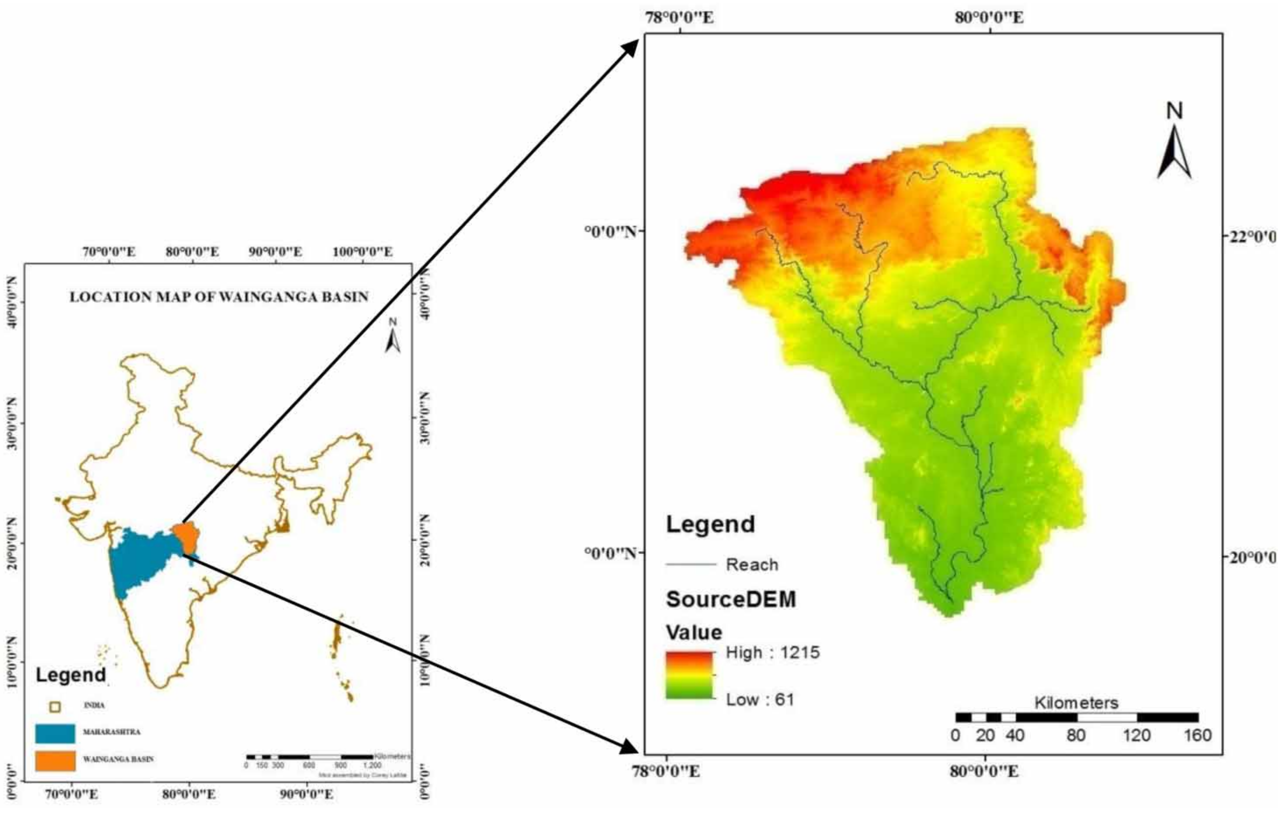

Figure 1 | Wainganga basin located in Maharashtra, India.

quantification from the area was estimated using the SWAT model which combines the topographical parameters (DEM, LULC map, soil map, slope map) and weather parameters (rainfall, humidity, wind, solar radiation wind speed, and temperature). The Cartosat Digital Elevation Model (DEM) used for watershed delineation, having a spatial resolution of 30 m, was procured from the National Remote Sensing Centre (https://www.nrsc.gov.in/). The simulation was carried out using a monthly time format for a period of 23 years (1990–2013), the first three years being the warm-up period.

To foresee the rainfall scenario of the basin, a non-parametric rainfall trend analysis was carried out using gridded data having 0.25×0.25° spatial resolution. The Mann-Kendall (M-K) test method is a popular method to detect linear-non linear variation in climatic parameters and was used for trend detection (Ryu *et al.* 2018; Sharma *et al.* 2018; Nair & Mirajkar 2020). LULC analysis was carried out using data from 1985 and 2005, procured from Goddard Earth Sciences Data and Information Services Center GES-DISC, to detect the decadal variation (https://daac.ornl.gov/). The LULC data downloaded had a spatial resolution of 100 m with a companion file detailing the spatial and classification properties. The total area of 50,000 km^2 was classified into 12 classes and the thematic analysis was carried out ArcGis 10.2 software. To conclude the remarks, the groundwater statistics were studied using well data collected from around 450 well points in and around the basin (Central Ground Water Board). Inverse distance weightage (IDW) methodology was used to generate choropleth maps of groundwater data.

4. RESULTS AND DISCUSSIONS

4.1. SWAT analysis

SWAT analysis was carried out to estimate the runoff volume from the basin using the Arc-SWAT interface. The digital elevation model was given as the input to delineate the watershed and stream network. The SWAT model defines 625 hydrologic response units (HRUs) for the Wainganga basin using the soil map, slope map, and LULC map. The model computation is based on the conflation of topographical parameters, weather parameters, and other basic features. The simulation was done for 23 years, the first three being the warm-up period; the simulated data obtained as for 20 years from 1993 to 2013 in a monthly format. Ashti station was selected as the outlet point of 28 sub-basins and it resulted that an average of 25,000 million cubic metres (MCM) of runoff is generated every year.

4.2. SWAT calibration and sensitivity analysis

The calibration and validation of the SWAT model was carried out for 12 parameters (Table 1), by the Sequential Uncertainty Fitting (SUFI-2) algorithm linked with the SWAT_CUP interface. During calibration (1999–2003), the objective functions of R^2 and Nash Sutcliffe Efficiency (NSE) values of the simulated daily data were compared with the observed gauge discharge data. It was found that the R^2 value coincides 0.71 and the NSE value obtained was 0.64. During validation (2004–2005), the

Table 1 | Global sensitivity of parameters

Parameter	Definition of parameter	t-stat	*p*-value
V CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/h)	8.12	0.000
R HRU_SLP.hru	Average slope steepness (m/m)	3.41	0.002
V GW_REVAP.gw	Base flow alpha factor	−1.04	0.301
V ALPHA_BF.gw	Base flow recession constant	0.705	0.501
RSOL_BD.sol	Baseline flow recession constant (days)	0.641	0.512
R GWQMN.gw	Depth of water in shallow aquifer	0.612	0.616
R SOL_AWC.sol	Available water capacity of soil layer	−0.531	0.593
V REVAPMN.gw	Threshold depth of water in the shallow aquifer for re evaporation to occur (mm)	0.525	0.618
RSLSUBBSN.hru	Average slope length	0.492	0.633
V CH_N2.rte	Manning's 'n' value for the channel	0.311	0.786
R OV_N.hru	Manning's 'n' value for overland flow	0.286	0.745
R CN2.mgt	Initial SCS runoff curve number for moisture condition II	−0.115	0.912

Definition of parameter (*source*: Abbaspour 2008).

R^2 was 0.55 and NSE was 0.43. According to Nash & Sutcliffe (1970), when the NSE value is more than 0.36 represents the simulated results are good. The results from calibration as well as validation show that the SWAT model results are applicable for the Wainganga river basin. The sensitivity of the parameters was determined based on *p*-value and t-test value; the more sensitive parameter has smaller *p*-value and greater would be the t-test value and vice versa. The *p*factor is the percentage of data bracketed by 95PPU (95% prediction uncertainty) calculated at 2.5 and 97.5 percentiles of the cumulative distribution. The parameters, HRU_SLP (average slope steepness), ALPHA_BF (base-flow alpha factor in days), CH-K2 (effective hydraulic conductivity), GW_REVAP (groundwater revap coefficient) and SOL_AWC (available water capacity of the soil layer) were observed to be the most sensitive.

4.3. Rainfall trend analysis

To ascertain the future rainfall conditions of the area, trend analysis was carried out using the M-K test. Gridded rainfall data of 0.25×0.25 spatial resolution from 1913 to 2013 (101 years) was used for the analysis. Annual rainfall data and annual maximum rainfall data were taken for the calculation. The data was checked for homogeneity and outliers to avoid errors. The analysis was carried out at a 5% significance level and the results are given in Table 2.

At a 5% significance level, M-K τ value was observed to be -2.9 for the average annual rainfall, recommending a decreasing trend in the rainfall series, and for the maximum rainfall series, a positive τ value of 2.0 was obtained confirming a positive trend. The trend analysis results clearly show the impact of climate change in the study area which is to be accounted for in the planning strategy. The increasing trend in peak rainfall indicates storm events of high intensity at short intervals which is the main reason for flash floods in the area. The seasonal rainfall distribution has distorted and heavy rains for short spells are becoming common. There should be a proper flood water channeling method implemented in the basin which can be beneficial for aquifer recharge and irrigation purposes.

4.4. Rainfall data and flood frequency analysis

The annual rainfall from 1913 to 2013 was procured from the India Meteorological Department, Pune, and the return period was calculated using Gumbel's distribution (Table 3). It was observed that rainfall of around 1500 mm magnitude is repeated every five years, which makes the basin flood-prone. Rainfall of more than 1200 mm is occurring every two years creating a runoff of 360 mm.

The recurrence interval shown in the table indicates that rainfall of severity more than 1500 mm is expected every five years, resulting in a similar runoff pattern. Hence it is important to seek proper management measures for this floodwater to prevent it from being wasted.

Table 2 | Trend analysis test results

Time series	Mann- Kendall τ value*	Trend
Avg. annual rainfall data	−2.9	Decreasing trend
Annual maximum rainfall data	+2.0	Increasing trend

*95% confidence interval).

Table 3 | Rainfall frequency analysis

Return period (year)	Frequency factor (K_T)	Expected flood (X_T)	Rainfall (mm)
2	−0.164	53.554	1,285.296
5	0.719	62.38102	1,497.144
10	1.305	68.23904	1,637.737
50	2.592	81.10469	1,946.513
100	3.137	86.55285	2,077.268

4.5. Land use land cover

LULC detailing of Wainganga basin having an approximate area of 50,000 km^2, shows that out of 12 classes' defined, agricultural land and forest area are the predominant classification. Fifty percent of the basin area constitutes agricultural land and another major share is various forest covers. LULC analysis over 20 year's (1985–2005) was carried out to detect the decadal variations. It was observed that from 1985 to 2005, 794 km^2 of water bodies were depleted and 1000 km^2 of forest area were cleared. Another noticeable change that occurred during this period was the increase in fallow land. In 20 years, an approximate 1200 km^2 area of fallow land was generated in the basin, which is a major threat to the ecosystem as it escalates runoff volume and topsoil erosion. The close monitoring of LULC maps of 1985 and 2005 shows that the Wainganga river path, which is visible in 1985, is not even showing the traits in 2005 and is given in Figure 2.

The overall changes reflected in the analysis mark the impact of urbanization in the area. The steady population growth has increased demand on agricultural production and built-up land. It is distinctly shown in Table 4 that the changes are mostly from 'land-cover to 'land-use' which means the conversion of the naturally existing landscape to man-made domains.

4.6. Soil characteristics

A major share of the Wainganga basin is characterized by black cotton soil which comes under the hydrologic soil group (HSG) - C. HSG-C soil type mainly constitutes 20–40% of clayey soil having a low infiltration rate. A thick top stratum of group C soil can impede the smooth percolation process and thereby accelerates runoff during a heavy storm event. The soil map having sub-classification of different soil types in the area is given in Figure 3.

The soil structure and slope study analysis proved that the area is a runoff potential zone with a gently rolling topography. The soil characteristics like bulk density and moisture content are favorable for runoff and hence the amount of runoff generated in the basin is likely to increase due to poor land management practices.

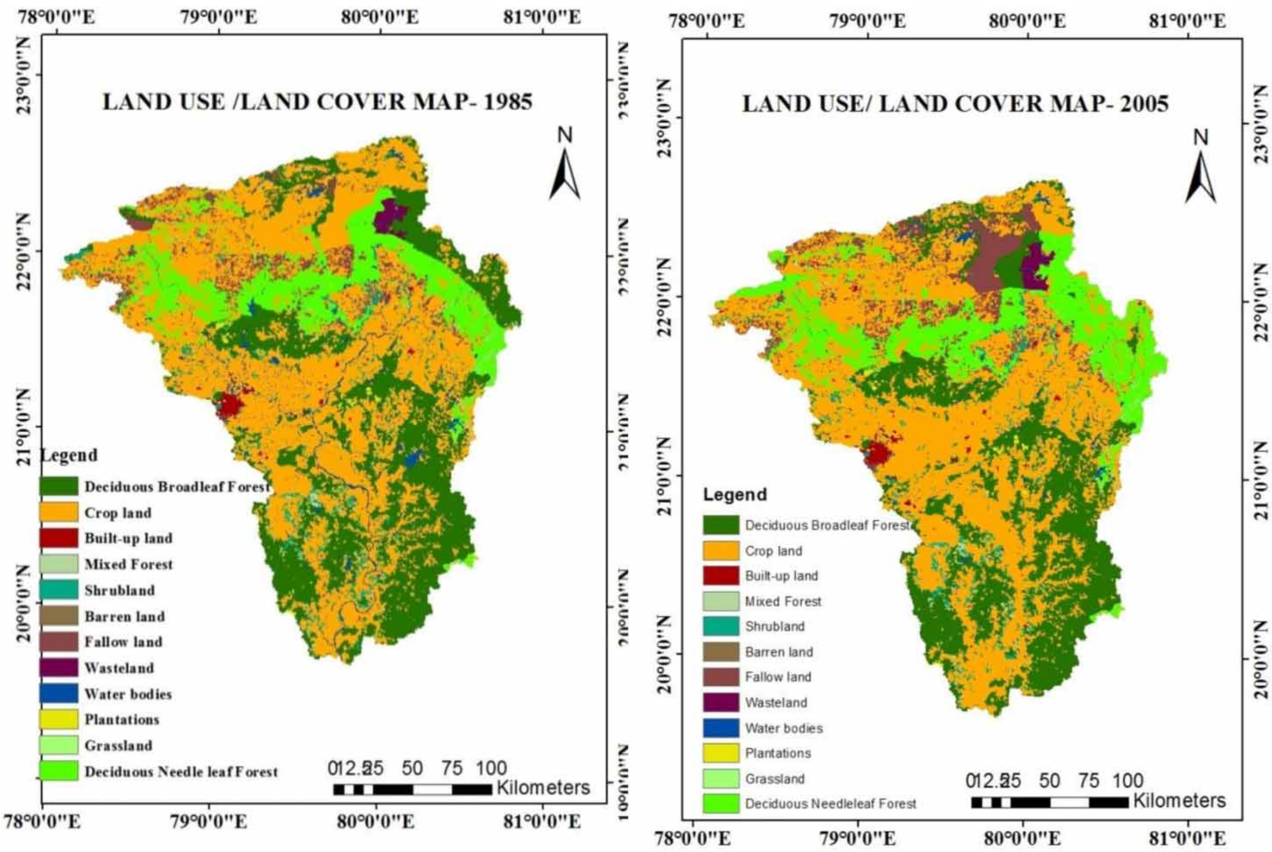

Figure 2 | LULC maps of Wainganga river basin over two decades (1985–2005) (*source*: Nair & Mirajkar 2019).

Table 4 | Area wise distribution of LULC for Wainganga basin

Land type	Area in 1985 (%)	Area in 2005 (%)
Deciduous broadleaf forest	26.22	23.62
Agricultural land	49.3	48.78
Residential area	0.65	0.70
Mixed forest	1.03	1.08
Shrubland	3.17	2.91
Barren land	0.02	0.02
Fallow land	3.81	6.30
Wasteland	0.63	0.74
Water bodies	2.63	1.08
Plantations	0.23	0.25
Grassland	0.01	0.01
Deciduous Needle leaf Forest	12.31	14.54
Total area (**51,296.2 km^2**)	**100**	

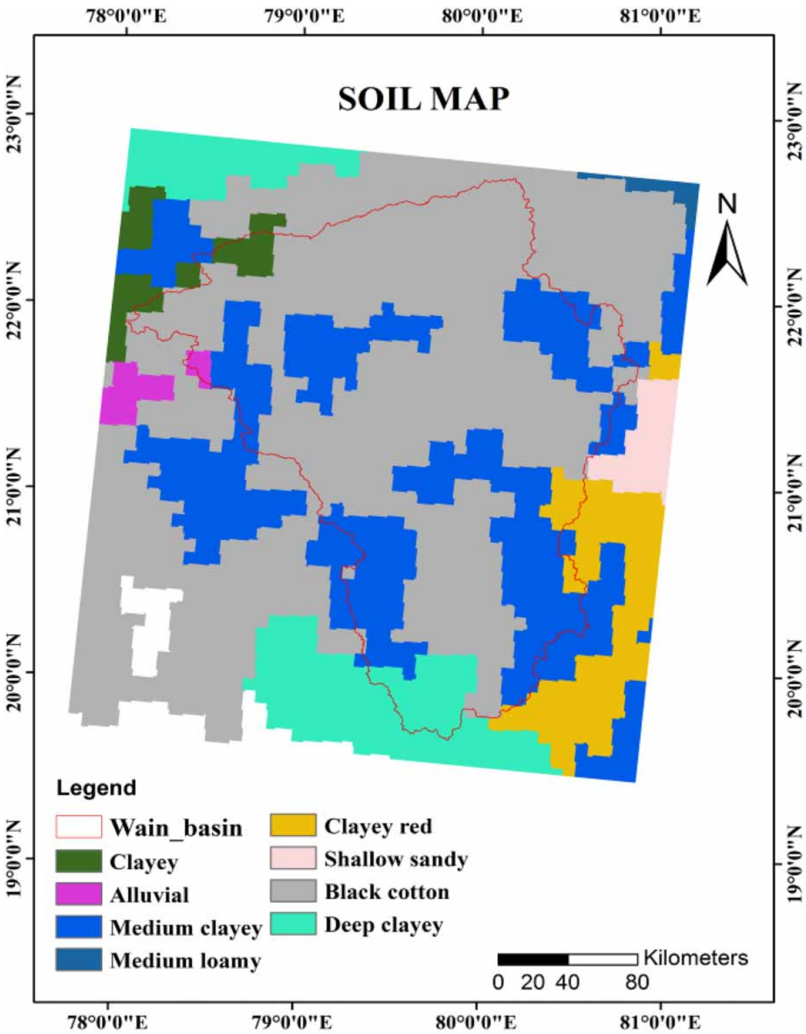

Figure 3 | Soil classification of Wainganga basin.

4.7. Groundwater conditions

The lithology of the Wainganga basin constitutes a Precambrian and basaltic structure, which can tap water in its crevices. The groundwater recharge is often through rainfall and the increase in runoff has created deep draw-down curves of the aquifer in the area. One method to utilize the flood water is to divert it back to the aquifer by proper technology and support systems. The groundwater potential of an area is getting directly affected by the erratic rainfall pattern and drastic climatic changes. Adding to this, the exploitation and contamination of the existing surface and groundwater resources are making the situation worst. According to the Central Groundwater Board, bore well-based irrigation has leapt from 1% to around 60% in the past 50 years (CGWB 2000). So it became imperative to reverse the situation by directing excess runoff/floodwater into the ground. The groundwater availability map of Wainganga pre-monsoon and post-monsoon is given in Figure 4.

The south-western districts of Wainganga basin are showing groundwater availability at a depth of 13–31 m below ground level as most of these regions are in the hilly area. Around 90% of the regions have groundwater availability within 10 m below ground level in both post-monsoon and pre-monsoon sessions, which shows that the groundwater conditions of the area are on a safer side to exploitation. Still, the excess flood water can be used for aquifer recharge as the bore well-based irrigation plans are advancing.

5. MANAGEMENT OPTIONS

The current scenario of the Wainganga basin is critically analyzed and it was observed that the area requires an immediate planning strategy to avoid resource privation. The key issues related to the basin are summarized in Table 5.

The LULC, rainfall, runoff, and groundwater parameters are interconnected to each other so that any changes in one will directly imbalance the system. Starting from the LULC, re-designing the land use to its already existing land-cover form by returning the anthropogenic intrusions can improve sustainability. A minimum of 33% of forest cover should be maintained to maintain the ecological balance of the system. Also, increasing the vegetation cover can improve the infiltration rate and

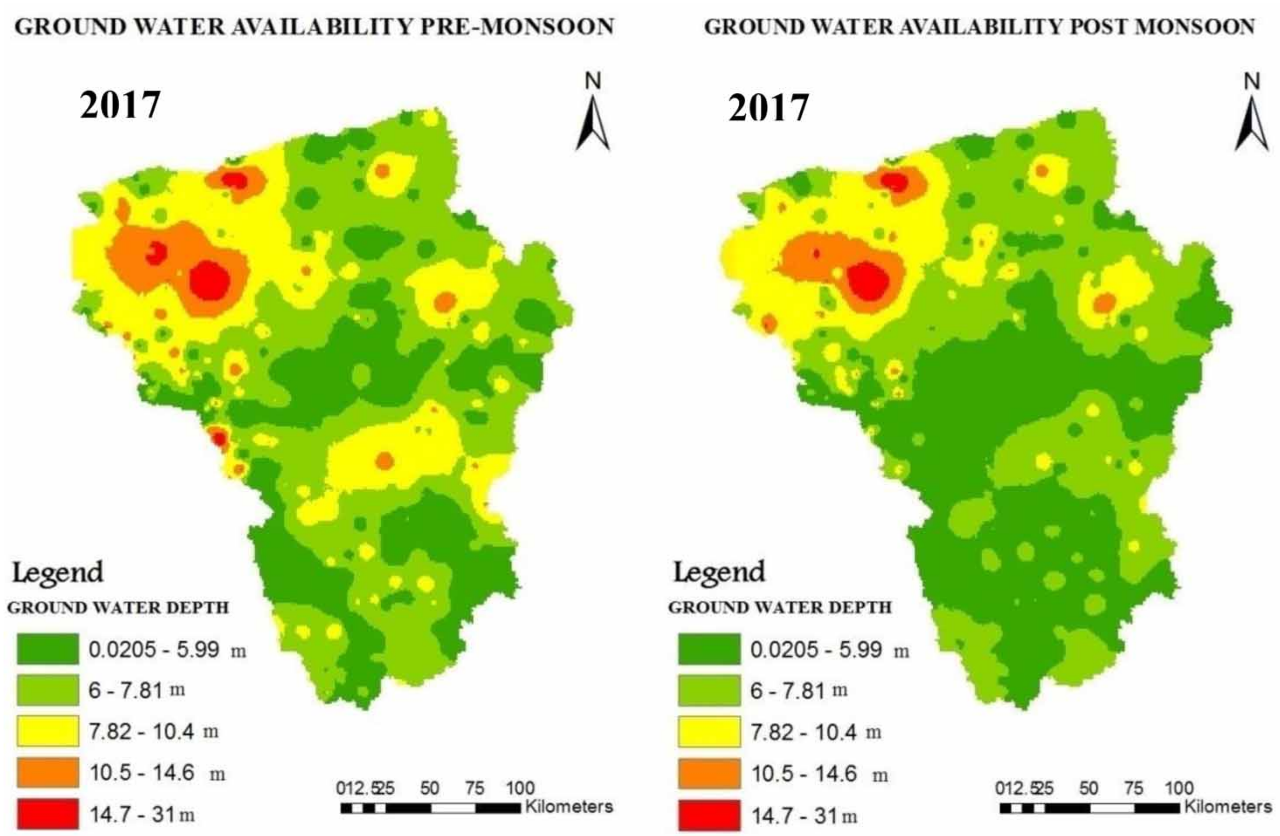

Figure 4 | Groundwater availability map of Wainganga basin before and after the monsoon for the year 2017.

Table 5 | Summary of watershed analysis with possible solutions

Parameter	Current scenario	Impact	Solution
Land use-land cover	Increased waste-land and decreased forest cover and water bodies	Increased runoff and decrease in infiltration rate	Re-designing landscapes to their natural pattern
Groundwater	Rapid draw-down in groundwater levels due to increased demand for agricultural needs	Drying of wells and other surface water bodies	Channeling excess runoff to aquifer recharge
Rainfall	Decreasing/no trend scenario with an increasing trend of peak rainfall events	Increased events of flash floods	Afforestation can help in rainfall and will reduce carbon emissions
Runoff	Increase in runoff rate because of the mismanagement of land-use practices	Sedimentation and topsoil erosion and reduce the base flow	Reduce the percentage of impervious areas and maintain the natural vegetation can trap runoff to a greater extent

reduce runoff. For a flood-prone domain like the Wainganga basin, there is a possibility of a 'Floodwater spreading system' which allows the flood water to sustain and percolate to the aquifer through hydraulic structures like diversion dams, conveyance paths, and water gateways (Hashemi *et al.* 2015). Groundwater replenishment can help in the augmentation of base-flow and surface water bodies.

6. CONCLUSIONS

The rainfall-runoff relationship, LULC variations, rainfall trend scenario, and groundwater status of the Wainganga basin was analyzed as a prerequisite to prepare a watershed management plan for the study area. The applicability of remote sensing in the topographical and climatological detailing of the Wainganga basin was analyzed and apprehended. Being in the moderate rainfall zone, the region is having flood events at times that affect the agrarian livelihood. The main points from the study are highlighted below:

- Runoff quantification using ArcSWAT shows that around 33% of the rainfall is getting converted to runoff. The sensitivity analysis of the model proved that CH-K2, HRU_SLP, GW_REVAP parameters are increasingly influencing the surface runoff in the basin.
- There is a critical rainfall scenario existing in the region with no significant trend observed in the future but with increased chances of peak rainfall events. There are chances of flash floods and heavy storm events which have to be managed using proper mitigation measures. There is the possibility of water shortages in near future due to escalating demands and depreciating rainfall trends which cannot be disregarded in this context.
- The return period analysis has shown that rainfall of severity more than 1500 mm is expected every five years, resulting in a similar runoff pattern. Hence it is important to seek proper management measures to prevent this floodwater from being wasted.
- The decadal variations in the LULC parameter explicate the human intrusions involved in the mismanagement of land use patterns. Rapid impairment in the surface water bodies and deforestation clearly explains the need for resource management in the area.
- The Wainganga basin is characterized by clayey soil having a low infiltration rate which promotes the flood rate of the area. Also, the rate at which the naturally existing land cover is being converted to impervious surfaces has a negative impact on the runoff potential.
- Due to increased agricultural demands, there is an overpressure being given to the groundwater sources, but the recharge rate is quite low due to the augmented runoff generation. If not properly monitored, there could be chances of groundwater drought.
- The findings of the study can be used to prepare a master plan for the basin to overcome the damages of the flood. A proper manifestation regarding the availability of resources and demands can help the existing agrarian crisis and farmer suicides in the study area. Proper measures to store the floodwater should be facilitated so that it can be used during demand periods.

ACKNOWLEDGEMENT

The authors are thankful to the Department of National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur, India for providing necessary soil data and the India Meteorological Department for providing rainfall data.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Abbaspour, K. C. 2008 *SWAT Calibration and Uncertainty Programs*. A User Manual, Eawag Zurich, Switzerland, p. 20.

Alfa, B., Hasholt, B., Jørgensen, N. O. & Banoeng-Yakubo, B. 2011 Rainfall and water resources of a coastal basin of Ghana. *Journal of Hydrologic Engineering* **16** (4), 316–323.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R. & Jha, M. K. 2012 Swat: model use, calibration, and validation. *Asabe* **55** (4), 1491–1508. https://doi.org/ISSN 2151-0032.

Bloom, D. E. 2011 *Population Dynamics in India and Implications for Economic Growth*. WDA-Forum, University of St. Gallen, St. Gallen, Switzerland.

Central Groundwater Board 2000 *Central Ground Water Board Ministry Of Water Resources Guide On Artificial Recharge, New Delhi*.

Fadil, A., Rhinane, H., Kaoukaya, A., Kharchaf, Y. & Bachir, O. A. 2011 Hydrologic modeling of the bouregreg watershed (Morocco) using GIS and SWAT model. *Journal of Geographic Information System* **3** (4), 279–289. https://doi.org/10.4236/jgis.2011.34024.

Goswami, M. & Rabha, D. 2020 *Trend Analysis of Ground-Water Levels and Rainfall to Assess the Sustainability of Groundwater in Kamrup Metropolitan District of Assam in Northeast India*.

Hashemi, H., Berndtsson, R. & Persson, M. 2015 Artificial recharge by floodwater spreading estimated by water balances and groundwater modeling in arid Iran. *Hydrological Sciences Journal* **60** (2), 336–350.

Himanshu, S. K., Pandey, A. & Patil, A. 2018 Hydrologic evaluation of the TMPA-3b42v7 precipitation data set over an agricultural watershed using the SWAT model. *Journal of Hydrologic Engineering* **23** (4), 05018003.

Jha, T. N. 2020 Population explosion and its remedial steps. *Journal of HR, Organizational Behaviour and Entrepreneurship Development* **3** (3), 20–23.

Karcher, S. C., VanBriesen, J. M. & Nietch, C. T. 2013 Alternative land-use method for spatially informed watershed management decision making using SWAT. *Journal of Environmental Engineering* **139**, 1413–1423. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000770.

Khazaei, M. R., Zahabiyoun, B. & Saghafian, B. 2012 Assessment of climate change impact on floods using weather generator and continuous rainfall-runoff model. *International Journal of Climatology* **32** (13), 1997–2006.

Madhurima, C. & Banerjee, A. 2013 Forest degradation and livelihood of local communities in India: a human rights approach. *Journal of Horticulture and Forestry* **5** (8), 122–129.

Mishra, S. 2006 Farmers' suicides in Maharashtra. *Economic and Political weekly* 1538–1545.

Nair, S. C. & Mirajkar, A. B. 2019 Understanding the Impact of Land Use – Land Cover Changes in the Climatic Variability of Wainganga Basin, Central India. In: Scott, G. F. & Hamilton, W. (eds). *World Environmental and Water Resources Congress 2019: Groundwater, Sustainability, Hydro-Climate/Climate Change, and Environmental Engineering*. American Society of Civil Engineers, Reston, VA, pp. 356–365.

Nair, S. C. & Mirajkar, A. B. 2020 Spatio–temporal rainfall trend anomalies in Vidarbha region using historic and predicted data: a case study. *Modeling Earth Systems and Environment* **7** (1), 503–510.

Nair, S. C. & Mirajkar, A. 2021 Land use-land cover anomalies and groundwater pattern with climate change for Western Vidarbha: a case study. *Arabian Journal of Geosciences* **14** (6), 1–9.

Nash, J. E. & Sutcliffe, J. V. 1970 River flow forecasting through conceptual models part I – A discussion of principles. *Journal of Hydrology* **10** (3), 282–290.

Ozturk, I., Erturk, A., Ekdal, A., Gurel, M., Cokgor, E., Insel, G., Pehlivanoglu, E., Ozabali, A. & Tanik, A. 2013 Integrated watershed management efforts: case study from Melen Watershed experiencing interbasin water transfer. *Water Science and Technology: Water Supply* **13** (5), 1272–1280.

Pan, S., Liu, D., Wang, Z., Zhao, Q., Zou, H., Hou, Y. & Xiong, L. 2017 Runoff responses to climate and land use/cover changes under future scenarios. *Water* **9** (7), 475.

Patil, G. B., Nagaraju, M. S. S., Prasad, J. & Srivastava, R. 2010 Characterization, evaluation, and mapping of land resources in Lendi watershed, Chandrapur district of Maharashtra using remote sensing and GIS. *Journal of the Indian Society of Soil Science* **58** (4), 442–448.

Prasad, Y. S., Rao, B. V. & Surinaidu, L. 2020 Groundwater flow modeling and prognostics of Kandivalasa river sub-basin, Andhra Pradesh, India. *Environment, Development, and Sustainability* **23** (2), 1823–1843.

Rao, K. N., Narendra, K. & Latha, P. S. 2010 An integrated study of geospatial information technologies for surface runoff estimation in an agricultural watershed, India. *Journal of the Indian Society of Remote Sensing* **38** (2), 255–267.

Resmi, S. R., Patel, P. L. & Timbadiya, P. V. 2020 Impact of land use-land cover and climatic pattern on sediment yield of two contrasting sub-catchments in Upper Tapi Basin, India. *Journal of the Geological Society of India* **96** (3), 253–264.
Ryu, J., Jang, W. S., Kim, J., Lee, G., Yoon, K., Kim, Y. S. & Lim, K. J. 2018 Development and evaluation of ArcGIS based watershed-scale L-THIA ACN-WQ system for watershed management. *Water Science and Technology: Water Supply* **18** (4), 1206–1221.
Sharma, P. J., Loliyana, V. D., Resmi, S. R., Timbadiya, P. V. & Patel, P. L. 2018 Spatiotemporal trends in extreme rainfall and temperature indices over Upper Tapi Basin, India. *Theoretical and Applied Climatology* **134** (3), 1329–1354.
Shi, P., Hou, Y., Xie, Y., Chen, C., Chen, X., Li, Q. & Srinivasan, R. 2013 Application of a SWAT model for Hydrological Modeling in the Xixian Watershed, China. *Journal Of Hydrologic Engineering* **18**, 1522–1529. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000578.
Shin, H. S. 2007 Water resource policies and management in Korea. *Water Science and Technology: Water Supply* **7** (2), 49–56.
Simin, Q., Weimin, B., Peng, S., Zhongbo, Y., Peng, L., Bo, Z. & Peng, J. 2012 Evaluation of runoff responses to land-use changes and land cover changes in the Upper Huaihe River Basin, China. *Journal of Hydrologic Engineering* **17** (7), 800–806.
Singh, C. K. & Katpatal, Y. B. 2017 A GIS based design of groundwater level monitoring network using multi-criteria analysis and geo-statistical method. *Water Resources Management* **31** (13), 4149–4163.
Thomas, T., Jaiswal, R. K., Galkate, R. & Singh, S. 2009 Development of a rainfall-recharge relationship for a fractured basaltic aquifer in central India. *Water Resources Management* **23** (15), 3101–3119.
Van der Gun, J. & Lipponen, A. 2010 Reconciling groundwater storage depletion due to pumping with sustainability. *Sustainability* **2** (11), 3418–3435.
Varalakshmi, V., Venkateswara Rao, B., SuriNaidu, L. & Tejaswini, M. 2014 Groundwater flow modeling of a hard rock aquifer: a case study. *Journal of Hydrologic Engineering* **19** (5), 877–886.
Zamani, R., Akhond-Ali, A. M., Ahmadianfar, I. & Elagib, N. A. 2017 Optimal reservoir operation under climate change based on a probabilistic approach. *Journal of Hydrologic Engineering* **22** (10), 05017019.
Zoltay, V. I., Vogel, R. M., Kirshen, P. H. & Westphal, K. S. 2010 Integrated watershed management modeling: generic optimization model applied to the Ipswich River Basin. *Journal of Water Resources Planning and Management* **136** (5), 566–575.

First received 12 July 2021; accepted in revised form 8 November 2021. Available online 19 November 2021