Songklanakarin J. Sci. Technol.
45 (1), 113–120, Jan. – Feb. 2023

http://www.sjst.psu.ac.th

Original Article

Morphometric analysis and hydrological inferences for water resource management in Warana River basin of Maharashtra, India, using remote sensing and GIS

Suraj Kalgonda Patil[1] and Tejaswini Nikhil Bhagwat[2]

[1] *Department of Civil Engineering,*
DKTEs Textile and Engineering Institute, Ichalkaranji, Maharashtra, India

[2] *Department of Studies in Civil Engineering,*
University B.D.T. College of Engineering, Davangere, Karnataka, India

Received: 23 July 2022; Revised: 9 December 2022; Accepted: 25 December 2022

Abstract

Morphometry of a basin's reaction to a particular hydrology, in particular in river basins where agriculture is the dominant industry, offers knowledge for watershed management. In order to gain an understanding of the hydrological situation for the Warana River basin as a case study location in Maharashtra, an attempt was made to comprehend the morphometric features. Geoprocessing methods in QGIS 3.16 were used to calculate the morphometric parameters. Seventh-order Warana River basin has a dendritic drainage pattern with high stream frequency (2.99/km), infiltration number (7.22), and drainage density (2.41 km/km^2), indicating high runoff potential; and a low Constant of channel maintenance (0.41) and lineament density (0.20 km/km^2), indicating moderate recharge potential. The basin has a moderate flood and recharge property, according to the interrelationship among the morphometric factors. The Warana River basin has regular floods, according to the flood frequency analysis done for the Shigaon River gauging station. Decadal time scales for water table variations revealed moderate to high recharge characteristics. The study's conclusions can be used to categorize river basins for future developments and for the management of water resources, as well as to choose the best sites for water-conservation infrastructure, such as check dams, percolation tanks, and artificial groundwater recharge.

Keywords: remote sensing, GIS, morphometry, drainage characteristics, quantitative geomorphology, groundwater fluctuations, irrigation water management

1. Introduction

The uneven distribution of water resources over space and time in arid and semi-arid regions forces one to create, plan, develop, and manage the resources (Bhaskar, Parida, & Nayak, 1997). Knowledge of the drainage pattern is a necessary precondition for analyzing the basin hydrology using morphometric parameters (Rajasekhar, Raju, Sudarsana, & Siddi, 2020). Drainage basin morphometry reflects the basin's distinctive hydrological state, environmental function, geology, and relief (Reddy, Maji, & Gajbhiye, 2004). Watershed morphometric appearances (Nag, 1998; Vittala, Govindaih & Gowda, 2004) and groundwater resource potential (Sreedevi, Owais, Khan, & Ahmed, 2009; Sreedevi, Subrahmanyam, & Ahmed, 2004) were used to characterize watersheds. Drainage features can be utilized to evaluate the basin's potential for surface and ground water because ground and surface waters are complementary components. The macro and micro levels of watershed management are therefore influenced by quantitative drainage network studies (Jensen, 1991; Sarangi, Madramootoo, & Singh, 2004). Drainage characteristics, in combination with geomorphology and geology, provide insight into basins, for collaborative water resource management (Esper, 2008). Morphometry is a

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*Corresponding author
Email address: patilsuru@gmail.com

technique for locating groundwater resources by analyzing diverse landforms and drainage systems (Adhikari, 2020). Recent years have seen the successful use of satellite data and Geographical Information Systems (GIS) to provide relevant data on spatial changes in drainage features for watershed management (Das & Mukherjee, 2005). Water management planning and operation strategies of the basin in a watershed are also determined by characteristics of the basin. Understanding the character of rock types and geologic structures in the construction of stream networks can be aided by learning the nature and category of drainage patterns, as well as by a quantitative morphometric analysis. Surface water harvesting and watershed management plans benefit greatly from morphometric studies of the basin area (Gidey *et al.*, 2021; Jahan *et al.*, 2018; Rai *et al.*, 2019).

2. Study Area

The River Warana (16° 47' 00"N to 17°15'15" N and 73°30'45" E to 74°30'00" E), a tributary of River Krishna, begins in the Sahyadri range in Patan Taluka, Satara District, Maharashtra, India, and runs southwest for 160 km before joining and pouring its waters to River Krishna at Haripur near Sangli (Figure 1). In the western part of the Deccan Plateau, the river drains a total area of 2,095 sq km. The eastern section of the basin is less mountainous than the western part and has a flat rolling landscape. The basin is located in the Western Ghats' rain-shadow zone and has a moderate climate (source: IMD, Pune) with three distinct seasons: monsoon (June to September), winter (October to January), and summer (February to May).

2.1 Climate, Geology, and Soil

The river basin has a wide range of rainfall patterns. It ranges from 600 mm upstream to 4000 mm in the ridges. Between June and September, 85 percent of the rain falls. The temperature in the basin area is moderate, ranging between 20 and 30 degrees Celsius in the winter and up to 45 degrees Celsius in the summer.

The Warana River basin is located in south India's Deccan Trap volcanic area. Laterites and bauxites cover the flat tops of the Warana basin's high plateau in the western area. The colluvium can be found near the base of steep scarps and on hill slopes. The lateritic scree can be seen in the basin's higher reaches. The terrain was tinted red due of the gravel and colluvium. Hard massive basalts have been coated in the eastern half of the basin by in-situ weathering material, also known as moorum, which is dark red-brown cream in color.

Laterite soils are dark red in color and dominate in the basin's extreme western section, which receives a lot of rain. Red soils are the products of weathering of basalts, red boles, and are partly mixed by lateritic material. Black cotton soils can be found primarily in the second and third segments of the main River Warana, notably along the river's banks and on flat structural terraces (Figure 2).

3. Material and Methods

The Warana River basin's morphometry is examined using open-source Quantum Geographical Information Systems (QGIS) 3.16 software (Figure 1). A scale of 1:50,000 was used to digitize the river basin and its drainage network using Survey of India topographic sheets 47G/12, 47G/6, 47H/13, 47K/4, 47L/1, 47L/5, and 47L/9. A 30 m digital elevation model from the Shuttle Radar Topographic Mission (SRTM) was imported using USGS Earth Explorer (Figure 2). The parameters for the aerial and relief components were established. A digital database for drainage networks was created in order to conduct additional morphometric study. The drainage characteristics were computed utilizing the conventional methods (Adhikari, 2020). Locating lineaments and examining their orientations required the use of the Linear Imaging Self Scanning Sensor (LISS III) dataset from the Resourcesat-1 Indian remote sensing satellite. With daily annual maximum peak values of

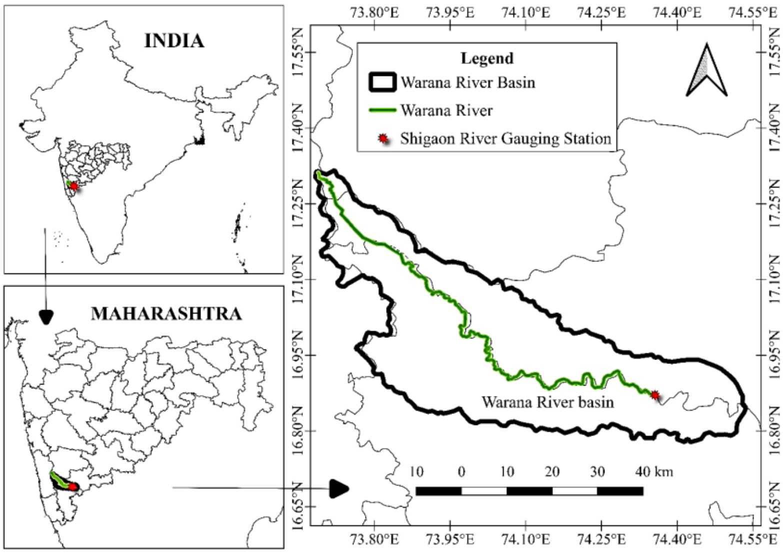


Figure 1. Location of the Warana River basin in Western Ghat region’s rain-shadow zone has a moderate climate (source: IMD, Pune, Maharashtra, India)

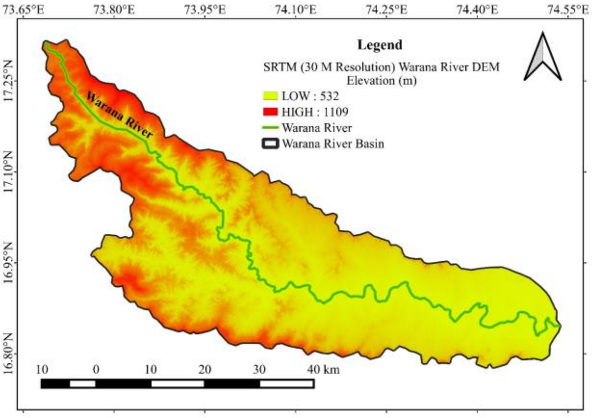


Figure 2. Shuttle Radar Topographic Mission (SRTM) (30 m Resolution) digital elevation model of Warana River basin

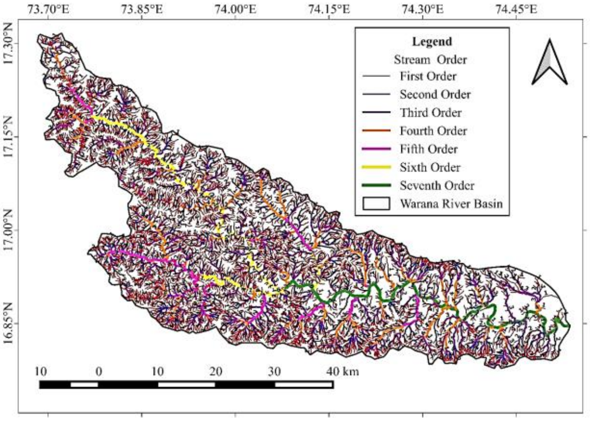


Figure 3. Stream order map by Strahler method for the Warana River basin

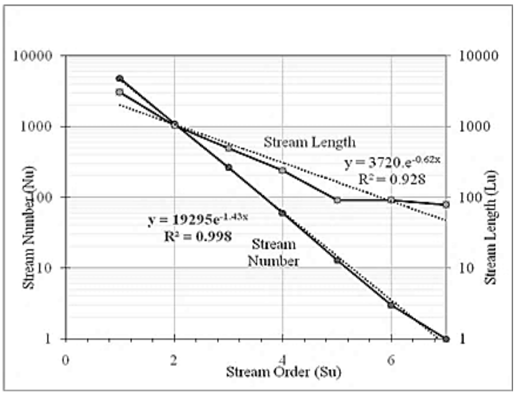


Figure 4. Plot of Stream Order (Su) v/s Stream Number (Nu) for the Warana River basin

25 years, the flood frequency curve was plotted using the normal distribution approach (1986-2010). Data from dug wells over a ten-year period are used to create maps of the groundwater table's pre- and post-monsoon fluctuations for the basin (2007–2016).

4. Morphometry

4.1 Basin linear aspects

4.1.1 Stream order (Su) and stream length (Lu)

Streams usually start with low resistance, either by creating valleys whose rock is readily erodible or by following a steeper slope gradient. The Warana River is a 7th order stream (Figure 3) (Table 1) (Strahler, 1964). Stream order is a function of the proportional size of streams. This suggests a well-drained basin with a dendritic structure (Figure 3). The average stream length for the first order basin tends to be larger, whereas fourth and fifth order streams are shorter in length (Figure 4). This indicates that the location has a steep incline upstream and a gentle incline downstream.

4.1.2 Bifurcation ratio (Rb)

An important statistic for evaluating the stages of river development is the bifurcation ratio, which is calculated by dividing the number of streams in the Nth order by the N+1th order (McCullagh, 1978). In an aged basin with even relief, there is orderly stream development and a relatively constant bifurcation ratio (Pakhmode, 2003). Although the bifurcation ratio differs from order to order, Horton's stream number law is based on the fact that it is relatively constant across the basin. Strahler and Schumm proposed using the weighted bifurcation ratio, as a result. Any variation from the mean bifurcation ratio in any of the orders indicates a drainage irregularity that is crucial for watershed management.

The Average of Bifurcation Ratio is utilized to calculate Mean Bifurcation Ratio (Rb_m), and results are summarized. The Warana River basin's mean bifurcation ratio is 4.15 (Table 1), indicating that geological formations did not affect drainage patterns (McCullagh, 1978). A bifurcation ratio is a crucial representative characteristic of a drainage basin because it controls the volume of flow after an unexpected heavy rain. Low bifurcation ratios are generated by the stream's branching being constrained by the relatively moderate slope (low relief) and correspondingly hard rock formations. When almost uniform and systematic stream branching patterns exist, which is caused by the underlying geological condition, uniform bifurcation values will be found (Manu & Anirudhan, 2008).

4.2 Aerial aspects of basin

4.2.1 Elongation ratio (Re)

Elongation ratio (Re) is defined as the ratio of the diameter of a circle with the same area as the basin to the longest basin length (Schumm, 1956). The elongation ratio (Re), which normally ranges from 0.6 to 1.0, is influenced by geology and climate. While values between 0.6 and 0.8 are related to significant relief and a steep ground gradient, values close to 1.0 are linked to little relief (Strahler, 1964). Three categories of values are established: round (>0.9), oval (0.9-0.8), and elongated (0.7) (Nyamathi & Kakkalameli, 2018). The Warana River basin's Elongation Ratio is 0.59 (Table 2), which displays the basin's considerable elongation (Chopra, Dhiman & Sharma, 2005).

Table 1. Drainage characteristics of Warana River basin

Stream Order (Su)	Number of Streams (Nu)	length of Stream (Lu) (Km)	Bifurcation Ratio (Rb)	Mean of Stream Length (Lu/Nu)	Ratio of Stream Length (Lu/Nu)
I	4828	3033.00	4.39	0.63	2.95
II	1101	1029.15	4.20	0.94	2.08
III	262	494.52	4.37	1.89	2.06
IV	60	240.09	4.62	4.00	2.62
V	13	91.82	4.33	7.06	1.01
VI	3	90.93	3.00	30.31	1.17
VII	1	77.67	NA	77.67	NA
Total	6268	5057.18	Mean (Rb_m) = 4.15		

Table 2. Morphometric parameters of Warana River basin

Basin characteristics	
Basin area (Sq.km)	2095.00
Basin perimeter (km)	343.46
Relative perimeter (km)	6.10
Length of basin (km)	104.72
Mean basin width (km)	20.10
Maximum elevation (m)	1109
Minimum elevation (m)	532
Watershed relief (m)	577
Main stream length (L) (km)	160.40
Slope of Watershed (S) (m/km)	3.60
Infiltration Number (If)	7.22
Form Factor ratio (Rf)	0.28
Length of Overland Flow (Lo) (km)	0.20
Constant of channel maintenance (C)	0.41
Elongation ratio (Re)	0.59
Drainage texture (Rt)	18.25
Circularity ratio (Rc)	0.22
Time of Concentration (Tc) (hr)	28.45
Stream Frequency (F) (no/km^2)	2.99
Drainage Density (D) (km/km^2)	2.41

4.2.2 Form factor ratio (Rf)

The form factor ratio (Rf), a dimensionless ratio of the basin's area to its square length, can be used to calculate the drainage basin's outline (Horton, 1945). A basin with a perfectly circular form has a shape factor greater than 0.785. The basin lengthens as the form factor decreases. Basins with higher form factors have larger peak discharges with shorter periods, whereas those with low form factors have reduced peak flows with long periods. The form factor ratio for the Warana River basin is 0.28 (Table 2), which illustrates the basin's elongated shape and suggests that it will take longer to reach peak.

4.2.3 Circulatory ratio (Rc)

The circulatory ratio is the ratio of the basin area to the area of a circle with the same circumference of the basin (Adhikari, 2020). It is impacted by slope characteristics and basin drainage patterns, as well as the length, frequency, and slope of streams of various orders (Strahler, 1957). The Rc ranges from '0' (least circularity) to '1' (maximum circularity). Stream frequency, geological structure, drainage density, climate, slope, relief, and other factors all influence Rc for any basin. A Rc of 0.22 (Table 2) for the Warana River basin indicates that it is significantly elongated and has a high peak flood flow during the monsoon season (Miller, 1953).

4.2.4 Drainage texture (Rt)

In drainage morphometric analysis, drainage texture is an important feature that is impacted by the terrain's soil type, infiltration capacity, and relief. There are five different drainage texture types: very fine (>8), fine (6-8), Moderate (4-6), coarse (2-4) and extremely coarse (2). The drainage texture rating for the Warana River basin is very fine (18.25) (Table 2), indicating moderate infiltration capacity, rock permeability, and sparse vegetation, all of which facilitate drainage development.

4.2.5 Stream frequency (F)

Stream frequency was defined by Horton as the ratio of number of streams (Nu) to total area of basin. It serves as an indicator for how close the drainage is. Low drainage frequency suggests greater percolation, which raises the probability of groundwater, while high drainage frequency indicates greater surface runoff (Sreedevi, Subrahmanyam, & Ahmed, 2004). It is a metric for the reaction of a drainage basin to runoff development. The Warana River basin has a high stream frequency (2.99/km) (Table 2). The frequency of streams in the study area is positively correlated with drainage density, indicating that the population of streams is growing as drainage density increases. In mountainous region, higher slopes and more rainfall will increase the stream frequency (F).

4.2.6. Drainage density (D)

The total length of streams in a catchment divided by the basin's area provides the drainage density (D), a measure of the basin's wetness. It is a typical geomorphological parameter used to connect the behavior of several watershed parameters to perform a hydrological study. It evaluates a variety of catchment parameters, such as soil, slope, climate, vegetation, lithology, land use, and the response of the watershed to rainfall (Kelson & Wells, 1989) Where impermeable rocks are present, a higher drainage density is achieved. Catchment geology, weathering resistance, and permeability of rock formations, as well as temperature and vegetation, all influence drainage density (D). Low relief, highly unaffected permeable materials with vegetation cover are found to have low drainage density (D).

In areas with poor and impermeable underlying material, little vegetation, and mountainous relief, the drainage density (D) is higher. With a drainage density (D) of 2.41 (Table 2), the Warana River basin is composed of impermeable material having moderate relief.

4.2.7 Time of concentration (Tc)

A key watershed parameter is time of concentration. The longest amount of time needed for a particle to go from a watershed divide to the watershed outlet is the time of concentration (Vittala, Govindaih, & Gowda, 2004). It is employed to determine the watershed's peak discharge. The time of concentration is determined by using the Kirpich equation. The longest watercourse in the watershed (L), its average slope (S), and a coefficient reflecting the kind of groundcover, are required inputs for the time of concentration calculation. Using QGIS 3.16, "L" and "S" are determined (Table 2). The equation (1) used to calculate time of concentration is

$$Tc=0.0662*L^{0.77}*S^{(-0.305)} \quad (1)$$

The hydrograph for the Warana River basin has a high peak and a moderate to high base period, according to the concentration time of 28.45 hours (Table 2).

4.2.8 Overland flow length (Lo)

The time it takes for rainwater to reach the ground surface before it will be localized into a particular channel is referred to as the “length of overland flow." The overland flow has been in the basin for a greater duration when it has a longer length. Indicating a well-developed drainage system with a higher slope, the shorter the flow length, the quicker surface runoff will enter the stream. Low value (<0.2), moderate value (0.2–0.3), and high value (> 0.3) are the three categories under which Lo is divided. Low Lo values represent high relief, shorter flow paths, greater runoff, and reduced infiltration, all of which raise the possibility of flash flooding (Sreedevi, Subrahmanyam, & Ahmed, 2004). The Warana River basin's overland flow is 0.20 km long (Table 2), which indicates that there is moderate runoff and moderate infiltration, making the area more susceptible to flooding.

4.2.9 Infiltration number (If)

The river basin's infiltration characteristics are expressed by the infiltration number, which is product of drainage density and stream frequency (Manu & Anirudhan, 2008). Infiltration number and runoff have a positive relationship; a lower infiltration and a higher runoff are associated with a higher infiltration number. Lower infiltration values (<6) imply stronger infiltration and very low run-off in watersheds. Infiltration values of 7-10 indicate moderate infiltration and moderate runoff potential in watersheds. Watersheds with high infiltration number (>10) have a strong runoff potential and very low infiltration. The Warana River basin's infiltration number is 7.22 (Table 2), indicating moderate infiltration and moderate to high runoff. Under saturated soil conditions, a small amount runoff will lead to high runoff.

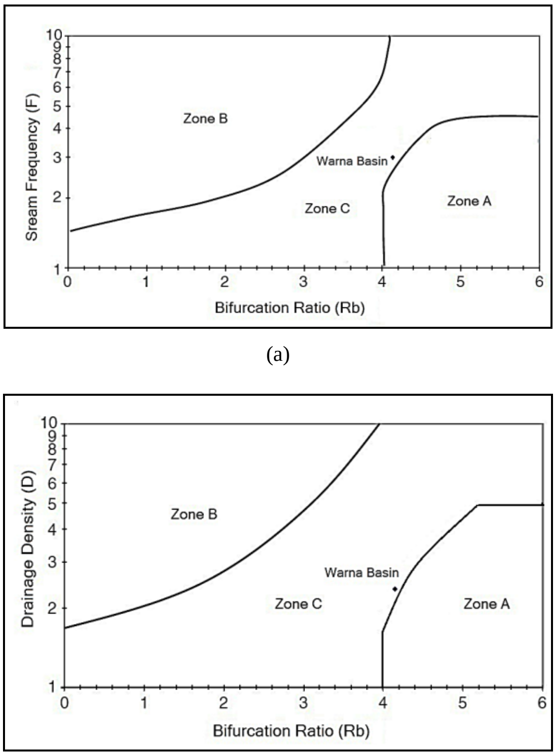
4.3 Relief parameters of the basin

4.3.1 Constant of channel maintenance (C)

According to Schumm the constant of channel maintenance is defined as the inverse of drainage density (Schumm, 1956). The lithology, relief, and climate of the basin all influence channel maintenance. It reduces when erodibility increases. Higher values of the channel maintenance constant indicate that more area is required to generate surface flow, increasing the probability that some water will be lost through evaporation, infiltration, as well as other means; a relatively low value shows that there are very few possibilities of percolation/infiltration and thus more surface runoff. The present study area's Constant of Channel Maintenance is low (0.41) (Table 2), indicating moderate permeability and moderate flood potential.

4.4 Relationships among different morphometric parameters

Basin is assessed for flood assessment and recharge potential using the relationship between stream frequency and bifurcation ratio and drainage density (Al-Saud, 2009; Bhagwat, Shetty & Hegde, 2011) (Figures 5a and 5b). The Warana River basin is classified as "Zone C" due to its stream frequency, bifurcation ratio and drainage density. This means the Warana River basin has a moderate flood potential and a moderate recharge property.



(a)

(b)

Figure 5. Potential of Warana River basin based on morphology parameters. “Zone C: Moderate to high flood property and moderate recharge property” (a) and (b)

5. Surface and Groundwater Potential

5.1 Flood frequency analysis

The Warana River basin is gauged at the location of Shigaon (Figure 1). Daily annual maximum peak values of 25 years (1986-2010) were used to plot the flood frequency curve (Figure 6). Normal distribution method was used for flood frequency analysis. For the return period, the probability factor is evaluated in percentage. In the process of Normal distribution method frequency analysis, initially data have been organized in descending order and then ranks were allotted to each value. Flood frequency curve indicates the recurrence interval of known discharge. The observation and river cross-section details at Shigaon river gauging station shows that the threshold is 1500 m^3/sec once in three years, implying that basin experiences flood once in three years.

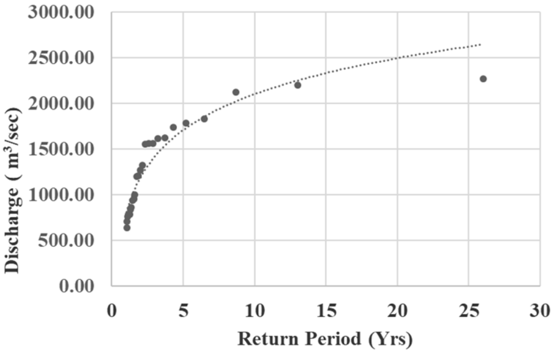


Figure 6. Flood Frequency analysis for 25 years (1986-2010) according to discharge gauged at Shigaon Warana River basin

5.2 Lineament density

Lineaments are geological formations that may be seen clearly in satellite images and range in shape from straight to curved. Specific tonal, textural, relief, and drainage qualities apply to these lineaments. They frequently indicate faults, joints, or limits between stratigraphic or lithologic deposits, and are considered to be possible sites for groundwater percolation. The lineament density is the sum of the lineaments per unit area. More percolation is possible the denser the lineaments are. Linear density in the Warana River basin is 0.20 km/km^2 (Figure 7).

5.3 Ground water table fluctuation

Precipitation in semi-arid and Hard-rock terrain, where groundwater originates in shallow weathered zones, is directly responsible for the rise in groundwater level. The eastern portion of the Warana River basin has fluctuations exceeding 5.0 m in the pre- and post-monsoon season water table fluctuation map (Figure 7), showing that groundwater in these areas is intensively used. As a result, recharging these places leads to long-term viability. The western section of the basin has a groundwater fluctuation of more than 3.0 m, indicating that it has a moderate groundwater recharge property.

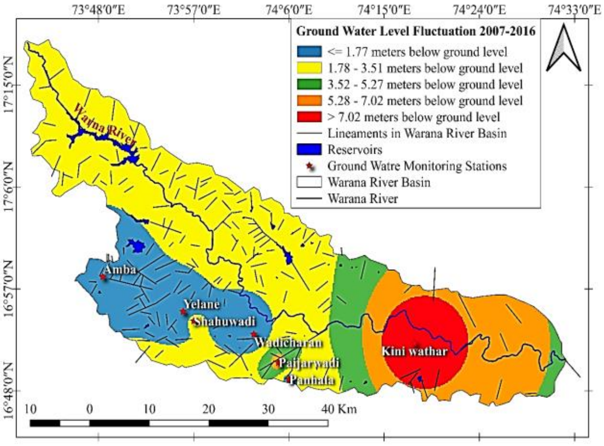


Figure 7. Groundwater table fluctuation map of pre- and post-monsoon seasons for 10 years (2007-2016) based on groundwater monitoring stations in the Warana River Basin.

6. Conclusions

Morphometric analyses of the basin region are very helpful for surface water harvesting and watershed management plans. In semiarid river basins with moderate groundwater potential and moderate to high flood hazard, irrigation water management techniques recommend the use of surface water storage facilities as both flood control and groundwater harvesting structures. Higher values of stream frequency and lineament density in the upper reaches of the Warana River basin indicate a large potential for recharging and surface water resources that might be used to build various irrigation and water-conservation projects and structures in the region. The Warana River basin's pre- and post-monsoon groundwater table fluctuations show that the basin has a moderate recharge property and that there is potential for the development of various groundwater recharge structures in the basin's lower reaches in the south-east. The Warana River basin's morphometric and flood frequency analysis suggests moderate to high flood property in the basin's upper reaches in the north-west. The study's findings will be helpful in categorizing river basins for future water resource development and management and in determining the best places to build water-conservation infrastructure like check dams, percolation tanks, and artificial groundwater recharge. Various ground water extraction schemes can also be developed, including those for irrigation at lower altitudes in the southeast of the basin. The results of the current study are useful for identifying the best methods for locating water resources, assessing the qualitative basin potential, and offering appropriate suggestions for irrigation watershed management at the upper and lower reaches of the Warana River basin. Making decisions on appropriate locations for different watershed management plans in the higher parts of the Warana River basin is also aided by this information.

Acknowledgements

Authors sincerely thank the authorities of the University B.D.T. College of Engineering, Davangere and

D.K.T.E. Textile and Engineering Institute, Ichalkaranji for the facility extended to carry out the present work and its publication. Authors also thank Hydrology Project Water Planning Division (Surface Water) Nashik for extending their support to carry out this work. Authors sincerely thank the anonymous reviewers for their critical comments and useful suggestions that helped in improving the quality of the manuscripts

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