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ORIGINAL ARTICLE

GIS-based assessment of morphological and hydrological parameters of Wainganga River Basin, Central India

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Abstract

River basin planning is a systematic approach to the specific problems related to availability and access to water for various purposes, and to simultaneously ensure the ecological integrity of a river system. GIS-based assessment of morphological and hydrological process inflows, rainfall–runoff modeling and regression equations was discussed using geographical information systems and remote sensing techniques. The Wainganga River emerges from a spring in the plains of Madhya Pradesh and has a meandering flow. The river is mostly shallow and wide in this region. The depth of the river increases in the backwaters of the Sanjay Sarovar Dam. In observation, the total number of streams of 27 sub-basins is 9472; the diverse geology implies geohydrological heterogeneity at the river basin scale. This heterogeneity could be amenable to comprehensive river-basin planning of recharge, discharge and conservation. The monthly rainfall–runoff models (*R*–*R* models) so developed are $R=1.019*P-418.20$ height in the Bhimkund catchment area, and the lowest is $R=0.532*P+194.60$ in Bamni catchment. The present study depicts the process of evaluating various morphological and hydrological parameters of the Wainganga River by applying remote sensing, geographical information system and global positioning system techniques. The data can be used for basin management, hydrological, and utilized in restoration and conservation of natural resource studies in the future.

Keywords Wainganga River · River morphometry · GPS · Drainage pattern

Introduction

Morphology of the river can be described by river morphometry, slope, DEM, channel patterns, and forms, runoff, sediment load material, discharge, depth and width of the channel (Roohi et al. 2020; Ghosh and Saha 2019; Carlston 1965; Chang 1979; Williams 1978). Morphological assessment of a river involves the valuation of the geometry of the river basin and how they respond to numerous processes and environmental settings over some time. Factors such as diversion of flow to and from channels, storage of water in reservoirs and increased use of groundwater have been discussed in many pieces of works of literature to have affected the distribution and timing of stream flow and transportation of sediments load (Grauso et al. 2020; Kuriqi et al. 2020). Hydrodynamic effects such as runoff, flow, sediment load and discharge of the basin areas arising out of the river constitute direct and very substantial changes in the structures of the rivers. River channels and their major tributaries undergo major changes in hydrological regime and morphology when the water resources of the basin began to be developed for agricultural, human beings and industrial uses.

The drainage basin is the landform most commonly analyzed in morphometry. In recent years the considerable conceptual change has taken place in geomorphology. Sophisticated quantitative techniques have been evolved to analyze the dynamic nature of the earth's form. The studies in this aspect of investigation have been initiated by Horton (1945), an eminent hydrologist and Strahler (1957, 1964) and are widely publicized by other Schumm (1956, 1963, 1968, 1969, 1972), Morisawa (1962), Leopold et al. (1960, 1964), Leopold (1964), Clarke (1966), Chorley (1966), Bridge (1977, 1978), Mark (1983) and the number of others. Morphometric analysis refers to the quantitative assessment of characteristics of the earth surface and any landform unit (Horton 1932; Sing et al. 2013; Schmidt et al. 2005; Srivastava 1997; Doke et al. 2018; Zolekar and Bhagat 2015). Studies have shown that river flows

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are related to the topographic and climatic characteristics of a drainage basin which controls the amount, time and space distributions of steam flow (Kale 1990, 2002) The morphometric analysis can be performed through measurement of linear, aerial, relief and gradient of channel network, types of channel, channel morphology, sediment yield, discharge, run-off (Gaikwad and Bhagat 2018; Pathare 2018; Sreedevi et al. 2013; Moore 1991; Mesa 2006; Rajasekhar et al. 2018; Gashaw et al. 2017; Pathare and Pathare 2020; Kudnar 2018; Sujatha et al. 2015).

The current study assessment of various morphological and hydrological parameters of the Wainganga basin in India was conducted by applying geoprocessing methods such as the ARC map module in ARC GIS 9.3 and ERDAS imagine 9.2. The stream order, bifurcation ratio, law of stream numbers, stream length ratio and the law of stream length, sinuosity indices, and geometry of basin shape, area ratio, stream frequency, average slope and relative relief area, channel pattern, sediment load, runoff, discharge, rainfall–runoff modeling, inflows, groundwater availability parameters were computed mathematically to analyze the characteristics of different morphological and hydrological parameters for sustainable development and planning of the river basin.

Study area

The Wainganga River Basin, a sub-basin of Godavari basin, is a geologically diverse region. The Wainganga River originates at an elevation of 640 m near village Partabpur (21° 57′ N and 79° 34′ E) about 20 km from the Satpura plateau and flows in a wide half-circle, bending and winding among the spurs of the hills from the west to the east of the Seoni District of Madhya Pradesh (Kudnar 2015a, b, 2017). The Wainganga basin extends over an area of 49,949.48 km^2. The extension of the Wainganga River Basin is 19° 30′ N to 22° 30′ N Latitudes and 79° 00′ E to 80° 30′ E Longitudes (Fig. 1). The river total length is 638.91 km out of 270.21 km in Madhya Pradesh and the rest, i.e. about 368.7 km in Maharashtra State. The Cairoli Hills form the watershed dividing the Wainganga basin from the Narmada basin. Near the Gundapet, the Wardha River and the Wainganga River flow together. Thereafter, it is known as the Pranhita River. The climate of the basin is characterized by hot summer from March to May with the rainy season from June to September. Nonetheless, the basin under study receives rainfall in the post-monsoon season. The upper Wainganga basin receives high rainfall; it ranges between 2000 and 4000 mm.

Methodology

The present study is based on field study. Apart from the general observation in the field, various topographical sheets were consulted for detailed morphological and hydrological parameters. GIS-based assessment of morphological and hydrological parameters of the Wainganga River Basin was carried out, using the SOI topographical maps on a 1:50,000 scale. The analysis includes river morphometry aspect (linear, areal, relief), drainage pattern, river meandering, discharge, sediment load material, etc. The drainage network of the basin was examined by results of the measures of Horton (1945) and Strahler (1964). SOI topographic maps were geo-referenced using WGS 84 datum (World Geodetic System), Universal Transverse Mercator (UTM) zone 44 N projection in ArcGIS desktop 9.3. In this study, the Wainganga River Basin was delineated and the drainage network was extracted using Cartosat-DEM (1 arcsec) in conjunction with SOI toposheets, GPS location, river hydrology including inflows, *R*–*R* Model, Regression Equation, sediment load material calculated. After completion of DEM, the flow direction was calculated for each pixel, to generate a drainage network, and the flow accumulation was taken into account, based on the flow direction of each cell (Kumar et al. 2011). Morphological and hydrological parameters were analyzed and calculated based on the formulas shown in Table 1, and also the flowchart of the methodology is illustrated in Fig. 2.

Results and discussion

The total area of the Wainganga basin is 49,949.48 km^2, and the total length of the Wainganga River is 638.91 km, of which 270.2 km lies in the Madhya Pradesh. The river flows along the border of Madhya Pradesh and Maharashtra for about 32 km. Further, it flows through Maharashtra for around 336.17 km length. Linear and aerial parameters are significant and their relationship among the basin area, stream order, bifurcation ratio (Rb), perimeter, basin length, circulatory ratio (Rc), elongation ratio (Re), drainage density (Dd), stream frequency (Fs), etc. information used on various morphometric parameters.

The River Wainganga shows dendritic pattern characteristics, and the network development in the Wainganga River is mainly controlled by structure. The basin is occupied by a comprehensive suite of sedimentary, metamorphic and igneous rocks. A major part of the basin is underlain by non-Deccan Trap rock formations, unlike most other river basins in the area which are composed of Deccan basalt rock, with a dominance of Precambrian rocks associated

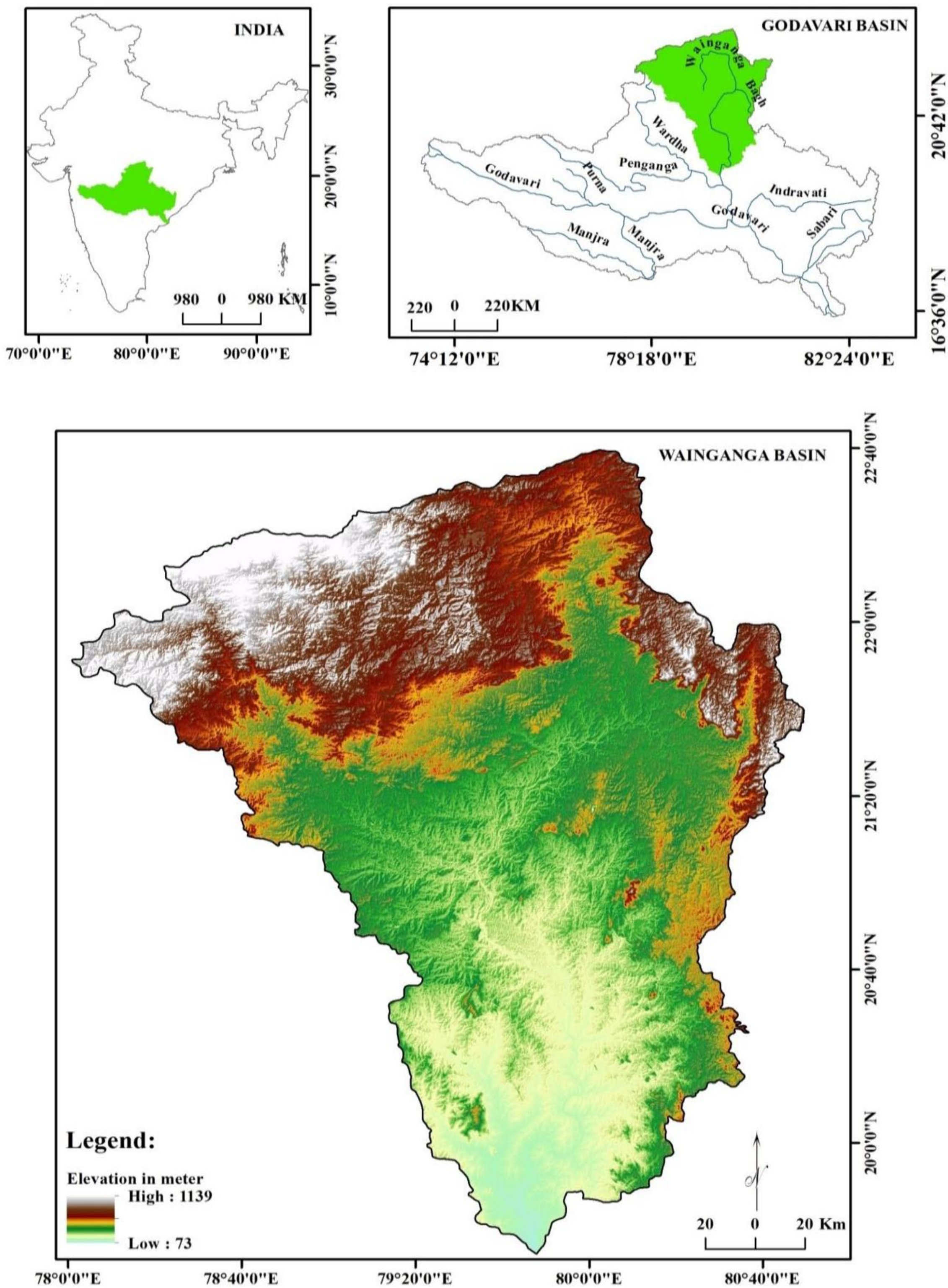
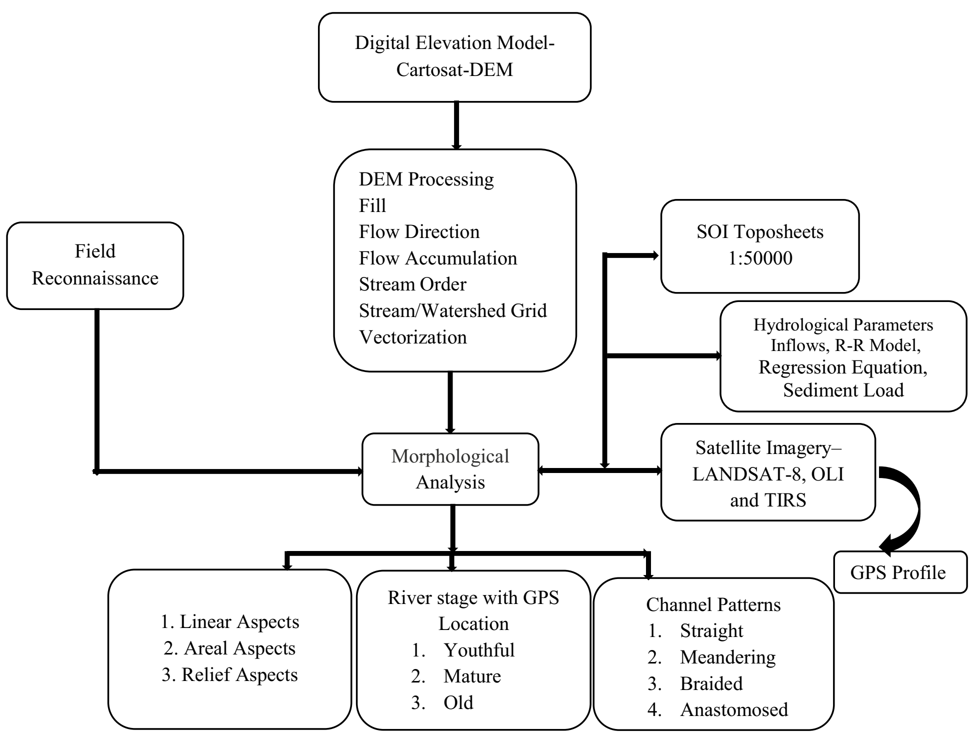


Fig. 1 Location map of the Wainganga River Basin

Table 1 Methodology adopted for computations of morphological and hydrological parameters

S. no.	Parameters	Formulae	References
1	Stream order (*U*)	Hierarchical rank	Strahler (1964)
2	Stream length (Lu)	Length of the stream	Horton (1945)
3	Mean stream length (Lsm)	Lsm = Lu/Nu	Strahler (1964)
4	Stream length ratio (RL)	RL = Lu/(Lu − 1)	Horton (1945)
5	Bifurcation ration (Rb)	Rb = Nu/Nu + 1	Schumm (1956)
6	Mean bifurcation ratio (Rbm)	Rbm = average of bifurcation ratios of all orders	Strahler (1957)
7	Drainage density (Dd)	Dd = Lu/*A*	Horton (1945)
8	Drainage texture (*T*)	*T* = Dd * Fs	Smith (1950)
9	Stream frequency (Fs)	Fs = Nu/*A*	Horton (1945)
10	Elongation ratio (Re)	Re = *D*/*L*	Schumm (1956)
11	Circularity ratio (Rc)	$Rc = 4pA/P^2$	Strahler (1964)
12	Relief	$R = H - h$	Hadley and Schumm (1961)
13	Relief ratio	Rr = *R*/*L*	Schumm (1963)
14	Discharge	$Q = w \times d \times v$	Morisawa (1985)
15	Rainfall–runoff modeling	$R = m^*P - C$	Leopold and Maddock (1953)
16	Channel sinuosity	OL/EL	Schumm (1963)

Fig. 2 Methodology



with exposure of wide-ranging lithology and age. Analysis of the stream orientation reveals that 7% streams join the mainstream the East, 5% from West, 6% from NE, 14% from SE, 19% from the north, 24% from the south, 13% from NW, 11% from SW. Most of the rivers that originate in the upland area of Deccan Plateau are sinuous in the source region (Bisen and Kudnar 2013; Rajasekhar et al. 2020).

However, the Wainganga River flows in a straight manner at the source (Fig. 2).

Morphological parameters

River morphological parameters including river morphometry, channel pattern, channel morphology, etc.

River morphometry

In the Wainganga River Basin, the fifth-order stream has the highest stream length ratio (3.78) and the sixth-order stream has the lowest value of stream length ratio (0.69). Relative relief is one of the techniques which are effectively capable of presenting the relief characteristics without considering sea level (Mangesh et al. 2013; Ray et al. 2006). In the river, the highest value of relative relief is a maximum of 1148 m and a minimum of 140 m, so relative relief is calculated as 1008 m. The grid shows the spatial relative relief height (Fig. 3). The basin total means bifurcation ratio is 3.97; it is a natural river system where uniformity is seen concerning climate, rock type and stage of development. The relative relief of study area portrays the real distribution of such variations, which has been classified into four groups: from 30 to 60 m, low relative relief area of 0.52%; from 60 to 120 m, moderately relative relief of 28.69%; from 120 to 240 m, moderately high relative relief of 58.00%; and above 240 m above the sea level, high relative relief of 12.78% (Kudnar and Rajasekhar 2020).

Length of overland flow

The length of the overland flow measure of steam typography and degree of dissection and is approximately one-half the reciprocal of the drainage density (Chorley 1969). The length of overland is strongly positively correlated with drainage density (0.19), strongly positively correlated with steam frequency (0.19 per km^2) and negatively correlated with average slope (0°–76°). The negative relationship between average slope and the length of overland indicates that the steeper the slope angles, the smaller the lengths of overland flow and vice versa (Table 2).

Sinuosity indices

The ratio of the sinuous length to the straight-line distance is channel sinuosity value for the reach (Schumm 1963). Channels with higher ratios are called meandering channels (Wolman and Miller 1964). It is clearly to be noted that the river may not have a straight course as close parallelism between the shortest straight length of a river and a length adopted by the river is a remote possibility. The sinuous course of the river measure, the river SSI ranges between 1.00 and 1.5, the meandering course is found when SSI is more than 1.5 (Table 3).

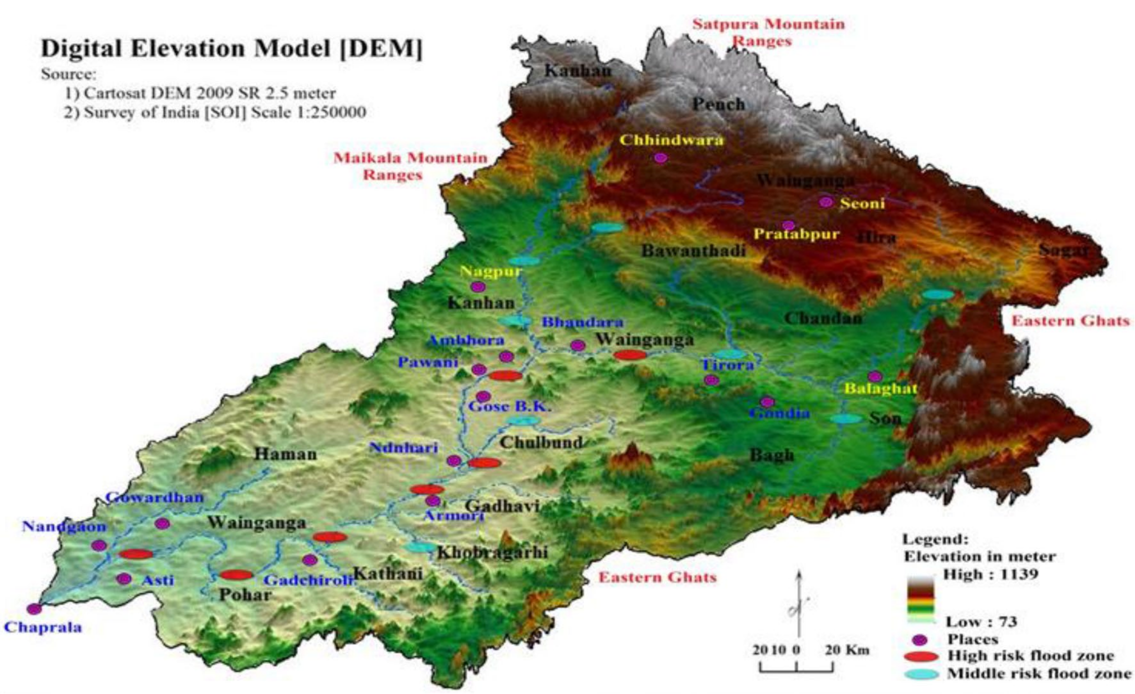


Fig. 3 Wainganga River Basin and DEM

Table 2 Length of overland flow

S. no.	River basin	Area (sq. km)	Lengths of overland flow	S. no.	River basin	Area (sq. km)	Lengths of overland flow
1	Ambi	830.37	0.08	15	Maru	727.90	0.14
2	Kanhan	7640.26	0.08	16	Sur	1004.24	0.13
3	Kathani	932.73	0.09	17	Tipagsrhi	796.49	0.08
4	Andhari	1223.88	0.09	18	Nahar	877.37	0.09
5	Bagh	2938.72	0.12	19	Pal	276.23	0.14
6	Chulbund	2537.22	0.08	20	Phuar	429.91	0.08
7	Deo	840.32	0.07	21	Pohar	874.55	0.14
8	Bawanthadi	2161.79	0.08	22	Pathari	514.29	0.14
9	Chandan	1145.29	0.08	23	Pench	4717.86	0.13
10	Haman	2078.26	0.08	24	Satti	830.85	0.09
11	Khobragarhi	200.52	0.12	25	Sagar	1065.46	0.15
12	Gadhavi	1557.23	0.07	26	Son	1428.96	0.14
13	Hira	1017.77	0.09	27	Wainganga (sub-basin)	11,160.66	0.14
14	Mal	140.39	0.16		Grand total	49,949.48	0.087

Table 3 Sinuosity indices

S. no.	River basin	CI	VI	HIS (%)	TSI (%)	SSI
1	Ambi	1.50	1.39	22.00	78.00	1.08
2	Kanhan	1.49	1.36	26.53	82.86	1.10
3	Kathani	2.41	2.17	17.15	58.41	1.12
4	Andhari	2.78	2.55	12.93	87.07	1.09
5	Bagh	2.23	1.87	29.27	70.72	1.19
6	Chulbund	1.49	1.46	6.12	96.10	1.02
7	Deo	1.76	1.73	3.89	79.06	1.01
8	Bawanthadi	1.50	1.36	28.00	87.69	1.10
9	Chandan	1.65	1.57	12.31	93.88	1.05
10	Haman	1.82	1.67	26.58	87.78	1.06
11	Khobragarhi	1.96	1.56	41.60	44.78	1.26
12	Gadhavi	1.43	1.34	20.93	73.40	1.07
13	Hira	2.23	2.08	12.20	73.47	1.07
14	Mal	1.67	1.30	55.22	50.00	1.28
15	Maru	1.70	1.35	50.00	90.81	1.26
16	Sur	1.73	1.55	24.66	87.84	1.12
17	Tipagsrhi	1.95	1.67	12.18	56.54	1.07
18	Nahar	1.98	1.89	9.19	66.29	1.05
19	Pal	1.89	1.59	33.71	57.37	1.19
20	Phuar	1.86	1.78	9.07	77.92	1.03
21	Pohar	1.77	1.60	27.07	47.95	1.11
22	Pathari	1.61	1.35	42.63	70.59	1.19
23	Pench	1.68	1.48	29.41	90.92	1.14
24	Satti	1.93	1.64	31.19	60.29	1.18
25	Sagar	1.73	1.35	52.05	68.81	1.28
26	Son	1.68	1.41	39.71	75.34	1.19
27	Wainganga (sub-basin)	1.92	1.52	43.48	56.52	1.26
Total Wainganga		2.15				

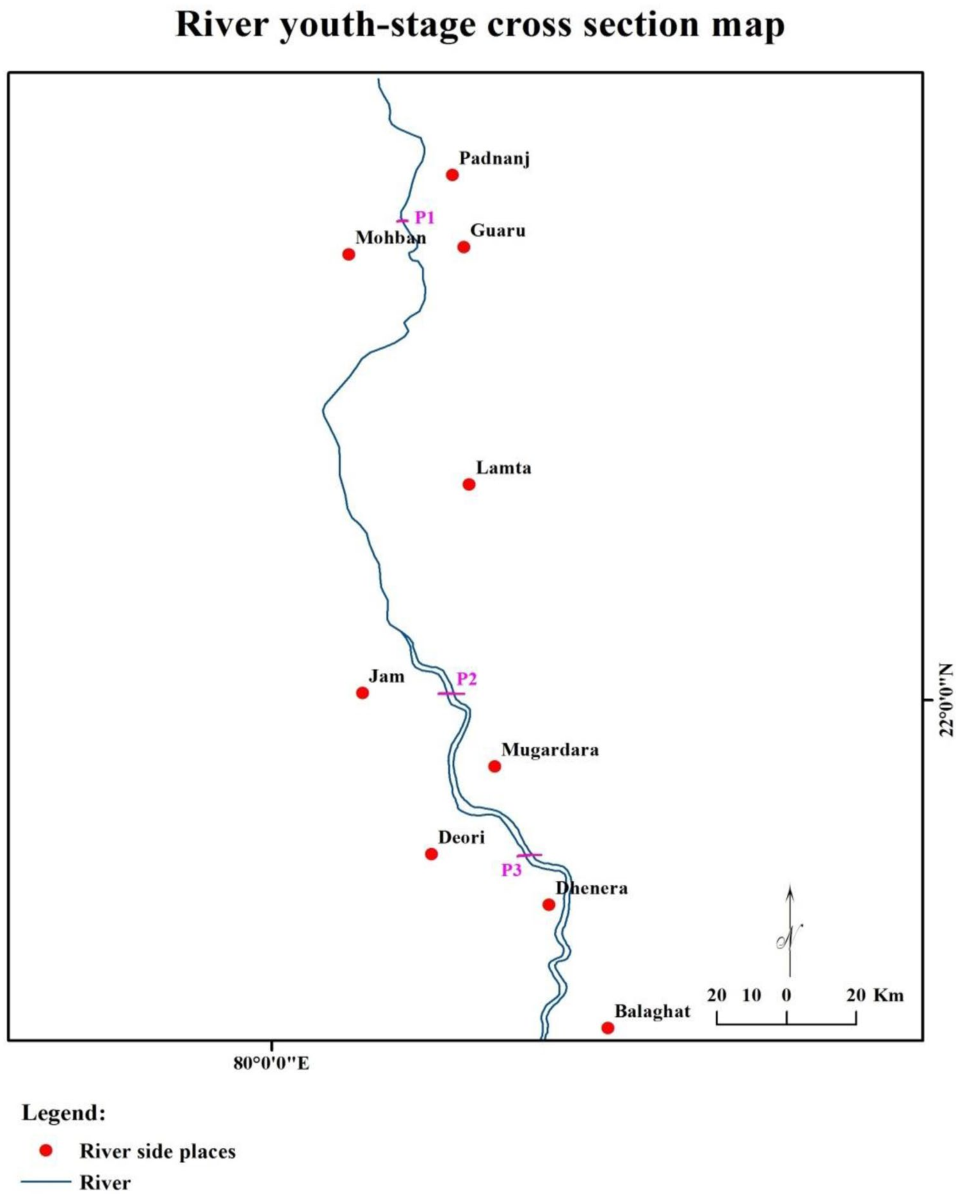


Fig. 4 River profile

River stage with GPS location

In the following, the three stages of the river, namely youthful, mature and old, are explained.

Youthful river

In the youth stage, the Wainganga River has a steep gradient, has very few tributaries and flows quickly. Its river channels erode deeper as shown in Fig. 4. Hydraulic action loosens and dislodges the rock, which further erodes near Guru Village the sides of the valley to move downslope causing the valley to become V-shaped; near Mohban waterfalls in the youthful river valley, a band of hard rock overlays a layer of soft rock. Differential erosion near Jam village occurs as the river erodes the soft rock more readily than the hard rock; this leaves the hard rock more elevated and to stand out from the river below. A plunge pool forms at the bottom and deepens as a result of hydraulic action and abrasion ((Table 4, Figs. 4, 5). The Wainganga River cross-profile changes as it moves from the upper to lower course in the river's energy and the processes that the river carries out. In the youth course, the valley and channel are narrow and deep as a result of a large amount of little and lateral vertical erosion. The sides of a river's valley in the upper course are very steep earning these valleys the nickname 'V-Shaped Valley' (Othman and Gloaguen 2014). The river's valley can be anything from a few meters to a few hundred meters in width depending on the lithology but the channel is rarely more than 6 m or 7 m

Table 4 Wainganga River cross section near Gokalpur, Khapa, Keolari (MP)

Cross-section location	GPS location		Height (Mts.)	Distance (Mts.)
Gokalpur (MP)	N 22° 38.52′	E 079° 54.46′	634	0
	N 22° 38.51′	E 079° 54.49′	625	20
	N 22° 38.48′	E 079° 54.44′	620	40
	N 22° 38.48′	E 079° 54.44′	635	60
Khapa (MP)	N 22° 40.08′	E 079° 65.64′	580	0
	N 22° 40.08′	E 079° 65.64′	565	25
	N 22° 40.08′	E 079° 65.64′	566	50
	N 22° 40.10′	E 079° 65.65′	578	60
Keolari (MP)	N 22° 37.39′	E 079° 92.24′	512	0
	N 22° 37.39′	E 079° 92.24′	504	25
	N 22° 37.41′	E 079° 92.28′	504	50
	N 22° 37.42′	E 079° 92.31′	513	75

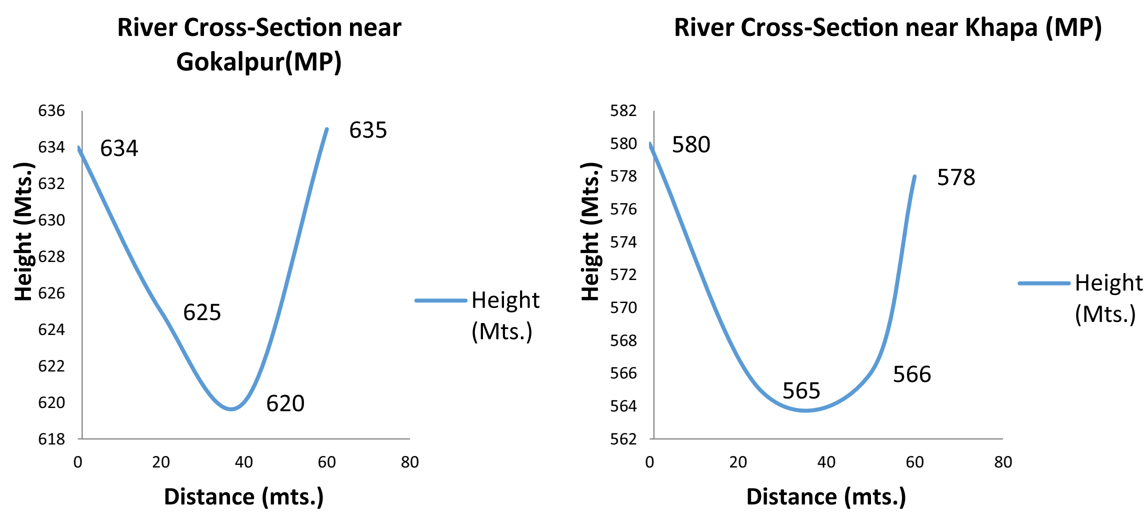


Fig. 5 River profile near Gokalpur and Khapa

wide. Archaean rocks are the oldest rock types belonging to Easter Ghat and Bengpal Groups in the river's youthful stage and covering an area of 10.6%. The Eastern Ghat Supergroup consists mostly of Khondalite: gray, red foliated garnet–sillimanite schist, with numerous brownish-red garnets. Exposed rocks in this group are cherty limestone, clay, sandstone and conglomerate exhibiting red, greenish, marly, usually sandy clay with sporadic pieces of chert; dirty white, green, fine-grained, granular, hard, compact limestone and grayish to greenish buffed, fine- to medium-grained sandstone are also observed.

Mature river

In this mature stage, the Wainganga River is a gradient slope that is less steep, has many tributaries and has more discharge than a youthful river. Its channels erode wider rather than deeper as shown in Fig. 6. Near the Khairlanji village, sediment yield is the total quantity of the particular matter reaching the outlet of a drainage basin over a fixed time frame which is found. Sediment transport processes are affected by drainage sediment type (lithology), area size, basin slope, vegetation cover, climate and human land use. Such sediment materials are found from Village Kauliwara to Bhandara as shown in Table 5, Figs. 6 and 7. The theoretical concept of the 'sediment transport ratio' captures the fact that not all of the sediment is eroded within a certain catchment that reaches out to the outlet (due to, for example, deposition on floodplains near Bhandara, Pauni). Such storage opportunities are typically augmented in catchments of superior size, thus leading to a lower yield and sediment transport ratio. The mature region is comprised of meta-basalt, phyllite, tuffaceous phyllite, carbonaceous phyllite, mica schist, cherty

Fig. 6 River profile

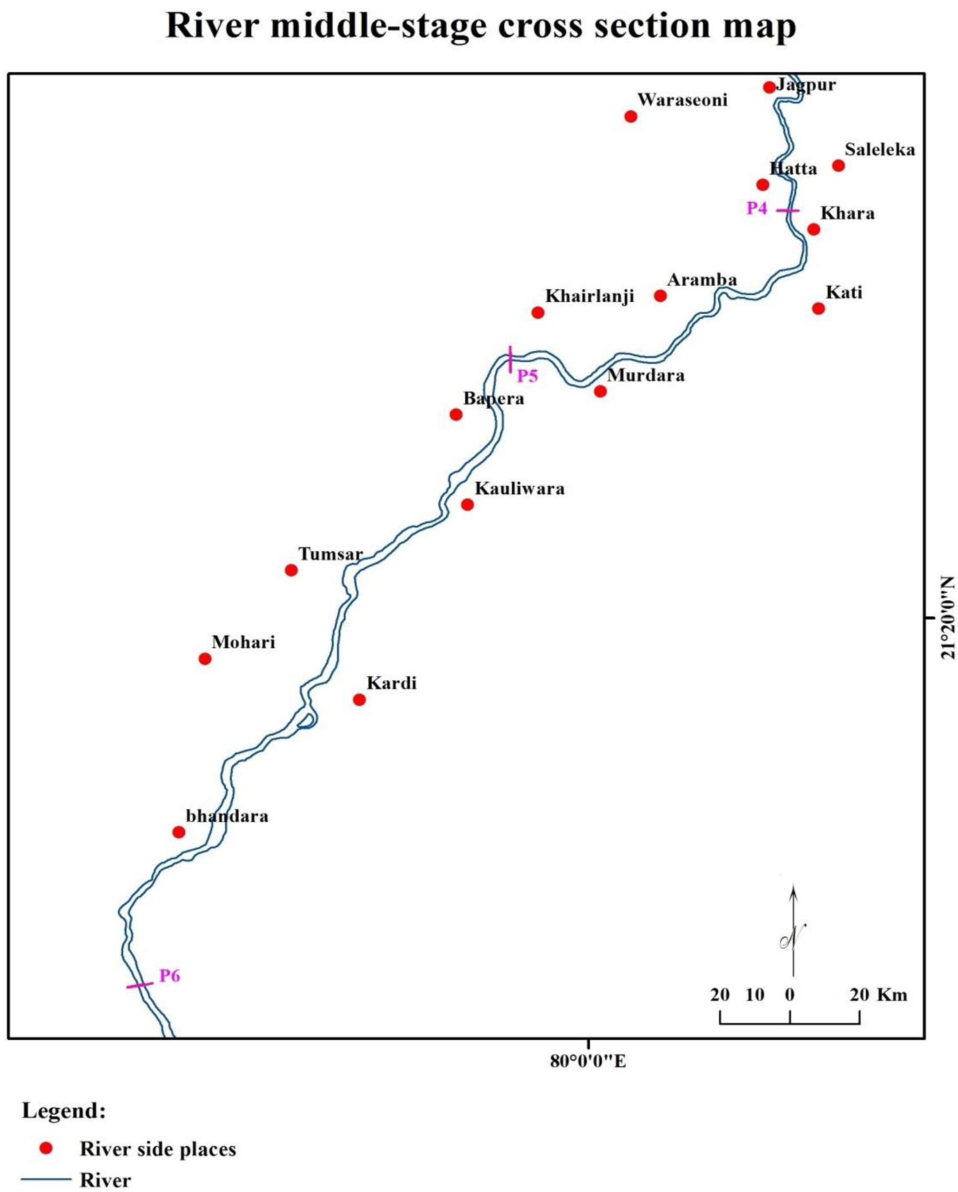


Table 5 Wainganga River cross section near Murdada (Arjuni Village) and Kardi (Sukali Village).

Cross-section location	GPS location		Height (Mts.)	Distance (Mts.)
Murdada (Arjuni Village)	N 21° 55.477′	E 079° 97.155′	282	0
	N 21° 55.479′	E 079° 97.157′	281	80
	N 21° 55.481′	E 079° 97.160′	268	160
	N 21° 55.483′	E 079° 97.163′	268	240
	N 21° 55.484′	E 079° 97.164′	269	320
	N 21° 55.486′	E 079° 97.167′	281	400
Kardi (Sukali village)	N 21° 29.206′	E 079° 77.053′	270	0
	N 21° 29.209′	E 079° 77.056′	269	95
	N 21° 29.210′	E 079° 77.059′	268	190
	N 21° 29.212′	E 079° 77.061′	266	285
	N 21° 29.215′	E 079° 77.065′	266	380
	N 21° 29.218′	E 079° 77.067′	270	475

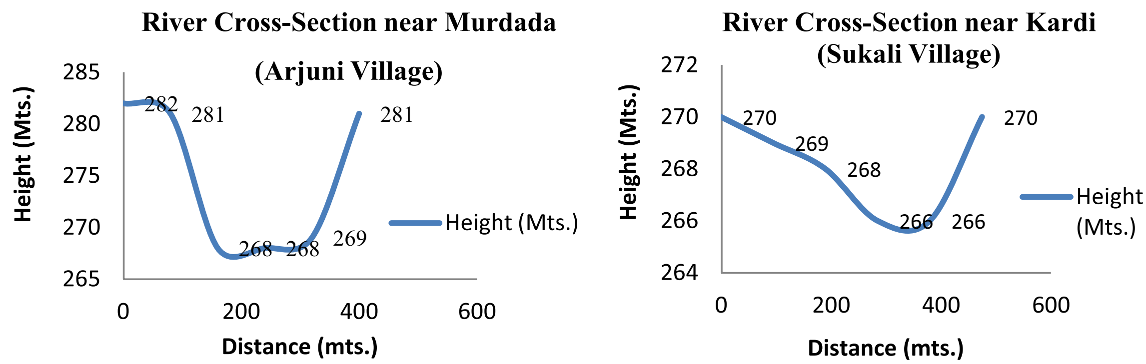


Fig. 7 River profile near Murdada (Arjuni village) and Kardi (Sukali village)

Table 6 Wainganga River's old-stage cross section

Cross-section location	GPS location		Height (Mts.)	Distance (Mts.)
Gadchiroli Mokhara (MS)	N 20° 13.298′	E 079° 92.207′	242	0
	N 20° 13.411′	E 079° 92.310′	240	100
	N 20° 13.556′	E 079° 92.422′	239	200
	N 20° 13.556′	E 079° 92.461′	239	300
	N 20° 13.644′	E 079° 92.516′	240	400
	N 20° 13.693′	E 079° 92.594′	241	510
Tarsa, Asti (MS)	N 19° 68.356′	E 079° 78.071′	210	0
	N 19° 68.366′	E 079° 78.200′	208	104
	N 19° 68.380′	E 079° 78.354′	208	208
	N 19° 68.421′	E 079° 78.526′	207	312
	N 19° 68.394′	E 079° 78.642′	208	416
	N 19° 68.441′	E 079° 78.749′	209	520

quartzite; in places, this group of rocks includes Banded Iron Formation (BIF), gritty quartzite, meta-arkose and conglomerate. Meta-basalt is earthy green in color, fine-grained, porphyritic and vesicular and amygdalar. Phyllites are gray, light greenish brown in color and show a soft, well-foliated and crenulated appearance. Mica schist has a silvery sheen with grayish to greenish-gray colors, is medium- to coarse-grained and well foliated. Cherty quartzite is thin to thickly intercalated, fine-grained and hard and appears as a compact chert band.

Old river

In this stage, the Wainganga River has a low slope with low-slung erosive energy which is found from Gadachiroli to the mouth of the river. Old rivers are categorized by floodplains shown in Table 6, Figs. 8 and 9. In the lower course, the valley is now very wide (often several kilometers) and the floodplain has augmented significantly in size. In this stage area, loamy deposits consisting of sand, silt and clay with pebbles and gravels at places with soft, unconsolidated appearance are common. Alluvial of quaternary covers an area of 619.78 sq. km. In old stages, mainly three types of basalt, namely vesicular amygdaloidal basalt, compact basalt and compound basalt, are shown. These basalts occur as alternating layers and are separated by flow top breccia with red boles or red tuffaceous horizon. Basalts are observed in a small area in the mouth of the Wainganga River and its tributaries' mouth of the Pench, Kanhan, Chandan, Bawanthadi, Sur, Ambi, Mari, Haman, Pathari, Andhari, Chulband, Gadhvi and Khobragadi.

Types of river channel patterns

The spatial relationship of all streams within a drainage system is known as the drainage pattern.The drainage pattern of the particular design in which the individual stream course collectively forms in the Wainganga River. In the river drainage patterns, an arrangement of channels is determined by hydrological and climatic variability, climate, slope, differing rock resistance, relief of the land and structural controls

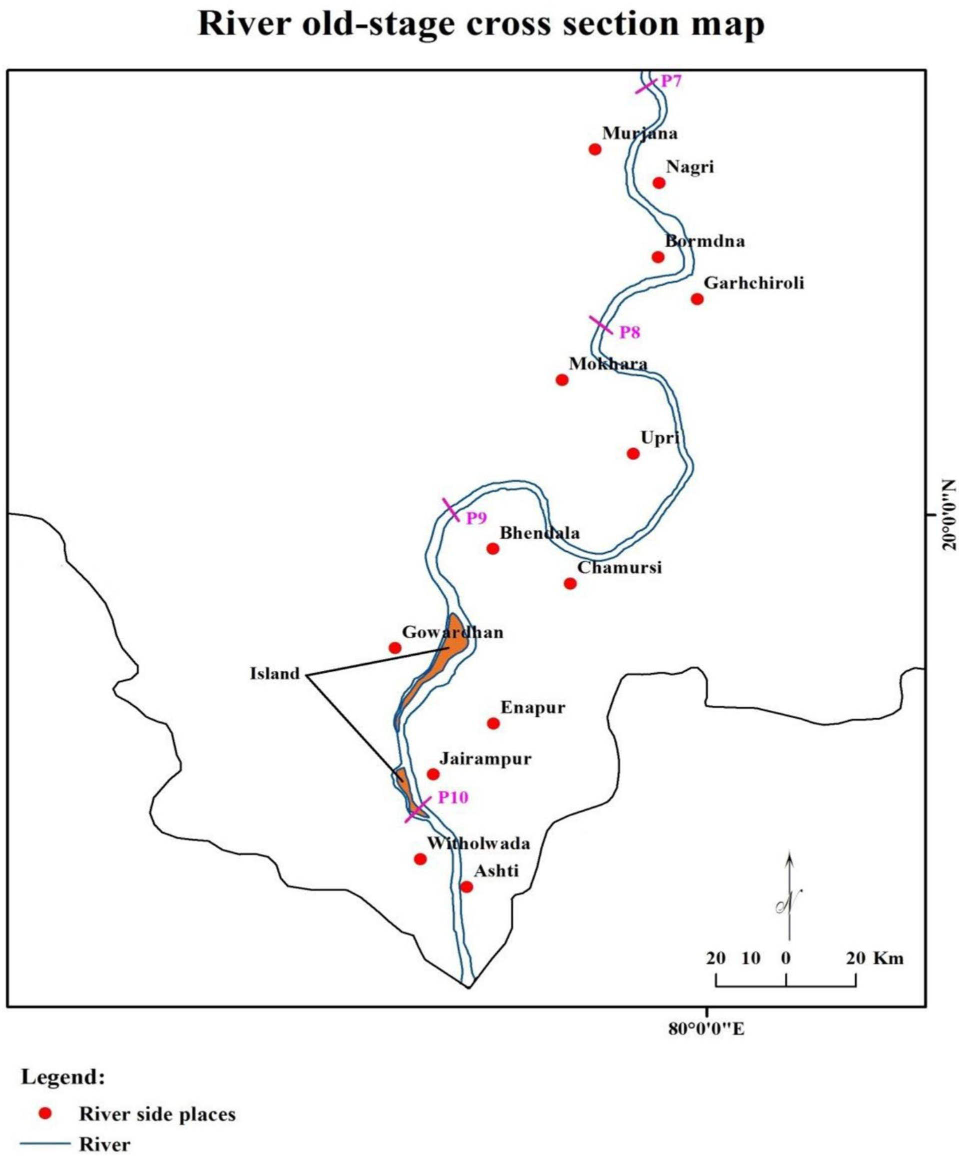


Fig. 8 River profile

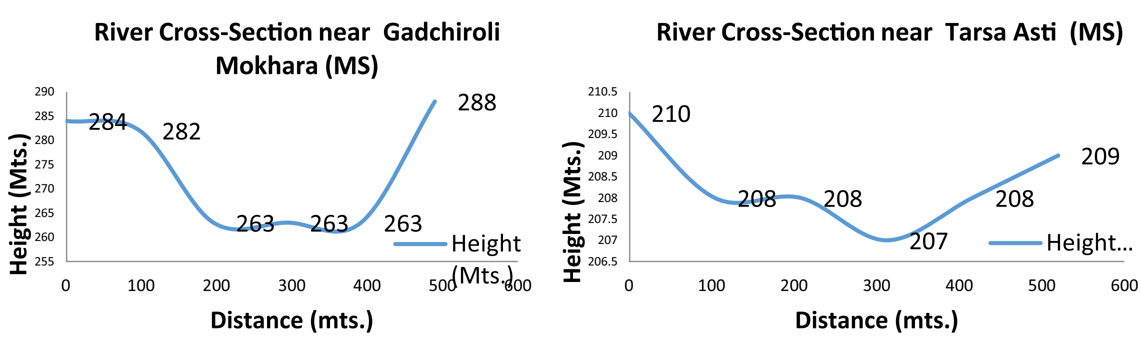


Fig. 9 River profile near Mokhara and Asti

imposed by the landscape. Based on lithology and rock formations, the Wainganga River channels may be classified into the following stages.

Straight channels

Youth stage of the Wainganga River near Padnanj to Mohban near 62 km. and Lama to Jam near 32 km. are found Straight channels it is generally erosional. Such channels are the characteristics of mountainous topography (Fig. 4) which rapidly develop pool-and-riffle sequences. Pools are spaced at about five-bed widths. The tributaries of the river in the upper part of the river emerge from relatively higher hills and therefore have a rapid flow. Despite the high rainfall in the catchment areas of these rivers, they are seasonal and quickly drain off their water into Wainganga.

Meandering channels

In the middle part of the Wainganga River shown in Fig. 6, near Jagpur, Hatta, Murdara, Kauliwara, there is a gentle slope, the degree of meandering of the channel of a river. The rivers with a single channel and sinuosity of 1.5 or more are defined as meandering streams or rivers; such channels can be observed in the course of Wainganga between Bhandara and Asti (Table 7). At Pauni Station, the reach is dominated by the alluvial cover which only leads to the incising of the right bank and formation point bar at the left bank (Slowik 2013).

In the Wainganga River Basin area, quaternary alluvial deposits consist of sand, silt, gravel, clay and are divided into the older alluvium and the newer alluvium. They overlie the older formations such as Archaeans, Gondwana and Basalt. The thickness of the alluvium varies from 6 to 35 m. Alluvium of resent to sub-resent age is found to be deposited along the rivers and their tributaries. There are many

Table 7 Meander property

S. no.	River basin	Symmetry of meander length %	Symmetry of meander height %	Symmetry of form ratio%	Repetition of symmetry %
1	Ambi	30.25	31.16	35.54	18.23
2	Kanhan	34.26	31.17	36.26	32.25
3	Kathani	27.19	32.16	22.24	19.16
4	Andhari	42.14	48.24	37.24	21.54
5	Bagh	30.15	29.22	26.25	11.15
6	Chulbund	35.15	34.14	40.00	25.00
7	Deo	36.14	35.24	35.12	20.36
8	Bawanthadi	32.15	31.17	30.24	20.24
9	Chandan	38.14	35.15	37.24	21.54
10	Haman	26.13	25.24	26.26	16.16
11	Khobragarhi	54.16	55.15	56.12	30.00
12	Gadhavi	30.16	28.25	32.16	25.00
13	Hira	35.18	35.02	36.23	20.16
14	Mal	52.16	47.60	51.41	50.12
15	Maru	55.60	57.50	58.12	42.16
16	Sur	40.15	30.14	46.23	22.24
17	Tipagsrhi	26.12	30.25	31.23	31.00
18	Nahar	30.60	36.24	32.13	15.00
19	Pal	32.25	39.14	31.16	12.00
20	Phuar	30.14	35.26	34.23	18.25
21	Pohar	40.15	48.26	41.15	33.16
22	Pathari	30.17	35.11	36.12	19.12
23	Pench	32.14	30.14	36.25	19.14
24	Satti	46.15	41.23	45.25	38.15
25	Sagar	59.63	50.21	54.20	50.24
26	Son	47.17	42.22	41.25	30.00
27	Wainganga (sub-basin)	55.23	59.62	51.21	44.00
Total Wainganga		42.14	48.24	37.24	21.54

dikes in the course of the river, e.g. at Madgi and Ambhora, where the Wainganga breaks and cuts across the rocky barriers. Due to the rocky beds and small and large bends in the river course, several whirlpools can be seen within the flow. Many deep pools have therefore been created in the riverbed, which acts as a refuge for fish during the summer months.

Braided channels

Figure 7 shows a few distinctly different channel types based on their geological structure and depositional environment near Kardi, Bhandara. Braided rivers carry fairly coarse-grained sediment down a fairly steep gradient found in Gowardhan, Jairampur (Fig. 8). In this river near Bhandara city, the mainstream of a river gets divided into numerous distributaries, which exhibit numerous channels that split off. Additionally, water discharge tends to be highly variable. According to Leopold and Wolman (1960), the braiding of a river channel begins with the deposition of a mid-channel bar or island, which bifurcates the channel and thus diverts the flow of water toward the banks having erodible materials. Channel bars formed by the deposition of the bed load of the rivers are frequently observed at Bhandara and Pauni station, whereas Ashti station is devoid of any channel bar formation. According to the Brahmankar (1996), Kanhan River also shows channel bar formation in the downstream reaches of the river before it joins the Wainganga River. The Gosekhurd Dam on the Wainganga River at Pauni acts as a huge intervention in its flow and is certain to change the river's rate of silt deposition and flooding regime. The survival of small and large pools downstream of Gosekhurd Dam is threatened. The river braids and splits in its lower regime and creates small islands. Jungaon near Mul is the biggest island within the flow of the river. At Chamorsi-Chaprala, the Wainganga takes a major turn, almost changing its southward course to a northward flow and forms a question mark like figure. The local community, therefore, refers to the river as 'Uttar-Vahini' or 'northward-flowing river.' In this segment, the river acquires great religious significance. The Wainganga River course at its tail end (in the dry months) is full of rocky deposits, and aquatic or wetland flora.

Anastomosed channels

Near Bhandara City is reserved for a type of river with multiple, interconnected, coexisting channel belts on alluvial plains. Based on its geomorphology, saucer-shaped islands called flood basins characterize anastomosing rivers (Fig. 8). The ox-bow lakes are confined to downstream reaches of the Wainganga and Kanhan Rivers and suggest limited local movements of river channels through meander cutoffs.

Morphological and hydrological parameters

It influences resistance to flow and can be regarded as an alternative to slope adjustments (Abrahams 1984; Bhagwat et al. 2011). According to Friend & Sinha (1993), the sinuosity of any river channel is valley length over reach length, i.e. S = Lomax. Lr., where Lomax is mid-channel length of the widest channel in a specific reach and Lr is the length of the river reach. For the Wainganga River, most of the reaches have sinuosity between 1 and 1.3 reflecting the moderate slope of channel bed and incising of the river banks (Schumm 1965). The two interventions in the river regime at Bhimgadh (Sanjay Sarovar Dam) and Gosekhurd (Indira Sagar Dam) are bound to cause a significant impact on the river morphology in the future. New zones of erosion and deposition may be seen, or there may be an increase in the rate of erosion and deposition. It would be important to mark out such zones and ensure that steps are taken to reduce, buffer or ameliorate the impact of erosion seen in these areas.

Hydrological parameters

Inflows

The received stage gauge and discharge data at Kardha, Pawani, Lakhandur, Bamni, Bhimkund and Ashti have been analyzed every month for the rainy season of June and October. The summary of such analysis is presented in Table 8. Surface water is available through flowing streams and rivers and used directly or through constructed storages or natural lakes. Surface water flows are time-variant as their source is rainfall. River gauging stations in this basin start from Mahalgaon on the main river to Wagholi downstream of the river. There are six gauging stations located in the river basin, at Kardha, Pawani, Lakhandur, Bamni, Bhimkund and Ashti. Velocities are measured by current meter and a stage–discharge curve is established before the beginning of every rainy season for all gauging sites. Stages are observed daily at 8.00 am, and discharges are worked out from an established stage–discharge curve. A bulk of the data are available since 1988. The Wainganga River Basin area in 5 major (Madhya Pradesh two major, and Maharashtra 3 major project), one major project (Gosekhurd Project) under construction in the Wainganga River Basin, 32 medium projects, (Madhya Pradesh 13, and Maharashtra 19), and around 410 minor irrigation tanks(this does not include the traditional Malguzari tanks) in the river basin.

Rainfall–runoff modeling

See Table 9.

Table 8 Inflows

Station	Parameters	Inflows Mm^3				
		June	July	August	September	October
Kardha GDS	Maximum	128.85	2189.98	1826.61	1058.40	297.11
	Minimum	25.85	28.96	234.44	37.71	58.83
	Mean	69.30	367.87	584.64	407.64	135.74
	STD	41.70	526.96	428.95	336.56	86.10
	Cv	0.60	1.43	0.73	0.83	0.63
Pawani GDS	Maximum	54.33	234.72	351.02	612.03	125.39
	Minimum	2.63	15.13	111.17	20.68	12.98
	Mean	22.25	111.87	203.11	184.56	44.75
	STD	17.56	68.01	69.25	164.32	35.79
	Cv	0.79	0.61	0.34	0.89	0.80
Bamni GDS	Maximum	108.27	455.15	329.59	149.19	77.15
	Minimum	53.95	70.41	178.05	25.23	59.01
	Mean	74.72	197.58	247.49	80.60	68.21
	STD	41.54	244.44	200.27	181.10	120.56
	Cv	0.56	1.24	0.81	2.25	1.77
Lakhandur GDS	Maximum	147.06	1219.30	1275.46	1239.64	204.99
	Minimum	2.71	21.33	106.91	16.30	4.80
	Mean	48.17	323.55	473.32	316.59	69.37
	STD	66.93	332.31	301.44	299.31	60.86
	Cv	1.39	1.03	0.64	0.95	0.88
Asti GDS	Maximum	237.29	761.89	771.71	815.20	166.72
	Minimum	3.11	38.91	346.62	65.63	27.96
	Mean	62.36	355.62	539.98	357.39	95.85
	STD	81.04	239.64	161.34	265.09	60.16
	Cv	1.30	0.67	0.30	0.74	0.63
Bhimkund GDS	Maximum	666.76	264.43	470.93	298.17	63.22
	Minimum	13.32	61.98	79.10	56.58	24.12
	Mean	143.03	153.39	270.99	161.64	45.04
	STD	257.39	92.24	150.12	98.72	19.69
	Cv	1.80	0.60	0.55	0.61	0.44

Regression equations

The regression equations as explained above every month for rainy season are established by weighted average rainfall over catchments by Thiessen Polygon method in mm and inflows from respective catchments. The monthly rainfall–runoff models (*R*–*R* models) so developed are summarized in Table 10.

The hydrological investigation shows that the climate of the basin is characterized by hot summer from March to May followed by a rainy season from June to September. The post-monsoon season is also observed in October. The annual mean rainfall range varies from 1000 to 1400 mm. However, a maximum of annual mean rainfall is found to be 1830.50 mm at Shivani and a minimum of 1000.07 mm at Sitekasa. Average observed (monsoon) runoff at CWC sites in the Wainganga river sub-basin (1996–2001) is at the height of 3.12 Cu. km in Kumhari, and the lowest is 0.65 Cu. km in Mul River in Rajoli Village. The received stage gauge and discharge data at Kardha, Pawani, Lakhandur, Bamni, Bhimkund and Ashti have been analyzed every month for the rainy season from June to October. The summary of such analysis is maximum river inflow of 2189.98 Mm^3 in July month in Kardha GDS and minimum river inflow of 2.63 Mm^3 in June month in Pawani GDS. The regression equations as explained above every month for rainy season are established by weighted average rainfall over catchments by Thiessen Polygon method in mm and inflows from respective catchments. The monthly rainfall–runoff models (*R*–*R* models) so developed are $R = 1.019 * P - 418.20$ height in the Bhimkund catchment area, and the lowest is $R = 0.532 * P + 194.60$ in Bamni catchment.

Table 9 Average observed (monsoon) run off at CWC sites in the Wainganga river sub-basin. (1996–2001). *Source*: Central Water Commission (CWC), Information System Organisation (ISO) (Hydrology Data Directorate)

S. no.	Name of the site	Name of the river	Catchment area sq. km	Run off (Cu. km.) June–Nov
1	Satrapur	Kanhan	11,100	2.23
2	Ramkona	Kanhan	2500	0.83
3	Rajagaon	Bagh	5380	2.27
4	Kumhari	Wainganga	8070	3.12
5	Keolari	Wainganga	29,600.97	0.97
6	Rajoli	Mul	1900	0.65
7	Wairagarh	Khobragarthi	2600	0.72
8	Salebardi	Chulband	1800	0.54
9	Pauni	Wainganga	35,520	9.53

The inflow can also refer to the average volume of incoming water in unit time. It is contrasted with the outflow. Inflow is mostly used when referring to rivers and the amount of water in units that enter the country

Sediment load

According to the Bagnold (1954) and Subramanan (1987), the Wainganga River sediment load detailed at Pauni is 41.109185 mt/year and at Ashti is 34.51207 mt/year. In the Deccan traps and Precambrian rocks covering of the basin and shale, dolomite, alluvial soils, sandstone, mica, laterite, granite, schist, etc. The annual rate of siltation varies between 2 and 20 ha m/100 km2, it is totally related to the river basin has varied rock formations.

Estimation of yield bin of the Wainganga catchment area

The estimation of yields for the Wainganga catchment area (49,949.48 sq. km) as a whole inclusive of several tributaries has been done by various agencies such as the Godavari Water Award, Water Resources Department, Government of Maharashtra, Water Resources Department, Government Madhya Pradesh. Similarly, the classification made by Water Resources and Irrigation Department, Government of Maharashtra, Water Resources and Irrigation Department, Government of Madhya Pradesh has divided the Wainganga River Basin area. Further, these assessments were made for allocation of water to the two states of Maharashtra and of Madhya Pradesh and include negotiated agreements on specific amounts of water added or subtracted instead of (additions and subtractions) other basins in Madhya Pradesh and Maharashtra. Second Maharashtra Irrigation Commission has estimated 75%, 50% and average yield as 8328, 9985 and 10,026 Mm^3 for the middle Wainganga sub-basin with a catchment area of 21,445 sq. km and yield rates as 0.38 Mm^3, 0.46 Mm^3 and 0.46 Mm^3/sq. km respectively.

Table 10 Monthly rainfall runoff models (*R*–*R* models)

Catchment	Month	Regression equation	r^2
Kardha	June	$R = 0.154 * P - 7.669$	0.47
	July	$R = 0.847 * P - 182.987$	0.64
	August	$R = 0.890 * P - 111.748$	0.61
	September	$R = 0.727 * P - 10.865$	0.75
	October	$R = 0.738 * P - 3.870$	0.87
	Annual	$R = 0.686 * P - 277.10$	0.93
Pawani	June	$R = 0.065 * P - 2.315$	0.67
	July	$R = 0.188 * P - 13.89$	0.64
	August	$R = 0.235 * P + 7.616$	0.54
	September	$R = 0.567 * P - 16.18$	0.72
	October	$R = 0.301 * P + 3.925$	0.68
	Annual	$R = 0.562 * P - 362.2$	0.72
Lakhandur	June	$R = 0.358 * P - 94.16$	0.71
	July	$R = 0.639 * P - 130.80$	0.67
	August	$R = 0.998 * P - 198.5$	0.73
	September	$R = 0.998 * P - 57.24$	0.65
	October	$R = 0.393 * P + 6.412$	0.70
	Annual	$R = 0.596 * P - 249.6$	0.89
Bamni	June	$R = 0.698 * P - 152.2$	0.99
	July	$R = 0.847 * P - 54.48$	0.36
	August	$R = 0.549 * P + 67.63$	0.53
	September	$R = 0.762 * P + 3.533$	0.93
	October	$R = 0.003 * P * P + 0.130 * P + 109.20$	1.00
	Annual	$R = 0.532 * P + 194.60$	0.84
Bhimkund	June	$R = 1.444 * P - 328.90$	0.86
	July	$R = 0.519 * P - 17.77$	0.75
	August	$R = 1.25 * P - 239.20$	0.66
	September	$R = 1.056 * P + 75.80$	0.53
	October	$R = 0416 * P + 28.05$	0.51
	Annual	$R = 1.019 * P - 418.20$	0.81
Asti	June	$R = 0.108 * P - 15.282$	0.63
	July	$R = 0.245 * P - 12.175$	0.64
	August	$R = 0.484 * P - 88.021$	0.75
	September	$R = 0.549 * P + 0.016$	0.57
	October	$R = 0.294 * P + 8.950$	0.74
	Annual	$R = 0.675 * P - 496.6$	0.80

The 75%, 50% and annual average yield for the Wainganga River Basin on the above prorate basis are 5324.62 Mm^3, 6384.04 Mm^3 and 6410.26 Mm^3, respectively. The details for the yield estimation done by the Water Resources Department of Government of Maharashtra are not available at this stage and will be incorporated as soon as these are made available. The average annual yield of the Wainganga sub-basin is 0.45 Mm^3/sq. km., in this catchment up to Kardh is 0.45 Mm^3/sq. km., Pawani 0.26 Mm^3/sq. km., Lakhandur 0.49 Mm^3/sq. km., Bamni 0.98 Mm^3/sq. km., Bhimkund 0.88 Mm^3/sq. km, and Asti 0.35 Mm^3/sq. km average annual yield rate.

Groundwater availability in the Wainganga River Basin

The lithology of various water-bearing formations is seen in the Wainganga River Basin. Granite gneisses (Precambrian) and basalts (Deccan Volcanic Province) outcrop over a major portion of the basin. Although these two rock types dominate the area, alluvial soil, shale, dolomite, mica, laterite, granite, sandstone and schist can be found in the Wainganga River Basin. The basin bears groundwater potential through shallow and deep aquifers, many of which get annually or periodically replenished through precipitation, irrigation return flow, canal seepage, tank seepage, influent seepage, etc. Net groundwater availability is $636.95 + 5083 = 6719.95$ Mm^3, present use of groundwater for irrigation is $1636.95 + 2700 = 4336.95$ Mm^3 and balance of groundwater available is 2383 Mm^3. In the south part of the Wainganga river sub-basin, up to a maximum depth of 300 m has revealed that potential aquifers exist between 30 and 100 m & 160 and 230 m, which can be developed. The yield of tube wells varies from 1.3 to 15 Ips, while '*T*' varies from 15 to 87 m^2/day. In the middle part of the Wainganga river sub-basin, a well-field was constructed which suggests that '*T*' varies from 85 to 250 m^2/day and '*S*' is 4.4×10^{-5}. In the middle part of the Wainganga river sub-basin, a depth ranges from 79 to 264 m.bgl, and that ranges from 10 to 137 m.bgl in the Gondwana formation. The yield of wells ranged from 0.78 to 16.4 Ips, which suggests that Gondwana below the Trap have a potential for groundwater development.

Groundwater occurrence and movement

The occurrence and movement of groundwater are governed by topography, lithology, slope, geological structure, thickness and nature of the weathered zone, drainage pattern, landform, land use and climatic parameters. The Wainganga basin area is underlain by a variety of rock types bearing unique structural features. Rock formations include a diverse suite of rocks ranging from very old crystalline Archaean rocks the(granites and gneisses) to the river alluvia from recent geological age. The water-bearing capacity of the rocks depends on their size, weathering, structure and fracturing patterns. It is effectively a function of the openings developed in these rocks. Given the variety of rock types present in the Wainganga basin, their water-bearing capacities vary significantly.

Most of the rocks in Archaean (the oldest suite) are invariably metamorphosed and therefore preclude large-scale accumulation of groundwater. The crystalline rocks comprised of gneiss, schist, pegmatite and quartzite, amphibolite are the main rocks in this category. Hydrogeologically, these rocks do not possess primary porosity, so groundwater can only occur in weathered zones, which is down to a depth of 25 m.bgl often forming important shallow (unconfined or phreatic) aquifers tapped by joints and fractures, wherever such openings exist. Higher yields are generally associated with lineaments, long, often narrow zones of dense and frequent fracturing. Groundwater, at places, occurs in fractured zones at depth, under semi-confined to confined conditions. Laterite is commonly found as capping the weathered rock at some places. Laterites, in this region, have generally low permeability and tend to impede infiltration. The groundwater abstraction structures constructed in these rocks have poor yields.

Conclusion

The present study of the morphological and hydrological parameters showed that the Wainganga River Basin is a relatively small watershed with an undulating landscape and is elongated, narrow and not very steep in slope; thus, water takes a relatively long time to reach the river. The area is underlain by Gneissic Complex Achaean of rocks, which covers 48.18% of the area. The hydrological data analysis of the basin indicated that the volume of inflows, rainfall-runoff modeling, regression equation, sediment load, groundwater that contributes to runoff is relatively small compared to the total rainfall. This could be as a result of medium inflow, discharge, sediment load losses within the drainage area. The two interventions in the river regime Bhimgadh (Sanjay Sarovar Dam) and at Gosekhurd (Indira Sagar Dam) are bound to cause a significant impact on the river morphology in the future. New zones of erosion and deposition may be seen, or there may be an increase in the rate of erosion and deposition. It would be important to mark out such zones and ensure that steps are taken to reduce, buffer or ameliorate the impact of erosion seen in these areas. The hydrogeological network should be balanced, but groundwater availability varies in time, space and depth given the diversity of hydrogeological conditions.

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