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Appraisal and Assessment of Hydraulic Geometry and Development of Potholes on Bedrock Channel of Kukadi River, Maharashtra, India

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Abstract

Objectives: The present research aims to study the hydrogeomorphology, mechanism of channel morphology, development and distribution of the potholes in the Kukadi River, Maharashtra. To ascertain the size and shape relationship of the potholes. To find out the recent anthropogenic effects on the bedrock lithology of the Kukadi River. **Methods:** The comprehensive methods of Remote Sensing and GIS techniques are used to determine hydraulic geometry and pothole development. Six geomorphological sites were selected for section-based profiling. The measurements were taken by dumpy level, GPS and total station survey. Field survey was conducted to determine the geometry of the size shape and depth of the potholes. Pebbles and grinding tools within the potholes were also collected to analyse the capacity and role of joints, cracks and fractures in the development of potholes. All maps were prepared in a GIS environment. **Findings:** The present study reveals the mechanism of pothole development at six major sites. Section-based profiling highlights the dominance of hydrodynamics, stream energy and capacity. The hydraulic geometry of the Kukadi river conforms to the relationship between the depth and diameter of potholes. It also ascertains the role of joints, cracks and fractures at riverbeds in the development of potholes. Thus Depth and diameter of the Kukadi river are almost maintained by lithology. Based on shape Honewadi (585 MSL) 29.03% (31) potholes are irregular in shape, Gadilgaon(575 MSL) is 27.08%(48) rounded, Gunore(570 MSL) is 26.78% (15) irregular, Dongargaon(565 MSL) 25.01%(44), Kohokadi (560 MSL) 28.26% (13)irregular while Mhase(565 MSL)39.95% (13) Club shape in nature **Novelty:** The scope of the present research is to provide a comprehensive assessment of the hydraulic geometry and potholes development on bedrock channel, which has received limited attention in previous studies. The study employs a multidisciplinary approach that combines field observation, hydrological and geomorphological measurement.Thus the study highlights their geoenvironmental, ecological and cultural values in the context of sustainable river management and conservation

Keywords: Potholes; Hydraulic Geometry; Hydrodynamics; Geometrical Shapes; Depth And Diameter Relationship; Remote Sensing and GIS

1 Introduction

The fluvial system is a physically dynamic environment in which both channels and adjacent lithology spontaneously adapt to changes in fluvial processes and sediment discharge over time [1]. The geomorphological variations in landforms and underlying processes make natural rivers diverse and dynamic. Throughout the geological period, rivers have altered their channels through erosion and deposition or human intervention. Both shearing (geological) and huge discharge (hydrological) responses are the concerned mechanisms in the development of potholes as micro fluvial landforms [2].

The bedrock channel in the present study also reveals the responses to bedrock history. Potholes are common landforms in bedrock channels**.** Their formation can be associated with a significant proportion of the total erosion in many bedrock channels [3] . Potholes are commonly found at bedrock channels of the first stage of the river. Such type of bedrock channels are commonly observed in the western uplands in Maharashtra state. Potholes are important micro geomorphic landforms of bedrock channels that indicate bedrock erosion and channel incision [4] . The size and shape of the largest bed forms employ first-order stream formations with significantly high velocities. The morphology of potholes likely exerts a primary control on turbulent flow structures, erosion rates, and patterns, coarse sediment transport rate [5] . The whirls and eddies formed by shear flow enter in these incipient depressions, at which point sediments entrained in the flow, grind against the sides and bottoms of the depressions, resulting in pothole growth [6] .The major development of potholes is based on geological aspects like joint orientation and placement of potholes [7] . Thus, the controls on rates of river incision into bedrock channels largely prescribe the relationships among climate, lithology, tectonics, and topography. Joint density is an important factor in the creation of new potholes and water discharge and flow velocity play another important role in the growth of potholes [5,7].

River bed geology like joints, fractures and joint orientation play a primary role in pothole development but river hydrodynamics is more significant for new potholes [8] . Multiple potholes and new potholes in this area were found after the monsoon. Pothole sizes are calculated in the field using a micro-scale (cm and meter). The position of the potholes from the active channel is the key factor for pothole geometry and it provides the real scenario of pothole mapping [2] . In the present study, the bedrock channel incision affected the evolution of the present channel forms while the shape, size, pattern, gradient, and planation surface of the rocky channel are largely determined by the physical characteristics of the bedrock of the study area.

Hydraulic geometry is the study of the size, shape and pattern of a river and its associated features. Potholes in the river course form due to the strong action of river water current and due to abrasion, corrosion etc. hydrogeomorphic processes. As the river flows, the fast-moving water moves sediments such as gravel and sand that are carried out along with it. As these particles rub together, they create small cavities in the bedrock. These cavities are then widened and by the continual action of rivers, strong currents form potholes. These potholes are typically found on the riverbed or the walls of the channels and are usually a few centimetres to a few meters in diameter. The size and shape of the potholes will also depend on the rate direction of the flow of the river. Additionally, the shape and size of the potholes can change over time as the river's flow and sediment load change. Hence the potholes are an important geomorphic feature of bedrock channels that can provide valuable insights into the process that shape river channels and the role of bedrock in controlling channel from dynamics. This study will help scientists, researchers, fluvial geomorphologists and hydrologists to conserve and manage the river ecosystem [7].

Very little research has been carried out at the international level on the hydraulic geometry and pothole development of the Kukadi river at the international level. The research gap that needs to be investigated is the factors that influence the hydraulic geometry of the river and the development of potholes. There is also very little study on the impact of human activities on channel and potholes development. The proposed work can overcome the limitations of the existing literature in several ways; it can provide a better understanding of geomorphic processes that shape the bedrock channel of the Kukadi river. This can help identify the factors that control the development of potholes as well as hydraulic geometry which are not well understood in the existing literature. The present research work involves the quantitative analysis of the data collected from the field. This can help in identifying the relationships between the different variables that affect the development of potholes and hydraulic geometry which is lacking in the existing literature. This research provides valuable insights into geomorphic processes that shape the bedrock channel of the Kukadi River.

2 Methodology

2.1 The Study sites

The geographical location of the study area extends from 18°51'30" North to 18°57'30" North latitude and 74°15'00" East to 74°17'45" East longitude. The sites selected for this investigation are located along the Kukadi River and Ghod River basins (Figure 1). The total study area of this region is about 80 Km^2. The regional orientation of the river basins is NW to SE forming an elongated and linear drainage pattern [9] as depicted in (Figure 2). It attains a maximum elevation of 593m on the northwest side of the watershed and a maximum of 560 m above mean sea level (Figure 2). The area receives an annual average rainfall of 50 cm classifying it in the tropical semi-arid zone. The district in which study sites are situated in the rain shadow zone of Western Ghats, and often suffers from drought conditions. The average rainfall during 1995 – 2004 was 501.8 mm, which gradually decreased in the last ten years as compared to normal annual rainfall according to the hydrological report (2020) 407 mm(monsoonal rainfall).

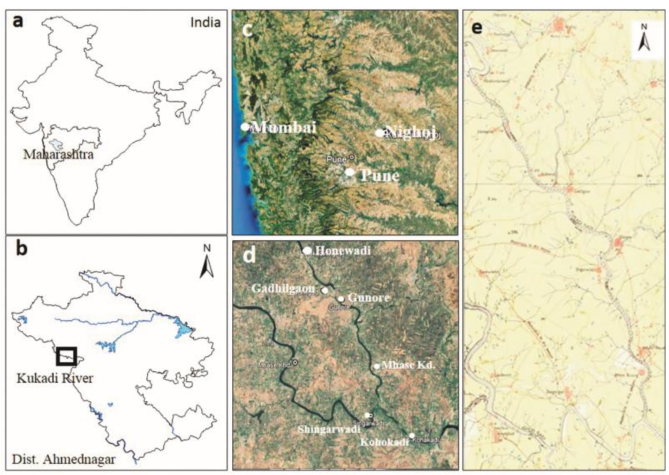

Fig 1. Location map of Kukadi River and selected study sites located in Ahmednagar district, Maharashtra State of India

Geologically the study area is part of the Deccan trap [10] . The Trappean landscape exhibits an erosional terrain over a relatively ancient and stable block of igneous basalt. The basaltic lava flows covering Maharashtra state do not have noticeable grain as they are horizontally cooled and determine nearly uniform resistance to erosion. Therefore the headword erosion by a tributary is governed by the local slope of the landscape. This probably helps in the formation of micro geomorphic landforms like potholes. The study areas include six major locations signified with potholes viz., Hanewadi (18°56'0.25"N, 74°15'49.60"E), Gadilgaon (18°54'48.25"N, 74°16'29.26"E), Gunore (18°54'31.86"N, 74°17'7.65"E), Mhase Khurd (18°52'37.82"N, 74°15'30.40"E), Dongargan (18°51'1.85"N, 74°18'7.74"E) and Kohakadi (18°50'24.19"N, 74°19'33.56"E). The surface feature of basaltic lava is classified as pahoehoe, aa, and blocky. The Hanewadi cross-section has characterized by a knick point waterfall (20 m deep). Other study sites are located on massive Deccan basaltic traps making them favorable for the formation of potholes [11].

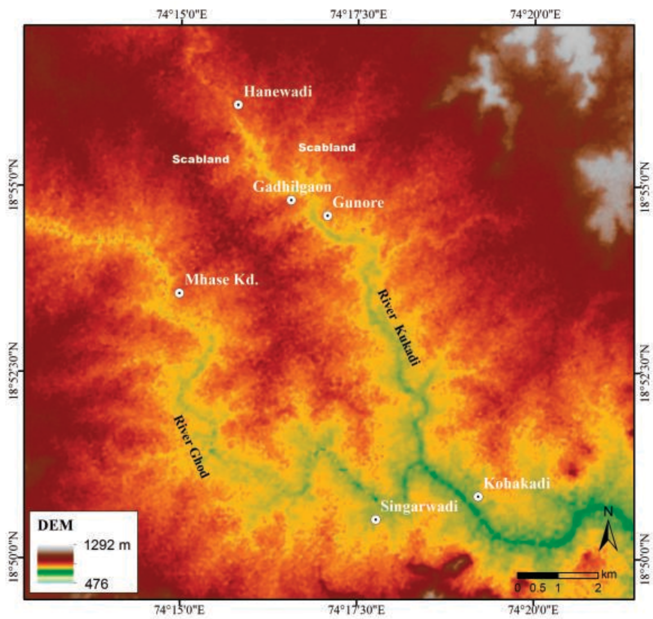

Fig 2. Location of study sites with reference to SRTM-DEM (2022) of Kukadi-Ghod riverbasins

The landscape of the Kukadi and Ghod River basin is characterized by a scabland that spreads over an 80 sq. km. area with a network of multiple tributaries (Table 1). The scabland topography is developed entirely in compound lava flows with amygdaloidal basalt[4] .The River Kukadi, rising from northeast of Nighoj, meets its major tributary river Ghod, near another significant pothole area – Kohakadi (Figure 3). These two rivers fall into a 25 -30 m deep and form another abrasive scabland. Four of the study sites are located on River Kukadi (Hanewadi, Gadhilgaon, and Gunore), one near the confluence (Kohakadi), and two along River Ghod towards the west. This landscape is featured numerous joints, structures, and fractures which favour pothole formations at intersections of joints or along the joints. Potholes are formed due to diverted water currents that result in eddies where the water whirls round and round with high velocity[12] . Meanwhile, pebbles, coarse gravel, and sand are observed within the potholes acting as grinding material that gives potholes a smooth and finer curve. These grinding tools spin along eddies and become churning tools. Due to churning action, the bedrock gets eroded and excavated into cylindrical holes. Potholes intersecting each other have formed a deep channel[13].

Table 1. The number of samples of grinding tools taken from all the study sites

Prominent shapes	Hanewadi		Gadhilgaon		Gunore		Kohakadi		Dongargan		Mhase Khurd	
	RB	LB	RB	LB	RB	LB	RB	LB	RB	LB	RB	LB
Total samples	12	19	24	24	31	25	18	28	21	23	16	26

2.2 Significance of study

The importance of the present research work is to understand the pattern of fluvial erosion and deposition in the fluvial system. It is also important for understanding the hydrological process that governs river dynamics. It is useful for the conservation of the river system. Additionally, by understanding the processes that govern river dynamics. It is useful for the conservation of the river system. Additionally, by understanding the process behind pothole formation. Knowledge of hydraulic geometry can be used to develop strategies to protect and enhance the river's natural ecosystem. This study can provide valuable insights into the long-term behaviour of river systems, which can be used to inform management decisions related to ecological conservation and management system. Nowadays RS and GIS tool has become a very important and useful technique to assess the potholes development in river bed course.

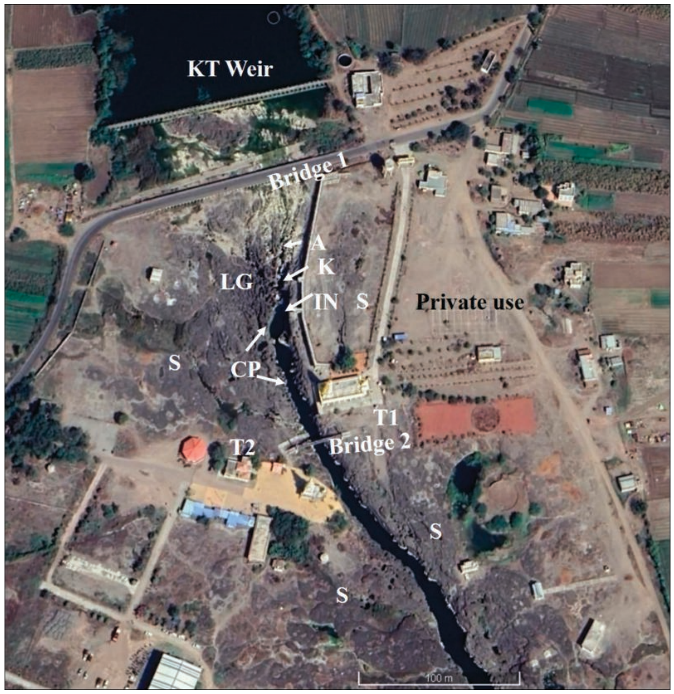

Fig 3. Google Earth image (May 2022) showing the pothole complex area. K = knick point with layered and segmented waterfalls and rapids, A = area abrasion faces, longitudinal grooves, and several incipient potholes, IN = inner channel, S = scabland, LG = longitudinal grooves, CP = classic coalesced potholes, T1 and T2 = temples (modified after Kale, 2016).

2.3 Database

The hydraulic geometry data of potholes is largely measured during field excursions. Six sample sites are selected in Kukadi – Ghod river basins. These six sites are Hanewadi, Gadilgaon, Gunore, Mhase Khurd, Dongargan, and Kohakadi. A major pothole site was observed near Nighoj which covers 78.3% of the total pothole area [7] . A random stratified sampling method was chosen to collect the geometrical sampling of the pothole study. The location of potholes was tracked with the help of GPS.

Table 2. Hydro-geomorphological characteristics of Kukadi –Ghod river basins (After Kale et.al. 2016)

Parameters	River Kukadi	River Ghod
Regional orientation of the valley	Elongate, linear	Elongate, linear
Channel orientations	95% towards the SE	30% towards the ESE 60% towards the SE
Basic drainage pattern	Sub-parallel to asymmetric trellis	Sub-parallel to sub-dendritic
River Valley characteristics	Beheaded drainage at the source with a wide flat-bottomed valley. Structurally controlled bedrock channels with a rectangular (trellis-like) drainage pattern upstream.	Narrow entrenched meandering channel with steep valley-sides in the first 5–7 km, that becomes gentler downstream
Significant knick points/waterfalls/ cascades	Knick point at Nighoj (583 m) followed by a straight linear channel and remarkable pothole development on banks, as well as in the channel of the river. Bedrock incised meanders persist across significant distances.	The Cascades in the 680–700 m segment.

Source: (Sengupta & Kale, 2011; Kale et.al. 2016.)

2.4 Measurement of pothole geometry and sampling

The present study is largely based on primary data which was collected during the field excursions held in the summer of 2018 and 2023. After related literature reviews to get a better understanding of pothole formation, study sites were visited and pothole measurements were taken from all six study sites. The survey instruments like Dumpy level, Total Station, and GPS were used here for taking the readings.

A quadrat method was used in this study to ascertain the development of potholes from the actual channel and away from the channel. The distances from the active channel were measured. Cross-profiling was performed to determine the gradient from the right bank to the left bank of the streams. The size, shape, depth, and length of each pothole were measured within each quadrant. The size and shape of the pothole were measured by using the general orientation of the long axis. The average length and depth of the pothole were measured concerning the profile line. The GPS was used to measure the orientation of fractures, structures, and joints along the scabland as well as the average slope of the quadrat. Pebbles and other grinding tools within the potholes were also collected to analyze stream energy and capacity and competence of the sediments. (Table 3) illustrates the number of sediment samples collected from the right bank and left bank of all the study sites. In the post-field work, the entire collected data was analyzed and summarised with the required documents (Figure 3).

Table 3. Frequency of prominent shapes along the left and right banks of study sites.

Prominent shapes	Hanewadi		Gadhilgaon		Gunore		Kohakadi		Dongargan		Mhase Khurd	
	RB	LB	RB	LB	RB	LB	RB	LB	RB	LB	RB	LB
Rounded	3	3	8	5	7	4	3	7	3	5	3	4
Sub-rounded	3	3	3	2	1	4	4	5	3	4	5	4
Elongated	1	2	2	4	2	1	1	2	2	0	0	0
Oval	0	1	2	4	2	2	0	3	2	4	1	1
Dumble	0	0	1	3	4	3	2	0	5	6	3	1
Club	0	6	4	2	4	7	2	4	0	2	4	9
Irregular	5	4	4	4	11	4	6	7	6	2	0	7
Total samples	12	19	24	24	31	25	18	28	21	23	16	26

2.5 Secondary data sources

The adopted methods of studying pothole morphology are divided into secondary data has been collected from Survey of India (SOI) toposheets, satellite data, and Google Earth applications (2021-22). The location of the study sites was georeferred from SOI toposheet (47 J/5) of 1:50,000 series, and some important relevant official published and unpublished documents of the Maharashtra state government. Elevation data were acquired from two sources viz., field visits and later digital sources. Digital elevation data was downloaded from the USGS Earth Explorer portal using datasets of SRTM-DEM (Shuttle Radar Topography Mission - Digital Elevation Model) at a spatial resolution of 1 arc-second V3 product (~30 meters) dated January 2015 (Figure 2).

3 Results and Discussion

3.1 Hydro-geomorphological study of the Kukadi –Ghod River basins

The Kukadi River forms an elongated and linear pattern of drainage with 95% of its orientation towards the southeast direction [(9)] . An abruptly angled knick point near the Nighoj (Hanewadi) pothole site of the present study is formed downstream exactly over which a KT weir is constructed. It is stratified with waterfalls (not more than 20 m in depth) and rapids. On either bank of the river, abrasion platforms 3 km wide are formed which are rigorously appraised during heavy monsoonal rain (Figure 3). The basin flowing from the north, suddenly narrow downs downstream, developing narrow gorges and entrenched meandering [(14)] . The development of these meanders is the result of a deep incision of Deccan basalt and indicates strong 'above grade' hydraulics of a river [(15)] . The formation of potholes has been explained by various scholars. According to Kale et al., (2016), the anomalous development of potholes is due to the segmentation of meandering channels and structural control of drainage development. Further, Kale and Joshi (2004) noted that amygdaloidal basalt with joints and fractures within the compound lava flows is responsible for pothole formation and the best example is the Kukadi river potholes. The Kukadi river basin becomes wider and flat-surfaced downstream exposing the bedrock. This can be observed prominently along the selected study sites – Hanewadi (581m), Gadhilgaon (575 m), Gunore (572 m), and Kohakadi (551m). Significant cascades and rapids are formed downstream. Hence basalt 'aa' type of rock lithology is responsible to develop knick points and potholes in the lower stretch of the Kukadi river.

Ghod river also forms an elongated and linear drainage shape with 60% of the orientation of the channel towards a southeast direction and 30% towards the east-south-east (ESE). Geologically it resembles with Kukadi river concerning structurally controlled bedrock. Ghod river valley is narrow, meandering, and steep-sided. The drainage pattern of this basin is sub-dendritic in the upstream region to sub-parallel downstream. Two study sites - Mhase Khurd (568m), and Dongargan (556m) are located on the left bank of Ghod river.

3.2 Cross section profiles of the study sites

The cross-sectional profiles were surveyed during the field visit in the study areas and were compiled for comparison. Both the rivers have steep and deeply incised upstream reaches and attribute to slope retreat with severe headward erosion. To understand the change in gradient at all study sites, it is crucial to study cross sections for the depths of potholes. The development of potholes is seen in multiple segments throughout the basins, but they are predominant in long Hanewadi and Kohakadi (Figure 4).

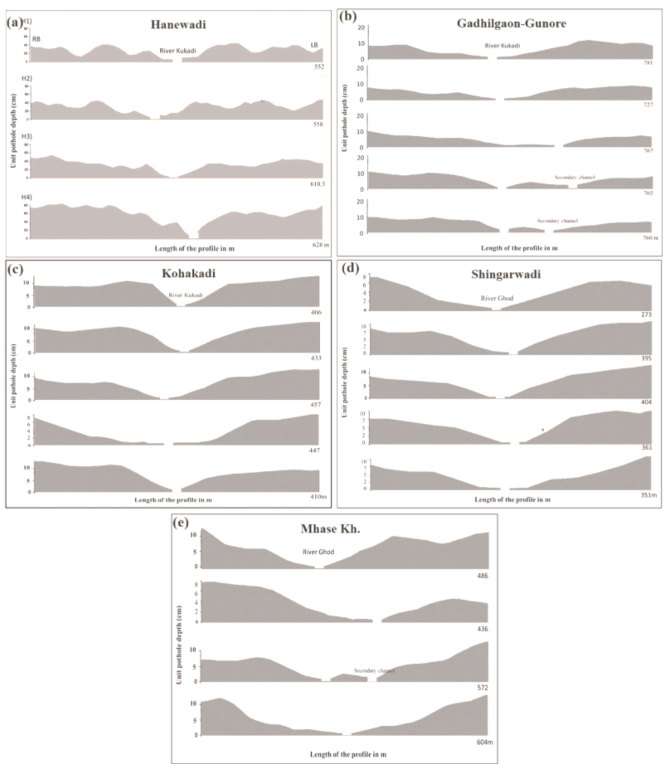

Fig 4. Cross-section profiles from upstream to downstream reach at an interval of ~100 m. (a) Hanewadi study site. Other study sites (Kohakadi, Dongargan and Mhase Khurd) have comparative linear and parallel segments obstructing deep pothole formations (c, d and e), while Gadhilgaon-Gunore study site is at gentle slopes (b)

3.2.1 Cross sections at Hanewadi potholes

The extensive development of potholes is seen near the knick point near Hanewadi in the Kukadi River. The Kukadi River has developed a knick point at Hanewadi where a deeply incised gorge has developed with a remarkable assemblage of potholes (Figure 4 a). These cylindrical or semi-cylindrical holes carved into the bedrock by swift-moving channel flows exhibit considerable variation in their density. Potholes may be characterizing the bedrock fluvial channels with incisions [4] · According to Selby (1980), lithology also plays an important role in bedrock river erosion. The joints, fractures, and veins of the area play an important role and are responsible for the development of potholes. Cross-section profiles from upstream to downstream reach an interval of ~100 m. The profile of the downstream region represents the highly incised bedrock channel of the Kukadi River[16] .

3.2.2 Cross sections at Gadhilgaon – Gunore potholes

A primary development of new potholes and remnants of worn-outs in the form of depression can be seen near Gadhilgaon and Gunore study sites in the Kukadi River. There are cylindrical or semi-cylindrical holes carved into the bedrock with shallow depths. The entire region is of bedrock characterizing the bedrock fluvial channels with the incision. The joints, fractures, and veins of the area play an important role and are responsible for the development of potholes. Probably the geological set-up in the area, i.e. compound pahoehoe flows highly indurated and crossed by numerous basic igneous bodies may have been the favourable factor for the extensive development of potholes along with the river incision process and structural aspects (Figure 4 b). Equally well-developed potholes and related features are seen at other localities like near Gunore .

3.2.3 Cross sections at Kohakadi potholes

A development of new potholes and depressions can be seen near Gadhilgaon and Gunore study sites in the Kukadi river(Figure 4 c). The depth of potholes ranges from 2 to 8 m, attaining the depth of Hanewadi potholes. The joints, fractures, and veins of the area play an important role and are responsible for the development of potholes.

3.2.4.Cross sections at Dongargan potholes

The channel section over here exposes the indurated units of a compound lava flow, thin brecciated veins are also seen in the area. Shattering and brecciated of the host rock is seen on the right bank, where evidence in the form of fragmented rock blocks can be seen in the area. The frequency of isolated potholes was found to be more than the coalesced potholes (Figure 4 d).

3.2.5.Cross sections at Mhase Khurd potholes

At Mhase Bu. in the river section a plug-like body is observed, which is highly pot-holed, along with the host rock. It is very interesting to note that the pothole incision is very common over the typical lithology of the secondary channel, thus indicating that the lithology has played a vital role in the excessive development of these features along with other factors of fluvial erosion (Figure 4 e). The channel section over here exposes the indurated units of compound pahoehoe flows, thin brecciated veins are also seen in the area. The frequency of isolated potholes was found to be more than the coalesced potholes similar to Dongargan.

3.3 Hydrological controls on pothole development

Potholes grow as a result of combined erosion of the bed and banks of the river. The rate of erosion phenomena determines differences in the erosion rate of the wall and floor of the potholes. All type of sediment sizes stored in potholes and involved in erosion is collectively called grinding tools. Hydrological components like discharge at-a-station, seasonal variation in discharge, the velocity of water, stream energy, etc., play a remarkable role in the development of potholes[8] . The monsoonal effect over the potholes is significant in the study sites though the region is a drought-prone area. Meanwhile, the development of potholes largely depends on the annual climatic conditions of the study sites.

Variation in discharge at study sites affects the capacity and competence of the river and ultimately the size, length, and depth of the potholes. Stream energy also increases along knick points and deep-cut banks[2] . A change or sudden break in a gradient of pothole sites indicates maximum variation in hydrodynamics and stream energy. Shear stress also makes a difference in the flow velocity and magnitude of a river. Bed topography, parallel ridges of resistive rocks, and the sub-parallel pattern of Kukadi and Ghod river highly affect the variation in the flow path and pothole development (Figure 5).

3.4 Role of joints, cracks, and fractures in the development of potholes

The formation of potholes initiates with the presence of joints, cracks, and fractures on the riverbed. The length and density of the potholes are directly correlated[2] . These have resulted from synoptic weathering processes – vertical erosion, abrasion, and monsoonal discharges. Turbulence in flow results in the entering of water into joints and fractures and corrodes the depressions (Figure 6). These depressions result in the initial development of embryo potholes. The density of potholes is directly correlated with the density of joints and fractures. These weaker sections on the bedrock play a crucial role in the development of potholes. During the field observation, many potholes were seen affected by seasonal water flow in their development stage. Regional weathering is also responsible for joint length, density, and area[2] .

Fig 5. Field photographs from different sites. (a) Massive tract of basalt bedrock with wide depressions at Gadhilgaon, (b) sculpted form and amalgamated potholes near Kohakadi and effect of weir construction on sudden break in the process, (c) abrasion platform atDongargan and field survey (d) Active bedrock channel with parallel ridges and longitudinal grooves of resistive rocks at Mhase Khurd, KT weir can also be seen. (Photos by authors)

Fig 6. Grinding tools embedded in the potholes at Hanewadi study site. The yellow colour indicates joints within potholes

3.5 Variations in geometrical shapes and horizontal development of potholes

The development of river potholes is highly influenced by local hydraulic conditions in the study sites. The geometric shapes of the potholes were adopted from the shape-from analysis through the morphometric index[(6,16)] . As the bedrock surfaces were exposed to the direction of river flow directly, variations in geometric shapes and frequency of prominent shapes were analyzed. The rose diagrams for the study sites are illustrated in (Figure 7) Observations of potholes demonstrate an inter-relationship between flow direction and geometric shapes. It is crucial to mention that the major direction of pothole development is approximately north-south along the Kukadi river study sites and SW to NE along the Ghod river study sites. Most of the grinding tools (especially pebbles and cobbles) are rounded – sub-rounded in shape. At Mhase Khurd, the shape is slightly different from club to irregular. This indicates a sudden break in the slope but low stream energy (Table 3).

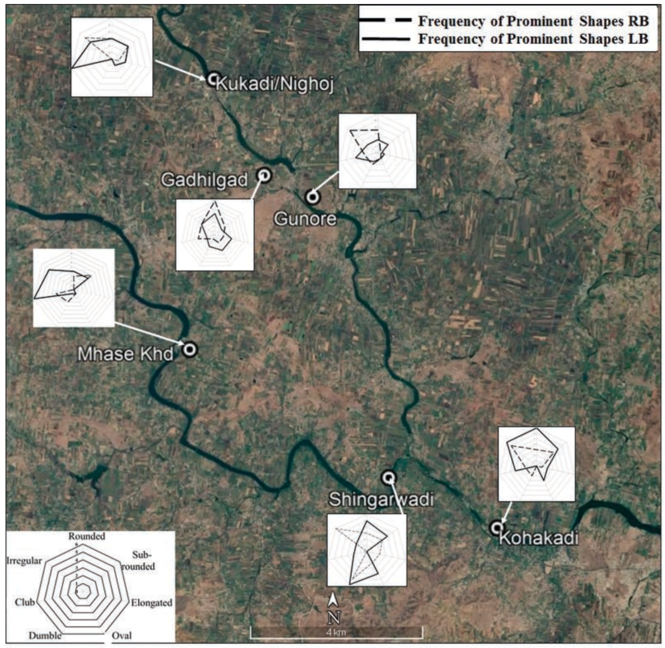

Fig 7. Gradient rose diagramshowing the orientation of different frequencies of prominent shapes along theleft and right banks of study sites

3.6 Determination of the relationship between the Depth and diameter of the potholes

In the present study, we have determined the depth and diameter of the selected sites' potholes along the riverside platforms and it is observed that the relationship of the depth and diameter of the potholes is controlled by rock properties, rock structure, joints and the lithology of the study area. A total of 36 potholes were selected from the six sites of the study area (Table 4). The morphology and the lithology of the Honewadi site is more dominant than the other sites. Most of the potholes are rounded or circular. According to some geologists, geomorphologists and hydrologists, the diameter and depth of the potholes usually remains their proportional relationship. Hence, because of the presence of the ultrastructure of the channel, with very dynamic fluvial-hydrological components, it becomes very difficult to decipher the relationship between the diameter and depth of the potholes. Diameter–depth relationship or the ratio of the potholes is almost maintained in homogeneous lithology with structures, but hence it is slightly varied due to heterogeneous channel-bed lithology as well as multi-structural units of the channel. The following formula can be used to calculate the depth-diameter relationship [17–20] .

$$D = Nh + M$$

(16)

Where N is the ratio of diameter, h is the depth and D means the diameter of the pothole, M is the critical size of the initial concavities.

3.7 Recent anthropogenic effects on the study sites

Intensive anthropogenic activities are engaged in all study sites. Being a sacred place of Malganga Temple, the Hanewadi pothole site is immensely disturbed by the construction of a KT weir, temples and surroundings, a major road bridge and a hanging bridge constructed exactly on the scabland of the Kukadi River . Similar constructions have been made across Kohakadi and Mhase Khurd. On either side of the banks at Dongargan, intensive agriculture practices and irrigation can be seen. Though the weir constructed across is away from Dongargan study sites, which makes it vulnerable concerning stream energy. All these changes severely affect the geomorphology of the area. Reduces the natural stream discharge and energy [21–25] . This situation can be quantified at Mhase Khurd in further studies.

Table 4. Kukadi River Potholes depth and diameter Relationship

Site No	Name of the site	Code	Latitudinal extent	Longitudinal extent	Depth in Cm	Diameter in Cm	Radius in Cm
1	Honewadi: Right bank Platform Potholes	a	18°55'57.7' N	74°15'44.4"E	140	80	40
2		b	18°55'58.1"N	74°15'44.7"E	210	120	60
3		c	18°55'58.3"N	74°15'44.4"E	130	110	55
4		d	18°15'58.5"N	74°15'44.8"E	120	110	55
5		e	18°55'57.0"N	74°15'14.6"E	220	60	30
1	Honewadi: Left bank Platform Potholes	a	18°55'50.1"N	74°15'49.6"E	390	250	125
2		b	18°55'51.2"N	74°15'49.0"E	80	40	20
3		c	18°55' 51.3"N	74°15'48.9"E	90	66	33
4		d	18°55'55.6"N	74°15'46.8"E	250	180	90
5		e	18°55'55.9"N	74°15'46.1"E	500	220	110
1	Gadillgaon:Left bank platform Potholes	a	18°54'48.1"N	74°16'54.3"E	30	20	10
2		b	18°54'47.2"N	74°16'52.2"E	70	32	16
3		c	18°54'46.8"N	74°16'54.6"E	80	40	20
4		d	18°54'46.2"N	74°16'54.7"E	160	110	55
1	Gadillgaon:Right bank platform Potholes	a	18°54'41"N	74°16' 50.5"E	60	50	25
2		b	18°54'40.9"N	74°16'50.8"E	70	40	20
3		c	18°54'40.6"N	74°16'50.7"E	90	50	25
4		d	18°54'37.0"N	74°16'51.2"E	210	90	45
1	Gunore : Left bank platform Potholes	a	18°53'52.7"N	74°17'49.2"E	190	150	75
2		b	18°53'52.5"N	74°17'49.5"E	50	110	55
3		c	18°53'52.1"N	74°17'49.4"E	100	500	250
1	Gunore : Right bank Potholes	a	18°53'52.7"N	74°17'48.0"E	140	160	80
2		b	18°53'52.5"N	74°17'48.3"E	140	190	95
3		c	18°53'52.6"N	74°17'48.5"E	110	170	85
1	Mhase : Right bank Potholes	a	18°51'51.4"N	74°18'19.8"E	140	160	80
2		b	18°51'51.5"N	74°18'20.0"E	90	70	35
3		c	18°51'51.6"N	74°18'20.2"E	40	23	11.5
1	Mahse Bk : Left bank Platform Potholes	a	18°51'53.1"N	74°18'19.8"E	90	200	100
2		b	18°51'52.3"N	74°18'22.7"E	30	80	40
3		c	18°51'52.1"N	74°18'21.3"E	20	16	8
1	Kohokadi : Right bank Potholes	a	18°50'55.0"N	74°20'58.6"E	160	130	65
2		b	18°50'54.8"N	74°20'58.6"E	170	120	60
3		c	18°50'54.1"N	74°20'57.9"E	210	70	35
1	Dongargan: Left bank Platform Potholes	a	18°51'24.5"N	74°17'8.7"E	30	70	35
2		b	18°51'26."N	74°17'6.8"E	60	130	65
3		c	18°51'26.3"N	74°17'7.2"E	80	16	8

4 Conclusion

The current study investigated the mechanism of pothole development, hydrogeometry and morphology at six major sites of the bedrock channels of the Kukadi river in the western uplands of Maharashtra. Hence one of the most important speciality observed in the Kukadi river ecosystem i.e. lower stage of the river is more dominant than the upper stage of the river because of the hydrodynamics, lithology, rock structure, joints and fractures present at the lower reach of Kukadi river. So it can be concluded that due to the presence of western uplands of the Deccan trap which is made up of massive bedrock basalt, i.e. 'aa' and 'pahoehoe type of flow, and steady slope and the geomorphic control in the river channel etc. factors are responsible for the formation of potholes at selected sites of the Kukadi river. The study also aims to highlight the dominance of hydrodynamics and stream energy. Stream capacity and shear stress of both rivers can be projected based on the geometry of grinding tools observed, parallel ridges of resistive rocks and orientation of pothole formations. The formation of the embryo, primary, and secondary potholes is persistent which indicates a strong influence of flow intensity and magnitude along all study sites. The outcome of the investigation can be very useful in the future to understand the frequent, periodic, and seasonal growth of potholes at every stage of their development. After collecting 267 griding tools from six geomorphological sites and 36 potholes from the same geocomposites selected to understand the shape, depth and diameter relationship. Hence depth and diameter relationship or the ratio of the potholes is almost maintained in homogeneous lithology with structures, but it is slightly varied due to heterogeneous channel-bed lithology as well as multi-structural units of the channel. Thus Depth and diameter of the Kukadi river are almost maintained by lithology. Based on shape as well as depth-diameter ratio outcome Honewadi (585MSL) 29.03% (31) potholes are irregular in shape, Gadilgaon(575MSL) 27.08%(48) rounded, Gunore(570 MSL) 26.78% (15) irregular, Dongargaon(565 MSL) 25.01%(44), Kohokadi (560 MSL) 28.26% (13)irregular while Mhase(565 MSL)39.95% (13) Club shape in nature. Hence the recommendation for sustainable development is essential to reduce the impact of anthropogenic activities which is present in the study area. Therefore hence it is strongly recommended to be aware to educate the related people for the conservation of the uniqueness of the study area.

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