Relationship between diameter and depth of potholes controlled by lithology and structure in the Rarh region of India

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A total of 263 riverbed potholes were studied at five sites with Precambrian Chhota Nagpur granitic-gneiss, tonalite gneiss and sandstone under Permo-Carboniferous age of Gondwana rocks. Fluvio-hydrological, geospatial and statistical techniques were used to determine the diameter – depth dynamics on lithology with structural diversity of the Rarh region of peninsular India. The diameter–depth relationship is required for site-specific regional projects such as excavation, channel-bed dredging and dam construction, specially in the stability analysis of environmental and hydraulic engineering projects. The result shows positive correlation between diameter and depth of different sites such as circular, oval and elongated sculpted forms. Lithology and multidimensional structural elements accelerate the growth and enlargement of potholes on various riverbeds of the Rarh region of India.

Keywords: Diameter–depth relationship, lithology, potholes, riverbed, structural diversity.

POTHOLES or sculpted forms of bedrock streambeds are basically various process-oriented researches which were carried out at manifold spatial and temporal scales[1–3]. Channel pothole morphologies refer as cylindrical or hemispherical concavities which are the combination of floor and wall erosion into channel beds[1,2,4–7]. This channel form is excavated by tools and grinders entrained within the persistent spiralling vortices[8,9]. Vortex or spiralling vortex is the product of interplay between liquid mass in the stream flow and preliminary depression[10]. Downward spiralling vortices apparently throw tools towards pothole walls because of centripetal force. Sediment particles within the pothole engaged in mechanical erosion are called tools, while bed loads in the pothole are termed as grinders. Bed loads or coarse tools within a pothole may skip, slide, saltate or roll and erode the pothole floor more efficiently than suspended sediments. Broadly, channel potholes are classified into three types: (i) eddy hole which is formed by mechanical corrasion in turbulent flow, (ii) gouge hole developed due to swift current, and (iii) plunge pool hole created by falling water due to knick points[9]. Based on their occurrences, potholes are also identified as (i) stream or fluvial, (ii) marine or coastal and (iii) hillside potholes[7]. These channel-bed forms or potholes require almost hundred to thousand years to develop[11], but a recent study reported that a minimum period of 60 years is required to form micro- to macro-potholes on man-made channel and basalt bedrock channel[5].

Recent studies conducted in different pockets of India reveal that different channel-bed forms such as circular, elliptical, oval, elongate, etc. have been exposed due to channel-bed lithological diversity with structural weakness and fluvio-hydrological dynamics[12–16]. Micro- to macro-scale (mm to m) bed forms generally appear due to the presence of tools and grinders within potholes, and prominent micro-geological structures like fractures and joints on the channel bed[17]. The degree of deepening and widening of potholes is controlled by wall erosion and floor abrasion[18]. Similarly, the development and assemblage of sculpted form is effectively regulated by fluvio-hydrological processes[7,19]. In the present study, we

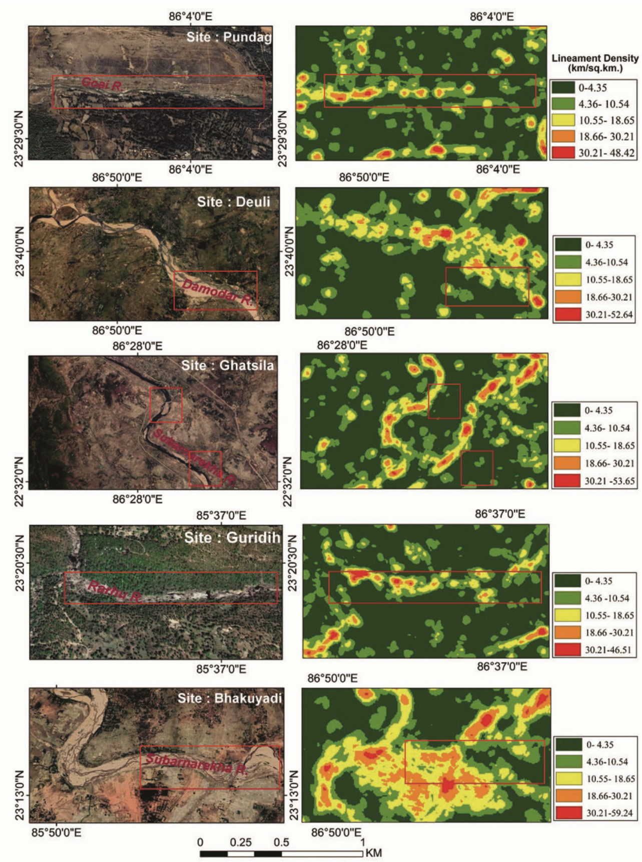

Figure 1. Lineament density map of specific channel beds and sample sites in the vicinity.

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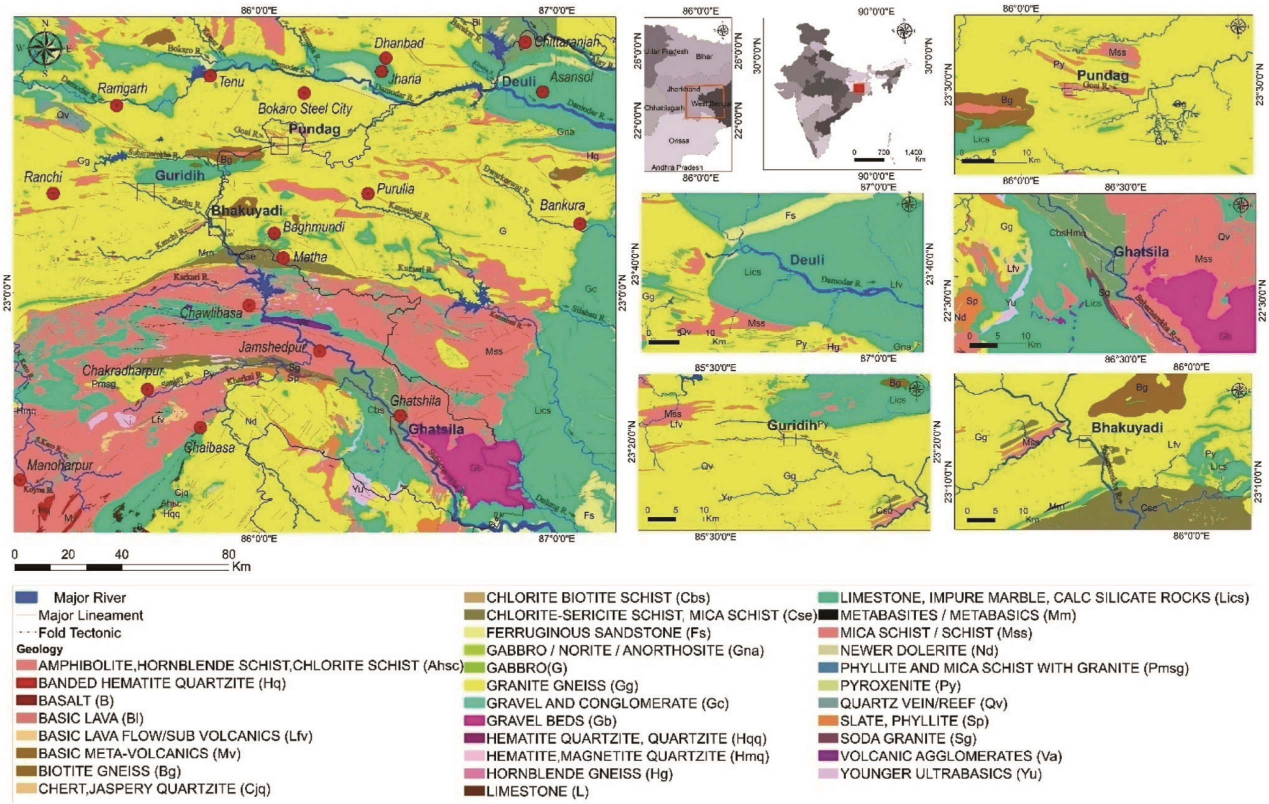

(Source: Geological Survey of India)

Figure 2. Geological map (lithology with structure) with major rivers of the Chhota Nagpur Plateau region.

determine the relationship between diameter and depth of potholes controlled by lithology and structure in the Rarh region of peninsular India.

A total of 263 channel-bed potholes were studied from five important river sites of Subarnarekha, Damodar and Goai of the Rarh region. These sites are Bhakuyadi (23°13′14.28″N, 85°51′26.68″E) ($n = 115$), Guridih (23°20′23.63″N, 85°37′06.41″E) ($n = 65$) and Ghatsila (22°34′04.99″N, 86°28′51.58″E) ($n = 35$) at Subarnarekha, Deuli (23°39′03.04″N, 86°53′03.09″E) ($n = 35$) at Damodar, and Pundag (23°29′30″N, 86°04′00″E) ($n = 13$) at Goai (Figure 1). All these rainfed rivers originate from the Chhota Nagpur Plateau and subsequently influx into the Bay of Bengal. The total catchment area of River Subarnarekha (395 km length) is 19,296 km^2 and mean discharge is 392 m^3/s, while River Damodar (547 km length) has 22,005 km^2 of the total catchment area and average discharge of 296 m^3/s (refs 20–22). River Goai is a small tributary of the Damodar and it runs roughly 1 km on undulating granitic-gneiss bedrock. The dominating Precambrian rocks of Chhota Nagpur Plateau are drained by significant rivers like Subarnarekha and Damodar, and their tributaries. The upstretch of Damodar, and up and middle stretches of Subarnarekha flow on Precambrian bedrock with narrow passage (Figure 2). During monsoon, these rivers generate strong energy and almost bankfull discharge due to the presence of numerous knick points and high channel gradient (Figure 3)[20–22].

Applying geospatial technique, lineaments was extracted using WNIR and SWIR bands of ETM and ASTER imageries. Lineament density index (LDI = $\sum_{i=1}^{N} x_i$ km/km^2) was calculated taking into account the total length of lineament per unit area to prepare the lineament density map[22]. Morphometric indices like surface index (SI), bottom index (BI) and vertical index (VI) of each pothole were earmarked by GPS and measured using fibreglass tape during fieldwork. SRTM DEM (30 m resolution) downloaded from USGS Earth Explorer and long profiles of rivers were prepared through stack profile (3D analyst tool) of ArcGIS version 10.3.1. The statistical and mathematical techniques were used to determine the diameter–depth relationship of potholes in different lithological sites of channel beds (Table 1).

Several studies showed that the dynamics of pothole growth (like initial to secondary stage as well as volumetric enlargement on sidewall and downward side) is controlled by the presence of structures and size of tools[6,11]. Volumetric erosion of wall and floor of potholes is quantified using empirical equations[6].

$$V_w/S_w, \tag{1}$$

where V_w is the volume substrate eroded from the wall and S_w is the surface area of the pothole wall. It is controlled by spatial variation in surface erosion rates.

Table 1. Various parameters of morphometric indices and statistics of rivers Goai, Damodar and Subarnarekha in the Rarh region of India

Sites (location of potholes)	Parameters	S_{max} (cm)	B_{max} (cm)	B_{min} (cm)	S_{min} (cm)	D (cm)	Surface index (SI)	Bottom index (BI)	Vertical index (VI)	Bedrock lithology
Pundag (Goai river; n = 13)	Radius (cm)	35	30	19	28	210	1.25	1.58	6.00	Granitic gneiss
	Diameter (cm)	70	60	38	56	–				
	Mean (cm)	0.21	0.16	0.10	0.15	0.49				
	Standard deviation (SD)	0.08	0.07	0.05	0.06	0.48				
	Coefficient of variation (CV, %)	38.09	43.75	50.00	40.00	97.95				
Deuli (Damodar river; n = 35)	Radius (cm)	113	111	103	100	110	1.13	1.08	0.97	Sandstone and shale
	Diameter (cm)	226	222	206	200	–				
	Mean (cm)	0.37	0.32	0.25	0.23	0.40				
	SD	0.21	0.22	0.21	0.19	0.19				
	CV (%)	56.75	68.75	84.00	82.60	47.5				
Bhakuyadi (Subarnarekha river; n = 115)	Radius (cm)	110	85	18.50	21.00	190	5.23	4.59	1.72	Chhota Nagpur granitic gneiss
	Diameter (cm)	220	170	37.00	42.00	–				
	Mean (cm)	49.50	40.81	23.92	25.10	60.96				
	SD	7.07	6.40	4.89	5.00	7.81				
	CV (%)	14.28	15.68	20.37	19.92	12.80				
Ghatsila (Subarnarekha river; n = 35)	Radius (cm)	69	46	13.00	18.00	138	3.83	3.53	2.00	Tonalite gneiss, Proterozoic metasediments and Chhota Nagpur granitic gneiss
	Diameter (cm)	138	92	26.00	36.00	–				
	Mean (cm)	24.60	19.98	16.83	12.56	27.96				
	SD	5	4.47	4.12	3.60	5.29				
	CV (%)	20.32	22.37	24.48	28.66	18.91				
Guridih (Subarnarekha river; n = 65)	Radius (cm)	95	63	15.60	17.00	165	5.58	4.03	1.73	Chhota Nagpur granitic gneiss
	Diameter (cm)	190	126	31.20	34.00	–				
	Mean (cm)	28.50	21.38	17.65	16.50	38.20				
	SD	5.38	4.58	4.24	4.12	6.16				
	CV (%)	18.87	21.42	24.00	24.96	16.12				

S_{max}, Largest diameter at the surface; S_{min}, Smallest diameter at the surface; D, Maximum vertical depth; B_{max}, Largest diameter at the bottom; B_{min}, Smallest diameter at the bottom.

Pothole dynamicity depends on the ratio between radius and depth and is determined as follows

$$\bar{r} = kd^{\varepsilon}, \tag{2}$$

where r is the radius, d is the depth, $k = 2.3$ (constant) and $\varepsilon = 0.57$ (constant).

The enlargement of depth and radius along the z–y plane requires water current with sediments and is expressed as $y = kz^{\varepsilon}$. Volumetric change of pothole floor and sidewall is calculated by integrating eq. (2)

$$V_{\mathrm{f}} = \pi k^2 \int_{z_n}^{z_{n+1}} Z^{2\varepsilon} \mathrm{d}z, \tag{3}$$

where V_{f} is the volume eroded from the pothole floor between two spacetime intervals (n, $n + 1$), Z the initial location of the pothole and k is the regression coefficient.

The volume of eroded materials from the given sites is derived using the following equation

$$2Z_n \int_{Y_n}^{Y_{n+1}} y \, \mathrm{d}z, \tag{4}$$

where Z_n is the erosional depth, Y_n the initial radius, y the radius of the pothole and Y_{n+1} is the secondary radius. The increase in the size of the pothole from primary to secondary form can be obtained as follows

$$\pi(Z_{n+1} - Z_n)y_{n+1}^2 - \pi k^2 \int_{z_n}^{z_{n+1}} z^{2\varepsilon} \mathrm{d}z, \tag{5}$$

where Z_n is the primary floor of the pothole, Z_{n+1} the secondary stage erosional pothole floor and k is the regression co-efficient.

Descriptive statistical techniques like mean

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{n} x_i,$$

correlation

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^{2-(\sum x)2}][n\sum y^{2-(\sum y)2}]}},$$

standard deviation

$$\mathrm{SD} = \sqrt{\frac{\sum(x - \bar{x})^2}{n}},$$

and coefficient of variation

$$\mathrm{CV} = \frac{\mathrm{SD}}{\mathrm{Mean}} \times 100\%,$$

were used to determine the relationship among principal components of pothole dynamics.

All the sample sites of River Subarnarekha (except Garanala confluence point which is located on the metasediments) are situated on the Chhota Nagpur granitic gneiss and tonalite gneiss. Large diameter multi-directional growth of potholes is confined on the upstretch of the Subarnarekha and its tributaries Garu and Kanchi due to the presence of moderate to high (10.55–18.65 km/km^2) and very high lineament density (30.21–59.24 km/km^2). In case of River Goai near Pundag, lineament density along the riverbed and surrounding is moderate to high (10.55–30.21 km/km^2). Around 1 km longitudinal stretch of Goai near Pundag is mostly occupied by potholes which are predominantly granitic gneiss. Rest of the region has no as such sculpted forms because of low channel gradient

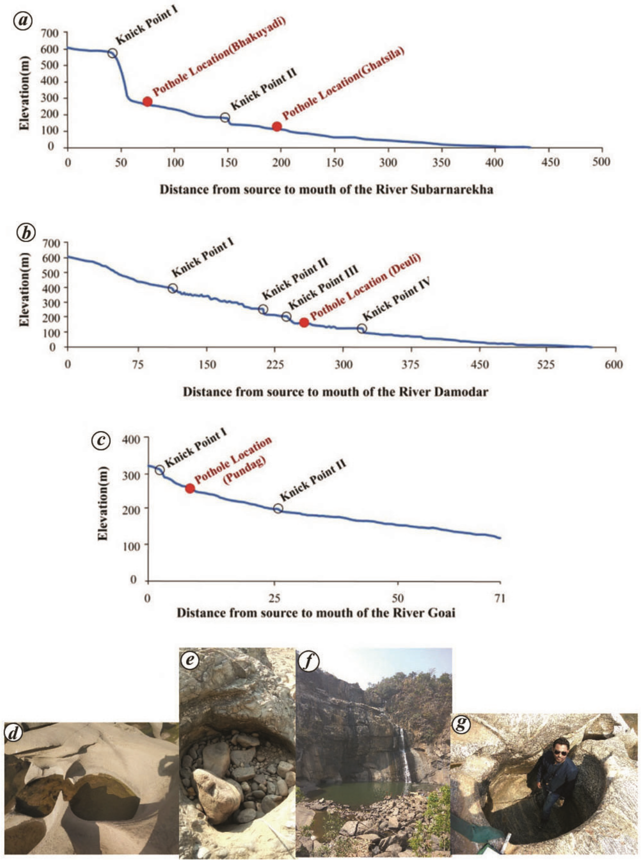

Figure 3. Location of knick points along the long profile of (***a***) Subarnarekha river, (***b***) Damodar river and (***c***) Goai river. ***d***, Truncated and amalgamated potholes with grinders on granitic-gneiss bedrock channel of Subarnarekha river at Guridih. ***e***, Potholes with tools and grinders on granitic-gneiss bedrock at Bhakuyadi site of Subarnarekha river. ***f***, Existence of knick points along upstretch of Subarnarekha river at Hundrufalls. ***g***, Large-sized pothole along with prominent joints and fractures on granitic-gneiss bedrock channel of Subarnarekha river.

with sand bed. Low to moderate (4.36–18.65 km/km^2) lineament density is found on the channel bed of River Damodar near Deuli, whereas channel-bed potholes are exposed on sandstone and shale. The dominant potholes in the upstretch of River Subarnarekha and its tributaries (like Raru and Kanchi) are mostly formed due to the existence of a series of knick points along the channel bed, followed by River Goai near Pundag (Figure 3). Multi-structural elements of bedrock channel and moderate to high channel gradient along with monsoonal high-velocity discharge and sediment load help in the growth of these significant fluvial-erosional features. Multi-dimensional growth of potholes is completely regulated by the presence of micro-geological structures and their attitude.

Using eq. (1), for example at Bhakuyadi site (River Subarnarekha), the average value of S_w was 2.98 m^2, whereas V_w was 3.45 m^3. Similarly, the average value of S_w was 0.56 m^2, whereas V_w was 1.56 m^3 for the Pundag site (Goai) and at Deuli (Damodar). The surface area of wall and floor was calculated with respect to the radius of the potholes. The volumetric substrate of wall and floor was measured by applying eq. (2) and it shows the spatial and temporal modification of channel-bed potholes. Applying eq. (2), the diameter and depth (D/h) of 263 potholes were measured at five different sites. We observed a positive relationship between diameter and depth for the above-mentioned sites (Figure 4). Subsequently, using eqs (3) and (4), the volumetric change or enhancement of the potholes along the z–y plane (z downward, y sideward) was measured. For a sample at Bhakuyadi site (River Subarnarekha), the initial area was 8.45 m^2, while the secondary area was found to be 10.54 m^2. Thus, the pothole area has enlarged by 2.09 m^2 through the amalgamation process. In all cases, area of pothole floor and sidewall had enlarged along the structural weakness on granitic gneiss and tonalite gneiss, but in the case of sandstone and shale a proportional change was recorded due to low structural geological imprints on the channel bed and surroundings. Applying eq. (5), the volume of material associated with the pothole was computed and total volume of the material (V_T) eroded between the wall and floor was calculated using the formula $V_T = V_w + V_f$. For an experimental sample at Bhakuyadi site (River Subarnarekha), V_T was approx. 57.45 metric tonnes. Such momentum change is mainly due to the oscillating spiralling vortex or turbulent flow along the flow direction of the river channel. As a result, the circular or round-shaped bedforms are generally transformed into elongate or oval-shaped potholes. Channel beds with high joints and fractures assist in the coalescence by potholes. The descending spiralling liquid directs erosive tools towards the pothole walls because of centripetal motion. The spiralling vortex of fluids accelerates the abrasion mechanism by grinders and it creates both vertical translation on the floor and radial enlargement on the walls[6]. Progressive truncation of potholes occurs at different sites of Subarnarekha and the result shows relatively larger D but smaller h (ref. 10). Here, potholes are removed rapidly due to coalescence or collapsing of the growing potholes. The erosion dynamics and consistency of geometrical properties of potholes depend on various regulating factors such as stream energy, presence of knick points, channel gradient, rock types with joints, fractures, etc.[2,5]. In this study, these diverse parameters were found to assist in the formation of different potholes, particularly of River Subarnarekha. Large-sized potholes are developed on the macro-structural elements on the channel bed. On amalgamation, the large-diameter sculpted forms (big potholes or canyons) were found on the river courses of the Rarh region of peninsular India.

Applying the morphometric indices like S_{max}, S_{min}, B_{max}, B_{min} and D (in case of Subarnarekha), 122 cylindrical, 42 elliptical and 46 elongated potholes were identified. Similarly, Goai and Damodar showed almost circular or round potholes due to micro-structural elements. CV showed that S_{max} and B_{max} are more consistent than S_{min} and B_{min} for Goai and Damodar, whereas it is moderately consistent in case of Subarnarekha (except Ghatsila site). The morphology of channel potholes at various sites of the Subarnarekha shows remarkable variation in terms of SI, BI and VI (Table 1). For example, Bhakuyadi (SI = 5.23; BI = 4.59; VI = 1.72), Guridih (SI = 5.58; BI = 4.03; VI = 1.73) and Ghatsila (SI = 3.83; BI = 3.53; VI = 2.00) reveal dramatic disparity due to existence of highly jointed structures and dynamics of fluvio-hydrological processes. River Goai shows no such significant variation particularly for SI, BI and VI (SI = 1.25, BI = 1.50 and VI = 2.28). Similarly, potholes at Damodar present no such large anomaly (SI = 1.13; BI = 1.08; VI = 0.97) due to the absence of structural grinders and low channel gradient. The fluvio-hydrological dynamics and landscape morphology also directly regulate the rapid growth of potholes on jointed bedrock channels of river Subarnarekha, while except at Deuli of Damodar, the entire middle and lower stretches of the river have been occupied by sand, silt and clay with low channel gradient. In case of Deuli, potholes stand on micro-jointed sandstone and shale channel bed. During field visit, we noticed that the tools mostly lay within sculpted forms. The monsoonal flood with high discharge directs the tools from top to bottom along the axial plane of the vortex. Therefore, smooth sculpted aperture is being formed (through abrasion) on sandstone and shale bedrock channel like at Deuli of River Damodar. Knick points (on the upstretch) of River Subarnarekha accelerate stream power and consequently channel planform has been swiftly altered into scallops like canyon. Here, fluvio-hydrological processes play a significant role in the modification, amalgamation and truncation of potholes.

According to hydro-geologists and geomorphologists, the depth and radius of channel potholes usually maintain proportional relationship. However, due to the presence

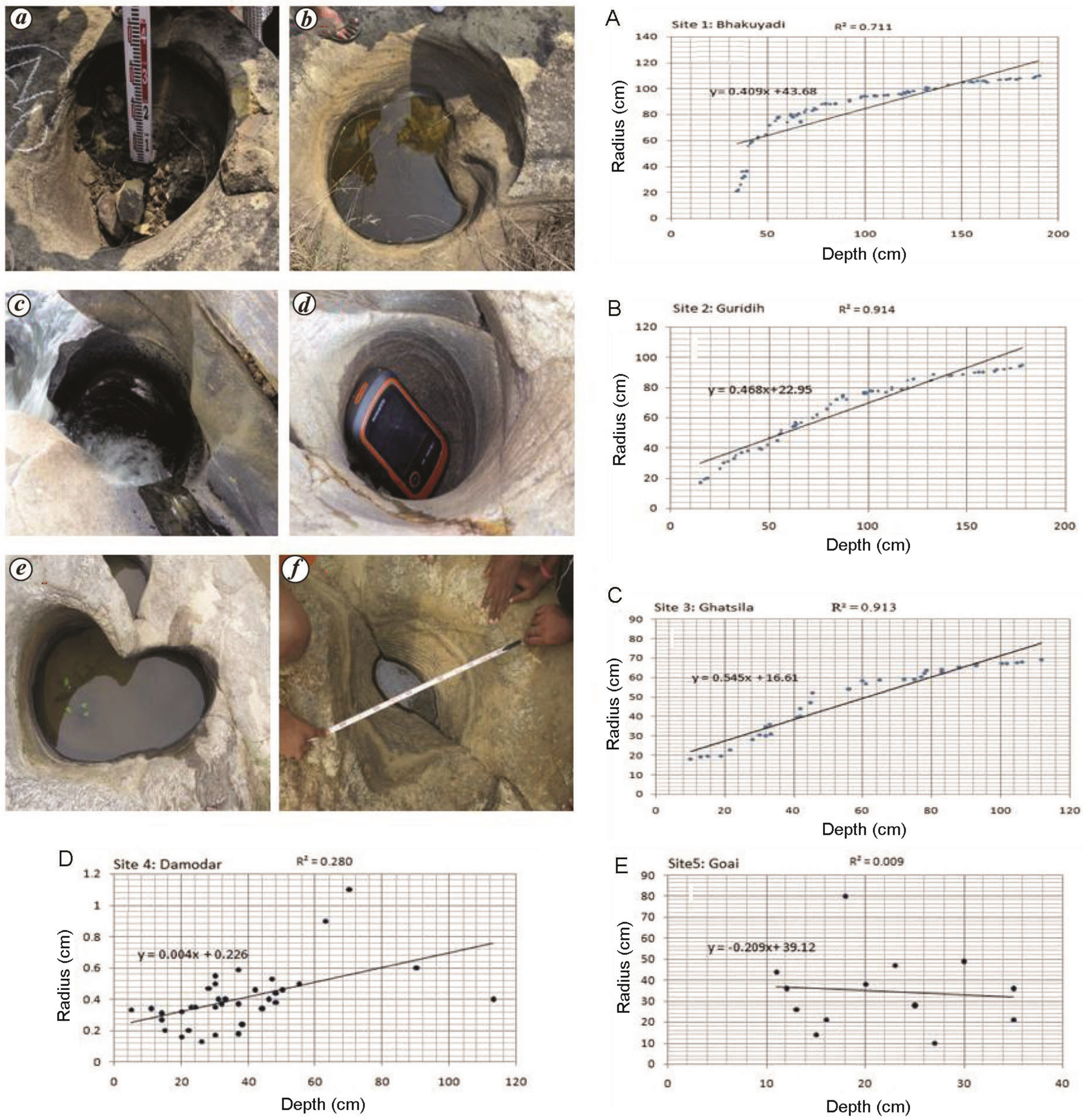

Figure 4. ***a***, ***b***, Almost round or circular potholes developed on sandstone and shale-dominated bedrock of Damodar river. ***c***, ***d***, Round as well as elliptical-shaped potholes exposed on granitic-gneiss (with prominent fractures) channel bed of Goai river. ***e***, ***f***, Elongated and irregular-shaped potholes on granitic-gneiss and tonalite gneiss with high lineament density zone of Subarnarekha river. A (Bhakuyadi) shows strong positive correlation. B (Guridih) represents strong positive correlation. C (Ghatsilla) signifies strong positive correlation. D (Damodar) shows moderate positive correlation. E (Goai) represents low correlation.

of complex geological structures coupled with dynamic fluvio-hydrological components, it becomes difficult to decipher the relationship between diameter and depth. At Subarnarekha (Bhakuyadir = 0.84; Guridihr = 0.96; Ghatsilar = 0.95), diameter and depth relationship reveals strong positive correlation. Moderate positive correlation is found at Damodar ($r = 0.52$) while low correlation exist at Goai ($r = 0.10$). The relationship between radius and depth of the above potholes was systematically evaluated and plotted (Figure 4). Strong or moderate positive correlation along with low diameter–depth (D/h) ratio signifies that the deepening and widening of potholes are proportionally escalating due to the presence of joints and fractures on the channel bed and high energy of the flowing fluids with tools and grinders. These are rainfed streams, but upstretch of River Damodar and the upper and middle stretches of River Subarnarekha flow on undulating topography with bedrock channel. Long profiles of rivers show the presence of knick points with high channel gradient. During monsoon, the rivers bring gravels, pebbles, cobbles and suspended sediments with high bank full discharge and these help accelerate the erosion rate. However the small tributary Goai (tributary of River Damodar) runs only 1 km stretch on undulating bedrock channel with low to moderate structures. Thus, potholes of River Goai show low positive correlation with moderate diameter–depth ratio. It is noticed that coarse sediments or tools are occupied in pothole floors, and low to moderate structures help in the growth of the sculpted forms while the fluvio-hydrological force does not permit effective deepening. Diameter–depth 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. Almost vertical depth of potholes is restricted with specific threshold value (maximum 60 cm in Subarnarekha and 30 cm in Damodar and Goai), but it could vary due to surface-exposed geological structures controlled by fluvio-hydrological factors.

From this study of channel-bed potholes (three rivers and their tributaries of the Chhota Nagpur Plateau), it is concluded that the horizontal incision of bedrock potholes and their growth is comparatively greater than the vertical depth due to first- and second-generation structural imprints on granitic-gneiss-dominated bedrocks. Similarly, due to the existence of multiple knick points along the course of River Subarnarekha, large-sized (diameter–depth) potholes are also exposed and accelerate the amalgamation process through sideward expansion. Vertical threshold of potholes is also restricted for specific lithology with structures and fluvio-hydrological factors (60 cm for Subarnarekha and 30 cm for Goai and Damodar) in almost all sites. Diameter–depth ratio indicates that deepening and widening of potholes are proportionally increasing due to the presence moderate to high joints and fractures and high energy of fluids with tools and grinders during the monsoonal seasons.

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