Pothole: a unique geomorphological feature from the bedrocks of Ghaghghar River, Son valley, India

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ABSTRACT
In this study, we report for the first time, the occurrence of pothole features and the processes of their development on the bedrocks of Ghaghghar River, Son valley, India. Pothole geometries were identified and measured from the middle reaches of Ghaghghar River, where it is flowing exclusively over the Rohtas limestone (a Meso-Proterozoic age) of Vindhyan Supergroup, near to the Gurma village. On the basis of field survey and remote sensing study, it has been ascertained that potholes developed in the river bed were only related to local geological and geomorphological conditions of a stream. They are mainly developed due to abrupt slope change along the river course and usually associated with intersect fractures, joints, and veins in the bedrock. The knick point of the river profile also confirms the abrupt slope change of the river in Gurma region. The river changes its course from E-W to N-S due to Markundi fault (ENE-WSW) occurring in the study area and causes the tectonic disturbances to support the development of potholes. The formations of potholes on bedrock of Ghaghghar River were generally governed by abrasion of rock fragments during high-flow regime. The geometrical dimensions of the potholes are controlled by the joints, fractures, and veins developed in bedrock of the river. The veins are typically calcitic in nature and the orientations of long axis of potholes are analogous to the trend direction of the vein. The collapse bedrocks suggest that a pothole can be formed within a short period, but cannot be fully developed and maintained for a long time in a strong incision of riverbed.

1. Introduction
Potholes in bedrocks of a river are significant with the geomorphic changes and can be produced in various ways. These are erosive features formed by fluvial processes (abrasion and or hydraulic action mainly) (Gui et al., 1999; Zhong, Ni, & Shen, 2002). Potholes may also be characterizing the bedrock fluvial channels with incision (Hancock, Anderson, & Whipple, 1998; Jennings, 1983; Kale & Shingade, 1987; Lorenc & Saavedra, 1980; Sato & Hayami, 1987; Springer, Tooth, & Wohl, 2006; Wohl, 1993). Basically, the developments of potholes are related to the position and geometric configuration of the channel but pothole shape is dependent on the bedrock mechanisms and channel hydraulics (Kale & Shingade, 1987; Springer, Tooth, & Wohl, 2005; Springer et al., 2006, Whipple, Hancock, & Anderson, 2000). Lithology also plays an important role in bedrock river erosion (Selby, 1980; Hancock et al., 1998; Richardson & CARLING, 2005; Springer et al., 2006; Wohl, 2008). Potholes can also form from relatively minor depressions associated with rock heterogeneities that result from weathering or abrasion by boulder impacts (Lorenc, Barco, & Saavedra, 1994; Wang, Liang, & Huang, 2009).

The joint, fractures, and veins of a particular area play an important role and are responsible for development of potholes. Joints can be a particularly important form of heterogeneity with respect to pothole initiation and development and can also facilitate block quarrying highlighting potential interactions between quarrying and potholes. Quarrying from zones of more locally jointed rock creates the rough bed and bank topography required to initiate flow separation and eddy formation, which in turn drive abrasion that can lead to potholes but quarrying can also remove blocks before potholes get sufficient time to form (Dubinski & Wohl, 2013). These features create a limit for the depth reached by potholes and control the occurrence of potholes (Springer et al., 2006; Whipple et al., 2000). The erosive mechanisms acting on bedrocks of a river are relevant for understanding the beginning of sculpted forms, although more in-depth understanding is needed of the processes that result in well-developed potholes. Plucking, abrasion, and cavitations can all contribute to pothole formation established the first-order scaling of forces involved in fluvial plucking and abrasion and related the relative contributions of saltation and suspended sediment grains to abrasion.

In India, Gopal (2016) reported the occurrence of pothole features in the middle reach of the River Ken.
Potholes have also been described from rivers with bedrock channels, such as the Indrayani and Kukadi in Maharashtra, India (Kale, 2014; Kale & Shingade, 1987).

The morphometric analyses of the Ghaghghar River Basin (GRB) have been studied by Singh, Kanhaiya, Singh, and Chaubey (2018a). The Ghaghghar River is third-order stream that shows dendritic to sub-dendritic drainage patterns. The trellies drainage patterns are additionally seen in a few regions of the basin which might be because of the impact of provincial tectonics. The bifurcation ratio is demonstrating normal basin which is by one means or another controlled by aerial tectonics. The low estimations of drainage density and stream frequency infer that surface run-off isn’t immediately expelled from the basin, making it prone to flooding (Singh et al., 2018a).

In the present study, we first time reported the occurrence of pothole in the bedrocks of Ghaghghar River, Son Valley, India. The possible tectonics and processes of pothole development were also discussed in detail using field survey and remote sensing and GIS techniques.

2. Geology and geomorphology of the area

The study area, located (Lat. 24°35’47.6 N Long 83°4’9.7’ E) in Sonbhadra district, Uttar Pradesh, India lies over the Vindhyan supergroup of rocks, the largest Proterozoic sedimentary basin of the Indian sub-continent (Figure 1). The Vindhyan Basin is one of the thickest (~4.5 km) Proterozoic sedimentary successions in India (Auden, 1933; Bhattacharya, 1996). The basin overlies the stable Bundelkhand Craton of Archean to Early Proterozoic age (Acharyya, 2003; Ram et al., 1996; Singh et al., 2013).

Vindhyan sedimentation commenced in an intracratonic rift setting that later transformed into a sag basin during Upper Vindhyan time (Bose, Sarkar, Chakrabarty, & Banerjee, 2001, Charkrabarti et al., 2007).

Meddlicott (1860) and Mallet (1869) divided Vindhyan supergroup into the lower Vindhyan and the upper Vindhyan. The Lower Vindhyan comprises Semri Group and the Upper Vindhyan constitutes Kaimur, Rewa, and Bhandar Group. The Semri Group includes characteristically alternating shales and carbonate units which are represented by four formations i.e., Basal, Kajrahat, Porcellanite, Kheinjua (Olive shale, Fawn limestone, Glaucolithic sandstone), and Rohtas Formation. The lower Vindhyan i.e., Semri Group and the upper Vindhyan are separated by an unconformity. Above the Rohtas Formation of the Semri Group, the Kaimur and the Rewa Groups lie, which represent sandstones, shales, and quartzites. Above the Rewa Group, the Bhandar Group lies which contain the only major carbonate unit in the Upper Vindhyan system (Bose et al., 2001) (Table 1).

In the Rohtas limestone, wavy laminations identified suggest the presence of sub angular to angular detrital quartz grains as observed in petrographic study by Sen & Mishra, 2015. All the quartz grains are scattered in predominantly micritic carbonate and minor clayey matrix. Large crystals of calcite showing polysynthetic twinning are also present. The major element chemistry is dominated by CaO (38.3–54.15 wt%), indicating carbonate precipitation (Sen & Mishra, 2015).

The Ghaghghar River starts its journey from Soma village (Lat. 24°32’58.02’ N Long. 83°23’19.02’ E) flowing in E-W direction and makes a major boundary between Bijaigarh shale and Scarp sandstone. Due to Markundi Fault striking ENE-WSW direction, the river changes its course abruptly and starts falling N-S trend before interning in the Rohtas limestone and after that in glauconitic sandstone before confluence with river Son near Patwadh village (Lat. 24°31’43.14’ N Long. 83°2’47.42’ E) (Figures 1 and 2).

3. Materials and methods

Various examinations uncovered that Shuttle Radar Topography Mission Digital Elevation (SRTM DEM) is greatly improved than ASTER DEM, in gave that generally exact information to morphometric investigations (Forkuor & Maathuis, 2012). SRTM DEM information is decided to ASTER DEM because of its nailing vertical and level precision (Forkuor & Maathuis, 2012; Kanhaiya, Singh, Singh, Mittal, & Srivastava, 2018; Patel, Katiyar, & Prasad, 2016; Singh & Kanhaiya, 2015; Singh et al., 2018b; Sun, Ranson, Kharuk, & Kovacs, 2003).

We characterized the field site using macro- and micro-scale analyses. Macro-scale analyses were based on digital elevation map (DEM) with a pixel size of 90 × 90 m obtained from the website http://srtm.csi.cgiar.org. All the lineaments, veins, and dikes were interpreted as linear structures, and the orientation of these features was compared to the orientation of the drainage network. All of the structural information of the drainages is represented in rose diagram. Regional joint patterns and dikes could be inferred from field survey and DEM analysis over the area. Micro-scale analyses involved systematic field measurements. Orientation of joints and pothole (plan view) main axes were measured with a clinometers compass. Primary and secondary flow directions were also inferred from local- and reach-scale bedrock morphology at every pothole. Primary flow direction was downstream in the channel, whereas secondary flow direction was identified based on local obstructions and evidence of flow separation.
4. Result and discussion

4.1. Morphotectonics of the Ghaghar River

4.1.1. Lineament study

The lineaments are one of the important components of the earth’s surface morphology and deformation (Nur, 1982). The orientation of various linear elements observed on the basis of sentinel-2 imagers and further validated by field studies. A total 112 linear structures have been mapped from sentinel-2 imagers and the orientations of these linear structures have been shown in the form of a rose diagram (Figure 3). Azimuthally the frequency of NW-SE and NE-SW trending lineaments is comparatively...
high. It is interesting to note that the maximum lineament direction same as or analogues Son-Narmada North Fault (SNNF) reveals that these fractures can be formed either due to tectonic activity of SNNF or secondary tectonic disturbances associated with them. Some of the lineaments do not follow regional trend and can be secondary faults generated due to the SNNF in the study area.

A number of veins and joints/factures have been observed in the study area during the field survey. We also determined the mineralogy of the veins present on the river bed by using X-ray diffractometry. The overall XRD results show the calcitic nature of these veins. A representative diffractogram is given in Figure 4(a,b).

### 4.1.2. Longitudinal profile of the river

The evolution of tectonic deformation can be signified based on drainage system of a region (Gloaguen, 2008; Holbrook & Schumm, 1999; Peters & Van Balen, 2007; Schumm, 1986). By altering the base level of erosion, tectonic activity will change stream flow characteristics mainly by altering incision rates or by causing diversion. If tectonically forced diversion has not occurred, analysis of stream characteristics can be used to infer the tectonic activity that caused the incision (Larue, 2008a). Channel longitudinal profiles result from the interaction between fluvial incision, lithology, tectonics, and base-level change (Brocard, van der Beek, Bourles, Siame, & Mugnier, 2003; Gelbert, Fornos, Pardo, Rosello, & Segura, 2005; Larue, 2008b; Snyder, Whipple, Tucker, & Merritts, 2000). Longitudinal profile development also depends on the variability of lithology (Duvall, Kirby, & Burbank, 2004; Stock & Montgomery, 1999). Longitudinal profile of rivers show tectonic activity through their overall morphology and knick points in locations where change in river gradient is rapid. River profile records long-term system equilibrium (Ritter, Kochel, & Miller, 2002), and rivers that are in equilibrium exhibit a concave upward shape where higher order streams have lower gradients than lower order streams (Keller & Pinter, 2002). Knick points, the steep reaches in the longitudinal profile can be caused by more resistant lithology or by an increase in shear stress or by surface uplift (Bishop, Hoey, Jansen, & Artza, 2005).

Longitudinal profile of Ghaghghar River show variable curves and gradients. In its catchment, two knick points have been identified and occurred before changing its stream direction from E-W to N-S due to affect of Markundi fault. First knick point occurred at 14 km and elevation 360 m, and second at 39 km and elevation 320 m as we go toward lower reaches of the river (Figure 5(a)). These anomalies in profile can indicate either a stream in equilibrium where the upstream retreat communicates changes in base level to upstream valley (Bishop et al., 2005) or in some cases a dynamic

**Table 1.** The generalized stratigraphy of Vindhyan Supergroup (Modified after Auden, 1933; Banerjee, Dutta, Palkaray, & Mann, 2006).

| Upper Vindhyan | Rewa Group | Kaimur Group | Lower Vindhyan |
|----------------|------------|--------------|---------------|
| Bhander Group  | Sirbu Shale Formation | Upper Kaimur Sandstone Formation | Rohtas Limestone |
|                | Lower Bhanter Sandstone Formation | Lower Kaimur Sandstone Formation | Rheinjua Shale |
|                | Bhanter Limestone Formation | Bijaghar Shale Formation | Porcellanite Formation |
|                | Ganurgarh Shale Formation | Lower Bhander Sandstone Formation | Kajrahat Formation |
|                | Bhanter Limestone Formation | Rewa Shale Formation | Deoland Formation |
|                | Sirbu Shale Formation | Rewa Sandstone Formation | |
equilibrium between fluvial processes and tectonic movements (Snow & Slingerland, 1990). These knick points correspond to the lithological variation and/or resultant of the regional tectonics. The cross-section profile of the river in the Gurma village has been also prepared showing left bank (elevation 150 m) having higher than right bank (144 m) with deep mid channel having elevation of 136 m from mean sea level (Figure 5(b,c)).

4.1.3. Asymmetry factor
Asymmetry factor includes directions of possible differential tectonic activity and is also sensitive to uplift and subsidence of discrete blocks versus broad tilting (Pinter, 2005). This factor gives a definite clue to establish the lateral tilting of a basin with respect to the river (Cox, 1994; Cuong & Zuchiewicz, 2001; Prakash, Mohanty, Pati, Singh, & Chaubey, 2016; Raj, 2012). The asymmetric factor (AF) is defined as:

$$AF = 100 \left( \frac{Ar}{At} \right)$$

where $Ar =$ area of the right side of the trunk stream, and $At =$ total area of the drainage basin. If $AF > 50$, then river has shifted toward the left side of the drainage basin (Molin, Pazzaglia, & Dramis, 2004). If $AF < 50$, then river has shifted toward the downstream right side of the drainage basin (Molin et al., 2004). Gaghgar basin has $AF = 38$ showing that channel has shifted right side of the basin i.e. in south ward direction.

4.2. Aerial morphotectonics
The Gaghgar River flows exclusively in Semri and Kaimur Group of rocks of the Vindhyan supergroup. The frequency maxima of the lineament in the Semri Group are showing concentration in N-S direction. Though the lineaments are smaller in size, orientated perpendicular to E-W trend which is the direction of major fold axis of the Semri Group. The relationship between fold axis (E-W) and the lineaments (N-S) suggest that they might have been developed during release fracture after folding in the area (Mohan, Srivastava, & Singh, 2007). The late upliftment might have caused the development of these fractures to release the sorted elastic strains contained in essentially solid rock materials (Price, 1966). The late tectonic strains may be stored elastically for tens or hundreds of millions of years and therefore these fractures may be from long time after the imprinting of stress condition (Mohan et al., 2007; Price, 1966). This suggests that the lineaments observed in the Semri Group (Lower Vindhyan) are very recent and are developed by the releasing of overburden with different types of erosional processes in the Son valley area (Figure 6(a)).

Another lithological unit is Kaimur Group of rocks (Upper Vindhyan) associated with the Gaghgar River. An ENE-WSW major fault system is present in the area commonly known as Markundi Fault having parallelism with SNNF in the southern side. The Markundi fault (ENE-WSW) makes the boundary between Lower Quartzite and Scarp Sandstone.
member of the Kaimur Group in the study area (Figure 1). The observed parallelism of the lineaments of the Kaimur group with the Markundi Fault and SNNF trend suggests that these lineaments may be reactivation of Markundi Fault and or SNNF. This finding of the present study supports the previous study of Mohan et al. (2007) (Figure 6(b)).

4.4. Pothole geometry

In general, the potholes were not usually found in the lower flow regime and majority of the potholes were developed on the high-flow regime condition (Wei et al., 2009). The potholes changed unevenly in size, shape, and depth depending upon flow velocity of the water. This indicates that development of pothole was only related to the geology, geomorphology, and flow patterns of the river (Wei et al., 2009).

On the basis of geometry, a total three types of potholes have been identified from the bedrocks of the Ghaghgar River. Circular potholes are the most common type of the potholes in the study area i.e., 63% of the total potholes have diameter from 22 to 132 cm and 4–12 cm depth on an average. They occur where the bedrocks are having veins of calcite and also joints/fractures. In these areas, the swirling water spins the load of the river and makes circular

Figure 4. a, b X-ray diffraction pattern of the samples of the Vein presented on the bedrock of the Ghaghgar River, Son Valley, India.
depressions in the bed rocks over which the river is flowing. The representative filed photographs are shown in Figure 7.

The elongated potholes are the second most common types of pot holes occurring in the study area after circular potholes. These potholes having 29% of
population among the all show orientation of long axis either along the flow direction of the river or parallel to the calcite veins in the area. These are also more deepening (19–27 cm) than the circular pothole. The long axis is 17–33 cm and the short axis is 4–18 cm accordingly. These types of potholes generally indicate the higher flow regime and low eddy currents (Figure 7). After long time, these pothole collapses and valley deepening takes place in the area (Figure 8).

The concentric potholes are often associated with the giant veins of the dolomite in the limestone bed rocks of the Ghaghgar River. The concentric and elongated potholes are found together in the present study. The concentric potholes are covering 16% of the total population after elongated and concentric potholes (Figure 7).

5. Conclusions

This is the first report of potholes’ occurrences and their development from the bedrocks of Ghaghgar River, Son Valley, India. The formation and development of stream potholes relate only to local conditions (i.e., geology, geomorphology, and flow dynamics of the river) where the potholes emerge. The augmentation of a pothole started from a primary depression which is a weakness or a triangular impact pit on bedrock of the river. The geometries of a pothole are controlled by tectonic joints/faults/veins. The possible model of the pothole development is given in Figure 9. The Potholes are more or less associated with regional tectonics that affect drainage dynamics of the river. Overall, the study summarizes that the development of potholes are controlled by lithology, geomorphology, and tectonics of the region.

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Figure 8. Field photograph is showing collapse type of pothole.

Figure 9. Conceptual model is showing the different processes of pothole development.
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