Chapter 1

Introduction

1.1 Rationale and significance of the study

A river is a natural water channel, usually freshwater, flowing towards an ocean, a lake, a sea, or another river. On the basis of the bed and bank materials, rivers are classified mainly into two categories namely alluvial and bedrock rivers and the combination of both may be called mixed bedrock-alluvial rivers.

An alluvial river is a river in which, the bed and banks are made up of mobile sediment and/or soil. Alluvial rivers have channels and floodplains that are self-formed in unconsolidated or weakly-consolidated sediments. Alluvial rivers erode their banks and deposit material on bars and their floodplains. A bedrock river is a river that typically has little to no alluvium mantling the bedrock over which it flows. Such rivers are common in upland and mountainous regions. They are formed by incision into bedrock by a combination of abrasion as sediment in the flow collides with the channel bed and removes bits of material, and "quarrying" or "plucking" as large blocks of bedrock are pulled from the bed (often near ledges and waterfalls) and transported downstream. Bedrock rivers form when the river downcuts through the sediments and into the underlying bedrock. This phenomenon occurs in regions that have experienced some kind of uplift or which have hard lithology. Rivers that go through patches of bedrock and patches of deep alluvial cover are classified as mixed bedrock-alluvial.

In the last two decades investigation on bedrock channels and fluvial erosion has seen a noteworthy increase in interest. It was accepted that these channels play a crucial role in the development of the entire landscape. They set the base-level for hillslope response, control the relief of a region and are major agents of sediment transport (Whipple, 2004). An idea of a dynamic combination between climate-driven erosion and tectonics received wide interest in the nineteen nineties (Molnar and England, 1990; Willett, 1999), and triggered exhaustive research in bedrock channels and fluvial erosion. Fluvial geomorphologists have recognized importance of bedrock channels because they behave quite differently than alluvial channels, which river
research had focused on for many decades (Tinkler and Wohl, 1998; Wohl and Merritts, 2001; Richardson and Carling, 2006; Turowski, 2010).

Previous work on Bedrock channels has been scanty and frequently focused on small-scale features of rock surface such as potholes, or upon the single catastrophic floods (Tinker and Wohl, 1998). Bedrock channels came into the focus of geomorphic research in the recent decades. Despite new insights, many research questions remain open. The subject of bedrock channels has a large but scattered literature dating back over a century. The world distribution of studies in bedrock channels has been shown by Tinker and Wohl (1998). Their map indicates that most of the bedrock channels investigations are from USA and Australia. Studies of bedrock channels from rest of the world are very limited. Like other countries of the world, the research on bedrock channels in India is also inadequate though the bedrock channels are existing in many areas.

The Par River has been selected for studies on bedrock channels. The river has its source in the Northern Maharashtra particularly in the western part of the Nashik District. The river is deeply incised into the upland plateau namely the Jawhar Plateau. The river is intact in terms of study of bedrock channels and the knowledge of the river is scanty. In addition to this, in August 1968, July 1976 and August 2004, major floods were reported from the Par River. Such events are rare and meteorologically, hydrologically, and geomorphologically extremely important. Such floods provide an opportunity to examine the role of floods in shaping bedrock channels. Therefore, in view of the insufficient existing knowledge of the bedrock channel of the Par River and in order to study various aspects of the bedrock channels in terms of its form and processes, it is decided to undertake a detailed study of the Par River.

1.2 Introduction

1.2.1 Definition(s) of bedrock channels

In concord with prior definitions of bedrock channels (Gilbert, 1877; Howard, 1980; Howard et al., 1994; Montgomery et al., 1996), Whipple (2004) wrote the definition as “bedrock channels lack a continuous cover of alluvial sediments, even at low flow, and exist only where transport capacity \((Q_c)\) exceeds sediment flux \((Q_s)\) over the long
term \((Qs/Qc<1)\). A second definition by Tinkler and Wohl (1998) identifies “bedrock channels as those reaches along which a substantial proportion of the boundary \((\geq 50\%)\) is exposed bedrock, or is covered by an alluvial veneer which is largely mobilized during high flows such that underlying bedrock geometry strongly influences patterns of flow hydraulics and sediment movement.” Both statements define bedrock channels according to the extent of alluvial cover on the bed and equate scarce cover with a physical condition in the river. However, Turowski et al. (2008) propose to define fluvial bedrock channels as “channels that cannot substantially widen, lower or shift its bed without eroding bedrock”.

Turowski et al. (2008) emphasised the twofold role of sediment in bedrock channels and introduced the tool and cover effect of sediment to define the bedrock channels. According to him, increasing sediment supply will boost the number of impacts per unit bed area and time and with it the erosion rate (i.e. the tools effect). Nonetheless, a further increase of sediment supply may result in increased bed cover, protecting the bed from impacts, and decreasing the erosion rate (i.e. the cover effect).

### 1.2.2 Morphological Features of the Par River

The morphological features of the bedrock channels are different than that of alluvial channels. Extensive literature is available on morphological features of alluvial channels as compared to bedrock-dominated channels. However, earth scientists have shown growing interest in bedrock rivers research in last one and half decades. Bedrock channel morphology reflects the interactions between erosive processes and the resistance of the channel substrate (Wohl, 1998). Five classes of single flow path bedrock channels according to reach morphology have been proposed by Wohl (1998) and Wohl and Merritt (2001). Duckson and Duckson (1995); Wohl (1998), Wohl and Grodek, (1994); Wohl and Legleiter (2002) and Wohl and Merritt (2001) have identified plane bed, pool-riffle, and step-pool channels in bedrock. Besides, Wohl et al. (1999) and Wohl and Merritt (2001) have observed channels with undulating walls and with inner channels as separate morphologies. In channel planform, straight, meandering and anastomosing channels have been studied by Moore, 1926; Wohl, 1998; Baker and Kale, 1998; Kale, 2005 and Barbour, 2008. A variety of fluvially sculpted surfaces and erosional bedforms were observed in bedrock channels, controlled by substrate type, flow regime and dominant erosional processes (e.g.,
Allen, 1971; Richardson and Carling, 2005; Springer and Wohl, 2002; Tinkler, 1997b). Wohl (1998) have identified the bedrock channel forms that result from erosional processes at various spatial scales (Table 2.1). Alluvial channels are self-formed through independent adjustments of the morphological variables comprising their hydraulic geometry (Leopold and Maddock, 1953; Maddock, 1976). Bedrock river channels present various thresholds to effective channel adjustments. Therefore, only relatively rare, high-magnitude flood discharges contribute to shaping their morphologies. Therefore, an attempt has been made to study the morphological features of bedrock channel of the Par River in detail.

Bedrock rivers are predominantly erosional, however, they exhibit abundant depositional features. Infrequent large magnitude floods are associated with the processes of extensive erosion and deposition in resistant-boundary channels. In bedrock channels erosion process takes place in the constricted reaches. These reaches of high flow energy and competence accelerate the amount of sediment transported and deposited by the flood. Therefore, an attempt has been made to measure and map the depositional features of the Par River.

1.2.3 Erosional Processes and Sediment Transport

The bedrock channels are supply limited (since the transport capacity of flow is greater than the supply of sediment) and the morphology of bedrock channels is dominated by the processes of erosion. The bedrock substrate is dominantly eroded by processes of (i) corrosion, or chemical weathering and solution, (ii) corrasion, or abrasion by sediment in transport along the channel, and (iii) cavitation and other hydrodynamic forces associated with flow turbulence (Wohl, 1998). Other processes such as shear detachment or fluid stressing, quarrying or plucking, hydraulic wedging and knickpoint migration may contribute for bedrock erosion. According to Hancock et al. (1998) the processes such as abrasion and quarrying appear to be very active in the erosion of bedrock channels, the process of cavitation is potentially important and other processes (e.g., chemical dissolution) are undoubtedly significant in some other bedrock channels; however, they appear to be less significant in the channels with hard lithology. Some evidences exhibit that bedrock channel dimensions also scale with flow notwithstanding the high erosional thresholds and substrate heterogeneity in bedrock channels (Montgomery and Gran 2001; Wohl and David, 2008). Local
bedrock properties, however, also influence channel morphology (Montgomery and Gran 2001). Thus, feedbacks between bedrock channel characteristics and hydraulic parameters expected to govern the balance between scaling of channel dimensions and spatial variability of channel forms by flow (Goode and Wohl, 2010).

Notably little information is available regarding the concrete processes by which bedrock channels are eroded. The reason may be very slow and infrequent bedrock erosion on a human time scale as efficiently prohibits direct measurement (Wohl, 1998). Due to above reasons bedrock erosion processes can be studied from indirect sources such as channel form. Scientists are gradually getting acquainted with the significance of rare events such as floods in shaping the landscape. These floods produce surprisingly spectacular geomorphic response (Baker and Costa, 1987). During such floods, the sediment particles lying on the channel bed of rivers are put in motion through continual impacts, they erode the exposed bedrock. Little quantitative hydraulic data on rare floods on the Par River are available. Therefore, the analysis of local flow hydraulics and its spatial variation were obtained by calculating the hydrodynamic variables within the different segments of cross-section. We used the parameters of flood hydraulics and hydrodynamics such as unit stream power, shear stress, Froude number, Reynolds number and critical velocity to understand geomorphic efficacy of floods. Critical unit stream power, boundary shear stress and mean velocity values necessary to entrain cobbles and boulders were estimated on the basis of empirical relationships for coarse sediment transport.

1.2.4 Role of Lithology and Tectonics

The morphology of channel is predominantly function of fluvial forces applied and bedrock resistance offered. The rock resistance to flow dynamics noticeably varies with respect to lithological considerations. The erodibility of rocks relies on the lithology which strongly controls the erosional processes. In this standpoint rocks are frequently referred to as ‘hard’ or ‘resistant’ or ‘weak’ and ‘non-resistant’ to erosional processes (Goudie, 2004). The rock resistance refers to the inherent property of the rock to resist any changes in its shape or size. It is significant property of rock to find out the efficiency of various processes like weathering and erosion. In order to find out effects of rock strength/role of lithology in shaping the landforms, weathering phenomena and relative dating, the Schmidt hammer (SH) has now been adopted by
Geomorphologists (e.g. Ericson, 2004). The instrument was devised by E. Schmidt in 1948. Primarily Schmidt hammer has been used by civil engineers to test the strength of concrete. However, from last few decades, Geomorphologists and Geologists have started using SH to estimate the strength of rocks for numerous reasons (Goudie, 2006). SH measures the distance of rebound of controlled impact on a surface and represents a relative measure of surface hardness or strength (Goudie, 2006). There are three versions of the Schmidt hammer i.e. N-type, L-type, and P-type. The ‘N’ type SH has most commonly been used by Geomorphologists. It has been used to study a wide range of rock types from weak to very strong with compressive strengths ranging from c. 20 to 250 MPa.

Along with lithology, tectonic uplift has also significant role in controlling the efficiency of erosional processes ultimately shaping the channels. Geomorphometric description of the tectonic characteristics of a landscape is an immensely complicated task. It is well recognized, however, that the commonly-used geomorphic indices of active tectonics (GAT) have been developed as basic reconnaissance tools to assess the relationship between tectonics and basin morphology on the regional or basin scale and to identify areas experiencing tectonic deformation (Bull and McFadden, 1977; Keller, 1986; Keller and Pinter, 1996; Burbank and Anderson, 2001; Della Seta et al., 2004; Kale and Shejwalkar, 2008). The results of several geomorphic indices can be combined to provide an assessment of a relative degree of tectonic activity in an area (Keller and Pinter, 1996). Therefore, an attempt has been made to ascertain the morphotectonic characteristics of the Par River by deriving the commonly used geomorphic indices of active tectonics (GAT). The analysis primarily addressed the response of bedrock channel of the Par River to lithology and tectonic upliftment, which play critical role to change the form of the channel.

1.2.5 Flood Hydrometeorology, Hydrology and Geomorphology

River incision into bedrock is a significant erosion process that has an impact on the rate of landscape response to changes in rock uplift rate and climate (Howard et al., 1994). According to Whipple (2004), bedrock rivers play a dominant role in erosional landscape progression, moreover, (i) they set the baselevel for hillslopes; (ii) they transport sediment to depositional basins and (iii) they commute changes in-between tectonic and climatic boundary setting all over the landscape. Rainfall, therefore
floods, is one of the conspicuous climatic elements playing a significant role in landscape development, whose characteristics, predominantly, the distribution in space and time are important from the standpoint of flood generation in the monsoonal regions. Consequently, the main objective of the present study is to analyze the available meteorological data and to identify the rainfall characteristics that produce large floods on the Par River. The Par River and its tributaries are rainfed. Therefore, all floods on the river are caused by heavy to very heavy rainfall during the southwest monsoon season. A variety of flood-generating meteorological conditions are responsible for producing excessive, widespread rainfalls. These comprise, (a) active to vigorous monsoon conditions, (b) low pressure systems (LPS) originating over the Bay of Bengal, and (c) land depressions. The characteristics of flood-producing rainfalls and the associated synoptic situations are described below. Rainfall data were available for five rain gauge stations located within and close to the basin (Figure 5.1). The data were available for more than 100 years except Surgana Station for which data were available for 50 years. The data were collected from India Meteorological Department (IMD), Pune.

According to Leopold et al. (1964) and Schumm (1977) the channel form and the processes of erosion and transportation in a river are closely associated with the river regimes specifically to the flows which they transmit. The regional hydro-climatic regime conditions strongly control the river regime (Beckinsale, 1969). Numerous case studies in the last four decades have showed that the geomorphic effects of a discharge of a given magnitude and frequency differ from one regime to another (Hire, 2000). For instance, Wolman and Miller (1960) revealed that the frequently occurring low and moderate flows largely determine the transfer of sediments and the channel size under humid temperate regime. On the contrary, infrequent large magnitude floods maintain and control the channel size of rivers in arid tropical regime (Wolman and Gerson, 1978). In semi-arid tropics the channel morphologic properties are not directed by a particular discharge but by a series of discharges taking place at different intervals (Pickup and Riger, 1979). Similar conclusion has been proposed by Gupta (1995a) he suggested that in seasonal tropics the rivers are not only controlled by the seasonality of discharge but also high-magnitude floods. Hire (2000) opines for the Tapi River that the low- or moderate-magnitude flows transport most of the fine-grained sediment (clay, silt and sand) and modify the
channel bedforms to some extent. However, the channel size and shape is maintained by large-magnitude floods that occur at long intervals. Considerable attention has been given to morphology of bedrock channels and dynamics and to fluvial erosional processes in recent years (Turowski et al., 2008 and references therein). These studies, therefore, point out that a systematic understanding of the main features of the fluvial and flood regime of a river is essential for the estimation of the pattern of geomorphic work. In the present study, hence, an attempt has been made to inspect the mean annual flow pattern and the flood regime of the Par River through the analysis of streamflow/discharge data.

Floods play a dominant role in shaping the river channel and the landscape in certain hydro-geomorphic environments, such as the seasonal tropics (Wohl, 1992b; Gupta, 1995a). In accordance with Bakers (1988) view, flood geomorphology is concerned with the processes, forms, effects, and causes of floods. The frequency and hydraulic properties of the high flows play foremost important role to shape the channel and to carry the sediment. Infrequent large floods that occur at an interval of several decades are associated with much higher levels of power expenditure and thus are capable of producing major channel changes and movement of coarse sediments (Baker and Kale, 1998). In flood geomorphology, the measurement and evaluation of the geomorphic effectiveness of flows of different magnitude has been one of the significant themes. Efficacy of events in shaping landforms is measured by the magnitude of flows, by the frequency with which they occur, and by the amount of suspended sediment they transport (Wolman and Miller, 1960). Recently, the potential of flood flows has also been assessed in terms of the channel boundary shear stress and stream power per unit boundary area (Baker and Costa, 1987), as well as the flood flow duration (Costa and O’Connor, 1995).
The Par River is primarily flood-controlled. Nonetheless, whether a large discharge occurrence on the river is geomorphologically effective can be determined by understanding the channel geometry, the hydraulic characteristics of floods and the dynamics of coarse sediment transport. Thus, in the present study, an attempt has been made to describe and analyze the channel size, shape and coarse sediment characteristics of the Par River to recognize the relative significance of low and high flows. Besides, hydraulic geometry and energy exerted by floods have also been determined for some sites to evaluate the geomorphic effectiveness of flows of different magnitude and return period.

1.3 Research questions

The present study attempted to seek the answers to the following questions on the basis of field surveys, available secondary data and suitable research techniques.

- What are the channel morphological features of the bedrock Par River?
- What are the erosional processes? and what are the modes of entrainment and transport of large clasts?
- How lithology controls erosional processes and channel morphology? and how bedrock channel of the Par River gives response to the tectonic upliftment?
- What are the hydrometeorological, hydrological and geomorphological characteristics of floods of the Par River?

1.4 Hypothesis

The present study has been based on a hypothesis which has given the direction to the work. Following hypothesis is formulated for the present research work.

- Changes in channel morphology in bedrock streams occur rapidly and episodically during infrequent intense large magnitude floods in contrast to the more frequent floods of low magnitude.

1.5 Main objectives of the study

- To record and explain the longitudinal variations in the morphologic features of the Par River.
- To investigate the characteristics of the Par River in term of erosional processes and sediment transport.
• To understand the role of lithology and the variations in the hydraulic conditions along the river.
• To examine the rainfall regime of the basin and to study meteorological characteristics associated with floods in the river basin.

1.6 Introduction to the study area

1.6.1 Geomorphic setting

The Par River from western India has been selected for the present study. It has its source near Harantekadi at an elevation of 982 m ASL. The Par River flows to the west through Maharashtra (46.45% area) and Gujarat (53.55% area) States and drains into the Arabian Sea near Umarsadi in the Gujarat State (Figure 1.1). The length of the river is 142 km. The Nar River, with the length of 87 km, is the major northern tributary of the Par River. Other tributaries of the Par River are the Keng, the Bhensdara, the Walandi, the Bhimtas, the Dholdo, the Jamul, the Vajri, the Mani, the Julwan, the Matuniya and the Manmora, etc. (Figure 1.2). The Par Basin extends over an area of 1664 km$^2$. It lies between 20°15′41″ and 20°35′32″ North latitude and between 72°53′14″ and 73°43′19″ East longitude. Physiographically, upper Par River and its tributaries flow on the Jawhar Plateau through highly meandering path, whereas, lower river flows on the Kokan Plains (Figure 1.1).

The Par Basin is bordered by, roughly east-west trending, Surgana and Peth Ranges to north and south respectively and by Western Ghats to the East (Figure 1.1). The altitude of Surgana and Peth Hills ranges from 450 to 750 m ASL. The Western Ghats (>900 m ASL) is higher in altitude than Surgana and Peth ranges. The basin relief, i.e. Kem Hill (1177 m), is located as offshoot of Western Ghats. The Par and the Nar Rivers are separated by a small Barhe Plateau which ranges in altitude between 450 and 750 m ASL. One of the tributaries of Bhimtas River (a tributary of the Par River) has breached the Barhe Plateau to the east of 73°20′E longitude and has developed a gap known as “Avalkhindi Gap” near village Avalkhindi (Figure 1.1).
1.6.2 Climate

The Par River and its tributaries are south-west summer monsoon fed (June to September). The basin is situated in an environment classic of monsoonal tropics, with periodic high-magnitude rainfall. The average annual rainfall of the basin is 2094 mm and 98% of the annual rainfall occurs during south-west summer monsoon season. July is the rainiest month throughout the basin followed by August and both the months account for 39% and 27% the total annual rainfall of the basin respectively.

Spatially, the annual rainfall displays a marked variation within the basin. This variation has been represented by isohyetal map of the Par Basin (Figure 1.3). Geographical location, orographic effect of Barhe Plateau (interfluves of Par and its major tributary Nar) and the east-west trending ranges in the Par Basin play significant role in rainfall distribution. For instance, Peth Range, Surgana Range and other interfluves act as barrier for the rain bearing south-west monsoon clouds (Figure 1.1). It attributes to maximum amount of rainfall in the middle of the Par Basin (2200 mm to 2300 mm).Being distant from the coast, the amount of rainfall reduces towards the source of the Par and Nar Rivers. It ranges between 1700 mm and 1800 mm. However, due to proximity of the coast the amount of rainfall is more at the western part of the basin ranging from 2000 mm to 2200 mm. Most part of the basin receives about 1800 mm to 2200 mm rainfall with average annual rainfall of 2094 mm (Figure 1.3). The basin occasionally receives heavy rains due to cyclonic storms and depressions originating over the Bay of Bengal or adjoining land and traverse toward the basin. The flood generating hydrometeorological conditions in the Par Basin have been discussed in greater details in the fourth chapter.
Figure 1.1 Geomorphic Setting of the Par Basin

Source: ASTER Data
Figure 1.2 Drainage Network of the Par River
Figure 1.3 Rain Gauge stations and Isohyets of the Par Basin

Rain Gauge Stations: 1 = Surgana; 2 = Devsane; 3 = Bhanwad; 4 = Nanashi; 5 = Peth; 6 = Pindval; 7 = Dhamni; 8 = Mandava; 9 = Nanivahial; 10 = Dharampur; 11 = Panchlai; 12 = Pardi.

1.6.3 Drainage basin and network characteristics

According to Schumm (1956), Morisawa (1962) and Leopold et al. (1964), the hydrological characteristics of a river are controlled to a large measure by the drainage basin and network characteristics. The drainage basin characteristics, for instance, basin relief, size, shape, drainage density, etc. play significant role in the generation of floods. Table 1.1 gives the primary basin and discharge characteristics of the Par Basin.

Table 1.1 Morphometric properties of the Par Basin

<table>
<thead>
<tr>
<th>Morphometric parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin area</td>
<td>1664 km²</td>
</tr>
<tr>
<td>Basin relief</td>
<td>1177 m</td>
</tr>
<tr>
<td>River length</td>
<td>142 km</td>
</tr>
<tr>
<td>Average channel slope</td>
<td>0.0069</td>
</tr>
<tr>
<td>Elongation ratio</td>
<td>0.49</td>
</tr>
<tr>
<td>Form factor</td>
<td>0.082</td>
</tr>
<tr>
<td>Peak on record</td>
<td>23820 m³/s (1968)</td>
</tr>
<tr>
<td>Unit discharge</td>
<td>5.4 - 101 m³/s/km²</td>
</tr>
</tbody>
</table>

The Par River and its tributaries have collectively created a dendritic drainage pattern. There are 12 major tributaries of the river (Figure 1.2; Table 1.2). The largest tributary, i.e. the Nar rises very close to the source of the Par River, at Kem Hill (1177 m), and flows generally towards west. It accounts for almost 25% of the total area of the Par Basin. The Nar River flows in highly meandering path, before entering in the Par River at Dhamni (Figure 1.1). Some of the other main tributaries of the river such as the Keng, the Dholdo, the Mani, the Matuniya, and the Manmora head in the Peth Range and the Bhensdhara and Amti originate in the Surgana Range (Figure 1.2). Most of the left bank tributaries, for instance, the Keng, the Manmora, the Mani, the Matuniya and the Bhensdara meet the Par River almost at the right-angle (Figure 1.2). The left bank tributaries are comparatively smaller in length than right bank tributaries. The drainage network arrangement exhibits a strong control of geologic structure and tectonics.
Table 1.2 Morphometric characteristics of the major tributaries of the Par River

<table>
<thead>
<tr>
<th>Name of the tributary</th>
<th>Elevation of the source in m</th>
<th>Length in km</th>
<th>Area in km²</th>
<th>Average Slope</th>
<th>Bank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nar</td>
<td>1177</td>
<td>87.0</td>
<td>407</td>
<td>0.01268</td>
<td>Right</td>
</tr>
<tr>
<td>Keng</td>
<td>600</td>
<td>30.8</td>
<td>135</td>
<td>0.01364</td>
<td>Left</td>
</tr>
<tr>
<td>Bhensdara</td>
<td>644</td>
<td>28.4</td>
<td>72</td>
<td>0.02126</td>
<td>Right</td>
</tr>
<tr>
<td>Walandi</td>
<td>850</td>
<td>26.0</td>
<td>72</td>
<td>0.03192</td>
<td>Right</td>
</tr>
<tr>
<td>Bhimtis</td>
<td>620</td>
<td>24.5</td>
<td>57</td>
<td>0.02041</td>
<td>Right</td>
</tr>
<tr>
<td>Dholdo</td>
<td>400</td>
<td>21.6</td>
<td>63</td>
<td>0.01573</td>
<td>Left</td>
</tr>
<tr>
<td>Jamul</td>
<td>600</td>
<td>19.2</td>
<td>46</td>
<td>0.02100</td>
<td>Left</td>
</tr>
<tr>
<td>Vajri</td>
<td>700</td>
<td>17.4</td>
<td>57</td>
<td>0.02064</td>
<td>Right</td>
</tr>
<tr>
<td>Mani</td>
<td>516</td>
<td>16.4</td>
<td>51</td>
<td>0.02533</td>
<td>Left</td>
</tr>
<tr>
<td>Julwan</td>
<td>140</td>
<td>14.4</td>
<td>20</td>
<td>0.00694</td>
<td>Right</td>
</tr>
<tr>
<td>Matuniya</td>
<td>300</td>
<td>13.8</td>
<td>32</td>
<td>0.01600</td>
<td>Left</td>
</tr>
<tr>
<td>Manmora</td>
<td>600</td>
<td>11.1</td>
<td>35</td>
<td>0.03949</td>
<td>Left</td>
</tr>
</tbody>
</table>

See Figure 1.2 for location of tributaries

1.6.4 Geology

The entire basin is underlain by horizontally bedded Cretaceous-Eocene Deccan Trap basalts (Figure 1.4). However, quaternary alluvium has been observed at a small reach of the Par River particularly at Nanivahial (Figure 1.5). The river has single, sinuous, and well-defined channel, incised into bedrock. The channel floor is either of bedrock or covered by pebbly/cobbly material or boulders. The alluvial channel, with tidal effect, is seen only in lower reaches for seven km from the mouth. The basin is characterised by a number of lineaments. Some of prominent lineaments have been shown in Figure 1.4.
Figure 1.4 Geological Setting of the Par Basin
1.7 Arrangement of the text

The present work is separated into five chapters. The first chapter is devoted to the introduction to the topic and introduction to the study area. Besides this, the chapter contains the research questions, hypothesis and main objectives of the study. The second chapter covers elaborative review of previous work done in the field of form and processes of bedrock channels. The third chapter deals with the methodology. The fourth chapter is of analysis and interpretation. The fifth chapter is devoted to major conclusions of the study.