Chapter 3

Research Methodology

3.1 Introduction

Research methodology is employed in every research to systematically solve the research problem. It is a process of dealing with research problem scientifically. The following section includes various steps that are adopted in the present work to study research problem along with the logic behind it.

3.2 Research Methodology

In order to attain the objectives of the present study given in section 1.5, the following methodology has been adopted.

3.2.1 Channel morphological features

(i) Bedrock channel planform

River planform is the form or shape of a river channel as viewed from above. Three channel planforms namely straight, meandering and anastomoising channels have been identified for the river under review. The straight channel reaches have been identified on Par and Nar Rivers with the help of field surveys, satellite images and topographical maps. In addition to this, the straight reaches of river under review have been mapped using software Google earth and ArcGIS 9.3.

Brice (1964) applied the Sinuosity index (Si) to differentiate straight river channels from sinuous and meandering river channels. If the Si <1.05 the channel is straight; Si between 1.05 and 1.5 is sinuous; and if Si> 1.5 the river channel is meandering. These values have been used for the river under review. Quantification of bend statistics for the river was made possible by means of ca. 30 m resolution Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data, by means of topographical maps and numerous field surveys. In addition to this, Google Earth Images have been used to represent and quantify meandering channel of the Par River. Traditional bend statistics such as meander wavelength ($\lambda$), meander length ($L_m$), mean radius of curvature ($R_{cm}$), channel width (W) and amplitude (A) (Figure
3.1) have been calculated for 23 meanders of the Par River using tools of ArcGIS 9.3. Sinuosity index (Si) was calculated by the ratio of meander length ($L_m$) to meander wavelength ($\lambda$).

$$Si = \frac{L_m}{\lambda}$$  \hspace{1cm} \text{Equation….. 3.1}

The relations between meander wavelength ($\lambda$) and mean radius of curvature ($Rc_m$), channel width ($W$) and amplitude ($Am$) have been expressed by power regression equations as under. Where $a$ and $b$ are constants.

$$\lambda = aW^b$$  \hspace{1cm} \text{Equation…..3.2}

$$\lambda = aRc_m^b$$  \hspace{1cm} \text{Equation…..3.3}

$$Am = aW^b$$  \hspace{1cm} \text{Equation…..3.4}

Leopold et al. (1964) proposed that meander wavelength ($\lambda$) is empirically associated with square root of effective or dominant discharge for alluvial rivers. Since channel width ($W$) is also allied to discharge, it has been proposed that there is fundamental relation between channel width ($W$) and meander wavelength ($\lambda$). Although the Par River is not the alluvial river, an attempt has been made to show relationship between channel width ($W$) and meander wavelength ($\lambda$).

![Figure 3.1 Sketch to define terms used in describing geometric characteristics of a meandering channel](image)

\textbf{Figure 3.1} Sketch to define terms used in describing geometric characteristics of a meandering channel
Like the other bedrock rivers, the Par River also flows through single flow path from its source to mouth. However, extensive bedrock outcrops in the form of multi-thread channels have been identified near Panchlai, furthermore, with the help of field surveys, topographical maps and google images and essential measurements have been taken. Besides, the multi-thread pattern of Par River channel has been mapped. In addition to this, an attempt has been made to find out the formation process of bedrock anastomised channel near Panchlai.

(ii) Channel form/channel geometry

Channel forms have been studied in terms of width, depth and form ratio for the Par River. Sixteen cross-sectional surveys have been carried out to study the form of the channel. Generally two groups of aspects are considered to describe channel cross sectional form – i) channel size and ii) channel shape. Perimeter lithology is an important factor to determine channel shape. Rosgen (1994) used boundary composition as one of the basic criteria to classify river channels. He produced 41 channel types on the basis of boundary composition. Similar scheme have been applied to classify the channels of the Par as well as its major tributary i.e. the Nar.

The adjustments in the width-depth ratio and hydraulic variables with discharge have been shown to very useful concepts in evaluating the potential of flows to be geomorphologically effective (Kale et al., 1994; Gupta, 1995a). Therefore, an attempt has been made to find out width-depth ratio(s) and hydraulic variables of the Par River.

In order to examine the relationship between width and discharge (Q) or drainage area (A), it is necessary to define reference discharge. However, due to scarcity of data for river under review, such discharges were not available. The width of most bedrock channels can be more readily defined on the basis of the zone of active scour, as indicated by the limit of established perennial vegetation (Montgomery and Gran, 2001). Therefore, an attempt has been made to examine the relation between channel width and drainage area, as they are relatively unambiguous to determine even for bedrock reaches (Montgomery and Gran, 2001). Several field surveys have been carried out to measure width of the active channels on the Par River. Drainage areas have been measured with the help of ASTER DEM data, toposheets (1:50000 and
1:250000) and GIS applications. Ultimately, the relation between channel width (W) and drainage area (A) is expressed as positive power function for the river as under;

\[ W = cA^b \]  

Equation …..3.5

Where c and b are constants.

(iii) Erosional features of bedrock channel

The main purpose of the present section is to recognize physical characteristics of morphology of different landforms and their formation processes. Therefore, in order to study erosional landforms, an extensive field survey was carried out from source to mouth of the Par River. Following erosional landforms have been identified in the field, measured, analysed and mapped with the help of toposheets, ArcGIS 9.3 and Google Earth.

- The locations of potholes in the Par River channel have been identified from source to mouth and careful measurements of size and shape of potholes have been carried out. The statistical parameters of various geometric properties of the potholes have been obtained and presented in tabular format. The coefficient of skewness (C_s) is one of the most commonly used moments in statistical analyses. It is the measure used to find out the degree of asymmetry of a statistical distribution. Therefore, analysis of coefficient of skewness of the morphometric parameters of the potholes of the Par River has been carried out. Coefficient of kurtosis (C_k) is a measure used to find out the degree of peakedness of a statistical distribution. In addition to this, the potholes have been categorised according to their prominent shapes. Furthermore, the empirical relationship between diameter (K) and depth of potholes (D*) has been established for the Par River as under;

\[ K = aD^{*b} \]  

Equation …..3.6

Where, K (cm) is Diameter of potholes and D* (cm) is Depth of potholes (cm), a and b are constants. The relationship between length (L) and depth of pothole (D*) has been expressed for the river under review as follows;
L = aD*^b \quad \text{Equation \ldots 3.7}

Where, L (cm) is length of potholes and D* (cm) is depth of potholes, a and b are constants.

- The locations of grooves in the Par River channel have been identified from source to mouth and careful measurements of the dimensions of grooves have been taken in the field. The statistical parameters of various geometric properties of the grooves have been obtained and represented in tabular format.

- Eight prominent inner channels of the Par River were identified in the field and measurements of dimensions were carried out to find out possible mechanism of their formation.

The downstream changes in the gradient have been shown by its longitudinal profile, which is a graph of elevation against distance along the channel. The elevations of the knickpoints have been measured in the field.

The channel distance (L) and slope (S) are correlated by a power function and attempt has been made to establish the relation between distance (L) and slope (S). The channel distance (L) and slope (S) are correlated by a power function as under;

\[ S = kL^n \quad \text{Equation \ldots 3.8} \]

Where S is slope of channel and L is distance, k and n are steepness and concavity variables respectively.

Numerous expansion bars have been formed at abrupt expansions downstream of constricted reaches of the Par River. In order to find out expansion, the Expanded reaches (Er)/Constricted reaches (Cr) ratio has been established. In addition to this, longitudinal bars and point bars have been identified in the field. The dimensions of bars such as width, length and height have been measured in the field and areas occupied by bars have been measured by means of satellite images and GIS applications. Moreover, depositional features have been mapped using ArcGIS 9.3.

An attempt has been made to find out hydraulic parameters such as bed shear stress, unit stream power, and mean velocity necessary to transport coarse-grained sediment.
Using the empirical relationships developed by Williams (1983), the threshold values of unit stream power, bed shear stress, and mean velocity necessary to transport the boulders were calculated.

### 3.2.2 Erosional processes and sediment transport

(i) Flood hydraulics and hydrodynamics

In order to find out effect of infrequent and large magnitude floods on the Par River, parameters of flood hydraulics and hydrodynamics such as unit stream power, bed shear stress, Froude number, Reynolds number and critical velocity for inception of cavitation were computed. 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.

a. Parameters of flood hydraulics and hydrodynamics

Due to lack of quantitative hydraulic data of rare floods for the Par River, sixteen cross-sectional surveys were carried out for the river under review. In addition to this, channel slope data have been constructed in the field. The aforementioned data have been used to procure hydraulic and hydrodynamics parameters such as unit stream power, boundary shear stress, Froude number, Reynolds number and critical velocity to understand geomorphic efficacy of rare flood events. The geomorphic effectiveness of a flood, which relates to its ability to affect the form of the landscape (Wolman and Gerson, 1978), is commonly linked to flood power and the degree of turbulence (Baker and Costa, 1987; Wohl, 1993; Baker and Kale, 1998; Kale and Hire, 2004, Hire and Kale, 2006, Kale and Hire, 2007). Therefore, for the known rare flood events, boundary shear stress, unit stream power per unit boundary area, Froude number, Reynolds number were computed (Leopold et al., 1964; Baker and Costa, 1987).

aa. Shear stress (τ)/fluid stressing/shear detachment

Shear stress (τ) is a measure of the frictional force from a fluid acting on a body in the path of that fluid. It is one of the critical causes behind entrainment of particles. In the case of open channel flow, it is the force of moving water against the bed of the
channel. Shear stress increases with flow depth and channel steepness. It is calculated as;

\[ \tau = \gamma RS \]  

…..Equation 3.9

where, \( \tau \) (shear stress is represented by the Greek letter tau, (\( \tau \))) is boundary shear stress expressed in Newton per square meter (N/m\(^2\)), \( \gamma \) (gamma) is specific weight of clear water (9800 N/m\(^2\)), R is hydraulic radius or mean depth of water in m, S is channel slope.

**ab. Unit stream power (\( \omega \))**

Unit stream power (\( \omega \)) is the capacity of a given flow to transport sediment. It represents the work done by a flow on a unit area of channel bed (Bangnold, 1980). Unit stream power is calculated as;

\[ \omega = \gamma QS/w \]  

…..Equation 3.10

where, \( \omega \) (lower-case omega, \( \omega \)) is unit stream power expressed in watts per square meter (W/m\(^2\)), Q is discharge in m\(^3\)/s, w is the water surface width in m.

In order to find out sediment transport rates, sediment entrainment and flow capacity of bedrock channel of the Par River, the shear stress and unit stream power for 16 cross-sectional sites have been calculated. To compute thresholds of shear and entrainment, boulders located at seven cross-sections have been analysed using William’s equations (Equation 3.15 to 3.17).

**ac. Froude number (\( Fr \))**

To study flow characteristics of the Par River, Froude numbers (\( Fr \)) have been calculated and classified. Froude number (\( Fr \)) is the ratio between inertial and gravitational forces.

\[ Fr = \sqrt{\frac{v}{gR^{0.5}}} \]  

…..Equation 3.11
where, Fr is Froude number, \( \bar{v} \) is mean flow velocity in m/s, g is acceleration due to gravity (9.8 m\(^2\)/s), R is hydraulic radius or mean depth of water in m. Three possibilities of flow exist according to the range of Fr (i) If Froude number is less than one (Fr < 1), the flow is said to be subcritical and gravitational force dominates (ii) on the contrary if value of Fr is more than one (Fr > 1), the flow is supercritical and inertial forces govern the flow. (iii) the value of Fr is equal or close to one (Fr = 1), in such case the flow is critical or transitional.

**ad. Reynolds number (Re)**

In order to measures the degree of turbulence, or random changes in flow direction and/or velocity superimposed on the main downstream movement of water of the Par River, Reynolds number (Re) were calculated.

\[
Re = \frac{\bar{v} R}{\nu}
\]

\( \ldots \text{Equation 3.12} \)

Re is Reynolds number, \( \bar{v} \) is mean velocity, R is hydraulic radius or mean depth of water in m, \( \nu \) (Greek small letter Nu) is kinematic viscosity \( (1 \times 10^{-7} \text{m}^2/\text{s} \text{ for water temperature of } 20^\circ \text{C}) \) (Leopold et al., 1964; Petts and Foster, 1985). The values of Re are efficient to find out whether the flow is laminar or turbulent. At low Re numbers (<500) viscous forces dominate and the flow is laminar. High Re numbers (>2100) indicate turbulent flow; transitional flow is observed between Re values of 500 and 2,100.

**ae. Critical velocity for inception of cavitation (Vc)**

In order to find out intense bedrock scouring which results from cavitating flow condition, critical velocity required for inception of cavitation (Vc) have been calculated for the cross-sectional sites of the Par River as follows.

\[
Vc = 2.6 (10+D)^{0.5}
\]

\( \ldots \text{Equation 3.13} \)

Where, Vc is the critical velocity for the inception of cavitation in m/s and D is flow depth.
af. Hydraulic plucking

Numerous crisscross dykes have been observed in the Par Basin, of which, majority of dykes are highly dissected due to plucking. The plucked blocks of such dykes have been identified in the field and the distances of plucked blocks from the dykes (source) have been measured. The plucking has also been observed other than dykes in the channel of the Par River.

ag. Knickpoint migration and river incision

The upstream migration of knickpoints has been recognized as significant means of bedrock channel lowering, however, little is known about the mechanisms that control the shapes and migrations of knickpoints (Miller, 1991; Seidl and Dietrich, 1992; Seidl, 1993; Whipple et al., 2000 (a, b); Zaprowski et al., 2001). Therefore, attempts have been made to find out examples of knickpoint migration and to estimate rate of incision for the Par River. According to Baker (1988); Wohl (1992, 1998 and 2000) and Ikeda (1997), headward migration of a knickpoint through resistant substrate can leave behind a deep and narrow gorge, it reflects the erosional resistance of the channel boundaries, and maximizes the shear stress and stream power per unit area of a given discharge and channel gradient. Similar observations have been noted for the Par River as well as its tributaries, where, deep and narrow gorges are observed immediately downstream of knickpoints. Several equations and models have been developed by researchers to predict channel incision of a river into its bed. The comprehensive and most commonly used stream power erosion model (SPEM) is of great use, since, there are few variables and can be measured against topographical data (Howard and Kerby, 1983; Skylar and Dietrich, 2001). It is argued by Howard and Kerby (1983) that the Stream Power Law/model (SPEM) is most applicable because it is related to physics of erosion. Therefore, to estimate the incision rate and migration of knickpoints of the Par River stream power erosion model has been applied. The stream power erosion model has been applied as follows;

\[ \varepsilon = K A^m S^n \]  

..... Equation 3.14
where, $\varepsilon$ is (Greek small letter epsilon) vertical erosion rate (m/yr); $K$ is coefficient of erosion (m/yr); $A$ is upstream drainage area ($m^2$); $S$ is channel bed gradient/local slope; $m$ and $n$ are exponents.

The major controls on the equation are that of slope, discharge/upstream drainage area and erodibility of the rock. The constant $K$ in the stream power model is a dimensional coefficient of erosion incorporating effects due to lithology, climate, channel width, hydraulics, sediment load (Sklar and Dietrich, 2001), rock strength and the erosional capabilities of the fluvial system (Whipple, 2001). Stock and Montgomery (1999) have applied stream power erosion model for Kaulaula and Waipao Rivers, which flow through basalt lithology. For the above-mentioned rivers they have used $K$ values as $6.7 \times 10^{-6}$ and $7.3 \times 10^{-6}$ respectively. Being similar lithology, average of above values (i.e. $7 \times 10^{-6}$) has been calculated and used to compute the model for the Par River. Howard and Kerby (1983) recommended that for construction of stream power erosion model, upslope drainage area can be used as a surrogate for dominant discharge. Howard et al. (1994) and Dietrich and Seidl (1994) opined that the proxy is possible since the average long term incision rate is proportional to the sheer stress exerted by the dominant discharge within the channel. Thus, upstream drainage area has been substituted for dominant discharge for construction of SPEM for the Par River. By using topographical maps, channel slope ($S$) has been calculated for Kalmane (0.0068) and Bhimtas (0.0304) reaches. In SPEM, $m$ and $n$ are area and slope exponents respectively (Whipple and Tucker, 1999). Stock and Montgomery (1999) recognize the exponent $m$ as the account of the discharge drainage area interaction which is weighted by the significance of discharge on the process incision. Conversely, little information is available on the slope exponent ($n$), probably due to the process involved not being entirely understood. Fewer studies have reported the values for the exponent $m$ and $n$. For construction of SPEM for the Par River, exponents given by Gardner (1983) and Howard et al. (1994) have been used, according to which if bedrock incision is proportional to shear stress, $m = 0.3$ and $n = 0.7$. Gilbert (1877) and Gannet (1893) hypothesized that the rate of bedrock river incision should be a function of rock resistance river, discharge (surrogate by area) and slope. The parameters given by Gilbert (1877) and Gannet (1893) have been derived in order to run SPEM and to estimate incision rate for the Par River.
Unfortunately, the above analysis does not provide any information about upstream propagation of knickpoints. However, the Bhimtas River, a tributary of the Par River, has developed an excellent gorge downstream of the Bhimtas Knickpoint. It appears that the gorge widens proportionately for about 4.5 km downstream from the knickpoint. Therefore, an attempt has been made to find out correlation between the distance and the width of the gorge from the knickpoint. The width(s) and the distances of the gorge have been measured for 38 sites for 4.5 km of the knickpoint (Figure 4.70; Figure 4.71). The simple regression equation has been applied for the above data and plotted.

b. Coarse sediment transport

The resistant-boundary channels are supply-limited, coarse sediment entrainment and deposition is usually associated with infrequent and extreme floods (Baker, 1988). The channel of the Par River is dominated by resistant bed and coarse sediment. Therefore, large boulders were identified and intermediate-axis (i-axis) of boulders has been measured to evaluate the tendency and mobility of coarse sediment from sixteen sites (285 coarse sediment samples). In order to evaluate the mobility of these coarse sediment theoretically, the sediment-transport equations developed by Williams (1983) were applied, and the approximate minimum critical values of bed shear stress (τ), unit stream power (ω), and mean velocity (v) that could initiate coarse sediment movement were estimated with the help of following formulae;

\[
\omega = 0.079 \, d_{g}^{1.27} \quad \text{…..Equation 3.15}
\]
\[
\tau = 0.17 \, d_{g} \quad \text{…..Equation 3.16}
\]
\[
\bar{v} = 0.065 \, d_{g}^{0.5} \quad \text{…..Equation 3.17}
\]

where, \(d_{g}\) is the intermediate diameter of the grain in mm.

3.2.3 Role of lithology and tectonics

(i) Rock mass strength of resistant boundary channel of the Par River

In order to study the role of lithology and efficiency of processes to shape the channel, the Schmidt hammer rebound values (N) were derived by using ‘N’ type Schmidt
hammer (SH). 371 N values were obtained for 12 cross sectional sites on the Par and two cross sectional sites on the Nar River. For each site 20 to 30 rebound values were procured. Two cross sectional sites have been excluded namely Jhiri, which exhibit mainly depositional material and very sensitive proposed dam site of Chachpada (See location in Figure 4.12). The N values were used to estimate the Rock Mass Strength (RMS) i.e. the specific properties of the rock mass that control its strength and subsequent slope stability (Goudie, 2004). Several testing procedures were given by different researchers (Goktan and Gunes, 2005) mainly with regard to the number of impacts used to obtain Rock Mass Strength (RMS) values. According to recommendation of International Society for Rock Mechanics (ISRM) (1978), average of upper 10 values as of 20 rebound values from single impacts separated by at least a plunger diameter should be considered. Matthews and Shakesby (1984) suggested that from 15 rebound values for each sample 5 most deviating values from the mean being discarded. Katz et al. (2000) performed 32 to 40 individual impacts and averaged the upper 50%. In order to find out RMS for the Par River, method given by Katz et al. (2000) has been applied i.e. from 20 to 30 rebound values of each cross sectional site, upper 50% values have been used. 181 unusual low values of rebound (N) have been excluded to calculate RMS due to various reasons such as i) they may relate to the fact that the rock was weakened by the actual impact of the hammer on the rock surface ii) small rock flaws that were not spotted visually before the impact was applied (Goudie, 2006). The rebound values or impact values (N) derived by Schmidt hammer were converted into standard averages of RMS (N/mm$^2$) by calculating a statistical power-law relationship (Goudie, 2006). The following conversion curve was used to convert N values into RMS (Sengupta and Kale, 2011);

$$\text{RMS} = 0.1152 N^{1.6348} \quad \ldots\text{Equation 3.18}$$

where, RMS is Rock Mass Strength or rock resistance in N/mm$^2$; N is Schmidt rock hammer rebound value. The RMS values obtained from the N values were averaged in order to get the mean rock resistance of all cross sectional sites. The mean RMS of every cross sectional sites have been used to calculate average RMS of the Par river. Statistical parameters of RMS such as range, standard deviation ($\sigma$) and coefficient of variation (Cv) have been calculated.
The area under review is characterised by numerous crisscross lineaments and dykes. Thirty prominent dykes on Par River have been identified and measured. The position of dykes with respect to direction of flow has carefully been observed and attempts have been made to find out the control of dykes on path of channel. It could not become possible to measure the N values of all the dykes, nevertheless, 44 similar values of five dykes have been obtained from different cross sectional sites to get RMS values. By following the method given by Katz et al. (2000), 50% anomalous low values of rebound (i.e. 22 N values) have been excluded and upper 50% values have been used to calculate average RMS as well as other statistical parameters for dykes.

In order to semi-quantitatively assess rock erodibility between basalt and dykes, N and RMS values of basalt (167) and similar values of dykes (22) have been analysed. The comparison between these two substrate resistance has been represented with the help of box-whisker plots. It is hypothesised that there are differences in rock erodibility between basalt and dykes.

(ii) Geomorphic Indices of Active Tectonics (GAT) in morphotectonic analysis

The Par River Basin is very appropriate for this type of morphotectonic analysis and for making significant appraisals between basins and fluvial systems. Quantification of a number of geomorphometric indices for the river under review were made possible by means of the analysis of Digital Elevation Model (DEM) of ca. 30-m resolution Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data. Normally, 30-m resolution ASTER DEM with relative accuracy can be used effectively to assist mapping, geomorphic, geologic, tectonic, landform, and a range of environmental studies in remote areas of rugged terrain (Lang and Welch, 1999; Hirano et al., 2003; Figueroa and Knott, 2010). The digital elevation data were used to extract information about drainage basin, network and river profile. This was achieved by using standard procedures in ArcGIS 9.3 (Kale and Shejwalkar, 2007; Huasm, 2008; Kale and Shejwalkar, 2008; Wilschko et al., 2010; Dehbozorgi et al., 2010).

The morphotectonic analysis of the river under review is based on the calculation of five commonly used geomorphic indices of active tectonics (GAT) such as the
hypsometric integral (HI), the basin asymmetry factor (AF), the valley width-height ratio (Vf), the stream gradient-length ratio (SL), and the basin elongation ratio (Re). The mountain front sinuosity, one of the widely used geomorphic indices, is not evaluated in the present study. In addition to hypsometric integral, hypsometric curve has been derived for the basin under investigation. The procedures adopted to calculate the GAT indices are defined in Table 2.2. The indices were then assessed by field observations of the occurrence of knickpoints, incised meanders, gorges, etc., as markers of active tectonics.

It is pertinent to mention here about the longitudinal profile extracted from the ASTER-DEM data. Because of stepping in adjacent elevations on the ASTER-DEM and the effect of water bodies such as ponds and dams, the recognition of substantial breaks and knick zones in the longitudinal profiles is not a very simple and straightforward task especially for low-gradient reaches (Kale and Shejwalkar, 2008). A running mean (aka moving average) of 11 consecutive elevation values used for smoothing the long profile partially reduces the problem but does not remove it completely (Kale and Shejwalkar, 2008). Therefore, zones of steeper reaches (knickpoints or zones) could not be identified. Hence, the knickpoints identified in the field have been mapped and discussed.

3.2.4 Flood Hydrometeorology, Hydrology and Geomorphology

(i) Flood hydrometeorology

In order to understand the meteorological causes of floods, the analyses of synoptic conditions connected with large floods in the Par Basin was carried out. This encompasses analysis of (i) rainfall; (ii) analysis of storm tracts and; (iii) evaluation of the correlation between El Niño and monsoon rainfall in the basin.

Meteorological data of five stations located within and close to the Par Basin have been obtained from India Meteorological Department (IMD), Pune and analysed to identify the rainfall characteristics that produce large floods on the Par River. The data were available for more than 100 years except Surgana Station for which data availability is for 50 years. The general rainfall characteristics, for instance, monthly
and annual averages of rainfall, monsoonal rainfall and non-monsoonal rainfall, etc. for the five stations in the Par Basin have been calculated and shown graphically.

**a. Rainfall regime characteristics**

The average rainfall characteristics for the five stations in the Par Basin have been shown graphically and given in tabular format. Annual rainfall data of the above-mentioned five stations were averaged to obtain annual rainfall of the basin and displayed in Figure 4.90. Like other parts of the monsoon tropics, there is variability in the annual as well as monsoon rainfall between years. The interannual variability of selected stations and for the whole Par Basin have been calculated and represented graphically.

**b. Flood-generating meteorological conditions**

In the humid and seasonal tropics, large floods are mostly associated with high-magnitude rainfall caused by synoptic events ranging in force from lows to cyclones (Gupta, 1988; 1995a). Therefore, the tracks of the low pressure system, that affect the basin, have been identified using software eAtlas and analysed with the help of ArcGIS 9.3.

In general, during the passage of LPS, it causes heavy falls of rain along and near their tracks (Dhar at al., 1984). The LPS (Bay or land depressions) which follow a westward track through Tapi Basin are more effective in causing heavy rainfall and floods in the Par Basin. Therefore, an attempt has been made to identify and analyse the mean track of such LPS using software eAtlas (procured from IMD, Chennai) and ArcGIS 9.3. The software eAtlas contains data regarding tracks of LPS from year 1891 to 2007, thus, similar range have been adopted for further analyses. In general tropical cyclones range in diameter from 100 to well over 1000 km (Glossary of American Meteorological Society, 1959). Hence, a circle having thousand kilometre of diameter has been plotted from the centre of the basin and those LPS tracks which pass through the circle, as shown in Figure 4.92, have been identified and analysed. The latitudinal and longitudinal positions of such cyclones were taken into consideration for each day of their life span (Mooley and Shukla, 1987). Using these data the mean latitudinal and longitudinal positions were calculated. The above-
mentioned methodology has been adopted by Hire (2000), who has prepared mean LPS track for the Tapi Basin. As the areal extent of Tapi Basin (65145 km$^2$) is much greater than that of Par, those LPS tracks which range within five-hundred kilometres from the peripheral area of the Tapi basin have been selected by him. Being small in size, a circle drawn from the centre has been used instead of aforementioned method for Par Basin.

c. Normalized accumulated departure from mean (NADM) method

The year to year fluctuations in rainfall of the region cause complexity in recognition of the direction of change in the rainfall. Thus, some effective statistical methods are to be applied to identify the nature of long-term variability in monsoon rainfall. The frequently used method to study the variability of rainfall is Normalized Accumulated Departure from mean (NADM). Consequently, the NADM plotting method has been used to emphasize the long-term variability by minimizing short-term fluctuations in the monsoon rainfall. According to Thomas (1993), the NADM is the Accumulated Departure from Mean (ADM), divided by the largest number (absolute) in order to plot between -1 and +1. Therefore, the normalized ADM allows apparent as well as statistical association of dissimilar data (Thomas, 1993). Periods featured by above-average state are usually shown by positive slopes of the graph and vice-versa (Gregory, 1989b; Thomas, 1993). In contrast with other methods used for similar purpose, such as running means, the ADM clearly shows the difference between periods of high and low rainfalls (Probst and Tardy, 1987).

d. Long-period fluctuations in monsoon rainfall and floods

In order to further estimate the fluctuations in monsoon rainfall and floods, the long-term annual rainfall data of the Par Basin, has been compared with the fifty years flood data available for Nanivahial gauging site and represented graphically.

The Indian southwest monsoon is teleconnected with the ENSO events. Therefore, an attempt has been made to recognize natural variability in annual rainfall (and therefore floods) in the Par Basin and its correlation with ENSO events. The annual rainfall data for the period of 104 years (1901-2004) of the basin have been used to establish the relationship with ENSO events.
In order to detect future changes in the rainfall, the non-parametric Mann-Kendall test has been used. The Mann-Kendall’s Tau ($\tau$) has been obtained by following equation;

$$\tau = \frac{\text{Actual total of scores (ATS)}}{\text{Maximum possible total}} \quad \ldots \quad \text{Equation 3.19}$$

Where, actual total of scores (ATS) is the total of all sum(s) as calculated by the method adopted by Gunjal, (2016).

The maximum possible total has been acquired with following equation;

$$\text{Maximum possible total} = \frac{N(N-1)}{2} \quad \ldots \quad \text{Equation 3.20}$$

Where, $N =$ Number of observations. The Mann-Kendall’s $\tau$ is obtained by putting values in Equation 3.19.

The trend derived by Mann-Kendall test is practically significant or not is to be tested by testing the significance of Tau ($\tau$). The method delineated for testing the significance of $\tau$ becomes extremely burdensome for the large $N$. Nevertheless, Kendall (1955) has revealed that when $N$ is greater than 8, the theoretical distribution of all probable values of $\tau$ approaches the normal distribution. The $\tau$ may be transformed into a normal standard deviate as follows;

$$z = \frac{\tau}{\sqrt{2(2N + 5)/9N(N-1)}} \quad \ldots \quad \text{Equation 3.21}$$

The value of the $z$ can be obtained while substituting the calculated value of $\tau$. For large number of observations ($N > 30$), $z$ value has to be greater than 2.32 at 0.01 level and 1.64 at 0.05 level for the sample to be statistically significant.

This exercise mainly proposed to observe the change/trend over the basin scale, hence, Mann-Kendall’s $\tau$ and $z$ scores are obtained for the whole basin and the results
are given in tabular format. The application of this non-parametric test to the annual rainfall data of the basin designates no significant trend at 0.01 and 0.05 level.

Student’s t-test has been used (Chiew and McMohan, 1993; Marengo, 1995) to find out the percentage change essential in the mean of the future rainfall data series prior it can be considered to be appreciably different from the historical gauge record. The percentage change can be estimated as:

\[ t = \sigma \times t_{\alpha} \left( \frac{1}{n_h} + \frac{1}{n_f} \right) \]  

\[ \text{Change} = \left( \frac{t}{\text{AAR}} \right) \times 100 \]

Where,
\( t \) = Student’s t value  
\( \sigma \) = standard deviation of the historical gauge data  
\( n_h \) = length of historical rainfall series  
\( n_f \) = length of future rainfall data  
\( t_{\alpha} \) = the critical value of the t-statistics at 95% level of significance and  
\( \text{AAR} \) = average annual rainfall

(ii) Flood hydrology

a. Flood hydrology of the Par River

The Par River, similar to other monsoonal rivers, also subjected to high-magnitude floods at regular intervals. Thus, it is of paramount significant to know the hydrologic characteristics of floods in terms of magnitude, frequency, and distribution.

aa. Annual flood series data and analysis

In order to comprehend the flood hydrological characteristics, the annual maximum series (AMS)/stage data were procured from Irrigation Department of Gujarat State for a gauging site namely Nanivahial on Par River for 45 years specifically from 1960
to 2005. Moreover, based on Qm (Mean annual peak discharge) and Qm+1σ, AMS data have been estimated for years 2006 to 2009.

**ab. Stage discharge curve/rating curve**

In order to find out relation between stage and discharge for the Nanivahial site, rating curve has been plotted with the help of forty-five datasets of stage and corresponding discharge (Figure 4.96). The limited gauge records have been used to evaluate floods and flood flow frequencies. Primarily the AMS data have been presented in the form of time series plots to understand the interannual variations in the annual peak flood magnitudes. Second, to reduce and summarize the characteristics of floods, simple statistical analyses of AMS data have been carried out. The statistical parameters that are expressed in terms of the moments such as central tendency, variability and skewness as well as coefficient of variation have been calculated. In addition to this, flash flood magnitude index (FFMI) and unit discharges have been derived to evaluate the variability and the potential of large floods on the Par River.

**ac. Flood regime characteristics**

The temporal pattern of variation in the annual peak discharges at Nanivahial site on the Par River is demonstrated graphically. Interannual variability in annual peak discharges and average magnitude and variability for Nanivahial Site on Par River have been constructed. The Qmax/Qm ratio has been calculated to find out the credibility of floods to cause remarkable geomorphic changes and to generate discharges many times beyond the mean flows experienced by a river. Besides the Qmax/Qm ratio, the coefficient of variation (Cv) is another useful measure of variability in the annual peak discharges. It is the ratio between standard deviation and the mean. In order to further highlight the extent of variability in peak discharges from one year to other, deviations from mean annual peaks has been shown graphically for Nanivahial site (Figure 4.98).

Numerous workers have used the Beard’s flash flood magnitude index (FFMI) to estimate the variability of flood frequency measured as an index of flood flashiness (Baker, 1977). The FFMI values are calculated from the standard deviation of logarithms of AMS as given below:
where, \( X = X_m - Q_m \), \( X_m \) = annual maximum event, \( Q_m \) = mean annual peak discharge, \( N \) = number of years of record (\( X, X_m \), and \( Q_m \) expressed as logarithms to the base of 10).

Skewness is one of the most commonly used moments in the flood hydrology. Since most of the AMS data are not normally distributed, it is important to find the skewness of the data. Therefore, the coefficient of skewness (\( C_s \)) of the AMS data has been calculated. To verify the degree of skewness, the ratio between skewness and coefficient of variation has also been used by some hydrologists (Shaligram and Lele, 1978).

Unit discharge is another useful measure of the potential of large floods on a river (Gupta, 1988). It is the ratio between maximum annual peak discharge (\( Q_{max} \)) and the upstream catchment area (\( A \)). It gives discharge (or water yield) per unit drainage area (\( m^3/s/km^2 \)).

b. Flood frequency analyses

ba. Magnitude-frequency analysis

FFA necessitates a good quality, long and continuous records. Typically the AMS data have been more frequently used for the analysis. In case of the study area, the AMS data of flood stage and magnitude are available for Nanivahial site on the Par River for the last 49 years (since 1961). This data have been used for magnitude-frequency analysis. The return periods of the Nanivahial flood data have been estimated by applying Weibull’s method. In order to estimate discharges of a given return period, a frequency distribution is compiled from a data series of extreme events. By using Gumbel extreme value type I (GEVI) probability distribution, peak flows have been estimated for different return periods such as 2, 5, 10, 25, 50, and 100 years. The distribution has also been employed to estimate the recurrence interval of mean annual peak discharge (\( Q_m \)), large flood (\( Q_{lf} \)) and actually observed maximum annual peak discharge (\( Q_{max} \)). A visual inspection of the fit of the

\[
FFMI = \sqrt{\frac{\sum X^2}{N-1}}
\]
frequency distribution is possibly the best way in determining how fine an individual
distribution fits the AMS dataset or which distribution fits “best” (Bedient and Huber,
1989). Therefore, flood frequency of the Nanivahial site is represented graphically
(Figure 4.100) which fairly represents the Par Basin.

**bb. Gumbel extreme value type I (GEVI) distribution**

Assuming the GEVI distribution for the AMS data of the selected site, an estimate of
flows for a desired recurrence interval were obtained by using the following equation
(Shaw, 1988).

\[ Q_T = Qm + [K(T)*\sigma Q] \]  

.....Equation 3.25

where, \( Q_T \) = discharge of required return period, \( Qm \) = mean annual peak discharge,
\( \sigma Q \) = standard deviation of AMS, and \( K(T) \) = frequency factor and is the function of
the return period \( T \). \( K(T) \) values were obtained from tables provided in the standard
books on Applied Hydrology.

The recurrence intervals (\( T \)) of given discharges (\( X \)), such as mean annual peak
discharge (\( Qm \)), large flood (\( Qlf \)) and peak on record (\( Qmax \)), have been estimated by
applying the following equation (Shaw, 1988).

\[ \frac{1}{T} = 1 - F(X) = 1 - \exp[-e^{b(X-a)}] \]  

.....Equation 3.26

where, \( T \) = recurrence interval for a given discharge, \( F(X) \) = probability of an annual
maximum \( Q \leq X \), and \( a \) and \( b \) are two parameters related to the moments of
population of \( Q \) values. The parameters \( a \) and \( b \) were determined by the following
equations.

\[ a = Qm - \frac{\gamma}{b} \quad (\gamma = 0.5772) \]  

.....Equation 3.27

\[ b = \frac{\pi}{\sigma Q \sqrt{6}} \]  

.....Equation 3.28
where, \(Q_m\) = mean annual peak discharge, and \(\sigma_Q\) = standard deviation of annual peak discharge. The return periods of required discharges have been calculated by applying Equation 3.27.

In the GEVI analysis, the observed annual peak discharges have been plotted against the return period or \(F(X)\) values (plotting positions) on the Gumbel graph paper, designed for GEVI probability distribution. Several formulae have been used to calculate plotting positions, however, of the several formulae in use, the best is due to Gringorten since the outliers fall into line better than other plotting positions (Shaw, 1988). The \(F(X)\) values have been calculated as follows;

\[
P(X) = 1 - F(X) = \frac{r - 0.44}{N + 0.12} \quad \text{.....Equation 3.29}
\]

where, \(r\) = flood magnitude rank and \(N\) = the number of years of records.

A line can be drawn by eye to fit the scatter, especially using the Gringorten plotting positions. However, it is sensible to draw the line mathematically. Additionally, since most of the AMS data are available for short period of time, it is essential to construct confidence limits about the fitted line relationship between the AMS and the linearized probability variable (Shaw, 1988). Shaw (1988) has given procedure to fit the line mathematically and to construct the confidence limits. The same procedure has been followed in this study.

**bc. Weibull’s method**

In addition to above probability distribution, the recurrence interval of high-magnitude flood events that have occurred on the Par River at Nanivahial were predicted by using the following Weibull formula.

\[
T = \frac{N + 1}{r} \quad \text{.....Equation 3.30}
\]

where, \(N\) = the number of years of record, and \(r\) = flood magnitude rank. The results obtained with the help of above equation are presented in Table 4.43.
c. Discharge-area envelope curve

The envelope curve for the Par Basin has been prepared with the help of data regarding estimated peak discharges (Qmax) and calculated drainage areas (A) for 15 sites and gauged data of a site in the Par Basin. The curve is shown in Figure 4.101. Further, for comparison, the envelope curve prepared by Baker (1995) for the world has been plotted on the same figure.

(iii) Flood geomorphology

In flood geomorphology, the measurement and evaluation of the geomorphic effectiveness of flows of different magnitude has been one of the significant themes. Large floods can generate noteworthy geomorphic impact on channel morphology and landscape. Therefore, to evaluate the geomorphic significance of floods of different magnitude and frequency, the following methodology has been adopted.

To determine the geomorphic effect of floods, the geometry of river channels is considered to be a significant factor (Kochel, 1988). Therefore, to assess the channel geometry/morphology of the Par River, the cross sectional surveys were carried out and fifteen cross-sections were constructed from field surveys and a cross-section has been obtained from Gujarat Irrigation Department. Furthermore, cross-sectional parameters of all the stations at high flood level (HFL) have been derived, analyzed and tabulated.

In order to derive the downstream hydraulic geometry equations, the values of width, depth and velocity for mean annual discharge data along the river are required. Due to unavailability such data, it is not possible to evaluate the downstream hydraulic geometry of the Par River. However, at-a-station hydraulic geometry has been established since data regarding hydraulic geometry variables associated with annual maximum series (AMS) are available for a site on the Par River, viz. Nanivahial. This data have been obtained from Gujarat Irrigation Department and used to derive the at-a-station hydraulic geometry equations to understand the nature of adjustments in the hydraulic variables with discharge. Moreover, the hydraulic geometry exponents (b, f, and m) of the Nanivahial gauging station were plotted on Rhodes’ (1977) ternary
diagram. According to whom ternary diagram is a tool for interpretation of hydraulic geometry.

**a. Changes in hydraulic variables with discharge**

Hydraulic geometry refers to the geometric rate of change of hydraulic variables, namely width \( w \), mean depth \( d \), and mean velocity \( v \), as discharge \( Q \) increases (Leopold and Maddock, 1953). These changes in the three variables are elementary to hydraulic geometry. The functions derived for a given cross section and among numerous cross sections along the river vary only in numerical values of coefficients and exponent. These functions are:

\[
\begin{align*}
\text{w} &= aQ^b \\
\text{d} &= cQ^f \\
\text{v} &= kQ^m
\end{align*}
\]

where, \( w \) = width; \( d \) = mean depth; \( v \) = mean velocity; \( Q \) = water discharge in cubic meter per second \((m^2/s)\); \( a \), \( c \), \( k \), \( b \), \( f \) and \( m \) are numerical constants.

Hydraulic geometry of alluvial channel does not applicable to highly variable bedrock channels (Wohl, 1998). Nonetheless, attempts have been made to establish hydraulic geometry equations for the river under review based on available data. The highest discharges of given site flows over the bank, this work is not concerned with discharges above bankful stage (Leopold and Maddock, 1953) the extreme values of overbank flooding for year 1968, 1976, 2004 and 2005 have been excluded and the values of HFL below gauge 8.45 m have been used for construction of at-a-station hydraulic geometry equations (Figure 4.113). The data of hydraulic variables, such as mean depth and mean velocity were not available, these variables were procured through stage and discharge data of AMS. The results of changes in hydraulic variables are given in Table 4.45 and comparison, width, depth, and velocity are plotted on logarithmic scales against discharge in Figure 4.113. The hydraulic geometry exponents (\( b \), \( f \), and \( m \)) of the Nanivhahial gauging station were plotted on Rhodes (1977) ternary diagram (Figure 4.114).