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CHANNEL MORPHOLOGY AND HYDRAULIC CHARACTERISTICS OF VASHISHTHI RIVER, MAHARASHTRA (INDIA)

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ABSTRACT : In order to understand the channel morphology and the hydromorphological relations the fluvial system of Vashishthi river has been investigated and studied. Data regarding hydraulic factors like depth, width channel capacity, velocity etc. and channel sediments were collected. Besides the evaluation, an attempt has been made to explain the probable causes of the present braided pattern of the Vashishthi river channel. The investigation and the hydraulic exponents show that although there are definite downstream trends in the hydraulic geometry, the hydraulic factors vary from one segment to another. This has been attributed to the nature of bed and bank material, the channel slope and the planform. The textural and stratigraphical properties of the alluvial deposits provide evidences of river metamorphosis during the late Holocene period.

GENERAL

Much of the past geomorphological effort in India has concentrated on drainage and basin morphology (Singh, 1983 , Vaidyanadhan, 1983) and on the fluviatile deposits within major valleys. The lack or insufficiency of essential data base, concerning channel geometry and morphology in India, has put severe limitations in the understanding of channel hydraulics and processes. Although hydrologists and engineers have gauged and studied rivers extensively, their approach has primarily been towards the assessment of water resources and not towards the understanding of the channel processes and morphology. Hence, there is a need to give substantial attention to the study of hydraulic geometry and hydromorphological relations of modern fluvial systems to acquire knowledge about the hydraulic characteristics and channel processes as well as for palaeohydraulic interpretations. In this report a modest attempt has been made to investigate and study, from this point of view, a modern fluvial system – the Vashishthi river.

The Vashishthi river flows westwards from the Western Ghats. Geographically, it forms a part of the Konkan lowland, geologically it occupies the Deccan Traps and geomorphologically it reflects a humid tropical landscape. This report is based on a study of the channel and hydraulic characteristics of the Vashishthi river and its tributary Jagbudi (Fig. 1-A). The purpose of the overall study is to present the channel data and to examine the changes in the channel morphology in the downstream direction and then to assess the probable causes of the braid development.

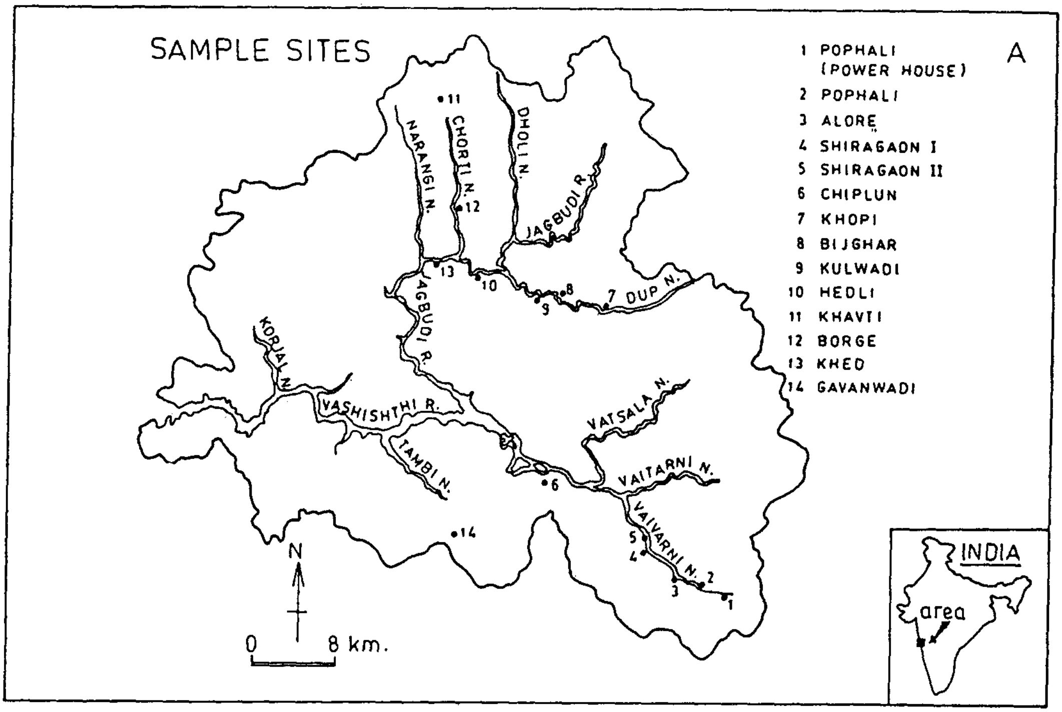

Fig. 1 (A)

MORPHOLOGY

The Vashishthi river drainage basin has an area of 2,115 Km^2. The total length of the river is about 74.8 Km and the channel slope is about 0.0156. The lower part of the river is tidal in nature (33 Km).

The river has a braided channel pattern and the Brice's index varies from 4.82 to less and 1.5. The overall sinuosity of the channel is low, and meandering and straight channel patterns are observed in segments. A long profile (Fig. 1-B) was drawn from topographic maps from source to mouth. The river flows only within unconsolidated alluvium and gravel for most of its course and therefore, the river profile is gently curved. A knick point was located near Shirgaon on Vashishthi river and another near Khopi on river Jagbudi (Dup).

MORPHOLOGIC CHARACTERISTICS OF THE CHANNELS

The variables that determine the channel morphology of modern and palaeo-channels are discharge and the sediment load. Data on discharge and sediment load are not available for the modern channels of Vashishthi river and its tributaries. It is, therefore, necessary to collect information about the modern cross-sections of the river system under review. The shape, size and area of the channels are closely related to the discharge (Schumm, 1977). The Form ratio (w/d) and channel capacity (wd) therefore, can be substituted for discharge, to get some idea about the hydraulic characteristics. The width and depth parameters are significantly related to other morphological characteristics of a channel (like, gradient, wave length, sinuosity and perimeter sedimentology) and to its hydrology. Hence, data pertaining to channel morphology was collected from ten sites from the basin. Schumm's (1960) approach to the channel study was adopted. The data accordingly collected is given in Table I.

1) . *Channel Width*: Early investigators have demonstrated that width of channel is significantly related to channel cross-section and to discharge (Leopold and Wolman, 1970, Schumm, 1977). In the study area, the average width varies between 5 and 100 metres. The parameter increases downstream. In certain sections, as at Pophali, the channel width considerably increases due to braiding (+ 150 m). The width is highly correlated with channel

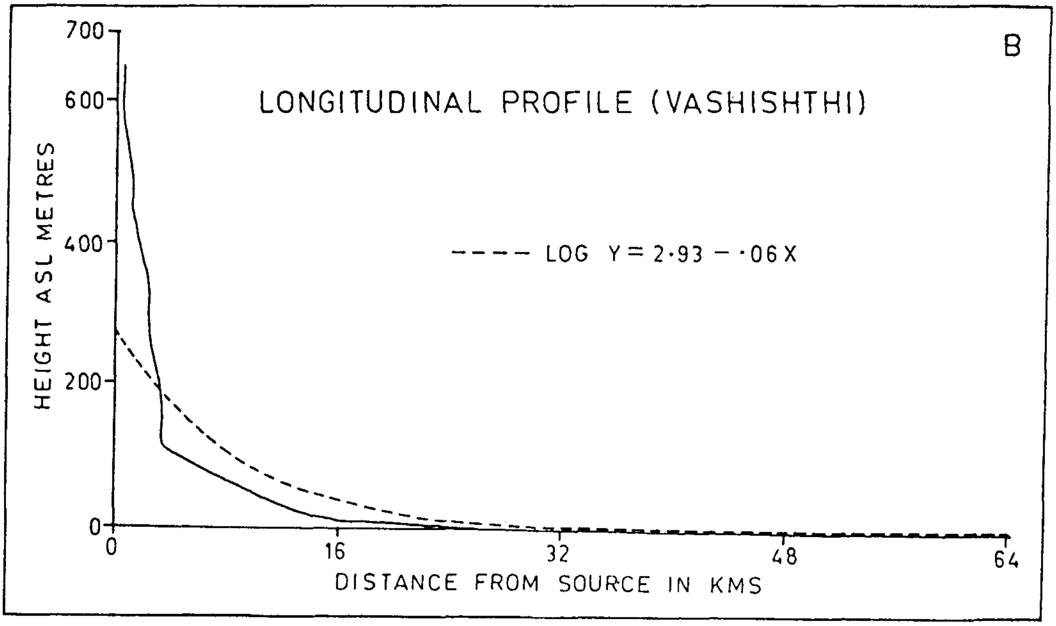

FIG. 1(B)

TABLE - 1

Site	Channel width (m)	Channel depth (m)	Form ratio	Channel capacity (Sq. m.)	Hydraulic radius (m)
Alore	59.0	3.5	16.86	206.50	3.13
Chiplun	90.0	6.4	14.06	576.00	5.60
Bijghar	54.0	4.4	7.73	149.60	3.50
Kulwadi	12.2	3.7	3.30	45.14	2.13
Khopi	13.0	3.2	4.06	41.60	2.14
Medli	13.0	4.8	2.71	62.40	2.76
Khavti	25.0	3.1	8.06	77.50	2.48
Borge	29.0	4.2	6.90	121.80	3.26
Khed	77.3	8.2	9.43	633.86	6.76
Gavanwadi	4.6	2.19	2.19	9.66	1.09

capacity (r = 0.97), Form ratio (r = 0.93), hydraulic radius (r = 0.92) and depth (r = 0.75). Bivariate and multivariate regression and correlation analysis were performed to establish the relationship between width and other parameters. The equations obtained are as follows:

$$w = 1.7196\,(d)^{1.9337} \ldots\ldots \qquad \text{(Eq. 1)}$$

$$r = 0.7681$$

$$w = 2.96 \left(\frac{d^{1.25}\, F^{1.47}\, R^{1.33}}{K^{0.79}} \right) \ldots \qquad \text{(Eq. 2)}$$

$$r = 0.9803$$

In the above equations, the width is directly related to depth (d), Form ratio (F) and hydraulic radius (R) and is inversely related to channel capacity (K). That is, an increase in width reflects a greater percentage of bedload, which is associated with shallow and wide channels.

2) *Channel depth*: With the onset of flood discharge, the hydraulic characteristics of the Vashishthi river and its tributaries change from small channel flows to sheet (flood) flows. Small channels which during post – and pre-monsoon period directed water movement in braided patterns give way to an influx of strong sediment-laden water during monsoons, which covers much of the river channel. Measurements made at the sample sites reveal that channel depth seldom exceeds 10 metres. The water depth ranges between 0.12 and 8.5 metres. In the monsoon, the water depth increases by two to three times, causing considerable increase in the shear along the channel walls. Unlike width, the average and maximum depth increases downstream at a low and highly variable rate. Correlation analysis shows that the change in depth accounts for more than 70 per cent of the changes in the hydraulic radius and capacity. Nearly 59%

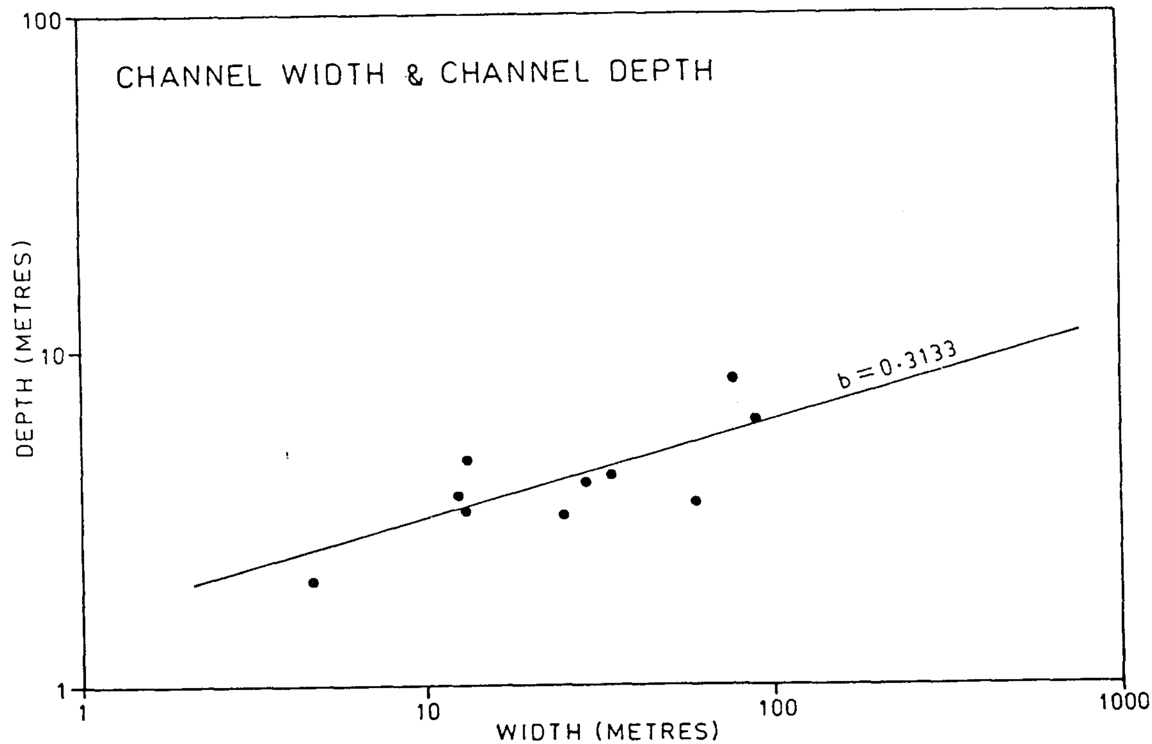

FIG. 2

of the variation in the width is accounted by depth. The log-log relation between w and d was found to be as follows (Fig. 2):

$$d = 1.4853\,(w)^{0.3133} \ldots \qquad \text{(Eq. 3)}$$

The parameter of channel depth is weakly correlated with the Form ratio (r = 0.48) and suggests that width determines the channel shape and capacity to a larger extent, than depth.

3) *Form ratio*: Schumm's (1960) studies indicate that Form ratio (F) reflects the nature of sediments in the bed and banks. The ratio is directly related to peak discharge and is inversely related to gradient. In a general way, the ratio exhibits an increase in the downstream direction, indicating a downstream increase in discharge, but a decrease in sediment size and channel gradient. The ratio is strongly correlated with width (r = 0.93) and channel capacity (r = 0.85). The multiple regression equation of depth (d), width (w), channel capacity (K) and hydraulic radius (R) on Form ratio (F) was performed. The equation obtained is as follows:

$$F = \frac{w^{0.02}\,K^{1.02}}{1.15\,(d^{1.86}\,R^{0.25})} \ldots \qquad \text{(Eq. 4)}$$

$$r = 0.9994$$

The above multivariate equation denotes that Form ratio is directly related to channel width and capacity; and is inversely related to channel depth (d) and hydraulic radius (R). Among the four dependent variables the parameter of depth exhibits highest exponent value (b = 1.86) which perhaps indicates that Form ratio changes rapidly with depth in a multivariate relationship.

Other channel parameters also show similar downstream change in their values. It can, therefore, be inferred that there is a definite increase in discharge in the downstream direction, with a corresponding increase in channel Form ratio and capacity. In order to assess this relationship, velocity and discharge measurements were made at a few sites, during the monsoon and post-monsoon period. The discharge was found to vary between 0.15 m^3/sec. and 30 m^3/sec during the post-monsoon season and between 40 and 800 + m^3/sec in the monsoon season. Although, there are definite downstream trends in the hydraulic geometry morphology, the adjustment in the hydraulic factors, varies from one segment to another on the rivers. This perhaps can be attributed to a complex interaction of hydrology, hydraulics and the resistance of bed and bank material.

SEDIMENT CHARACTERISTICS

a) *Suspended sediments*: Suspended sediment concentration is variable and directly related to discharge. During the post-monsoon field season, the bed forms were easily seen, but during the monsoon investigation the suspended sediment content was relatively high and the channel forms were relatively obscured. Samples collected during the monsoon period, from eight different sites (Table 2) had suspended sediment concentration between 0.02 and 12.0 mg/1 (0.2 to 120 ppm).

b) *Bed Material*: Cobble and pebble-sized material occupying the river bed was collected for shape and size analysis. Compositionally, compact basalt is found in abundence. Occasionally, quartz and amgdaloidal basalts are also encountered. The mean diameter varies from 11.26 to 5.25 cm. The percentage of fine fractions (silt and clay) was found to be substantially low from the source to Chiplun. Other

TABLE 2 : SUSPENDED LOAD AND FIELD pH DATA (MONSOONA SEASON)

Sample sites	Suspended load (mg/1)	Field pH of river water
Phophali	2.00	7.2
Alore	0.02	--
Chiplun	10.01	7.1
Bijghar	0.01	7.1
Hedli	12.00	7.0
Khavti	0.03	7.5
Borge	4.70	7.7
Khed	8.01	--

Vide Fig. 1-A for the location of sample sites.

details of bedload sediments are given in Table 3. The table shows that the mean thickness, length and breadth decreases downstream, and the sediments are, by and large, coarse. The Krumbein's sphericity index implies moderate sphericity of bed material. Computation of Cailleux's flatness index reveals that the flatness increases downstream. Furthermore, a detailed study of the pebbles shows that they are oriented perpendicular to the flow direction in the lower reaches. The absence of fine sediments (silt + clay) during the post-monsoon and monsoon season, on the channel bed was conspicuously noted. Absence of patina on the material suggests that they are being continuously worked upon by the process of abrasion or attrition.

c) *Bedform and Bank Material*: Mechanism of bank erosion depends on the structure of banks and the properties of its constituent material. The banks may be classified as being cohesive, non-cohesive or composite. The banks of river Vashishthi and Jagbudi have a non-cohesive and composite structure. The banks consist of non-cohesive sand, gravel, pebbles and cobbles formed from relic bars and relatively thin cohesive silt sediments, deposited by over-

TABLE 3 : BED MATERIAL MORPHOLOGY

	Parameters	Pophali	Shirgaon	Chiplun
1.	Mean length (cm)	13.40	11.30	6.27
2.	Mean breadth (cm)	9.13	8.23	4.18
3.	Mean thickness (cm)	6.13	5.27	2.11
4.	Mean diameter (cm)	11.27	9.77	8.36
5.	Krumbein's Sphericity Index	0.69	0.70	0.61
6.	Cailleux's flathness Index	183.70	185.29	247.63

bank flow and on top of bar deposits. The characteristic composite bankform shows cohesionless deposits (2-4 metres) overlain by a capping of relatively thin cohesive material, about 10-55 cm. thick (Fig. 3). Some of the pebbles show slight imbrication and the pebble to pebble contact in the lower facie is good. Weathering and pedogenesis of the sediments is not seen prominently, except near Shirgaon.

Measurements of bank resistence by using a penetrometer were carried out during the two field works. The data demonstrates a high resistence value for the upper finner sediments, during the monsoon period (1.3 to 3.7 kg/cm^2). In the post-monsoon period the values decreased to 1.4 to 1.6 kg. per square cm. (Table 4).

TABLE 4 : BANK RESISTANCE

Sample site	Monsoon Bank Resistance (Kg / Cm^2)	Post-Monsoon Bank Resistance (Kg/Cm^2)
Pophali	1.25	1.50
Alore	1.70	1.60
Shirgaon I	1.30	1.60
Chiplun	2.25	1.50
Kulwadi	2.25	1.51
Khed	3.70	1.70
Gavanwadi	–	1.42

SEDIMENTS AND CHANNEL MORPHOLOGY

Observations show that there is considerable variation in channel width and depth in the downstream direction along the Vashishthi river. The width and depth does not increase progressively as predicted by hydraulic geometry relationships. The manner in which the channel dimension changes clearly indicates the importance of sediment load in channel morphology.

Earlier studies by Leopold and Wolman (1970) and by Schumm and Khan (1972) have demonstrated that sediment load affects the channel geometry. The larger the sediment size and larger the load that is to be transported, the steeper is the stream gradient. Hack has developed an equation between median bed sediment size (D_{50}), drainage area (A) and stream bed slope (s_b). Although the equation may not be suitably applicable to the Konkan river, it appears to be basically sound for roughly estimating the desired parameter. Thus, the stream bed slope was calculated by employing the following equation:

$$S_b = \frac{18\,(D_{50})^{0.6}}{A}$$

The equation gives a value of 0.0288 for the Vashishthi river. Thus, with a given bed material size the channel slope should have been much higher than its present stream bed slope (0.0157). It appears, therefore, that the river has to aggrade significantly to attain the required bed slope. It is only in the subsequent period that the river would become more efficient to transport the load.

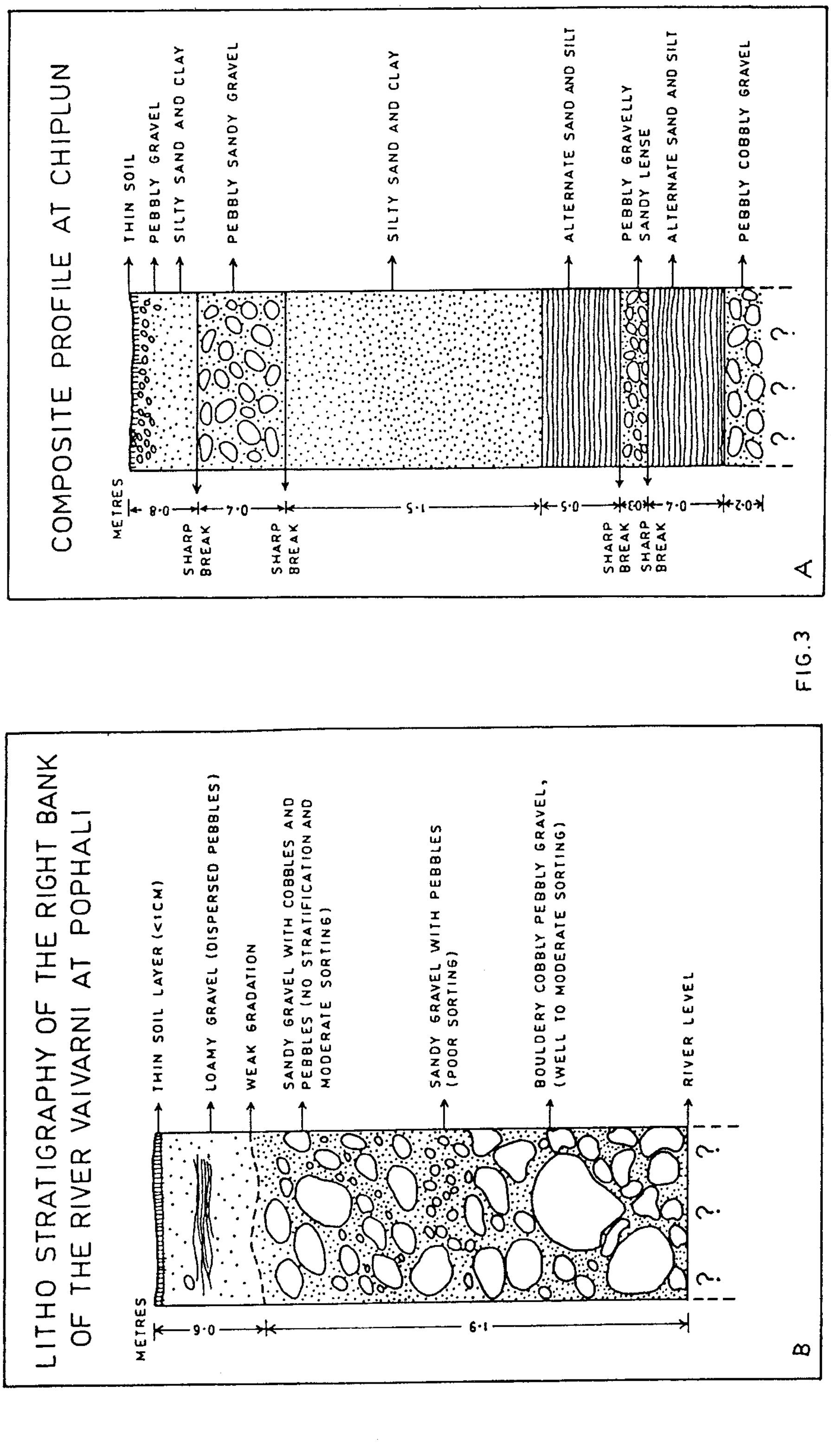
COMPOSITE PROFILE AT CHIPLUN
METRES
THIN SOIL
PEBBLY GRAVEL
SILTY SAND AND CLAY
PEBBLY SANDY GRAVEL
SILTY SAND AND CLAY
ALTERNATE SAND AND SILT
PEBBLY GRAVELLY SANDY LENSE
ALTERNATE SAND AND SILT
PEBBLY COBBLY GRAVEL
0·8
0·4
1·5
0·5
0·3
0·4
0·2
SHARP BREAK
SHARP BREAK
SHARP BREAK
SHARP BREAK
A
LITHO STRATIGRAPHY OF THE RIGHT BANK OF THE RIVER VAIVARNI AT POPHALI
METRES
THIN SOIL LAYER (<1CM)
LOAMY GRAVEL (DISPERSED PEBBLES)
WEAK GRADATION
SANDY GRAVEL WITH COBBLES AND PEBBLES (NO STRATIFICATION AND MODERATE SORTING)
SANDY GRAVEL WITH PEBBLES (POOR SORTING)
BOULDERY COBBLY PEBBLY GRAVEL, (WELL TO MODERATE SORTING)
RIVER LEVEL
0·6
1·9
B

FIG.3

The appearance of rectangularity of the river cross-sections is also related to the nature of bank material. For a given channel slope and roughness the size of the channel is perhaps the function of bank material and discharge. Because the non-cohesive bank material of the Vashishthi river, is unable to withstand an increase in shear stress associated with an increase in the discharge (and depth), the banks give way and the channel simply enlarge, leading to an increase in the channel width and Form ratio (F).

PLANFORM AND HYDRAULIC CHARACTERISTICS

The Brice's index computed for the river clearly demonstrates that the Vashishthi river has a braided channel pattern. By definition a braided channel is one where the many divided channel ways are always shifting (Schumm, 1977). According to Rust (1982) a multi-channel and low sinuosity system can be termed as 'braided'. Thus, in all respect the channel of Vashishthi river is braided.

Field studies of channel morphology show that the braids of various size are encountered in the channel. The braids are aligned to the flow and are diamond shaped and can be classified as longitudinal bars. The size, dimension and pattern of the river channel are related to the nature of the sediment in the bed and banks. Earlier studies in various parts of the world (Schumm, 1977, Miall, 1982) demonstrate that the channel Form ratio (F), the percentage of fine sediments and the channel patterns are interrelated and inter-dependent. Schumm (1960) and Jackson (1982) maintain that coarse gravel and wide channels are diagnostic of a proximal non-meandering (braided) stream; and substantial mud content in coarse member and thick fine member are strongly indicative of a meandering stream.

The hydromorphological relationships are clearly illustrated by the channel of river Vashishthi. The low silt-clay content of the banks suggests that they are non-cohesive and easily erodable. The relative rapid increase in the channel width ($b = 0.51$) in general and dramatic increase in the parameter in certain parts, acknowledge the tendency of the channel to widen itself in response to flashy floods. The initiation of the braids and their subsequent growth appears to lead to a reduction in channel width (relative) and channel capacity. This reduction perhaps enhances the process of bank erosion and channel widenning.

Hydrologically the regime of Vashishthi river appears to have a highly variable discharge with, flood peakedness. The discharge data collected during the two field seasons and the information obtained from the local persons leads to the above inference.

Computation of the sediment load shows that the percentage of suspended load is much below the normal expectations (Table 3). The wash load amount certainly increases downstream but not as rapidly as discharge. This means that the concentration of wash load decreases downstream (Morisawa, 1985). Information collected from the local farmers demonstrates that the percentage of suspended sediments is high, immediately after the onset of monsoons. It seems therefore, that the sediments derived from the basin are removed during the initial runoff and the peak sediment load follows the peak stage. Stabilization of the hillslopes due to an increase in the moisture content and due to an increase in the vegetative screen, perhaps leads to a reduction in the wash load, in the subsequent period.

Furthermore, beds of fine material on the channel floor, transported in suspension are rare, partly because the general regime is against their deposition but more importantly because the endless and rapid channel flows gives them an extremely low preservation potential (Allen, 1970).

Cursory examination of the suspended load data from different sites in the Upper Bhima and Krishna basins reveals that the wash load in the Vashishthi river is not abnormally low. The suspended load in the former basins varies between 1 and 10 mg. per litre. This finding, therefore, leads to an inference that the fluvial regimes of the Western Trappean landscape are not wash-load dominant but mixed load dominant systems.

DEVELOPMENT OF THE BRAIDED PATTERN

Conditions which favour braiding are suggested by the area in which the pattern occurs. Bedload has been accepted to be an essential prerequisite and this is available in large quantities in the river. Similarly, variable and irregular discharge with seasonal peaks also seem to be one of the major reasons of the development of braided channel. Thirdly, erodable banks with low resistence have also favoured widening of the channels and the development of braided pattern. A final factor which appears to have influenced the occurrence of channel is the presence of steep slopes in the Ghat zone and the presence of fan deposits, particularly at the junction of these steep slopes of the Ghats and the gentle slopes (of the sub-Ghat) river segments (as near Phophali).

THE QUASI-EQUILIBRIUM

The incidence of braiding in the Vashishthi river seems to have developed into a braided system to restore the quasi-equilibrium. The restortion of the apparent equilibrium and adjustment between the parameters of channel form and process appears to connote three possibilities:

1. An ineffective and incompetent river, which is unable to efficiently transport the sediments (Schumm and Khan, 1972, Knighton, 1972). Therefore, the river deposits its sediments to increase the gradient as well as its competence. The wedge of coarse sediments thinning downstream indicates an upstream control (Morisawa, 1985). Such a control suggests a large amount of coarse debris imposed from upstream (fan deposits). The river, therefore would react by aggrading to steepen its channel slope and to increase it efficiency.

2. The bedload size (dia - 8 to 11 cm.) implies a large calibar of load. In order to transport these coarse sediments a wide and shallow channel is required. A wide and shallow channel increases turbulance as well as the critical tractive force (upto a certain level). Schumm (1977) and Schumm and Khan (1972) have inferred that while narrow and deep channel is effective in transporting wash load, wide and shallow channel is effective in transporting bedload material. Therefore, the wide channel and coarse bedload and irregular cross-section suggest high energy conditions (Petts, 1983). Further, the absence of fine sediments on the channel floor provides a strong proof of the high stream power of the Vashishthi river. Thus, the channel of Vashishthi is bedload dominant stream with high stream power.

3. Thirdly, the pattern of Vashishthi appears to have been developed by intrinsic factors and not by extrinsic factors. It is evident that a major portion of the present bedload has been derived by the erosion of the bank material, which are in fact relict channel bar deposits. It appears therefore, that the coarse sediments were laid by a palaeo-channel and the present river is not

capable enough to transport them. Hence, the river is restoring its balance by braiding and by decreasing its relative width (not absolute) and by increasing its flow velocities.

Thus, the channel processes appear to be reaching the state of quasi-equilibrium by minimizing the total energy expenditure. The present channel morphology and hydraulic geometry of Vashishthi river emphasises a mechanism whereby channel slope may be adjusted to the parameters of channel from and processes.

LATE-HOLOCENE FLUVIAL REGIME

The braided channel pattern of Vashishthi river reflects a particular environment condition. By and large, braiding in the river appears to have been favoured by high energy fluvial environment with steep channel gradient, large and highly variable discharge, dominant bedload transport and non-cohesive banks, lacking stabilization by vegetation. However, the exact explanation of the channel processes and causes are difficult to determine. Nevertheless, on the basis of field investigations and observations it appears that the plan and channel geometry of the river is related to (i) noncohesive quality of channel bank and (ii) to sufficient annual supply of coarse sediments.

The percentage of suspended or wash load is low, in the river. However, taking into account the channel pattern it does not appear to be anomalous. Schumm (1960) correlated channel slope and silt-clay content and is of the view' that braided systems deposit little silt and clay, without subsequent working. It is the lack of fine cohesive sediments that results in easily eroadable banks. Channels therefore, divide and relocate with minimum difficulty.

Efforts to establish the age of the fluvial deposits (braid) in Konkan, have not yet provided results conclusive enough to report in finial form. Nevertheless, a radio carbon date of fossilized wood buried about 84 cm. below the terrace top was discovered in a trench, roughly 35 metres away from the left bank of Vashishthi river, at Pophali (Kale et al, 1986). This one sample temporarily indicates a major period of fan deposition and river aggradation in the piedmont zone before 1300 A. D. The age and location of the drift wood suggest that the channels in the area are highly dynamic. The date further suggests that, not only the Vashishthi river has changed its regime but has also migrated at an average rate of 5 cm yr^{-1} in the last 700 years or so. If we assume that the present above-grade conditions are of post-wood-burial period then a rough rate of 2.85 mm yr^{-1} of vertical erosion (linear) can be computed for the late-Historical period.

On the basis of the textural and stratigraphical characteristics, two distincty different channel fill types viz. bedload channel fill and suspended load channel fill are apparent in the Vashishthi basin. Schumms (1960) work suggests that bedload channels-fills, dominated by sands, pebbles and cobbles are laid down by shallow, wide (high Form ratio) and less sinuous,streams and; the suspended load channels dominated by silts and clay are narrow (low Form ratio), deep and meandering. This appears to be true for the area investigated. During early historical period seasonally high discharge bedload streams were actively aggrading and deposited large volumes of sand and gravel across the riverine plain (Fig. 4-A). By about 1300 A. D. the competence had decreased and only fine sediments were deposited on the flood plain by meandering channels of Vashishthi and Jagbudi (Fig. 4-B). Thus, early historical low sinuosity bedload streams gave way to high sinuosity suspended load streams (river metamorphosis),

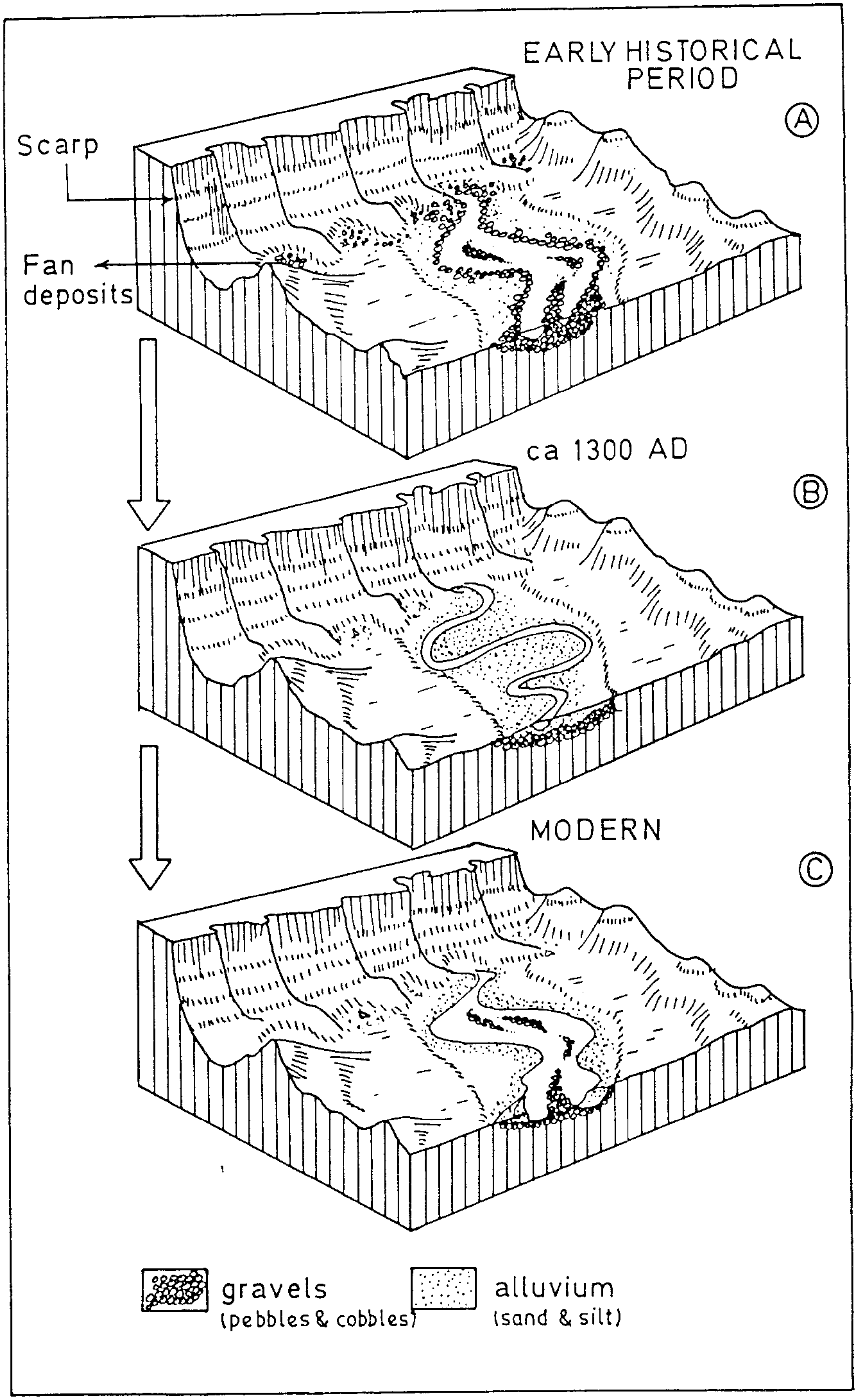
EARLY HISTORICAL PERIOD
A
Scarp
Fan deposits
ca 1300 AD
B
MODERN
C
gravels
(pebbles & cobbles)
alluvium
(sand & silt)

FIG. 4

which then actively incised the flood plain, during late historical period to give rise to the present terraces (Fig. 4-C).

Although, it is difficult to encounter similar geomorphic conditions in other part of the tropical areas, the studies carried out by Davies et al. (1982) provide an interesting analogy to the Vashishthi basin. Davies and others have reported very young but homologous aggradational deposits in Rio Pantaleon and Achiquate basins of Gautemala (Central America). The two rivers are short and swift flowing, with very steep upper segments. There also the braided channel pattern, morphologies and flow conditions show a strong relation with the rapid downstream gradient change. Decreasing flood flow competence caused by decreasing slope and flow depth results in a major downstream modification in grain size, channel Form ratio and capacity. The presence of fan deposits are, by and large, similar in the Vashishthi and the formers basins, but the only difference is that the former rivers drain an area of active volcanisum in Gautemala and the sediment in transportation are fresh olivine basalts produced by major erruption of Fuego Volcano; and thus is different from Vashisthi, where the sediments in transportation are largely relict bar deposits of post early-historical period. Nevertheless, the rivers from Gautemala and Konkan (India) suggest that large supply of sediment load and non-cohesive quality of channel banks, in such short and swift flowing streams can give rise to multi-thread and braided channel patterns.

The infrences drawn about the hydromorphological relationships and the hydraulic geometry are certainly tentative and there are many unresolved problems. Lack or insufficiency of data (both in space and time) have put strong limitations in the evaluation of channel processes and hydraulic geometry. Therefore, future hydrological and geomorphological studies in this respect would be both academically and economically vital.

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