

A STUDY OF AGGRADATION AND DEGRADATION OF THE KHOWAI RIVER

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**A STUDY OF AGGRADATION AND DEGRADATION
OF THE KHOWAI RIVER**

Submitted by

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**In partial fulfilment of the requirements for the degree of Master of Engineering
(Water Resources)**

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CERTIFICATE

This is to certify that this work has been done by me and this report nor any part thereof has been submitted elsewhere for the award of any degree or diploma.

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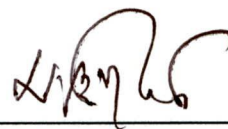
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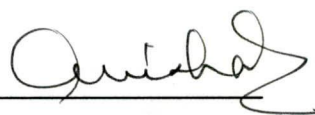
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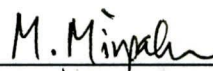
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ABSTRACT

The study was conducted to investigate the aggradation and degradation of the Khowai River bed. Assessment of future sedimentation along the Khowai river was also carried out. The reach extends from Ballah to the confluence of Khowai- Dhaleswari River and has an overall length of 87 km. To carry out the investigations 39 sections of the Khowai River from Ballah to the Khowai-Dhaleswari confluence for the year 1988, 17 cross sections from Shaistaganj to Khowai-Dhaleswari confluence for the year 1994 and a thalweg profile for the year 1965 were collected in the digitized form from FAP-6. Data on suspended sediment concentrations at the Shaistaganj station between years 1964 and 1993 were also collected from River Research Institute (RRI), Faridpur. Mean daily water levels for the gauge stations at Ballah, Chunarughat, Shaistaganj and Habiganj from 1964 to 1994 and mean daily discharges at Shaistaganj station for the same years were collected from Surface Water Modelling Centre (SWMC). Bed material gradation curves for the year 1992 at Chunarughat gauge, Shaistaganj gauge, Habiganj gauge and downstream of Habiganj gauge were collected from FAP-6. Suspended sediment particle size distribution curves for the years 1991 and 1992 at Shaistaganj were collected from SWMC.

Cross-sectional properties at 17 locations between Shaistaganj and the Khowai-Dhaleswari confluence between years 1988 and 1994 were analyzed and it was observed that the river between the reach is becoming narrower and the average thalweg level has degraded by 1.29 m between Shaistaganj and 6.6 km downstream of Habiganj. The total reach of this degraded thalweg is about 21 km in length. After that up to the confluence of Khowai and Dhaleswari River the average thalweg level has again suffered degradation by 2.03 m on an average during the study period. The cross sectional area at bankfull stage is being increased at the rate of 10.1 m² per year since 1988. It was also observed that in most of the occasions the cross sectional area above bankfull stage has reduced indicating deposition of sediment on the berms and flood plain on both sides of the river. The overall cross section of the 23.44 km reach below Shaistaganj is being reduced at the rate of 14.84 m² per year since 1988.

It was also observed from the analysis of the water level records between years 1964 and 1994 that Khowai river bed level is being aggraded at the gauge stations at Ballah, Chunarughat, Shaistaganj and Habiganj by 0.96 m, 0.2 m, over 1 m, and 1.5 m respectively since 1964.

Study of the thalweg profiles between years 1965 and 1988 suggested that the Khowai River has aggraded by 1 m between Ballah and Chaunarughat and degraded by 1 m between Chunarughat and Shaistaganj. Mean bed level profiles of 1988 and 1994 suggested average aggradation by 0.4 m between Shaistaganj and 6.6 km downstream of Habiganj. After that up to the end of the river i.e. the confluence of Khowai and Dhaleswari River it suffered degradation by 0.5 m. The mean bed level profile of 1994 showed a scour hole due to the loop cut made by BWDB in the year 1992 at 9 km downstream of Habiganj.

Analysis of bed material curves and suspended sediment particle size distribution curves based on Einstein's theory suggested that the inflowing sediment load at Shaistaganj stations consisted of 30% coarser fraction of the suspended load and 70% wash load.

Future prediction on the Khowai River sedimentation was made using HEC-6 based on channel geometry of 1988. The study revealed that there would be continued deposition of sediment indicating continued aggradation of the bed level along the study reach of the river.

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NOTATIONS AND ABBREVIATIONS

A	Cross Section area
A_j	Area of subsection
B_o	Width of movable bed
d	Grain diameter
d_a	Smallest stable grain size in armour layer
d_{10}	Particle size of which 10% is finer
D	Water depth
DD	Duration of time step
D_*	Dimensionless particle diameter (based on D_{35})
D_{se}	Depth of bed material which must be removed to reach equilibrium in time step
D_{35}	Particle size at which 35% by weight is finer;
g	Acceleration due to gravity
G	Sediment discharge
h	Water depth
h_e	Energy loss
J	Total number of subsections across cross section
K	Dimensionless coefficient;
L_j	Length of jth strip between subsections
m	Dimensionless coefficient;
n	Manning's Roughness coefficient
N	Number of sediment grains on the bed surface
NSS	Total number of subsections
PC	Percent of bed material coarser than size d
P_j	Wetted perimeter of subsection
q_t	Volumetric total load, excluding pores per unit of width;

Q	Water discharge (m^3/s)
Q_s	Suspended sediment discharge (tons/day)
R	Hydraulic radius
R_j	Hydraulic radius of subsection
SA	Bed surface area
SAE	Ratio of surface area of potential scour to total surface area
S_f	Friction slope
U	Depth-average flow velocity
U_*	Shear velocity
V	Average velocities
V_{se}	Volume of bed material which must be removed to reach equilibrium in a time step
WS	Water surface elevations
x	Distance along the channel
Y	Particle mobility parameter
Y_s	Depth of sediment in control volume
Y_{cr}	Critical particle mobility parameter;
α	Velocity distribution coefficient for flow
Δ	Relative submerged sediment density;
ρ_s	Sediment density
ρ_s	Density of sand grains
ρ_f	Density of water
ρ	Water density; and
ν	Kinematic viscosity
ψ	Transport intensity from Einstein's bed load function, related to the inverse of Shield's parameter
ACE	Associated Consulting Engineers
ADB	Asian Development Bank
AGU	American Geophysical Union
BWDB	Bangladesh Water Development Board

EPWAPDA	East Pakistan Water and Power Development Authority
FAP	Flood Action Plan
FPCO	Flood Plan Coordinarion Organization
HEC	Hydrologic Engineering Center
PWD	Public Works Department
RRI	River Research Institute
SWMC	Surface Water Modelling Center
WARPO	Water Resources Planning Organization

CHAPTER 1

INTRODUCTION



1.1 GENERAL

Natural streams never attain equilibrium conditions. However a dynamic equilibrium is established after a prolonged period. Again the process of dynamic equilibrium is often disturbed by natural occurrences like landslides, droughts etc. or construction of hydraulic structure and dyke/levees for human benefits. Moreover the uncontrolled deforestation, forest fires, overgrazing, improper methods of tillage and unwise agricultural practices have accelerated soil erosion resulting in a large increase of sediment flow in streams. When the sediment load entering the reach of an alluvial channel is equal to its transport capacity, the reach is in equilibrium; the bed level at a section then shows no variation with time except for the small periodic changes taking place due to the migration of the bed undulations, if the channel is in such a regime (Murthy, 1980).

Aggradation occurs when sediment transport capacity of a channel reach is less than the inflowing sediment load resulting in rise of the elevation of the bed level. In alluvial channels or streams, bed aggradation (i.e. raising of the river bed by deposition) evolves primarily from the passage of flood events. The rise of the bed profile consequently reduces the conveyance capacity of the channel. Sediment deposition along streams or in reservoirs is a complex and troublesome process. It creates a variety of problems such as raising of stream beds and increasing flood heights, meandering and overflow along the banks, choking up of navigation and irrigation canals, and depletion of capacity of storage reservoir (Ranga Raju, 1980)

Bed degradation (i.e. lowering of the bed by scouring) on the other hand, which simultaneously occur in the same alluvial stream, threatens in-stream and bank structures. Bridge piers, power lines and flood control levees are some common structures that are greatly affected by excessive bed degradation evolving from the passage of floods. The most common situation in which degradation occurs is that downstream of a large-reservoir. Degradation also occurs when urban drainage or return flow from irrigation enters an alluvial stream. An important

characteristic of degradation in case of non-uniform sediments is the coarsening of the bed material due to progressive removal of the fines (Ranga Raju, 1980).

The causes of degradation and aggradation are well understood by reference to Lane's balance analogy. He visualised discharge and sediment load in one pan of the balance and slope and sediment size in the other. The phenomena can also be understood in mathematical terms by reference to the equation of sediment continuity, viz. (after Ranga Raju, 1980)

$$\frac{\delta z}{\delta t} + \frac{1}{(1-\lambda)} \frac{\delta G}{\delta x} = 0 \dots\dots\dots (1)$$

Here z is the elevation of the bed above a datum at a distance x from the origin at time t , λ is the porosity of the sand mass, G is the sediment rate per unit width in absolute volume. Obviously, degradation occurs if the transport rate increases along the length, while a decrease in G along the length leads to aggradation.

1.2 KHOWAI RIVER SYSTEM

The Khowai River flows northwards from the Tripura Hills in India and crosses into Bangladesh near the town of Ballah. Downstream of Ballah, the Khowai River flows in a meandering sand bed channel for a distance of about 60 km to the town of Habiganj. The river turns westward when it crosses into the low-lying, deeply flooded Central Basin. Downstream of this point it becomes known as the "Barak River". The river rapidly decreases in size and flows for about 30 km before joining the Dhaleswari River at Madna. At present the river is embanked (full flood control embankment) from about 6 km downstream of Habiganj to Chunarughat on the right bank and to Raza Bazar (5 km further upstream of Chunarughat) on the left bank. The embankments were constructed between 1976 and 1985. Figure 1.1 shows the Khowai River System.

The Khowai River flows in a sinuously meandering sand-bed channel throughout most of its length. At Shaistaganj, the river flows on top of a broad floodplain that is up to 3 m higher

than the adjacent flood plain basin lands. The channel width and mean depth at bankfull stage average around 70 m and 5 m respectively between Ballah and Habiganj. Downstream of Habiganj the channel narrows to about 20 m after it flows onto the low-lying Central Basin. The channel virtually vanishes in the broad flat lowlands which are covered by ancient channel scars, scroll bars and ox-bow lakes from an ancient river (possibly an early Meghna River) which flowed through this area.

According to FPCO (1993) study, the drainage area at the Indian border is about 1113 km². Prior to embankment construction in the 1980's, local tributary inflows increased the drainage area by approximately 200 km² between Ballah and Shaistaganj. After the flood embankments were constructed, most of this local drainage would have cutoff from the main channel.

The Khowai River has a flashy flood regime and several flood peaks typically occur between May and October each year and experiences frequent flooding and sediment deposition and scouring. Daily discharge data is available from the hydrometric station at Shaistaganj. The station have been operated since the mid-1950's. Water levels have also been recorded along the river at Ballah (gauge 157) near Indian border, at Chunarughat (gauge 158), at Shaistaganj (gauge 158.1) and at Habiganj (gauge 159). The average daily discharge at Shaistaganj during the period 1964 - 1994 was 36 m³/s and mean monthly flow in June was 66.4 m³/s. The minimum flows during the last 31 years was 0.8 m³/s and the maximum mean daily flow was 1050 m³/s. The seasonal distribution of the flow at Shaistaganj is given in table 1.1a. Table 1.1b shows the seasonal distribution of water levels at gauges along Khowai River.

1.2.1 CLIMATE

The climate in and around Khowai River area experiences the sub-tropical monsoon climate typical of Bangladesh, but with variations due to its surrounding topography. Rainfall is most significant and variable aspect of the climate, causing severe floods and flooding in summer and drought in winter.

1.2.2 VARIATIONS IN ANNUAL RAINFALL

The variations of annual rainfall around Khowai River is best represented by data for 1961-90 for the two BWDB rain gauges at Srimongal and Habignaj. The data of the two stations are shown in Table 1.2. The data show that annual rainfall increased from an average of 2447 mm/year to 2542 mm/year. There are four distinct seasons in Bangladesh relative to the annual cycle of water resource activity which reflects the seasonal distribution of the annual rainfall. Table 1.3 shows the seasons of Bangladesh with the calendar period. The seasonal distribution of the annual rainfall is shown in Table 1.4. It can be observed from the Table 1.4 that the rainfall is heavily concentrated in the monsoon and pre-monsoon seasons.

1.2.3 CLIMATOLOGICAL AVERAGES AND EXTREMES

The climate of the Khowai River area as a whole is best represented by the data for Srimongal, the nearest BMD climatological station, located east of the Shaistaganj. The monthly averages of the climatological data (temperature, wind speed, rainfall etc.) for 1948-91 (44 years) are given in Table 1.5 and Table 1.6. Table 1.7 shows the extremes of the temperature, rainfall and wind speed records.

Annual sunshine hours average 6.2 hours/day, and average monthly sunshine hours range from a minimum of 4.2 hours/day in July to a maximum of 8.1 hours/day in February.

Mean annual temperature is 24.9°C, and average monthly temperatures range from a minimum of 17.6°C in January to a maximum of 28.7°C in August.

Monthly mean minimum temperatures range from 9.3°C in January to 25.1°C in July/August, and extreme minimum temperatures of record range from 2.8°C in January to 21.2°C in August.

Monthly mean maximum temperatures range from 25.6°C in January to 33.2°C in April,

and extreme maximum temperatures have ranged from 31.1°C in January to 43.4°C in April.

The annual mean humidity is 81%, and monthly averages range from 73% in March to 88% in August and September.

The annual mean wind speed is 7.3 km/hour from the east-southeast. Monthly average wind speeds range from 5.7 km/hour to 9.9 km/hour, but the extreme gust of record is 167 km/hour. Winds are generally blow from the southeast during the monsoon season, and vary between southeast and east-northeast in the other seasons.

The mean annual rainfall is 2431 mm. Average monthly rainfalls range from 6 mm in December to 483 mm in June, and monthly rainfalls have ranged from 0 mm in November through April to as much as 1285 mm in June. The extreme daily rainfall record is 514 mm.

Potential evapotranspiration averages 1460 mm/year, and ranges from 141 mm (4.7 mm/day) in September to 243 mm (8.1 mm/day) in April.

The surface water balance of the Khowai River basin shows an annual excess of 971 mm which runs off into the river system or recharges the aquifers. The monthly water balance is positive in May through September and ranges up to 324 mm/month in June, but during October through April the balance is negative reaching as low as -139 mm in January. The winter surface moisture deficit is generally met from residual soil moisture until February after which a demand for irrigation normally arises.

1.3 OBJECTIVES OF THE STUDY

The specific objectives of the study are as follows:

- 1) to assess the aggradation-degradation in the reach between Ballah and the confluence of the Barak-Dhaleswari near Madna
- 2) to estimate the future sediment transport rate and the future channel aggradation/

degradation based on channel geometry using HEC-6 (1991).

HEC-6 (1991) is a one-dimensional numerical model of river mechanics that computes scour and deposition by simulating the interaction between the hydraulics of the flow and the rate of sediment transport. This model developed by the U.S. Army Corps of Engineers and gained a widespread recognition for the analysis of long-term river and reservoir behaviour rather than the response of stream systems to short-term, single event, flood. HEC-6 does not simulate bank erosion or lateral channel migration.

1.4 LIMITATIONS OF THE STUDY

1. Only 39 cross sections are available to represent the 87 kilometre channel geometry of the year 1988. If more cross sections were available, HEC-6 model would have provided a more better prediction.
2. Review of the available cross sections for the year 1988 and 1994 revealed that their locations are not exactly at the same place. The comparisons of the cross sections would have provided a better aggradation and degradation study if the sections for different years were located exactly at the same place.
3. As the reference point of the cross sections survey in different years are different (not known) the superimposition of the sections are not possible. This has happened probably due to the survey of the river by different organizations. It is to be noted that BWDB does not have regular river survey program in Khowai River as they normally do for the cases of major rivers of Bangladesh.

CHAPTER 2

REVIEW OF LITERATURE

2.1 GENERAL

Several studies have been made to evaluate flow and bed variation in meandering channels by Englund (1974), Odgaard (1986), Ikeda et. al. (1987), Falcon and Kenedy (1983). Most of their studies were primarily concerned with flows and bed variations in curved channels with point bar. Shimizu and Itakura (1989) applied a two dimensional model in calculating the bed variation in alluvial channels. The model was applied to analyze the bed variations with or without meso-scale bed configuration such as alternating bars (pool and riffles) and braided bars, which can be observed even in straight channel. Leopold and Wolman (1957) and many other researchers have investigated the channel patterns and river bed characteristics of pool-riffle bars and braided bars. Soni et. al. (1980) carried out study on the aggradation caused in an alluvial stream due to increase in sediment supply rate. In such a case the stream bed both up-stream and down-stream of the section of the increased sediment supply shall aggrade. They considered only the aggradation in the downstream reach and assumed that sediment supply to be taking place continuously at a constant rate. Their primary objective has been to predict analytically the transient bed and water surface profiles under such condition. Jaramillo and Jain (1984) performed investigations on the aggradation and degradation of alluvial channel bed and introduced a one dimensional nonlinear parabolic model for non equilibrium processes in the alluvial rivers. Their model can be used as a tool for predicting aggradation - degradation processes in alluvial rivers.

Ranga Raju (1980) did a study on the practical computation of degradation and aggradation on alluvial rivers based largely on the works carried out in India. He presented semi-empirical methods for the computation of bed and water surface profiles for some of the commonly encountered cases of aggradation. Independent researches on the evaluation of aggradation and degradation in the rivers and reservoirs in India and Pakistan were conducted by Murthy, Vittal, Ayoob in 1980.

Jain (1989) proposed a guide for estimating riverbed degradation. The rate and extent of riverbed degradation resulting from sediment interruption were determined by means of computer-based numerical experiments. He presented the results of numerical experiments in the form of algebraic relations that can be easily applied by practicing engineers to estimate the temporal and optimal riverbed degradation during the preliminary phase of the engineering designs. The proposed relationship for the bed degradation has been verified with the field data of Missouri River.

2.2 MORPHOLOGIC STUDIES IN THE RIVERS OF BANGLADESH

There have been many studies done on the erosion and deposition and bed level variations in many of the rivers of Bangladesh. Mostly the studies were carried out in the major rivers like the Ganges, the Brahmaputra, the Meghna and the Teesta River.

Hossain (1991) carried out studies on the aggradation and degradation of the Brahmaputra River, the Ganges River and the Teesta River. In his studies he had shown the variations of the mean bed levels of the above rivers and also concluded the extent of aggradation and degradations including net sedimentation in different reaches of the river. His study reach in the case of Ganges River extends from Baghgokulpur to Aricha (125 km) and compared the mean bed levels between years 1967-68 and 1985-86. The findings were aggradation of the bed level between Baghokulpur and 75 km upstream of Aricha with a maximum rise of the bed level by 3 m at 122 km upstream of Aricha and degradation in the 75 km reach upstream of Aricha. In the case of Brahmaputra River the study reach extends from Charnatua to Aricha (230 km reach) and comparison of the mean bed levels were done between years 1965-66 and 1985-86. His study showed that aggradation has taken place in the upper 159 km reach (i.e. between Charnatua to 159 km downstream) with a maximum rise of 4.5 m and the rest of the downstream reach (i.e. 71 km) suffered degradation with a maximum fall of the bed level by 3.7 m. Hossain's study on the mean bed level variations of the Teesta River was confined within 13 cross sections for a 10 km reach and he compared the mean bed levels between years 1970 and 1987. He concluded that the mean bed levels at various section showed erratic trend of fall and rise and on an average, the mean bed level profiles do not show significant trend of change

over the study reach. His study revealed highest rise of the bed level by 0.4 m and fall by 0.7 m within the study reach.

Hossain (1991) also carried out study on the sedimentation that has experienced by the Ganges, the Brahmaputra and the Teesta River within the study reach. He concluded that the net total volume of material deposited in the 125 km reach for the Ganges in 18 years was $4.26 \times 10^8 \text{ m}^3$, for the Brahmaputra River in 20 years for a reach of 230 km was $3.4 \times 10^8 \text{ m}^3$ and for the Teesta River net deposition was about $2.5 \times 10^5 \text{ m}^3$ in 18 years.

Habibullah (1987) determined the bed level variations and bankline movements between Aricha and Charnatua. According to the study the reach length between Aricha and Charnatua was 211.39 km. He studied 32 sections for the bank line movement and 20 sections for the bed level variations between years 1965-66 and 1983-84. His bankline movement study revealed that the maximum amount of bankline erosion and deposition were 348 m/year and 335 m/year respectively in 18 years period since 1965-66. His study on mean bed level variations showed that the mean gradient of the river bed has increased from 6.74 cm/km in 1965-66 to 7.99 cm/km in 1983-84.

He also carried out study on the overall erosion and deposition within 210 km reach between Charnatua and Aricha and concluded that the total volume of material eroded and deposited in 18 years from 1965-66 were $1.22 \times 10^9 \text{ m}^3$ and $4.443 \times 10^8 \text{ m}^3$ respectively. He also concluded that the overall net erosion in 18 years since 1965-66 in the 210 km reach was $7.77 \times 10^8 \text{ m}^3$.

Miah and Husain (1991) studied the sedimentation aspects of flood-plain management of Bangladesh. In their study they have done a time trend analysis of low flow of the Brahmaputra River at Bhahadurabad and showed that the low water level had gone up considerably without any viable change in the low flow regime.

Kamrunnessa (1994) investigated the geometric and sediment transport characteristics

of the Surma River. Her study showed the variation of mean bed levels between 1970 and 1988-89 and concluded the ranges of aggradation and degradation within a selected reach of the Surma River.

WARPO (1997) has done investigations on the vertical changes of the Dhaleswari River for their feasibility study of the Kalni-Kushiyara River Improvement Project. In their study they have shown the average bed level changes in the 24 km reach from the Issapur bifurcation to the point where the Baida channel re-joins the Dhaleswari River. The comparisons were made using surveys from 1963, 1975 and 1988. WARPO (1997) has also done assessment of aggradation and degradation of the bed level in the lower Kushiyara/Kalni River. In this study they have used BIWTA navigation charts from 1963, 1975, 1977 and 1988. The reach they have studied extended between 50 km upstream of Bhairab Bazaar and Fenchuganj (around 225 km upstream of Bhairab)

Klaassen and Struiksmma (1988) conducted a study on the scour in the Jamuna River due to the constriction by the construction of Jamuna Multipurpose Bridge approaches. They developed an analytical method for the estimation of scour. In the study both ultimate scour and time dependent scour were performed and the methods were checked with numerical model.

Van der Knaap (1994) performed a study on the Jamuna River bed aggradation. He developed a simplified model for assessing the river bed aggradation through the application of recurrent measures in both single channel system and a bifurcating channel system. The simplified models were calibrated and verified with computational results of the one dimensional model MIKE 11.

Review of the reports revealed that several studies have been carried out on the Khowai River since 1964. According to BWDB (1974), in the early sixties there was a crying demand from the people of Habiganj, specially those living on both sides of the Khowai River for some solution of their flood problem to alleviate their suffering.

Protection of lands along the Khowai River was examined in the first Master Plan study by EPWAPDA (1964). Subsequently a feasibility study was made by EPWAPDA (1969) which dealt with the river upstream of Shaistaganj upto Indian border. The project proposal were updated by BWDB in the year 1974, and the reach downstream of Shaistaganj to Habiganj was also examined by BWDB.

Northwest hydraulic Consultants Ltd (1976) reviewed various aspects of the proposals which were submitted to the Asian Development Bank for funding. Essentially the project involved flood control embankments on both sides of the river from Indian border to some downstream of Habiganj to benefit about 16000 ha, plus combined pumping-gravity irrigation from the river to benefit about 4500 ha. but the project was not approved by ADB. By late 1985, embankments were constructed by BWDB on both sides of the river from below Habiganj to above Chunarughat. The design criteria used in the construction to the embankments was to accommodate a discharge of 750 cumec with adequate freeboard. The discharge value was estimated to represent a 50 year flood from the analysis of streamflow data available in the 1970s.

From the study of Galay, (1976) it has been revealed a systematic rise in water levels in the Khowai River at Habiganj between 1949 and 1965, with a further rise to 1976, and ascribed this result mainly to progressive sedimentation/aggradation of the river bed. But the computation of the corresponding levels for 1985 cross-sections by the consultants of BWDB (1986), however does not give much support to this connection and suggests that there has been little change in water levels since 1960. It has also been pointed out that Galay's study may have been based on inconsistent discharge data.

The consultants of BWDB (1986) carried out a study "pre-Feasibility study for Northeast Rivers Flood Protection" which included the review of the three concepts (extending embankment upto Indian border, Ballah, providing diversion from the Khowai River to the Sutang River upstream of Shaistaganj and providing a diversion from the Khowai River into the Karangi River) for improving flood protection along the Khowai River.

Ahmed and Ahmed (1988) carried out investigations of the causes of severe recent floods in Khowai River basin. The study reveals that heavy siltation is taking place in the Khowai River bed. It has also been concluded that the increasing trend of peak water level and resulting increase in flood magnitude during the recent years may have contributed to i) increase in peak discharge from the upper catchments, ii) channel confinement and prevention of lateral outflows by embankments and iii) heavy siltation on the river bed.

FPCO (1994) completed a specialist study on the channel sedimentation and morphology in the Northeast region of Bangladesh. Part of the study summarizes the results of the investigation of the Khowai River sedimentation and morphology and the role of sedimentation contributing to flooding, channel erosion and flood plain deposition etc.

All the above studies were mainly flood protection oriented. BWDB in 1974, studied the channel siltation based on the comparison of the cross section of 1963 and 1974. The comparison showed that the bed is being silted up. Later in the FPCO (1994) sedimentation study they compared the longitudinal profile of 1965 and 1988. This comparison suggested that the bed level have risen approximately 1m between Ballah and Chunarghat indicating the channel has aggraded. This comparison also showed a degradation of about 1 m in the embanked reach upstream of Shaistaganj between Chunarghat and Shaistaganj. Downstream of Shaistaganj aggradation of 1-3 m were estimated. In addition to the comparison of the longitudinal profile the effect of channel siltation on the river stages were studied by EPWAPDA (1969) and FPCO (1994) from the available hydrological data. The confinement effect on the water level due to the recently (1992) completed loop-cut and embankment extension 6km d/s of Habiganj were studied by FPCO (1994) using HEC-2 steady state gradually varied flow profile.

None of the above studies estimated the future sediment transport rate along the Khowai River. In the present study, in addition to the vertical channel changes based on the available field data, efforts will be made to estimate the future channel aggradation/degradation based on channel geometry and as well as using HEC-6.

CHAPTER 3

THEORETICAL BASIS FOR HEC-6 CALCULATIONS

3.1 GENERAL

HEC-6 is a one-dimensional numerical model of river mechanics that computes scour and deposition by simulating the interaction between the hydraulics of the flow and the rate of sediment transport. HEC-6 processes a discharge hydrograph as a sequence of (steady) flows of variable duration. Based on continuity of sediment, changes are calculated with respect to time and distance along the study reach for the following: total sediment load, volume and gradation of sediment that is scoured or deposited and the resulting bed elevation. In addition, sediment outflow at the downstream end of the study reach is calculated.

3.2 GEOMETRY

Geometry of the river system is presented by cross sections which are specified by coordinate points (stations and elevations) and the distance between cross sections. HEC-6 raises or lowers cross section elevations to reflect deposition and scour. The horizontal locations of the channel banks are considered fixed and the floodplain on each side of the channel are considered as having fixed ground locations but can move vertically if within the movable bed.

3.3 HYDRAULICS AND HYDROLOGY

The water discharge hydrograph is approximated by sequence of steady flow discharges, each of which last for a specified period of time. Water surface profiles are calculated by using the Standard step method to solve the energy and continuity equations. Friction loss is calculated by the Manning's equation and expansion and contraction losses are calculated if the representative loss coefficients are specified. Hydraulic roughness is described by Manning's 'n' values and can vary from cross section to cross section. It is necessary to specify the downstream water surface elevation for water surface profile calculations.

The hydraulic parameters needed to calculate sediment transport capacity are velocity, depth, width and slope - all of which come from water surface profile calculations. The one-dimensional energy equation, shown below, is solved using the standard step method and the above hydraulic parameters are calculated at each cross sections for each successive discharge. Figure 3.1 shows a representation of the terms in the energy equation.

$$WS_2 + \frac{\alpha_2 V_2^2}{2g} = WS_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \quad \dots\dots\dots (3.1)$$

Where: g = Acceleration due to gravity
 h_e = energy loss
 V_1, V_2 = average velocities at ends of reach 1 and 2 respectively
 WS_1, WS_2 = Water surface elevations at ends of reach 1 and 2 respectively
 α_1, α_2 = Velocity distribution coefficients for flow at ends of reach 1 and reach 2

The energy loss term h_e , in equation (3.1) is composed of friction loss h_f , and form losses h_o , as shown in Equation 2. Only the contraction and expansion losses are considered in the geometric form loss term.

$$h_e = h_f + h_o \quad \dots\dots\dots (3.2)$$

To approximate the transverse distribution of flow the river is divided into strips having similar hydraulic properties in the direction of flow. Each cross section is subdivided into portions that are referred to as subsections. Friction losses are calculated as below.

$$h_f = \left(\frac{Q}{K'} \right)^2 \quad \dots\dots\dots (3.3)$$

in which:

$$K' = \sum_{j=1}^J \left[\frac{1.49}{n_j} \right] \frac{\left(\frac{A_1 + A_2}{2} \right)_j \left[\frac{R_2 + R_1}{2} \right]_j^{1/2}}{L_j^{1/2}} \quad \dots\dots\dots (3.4)$$

Where: A_1, A_2 = Downstream and Upstream area, in ft^2 respectively, of the cross sectional flow normal to the flow direction.
 J = Total number of subsections across cross section
 L_j = Length of j th strip between subsections in feet
 n = Manning's roughness coefficient
 Q = Water discharge (fr^3/sec)
 R_1, R_2 = Downstream and upstream hydraulic radius, respectively

Energy losses due to contraction and expansions are computed by the following equation:

$$h_o = C_L \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \dots \dots \dots (3.5)$$

Where: C_L = Loss coefficient for expansion or contraction

If the quantity within the absolute value notation is negative, flow is contracting and C_L is the coefficient of contraction; if it is positive, flow is expanding and C_L is the coefficient of expansion.

The hydraulic radius is calculated for each subsection j by:

$$R_j = \frac{A_j}{P_j} \dots \dots \dots (3.6)$$

Where: A_j = Area of subsection (ft^2)
 P_j = Wetted perimeter of subsection (ft)
 R_j = Hydraulic radius of subsection (ft)

The conveyance K_j , is computed for each subsection j by:

$$K_j = \frac{1.49}{n_j} A_j R_j^{2/3} \dots \dots \dots (3.7)$$

The total conveyance in the cross section is :

$$K_t = \sum_{j=1}^{NSS} K_j \quad \dots \dots \dots (3.8)$$

Where: NSS = Total number of subsections

The factor 'α' is an energy correction factor (also called velocity distribution factor) to account for the transverse distribution of velocity across the floodplains and channel is computed as follows:

$$\alpha = \frac{\sum_{j=1}^{NSS} \left[\frac{K_j^3}{A_j^2} \right]}{\left[\frac{K_t^3}{A_t^2} \right]} \quad \dots \dots \dots (3.9)$$

The boundary roughness for an alluvial stream is closely tied to sediment transport and the movement of bed material. Energy losses for water surface profile calculations must include the effects of all losses: grain roughness of the movable bed, form roughness of the movable bed, bank irregularities, vegetation, contraction/expansion losses, bend losses and junction losses. All these losses except the contraction/expansion losses are embodied in a single roughness parameter, Manning's 'n'.

3.4 SEDIMENT TRANSPORT

Inflowing sediment loads are related to water discharge by sediment -discharge curves for the upstream ends of the main stream, tributaries and local inflow points. For realistic computation of scour and equilibrium conditions, the gradation of the material forming the stream bed must be measured. It can be specified at each cross section.

Sediment mixtures are classified by grain size using the American geophysical Union scale. The

program accommodates clay (particles less than 0.004 mm diameter), four classes of silt (0.004-0.0625 mm), five classes of sand (from very fine sand, 0.0625 mm, to very coarse sand, 2.0 mm), and five classes of gravel (from very fine gravel, 2.0 mm, to very coarse gravel, 64 mm).

Transport capacity is determined at each cross section by using hydraulic information from the water surface profile calculation (e.g., width, depth, energy slope, and flow velocity) and the gradation of bed material. Sediment is routed downstream after the backwater computations are made for each successive discharge.

Sediment transport rates are calculated for grain sizes up to 64 mm. Sediment sizes larger than 64 mm that may exit in the bed are used for sorting computations but are not transported. For deposition and erosion of clay and silt sizes up to 0.0625 mm Krone's method (1962) is used for deposition and Ariathurai's adaptation of Parthenaides method (1965) is used for scour.

The sediment transport function for bed material load is selected by the user. Several transport formulas are available in the program. In our study Ackers-White (1973) formula, given below has been selected.

Ackers and White Equation (1973):

$$q_t = KUD_{35} \left[\frac{U}{U_*} \right]^n \left[\frac{Y - Y_{cr}}{Y_{cr}} \right]^m \dots\dots\dots (3.10)$$

and

$$Y = \left[\frac{U_*^n}{\sqrt{g\Delta D_{35}}} \right] \left[\frac{U}{5.661 \log \left(\frac{10h}{D_{35}} \right)} \right]^{(1-n)} \dots\dots\dots (3.11)$$

$$D_* = D_{35} \left[\frac{g\Delta}{v^2} \right]^{\frac{1}{3}} \quad \dots\dots (3.12)$$

For $1 < D_* < 60$

$$K = 10^{-3.53 + 2.86 \log(D_*) - (\log(D_*))^2} \quad \dots\dots (3.13)$$

$$n = 1 - 0.56 \log(D_*) \quad \dots\dots (3.14)$$

$$m = \frac{9.66}{D_*} + 0.14 \quad \dots\dots (3.15)$$

$$Y_{cr} = 0. \frac{23}{D_*^{0.5}} + 0.14 \quad \dots\dots (3.16)$$

$$\text{For } D_* \geq 60 \quad K = 0.025, \quad n = 0, \quad m = 1.5, \quad Y_{cr} = 0.17 \quad \dots\dots (3.17)$$

where,

D_* = Dimensionless particle diameter (based on D_{35});

D_{35} = Particle size at which 35% by weight is finer;

g = Acceleration due to gravity;

h = Water depth;

K = Dimensionless coefficient;

- m = Dimensionless coefficient;
 n = Dimensionless coefficient;
 q_t = Volumetric total load, excluding pores per unit of width;
 U = Depth-average flow velocity;
 U_* = $(ghS)^{1/2}$ = Shear velocity;
 Y = Particle mobility parameter;
 Y_{cr} = Critical particle mobility parameter;
 Δ = $(\rho_s - \rho)/\rho$ = Relative submerged sediment density;
 ρ_s = Sediment density;
 ρ = Water density; and
 ν = Kinematic viscosity

The basis for simulation vertical movement of the bed is the continuity equation for sediment material (the Exner equation):

$$\frac{\delta G}{\delta x} + B_o \cdot \frac{\delta Y_s}{\delta (DD)} = 0 \quad \dots \quad (3.18)$$

- Where:
- | | | |
|-------|---|---|
| B_o | = | Width of movable bed |
| DD | = | Duration of time step |
| G | = | Sediment discharge (ft ³ /sec) |
| x | = | Distance along the channel |
| Y_s | = | Depth of sediment in control volume |

The minimum hydraulic condition at which a particular grain size will be immobile on the bed surface can be calculated by combining Manning's, Strickler's, and Einstein's equations, respectively:

$$V = \frac{1.49}{n} R^{2/3} S_f^{1/2} \quad \dots \quad (3.19)$$

• • • • •

• • • • •

$$S_f = \text{friction slope}$$

gravity of sand of 2.65 and with ψ set at 30 yields

• • • • •

D, and multiplying the velocity by the depth to get unit discharge yields:

• • • • •

• • • • •

q

The equilibrium depth for a given grain size and unit discharge is therefore;

$$D_e = D = \left[\frac{q}{10.21 d^{1/3}} \right]^{6/7} \quad \dots\dots (3.25)$$

Where: D_e = The minimum water depth for no sediment transport (i.e., equilibrium depth) for grain size d

Where the bed material is a mixture of grain sizes, the scour depth required to accumulate a sufficient amount of coarse surface material to armour the bed is calculated as follows:

$$SA = N \left[\frac{\pi d^2}{4} \right] \quad \dots\dots (3.26)$$

$$N = \frac{SA}{\left[\frac{\pi d^2}{4} \right]} \quad \dots\dots (3.27)$$

Where: N = Number of sediment grains on the bed surface
 SA = bed surface area

The surface area of the column may be partially shielded by a rock outcrop or an armour layer such that the potential scour area is less than the total surface area of the column. This reduces the number of grains exposed to scour as follows.

$$N = \frac{SA \cdot SAE}{\left[\frac{\pi d^2}{4} \right]} \quad \dots\dots (3.28)$$

Where: SAE = Ratio of surface area of potential scour to total surface area

Assuming a heterogeneous mixture, the depth of scour required to produce a volume of a

particular grain size sufficient to completely cover the bed to a thickness of one grain diameter is:

$$V_{se} = PC \cdot SA \cdot D_{se} = N \frac{\pi d_a^3}{6} \quad \dots\dots\dots (3.29)$$

Where: d_a = Smallest stable grain size in armour layer
 D_{sc} = Depth of bed material which must be removed to reach equilibrium in time step
 PC = Percent of bed material coarser than size d
 V_{sc} = Volume of bed material which must be removed to reach equilibrium in a time step

Combining the surface area and volume equations and solving for the required depth of scour to fully develop the armour layer gives:

$$D_{se} = \left[\frac{SA \cdot SAE}{(\pi d^2/4)} \right] \cdot \left[\frac{(\pi d^3/6)}{PC \cdot SA} \right] \quad \dots\dots\dots (3.30)$$

Which reduces to:

$$D_{se} = \left(\frac{2}{3} \right) \left[\frac{SAE \cdot d}{PC} \right] \quad \dots\dots\dots (3.31)$$

Equation (3.31) is used with equation (3.25) to calculate a equilibrium depth for a mixture of grain sizes. In order to determine the PC to use in equation (3.31), the proper segment on the bed gradation curve is found by approximating the functional relationship between d and PC (the gradation curve).

CHAPTER 4

METHODOLOGY

4.1 DATA ANALYSIS

In the present study efforts have been made for the assessment of Aggradation and degradation along the Khowai River by several methods. They are Specific gauge analysis, Area-elevation analysis of the cross sections, historic water level analysis, comparison of the longitudinal thalweg profiles and comparison of the mean bed level profiles.

4.1.1 SPECIFIC GAUGE ANALYSIS

Specific gauge analysis in fact gives the idea about the trend in change in water level for a specific discharge at a particular discharge station. This change in water levels indicate the variations in the bed level due to erosion or deposition of sediment for that specific location particularly at lower discharges. In the present study there is only one discharge station which is located at Shaistaganj. A series of water level rating curves (1964 to 1994 total 31 nos.) based on mean daily discharge data for each year has been established and then a historic variation in stage for different discharges (for $Q = 10, 20, 30, 40, 50, 100$ and 150 cumec) were plotted. Specific gauge plot for $Q = 50, 100$ and 150 cumec as shown in Figure 4.13 is based on the observed discharges at Shaistaganj. Figure 4.14 through Figure 4.18 show the specific gauge plots for $Q = 10, 20, 30, 40$ and 50 cumec based on the mean daily discharge record (1964 - 1994) with the best fit lines. Best fit lines were established by normal regression techniques.

4.1.2 AREA ELEVATION RELATION

Area-elevation relationships were established for the cross-sections of 1988 and 1994 at 10 locations between Shaistaganj and approximately 10 kilometers downstream of Habiganj gauge. Cross section areas at the rate of 0.5 m intervals from the bottom to the top of each sections were computed and plotted them as elevation versus area. Then efforts were made to quantify the

changes in the cross section area from 1988 to 1994 for different elevations. This has been done by superimposing the area-elevation curve of 1994 on 1988 for each of the selected locations. Figure 4.19 shows the superimposed area-elevation curves. The superimposed plot gives the definite idea about the aggradation and degradation in the channel and the flood plain for a particular location. Tables 4.4 and 4.5 representing the computed areas at different elevations for the cross sections of the years 1988 and 1994. Figure 4.20 and Figure 4.21 show profile of the cross section areas at bankfull stages and profile of the bankfull elevation respectively along the river for the years 1988 and 1994.

4.1.3 TOP WIDTH ELEVATION REALTION

Top width-elevation relationship for the same cross sections were developed and plotted the same way as the area-elevation curves. This gives a picture of the change in top width between 1988 and 1994 of a specific channel section. The computed output of the topwidth for different elevations are shown in the Table 4.6 and Table 4.7. The decrease in top width means the channel has been constricted by deposition of sediment on the edges and the increase in top width results from side wise erosion. Figure 4.22 shows the topwidth-elevation relationships.

4.1.4 THALWEG PROFILE (1965-1988-1994)

Efforts were made to assess the vertical channel changes (i.e aggradation/ and degradatoion) by comparing the longitudinal thalweg profile published in ACE (1969) with the 1988 BWDB data. This comparison were made between Ballah and Shaistaganj by superimposing 1988 BWDB thalweg profile on the 1965 profile. Figure 4.23 shows the longitudinal deep channel profiles of 1965 and 1988. During preparation of the thalweg profiles the minimum elevations (m, PWD) of cross sections with the respective chainages (km) were sorted out and plotted them as elevations versus chainages. Infact thalweg profile does not give a clear idea about the average bed level positions, but it definitely has impacts on the average bed level elevations. The average variations of the bed levels can best be understood from the comparison of mean bed level profiles for different years. Thalwegs for the year 1994 have also been computed for every sections and then

a comparison with the 1988 thalwegs was carried out.

4.1.5 MEAN BED LEVEL PROFILE (1988 - 1994)

Efforts were also made for the assessment of aggradation and degradation by comparing 1988 BWDB mean bed level profile with the 1994 (FAP-6) profile between Shaistaganj and the end of the Khowai River. Figure 4.24 shows the superimposed mean bed level profiles. Computations for the mean bed level profiles were carried out at bankfull stage conditions and the computed results are shown in Table 4.8 and Table 4.9.

4.1.6 DAILY WATER LEVEL RECORD (1964 - 1994)

Figure 4.25 through Figure 4.28 show daily water levels recorded at Ballah, Chunarughat, Shaistaganj and Habiganj. These water levels, specially the minimum water levels provide a definite trend of vertical channel changes (aggradation or degradation). In order to show the trend of vertical channel changes, water levels for all the 4 stations between 1964 and 1994 have been plotted. Table 4.10 shows the summary of the historic water levels from 1964 to 1994.

4.1.7 MODEL PREPARATION FOR PREDICTION

Finally for the preparation of HEC-6 model in order to predict the future trend of bed levels along the Khowai River the following analysis were done. These analysis are mostly based on the properties of sediments existing in the river bed and in suspension and they were used as input data. River cross sections of 1988 surveyed by BWDB with reach length (i.e. the distance between present cross section and the next downstream cross section) have been used to represent the initial channel geometry. Mannings approximate roughness coefficients for the main channel portion have been used as $n=0.022$ from Habiganj to downstream, $n=0.026$ from Shaistaganj to Habiganj and $n=0.022$ from Shaistaganj to upstream. According FAP-6 (1993) the best agreement during the verification of their Khowai River HEC-2 model, occurred with an n value of 0.025 for the 1991 flow conditions and 0.022 for the highest flows in 1988. Sediment data

were specified in the model. These data include the inflowing sediment load, gradation of material (obtained from the grain size distribution curves, Figure 4.10) in the stream bed and information about fluid and sediment properties (i.e water density, sediment density etc.). In order to prepare the inflowing sediment load at Shaistaganj a sediment rating curve shown in Figure 4.29 had to be established. During preparation of the rating curve suspended sediment concentration data and water discharge data for the Shaistaganj Station between 1964 and 1993 were used. Preparation of the inflowing sediment rating curve is discussed later in this chapter in detail. Specifications of the grain size fraction (obtained from the gradation curves) of the bed material were provided. The grain sizes of sediment particles commonly transported by rivers may range over seven log cycles. Small sizes behave much differently from large sizes. Therefore, it is necessary to classify sediment material into groups for application of different transport theories. Three basic classes considered by HEC-6 are clay, silt and sand/gravel. The groups are identified and subdivided based on American Geophysical Union (AGU) classification scale as shown in Table 4.11. Finally hydrologic data were specified for the verification of the model. The hydrologic data include water discharge at Shaistaganj, water temperature (considered 70°F), water level elevations at Madna and flow duration. The mean daily discharges at Shaistaganj and the corresponding mean daily water levels at Madna from 1989 and 1994 were used. The hydrologic data required a table of frequency of different discharges from 1989 to 1994 for different ranges of water levels. Table 4.12 shows the frequency table. The verification runs were then made by tuning the movable bed limits. The computed change in bed levels were compared with the change in bed levels obtained from the historic water levels at Chunarughat, Shaistaganj and Habiganj. Table 4.13 shows the computed bed level changes and observed bed level changes. After the model had been verified, future prediction runs were executed by adding the same hydrologic data according to the requirements. In the present study runs were made for the prediction of the future 5 year, 10 years and 15 years sedimentation along the river. The predicted Cumulative sediment deposit in tons, sediment deposit in tons, sediment passing in tons, changes in thalweg level in meter and deep channel profiles along Khowai River as obtained from the model output are shown in Figure 4.30 through Figure 4.34. It is to be noted that 4.94 km downstream of Ballah gauge was assumed as upstream boundary (water discharge and sediment data of Shaistaganj were used at km 4.94 since there is no variation in discharge) and the confluence of Barak and Dhaleswari River near

Madna as downstream boundary for the model. The theoretical basis of HEC-6 computations have already been discussed in Chapter 2.

Suspended sediment concentration data between 1964 and 1993 and the corresponding discharges for the Khowai river at Shaistaganj were used to prepare a rating curve (Figure 4.29) for the suspended sediment load (Tons/day). During the preparation of the data for the rating curve all the outliers were removed. The remaining data were used in the power regression analysis. The relationship obtained from the regression analysis for the years between 1964 and 1994 is as follows:

$$Q_s = 0.900055 * Q^{1.988396} \quad R^2 = 0.85$$

Where Q_s is the sediment discharge in tons per day and Q is the water discharge in m^3/sec and R is the coefficient of correlation. Bed load as percentage of suspended sediment transport were estimated from the grain size distribution results for both the suspended sediment and bed load. The total inflowing sediment load (i.e. the suspended load plus the bed load) in tons/day and the corresponding water discharge in ft^3/s from this relationship were used in the model. Particle size distribution of the bed material and suspended material are shown in Figure 4.10 through Figure 4.12.

In the present study, the following definitions were used to specify sediment sizes:

- "sand" is sediment in the range of 0.063 mm - 2.0 mm
- "silt" is sediment in the range of 0.063 mm - 0.004 mm
- "clay" is sediment finer than 0.004 mm

The classification of the sediment transport are generally done according to its sources (wash load or bed material load), mode of movement (in suspension, saltation or by traction) and its methods of measurement. "Wash load" consists of fine sediment (usually silt and clay)

that is generated from mass wasting and erosion processes in the watershed. Its transport rate depends solely on the rate of supply from the watershed, not on the streams transport capacity (which is usually much greater). Consequently, wash load materials are not found in the channel bed material. These finer sediments are flushed through the channel system but can be deposited in overbank areas on the floodplain where velocities are low. The "bed material load" consists of river bed sediments (usually sand) that move by traction and saltation (the "bed load") and in suspension (the suspended bed material load).

The suspended fraction of the bed material load is usually determined by an examination of bed material particle size distribution curves. According to Einstein (1940), the D_{10} bed material size can be used for estimating the suspended fraction of the bed material load. According to the gradation curve (Figure 4.10), D_{10} sizes of the bed material in Khowai River at Chunarughat gauge, Shaistaganj gauge, Habiganj gauge and downstream of Habiganj are 0.1 mm, 0.07 mm, 0.08 mm and 0.065 mm respectively. Therefore in this river, the sand load (fraction coarser than 0.07 mm) existing in the suspended sediment portion can be taken to represent the bed material load, while the silt and clay load can be considered as wash load. According to the grain size distribution of the suspended material (Figure 4.11 and Figure 4.12) at shaistaganj station for the years 1991 and 1992, it was observed that an average of 30% (ranges from a minimum of 10% to a maximum of 51%) of the suspended load could be considered as the bed material load. Therefore in our study, 30% of the inflowing sediment load is considered as the bed material load and 70% as wash load.

4.2 DATA COLLECTION

Data collected for the present study were cross sections, discharge, water level, velocity, observed suspended sediment load, and grain size distribution for the bed and suspended material for the Khowai River. The earliest survey data was the longitudinal profile published in EPWAPDA (1969) have been collected from the BWDB Planning General library. Cross section data of the year 1988 at 39 locations along the Khowai River from Ballah to the end of the river have been collected from FAP-6. These sections were surveyed by BWDB,

Habiganj division are shown in Figures 4.1 through 4.4. Cross sections at 17 locations surveyed by FAP-6 in the year 1994 have also been obtained from the same office (Figure 4.5 and Figure 4.6). Sophisticated portable depth echo sounder were used in the cross section survey. These sections are located between Shaistaganj and the confluence of Barak and Dhaleswari River. Figure 4.7 and figure 4.8 shows locations of both 1988 and 1994 sections. Observed discharge data with cross sectional properties between 1964 and 1994 (Cross sectional area, topwidth, mean velocity etc.) for the Shaistaganj station were collected from Surface Water Hydrology-2, Bangladesh Water Development Board and SWMC. Mean daily water levels for the stations at Ballah, Chunarghat, Shaistaganj, Habiganj and Madna and mean daily discharge at Shaistaganj since 1964 have been obtained from the Surface Water Hydrology-2 office of BWDB. The hydrometric stations so far mentioned above were installed by the Water Development Board between 1949 and 1964. The yearly minimum, maximum and mean of the mean daily water levels and discharge are shown in Table 4.1 and Table 4.2. Figure 4.9 shows the mean daily discharges at Shaistaganj from 1964 to 1994. Suspended sediment concentration data for the Shaistaganj station of BWDB from 1964 to 1993 have been collected from the River Research Institute (RRI), Faridpur. Grain size distribution curves for the bed material (Figure 4.10) at Chunarghat, Shaistaganj, Habiganj and downstream of Habiganj were obtained from FAP-6. These bed materials were collected by FAP-6 in february 1992 and were sent to SWMC laboratory for the analysis. Grab sampler was used in the collection. Grain size distribution data on the suspended sediment (Figure 4.11 and Figure 4.12) were collected for the Shaistaganj Station from SWMC. These samples were collected and analyzed (Hydrometer analysis using Andreason tube) in the SWMC laboratory in the years 1991 and 1992. Pump samplers were used in the collection.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 SPECIFIC GAUGE ANALYSIS

Figure 4.13 shows the specific gauge plot based on observed discharges for the Shaistaganj hydrometric station. The plot shows an abrupt fall in water levels of over 1 m took place between 1967 and 1970. Between 1975 and 1991, water level at discharges of $100 \text{ m}^3/\text{s}$ and $150 \text{ m}^3/\text{s}$ have lowered by about 0.5 m, with abrupt fluctuations of up to 1 m between 1984 and 1987. At $50 \text{ m}^3/\text{s}$, water level has risen steadily by 0.5 m between 1975 and 1991. The rise in water levels indicates the reduction in the cross section due to siltation within the channel. This reduction in cross section area occurred either by the aggradation of the river bed or by reduction in the width of the channel.

Figure 4.14 through Figure 4.18 show the specific gauge plots based on the mean daily discharges at Shaistaganj from 1964 to 1994. These plots were deliberately done for low flow conditions (for $Q=10, 20, 30, 40$ and 50 cumec) since the low flow conditions give the definite idea about the aggradation and degradation of the average bed level. The best fit lines in the figures suggest the aggradation of the average bed level by 0.73 m for $Q=10$ cumec, 0.66 m for $Q=20$ cumec, 0.57 m for $Q=30$ cumec, 0.44 m for $Q=40$ cumec and 0.39 m for $Q=50$ cumec. It is observed from the results that there is a gradual decrease in the change in bed level rise with the increase in discharges (Figure 4.35). So it is clear that the side wise erosion is responsible for the decrease in the bed level changes in case of higher flows. Therefore the analysis of aggradation and degradation by specific gauge method would be best for the low flows.

The channel sedimentation is definitely responsible for the process of aggradation and constriction in channel width. The sedimentation process is clearly understood for low flow conditions since the water level are confined within the channel and also near the channel bed. But in cases of high flow condition the water level may not confine within the channel. There may be occurrences of breaching or overtopping of the river embankments or banks on either

side in the upstream and down stream of the gauge station and as a result the recorded water level would be low. The specific gauge analysis shows that the sediment is being deposited in the Khowai River at the Shaistaganj station since 1970.

5.2 AREA-ELEVATION RELATIONS

Area-elevation curves have been plotted to clearly visualize the sedimentation process at a particular section over a period. In the present study area-elevation curves for ten selected sections were plotted. Figure 4.19 shows the superimposed area-elevation curves for the years 1994 on 1988. Figure 4.7 and Figure 4.8 show the location of the cross sections. The computed area for different elevations are given in Tables 4.4 and 4.5.

Section 1 (km 38.09) of Figure 4.19 shows the overall sediment deposition over the period 1988 to 1994. Between elevations 8 m and 16.5 m, the estimated decrease in cross section area over the period (1988 - 1994) is 57.42 m^2 . The interesting case is that the deepest level of the section remains unchanged.

In Section 2 (km 42.05) of Figure 4.19, the thalweg level has experienced degradation by 3.37 meters. The plot shows increase in cross section area by 3.23 m^2 due to erosion between elevations of 3.5 m and 13 m. From elevation 13.5 m to 16 m deposition of sediment has occurred which resulted in a decrease in sectional area by 196.91 m^2 . The overall status of the cross section is that it has experienced decrease in area by 193.68 m^2 between elevations 3.5 m and 16 m. This indicates an overall deposition of sediment in section 2 over the period 1988 and 1994.

Section 3 (km 43.7) of Figure 4.19 shows degradation of the thalweg level by 1.76 m over the period 1988 and 1994. It also shows increase in cross section area by 8.69 m^2 between elevations 5.5 m and 11 m. Between elevations 11.5 m and 15 m the cross section has reduced by 259.59 m^2 . The overall section has reduced by 250.9 m^2 indicating overall siltation within the section between the period 1988 and 1994.

Section 4 (km 46.13) of Figure 4.19 suggests degradation of the thalweg by 1.0 m between 1988 and 1994. The overall cross section area between elevations 5.5 m and 14 m has increased by 179.04 m² indicating erosion within the section

Section 5 (km 50.19) of Figure 4.19 shows degradation of the thalweg by 0.44 m over the period of 1988 and 1994. From elevation 5 m up to elevation 6.5 m the cross section area has increased by 3.7 m² and from elevation 7 m to elevation 14.5 m the area has decreased by 114.79 m². The overall (i.e. between elevations 5 m and 14 m) cross section area has reduced by 171.09 m².

In section 6 (km 52.5) the thalweg level has been aggraded by 0.76 m between years 1988 and 1994. From elevation 2.5 m to elevation 5 m the cross section area has reduced by 2.73 m² indicating deposition of sediment. Between elevations 6 m and 8 m the cross section area has increased by 12.23 m² indicating erosion. Again between elevations 8.5 m and 12.5 m the area-elevation relation shows that the cross section area of 1994 has reduced by 595.93 m², which indicates significant amount of deposition of sediment. The overall section i.e. between elevations 2.5 m and 12.5 m shows reduction in area by 586.43 m² between years 1988 and 1994.

Section 7 (km 53.72) shows degradation of the thalweg level by 1.35 m. It also shows an overall increase in cross section area between elevations 4 m and 12 m by 45.27 m². So this section has experienced erosion over the period 1988 and 1994.

Section 8 (km 56.16) shows degradation of the deepest channel level by 1.4 m. Between elevations 3.5 m and 8 m it shows increase in section area by 11.53 m² and between elevations 8.5 m and 12 m decrease in cross section area by 247.72 m². The overall cross section area (i.e. between elevations 3.5 m and 12 m) has reduced by 236.19 m² indicating deposition.

Section 9 (km 59.1) shows degradation of the thalweg level by 0.97 m. Between elevations 1 m and 6.5 m the area-elevation relationship shows an increase in section area by

19.2 m² and between elevations 7 m and 11.5 m the sectional area has reduced by 183.97 m². The overall cross section (i.e. between elevations 1 m and 11.5 m) has reduced by 164.77 m².

Section 10 (km 61.53) shows huge degradation of the thalweg level amounting 11.5 m. The area elevation relationship shows an overall increase in cross section area by 545.98 m². This indicates that the section has experienced huge erosion over the period 1988 and 1994. This increase in cross section and degradation occurred because of the loop-cut made by BWDB at this place in the year 1992.

From the above findings and discussions it has become clear that the over all cross section area of the 23.44 km reach from shaistaganj to downstream (i.e. km 38.09 and km 61.53) is being reduced approximately at the rate of 14.84 m²/year since 1988. The total amount of sediment deposition within this 23.44 km is estimated as 5.5 million tons in 6 years (i.e. 0.92 million tons/year).

Figure 4.20 and Figure 4.21 show the cross section areas at bankfull stages and profiles of bankfull elevations respectively along the river for the years 1988 and 1994. The figures suggest that the average section area at bankfull stage between Shaistaganj and the Khowai-Dhaleswari confluence has increased by 60.6 m² and the average bankfull elevation has lowered by 0.53 m over the period i.e. from 1988 to 1994. The cross section area at bankfull stage within the 23.44 km reach below Shaistaganj has increased by 121.86 m² (i.e. at the rate of 20.31 m² per year) and the rest of the lower reach by 8.76 m² in 6 years period from 1988.

5.3 TOP WIDTH-ELEVATION RELATIONS

A comparison of the top width between years 1988 and 1994 has been done in order to estimate the lateral erosion/deposition of sediment i.e. the bank erosion/deposition. The same cross sections as in the case of area-elevation study were selected. Table 4.6 and Table 4.7 representing the magnitude of the change in top width at different elevations over the cross sections. Table 4.8 and Table 4.9 suggest that the average width at bankfull stage has increased

by 10.5 m between Shaistaganj and the end of the river over the period 1988 and 1994. Figure 4.22 also shows a clear understanding about the change in top width with the corresponding elevation over the period of 1988 and 1994.

Section 1 (km 38.09) of Figure 4.22 depicts an average increase in top width by 16.5 m from elevation 8 m to elevation 13 m and an average decrease by 11 m between elevations 13.5 m and 16 m. It also suggests an average overall reduction in top width (i.e. between elevations 8 m and 16 m) by 7 m. It may be noted that the changes has occurred between the years 1988 and 1994.

Section 2 (km 42.05) of figure 4.22 suggests an increase in top width by 18.5 m between elevations 3 m and 8.5 m. From elevation 9 m to elevation 16 m the top width has reduced by 42 m. The overall top width between elevations 3 m and 16 m has reduced by 19.5 m indicating overall siltation in the river between years 1988 and 1994.

Section 3 (km 43.7) suggests increase in top width by 7 m between elevations 5 m and 9.5 m. Between elevations 10 m and 15 m the top width has reduced by an average of 35 m. The over all width (i.e. between elevations 5 m and 15 m) of the section has reduced by 16 m indicating siltation between years 1988 and 1994.

Section 4 (km 46.13) suggests an overall increase in width between elevations 5 m and 14 m by 20 m indicating lateral erosion of the cross section over the period 1988 and 1994.

Section 5 (km 50.19) suggests increase in width by 6 m between elevations 5 m and 6.5 m and decrease by 25.5 m form elevation 7 m to 14 m. The overall width (i.e. between elevation 5 m and 14 m) has reduced by 20 m indicating overall siltation.

Section 6 (km 52.5) shows increase in width by around 6 m between elevations 2.5 m and 6.5 m and decrease in width by 109 m between elevations 7 m and 12.5 m. The overall width has reduced by 71 m between years 1988 and 1994.

Section 7 (km 53.72) suggests increase in width by 17.5 m between elevations 4 m and 6 m, decrease in width by 14.5 m between elevations 6.5 m and 8.5 m and again an increase in width by 4 m between elevations 9 m and 12 m. The overall average width between elevations 4 m and 12 m has widened by 0.6 m indicating overall erosion.

Section 8 (km 56.16) suggests increase in width by 7.5 m between elevations 3 m and 6 m and decrease in width by 50.5 m between elevations 6.5 m and 12 m. The overall average width of the section has reduced by 36 m between elevations 3 m and 12 m indicating overall siltation.

Section 9 (km 59.1) depicts increase in width by 9 m between elevations 1 m and 5 m and decrease in width by 31 m between elevations 5.5 m and 11.5 m. The overall average width of the section has reduced by 31 m.

Section 10 (km 61.53) suggests increase in width by 40 m between elevations -11 m and 5 m and decrease in width by 39 m between elevations 5.5 m and 10 m. The overall average width (i.e. between elevations -11 m and 10 m) has increased by 16 m indicating overall lateral erosion.

From the above analysis it has become clear that the the width of Khowai River between km 38.09 and km 61.53 (i.e. 23.44 km reach) has reduced due to siltation on the banks over the period 1988 and 1994. The average reduction in width for this 23.44 km reach has been estimated as 18.2 m.

5.4 LONGITUDINAL THALWEG PROFILE (1965-1988-1994)

The only survey data in the reach Ballah and Chunarughat was the longitudinal thalweg profile of 1965 published in EPWAPDA (1969). This profile is compared with the 1988 BWDB data in Figure 4.23. The comparison suggests bed levels on an average have risen by approximately 1 m, indicating the channel bed has degraded. Comparison of the 1965

longitudinal profile with the 1988 data between Chunarughat and Shaistaganj reach showed thalweg levels have lowered by around 1 m on an average. Tables 4.8 and 4.9 show the computed talweg levels for the year 1988 and 1994 respectively. It was observed from the comparison that the average thalweg level of the 23.44 km reach below Shaistaganj has degraded by 1.29 m and after that up to the confluence of khowai-Dhaleswari River the thalweg level suffered degradation of 2.03 m on an average.

5.5 LONGITUDINAL MEAN BED LEVEL PROFILE (1988-1994)

Comparison of the 1994 mean bed level profile between Shaistaganj and the end of the Khowai River with the 1988 data is shown in Figure 4.24. Table 4.8 and Table 4.9 show the computations of the mean bed level profile with respect to the bankfull stage conditions. The mean bed level profiles suggests an aggradation of the average bed level between Shaistaganj and 6.6 kilometres downstream of Habiganj reach by 0.4 m. At 9 kilometres downstream of Habiganj shows huge degradation of 6.75 m. This is because of the loop-cut made by BWDB close to that location in the year 1992. The profiles also suggest degradation of the average bed level by 0.5 m between 13 kilometres downstream of Habiganj and the end of the Khowai River reach.

5.6 HISTORIC WATER LEVEL RECORDS (1964-1994)

Figure 4.25 through Figure 4.28 show the plot of the mean daily water level records at Ballah, Chunarughat, Shaistaganj and Habiganj hydrometric stations of BWDB along the Khowai River. These water level records suggests aggradation of the bed level by 0.96 m at Ballah, 0.2 m at Chunarughat, over 1 m at Shaistaganj and 1.51 m at Habiganj since 1964.

5.7 PREDICTION OF HEC-6 MODEL

The over all sediment that would be deposited (i.e. the cumulative sediment deposition) along the course of the river according to the HEC-6 model prediction is shown in Figure 16.

It shows a overall deposition of sediment would be 17 million tons by the year 1993, 34 million tons by the year 1998 and 50 million tons by the year 2003.

Figure 4.31 shows the future sediment deposition along the river. It shows there would be a maximum erosion of 0.19 million tons of sediment at chainage 7.07 km and a maximum deposition of 1.35 million ton at chainage 73.53 in the year 1993. In the year 1998 there would be a maximum erosion of 0.29 million tons at chainage 77.53 km and a maximum deposition of 2.6 million tons at chainage 73.53 km. In the year 2003 there would be a maximum erosion of 0.36 million tons at chainage 77.53 km and a maximum deposition of 3.36 million tons at chainage 73.53 km.

The sediment that would pass along the Khowai river according the HEC-6 model is shown in Figure 4.32. It shows that the sediment passing along the river would be a minimum of 2.4 million tons at chainage 73.53 km and a maximum of 9.98 million tons at chainage 4.94 km in the year 1993, a minimum of 4.5 million tons at chainage 73.53 km and a maximum of 22.22 million tons at chainage 4.94 km in the year 1998 and a minimum of 7.47 million tons at chainage 73.53 km and a maximum of 34.93 million tons at chainage 4.94 km in the year 2003.

HEC-6 predicts future changes in thalweg level in the years 1993, 1998 and 2003 as shown in Figure 4.33. It shows that the change of bed level would range from -1.26 m to 4.26 m with an average aggradation of 0.84 m in the year 1993, from -1.34 m to 5.3 m with an average aggradation of 1.47 m in the year 1998 and from -2.02 m to 6.16 m with an average aggradation of 2.41 m in the year 2003.

Figure 4.34 shows the future thalweg profile after 5 years, 10 years and 15 years respectively from the base year 1988. It predicts the average thalweg level would be 8.72 m ranging between -0.33 m and 19.38 m in the year 1993, 9.32 m ranging between -0.41 m and 18.55 m in the year 1998 and 10.32 m ranging between -1.38 m to 21.73 m in the year 2003.

HEC-6 can be used by the planners and decision makers as a tool to assess the anticipated scenario of sedimentation in a river system. In the present study HEC-6 output revealed that there would be continued siltation in the river bed in the next 15 years from 1988. This siltation will increase flooding problem in future. On the basis of the study based on practical data and future predictions, the planner and decision makers should decide what actions to be taken to avoid the anticipated sedimentation and consequently flooding problems in future. There are many solutions to reduce the sedimentation and flooding in future, some of them are: i) increase the height of the embankments ii) Make a structure at the entrance of the river (i.e. near Ballah), so that the incoming sediments are trapped and release clear water, and iii) regular maintenance of the river bed with dredger, so that the river bed will remain to the required level as is desired by the planners and decision makers.

5.8 SUMMARY AND ANALYSES OF FINDINGS

The study revealed that the bed level from Ballah to Chunarughat has aggraded and from Chunarughat to Shaistaganj has degraded between years 1965 and 1988. Again the analysis showed that the river bed of the 23.44 km reach below Shaistaganj has aggraded between years 1988 and 1994 and after that up to the confluence of Khowai-Dhaleswari River the bed level suffered degradation. The reasons of the findings are summarized below.

5.8.1 AGGRADATION BETWEEN BALLAH AND CHUNARUGHAT

Comparisons of the thalweg profiles between years 1965 and 1988 shows that the Khowai River thalweg between Ballah and Chunarughat has aggraded by 1 m. The reach between Ballah and Chunarughat is unembanked and is subject to channel instability from overbank spills and bank breaching. According to FPCO (1993), major spills have occurred regularly in the upstream of Chunarughat. So it is justified that during the high flow conditions spilling and bank breaching is a regular phenomena between the Ballah and Chunarughat reach which reduces the velocity of flow and causes sedimentation within the channel and flood plain. This kind of sedimentation is the main reason for the aggradation of the bed level between the reach.

5.8.2 DEGRADATION BETWEEN CHUNARUGHAT AND SHAISTAGANJ

The same profiles between years 1965 and 1988 shows degradation by 1 m between Chunarughat and Shaistaganj. It is to be noted that there have been a series of major cutoffs (total 6 loop cuts) and channelization works done by BWDB between years 1965 and 1988 within the Chunarughat-Shaistaganj Reach. Figure 4.36 Shows the cutoffs with their locations. These cutoffs reduces the length of the reach to a significant amount and as a result the slope of the river bed has increased. This increased slope caused high velocity of flow within this reach and ultimately degraded the bed level. So the degradation of the bed level between Chunarughat and Shaistaganj appears to be logical.

5.8.3 AGGRADATION OF 23.44 KM REACH BELOW SHAISTAGANJ

The present study revealed that the river bed of the 23.44 km reach below Shaistaganj has aggraded by 0.4 m. This aggradation has taken place because of the reduction of the velocity of flow within the reach during the 6 years period from 1988. Cross section analysis shows that there has been an average increase in cross section area at bankfull stage at the rate of 20.31 m² per year from 1988 to 1994 within the 23.44 km reach below Shaistaganj. This is the major cause of reduction of the velocity of flow when the water level is at bankfull stage. The study also revealed that the cross section area above bankfull stage is being reduced since 1988. This is mainly due to the deposition of sediments on the berms and levees on both sides of the river. Sugar cane planting within the embanked Khowai River floodway is the primary cause of the deposition of sediment on the berms and levees. This has become a popular practice of the local people to grow sugar cane on the berms of the river which trap the sediment within the berms to a significant amount during flash flood as well as during the monsoon period. Sugar cane is also responsible for the aggradation of the average bed level because it reduces the overall velocity of flow by raising the water level within the 23.44 km reach below Shaistaganj.

5.8.4 DEGRADATION OF THE LOWER REACH OF THE RIVER

The study also revealed that the reach between the end of the full flood embankment and the confluence of the Khowai-Dhaleswari River has suffered an average degradation of the bed level by 0.5 m. This degradation has occurred between the period 1988 and 1994. The analysis of the average bed level profiles showed a deep scour hole of 6.75 meters near the lower end of the confined reach (at 9 km downstream of Habiganj) and this is because of the loop cut made by BWDB in the year 1992. This loop cut has shortened the lower reach of the river by around 1 km and was made to achieve fast drainage during the flash flood in the respective reach. The scour hole was formed due to the draw down effect and very high velocities that had developed at the downstream end of the embanked reach. This increased velocities would have sustained up to the end of the river and therefore the lower reach of the river has suffered degradation of the average bed level.

5.8.5 COMPARISON OF HEC-6 RESULT WITH THE ANALYTICAL SOLUTION

Prediction of HEC-6 model showed an overall deposition of sediment amounting to about 17 million tons by the year 1993, 34 million tons by the year 1998 and 50 million tons by the year 2003. It was also observed that the deposition within the 23.44 km reach below Shaistaganj would be 5.01 million tons by the year 1993 (base year is 1988). The cross section analysis revealed that 5.5 million tons of sediment has been deposited within the 23.44 km reach below Shaistaganj in 6 years from 1988. So $5.5 \times \frac{5}{6} = 4.6$ million tons of sediment has been deposited in 5 years period from 1988 which complies well with the HEC-6 result. Again HEC-6 results have been verified with the magnitude of aggradation obtained from the historic water level analysis at Shaistaganj and Habiganj. The comparisons have been shown in the Table 4.13. The table shows close agreement of both the HEC-6 result and analytical solution obtained from historic water level analysis at Shaistaganj and Habiganj.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The following conclusions may be drawn from the present study

1. It is observed from the present study that the Khowai River bed is being aggraded at the rate of 67 mm per year up to 6.6 km downstream of Habiganj from Shaistaganj since 1988. The aggradation of the bed level will cause, i) increase in flood frequency, ii) increase in flood intensity and iii) damage or make ineffective to the existing structures in the river. The rest of the downstream reach suffered degradation at the rate of 83 mm per year.
2. The cross section area at bankfull stage between Shaistaganj and the end of the river i.e. the confluence of Khowai and Dhaleswari River is being increased at the rate of 10.1 m²/year since 1988. However the study revealed that the cross sectional area above bankfull stage has reduced indicating deposition of sediment on the berms and flood plain on both sides of the river. The overall cross section of the 23.44 km reach below Shaistagenj is being reduced at the rate of 14.84 m²/year on an average since 1988.
3. The 23.44 km reach of the river from Shaistaganj has suffered a reduction in overall width. The reduction occurred on an average of 3 m/year indicating siltation within the channel and on the berms.
4. The inflowing sediment load at Shaistaganj consist of 30% coarse fraction of the Suspended load and 70% wash load.
5. The one dimensional morphologic model HEC-6 predicted that there would be continued deposition of sediment indicating continued average aggradation of the bed level by 0.84 m in 1993, 1.47 m in 1998 and 2.41 m in the year 2003 along the study reach (87 km) of the river with respect to the year 1988.

6.2 RECOMMENDATIONS FOR FURTHER STUDY

1. There are many prediction formula suggested by different researchers related to overall sediment transport. In the present study Ackers and White (1973) formula has been used. It is recommended to carry out a study on the well accepted overall sediment prediction formulas and find out which one agrees best for the Khowai River at Shaistaganj.
2. The lower part of the Khowai River i.e. below 10 kilometres of Habiganj suffer frequent flooding by the flash flood in the pre-monsoon season, as that reach of the river is not embanked on both sides. So there are lot of problems in the agricultural activity. Many of the times people suffered loss of the crops even during the period of harvesting. It would be very interesting if a study could be done on the impact of upstream water levels during the pre-monsoon period assuming that the submersible embankments on both sides were extended in the lower part of the river.
3. In the present study prediction on the sedimentation by HEC-6 model along the Khowai River has been done using Ackers and White Formula. The model has options to select some other prediction formula. It is also recommended to study the future sedimentation in the same river using different prediction formula and make a comparison with the results so far obtained using Ackers and White (1973).

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Table 1.1a: Seasonal Distribution of Flow at Shaistaganj (1964-1994)

Season	Calender Period	Mean Discharge (m ³ /s)	Mean Runoff	
			(MCM)	(%)
Pre-Monsoon	April and May	37.92	200	17.02
Monsoon	June through September	63.19	666	56.68
Post-Monsoon	October and November	33.69	178	15.15
Dry-Season	December through March	12.54	131	11.15
Year	April through March	37.25	1175	100

Note: MCM= Million Cubic Meter

Table 1.1b: Seasonal Distribution of WL along Khowai River (1964-1994)

Season	Calender Period	Mean Water Levels (m, PWD) at Gauge			
		Ballah	Chunarughat	Shaistaganj	Habiganj
Pre-Monsoon	April and May	20.20	13.58	9.36	6.69
Monsoon	June through September	20.71	14.15	10.01	7.34
Post-Monsoon	October and November	20.16	13.56	9.36	6.70
Dry-Season	December through March	19.77	13.08	8.88	6.26
Year	April through March	20.22	13.62	9.38	6.77

Table 1.2: Average Rainfall around Khowai River, 1961-1990

Period	Srimangal R-126 (mm)	Habiganj R-110 (mm)
January	10	13
February	27	23
March	96	71
April	263	224
May	434	446
June	471	491
July	361	415
August	338	398
September	248	272
October	149	152
November	41	25
December	12	9
Year	2447	2542

Table 1.3: Definition of Seasons

Season	Activity	Calender Period
Dry	Irrigation	December through March
Pre-Monsoon	Flash Floods	April and May
Monsoon	Flooding	June through September
Post-Monsoon	Drainage	October and November

Table 1.4: Seasonal Distribution of Rainfall around Khowai River

Season	Percent of Annual Rainfall	
	Srimangal	Habiganj
Dry	6	5
Pre-Monsoon	28	26
Monsoon	58	62
Post-Monsoon	8	7
Year	100	100

Source: BWDB

Table 1.5: Climatological Averages, Srimangal (1948-1991)

Month	Sunshine (hrs)	Temperature			Humidity (%)
		Mean Max (°C)	Mean Min (°C)	Mean (°C)	
January	7.8	25.6	9.3	17.6	83
February	8.1	27.9	11.7	19.8	77
March	7.3	31.9	16.8	24.5	73
April	7.1	33.2	21.1	27.2	75
May	9.7	32.4	22.9	27.7	81
June	5.0	31.7	24.7	28.3	86
July	4.2	31.9	15.1	28.5	87
August	4.8	32.2	25.1	28.7	88
September	4.4	32.0	24.5	28.3	88
October	6.4	31.1	21.8	26.7	87
November	8.1	28.9	15.9	22.4	85
December	8.0	26.4	10.9	19.1	78
Year	6.2	33.2	9.3	24.9	81

Source : BMD

Table 1.6: Climatological Averages, Srimongal (1948-1991)

Month	Wind		Rain (mm)	PET (mm)	Surplus/Deficit (mm)
	Speed (km/hr)	Direction			
January	5.7	SSE	7	146	-139
February	7.6	SSW	39	160	-121
March	9.0	S	48	214	-130
April	7.8	SSE	237	243	-6
May	7.5	SSE	404	198	206
June	7.3	SSE	483	159	324
July	7.3	SSE	319	158	161
August	7.1	SSE	345	133	212
September	7.1	SE	265	141	124
October	7.1	SE	159	177	-18
November	5.7	SE	50	171	-121
December	9.9	SE	6	143	-137
Year	7.3	SSE	2431	1460	971

Source: BMD & BRAC for PET

Table 1.7: Climatic Extremes of Record, Srimangal (1948-1991)

Month	Daily Temperature		Monthly Rainfall		Mamimum Daily	
	Max (°C)	Min (°C)	Max (mm)	Min (mm)	Rainfall (mm)	Wind Speed (km/hr)
January	31.1	3.4	71	0	42	20
February	34.4	2.8	129	0	86	33
March	38.4	6.7	376	0	91	67
April	43.4	10.6	695	0	213	130
May	40.0	14.8	651	12	177	80
June	39.8	20.3	1285	283	225	39
July	37.8	16.2	655	119	131	167
August	37.3	21.2	544	181	260	65
September	37.0	19.1	602	22	514	30
October	35.3	14.3	398	36	155	65
November	33.9	6.5	211	0	96	28
December	31.2	4.4	66	0	18	22
Year	43.4	2.8	1285	0	514	1067

Source: BMD

Table 4.1: Yearly maximum, mean and minimum of the mean daily WL

Year	Water Level in meters, PWD														
	Ballah Gauge			Chunarughat Gauge			Shaistaganj Gauge			Habiganj Gauge			Madna Gauge		
	min	mean	max	min	mean	max	min	mean	max	min	mean	max	min	mean	max
1964	19.14	20.04	24.94	12.66	13.53	16.75	NA	NA	NA	5.24	6.49	8.11	0.91	4.08	7.65
1965	19.14	19.78	23.73	12.54	13.28	17.07	8.12	9.00	12.32	4.92	6.11	8.41	0.94	3.59	6.98
1966	19.14	20.04	24.73	12.62	13.66	17.74	8.17	9.52	11.83	4.88	6.63	8.20	1.13	3.80	7.36
1967	19.24	19.92	24.89	12.71	13.42	16.82	8.49	9.35	12.33	5.06	6.21	8.24	0.94	3.46	6.77
1968	19.25	20.03	23.83	12.71	13.78	17.36	NA	NA	NA	5.03	6.28	8.28	1.30	3.75	7.32
1969	19.33	19.84	24.49	12.66	13.31	17.12	8.32	9.04	12.17	5.04	6.05	8.30	0.94	3.60	7.17
1970	19.03	19.58	23.00	12.44	13.26	16.83	8.23	8.92	12.12	NA	6.35	8.30	1.34	4.21	7.60
1971	NA	NA	NA	NA	NA	NA	NA	NA	NA	4.75	6.11	8.11	1.32	3.81	7.00
1972	NA	NA	NA	12.62	13.02	16.03	8.16	8.66	12.65	5.24	6.08	8.38	1.08	3.47	6.56
1973	NA	NA	NA	12.57	13.61	17.84	8.16	9.13	11.64	5.16	6.47	8.40	1.37	4.10	7.01
1974	19.35	20.30	23.67	12.79	13.76	17.10	8.23	9.23	12.35	5.81	6.78	8.28	1.22	4.15	8.15
1975	19.43	20.02	22.52	12.76	13.42	16.89	8.20	8.95	12.61	5.52	6.43	8.53	1.37	2.78	6.02
1976	19.07	20.28	24.84	12.83	13.70	16.94	8.23	9.30	12.02	5.53	6.64	8.08	NA	NA	NA
1977	19.61	20.36	23.11	12.92	13.83	17.11	8.38	9.41	12.66	5.58	6.82	8.32	1.02	3.97	6.89
1978	19.68	20.57	24.79	12.92	14.00	17.13	8.29	9.56	12.72	6.65	7.27	8.71	1.10	3.58	6.40
1979	19.37	19.99	24.23	13.55	14.23	17.88	8.49	9.05	12.43	6.42	6.80	8.69	1.40	4.42	6.89
1980	19.55	20.28	23.72	13.27	13.92	17.11	8.40	9.29	12.49	6.46	6.92	8.68	1.16	3.79	6.65
1981	19.74	20.23	23.26	13.03	13.69	17.57	8.32	9.28	12.48	6.45	7.24	9.38	NA	NA	NA
1982	19.65	20.23	24.27	12.99	13.56	17.88	8.46	9.38	12.65	6.68	7.25	9.33	1.19	3.56	7.02
1983	19.76	20.72	26.10	12.90	13.73	18.14	NA	NA	NA	6.68	7.33	9.07	1.10	4.11	7.44
1984	NA	NA	NA	12.73	13.63	18.03	8.60	9.58	12.94	6.50	7.35	9.78	1.41	4.01	7.41
1985	19.84	20.53	24.09	12.84	13.60	18.01	NA	NA	NA	6.50	7.20	10.49	1.18	3.74	6.83
1986	19.51	20.24	23.09	12.92	13.63	17.36	8.78	9.66	14.07	6.43	7.08	10.58	1.34	3.54	6.13
1987	19.45	20.13	23.83	12.92	13.48	17.62	8.61	9.37	14.08	6.32	6.87	10.21	1.59	4.21	7.42
1988	19.80	20.43	24.85	12.92	13.96	18.17	8.55	9.75	15.05	6.19	7.17	10.96	1.60	4.38	7.99
1989	19.91	20.33	22.98	13.23	13.79	17.17	8.87	9.56	14.04	6.23	6.90	10.29	1.44	3.96	6.97
1990	19.91	20.46	22.56	13.11	13.80	16.78	9.00	9.70	13.87	6.34	6.95	10.31	1.45	4.03	6.67
1991	20.01	20.72	23.29	12.81	13.71	17.25	9.14	10.20	14.52	6.39	7.21	10.74	1.48	4.23	6.79
1992	20.01	20.34	21.81	12.70	13.09	15.01	9.17	9.58	11.95	6.12	6.85	9.10	1.48	3.47	6.19
1993	19.81	20.42	25.40	12.67	13.64	18.13	9.14	10.16	14.66	6.43	7.32	11.37	1.44	4.08	7.53
1994	19.79	20.04	21.67	12.61	13.05	15.13	9.23	9.59	11.84	6.25	6.66	8.76	1.22	3.42	6.08

Note: All the Water Levels analyzed were recorded by BWDB

Table 4.2: Summary of yearly Discharge at Shaistaganj

Year	Min (cumec)	Mean (cumec)	Max (cumec)
1964	8.4	NA	566.0
1965	5.7	38.2	385.0
1966	2.0	NA	222.0
1967	6.6	32.5	156.0
1968	5.2	26.0	156.0
1969	4.9	23.5	112.0
1970	4.4	25.9	173.0
1972	4.9	16.4	117.0
1973	6.0	29.1	145.0
1974	4.9	38.0	204.0
1975	3.3	28.7	209.0
1976	4.9	38.0	187.0
1977	6.0	41.9	154.0
1978	4.6	42.2	174.0
1979	5.4	21.7	157.0
1980	5.1	28.3	120.0
1981	0.8	26.1	145.0
1982	5.6	NA	NA
1983	6.0	NA	NA
1984	4.8	NA	NA
1985	6.4	NA	NA
1986	6.7	35.2	431.0
1987	7.3	27.2	283.0
1988	6.1	67.0	1050.0
1989	5.9	35.1	439.0
1990	6.3	40.3	628.0
1991	12.0	73.0	597.5
1992	12.8	30.2	207.3
1993	12.0	70.2	622.9
1994	14.6	29.6	195.9

Record (Years)	min (cumec)	Mean (cumec)	Max (cumec)
30	0.8	36.0	1050.0

Table 4.3: Water Levels for Specific Discharges at Shaistaganj

YEAR	Water levels for different discharges in cumec				
	WL10 (m, PWD)	WL20 (m, PWD)	WL30 (m, PWD)	WL40 (m, PWD)	WL50 (m, PWD)
1965	8.39	8.87	9.19	9.44	9.65
1966	8.67	8.99	9.24	9.46	9.65
1967	8.68	9.01	9.32	9.61	9.89
1969	8.52	8.94	9.32	9.69	10.04
1970	8.45	8.79	9.11	9.41	9.69
1972	8.41	8.75	9.10	9.46	9.83
1973	8.37	8.94	9.35	9.68	9.97
1975	8.43	8.74	9.20	9.85	9.50
1976	8.56	8.95	9.26	9.53	9.77
1977	8.53	8.81	9.09	9.37	9.64
1978	8.60	9.02	9.36	9.67	9.94
1979	8.69	9.04	9.35	9.64	9.92
1980	8.66	9.01	9.36	9.70	10.03
1981	8.77	9.12	9.45	9.75	10.04
1982	8.98	9.34	9.61	9.84	10.05
1983	8.87	9.23	9.54	9.82	10.07
1984	8.93	9.24	9.49	9.70	9.88
1985	8.98	9.34	9.62	9.87	10.09
1986	9.07	9.45	9.74	9.98	10.20
1987	8.81	9.24	9.58	9.89	10.16
1988	8.95	9.25	9.49	9.69	9.86
1989	9.04	9.33	9.57	9.79	9.98
1990	9.13	9.46	9.71	9.91	10.09
1991	9.05	9.40	9.66	9.88	10.07
1992	9.06	9.40	9.66	9.87	10.06
1993	9.06	9.40	9.66	9.87	10.06
1994	9.06	9.40	9.65	9.87	10.06

Note: WL10 = Water Level (m, PWD) for Q=10 cumec

Table 4.4: Comparison of Cross Section Area between years 1988 and 1994 (Sec 1 to Sec 5)

Elevation m, PWD	sec-1 (38.09)			sec-2 (42.05)			sec-3 (43.7)			sec-4 (46.13)			sec-5 (50.19)		
	1988 (m ²)	1994 (m ²)	Change (m ²)	1988 (m ²)	1994 (m ²)	Change (m ²)	1988 (m ²)	1994 (m ²)	Change (m ²)	1988 (m ²)	1994 (m ²)	Change (m ²)	1988 (m ²)	1994 (m ²)	Change (m ²)
3					0	0									
4					3.64	-3.64									
5					23.06	-23.06		0	0		0	0	0	0	0
6					52.19	-52.19		1.22	-1.22		0.05	-0.05	4.1	5.53	-1.43
6.5				0	62.29	-62.29		4.91	-4.91	0	3.19	-3.19	14.3	18	-3.7
7				0.11	87.67	-87.56	0	14.39	-14.39	0.1	13.72	-13.62	41.42	33.83	7.59
7.5				4.55	107	-102.45	4.46	30.64	-26.18	9.8	35.16	-25.36	78.47	52.41	26.06
8	0	0	0	18.68	127.25	-108.57	27.32	53.08	-25.76	22.93	63.64	-40.71	119.46	73.58	45.88
8.5	2.13	0.45	1.68	35.61	148.4	-112.79	52.52	81.76	-29.24	37.24	97.43	-60.19	165.7	97.58	68.12
9	21.09	3.56	17.53	60.78	170.85	-110.07	78.97	112.34	-33.37	53.32	132.92	-79.6	221.73	124.89	96.84
9.5	44.51	9.08	35.43	89.36	195	-105.64	107.39	144.5	-37.11	72.6	169.91	-97.31	253.1	155.54	97.56
10	70.49	25.61	44.88	120.71	221.5	-100.79	142.18	178.28	-36.1	95.15	208.34	-113.19	287.79	189.52	98.27
10.5	99.12	56.45	42.67	155.89	256.28	-100.39	185.54	213.68	-28.14	121.09	248.13	-127.04	363.43	230.22	133.21
11	132.51	88.66	43.85	194.31	298.26	-103.95	242.01	250.7	-8.69	161.68	295.21	-133.53	442.43	284.28	158.15
11.5	172.48	122.44	50.04	256.06	349.65	-93.59	385.67	292.67	93	211.97	353.4	-141.43	523.44	359.43	164.01
12	216.39	157.65	58.74	336.22	404.33	-68.11	469.8	354.87	114.93	272.18	423.25	-151.07	606.46	443.89	162.57
12.5	268.03	193.94	74.09	424.05	461.49	-37.44	556.04	421.28	134.76	336.82	495.39	-158.57	691.48	529.33	162.15
13	326.1	238.57	87.53	521.23	524.46	-3.23	644.84	489.17	155.67	403.32	568.73	-165.41	778.51	615.77	162.74
13.5	388.8	298.76	90.04	620.41	590.38	30.03	735.56	558.29	177.27	471.68	643.26	-171.58	868.13	703.19	164.94
14	454.52	364.17	90.35	721.6	658.6	63	830.01	628.64	201.37	541.9	720.94	-179.04	960.35	792.67	167.68
14.5	522.81	434.08	88.73	824.79	729.11	95.68	926.14	700.22	225.92				1054.74	883.65	171.09
15	593.67	512.59	81.08	930	801.91	128.09	1025.22	774.32	250.9						
15.5	667.09	593.5	73.59	1038.45	877.49	160.96									
16	743.09	677.38	65.71	1149.69	956.01	193.68									
16.5	822.3	764.88	57.42	1260.97											

"+" Sign indicates decrease in cross section area due to deposition of sediment

"-" Sign indicates increase in cross section area due to deposition of sediment

Table 4.5: Comparison of Cross Section Area between years 1988 and 1994 (Sec 1 to Sec 5)

Elevation m, PWD	sec-6 (ch. 52.5)			sec-7 (ch. 53.72)			sec-8 (ch. 56.16)			sec-9 (ch. 59.1)			sec-10 (ch. 61.53)		
	1988 (m ²)	1994 (m ²)	Change (m ²)	1988 (m ²)	1994 (m ²)	Change (m ²)	1988 (m ²)	1994 (m ²)	Change (m ²)	1988 (m ²)	1994 (m ²)	Change (m ²)	1988 (m ²)	1994 (m ²)	Change (m ²)
-11														0	0
-10.5														2.6	-2.6
-10														9.95	-9.95
-9.5														20.18	-20.18
-9														32.28	-32.28
-8														62.06	-62.06
-7														98.43	-98.43
-6														139.8	-139.8
-5														185	-185
-4														233.69	-233.69
-3														285.53	-285.53
-2														340.39	-340.39
-1														398.28	-398.28
0													0	459.22	-459.22
1											0	0	1.25	523.94	-522.69
1.5											1.36	-1.36	9.34	557.69	-548.35
2										0	8.46	-8.46	21.12	592.35	-571.23
2.5	0		0							0.69	17.94	-17.25	35.35	627.94	-592.59
3	0.19	0	0.19					0	0	5.57	29.33	-23.76	51.15	664.57	-613.42
4	6.61	1.81	4.8		0	0	0	4.35	-4.35	28.92	57.14	-28.22	84.84	741.97	-657.13
5	19.73	17	2.73	0	23.31	-23.31	4.65	43.91	-39.26	58.79	92	-33.21	121.21	821.9	-700.69
6	43.13	63.41	-20.28	12.85	76.32	-63.47	44.82	91.71	-46.89	103.31	132.41	-29.1	198.79	905.26	-706.47
6.5	63.42	91.04	-27.62	41.83	105.36	-63.53	70.95	117.06	-46.11	135.78	154.98	-19.2	255.31	951.3	-695.99
7	91.47	119.92	-28.45	75.35	135.99	-60.64	102.12	143.39	-41.27	189.5	178.32	11.18	333.17	1020.99	-687.82
7.5	127.14	149.94	-22.8	113.73	170.46	-56.73	142.41	171.39	-28.98	260.37	202.33	58.04	429.52	1101.51	-671.99
8	171.63	181.13	-9.5	159.24	213.19	-53.95	190.6	202.13	-11.53	344.75	243.05	101.7	531.68	1183.57	-651.89
8.5	227.95	213.49	14.46	226.29	246.73	-20.44	246.1	235.51	10.59	439.3	327.86	111.44	637.83	1267.17	-629.34
9	292.91	251.71	41.2	305.42	339.26	-33.84	308.68	270.68	38	539.37	426.02	113.35	749.66	1352.3	-602.64
9.5	368.77	299.59	69.18	395.24	428	-32.76	374.49	307.21	67.28	643.72	523.24	120.48	864.22	1438.98	-574.76
10	478.11	365.46	112.65	487.34	519.98	-32.64	442.69	344.74	97.95	752.22	624.26	127.96	980.7	1526.68	-545.98
10.5	633.04	436.41	196.63	581.29	615.22	-33.93	513.28	383.29	129.99	863.34	726.03	137.31			
11	801.41	508.75	292.66	677.06	713.69	-36.63	586.26	422.75	163.51	979.02	828.89	150.13			
11.5	971.83	582.48	389.35	774.68	815.42	-40.74	661.64	462.81	198.83	1097.15	932.38	164.77			
12	1144.28	657.48	486.8	874.12	919.39	-45.27	739.43	503.24	236.19						
12.5	1319.31	732.88	586.43												

"+" Sign indicates decrease in cross section area due to deposition of sediment

"-" Sign indicates increase in cross section area due to deposition of sediment

Table 4.6: Comparison of Topwidth between years 1988 and 1994 (Sec 1 to Sec 5)

Elevation m, PWD	Section 1 (ch. 38.09)			Section 2 (ch. 42.05)			Section 3 (ch. 43.7)			Section 4 (ch. 46.13)			Section 5 (ch. 46.13)		
	1988 (m)	1994 (m)	Change in width (m)	1988	1994	Change in width (m)	1988	1994	Change in width (m)	1988	1994	Change in width (m)	1988	1994	Change in width (m)
3					0	0									
4					12.67	-12.67									
5					24.74	-24.74		0	0		0	0		0	0
6					32.84	-32.84		4.88	-4.88		1.37	-1.37	13.44	28.5	-15.06
6.5				0	35.55	-35.55		10.82	-10.82	0	11.29	-11.29	31.97	34.59	-2.62
7				2.09	37.76	-35.67	0	26.19	-26.19	3.81	32.6	-28.79	61.74	39.75	21.99
7.5				25.11	39.58	-14.47	39.33	38.38	0.95	24.14	50.32	-26.18	78.23	44.96	33.27
8	0	0	0	31.1	41.4	-10.3	48.27	52.35	-4.08	27.84	63.6	-35.76	85.92	51.29	34.63
8.5	21.54	3.33	18.21	39.7	43.23	-3.53	51.93	59.62	-7.69	29.39	64.48	-35.09	104.23	57.96	46.27
9	42.89	8.72	34.17	55.51	56.6	-1.09	53.89	62.73	-8.84	37.33	72.49	-35.16	122.73	64.64	58.09
9.5	50.11	13.34	36.77	58.82	50.04	8.78	62.35	65.93	-3.58	39.79	75.49	-35.7	144.01	71.43	72.58
10	53.36	59.06	-5.7	68.42	58.18	10.24	72.55	69.17	3.38	46.93	78.22	-31.29	156	91.37	64.63
10.5	62.46	62.93	-0.47	72.27	78.04	-5.77	103.83	72.42	31.41	35.67	80.94	-45.27	160.01	126.04	33.97
11	76.97	65.98	10.99	82	93.47	-11.47	120.22	75.67	44.55	92.57	108.68	-16.11	164.03	167.92	-3.89
11.5	82.34	69.1	13.24	153.29	107.47	45.82	138.5	110.63	27.87	108.58	120.77	-12.19	168.04	169.9	-1.86
12	95.06	71.53	23.53	167.35	111.53	55.82	158.79	130.79	28	127.42	143.1	-15.68	172.05	171.88	0.17
12.5	110.81	73.63	37.18	192.34	118.37	73.97	170.78	134.55	36.23	131.14	145.48	-14.34	176	173.86	2.14
13	121.3	108.15	13.15	196.35	129.55	66.8	175.04	137.01	38.03	134.86	147.87	-13.01	183.42	175.84	7.58
13.5	128.88	129.3	-0.42	200.36	134.14	66.22	179.3	139.47	39.83	138.58	150.28	-11.7	185.49	181.42	4.07
14	134.02	132.77	1.25	204.38	138.73	65.65	183.56	141.93	41.63	142.3	160.3	-18	190.55	182.49	8.06
14.5	139.15	154.64	-15.49	208.4	143.31	65.09	190.36	144.39	45.97						
15	144.28	159.42	-15.14	212.41	147.9	64.51	198.17	153	45.17						
15.5	149.42	164.2	-14.78	220.73	152.5	68.23									
16	154.55	175	-20.45	222.56	165.2	57.36									

" + " Sign indicates decrease in Topwidth due to deposition of sediment on the river banks/bed

" - " Sign indicates increase in topwidth due to erosion of the river banks/bed

Table 4.7: Comparison of Topwidth between years 1988 and 1994 (Sec 6 to Sec 10)

Elevation m, PWD	Section 6 (ch. 52.5)			Section 7 (ch. 53.72)			Section 8 (ch. 56.16)			Section 9 (ch. 59.1)			Section 10 (ch. 61.53)		
	1988 (m)	1994 (m)	Change in width (m)	1988	1994	Change in width (m)	1988	1994	Change in width (m)	1988	1994	Change in width (m)	1988	1994	Change in width (m)
-11														0	0
-10.5														10.15	-10.15
-10														18.56	-18.56
-9.5														22.33	-22.33
-9														26.1	-26.1
-8														33.42	-33.42
-7														38.98	-38.98
-6														43.39	-43.39
-5														47	-47
-4														50.34	-50.34
-3														53.35	-53.35
-2														56.37	-56.37
-1														59.42	-59.42
0													0	62.68	-62.68
1											0	0	6.93	66.65	-59.72
1.5											10.05	-10.05	20.12	68.36	-48.24
2											0	16.87	26.82	70.25	-43.43
2.5	0	0	0							5.14	21.01	-15.87	30.46	72.13	-41.67
3	1.95	0	1.95					0	0	13.67	24.43	-10.76	32.32	74.76	-42.44
4	10.32	7.56	2.76		0	0		11.06	-11.06	27.48	32.33	-4.85	35.04	79.05	-44.01
5	15.13	26.51	-11.38	0	47.74	-47.74	29.57	46.01	-16.44	32.25	37	-4.75	37.65	80.8	-43.15
6	33.69	54.17	-20.48	51.35	56.5	-5.15	47.32	49.73	-2.41	58.3	43.81	14.49	100.96	85.92	15.04
6.5	48.48	56.52	-8.04	62.41	59.67	2.74	57.3	51.68	5.62	81.51	45.99	35.52	130.72	100.36	30.36
7	63.42	58.86	4.56	74.23	62.85	11.38	67.37	53.62	13.75	125.86	47.35	78.51	167.76	159.51	8.25
7.5	78.97	61.21	17.76	79.31	76.67	2.64	90.04	58.74	31.3	156.32	78.71	77.61	200.31	162.59	37.72
8	103.99	63.55	40.44	113.06	94.27	18.79	103.4	64.21	39.19	177.2	134.09	43.11	208.31	165.66	42.65
8.5	121.28	65.9	55.38	148.68	111.86	36.82	118.6	68.76	49.84	195.9	188.99	6.91	216.31	168.73	47.58
9	138.57	88.65	49.92	172.68	174.23	-1.55	129.23	71.93	57.3	204.41	198.06	6.35	227.19	171.81	55.38
9.5	179.61	113.09	66.52	182.38	180.72	1.66	134.01	74.06	59.95	214.39	200.24	14.15	231.04	174.88	56.16
10	241.38	140.51	100.87	186.05	187.21	-1.16	138.79	76.08	62.71	219.61	202.43	17.18	234.89	175.5	59.39
10.5	334.72	143.29	191.43	189.72	193.71	-3.99	143.57	78.09	65.48	224.84	204.63	20.21			
11	338.79	146.07	192.72	193.39	200.2	-6.81	148.36	79.56	68.8	236.14	206.82	29.32			
11.5	342.86	148.86	194	197.06	206.69	-9.63	153.14	80.66	72.48	236.28	207	29.28			
12	346.93	150.77	196.16	200.73	208.1	-7.37	160.52	80.9	79.62						
12.5	354.35	150.8	203.55												

" + " Sign indicates decrease in Topwidth due to deposition of sediment on the river banks/bed

" - " Sign indicates increase in topwidth due to erosion of the river banks/bed

Table 4.8: Cross Section Geometry, 1988

BWDB Gauge Station	Chainage (km)	Thalweg (m)	Bankfull el. (m, PWD)	Topwidth (m)	Area (m ²)	Mean depth (m)	Mean bed el. (m, PWD)
Habiganj	85.53	0.64	3.78	38.63	67.93	1.76	2.02
	81.53	0.64	3.78	38.63	67.93	1.76	2.02
	77.53	2.5	4.15	25.85	38.59	1.49	2.66
	73.53	2.99	4.63	25.85	38.34	1.48	3.15
	69.53	3.48	5.12	25.85	38.34	1.48	3.64
	65.53	3.96	5.61	25.85	38.56	1.49	4.12
	61.53	0.64	7.04	42.65	203.11	4.76	2.28
	59.1	2.23	9.27	59.65	241.47	4.05	5.22
	56.16	4.79	8.72	107.06	250.03	2.34	6.38
	53.72	5.46	8.29	106.05	174.25	1.64	6.65
	52.5	2.8	9.79	117.8	285.62	2.42	7.37
	50.19	5.58	9.85	118.02	313.85	2.66	7.19
	48.27	5.37	11.28	130.81	407.99	3.12	8.16
	46.13	6.95	11.52	38.72	140.08	3.62	7.90
	43.7	7.26	11.34	63.08	215.83	3.42	7.92
	42.05	6.89	12.26	77.1	276.93	3.59	8.67
	39.98	6.34	12.77	95.67	345.57	3.61	9.16
	39	6.83	12.84	79.7	265.06	3.33	9.51
	38.5	6.8	13.11	82.13	281.68	3.43	9.68
Shaistaganj	38.09	8.23	12.07	73.83	194.81	2.64	9.43
	36.87	8.38	13.99	76.87	338.11	4.40	9.59
	34.53	8.9	13.66	63.5	247.55	3.90	9.76
	32.25	10	14.18	80.63	273.02	3.39	10.79
	31.03	9.88	14.82	84.67	359.79	4.25	10.57
Chunarughat	28.65	10.43	14.63	74.03	274.38	3.71	10.92
	27.43	10.15	16.37	53.08	248.4	4.68	11.69
	24.99	11.77	16.8	62.35	279.22	4.48	12.32
	23.35	11.95	17.84	62.01	282.16	4.55	13.29
	20.91	12.68	19.02	80.73	421.24	5.22	13.80
	18.71	13.99	19.15	92.94	398.2	4.28	14.87
	14.45	14.79	20.15	91.1	381.09	4.18	15.97
	11.94	15.67	20.95	120.29	452.95	3.77	17.18
	9.51	16.28	20.55	85.46	278.96	3.26	17.29
	7.07	16.49	21.25	98.35	293.47	2.98	18.27
	4.94	16.49	21.74	99.56	269.16	2.70	19.04
	3.11	17.38	22.29	83.15	329.95	3.97	18.32
	1.89	18.32	23.9	81.56	347.06	4.26	19.64
Ballah	0.8	18.48	23.9	81.54	328.98	4.03	19.87
	0	18.78	23.9	81.54	316.13	3.88	20.02

Table 4.9: Cross Section Geometry, 1994

BWDB Gauge Station	Chainage (km)	Thalweg (m)	Bankfull el. (m, PWD)	Topwidth (m)	Area (m ²)	Mean depth (m)	Mean bed el. (m, PWD)
Habiganj	86.63	-0.70	1.02	17.60	22.92	1.30	-0.28
	83.35	0.14	1.76	25.00	23.46	0.94	0.82
	79.73	1.41	3.39	32.81	49.40	1.51	1.88
	73.94	2.11	4.56	44.67	69.89	1.56	3.00
	71.12	2.40	5.16	27.78	58.56	2.11	3.05
	68.96	2.59	5.77	40.42	77.10	1.91	3.86
	65.35	3.63	6.33	50.64	85.28	1.68	4.65
	62.37	-10.92	6.09	86.39	913.02	10.57	-4.48
	59.06	1.26	8.29	58.27	244.22	4.19	4.10
	56.41	3.39	9.06	72.31	275.01	3.80	5.26
	55.16	4.11	8.90	172.93	321.90	1.86	7.04
	52.88	3.56	8.61	66.41	220.77	3.32	5.29
	50.19	5.14	10.70	136.95	310.57	2.27	8.43
	46.96	5.93	11.49	118.91	352.20	2.96	8.53
	44.62	5.50	11.77	128.89	325.01	2.52	9.25
Shaistaganj	41.46	3.52	12.07	112.17	412.16	3.67	8.40
	38.03	8.23	14.36	153.38	412.52	2.69	11.67

Table 4.10: Summary of Historic Water Levels in Khowai River

BWDB Gauge Station	Record (Years)	Water Level			Range (m, PWD)
		Mean (m, PWD)	Min (m, PWD)	Max (m, PWD)	
Ballah	27	20.22	19.03	26.10	7.07
Chunarughat	30	13.60	12.44	18.17	5.73
Shaistaganj	26	9.39	8.12	15.05	6.93
Habiganj	30	6.78	4.75	11.37	6.61

Note: All the Water levels analyzed are from 1964 to 1994 & were recorded by BWDB

Table 4.11: Grain Size Classification of Sediment Material

Class Size Number Used In HEC-6	Sediment Material	Grain Diameter (mm)
1	Clay clay	0.002-0.004
1	Silt Very Fine Silt	0.004-0.008
2	Fine Silt	0.008-0.016
3	Medium Silt	0.016-0.032
4	Coarse Silt	0.032-0.0625
1	Sand and Gravel Very Fine Sand (VFS)	0.0625-0.125
2	Fine Sand (FS)	0.125-0.250
3	Medium Sand (MS)	0.250-0.500
4	Coarse Sand (CS)	0.500-1.000
5	Very Coarse Sand (VCS)	1.000-2.000
6	Very Fine Gravel (VFG)	2.000-4.000
7	Fine Gravel (FG)	4.000-8.000
8	Medium Gravel (MG)	8.000-16.000
9	Coarse Gravel (CG)	16.000-32.000
10	Very Coarse Gravel (VCG)	32.000-64.000

Table 4.12: Frequency of Discharges, Khowai River at Shaistaganj

Water Level Range (m, PWD)	Average Water Level (m, PWD)	Frequency of Discharge ranges, cumec (1989 - 1993)								
		5 - 20	20 - 50	50 - 100	100 - 150	150 - 250	250 - 350	350 - 450	450 - 550	550 - 650
		12.5	35	75	125	200	300	400	500	600
1.5 - 2.0	1.75	284	100	1	0	0	0	0	0	0
2.0 - 3.0	2.5	235	122	16	9	5	1	1	0	0
3.0 - 4.0	3.5	43	67	26	10	10	0	5	0	2
4.0 - 5.0	4.5	6	71	24	9	9	4	5	0	1
5.0 - 6.0	5.5	20	125	88	28	18	7	6	0	2
6.0 - 7.0	6.5	15	147	147	31	24	1	2	1	1
7.0 - 8.0	7.5	0	0	6	2	2	1	0	1	1

Note: All the data were analyzed based on BWDB recorded WL & Q at Shaistaganj

Table 4.13: Future Bed level Changes

Chainage (km)	Bed change accordig to historic WL After 5 yr.	Computed Bed Change in meter		
		After 5 yr.	After 10 yr.	After 15 yr.
4.94		2.88	-1.34	2.11
7.07		-1.01	1.59	1.15
9.51		1.82	2.27	4.50
11.94		-0.02	1.79	1.36
14.45		1.49	2.69	6.16
18.47		-0.06	1.40	2.03
20.91		2.05	3.31	5.39
23.35		0.66	2.28	2.71
24.99		1.93	3.05	4.91
27.43		1.24	2.97	3.20
28.65		2.16	2.86	5.67
31.03		1.06	2.70	3.44
32.25		1.63	2.22	3.81
34.53		0.97	2.75	3.28
36.87		1.01	1.27	3.49
38.09		-0.23	1.67	2.80
38.5	0.9	1.08	-0.86	0.83
39		1.89	0.15	1.83
39.98		0.42	1.72	3.63
42.05		0.79	1.55	1.09
43.7		0.31	0.95	2.48
46.13		-0.69	0.82	0.55
48.27		0.09	0.85	2.44
50.19		0.38	1.03	1.09
52.5	0.3	0.43	1.42	3.43
53.72		0.24	0.90	1.20
56.16		0.15	0.90	1.70
59.1		2.36	2.55	2.88
61.53		2.71	3.54	4.07
65.53		-0.68	-0.13	0.67
69.53		-1.26	-0.78	-0.23
73.53		4.26	5.30	3.89
77.53		-0.07	-0.32	-1.05
81.53		0.26	-0.43	-0.19
85.53		-0.97	-1.05	-2.02

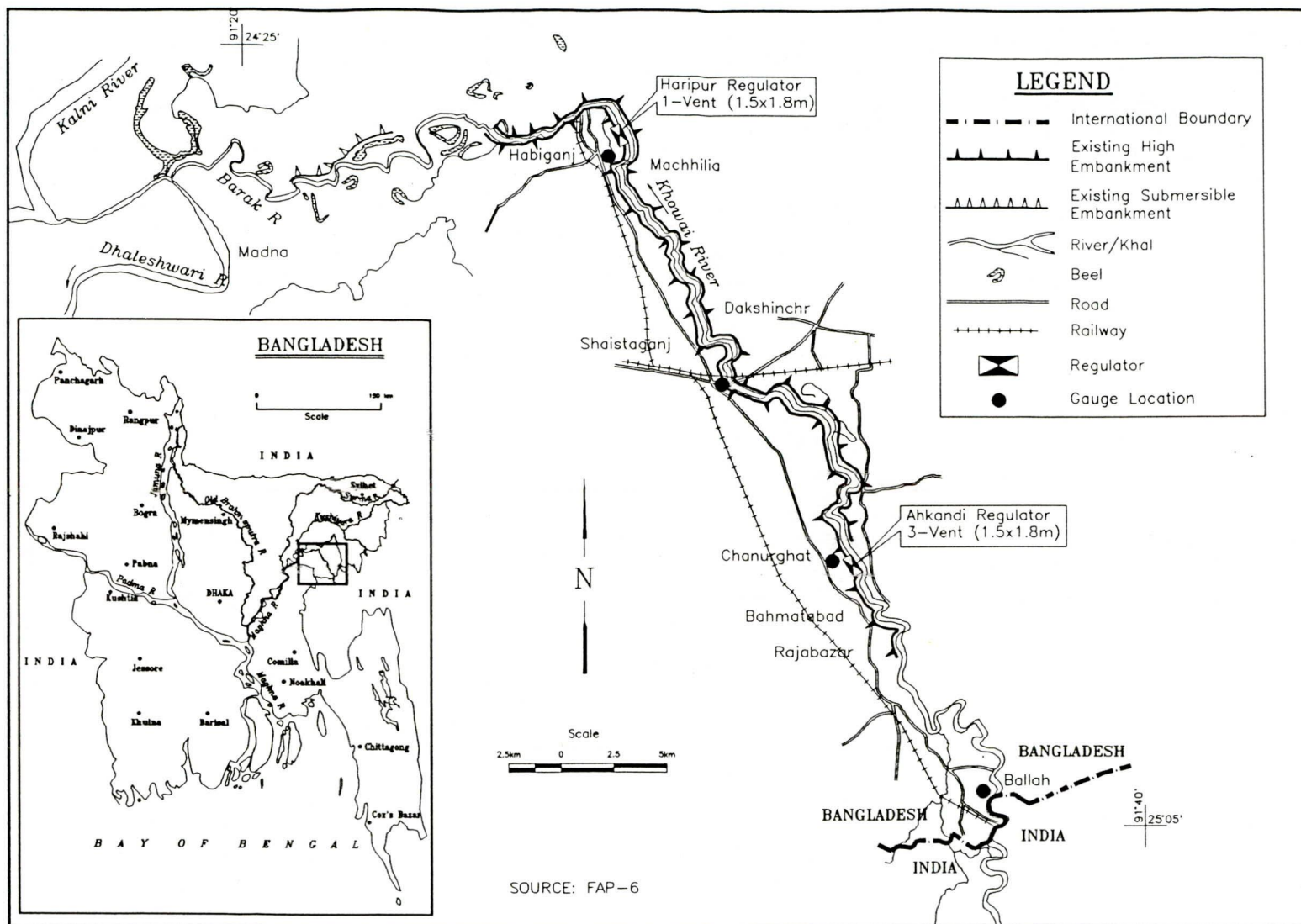


Figure 1.1: Khowai River System

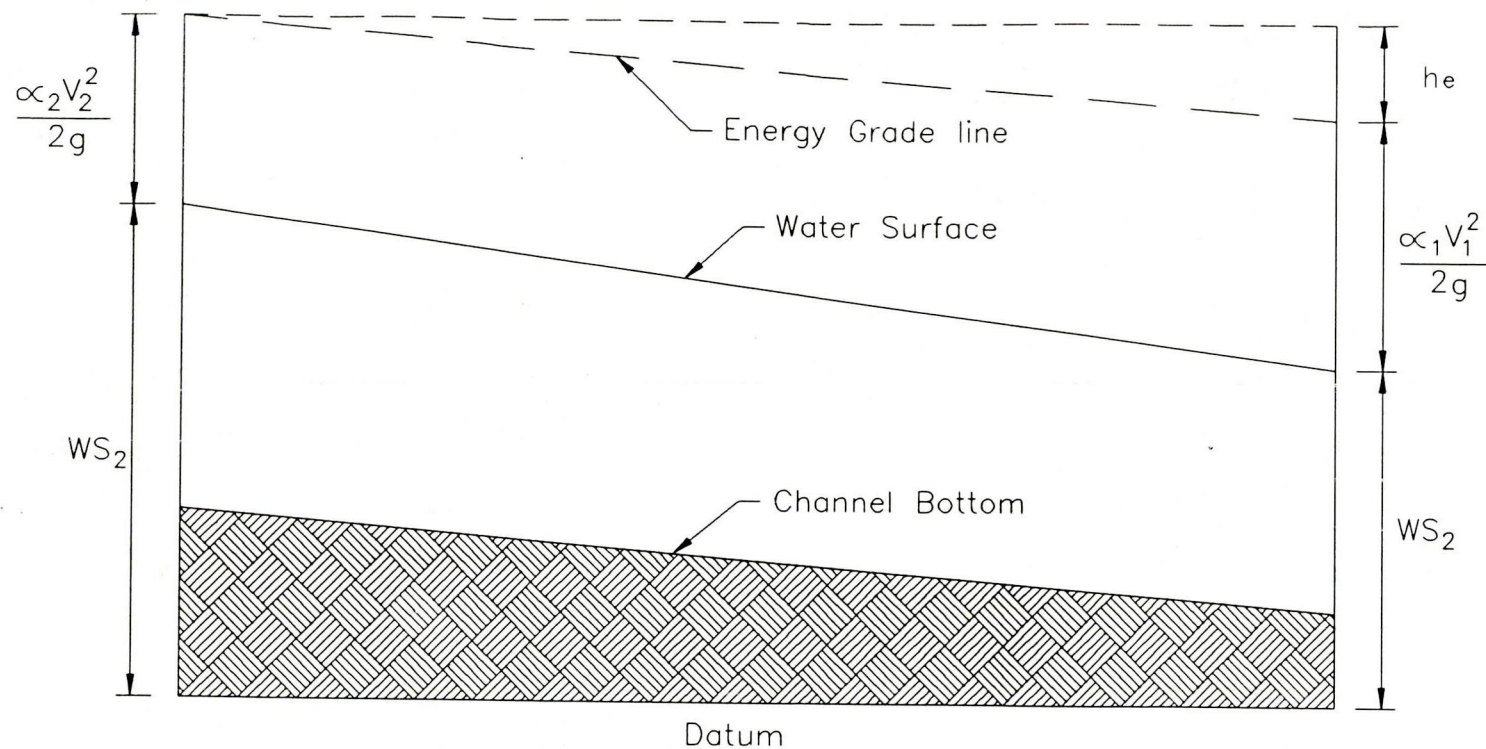


Figure 3.1: Representation of Terms in Energy Equation

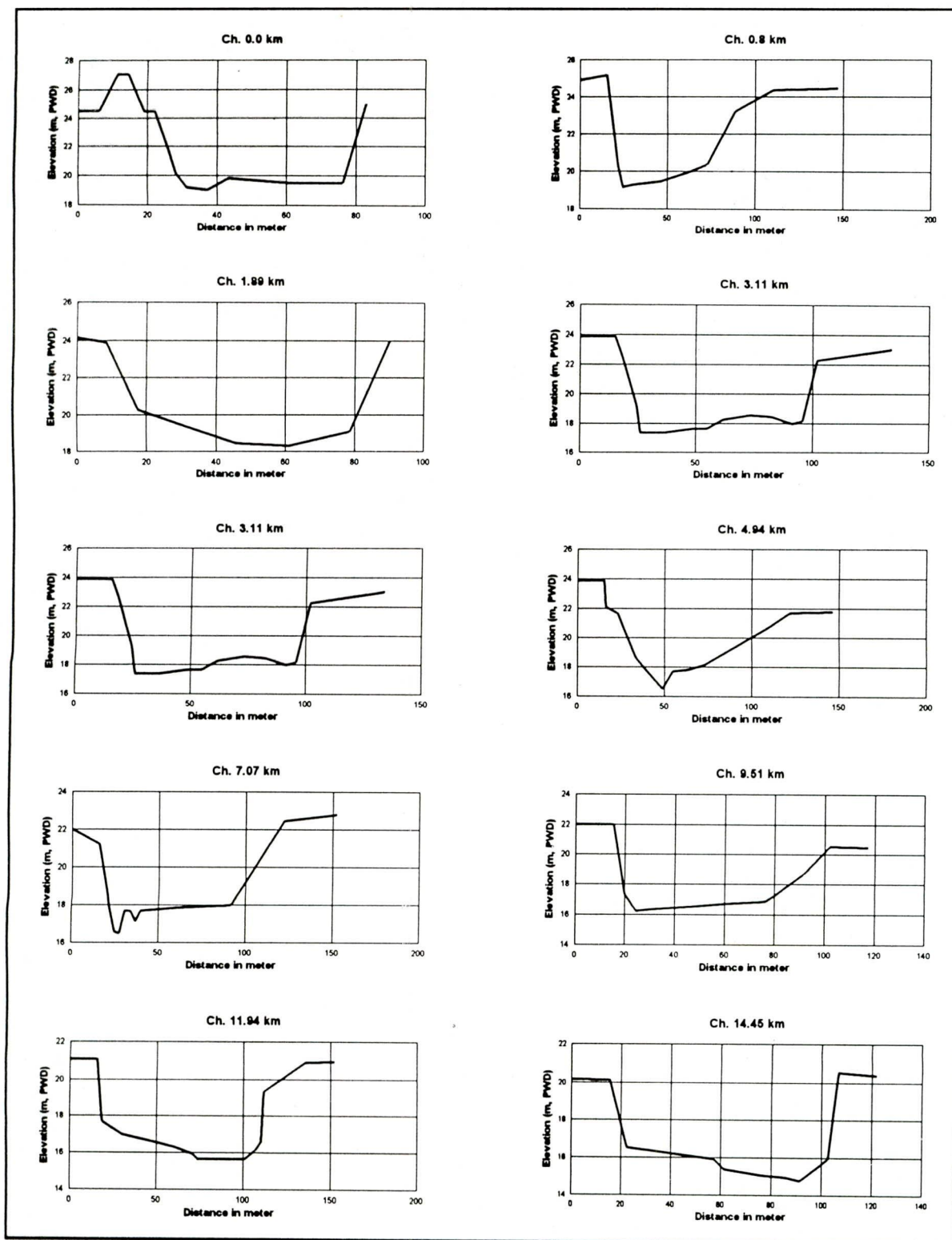


Figure 4.1: Khowai River Cross Sections, Feb 1988 (km 0 to km 14.45)

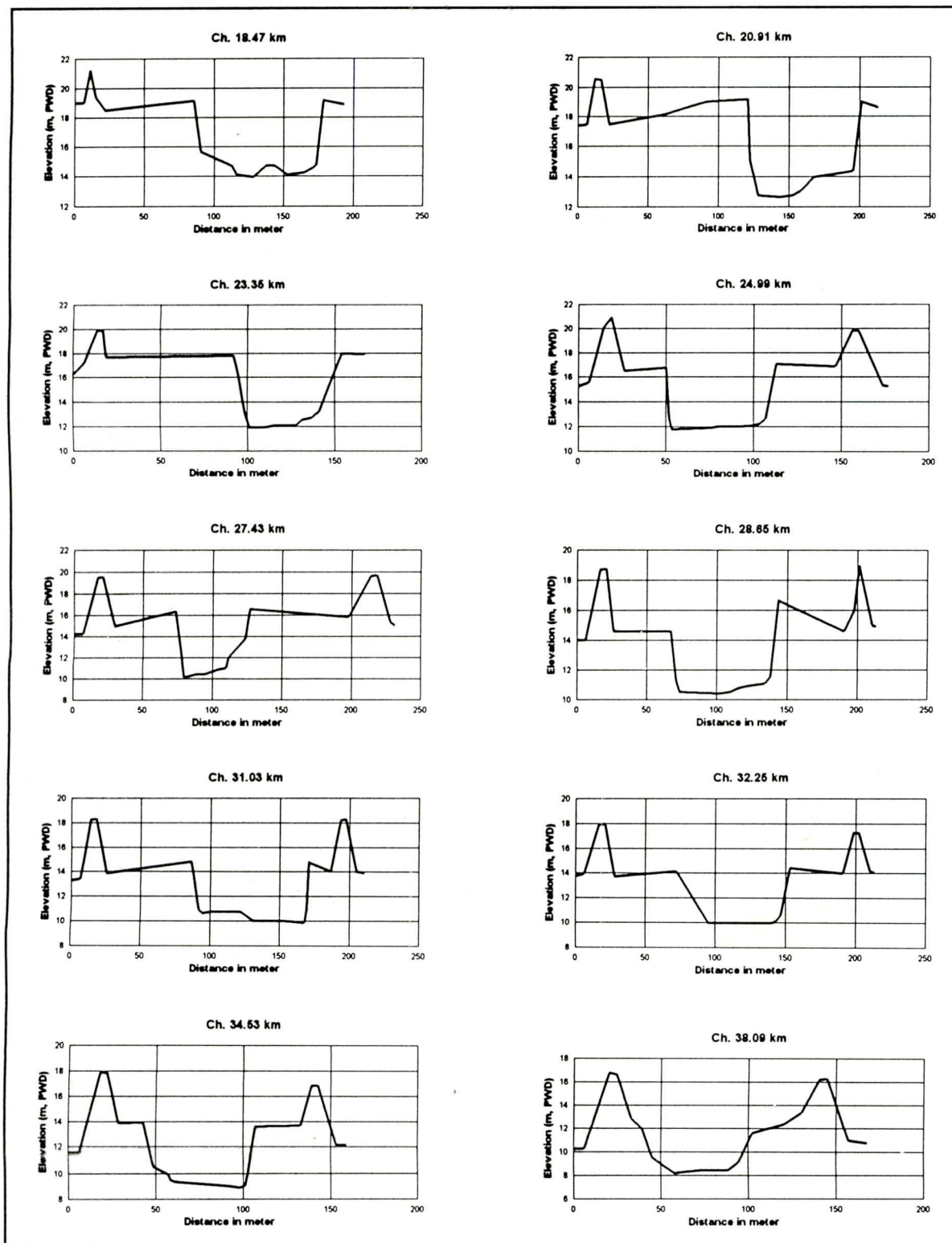


Figure 4.2: Khowai River Cross Sections, Feb 1988 (km 18.47 to km 38.09)

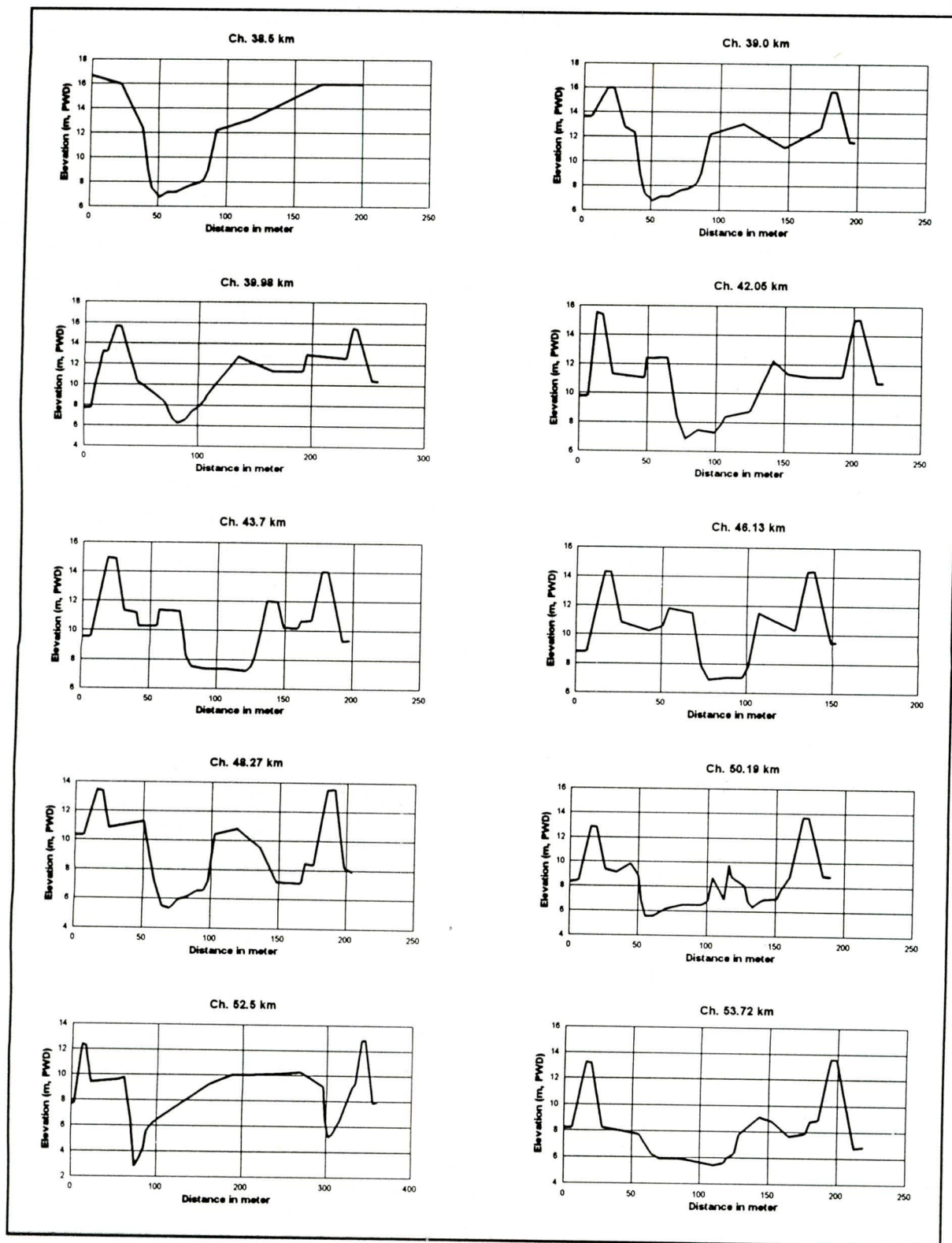


Figure 4.3: Khowai River Cross Sections, Feb 1988 (km 38.5 to km 53.72)

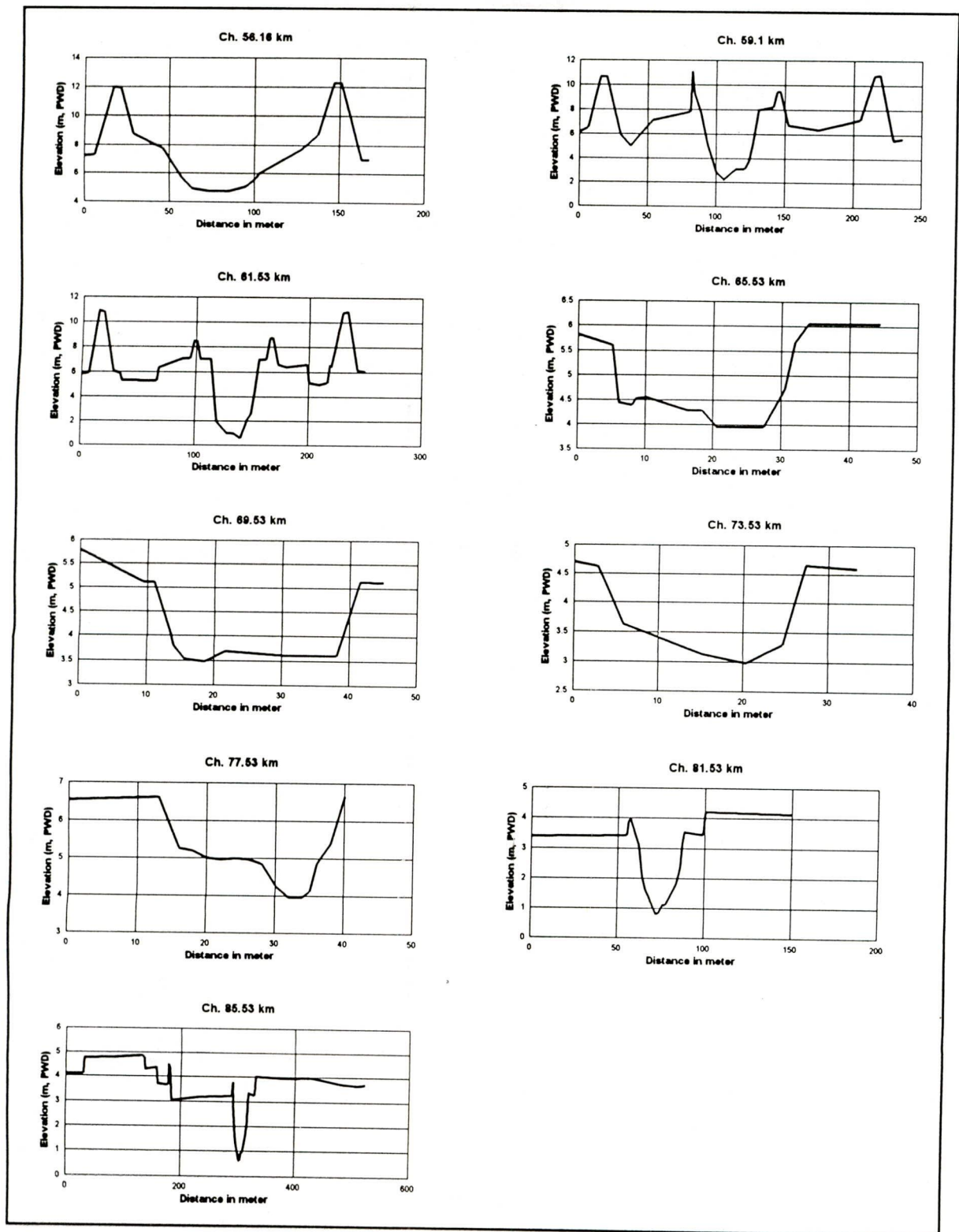


Figure 4.4: Khowai River Cross Sections, Feb 1988 (km 56.16 to km 85.53)

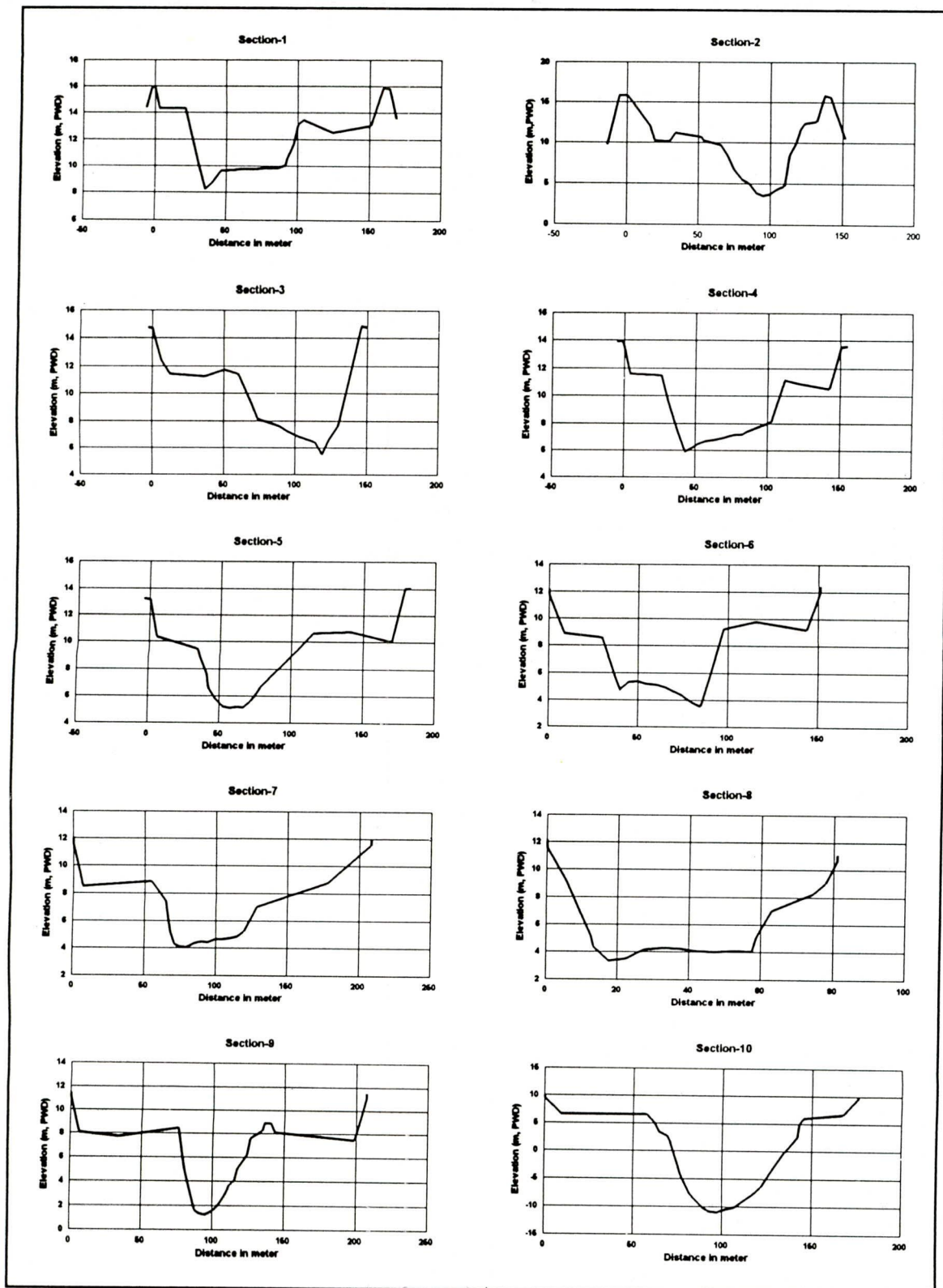


Figure 4.5: Cross section 1994 (Sec 1 to Sec 10)

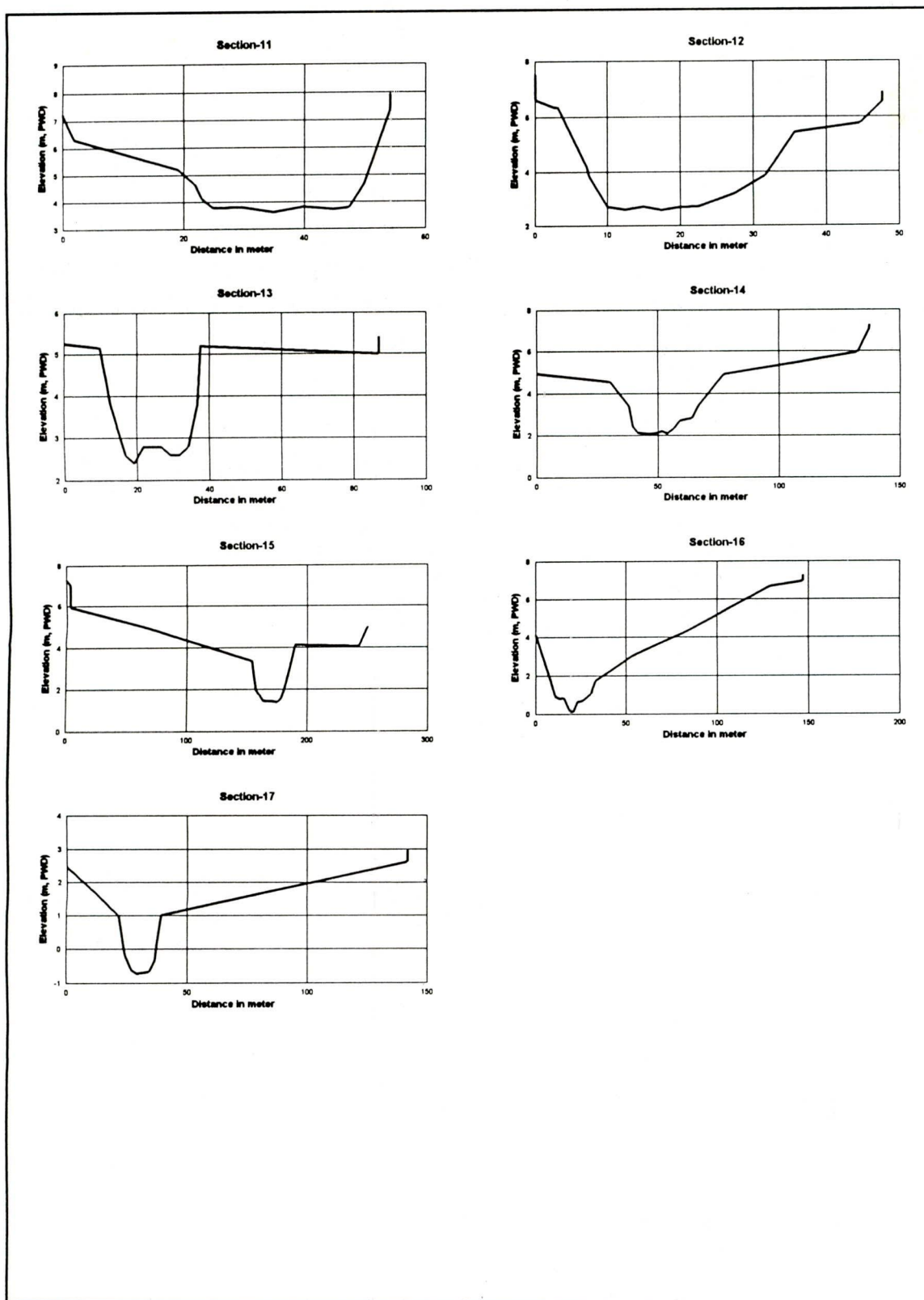


Figure 4.6: Cross Sections 1994 (Sec 11 to Sec 17)

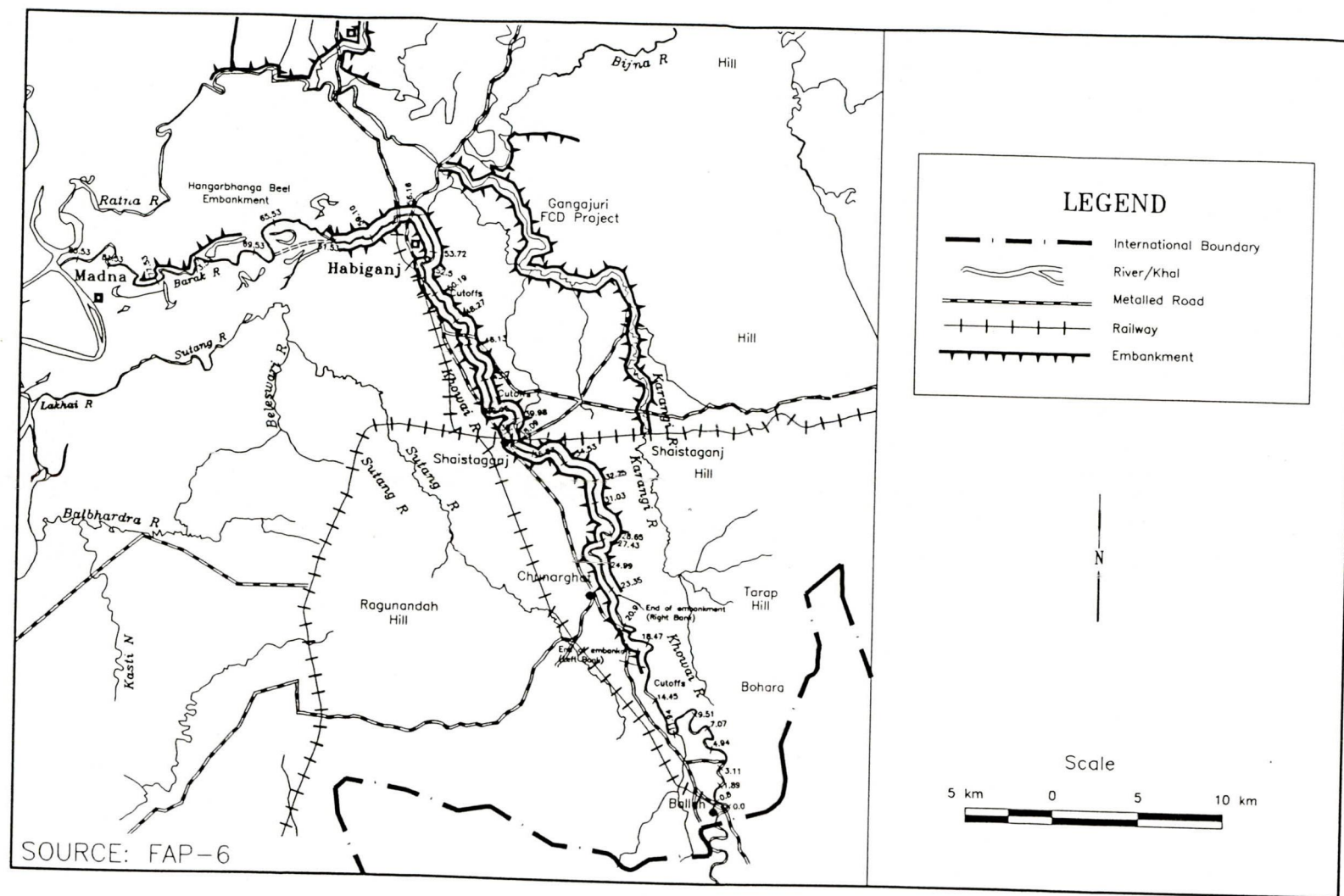


Figure 4.7: Cross Section Locations, Feb. 1988

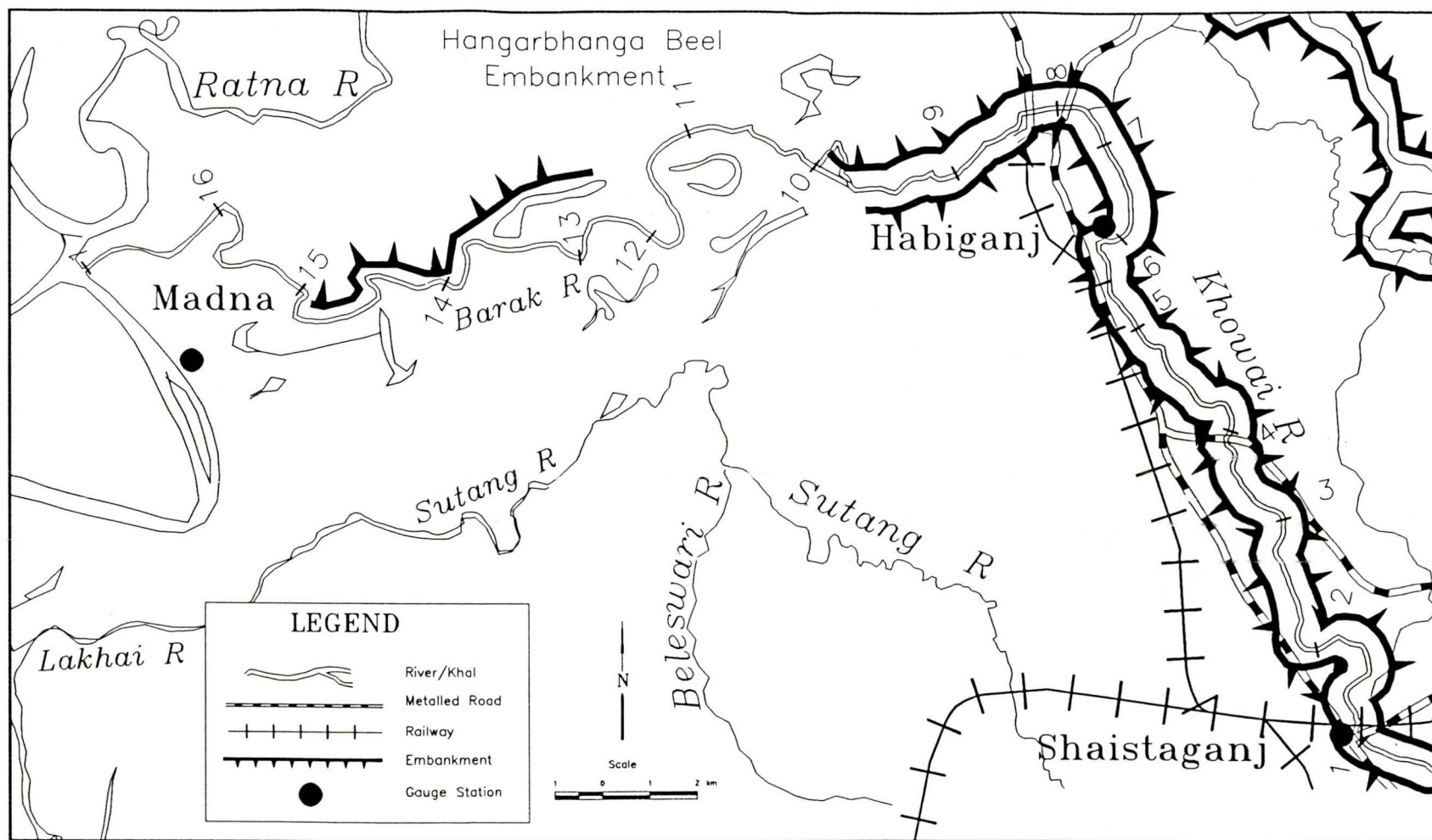


Figure 4.8: Cross Section Locations Feb. 1994

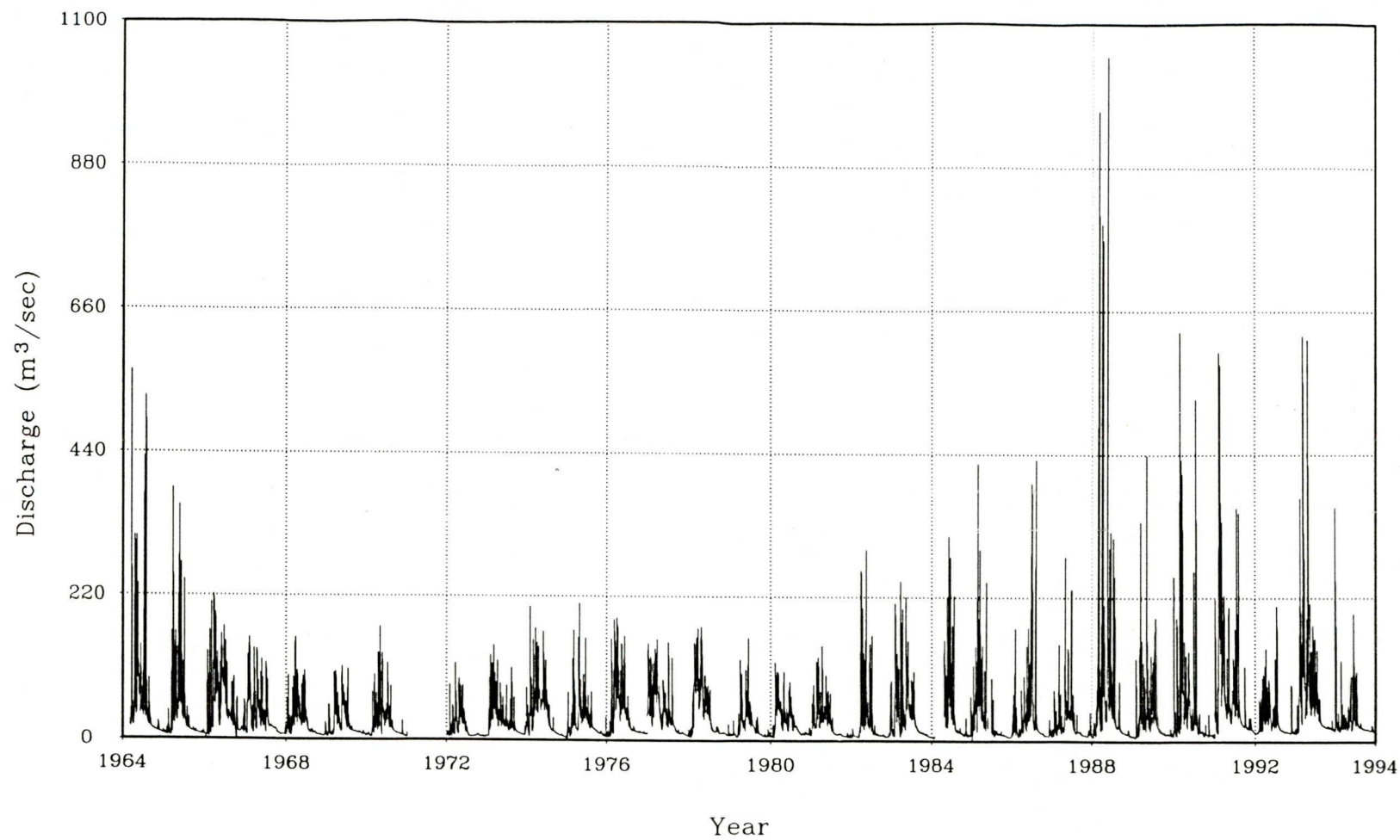


Figure 4.9: Mean Daily Discharges at Shaistaganj

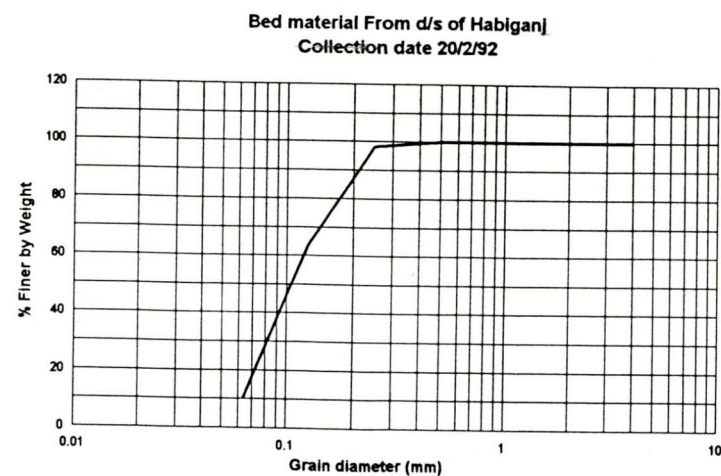
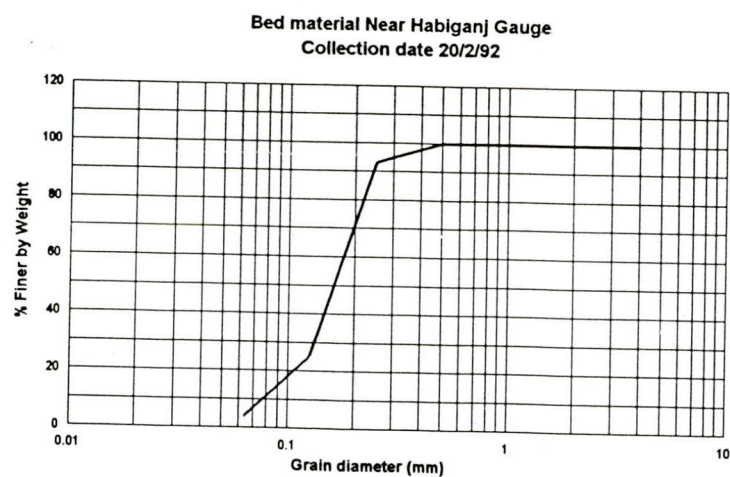
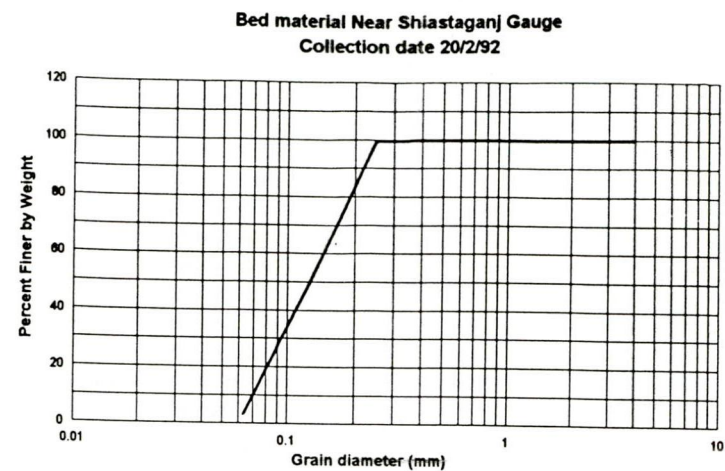
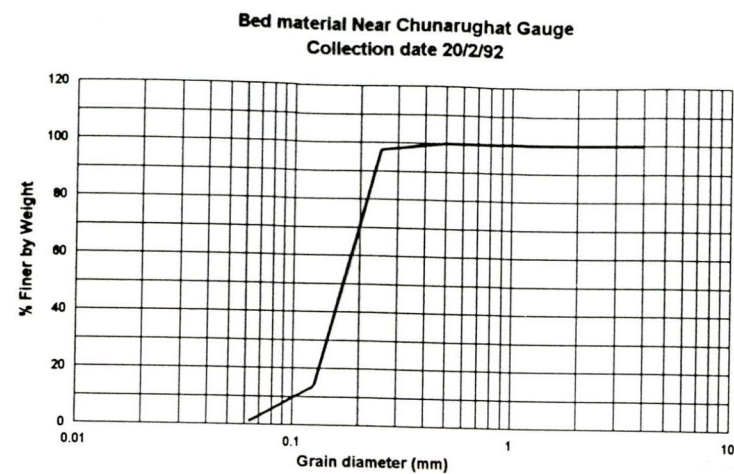


Figure 4.10: Bed Material Gradation Curve Along Khowai River

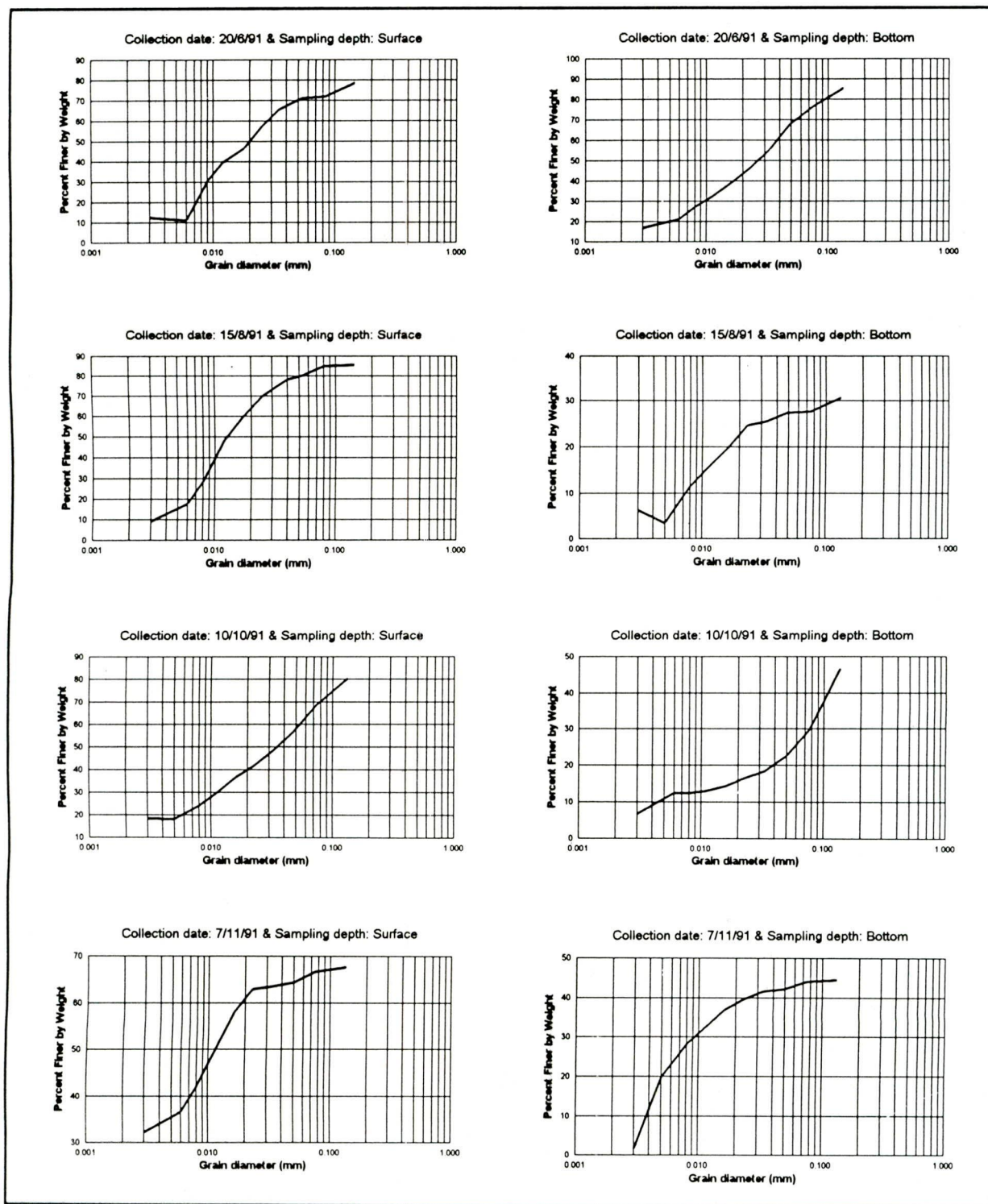


Figure 4.11: Particle Size Distribution (Suspended Sample)

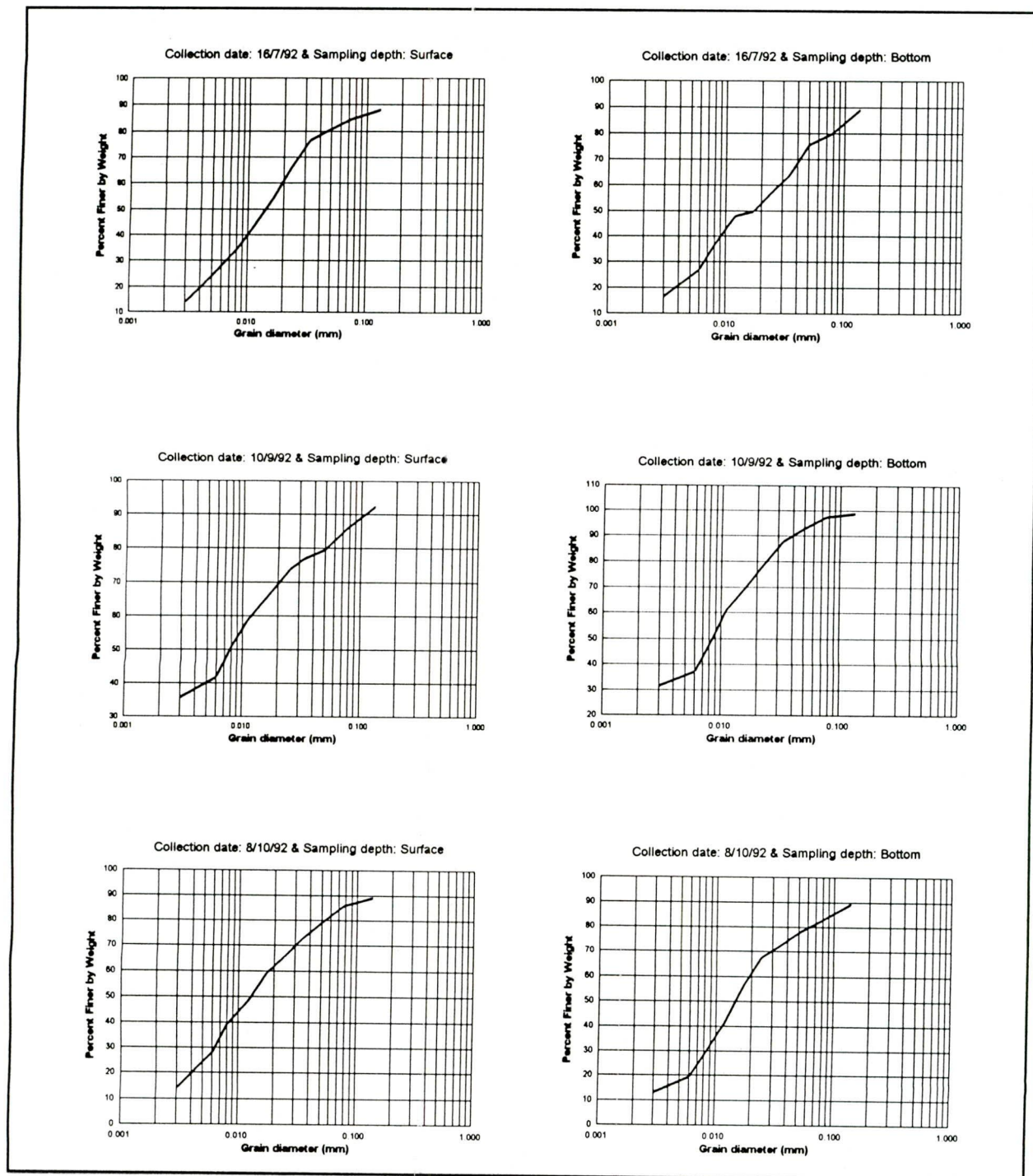


Figure 4.12: Particle Size Distribution (Suspended Sample)

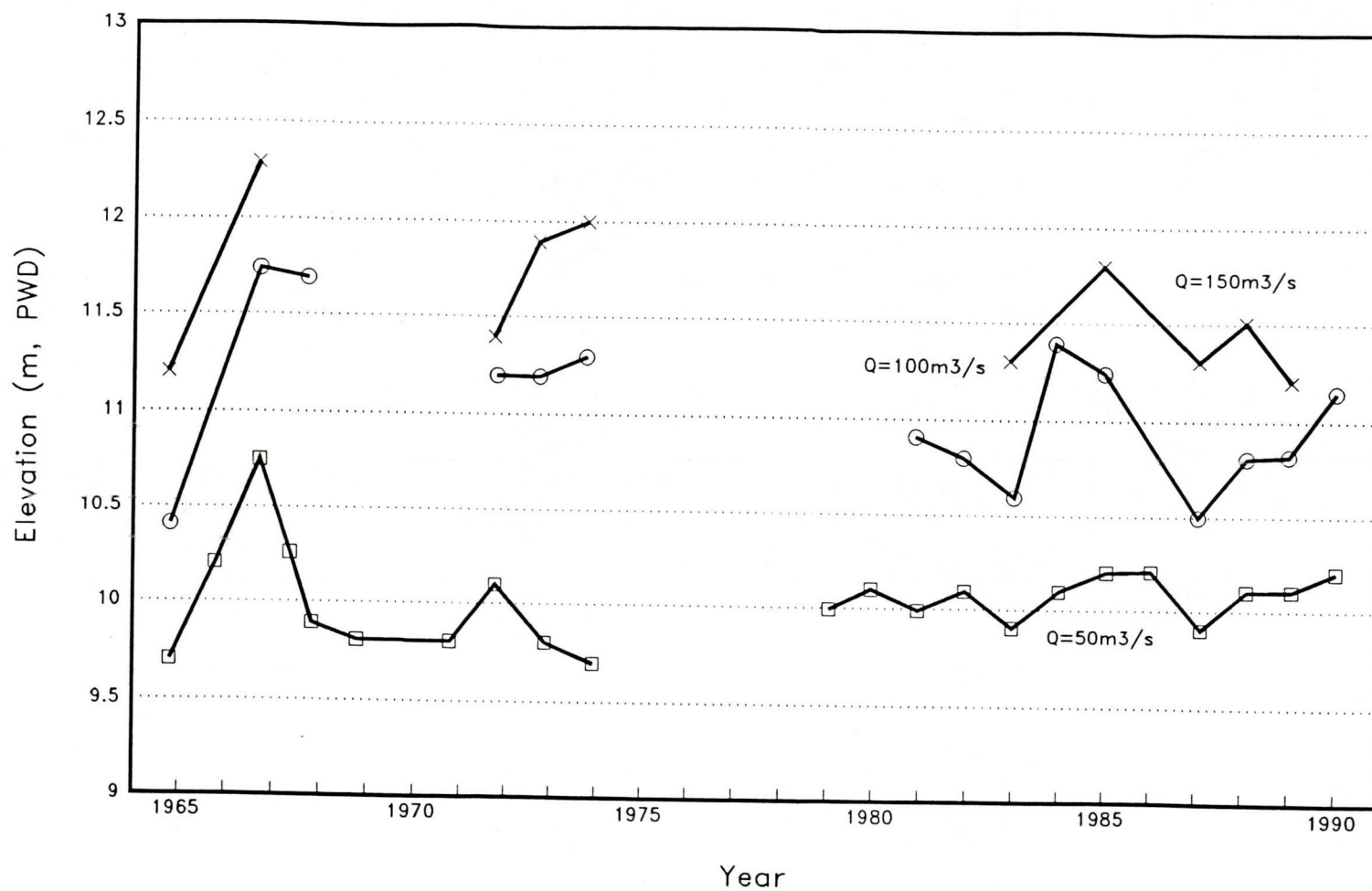


Figure 4.13: Specific Gauge plot, Khowai River at Shaistaganj

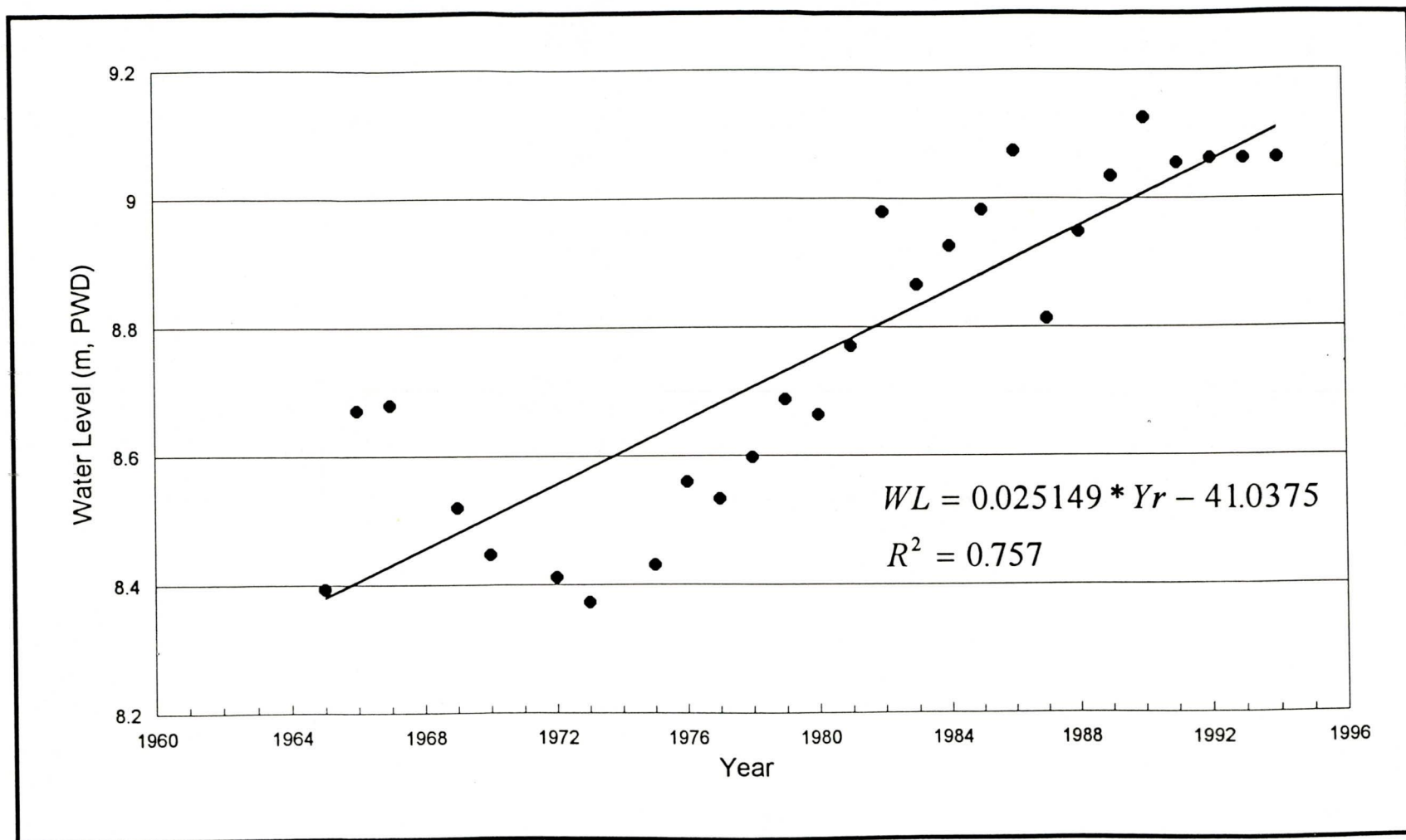


Figure 4.14: Specific gauge plot (Q=10 cumec), Khowai River at Shaistaganj

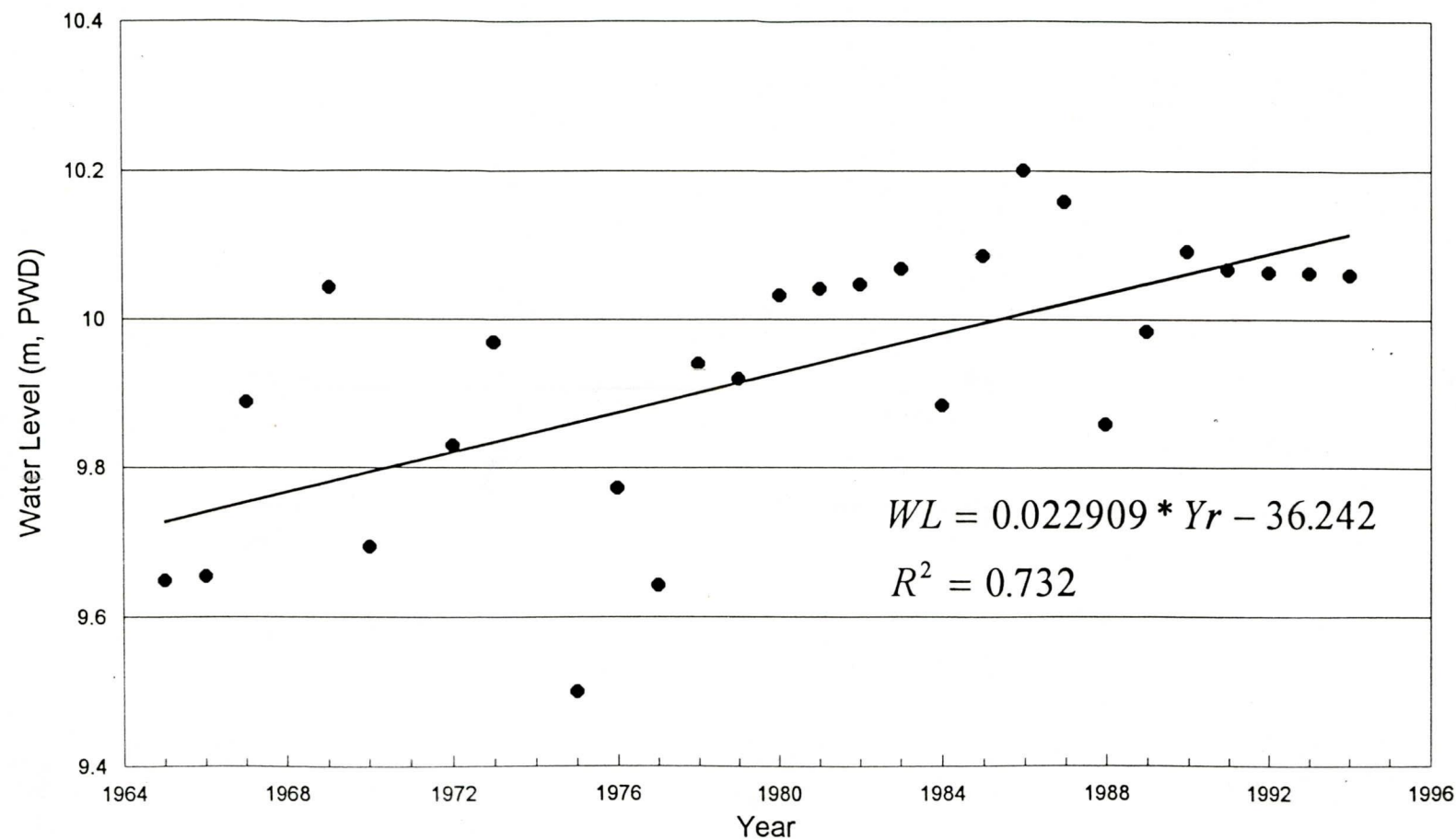


Figure 4.15: Specific gauge plot (Q=20 cumec), Khowai River at Shaistaganj

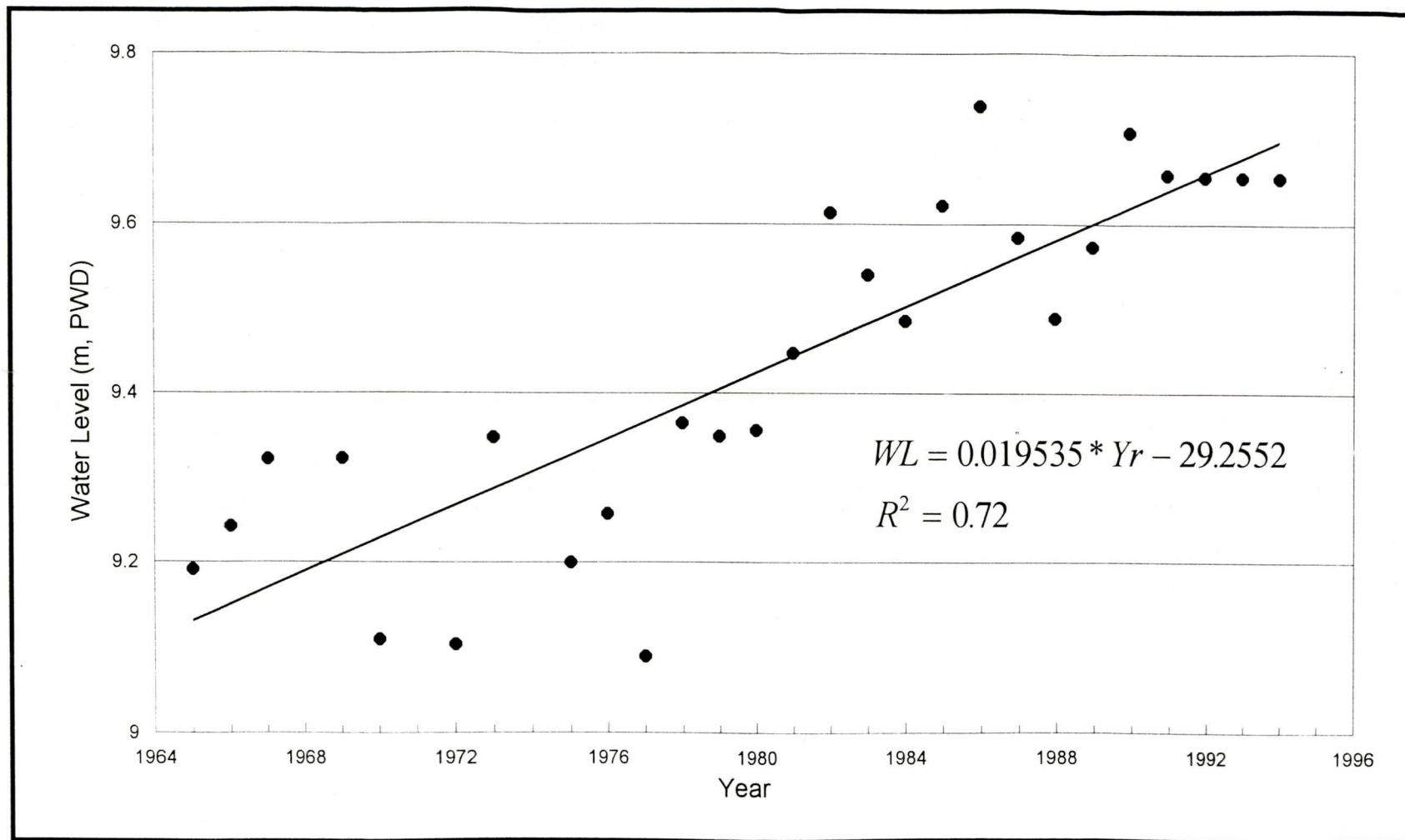


Figure 4.16: Specific gauge plot (Q=30 cumec), Khowai River at Shaistaganj

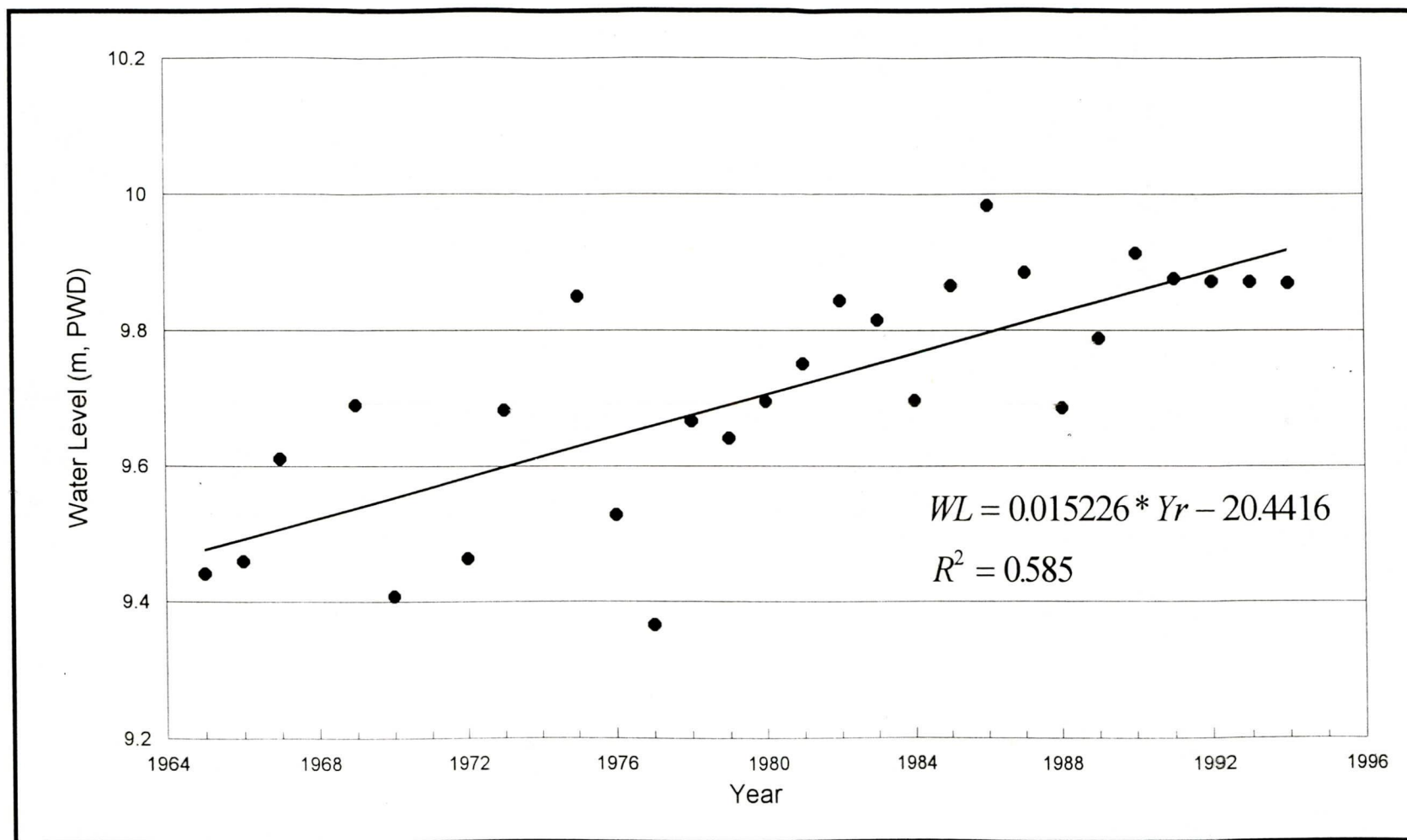


Figure 4.17: Specific gauge plot (Q=40 cumec), Khowai River at Shaistaganj

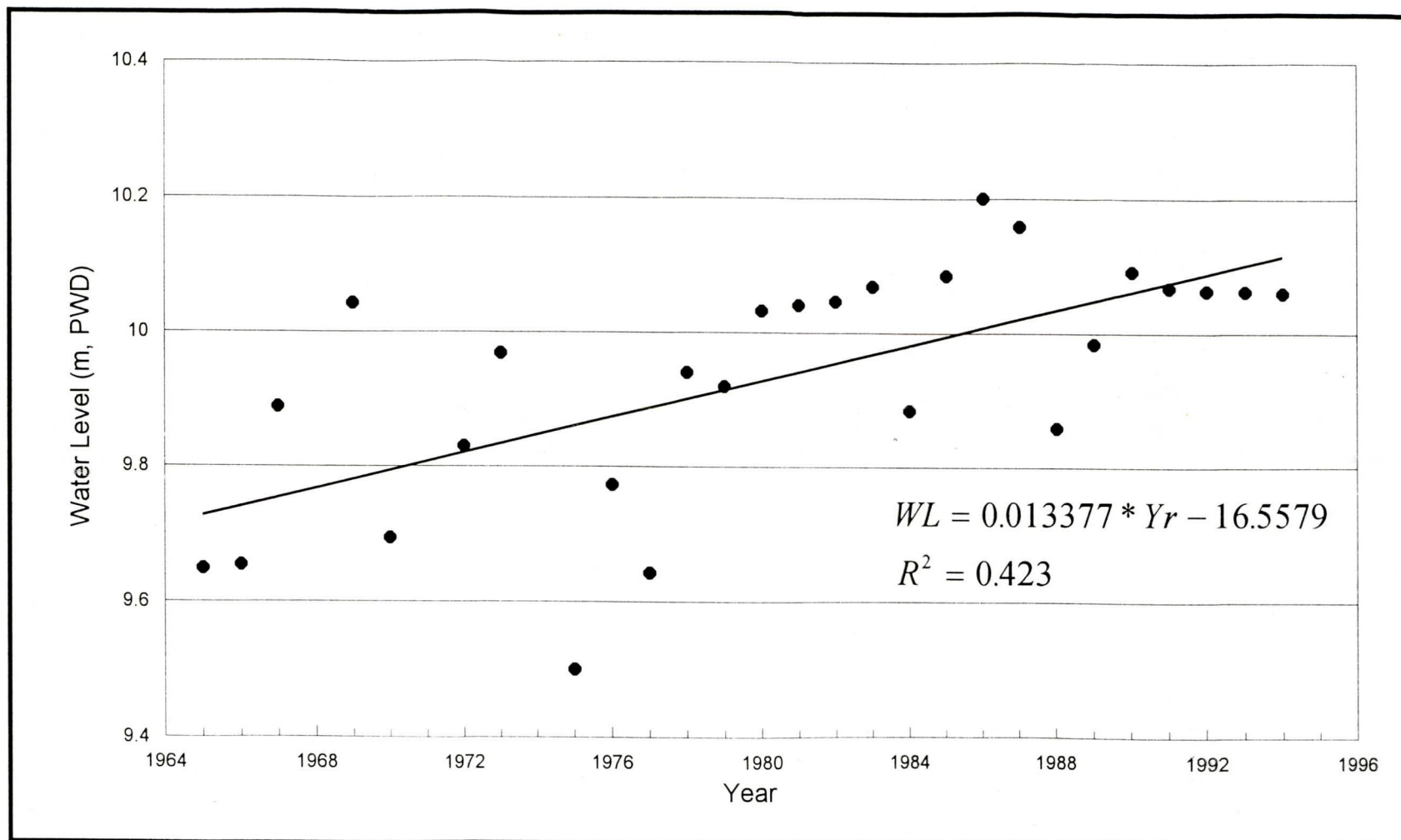


Figure 4.18: Specific gauge plot (Q=50 cumec), Khowai River at Shaistaganj

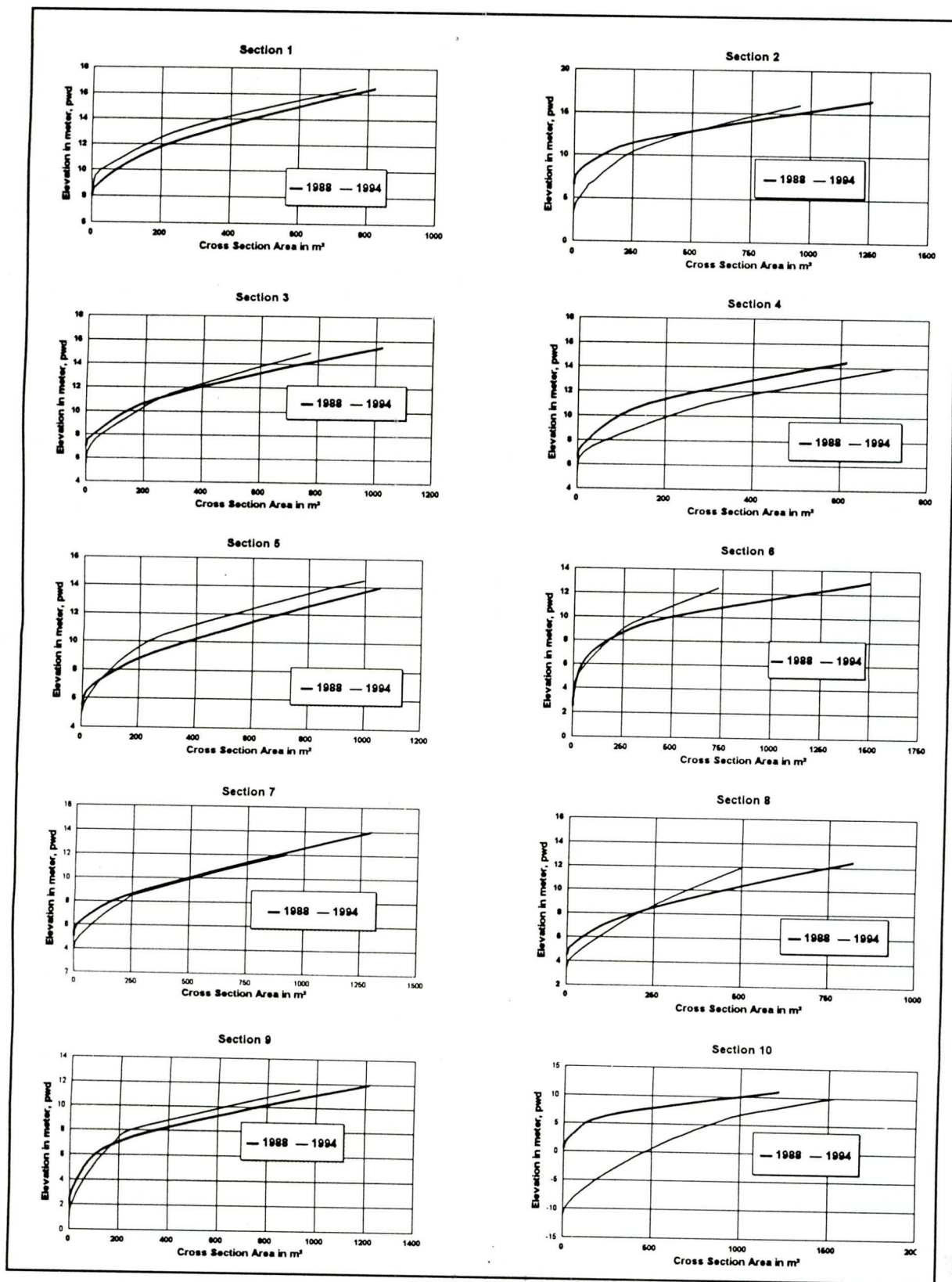


Figure 4.19: Area Elevation curves (Sec 1 to Sec 10)

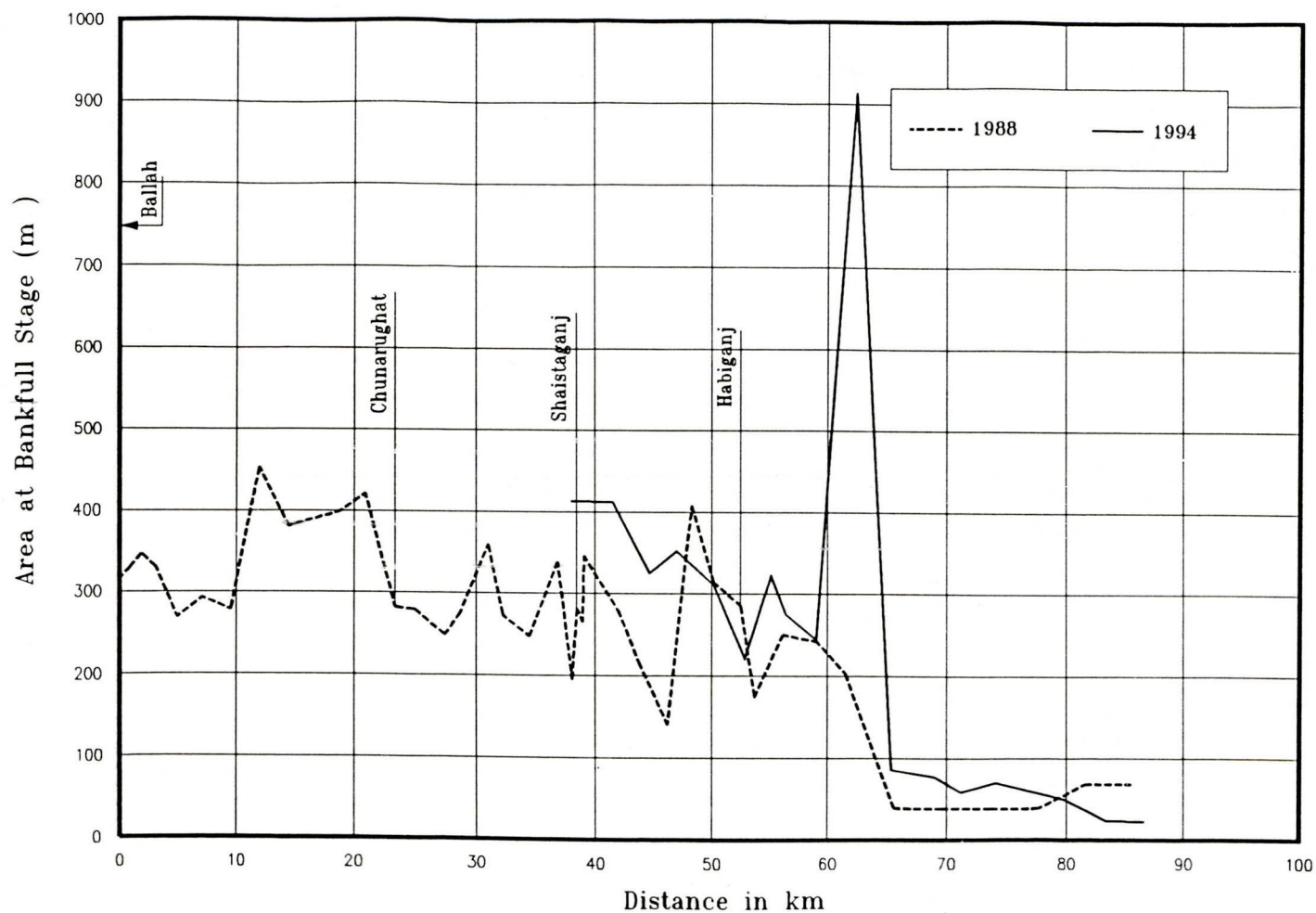


Figure 4.20: Profiles of the Cross Section Area at Bankfull Stages
1988 and 1994

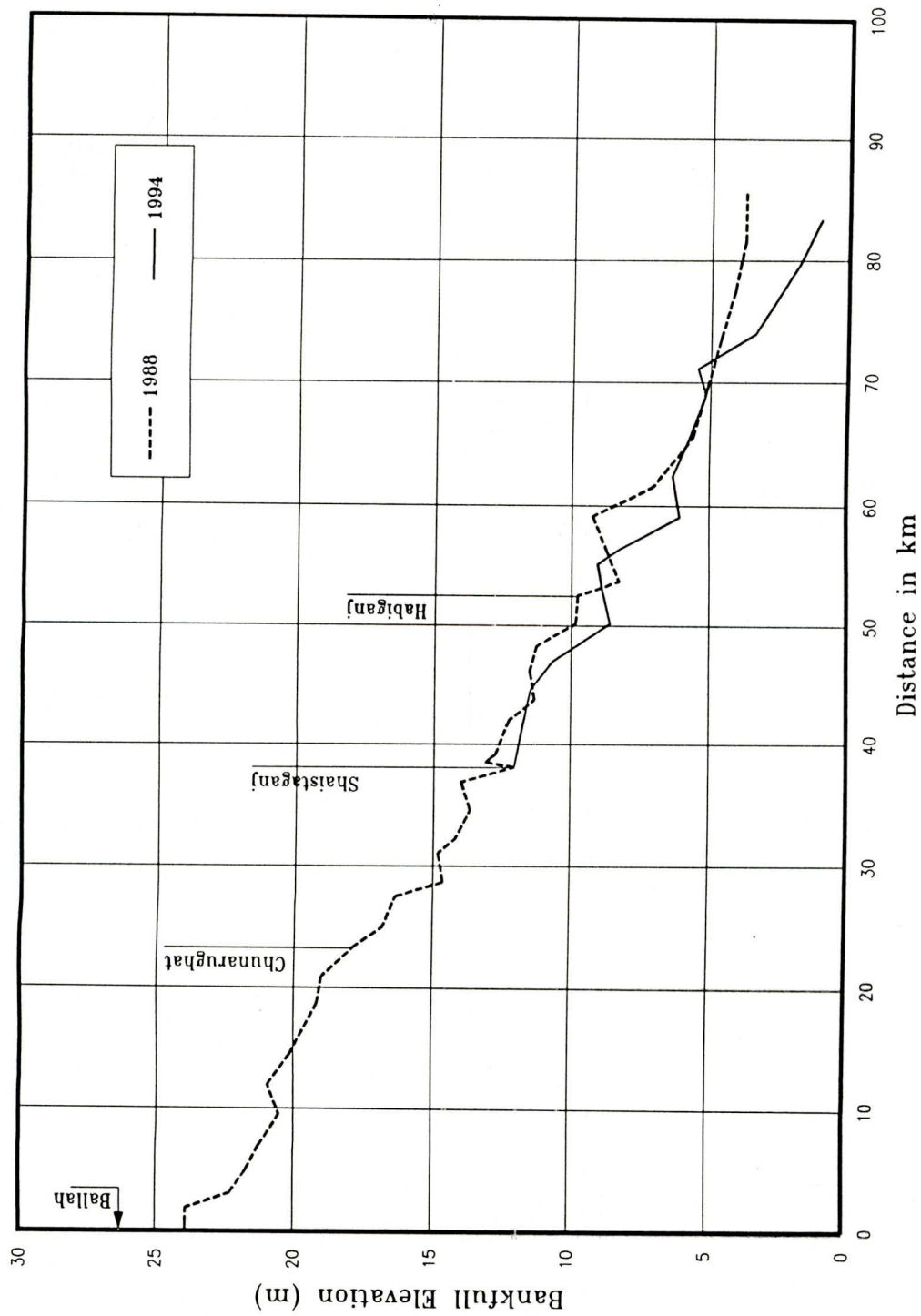


Figure 4.21: Profiles of the Bankfull Elevations, 1988 and 1994

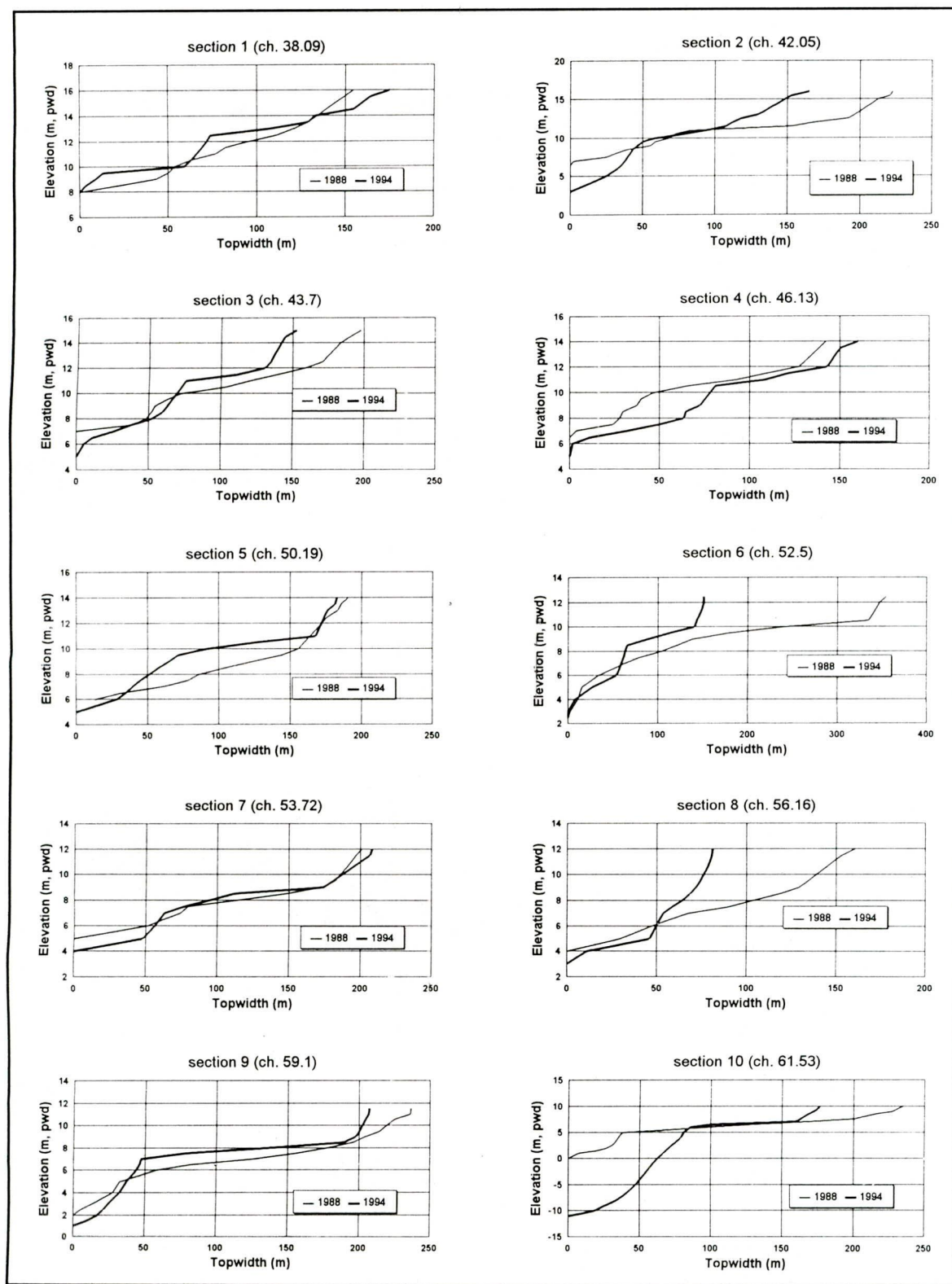
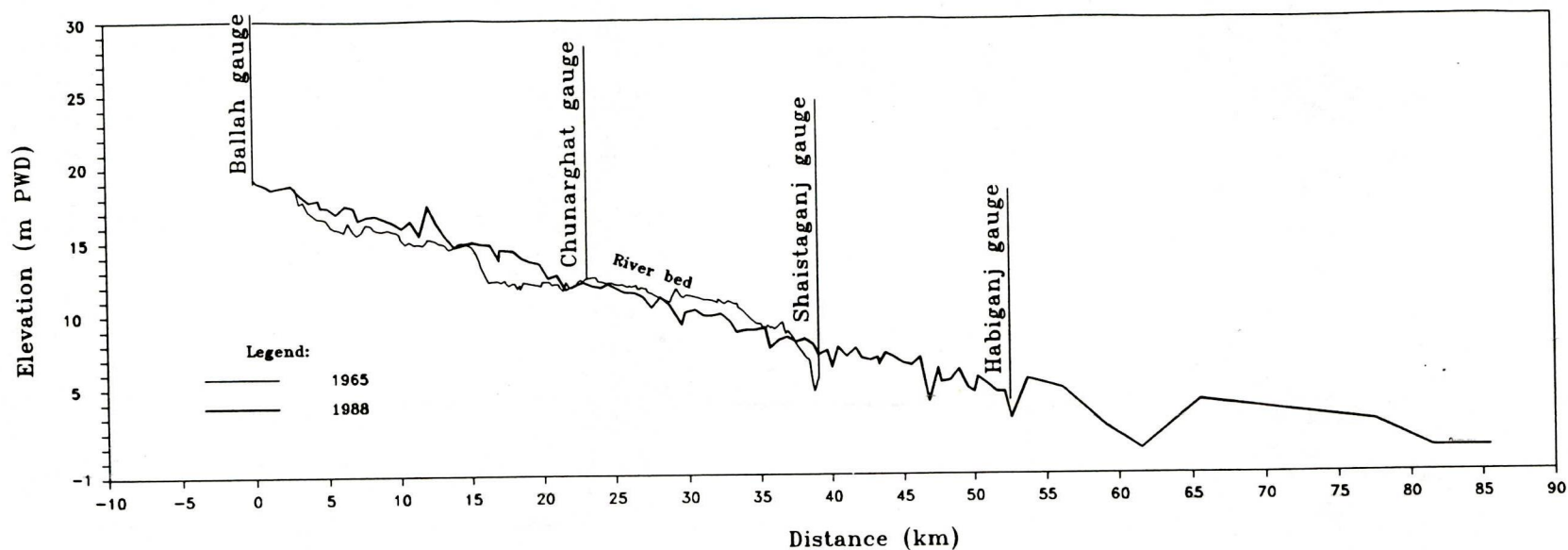


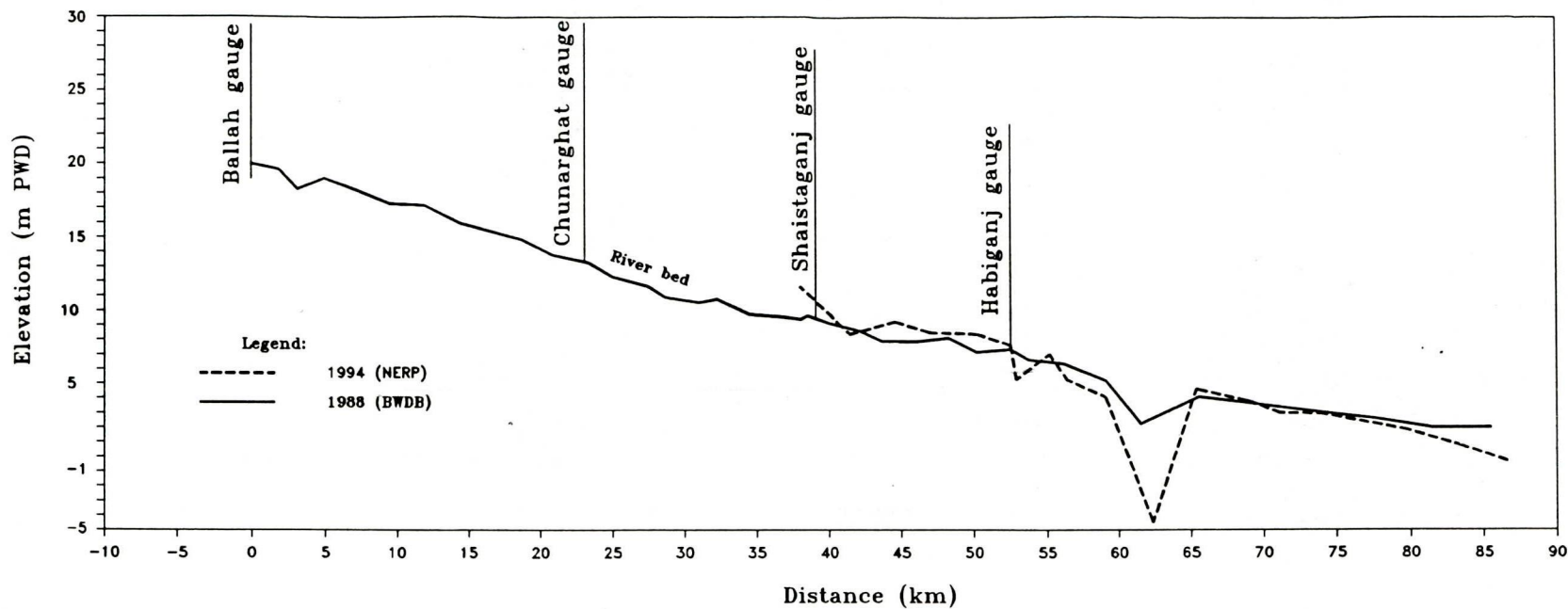
Figure 4.22: Topwidth Elevation Curves (Sec 1 to Sec 10)



Note:

All chainages based on BWDB
Habiganj W.B. Division
Long Section of Khowai River
showing Deep Channel Line
dated 6/2/88

Figure 4.23: Khowai River Deep Channel Profiles, 1965 and 1988



Note:

All chainages based on BWDB
 Habiganj W.B. Division
 Long Section of Khowai River
 showing Mean Bed Level Profile

Figure 4.24: Khowai River Mean Bed Profiles, 1988 and 1994

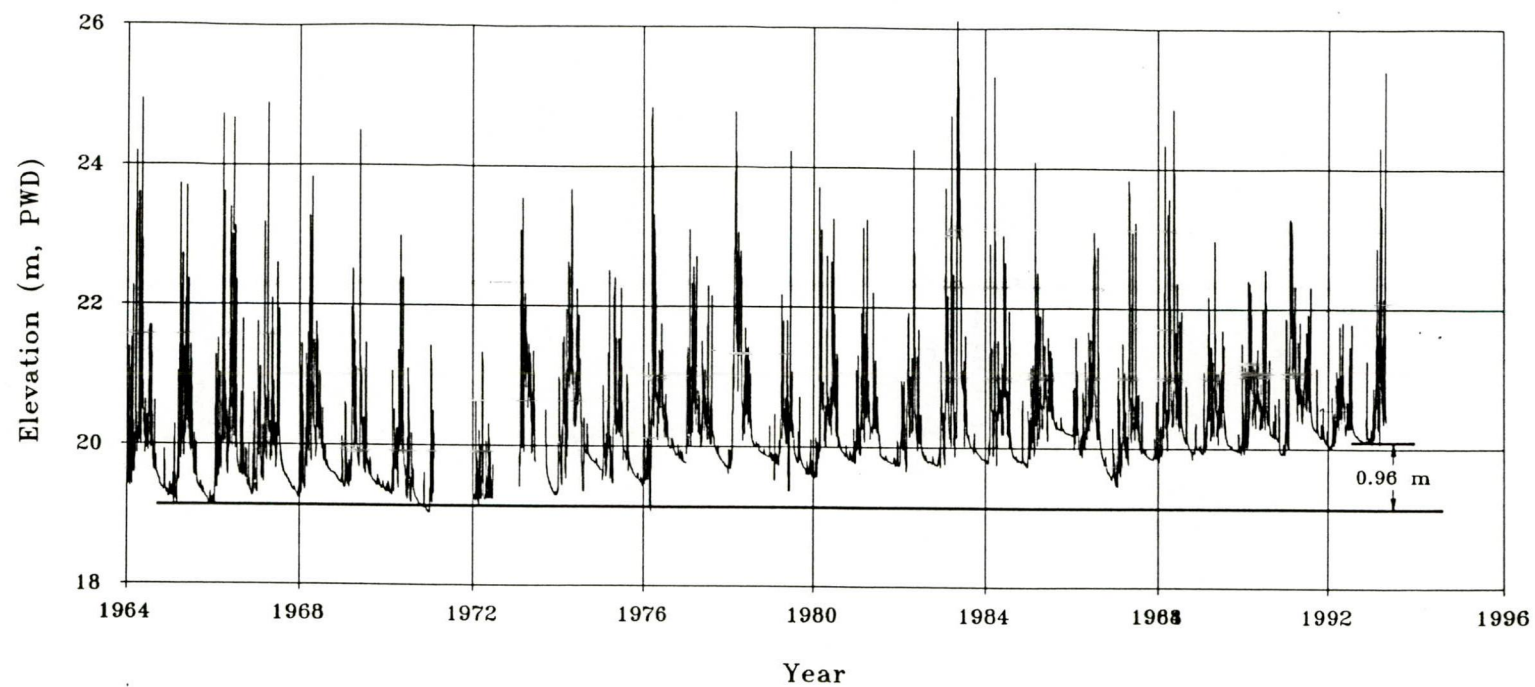


Figure 4.25: Historic Water Level (1964-1994), Khowai River at Ballah Gauge

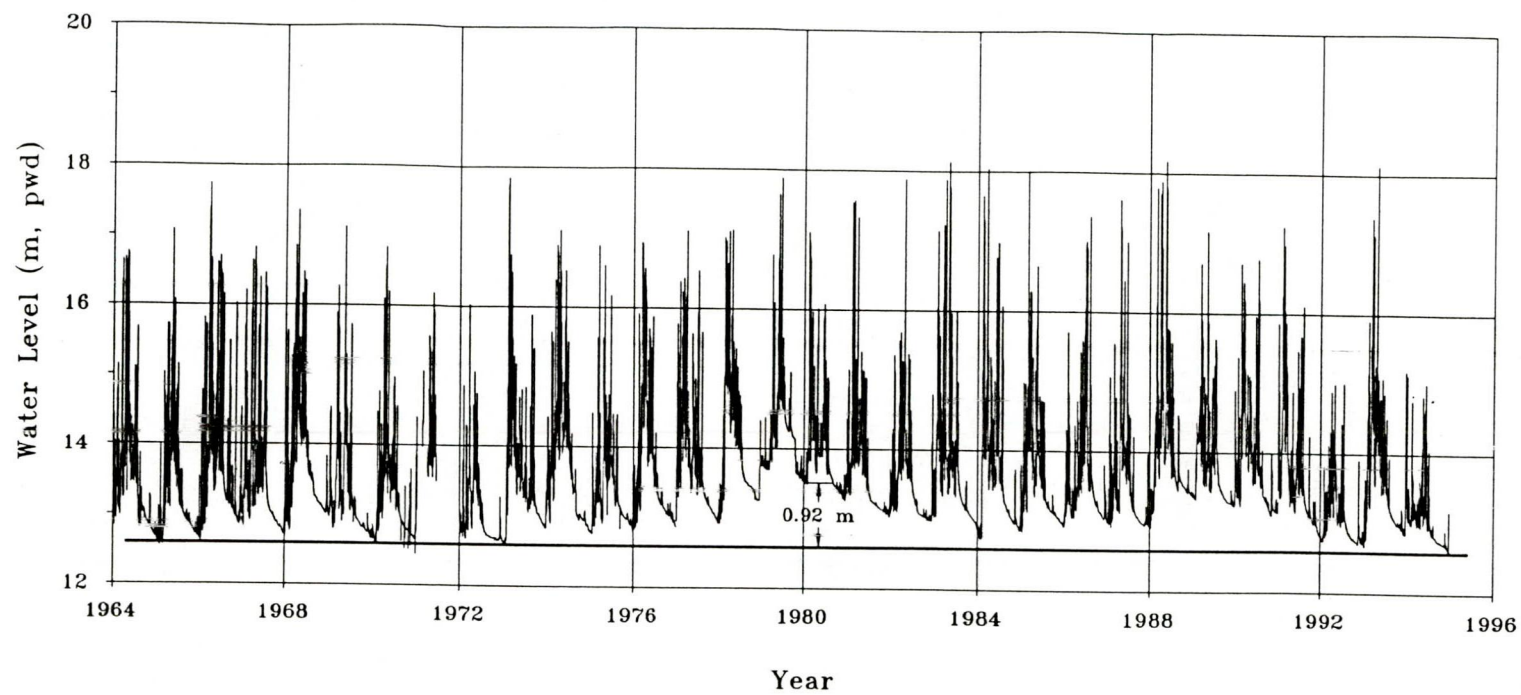


Figure 4.26: Historic Water Level (1964-1994), Khowai River at Chunarughat Gauge

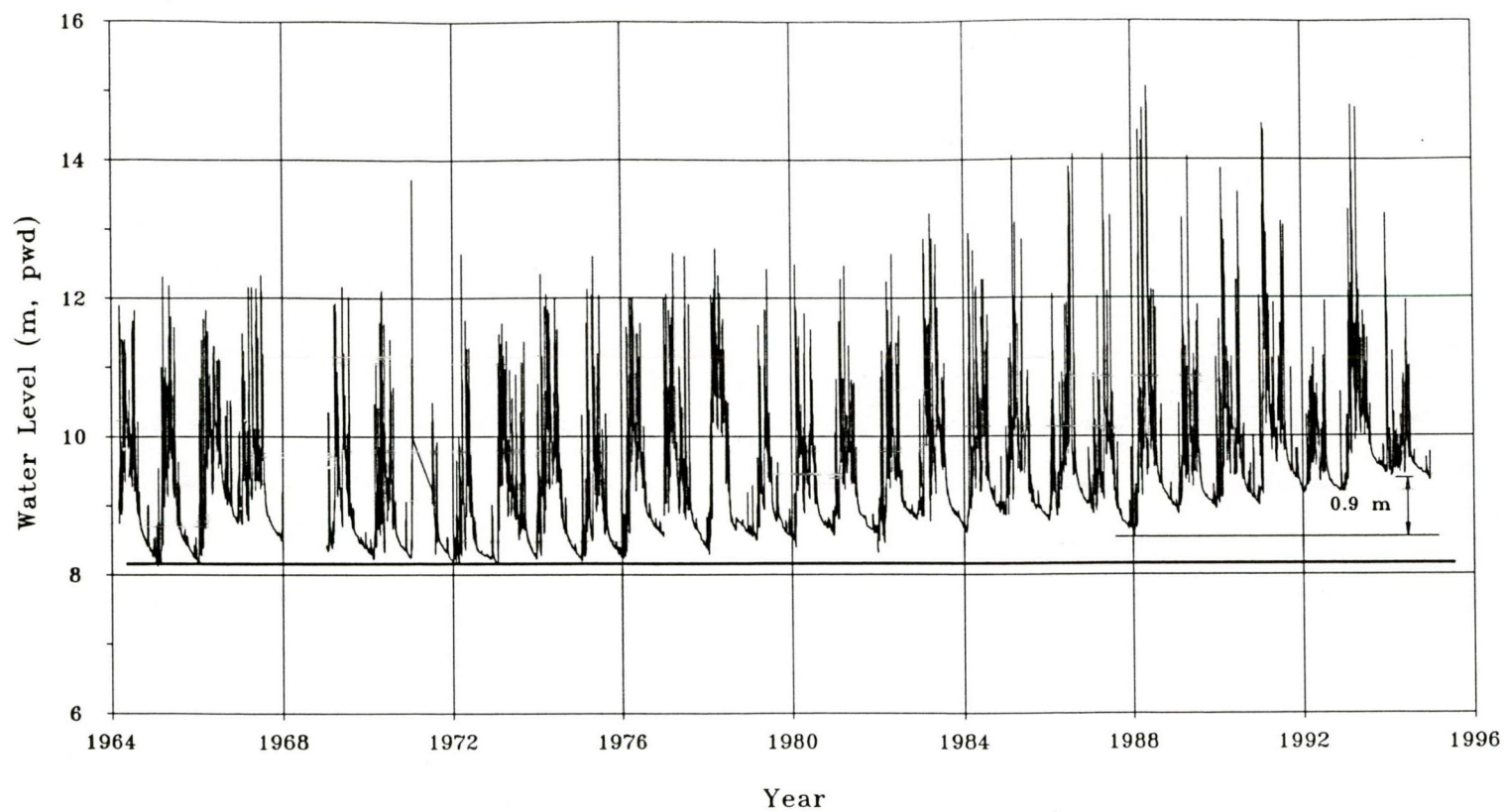


Figure 4.27: Historic Water Level (1964-1994), Khowai River at Shaistaganj Gauge

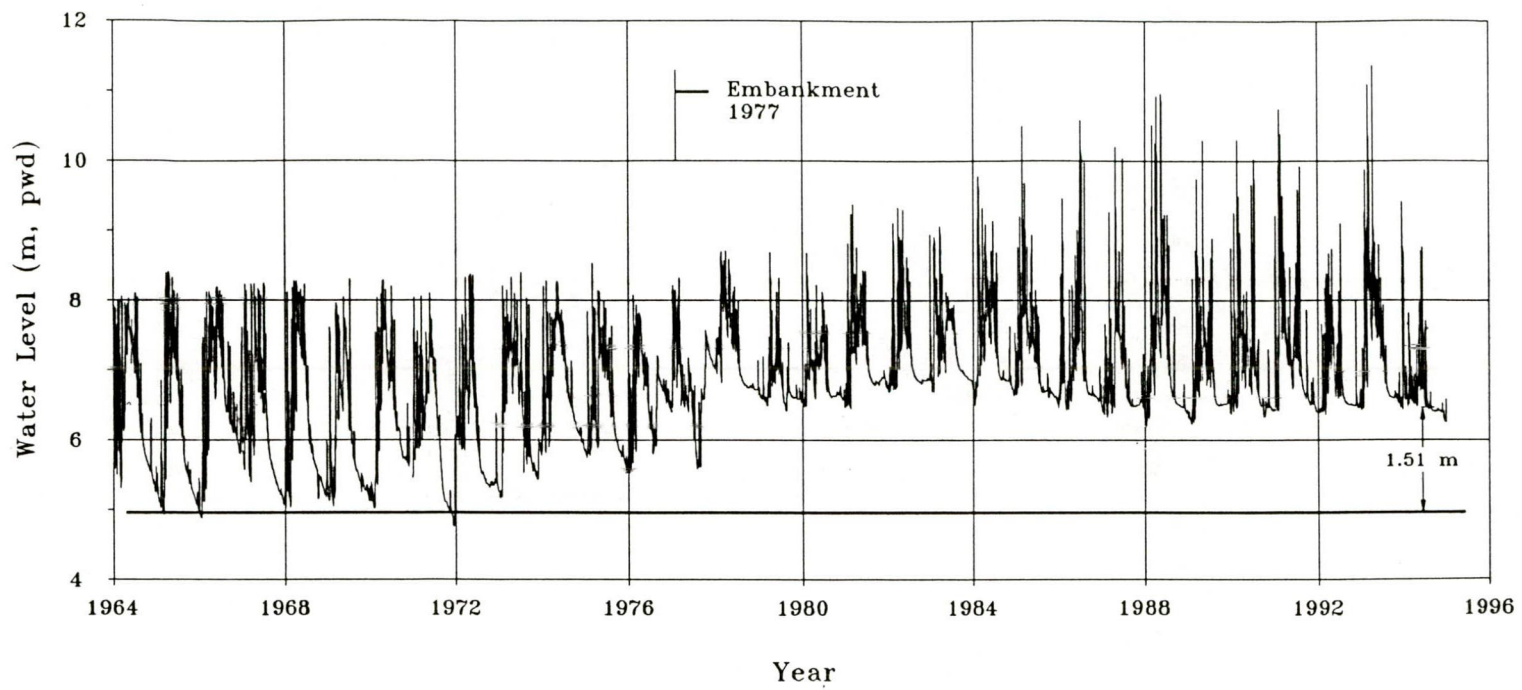


Figure 4.28: Historic Water Level (1964–1994), Khowai River at Habiganj Gauge

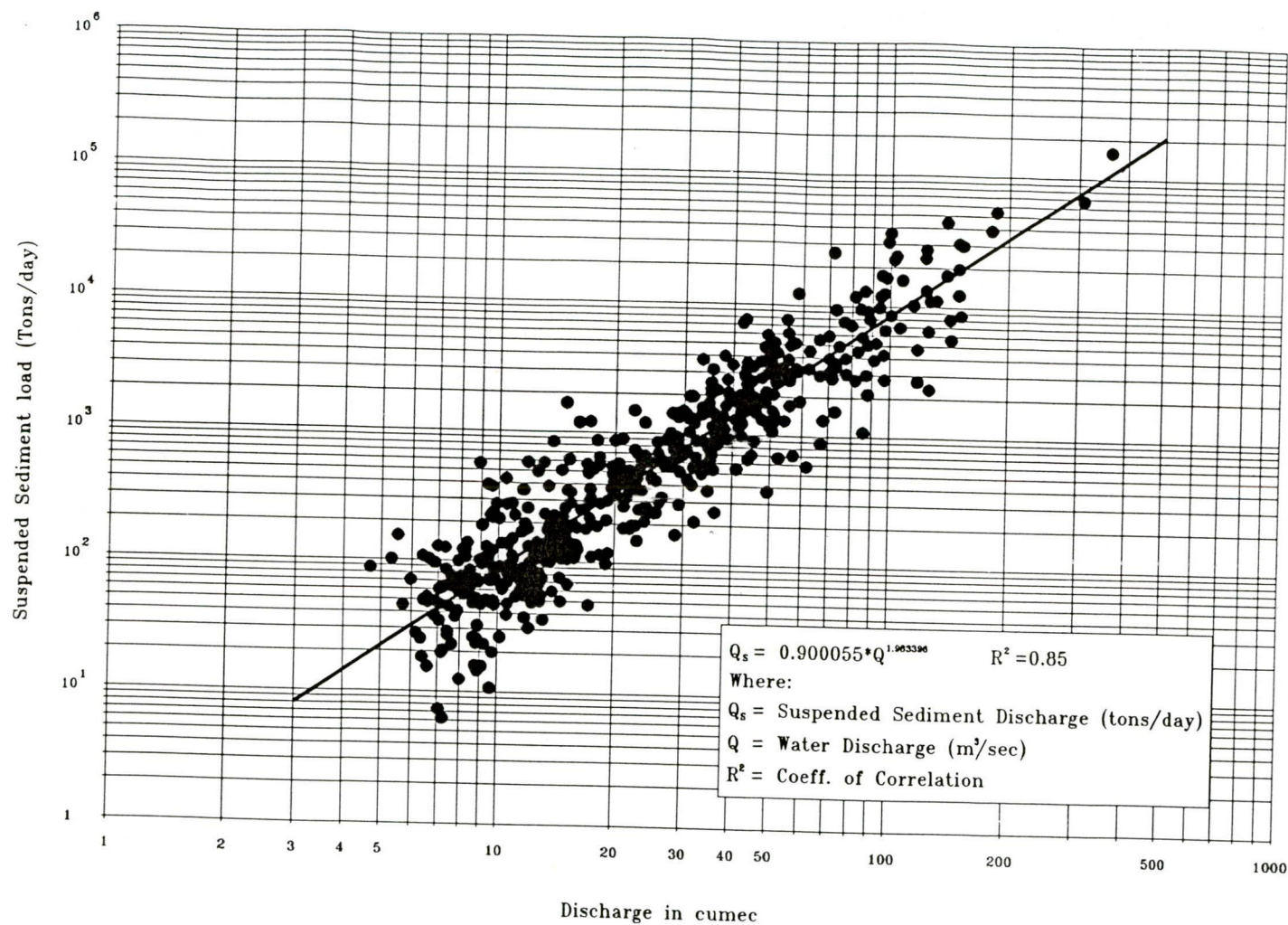


Figure 4.29: Suspended Sediment Rating Curve (1964-93)
Khowai River at Shaistaganj

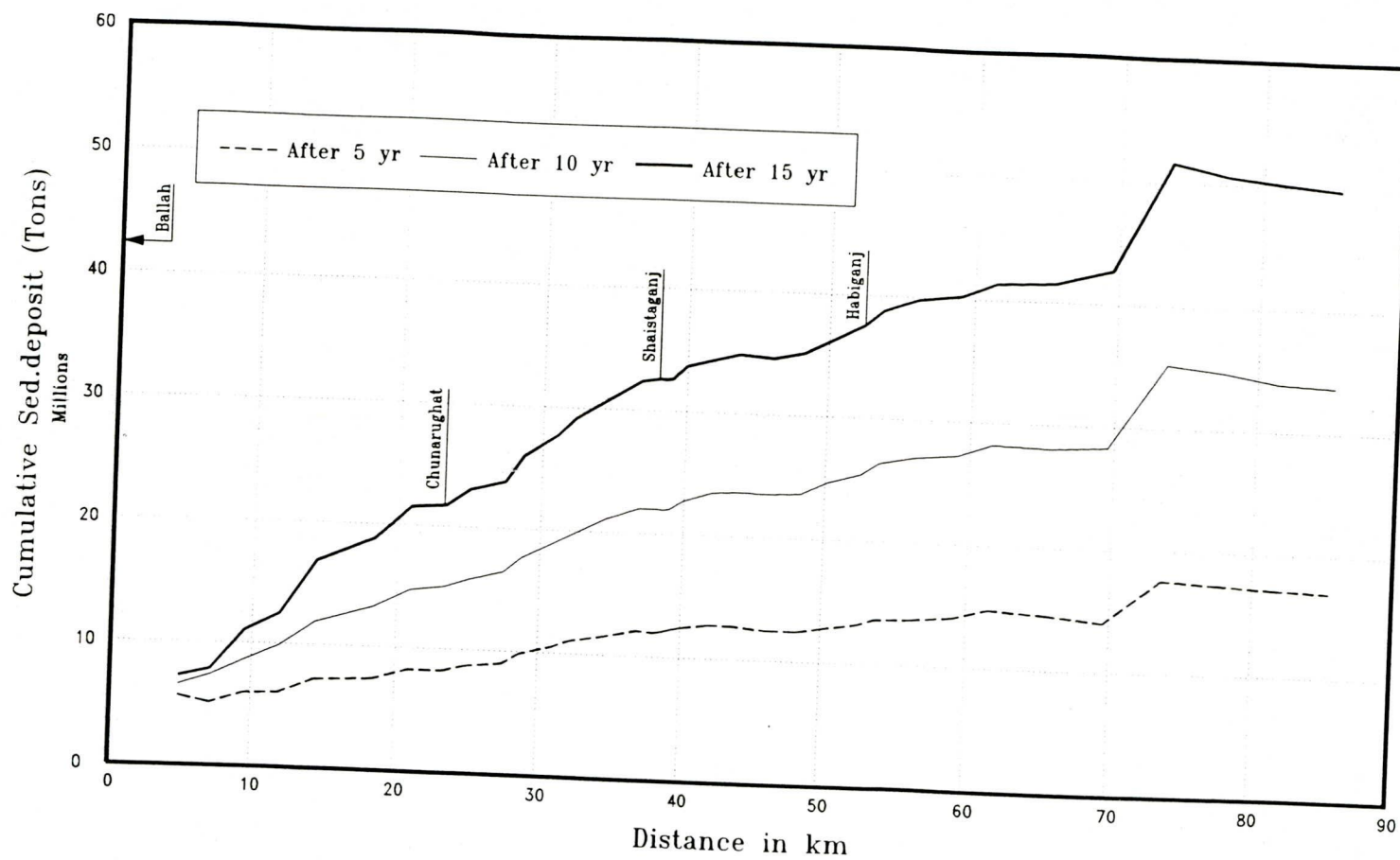


Figure 4.30: Cumulative Sediment Deposition in Khowai River

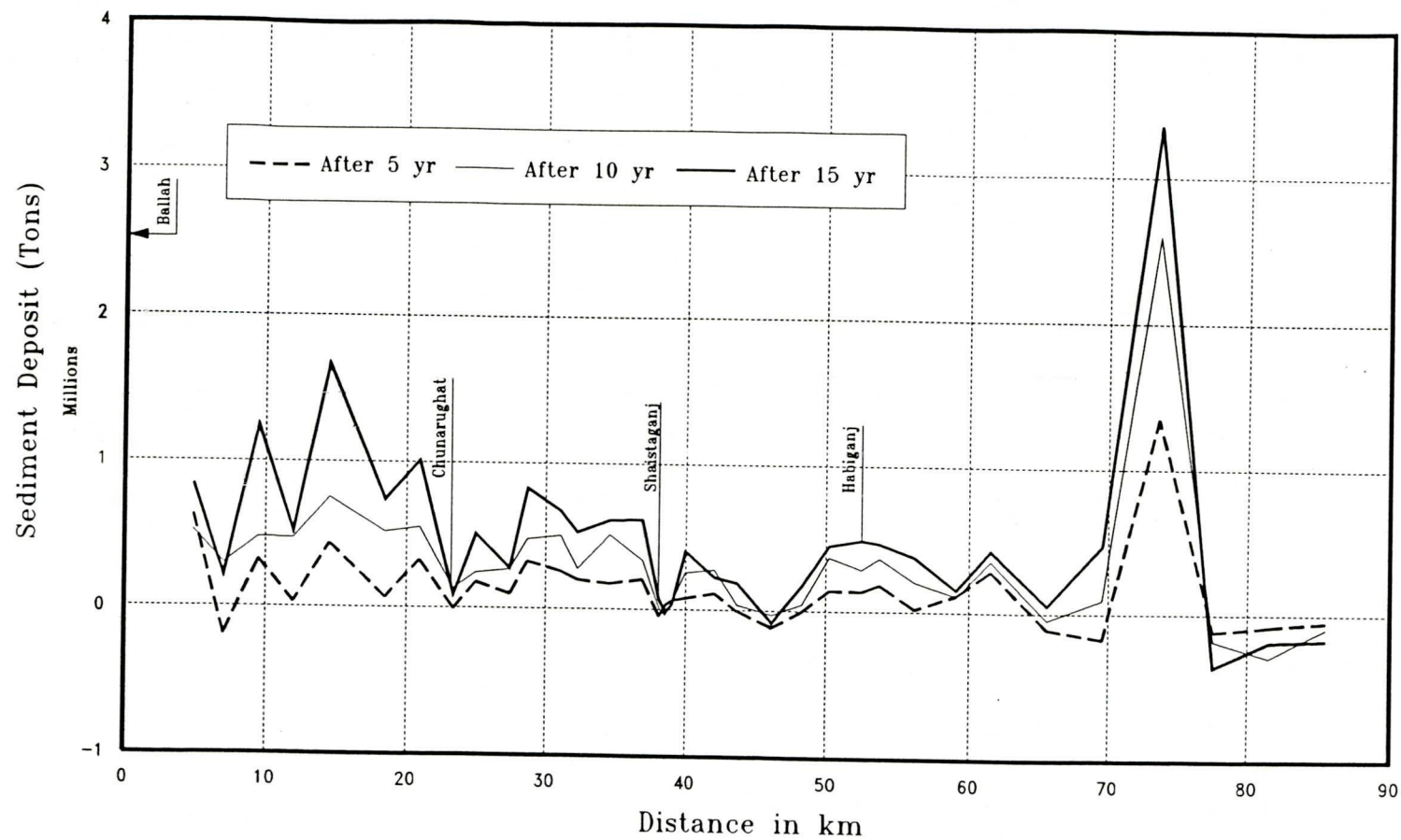


Figure 4.31: Sediment Disposition in Khowai River

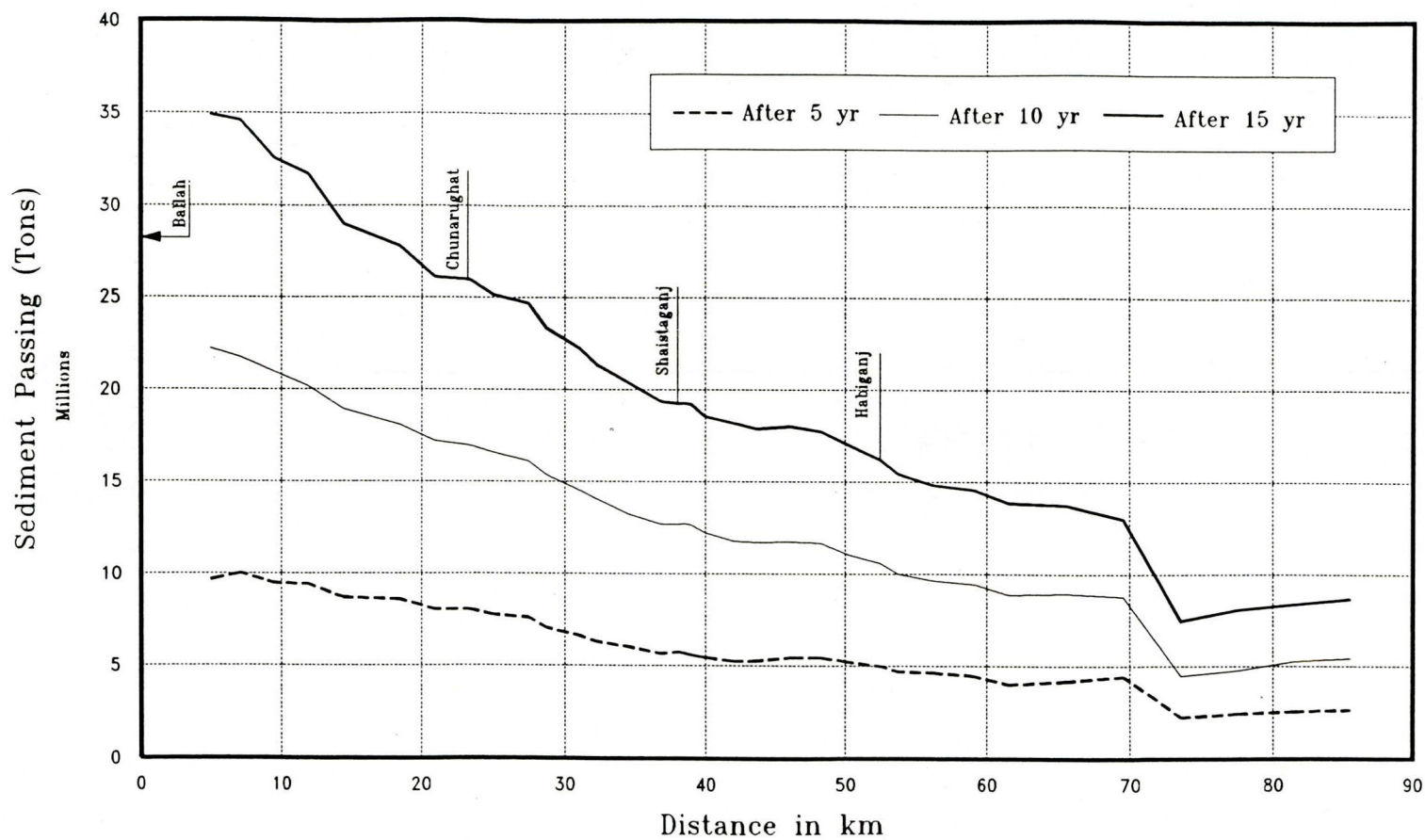


Figure 4.32: Sediment Passing along Khowai River

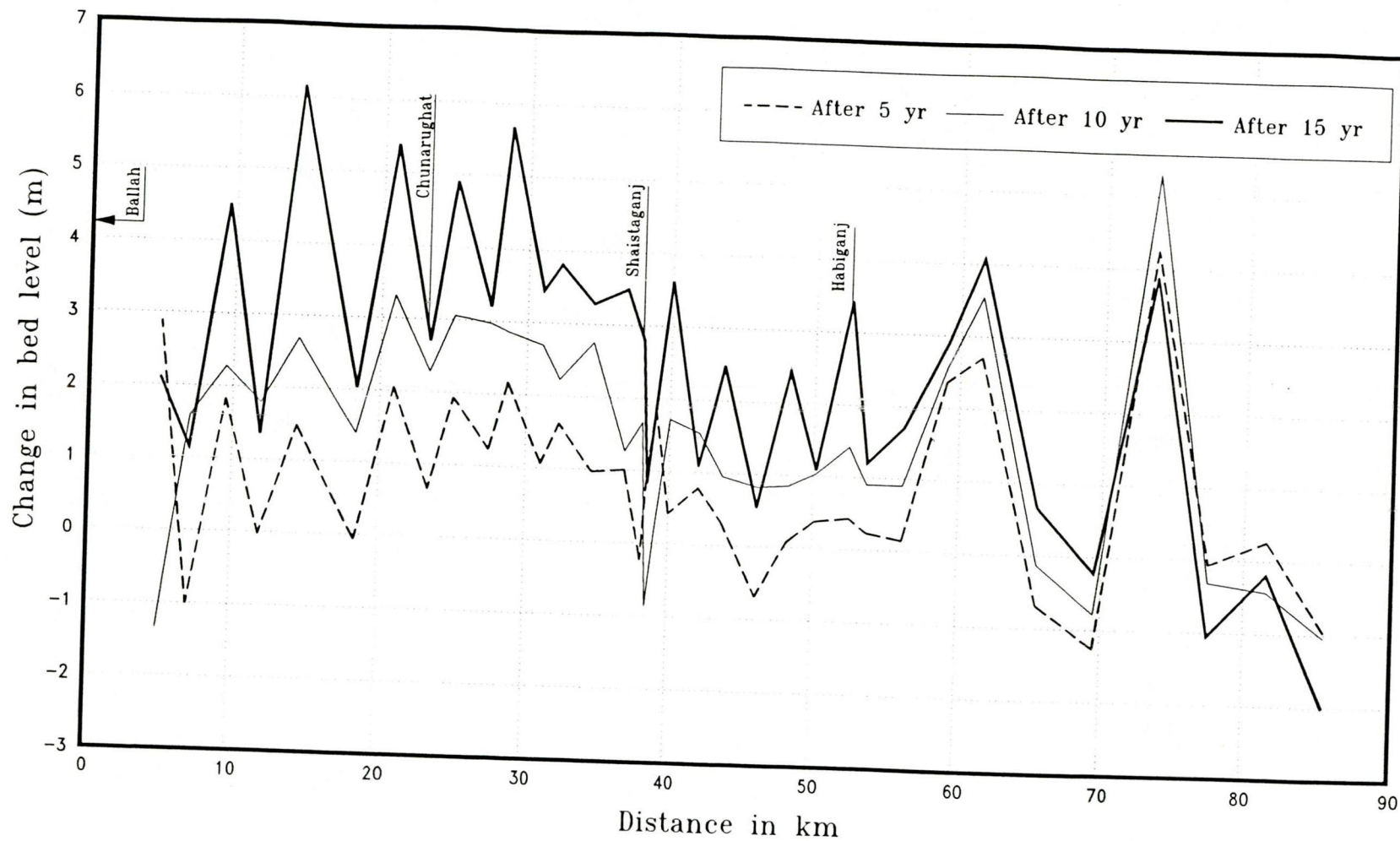


Figure 4.33: Thalweg Changes along Khowai River

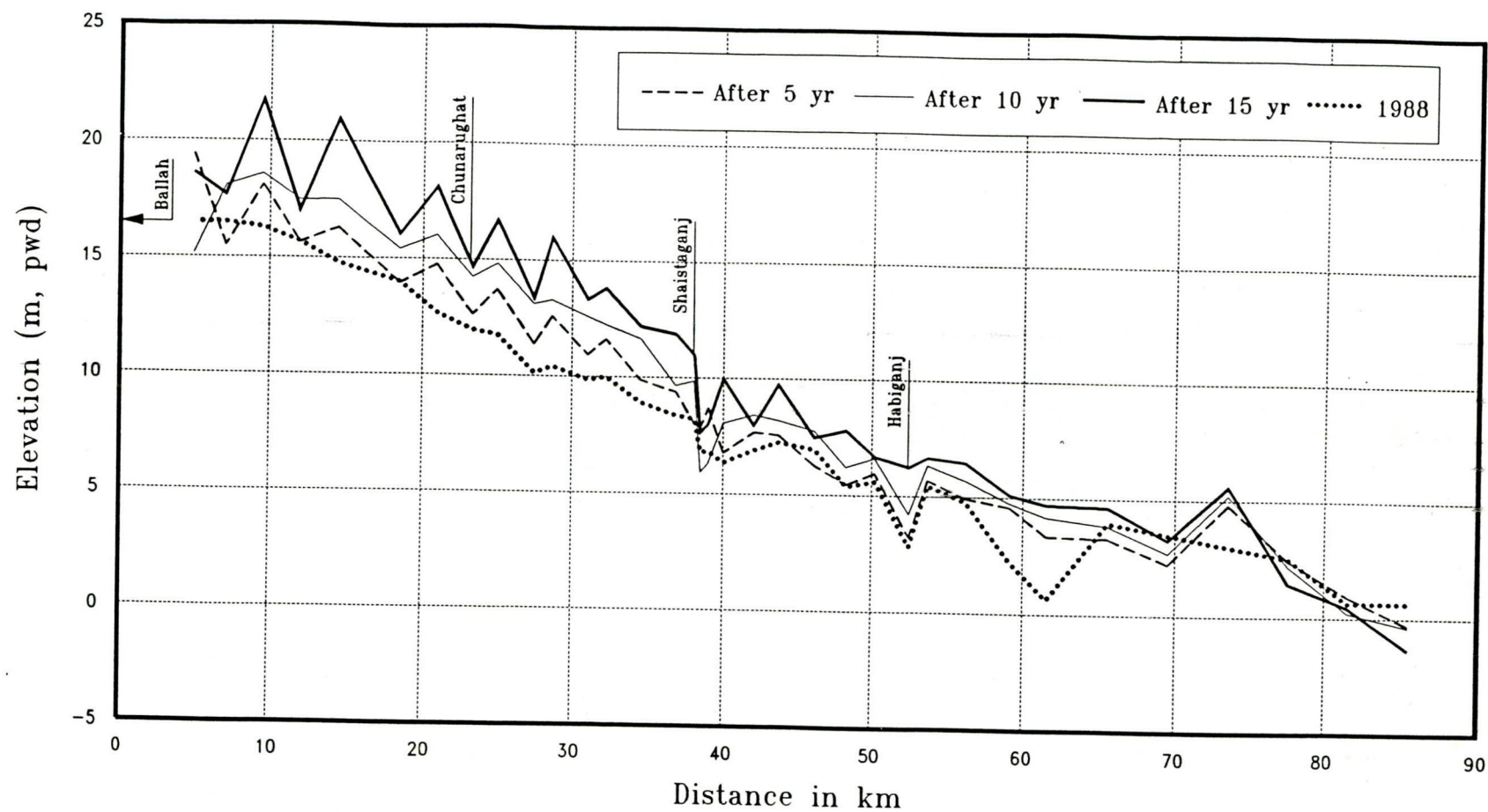


Figure 4.34: Thalweg Profiles of Khowai River

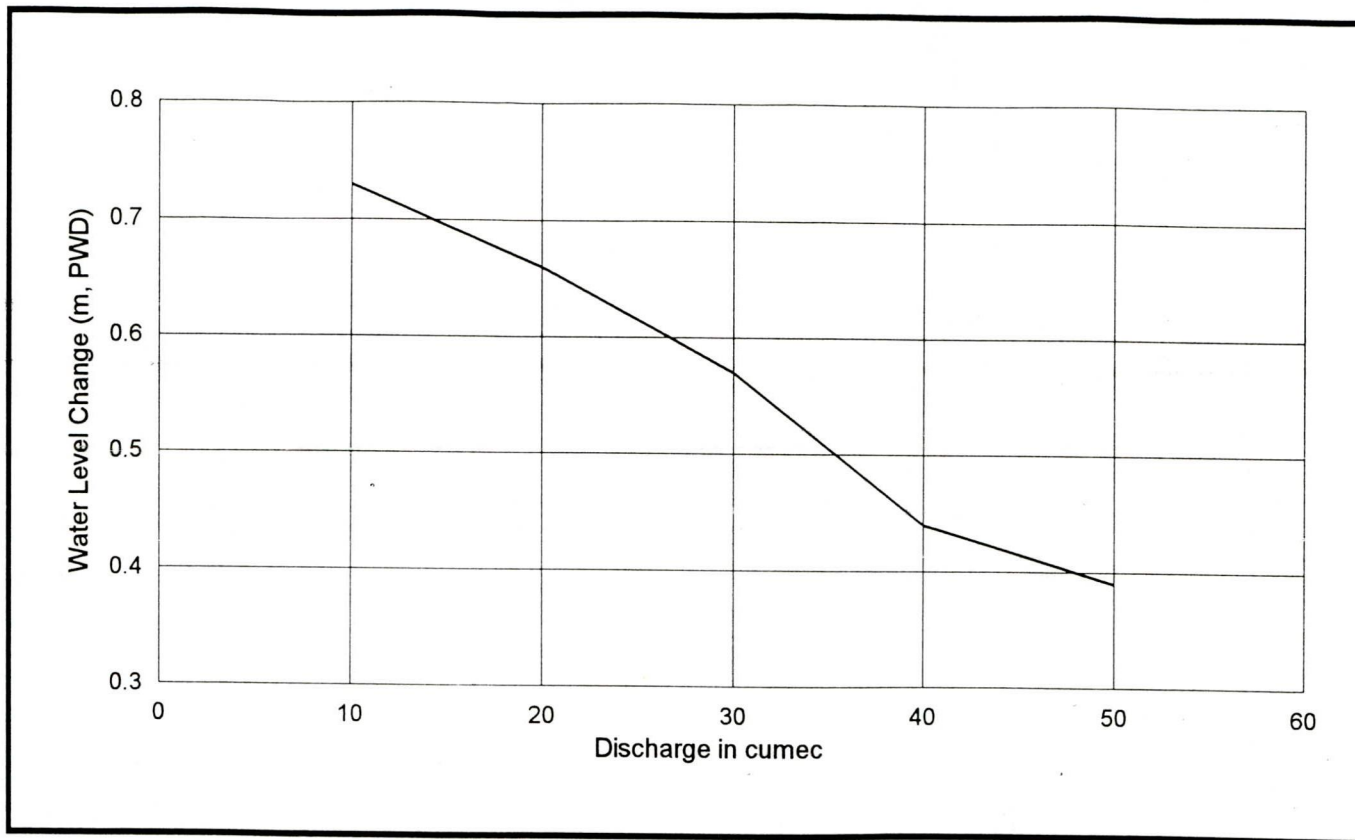


Figure 4.35: Changes in Water Levels with Increased Discharges at Shaistaganj

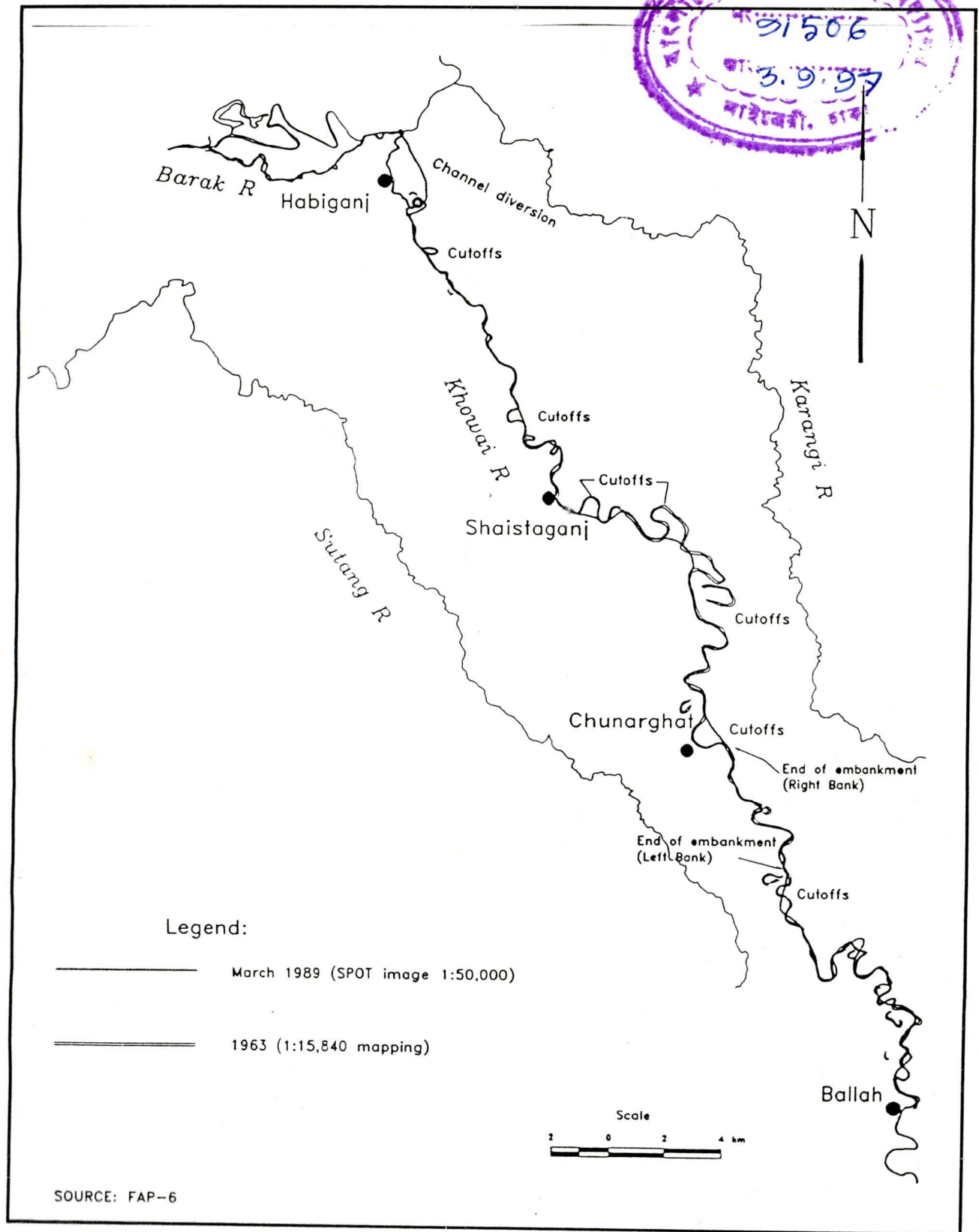
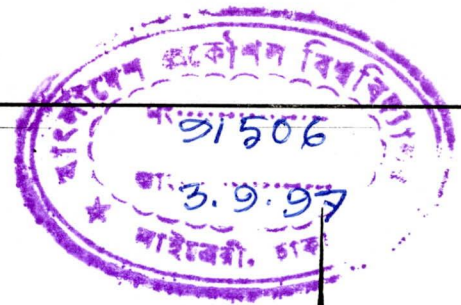


Figure 4.36: Channel Changes along Khowai River