EFFECTS OF BOULDER LIFTING ON THE FLUVIAL CHARACTERISTICS OF LOWER BALASON BASIN IN DARJEELING DISTRICT, WEST BENGAL

A Thesis submitted to the University of North Bengal

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BY
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DECLARATION

I declare that the thesis entitled "*Effects of Boulder lifting on the fluvial characteristics of the lower Balason basin in Darjeeling District, West Bengal*" has been prepared by me under the guidance of Dr. Deepak Kumar Mandal, Associate Professor, Department of Geography & Applied Geography, University of North Bengal. No part of this thesis has been formed the basis of award of any degree or fellowship previously.

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CERTIFICATE

I certify that, Lakpa Tamang has prepared the thesis entitled "*Effects of boulder lifting on the fluvial characteristics of the lower Balason basin in Darjeeling District, West Bengal*", for the award of PhD degree of the University of North Bengal under my guidance. He has carried out the work at the Department of Geography & Applied Geography, University of North Bengal.

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ABSTRACT

Almost all the rivers originating from the Darjeeling Himalayas have witnessed changes in its behaviour either due to natural (tectonic, catastrophe) or by increasing human interferences with changes in land use pattern. Degradation, channel shifting, lateral erosion, changes in bed form and sediment distribution are common amongst these rivers, thereby forcing the rivers to adjust within the changing environment. Human interferences with increasing pressure over the existing natural resources of the region has also been responsible for the change in the competency and capacity of these rivers. The use of region’s water resources for various human needs and also the gradual encroachment of adjacent lands is a common scenario in this region. Although the available water resources of the region are adjusting with the growing demand from increasing population, the equilibrium in this supply-demand is sometimes disrupted in order to fulfil the never ending needs of human beings.

From the source area till its confluence, the Balason river faces acute anthropogenic problems, ranging from deforestation, landslides, unplanned and unscientific construction of settlement and roads to innumerable reckless usage of land and water resources. The fluctuating discharge, excessive bed load supply and highly erodible banks have resulted in braided nature with ephemeral bars in its lower course. This has restricted the free passage to an excessive amount of run-off during heavy and concentrated rainfall causing floods in its lower segments. High intensity rains induced landslides and high surface run-off in its upper catchment also provides huge quantities of weathered materials as sediment load which are being deposited in its lower course. These materials can easily be extracted directly from the river bed and due to its corrosive nature do not require much processing. Hence, the bed materials from the lower Balason river has become an ideal source of demand for growing construction industries of the region as well as the neighbouring districts and states.

The common practice of extracting the bed materials along the lower Balason river is a traditional one with labours still using their physical strength

and few tools for extraction process is dependent upon its size, amount and quality of bed materials available. During the dry period, the entire stretch of lower Balason river seems to be like a mining site with the entire river bed as well as adjacent terraces and flood plains are excavated up to 2 m for extracting the deposited bed materials. But during monsoon period, this activity ceases to the near bank locations, since the high flow of the river disrupt the in-bed extraction. Although the near bank extraction continues, mostly boulders and sands are extracted, but during this period the labours collects the larger materials brought down with monsoon flows and are broken into different grades.

Presently, the extent and intensity of bed material extraction in the lower Balason river have taken such a dimension that it needs immediate attention to manage the associated effects on its form and processes. The problem though seems local, proper management is very much essential both in the lower course as well as the upper catchments of the Balason river. The continuous extraction inducing lowering of bed elevations and resultant bed erosion and also lifting specified size gravels and leaving behind the smaller one thus disrupting the sediment transportation and distribution have resulted into head ward erosion which is being transformed into its upper segments beyond the margins of the lower plains. The adjustment by the river in the form of scouring and filling have also resulted into undercutting below bridges and embankments due to narrow channel width causing retention of flows. Besides, human settlements near the banks and adjacent flood plains for easy access to river bed and also construction of roads near banks for transportation of extracted bed materials have reduced the vegetation thus triggering the exposed banks to retreat further resulting into loss of nearby agricultural lands, tea garden and even residential areas in few sites.

Although the concerned authorities have formulated different prohibitions but their proper implementation has not taken place due to callousness of the authority and the role played by the permit-holders as middle man. The people dependent upon such activities are not concerned about the ultimate effects and with more demand from local markets; the illegal extraction is a common practice. Extraction of bed materials from below the bridges and embankments although have been prohibited but in reality the extraction are done as per the convenience of loading and transporting of the extracted materials. Hence, an overall assessment should be under taken based on the river adjustment of its fluvio-geomorphic characteristics. Such an integrated assessment of river modifications will help resource management decisions including protection of its fluvial characteristic so that the boulder lifting activities does not jeopardise the sustainability of other appropriate river users and values. This could be possible by implementing long term management plans with proper understanding and management of sediments at basin level and a wider application of the available scientific knowledge, particularly of fluvial geomorphology and hydraulics.

PREFACE

River systems are complex entities that adjust their channel geometry and shape to different hydrologic and sediment regimes in order to establish or maintain an equilibrium state. This equilibrium state is maintained by adjustments in multiple factors, but mainly channels morphology, discharge, sediment transport and capacity at varying spatial and temporal scales. Stream channels rarely achieve this state of equilibrium due in part to constantly having to adjust to variations in its form and processes and human-induced changes.

Balason basin has been degrading due to increasing human transformations but, if proper management planning is formulated, it has lots of potentialities and scope for development. In its upper catchments, the acute anthropogenic problems ranging from deforestation, landslides, unplanned and unscientific construction of settlement and roads to innumerable reckless usage of land and water resources followed by extensive bed material extractions and human occupancies in its lower course has been largely responsible for the changing fluvial characteristic. The continuous extraction inducing lowering of bed elevations and resultant bed erosion and also lifting specified size gravels and leaving behind the smaller one thus disrupting the sediment transportation and distribution have resulted into head ward erosion which is being transformed into its upper segments beyond the margins of the lower plains.

As such the researcher has made an attempt in this dissertation to correlate the existing fluvio-geomorphic adjustment of the Balason river for evolving the long term management strategies for maintain sustainability of the available resources and its fluvial environment.

For the proper presentation of this long pursuit, I would like to thank my supervisor Dr. Deepak Kumar Mandal for the real autonomy he has given to me, so that I could explore the topic and enrich my own ideas. I express my sincere thanks to my parents, my wife and all the family members for all their sacrifices they have made in supporting and motivating me through all the difficult times.

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Date: **(Lakpa Tamang)**

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CHAPTER 1

Introduction

1.1 Introduction

The 20^{th} century development pattern in the Darjeeling hills has been responsible for the depletion of forest cover, increased export of medicinal plants, construction of water resource works, exploration and mining of minerals, enhanced tourism, introduction of commercial farming, and urban industrial growth in the foothills. The rapid growth of population since 1901 has steadily changed the land use pattern of the region as well as its pattern of utilization of available natural resources. The British established the Tea plantations and provided an opportunity for the local inhabitants to harness its natural resources. In these processes, the water resources from Teesta, Mahananda, Balason, etc supported the basic needs of the region. Since these rivers brought down huge bed loads from its upland catchment, mostly during the monsoon flush the river's run-off and high flows brought down million tonnes of bed materials which are deposited in its lower segments, thus providing an ample scope for local inhabitants to extract the deposited bed materials.

The heavy and concentrated rainfall (2000-2500 mm) and subsequent high surface erosivity and frequent landslides have favoured the Balason river to bring large quantities of bed materials to be deposited by the river in its lower course. These materials could be easily extracted directly from the river bed due to its corrosive nature and requires not much processing, thus providing an ideal source for growing construction industries of the region. However, the extensive extraction from the river bed in unplanned and unorganized manner is disturbing the form and processes of the Balason river. In order to adjust to the locally steeper gradients produced by extraction pits, the stream power has increased resulting into bed erosion. Similarly, the near-bank extraction is causing incision, thus increasing the bank heights and also diversion of main flow is wearing away the exposed banks during monsoon high flows.

1.2 Review of Literatures

Commercial bed material extraction from alluvial rivers is a global phenomenon, particularly intense in countries subject to rapid urban and industrial growth over recent decades and lacking alternative sediment sources. Extensive reviews, mainly focused on rivers of the USA, began to be published by Collins and Dunne and Kondolf in 1994, 1997), and specific recommendations for sediment management have been more recently proposed by Church et al., 2001 for the Fraser River, Canada. Although in some countries (e.g. France, Italy, Poland) bed material extraction has been limited or formally prohibited over recent decades, the demand for sediment exploitation is still continuing, and permissions are often granted under the motivation of flood control.

In India, despite of several prohibitions imposed by the authorities, the problems of sediment extraction from river beds are a common phenomenon in almost all major rivers and till now beside few studies no extensive study has been done to highlight this issue. In Madhya Pradesh the major rivers like Narmada, Chambal, Betwa or Wainganga or numerous rivulets and streams all are being ravaged for their sands. Also in many other states, like Gujarat, Karnataka, Tamil Nadu, Maharashtra, West Bengal, etc unchecked illegal sediment extraction is of serious concern without any strict phrobitions and scientific regulations. Some studies on impacts of sand and gravel extraction from river beds have been made in different states namely Gujarat by Patel (1985), Tamil Nadu by Viswanathan (2002), in Karnataka by Chandrasekhara and Hemalatha (2005) and in Andhra Pradesh again by Chandrasekhara (2006). In Kerala impacts of sand extraction was studied in several rivers like Bharathepuzha River (Aravindan, 2002); Manimala River (Nair, 2003); Kallada River (Ignatius Pereria,2004); Pumba River (CESS,2004); Vembanadu Lake (Padmalal, 2008) etc.

The Darjeeling Himalayas being a fragile terrestrial system have encouraged many studies and investigations of its typical geological, geomorphological, climatic and fluvial characteristics by researchers, government authorities and engineers. One of the first attempts of scientific study in this region was made by Hooker, (1854). During his two years of long travel (1848-1849), he traced the regional domal picture of gneisses and observed the overlying sedimentary bedding. According to him, these formations originating from glacial or glacio-fluviatile processes are cut into flat topped terraces, flanking the spurs of the mountains. He studied such stratified sand and gravel terraces, flanking the Balason river. Mallet (1874), Gansser (1964) and Bose (1990) also made detailed investigations on the geological and mineral characteristics of the region. The work of Geological Survey of India in this region began with the studies of the metamorphism of the rocks of Darjeeling area by Roy (1947) and also detail geological mapping by Ghosh (1950) and Dutta (1951) in his studies on landslips in Darjeeling observed that except the ridge top no portion of the Darjeeling town is absolutely stable. Nakata (1972) made detail survey of terraces and alluvial fans between Balason and Chel river while studying the geomorphic evolution of the mountain front of the Darjeeling Himalaya and crustal movements.

The investigations of development of alluvial fan in the foothills of Darjeeling Himalayas was studied by Basu and Sarkar (1990) in which the geomorphological and pedological characteristics of the region along with the role of rivers like Balason, Mahananda and their tributaries in the evolution of alluvial fan spread over the vast Terai plain of North Bengal has also been mentioned.

Several case studies has been included by Starkel and Basu, (2000), to demonstrate how such a dynamic fluvial system works in this deforested mountain of the monsoonal zone and also the frequency and the role of extreme precipitation in causing catastrophic damage over slopes and on the flood plains has been analyzed in detail. Similar attempt was also made by Starkel and Sarkar (2008) to show the role of tectonic activities, river catchments, extreme rainfall and floods clustering and also the human activities in present-day evolution of the Sikkimiese-Bhutanese Himalayan piedmont.

Jana (1997) in his study about the river basins in North Bengal and changes in land use and flood affected areas, drainage pattern and river courses through satellite imageries and topographical maps has stated that the river basins of North Bengal are susceptible to floods, soil erosion and landslides. So, flood hazard zonation, flood control and its treatment and soil conservation are some of the effective measures for river basin development and management in North Bengal. Restrictions on further infringement on the hill slopes and river beds will help in reducing the flood frequency and soil erosion. Human activities in the hills as well as in the plains of North Bengal are also responsible for all the hazards prevailing in the river basins of the region. So an integrated development plan for land and water resources involving local population is urgently required to manage the major rivers in this region.

The Balason river has also been a important river in the context of fluvio-geomorphological studies carried out in this region due to its dynamic nature and also the anthropogenic transformation with changing land use and region's carrying capacity. Dutta (1995) studied the changes in river behavior considering the channel adjustment under human modifications, gravel extraction from the river, rising of embankments and adjustment under the bridges. He has concluded that the hydraulic responses of the river Balason to the conditions induced by man through their activities are quite alarming. The aggravating river bed, the migrating channels and the retreating banks pose a severe threat to the riparian population downstream for which an immediate attention is necessary.

Jana and Dutta (1995) carried out detail study of the causes and rate of bank erosion along the right bank of Balason river while understanding their relationship with the lithological composition of the bed and bank materials and their impact on the riparian dwellers. The authors have found that the floods are not solely responsible for bank erosion in Balason river but shifting of river channel is responsible for high rate of erosion which is accelerated by extraction of bed materials from the river bed. Hence, the authors have suggested controlling the rate of extraction of bed materials from the river in order to check bank erosion.

Basu and De (1998) studied the nature and amount of soil loss calculated on the basis of FAO/UNEP, USLE, and USDA methods with a view to formulate proper measures for the conservation balance of the Balason basin.

The authors have identified 5 vulnerable zones, among which the zone falling between 600-1800 m has been identified as most susceptible to soil erosion mostly due to high rainfall, fragile geological structure, deforestation and unscientific use of the land ever growing population. In order to control the annual rate of soil loss, the authors have identified several conservative measures depending on the rate of soil loss (kg/m^2/year) which must be adopted without further delay to maintain the natural balance within the Balason basin.

The annual water resources of the basin and its seasonal distribution and conservation was studied by De (2007) in which the author has estimated the water resources in two different ways: (i) by the estimation of run-off empirically from the long term average rainfall and temperature data of 21 stations within Balason basin using Khosla's method,1950, and, (ii) by the estimation of run-off from the daily discharge data of 6 consecutive years (1989-94) at Matigara (near NH 31). The analysis of rainfall, run-off and discharge reveals that the long term empirical estimation of the total surface water yield is 764.422 mill.m^3, whereas, it is amounting to 931.822 mill.m^3 according to the 6 years average of the actual discharge through the river. The findings from this study stresses the need for suitable ways and means for the proper utilization of such water resources for which the author focuses on construction of check dams across the river at suitable sites to reserve the monsoonal supply for redistribution during draught periods.

The quantitative characteristics of the long and cross profiles of the river Balason was studied by De (2010) to follow the exact sequence of activities along the long profile of the river from its source to the confluence, a quantitative study by fitting exponential curves has been experiment with by the author. In order to study the changing nature of the channel bed and specially the impact of huge flood water on the channel form, the author have conducted a detailed survey of the cross-profiles in both monsoon and non-monsoon period for 6 years (1989-94) at 3 different sites. The findings reveals that the epirogenic history of the basin have been characterized by intermittent uplifts of the Himalayas interrupting the smooth running of a cycle of erosion and thereby, produced a number of sub-cycles along the long profile of the river demarcated by definite break in slopes. The study of cross profiles reveals no definite trend of change of the channel with alternate filling and scouring of the channel.

Many researchers have carried out their Ph D dissertations on the changing geomorphic and fluvial nature of the region. Among them, Sarkar (1983) conducted detailed study on Geo-environmental appraisal of the upper Mahananda basin of the Darjeeling Himalaya, Ghatowar (1986) studied the fluvial dynamics of the twin basins of the river Lish and Gish, Bhattacharya (1993) carried out a comprehensive study on the problem of management of the Rakti basin, De (1998) made detail study of the fluvial dynamics of Balason river and Lama (2003) also studied the environmental geomorphology in the Balason Basin.

1.3 The Study area

The Funnel shaped Balason basin has its source from a place named Lepchajagat, located on the Ghum-Simana ridge at an altitude of 2361 m and with latitude of 27˚03´55˝N and Longitude of 88˚14´12˝E. It is the major right bank tributary of Mahananda river covering an area of 367.42 km^2. The Balason being a perennial river has a total length of about 48.4 km of which 24.27 km is in the hills and remaining 24.13 km flows in the plain region. The right bank tributaries of Balason river are Pulungdung Khola, Rangbang Khola, Marma Khola, Manjwa jhora and Dudhia jhora. The left bank tributaries are Bhim khola, Rangmuk khola, Pachhim khola, Rinchigtong Khola and Ghatta Hussain Khola. At an altitude of 305 m, Balason river starts its lower course (figure 1.1) and from this area onwards mostly transportation and deposition by the river could be noticed. In its lower course, the river is joined by Rakthi khola, Rohini Khola, Panighata Khola, Chenga, Manjha, etc. It finally mixes with the Mahananda river near Siliguri town (latitude 26˚48´37˝N and longitude 88˚18´30˝E).

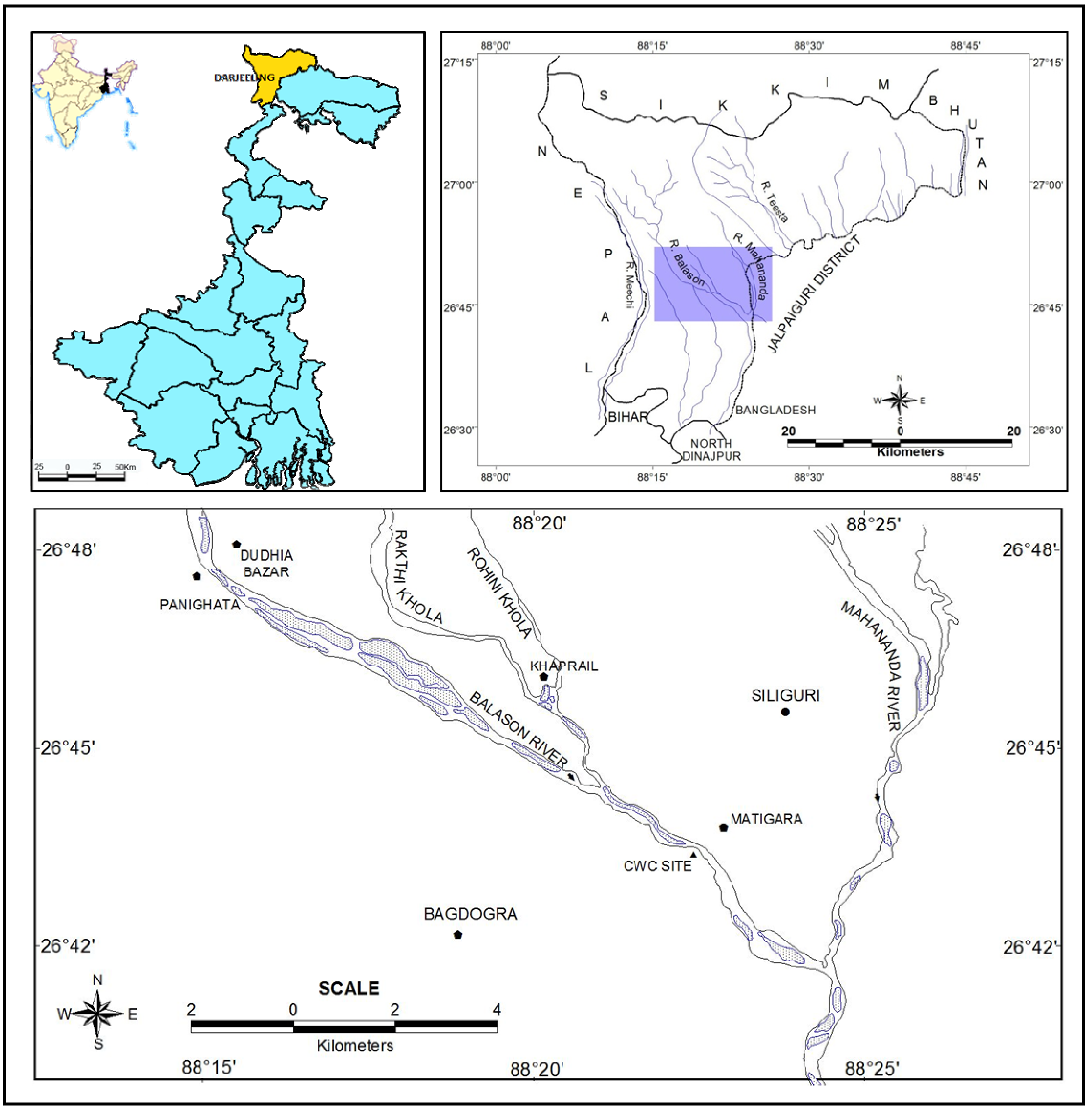


Figure 1.1 Location of the study area showing the lower course of Balason river with its two major tributaries, Rakthi and Rohini khola.

1.4 Problems of the Study Area

From the source area till its confluence, the Balason river faces acute anthropogenic problems, ranging from deforestation, landslides, unplanned and unscientific construction of settlement and roads to innumerable reckless usage of land and water resources. Due to massive surface run-off and occasional landslides resulting from heavy downpour and loss of surface vegetation in its source region, the river Balason carries huge amount of sediments to be deposited in the plain section of its course. This in turn results in the rising of river bed and excessive siltation in its lower reaches.

The soil erosion due to unchecked surface run-off also has reduced the water holding capacity leading to floods in its lower reaches.

As the river starts its lower course from the piedmont zones along the margins of vast alluvial fan, slowly the transporting capacity of river ceases and the Balason river attains the braiding pattern. The width of the river increase as it proceeds downstream with the resultant fall in gradient providing greater scope for lateral migration of channels. Also human induced activities of lifting brought down sediments ranging from medium to large sized boulders to fine sands in unplanned and unorganized manner are creating havoc to the river form as well as its mechanism. Such removal of bed materials not only produces localized effects on the river, but their effects are transmitted a considerable distance upstream and downstream much beyond the area of initial impact. It has been observed by M. Dutta during his field survey in 1995, that extraction near the banks has caused the channel shift towards the banks and erosion of banks as well. These activities at some sites are also causing varied flow, width and carrying capacity of the bed materials of the river. As a result only medium to finer sediments are carried below such sites which in turn affect hydrological condition of the whole basin.

1.5 Hypothesis of the study

i. Lifting of bed load sediments from river bed disrupts the balance between sediment supply and transportation capacity resulting in incision of upstream and downstream from the removal sites.
ii. Effect of scour and fill action resulting from boulder lifting activities creates a deficit in sediment flow which in turn results in bed degradation and change in channel morphology.
iii. Channel incision can also cause lateral instability by increasing stream bank height, resulting in bank failure and additional transport of sediment downstream.

1.6 Objectives of the Study

The following objectives were taken into consideration to study the effects of boulder lifting activities along the lower Balason river:

i. The physical characteristics of the whole Balason basin have been considered in detail for better understanding of its fluvio-geomorphic conditions.
ii. The fluvial characteristics of the lower Balason river keeping in view its morphology and hydraulic parameters are studied in detail.
iii. Detail observation of the nature and extent of boulder lifting activities along the lower course of the river Balason.
iv. The study of mechanism of sediment transport and the effect of boulder lifting especially in its lower course
v. The study of bank erosion in the lower course of the Balason river and also to analyze the effect of boulder lifting on bank failure.

1.7 Methodology followed for the study

In order to bring a reasonable outcome of the attempted study, a rationalistic methodology including quantitative assimilation of fluvio–Geomorphologic parameters of the study area has been followed.

For the physical set up of the Balason river such as Geomorphology, Geology, Land use, Soil and Climatic conditions, basic data and related maps has been prepared with the help of the Survey of India topographical maps no. 78 B/1, B/5, B/6, A/4 and A/8 (1:50,000) and also maps published by Forests Department and Government Land Reform Departments. The Geological Survey of India records, Satellite Imagery, research articles and reports published has been consulted for gathering the necessary secondary data.

In order to properly analyze the fluvial characteristics of the Lower Balason river, the long profile of the whole Balason river has been prepared with the help of the available SOI topographical maps, measuring the distance between two successive contours from the source of the river (Lepchajagat) till its confluence with Mahananda. Cross–sections along the entire lower course (24.13 km) has been surveyed during pre-monsoon and post monsoon periods with the help of Dumpy level at pre-determined sites at intervals of 200 m and 500 m respectively from 2008-2010. For better analysis of the bed-form morphology, during cross section surveys channel flow conditions are also incorporated with the help of the Central Water Commission (CWC) R. L of 119 m.

Various hydrological data like velocity, discharge, width, depth, and flow characteristics were measured directly from the field and also has been compared and validated with the data collected from the CWC Gauging & Discharge Site, Matigara . Data relating to morphology and hydrology has been computed and analyzed on daily, monthly and annual basis for depicting any changes of its form and processes that may correlate to spatial channel adjustment. Such processed data are interpreted with suitable statistical analysis, such as Correlation and regression analysis. For the study of flood magnitude analysis, the annual peak discharge from 1989-2010 obtained from the CWC G&D Site, Matigara (near NH 31) have been the used following the Gumbel's distribution. The Bank-full discharge condition during monsoon months has been documented and analyzed with photographs.

Extensive field work has been carried out along the entire lower course of the Balason river (24.13 km) for in-depth study of the nature and extent of boulder lifting. In order to estimate the actual amount of materials extracted, the number of trucks carrying extracted materials from the river have been recorded from different sites along with the official records of check posts and Land & Land Reform offices. The offices maintaining such records within which the study area falls has been visited and available data has been collected form 2002-2010.

Sediment size sampling of bed sediments (> 2 mm diameter) were done at 1 km interval throughout the lower course of Balason river to get an idea of sediment distribution and sediment sorting along the lower course of Balason river. The Grid sampling method is used following the Wentworth table of sediment classification. Sediment transport mechanism has been studied by considering slope, flow velocity and resultant forces and modified Einstein method (1955).

Nature, extent and causes of bank failure in the lower course of the river have been studied. The bank erosion rates were observed following the monsoon season and the recession or further erosion after monsoon flush were compared with the pre monsoon bank conditions with reference to selected permanent structures (houses, roads, pillars, trees, etc) along the bank line. Bank line survey using GPS has been done along the lower Balason river before and after monsoon period and the obtained results were also compared with past bank condition by superimposing over available satellite imageries.

The GIS softwares (Global Mapper, Map Info, Arcview GIS) and GPS has been used for preparing the necessary maps and the data relating to location and elevations to represent the proper results and field information. For tabulation, analysis and diagrammatic presentation of data, the MS Excel and Origin (data and graph analysis software) has been used. The photographs incorporated to validate the obtained results were edited and arranged using MS Paint & Office picture manager, Photoshop and CorelDraw.

To compile the bibliography for the present work, literatures and available information from the libraries of North Bengal University, Geological Survey of India, Calcutta University and National Library, Kolkata have been collected. All the collected data from the field and various institutional and other sources have been computed and processed in the Department of Geography & Applied Geography, University of North Bengal to predict the actual fluvial environment and to suggest the corrective remedial measures for scientific and appropriate management for reducing the effects of boulder lifting activities along the lower Balason river.

CHAPTER 2

Physical set up of the Balason basin

2.1 Introduction

The physical configuration of the Balason basin is largely dependent in its geologic structure, being the controlling factor in evolution of landforms. The resultant physical environment in the region is due to different geomorphic processes, each of which has developed its own characteristic assemblage of landforms. There are no flat valleys, no plains, no sizable lakes nor any cultural landscape except where virgin forests have yielded place for tea gardens or terraced fields. The main uplands wrap around and give-off spurs of second & third order in all directions. The valleys thus formed, presents a great variety in climate and elevation.

In this chapter, the physical set up of the Balason basin has been attempted to visualize the nature and extent of variations in landform characteristics. Mostly the Survey of India topographical maps and also available published literatures has been used for the detail study of about the geology, geomorphology, natural vegetation, soils, climate and land use pattern.

2.2. Geology of the Balason basin

The geology of the Balason basin is of complex formation with four major formations extending in N-S direction (Table 2.4.1.). The major portion of the basin (59%) is composed of Archaean formations with Darjeeling gneiss and Daling series rock type covering almost more than half of the total basin starting from the northern limit. The Darjeeling gneiss varies in texture from a fine grained to moderately coarse rock with dips ranging between 24° and 55° towards N-S and NW-SE. The Daling rock series follows the Darjeeling gneiss towards the south with dips of 30° to 80° towards N and NW.

Geological periods	Geological structure	Age (million years)	Type of rocks	% of Area occupied in the basin
Archaean	Darjeeling gneiss	3800	Carbonaceous mica-schists, Granetiferous mica-schists, golden-silvery mica-schists and coarse-grained gneiss.	48%
	Daling series		Phyllites surrounded by the pebbles of Quartz, slates (greenish to grey with perfect slaty cleavage), Chlorite-sericite schists with bands of grilty schists injected with gneiss, tourmaline & iron occur as accessories. Granites, pegmatites and quartz veins.	11%
Thrust Fault				
Permian	Damuda series (Lower Gondwana)	280	Quartzitic (hard & soft) sandstones with slaty bands, shales and slates, semi-anthracitic (graphitic) coal, Lamprophyre silts and minor bands of limestone.	3%
Thrust Fault (Main boundary fault)				
Miocene or Lower Tertiary	Nahan group; Lower Siwalik deposits	26	Soft greyish sandstone, mudstone, shales and conglomerates along with the bands of limestone, Shale and lignite.	7.5%
Himalayan Front (Tectonic line)				
Pleistocene or Sub-recent to recent	Alluvium (older & recent)	2	Boulder beds and other sands and gravels, drift formation and younger flood plain deposits comprising sand & gravel, pebbles, etc.	19.5%

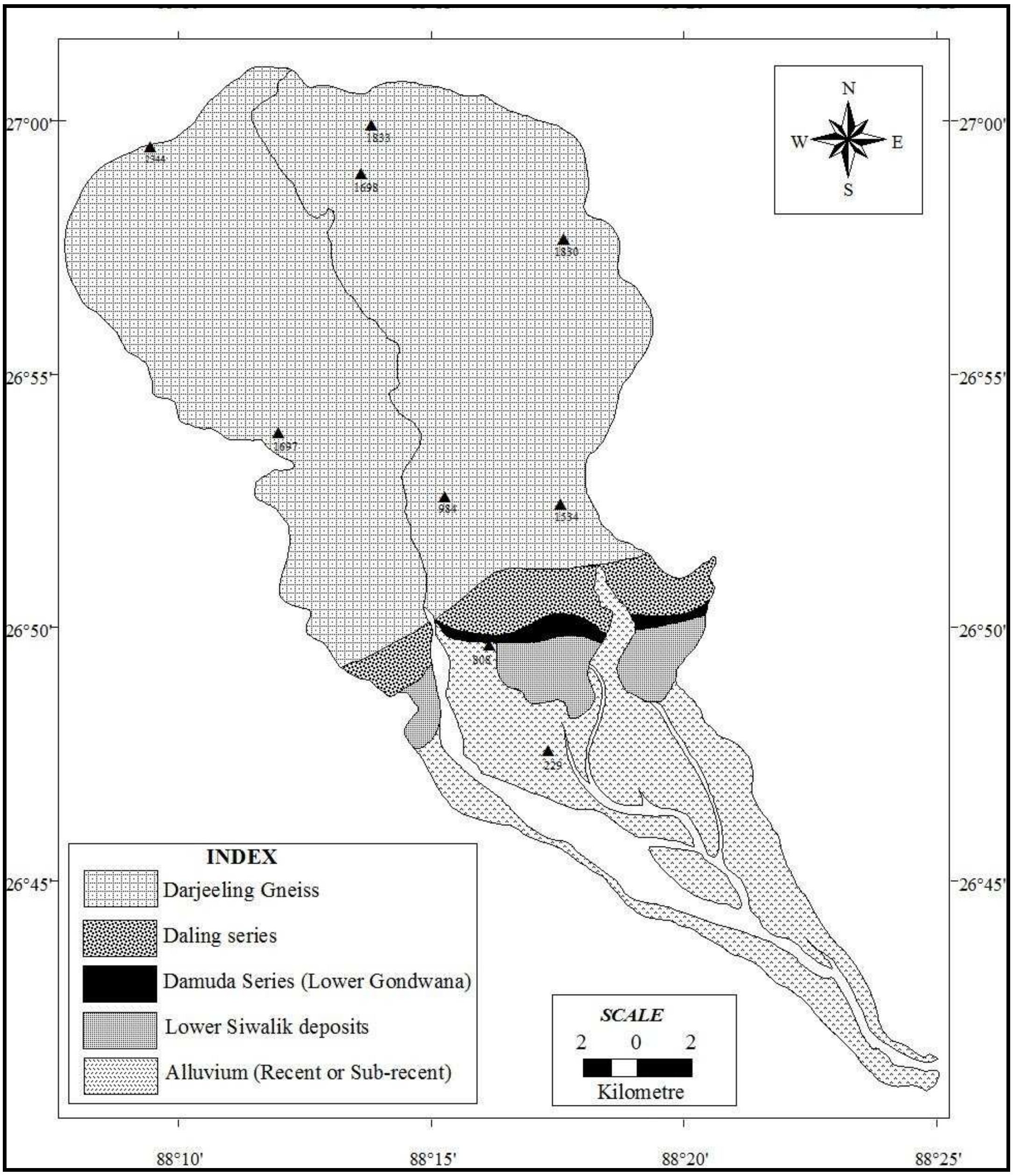
(Source: Based on Mallet, 1964 and Ganser, 1987)

Table 2.1 The rock types and geological structure and their occurrences *(in %)* in the Balason basin.

The Permian Damuda series rests along a thin belt mostly extending in an E-W direction. The rocks of this group have undergone great crushing and disturbances along with a great change in their lithological set up. The dips vary between 40° and 90° towards north-westerly direction and the beds have a generalized strike of ENE-WSW. These coal bearing lower Gondwana rocks is disrupted due to northward extension of alluvium patches of Tertiary series in to the eastern and western segments. There exists a continuous belt of semi-anthracitic coal seams between Pankhabari and Tindharia.

Another geological series of rocks named from Nahana of Siwalik hills occurs along foothill zones, with dips varying between 30°- 60° towards north northeast. It occurs above alluvium deposits and like Damuda series, its east-west continuation is also interrupted by northward extension of alluvium deposits and thus are divided into three segments. The top beds of this formation are usually pebbly and contain rounded pebbles of quartz, having either a random orientation or are aligned parallel to the bedding plane.

The southern plain of the Balason basin consists of alluvium deposits of recent or Sub-recent Pleistocene. It consists of mostly river deposited gravels and coarse sand forming several alluvial fans, which merges to form the vast piedmont plain of Terai with varying thickness and lithology. Major rivers carries immense load of sediments during rainy season and as soon as they reach the piedmont zone, the large part of sediment is deposited in the form of semicircular alluvial fans (Jana, 1997). In this segment the rock fragments are either fluvial in origin or the product of sub-aerial denudation.

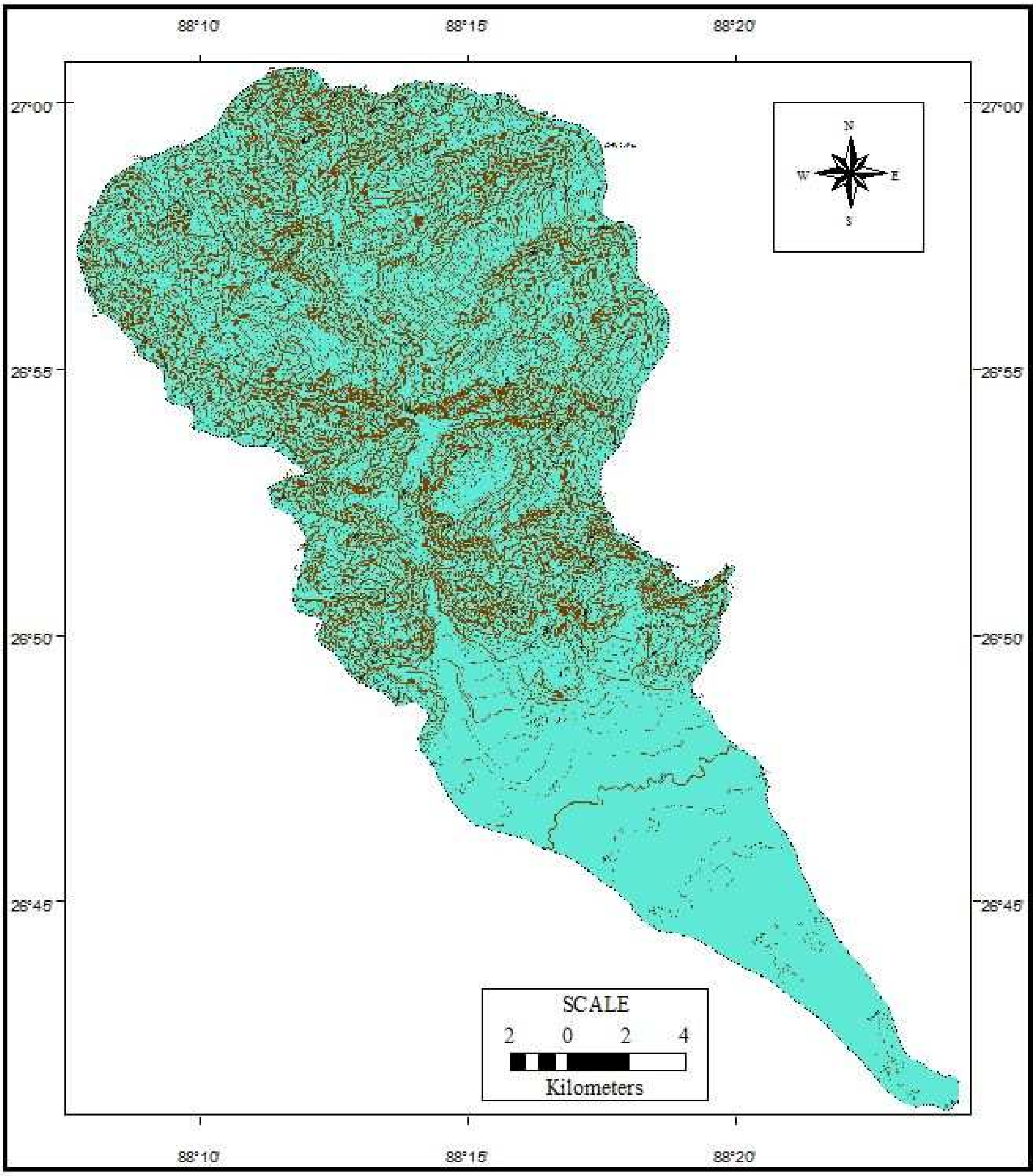


(After Lama, 2003)

Figure 2.1 The distribution of Geological formations in Balason basin.

2.3 Geomorphology of the Balason basin

Altitude and orientation of the basin, shape and ground slope of the watershed, relief, rock types and soil mantle and geologic structure are all elements in determining the hydrologic characteristic of a river system (Morisawa, 1968). Elevation of the Balason basin varies from 2416 m (Lepchajagat, Ghum-Simana) to 103 m (confluence with Mahananda river), which flows down from north to south through a funnel shaped basin. The watershed is delineated on its north by a ridge emanating from the massive Singalila range and going almost straight to the east forming the Maneybhanjyeng-Ghum ridge.



(Source: CIAT SRTM Data, V3)

Figure 2.2 The configuration of contours (m) in Balason basin.

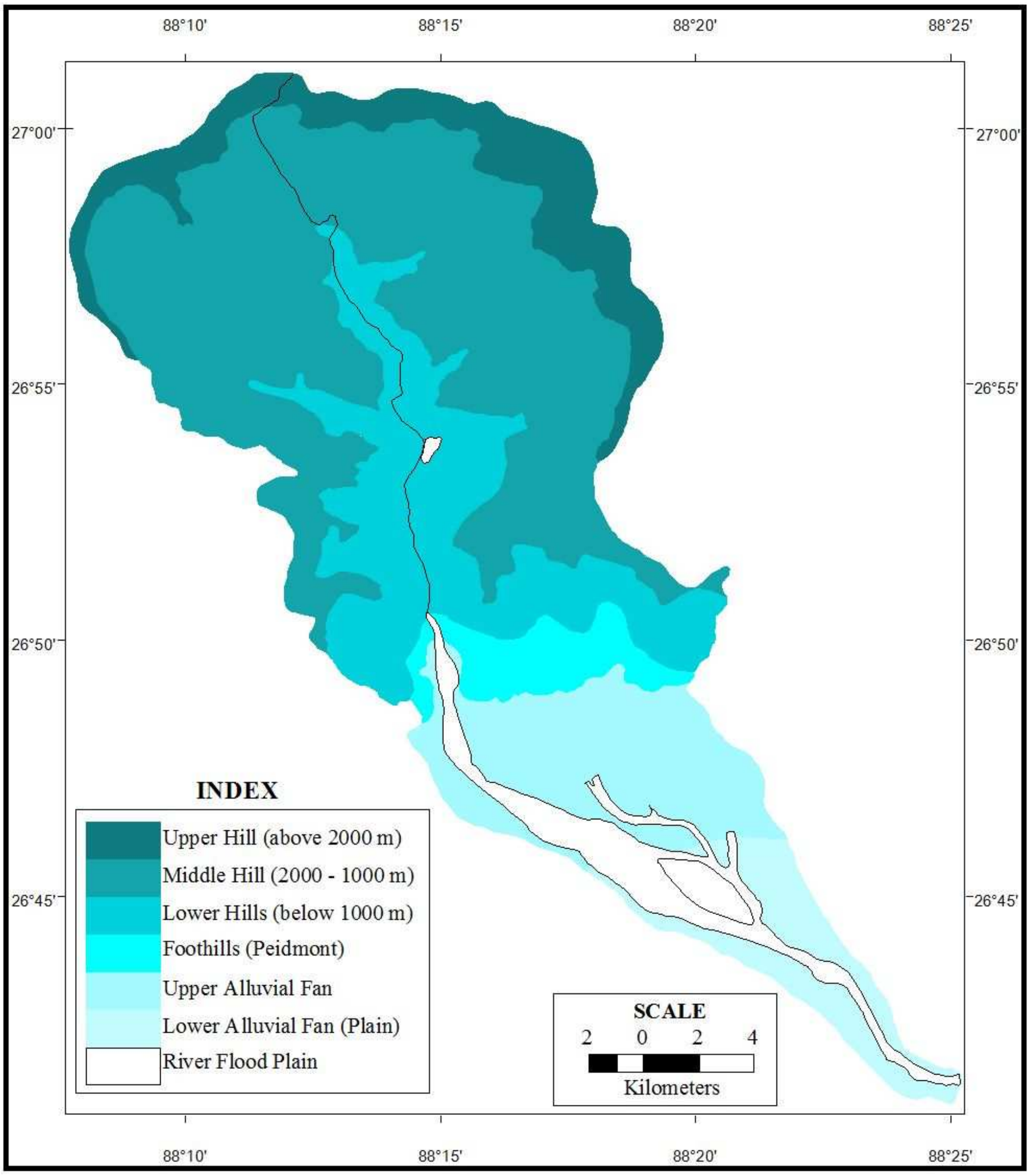
2.3.1 Geomorphic units of the Balason basin

A vast portion of an area on the south of the basin is consisted of wide open gently sloping plain where the river of the Balason drainage system have deposited huge amount of eroded materials carried down from the catchment areas, due to sudden decrease of velocity resulted from abrupt fall of slope. Just immediately above the rolling plain a foothill zone of comparatively higher dissection has started which being associated with active exogenetic processes and various geological disturbances have extended up to the sheared, thrusted and folded transition zone between Damuda – Daling series. Above this zone a comparatively less dissected but rugged zone of middle and upper hill topography having harder rocks of Daling series and Darjeeling gneiss with comparatively lower amplitude of relief has taken place. Thus, on the basis of the above characteristic differences the whole basin can be divided into three distinct geomorphic units.

I. The southern Alluvial Fan Zone.
II. The Dissected Foot Hill topography.
III. The Rugged Middle and Upper Hill Tract.

2.3.1.1 The Southern Alluvial Fan Zone

The deposited detritus carried down by the Balason river system has developed a series of Alluvial fans which are found mainly between 120 m and 400 m and even up to 480 m over the entire alluvial plain of the studied basin. These alluvial fans coalesce to form a pediment zone with textural diversities and different sediment patterns. These fans of the basin fall on the right bank of the Teesta river, the main river system of the region.



(After Lama, 2003)

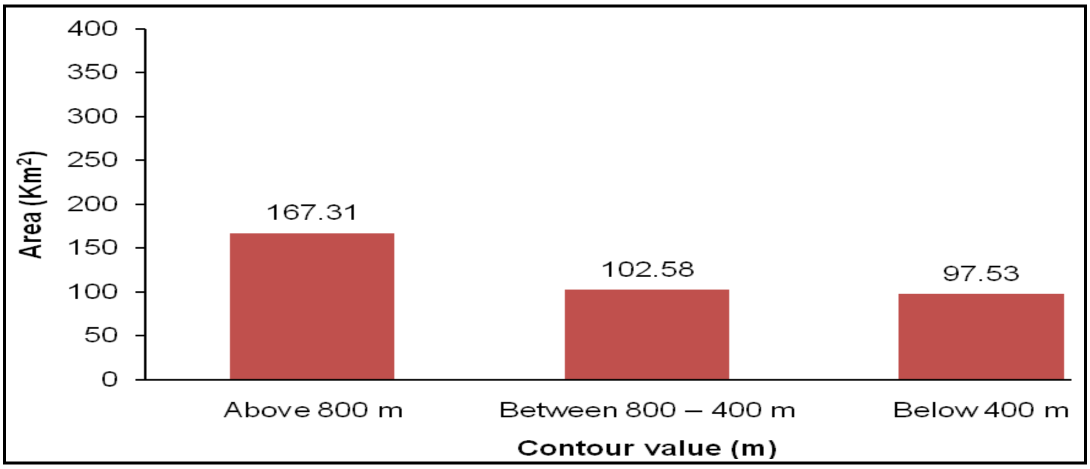
Figure 2.3 The distribution of different geomorphic units in Balason basin.

2.3.1.2 The Dissected Foot hill zone

The foothill region in the Basin with a series of ridges and varying valley forms, being associated with Siwalik-Damuda Sandstone and Shale with occasional coal bearings seams of the Permo-Carboniferous period, have depicted distinct thrusts between Siwalik-Damuda-Daling series contacts and thereby contributed sheared crusted and folded lithology over the region. Moreover, the sandstone and shale of this region have facilitated the better incision of the rivers with prominent valley side slope and ridges. The effect of regional episodic uplifts, which are frequent in the Teesta river system (Mukhopadhya, 1983) are also well manifested in the prevalent process and resulting landform characteristics over this geomorphic units with steep mass-wasted slopes, eroded fault scarps, etc. Thus, the whole geomorphic unit has exhibited highly dissected land surface and deeply developed mature soil horizons.

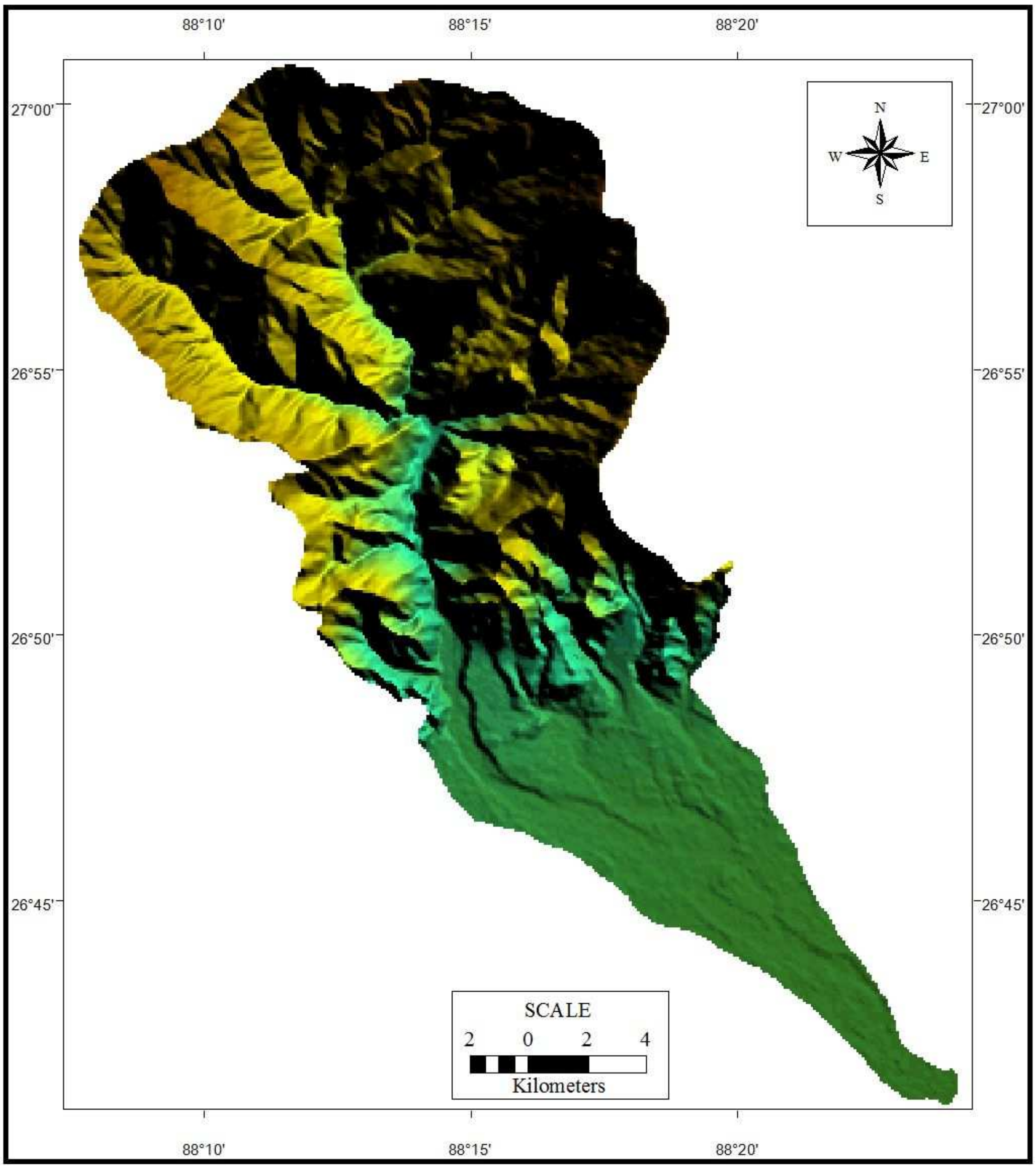
2.3.1.3 The Rugged Middle & Upper Hill zone

At an altitude of approximately 800 m there exists a distinct break of slope, which has separated the foothills below some distinctive characteristics of geologic and geomorphic origin. The entire region consisted of Daling series and Darjeeling gneiss type of rocks which exerts better resistance in the drainage incision as comparatively less valley side slopes with widely spaced ridges. The episodic and jerky uplifts have exerted little influence on these harder rocks of Archaean period and as a result of which this zone has been suffering from lesser amount of geological deformities which facilitated relatively low amplitude of relief and dissection. The initiation of higher amount of source heads and confluence points with occasional mass wasting, triggered up by chemical weathering on ferruginous rocks etc. have altogether made the terrain rugged. Domal topography in and around the Mirik region within the Basin is a peculiar topographic character of this zone.



(*Computed by researcher)*

Figure 2.4 The coverage of total area (Km^2) under different geomorphic units based on major contours.



(Source: CIAT SRTM Data, V3)

Figure 2.5 The Digital Elevation Model (DEM) of the Balason basin**.**

2.3.2 Relative Relief of the Balason Basin

An attempt has been made to divide the whole basin into different zones on the basis of amplitude or relative relief by considering the highest and lowest elevation falling within the grid of an area of km^2. The occurrence of various relative relief zones (figure 2.7) ranging from moderate to very high over the Basin under study clearly suggests that the entire hill region has been accompanied by different structural variations resulted from various geologic disturbances in association with selective weathering and mass wasting in the normal course of sculpturing of the said region (De, 1998).

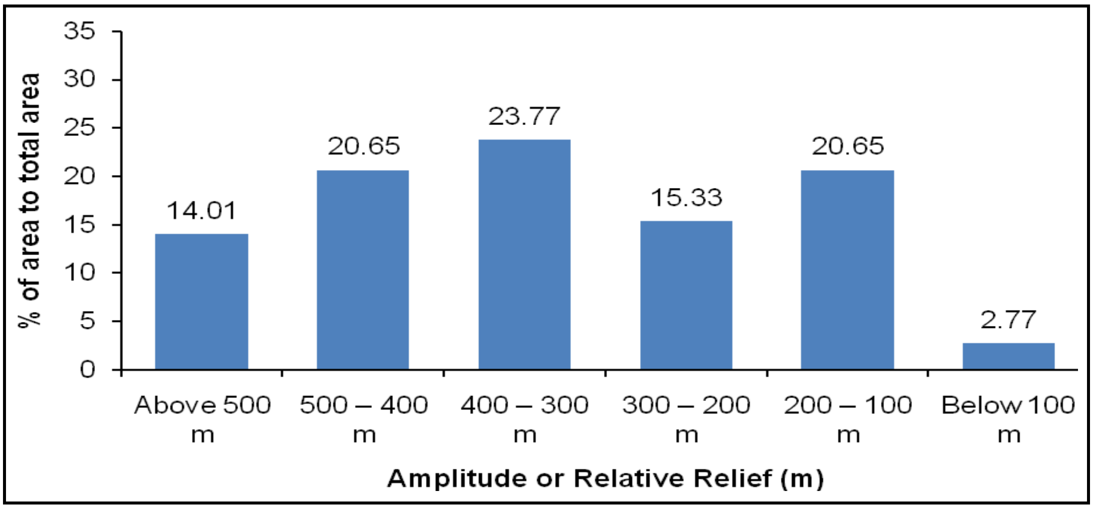


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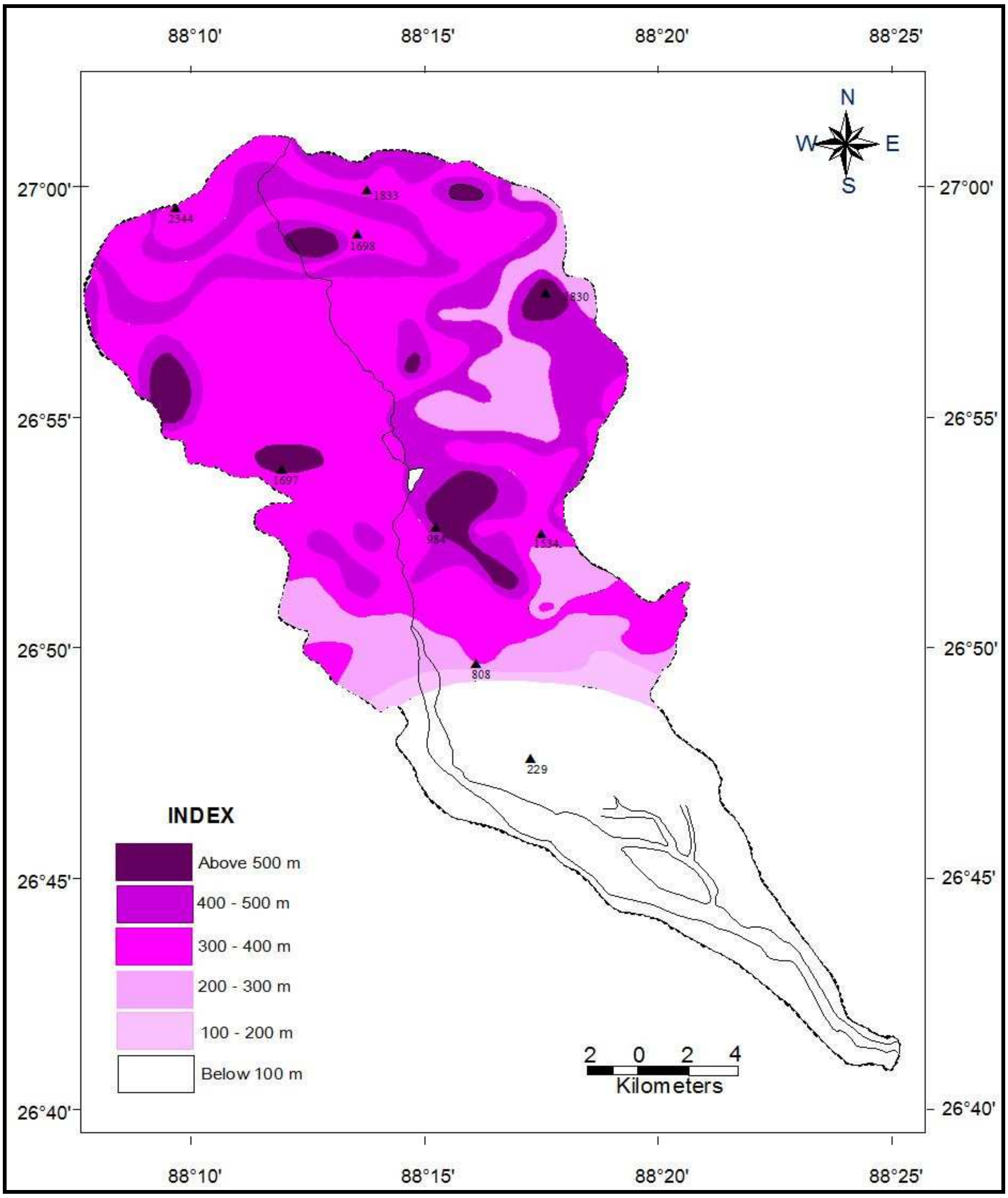
Figure 2.6 Area (in %) of Balason basin under different Amplitude or Relative relief zones

The whole basin has been categorically divided into six major relative zones ranging between 0 to 600 m. The maximum or highest amplitude occurs in the northern portion of the basin covering the upper hilly tracts (above 500 m) and it decreases towards the southern lowlands with minimum amplitude of below 100 m.



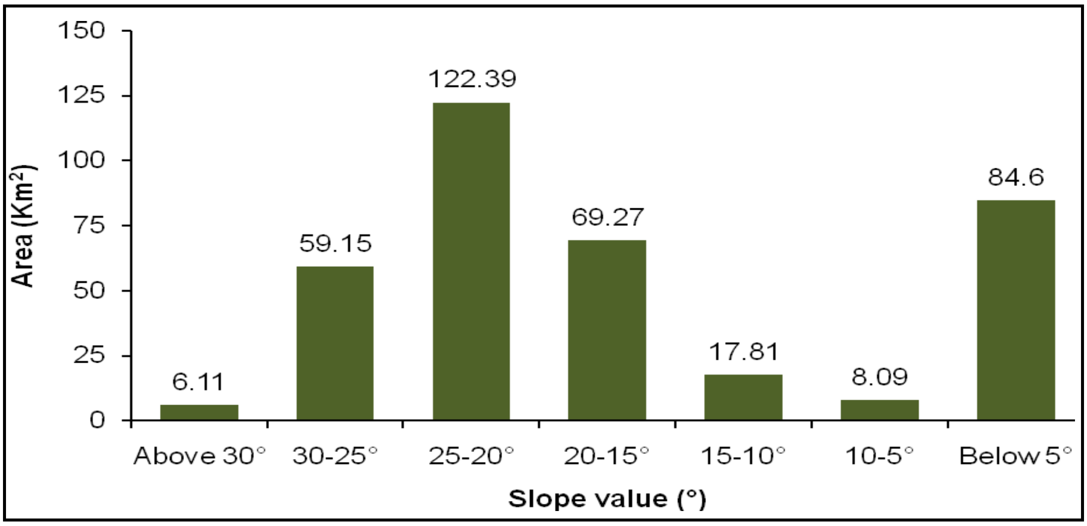
(After Lama, 2003)

Figure 2.7 The amplitude of relative relief (m) map of Balason basin.

2.3.3 Average slope of the Balason basin

Wentworth's (1930) method of slope analysis with the help of contour values has been followed to divide the whole basin into different slope zones. The major break in slope is identified along the southern margin which separates the entire basin into two broad slope zones: northern uplands and the southern undulating lowlands. Both convexity and concavity in slope form are found everywhere in the northern zone. However concavity is more pronounced along the mid-slope due to massive mass movement (Lama, 2003).

The analysis of slope categories (figure 2.8) indicates that the active down cutting process of Balason river have given rise to steeply inclined land surface over the hill portion indicating that the basin is still in the youthful stage of cycle of erosion. The majority of the basin area falls within the moderate steep to steep slope (10°- 30°), revealin g the activeness of the total erosional agents in its upper reaches. The slope zone of 20° - 25° falls commonly in the area of softer Daling rocks easing the high rainfall for erosional activities. The area above 25° slope cons ists comparatively harder Gneissic rocks which have mostly been deforested and affected by weathering processes.



(*Computed by the researcher)*

Figure 2.8 Total basin area (Km^2) of Balason basin under different Slope zones.

2.4 Soils of the Balason basin

The parent soil of the region has undergone changes, resulting in the alteration of its nature and it has actually undergone more than single formation (Lama, 2003). The records of its past history have been mostly obliterated, either by the formation of new soil on the truncated top of the older soil or by the complex removal of the original soil by erosion (Sarkar, 1990).

The soils conditions in the Balason basin are generally predominated by very shallow to deep soils. Red-yellow soils, usually gritty have developed in Darjeeling gneiss and schist. Darjeeling gneiss commonly decomposes into stiff red clay. The colour of red soils, derived as it is metamorphosed from gneiss and schist is due to wide diffusion than to high proportion of iron content. This type of soil occurring in the sandy area is mainly silicious and aluminous with free quartz as sand. It is usually poor in lime, magnesia, iron oxide, phosphorus and nitrogen but fairly rich in potassium derived from muscovite and feldspar.

The lower part of the basin mainly consists of fine textured clay loam soils. The area along 200 m contour encompasses with relatively coarse textured soil varying between sandy loams to loamy sand. Moreover, in some places the top soils are relatively finer in textural composition than the subsurface soil. Between 200 m to 320 m, the soils vary between sandy clay loams to sandy clay with distinctively leached horizon (De, 1998).

2.5 Natural Vegetation of the Balason basin

From the classifications of the natural vegetation of this region by some of the noted researchers like Hooker (1854), Champion (1936) Banerjee (1964), Bhujel (1968), etc, the Balason basin is covered by different types of forests. The differences in elevation and variable productivity of soil in combination with high variable temperature are responsible for such varied forests cover in this region. With pace in settlement occupancy enhancing loss of virgin forests, the original vegetation of the land hardly exists. Three major types of vegetation which are further subdivided into sub types could be found.

2.5.1 The Tropical forests (100 m to 800 m)

The tropical vegetation is characterised by the presence of deciduous trees with *Shorea robusta*. The important species in this type includes Khair (*Acacia catachu*) and Sissoo (*Dalbergia sissoo*), found along the Rakti and Rohini khola, in the lower part of the Balason river and around Simulbari. Other species includes Chilaune (*Schima wallichii*), Chikrassi (*Chukrasia tabularis*), Sidha (*Lagerstoemia perviflora*), Panisaj (*Terminalia tomentose*), Oodal (*Sterculia villosa*), Simul (*Bombax malabaricum*), Chapalish (*Artocarpus Chaplasha*), Lali (*Amoora wallichii*), Ambake (*Jambora Formosa*), etc. Bhujel (1968) have further sub divided it into four sub types:

I. The Ravine forest.
II. The Sal forest.
III. The Dry mixed forests.
IV. The Wet mixed forest.

2.5.2 The Sub Tropical forest (800 m to 1600 m)

This type of forests mainly consists of tropical genera and species and covers the area like upper Balason, Rangbang Khola, Marma Khola, Manjwa Jhora, Rakti Rohini khola. The main species includes Panisaj (*Terminalia myriocarpo*), Chilauni (*Nyssa sessiliflora*), Lampati (), Saur (*Betula species*), Angaree (*Phoebe Spec.*), Siris (*Albizzia spec*.), Mahua (*Engelhardtia spec.*), Tite Champ (*Michaelia cathcartii*), etc. In this forest large climbers with undergrowth are also found along with tree-fern thickets along moist and shaded areas.

2.5.3 The Temperate forests (1600 m to 2400 m)

The upper reaches of the Balason basin is covered mostly by temperate evergreen trees and which are stag-headed with epiphytes. The important species under this type includes Saur (*Betula spec*.), Toon (*Cedrela Spec*.), Katus (*Castanopis indica*), Lekh Dabdabe (*Meliosma willichi*), Phalado (*Erythrine indica*), Lapche Kawla (*Machilus pdulis*), Musre Katus (*Castanopsis tribuloides*), Lekh chilauni (*Nyssa sessiliflora*), Walnut (*Juglans regia*), Malata (*Macaranga spec*.), Arupate (*Prunus nepaulensis*), etc.

2.6 Climatic characteristic of the Balason basin

The Balason basin is characterised by a great degree of seasonality, due to the wide altitudinal variations and the precipitation brought by the southwest monsoon winds. The shift of monsoon trough towards the mountain margins and the peculiar configuration of the ridges and valleys also contribute very high intensity rainfall along the parts of southern slope, sometimes causing flash flood.

2.7.1 Seasons

The Balason basin experiences four dominant seasons with altitudinal variations both in duration and extent. The important seasons are as follows:

i. Summer season (May to September)
ii. Autumn season (October to November)
iii. Winter season (December to February)
iv. Spring season (March to April)

The upland portion experiences longer rainy days during summer season with mist and almost continuous rainfall. The winter is usually cold and few to nil rainfall followed by pleasant autumn and spring season. On the other hand, the southern lowlands experiences long humid summer and a mild winter.

2.7.2 Temperature

The mean annual temperature of the whole Balason basin is about 20.94℃. The northern uplands have a mean annual te mperature of 12℃ while the southern lowlands records 24.70℃. During summer, the mean temperature varies between 16℃ to 17℃ in the hill s and 27℃ to 28℃ in the lowlands. In winter season, there prevails cold temperature ranging between 1℃ to -5℃, whereas, the plain region experiences pleasant temperature between 17℃ to 19℃. The air humidity fluctuates f rom 87% to 58% in the lowlands during summer weather, but in the northern uplands, humidity is mostly high due to excessive cloudiness.

2.7.3 Rainfall

The rainfall in the entire Balason basin area is totally dependent on south-west monsoon winds which contribute about 85% of the total annual precipitation. The average annual rainfall for the whole basin is 2300 mm. The maximum rainfall occurs during the months of June to September. Beside, thunderstorms accompanied by rain also occur during April, May and in

October (figure 2.9). On an average, the number of rainy days with more than 2.5 mm of rain varies from below 100 days in the plains to 124 in the higher altitudes in the northern portion. The annual rainfall fluctuates from 2000 mm to about 5000 mm within the basin area. The foot hill tracts receive more rainfall (3446 mm) than the plains (3272 mm).

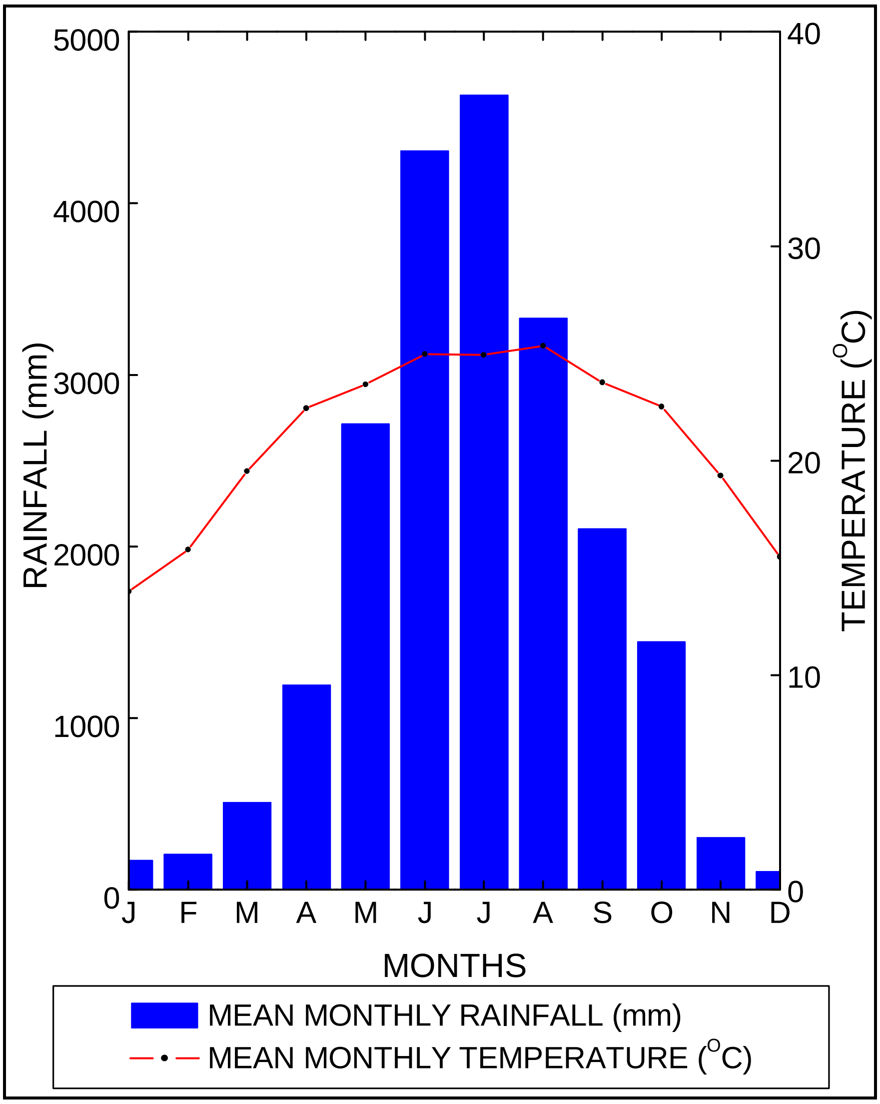
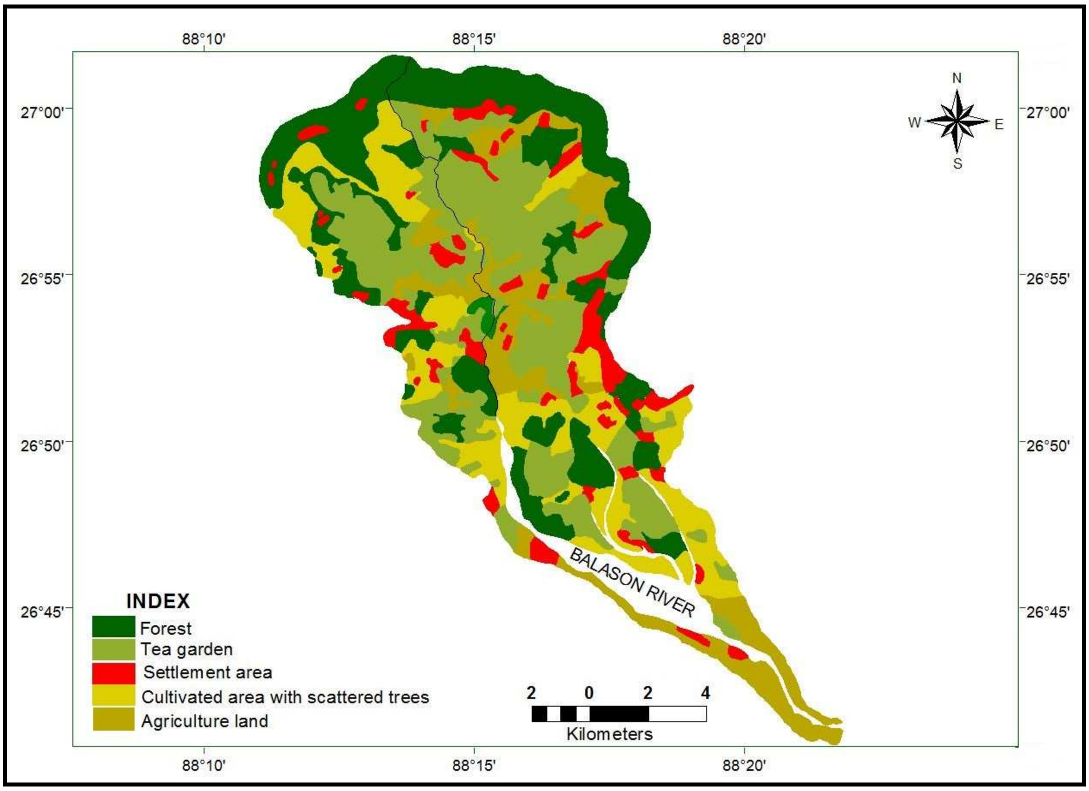


Figure 2.9 Mean monthly rainfall (mm) and temperature (℃) of the Balason basin *(Refer Appendix B Table 2.1).*

2.6 Land use of the Balason basin

Out of the total geographical area within the study area, most of it is occupied by tea plantation almost in all directions with patches of forests in the northern portions. Till 1835, the area was densely covered with forests with few migratory Lepchas in the hills and the Meches in the southern foothills. But with the construction of road (Hill Cart Road) in 1839, the degradation of these virgin natural forests slowly started. Soon large tracts of forests were replaced by roads, Tea Gardens railway lines and settlement (Lama, 2003). With time, a pronounced decrease in the forest cover became apparent and at present the forest is mainly restricted in the north and north-eastern section of the study area with small natural patches at Singbulli, Selim Hill, and Manjwa and between Pankhabari and Longview (Lama, 2003). Settlements with cultivated waste occur along the areas adjacent to tea gardens and agricultural patches in the middle portions of the study area (figure 2.10).

With the establishment of tea gardens in areas like Ambootia, Makaibari, Soureni, Phuguri, etc after 1860, the forests were cleared and settlement began to flourish along with roads. Hence by 1871, more than 20 tea gardens with approximately 890 hectares of forest area were leased out for tea plantation. At present, tea plantation occupies more than 27% of the total basin area (99.3 km^2) while the forest cover is about 26.2% (96.18 km^2).



(After Lama, 2003)

Figure 2.10 The distribution of different land use patterns in Balason basin.

2.8 Conclusions

The study of the physical characteristic of the Balason basin reveals that it is a geologically young and fragile region with intensely metamorphosed rocks like gneiss, schists, phyllites, etc, which are highly weathered, fractured and jointed, vulnerable to slope instability. The basin does not follow the law of absolute relief and slope frequency distribution, since maximum slope zones falls between 800 – 2200 m with relative relief value of 300 – 500 m; indicating the youth stage of the basin. The climatic characteristic also shows wide variation which is largely dependent on the altitude.

The drastic reduction of the natural forests, combined with the high annual rainfall exceeding 3000 mm in most part of the basin, makes the area highly vulnerable to soil erosion and landslides, reducing the soil fertility, choking the streams and leading them to change their courses. Thus, it can be concluded that, the Balason basin being geologically vulnerable coupled with headless deforestation and unscientific changes in its land use pattern poses serious threat to its fluvial characteristic.

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CHAPTER 3

Fluvial characteristics of the Lower Balason river

3.1 Introduction

Channel adjustments due to vertical and lateral instability along alluvial rivers, often induced by various types of human disturbance, may become unacceptable for the human activity itself when the alluvial plain adjacent to the river is densely populated and developed. The management and stabilization of unstable rivers pose several problems to river engineers and managers and the importance of the proper understanding of channel morphology and dynamics is providing useful guidance for stabilization schemes (Bravard, 1999).

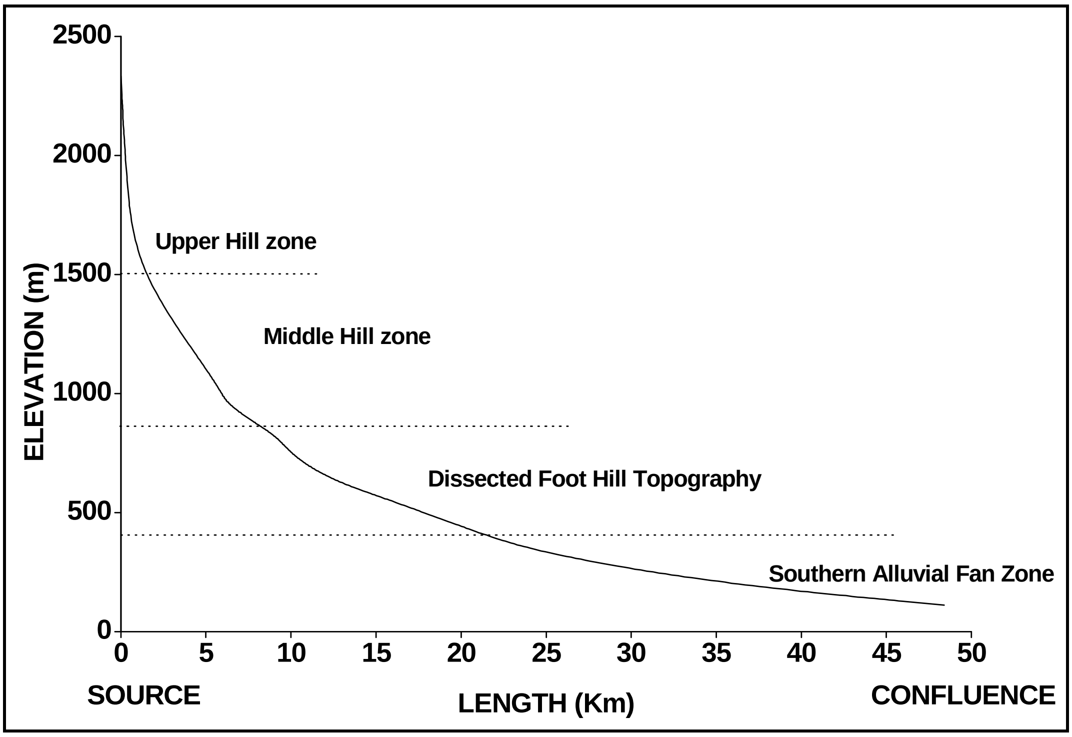
In order to get a clear idea about the channel forms and processes of Balason river, an attempt has been made in this chapter to make a quantitative study of the morphological and hydrological characteristics of the Balason river with an emphasis on its lower course.

3.2 Study of Morphology of lower Balason basin

River morphology is the shape or form of a river along its length and across its width. Transported materials are used in eroding a riverbed and thus shaping its morphology. The transported materials are deposited either temporarily or permanently along the course of a river when can no longer be transported. The shape of a stream channel at any point in the channel network is a result of a balance between the erosive force of moving water and the material over or through which the water is moving (Knighton, 1998). As the Balason river debouches onto the Terai plains, the fall in gradient and incompetence provides greater scope for the water to spread laterally. Thus, along the lower course, the river attains the braided pattern with several bars developed from irregular deposition and also successive divisions and rejoining of flows within the main braided channel which has increment the size of bars downstream. Such bars are unstable and change their size, shape and location due to varied channel erosion both during high flows (monsoon months) and also due to anthropogenic impacts (mostly boulder lifting activities). In this section, the morphological analysis considering the longitudinal and cross-sections has been carried out for proper understanding of the fluvial characteristics of the lower Balason river.

3.2.1 Study of the longitudinal profile

Rivers are linear systems which show a gradient of characters along their length. Ideally, the longitudinal profile of a river is concave with a steep upper portion near the source, giving ways to reaches of progressively less gradient as the mouth is approached. As the longitudinal profile tends to attain a state of equilibrium over time in relation to the basement, the cycle is interrupted by subsequent epirogenic movements and such interruptions may divide it into a number of segments pointing to sub-cycles.



(Source: SOI Topographical maps)

Figure 3.1 Longitudinal profile of the Balason river with different geomorphic units.

For the analysis of longitudinal profile of the Balason river (figure 3.1) the Survey of India (1964-65) Topographical maps ($78^A/_4$, $78^A/_8$, $78^B/_5$ & $78^B/_6$) at a scale of 1:50,000 have been used. From the source of the river (Lepchajagat) till its confluence with Mahananda river, the distance between two successive contours were measured and plotted in a scatter diagram.

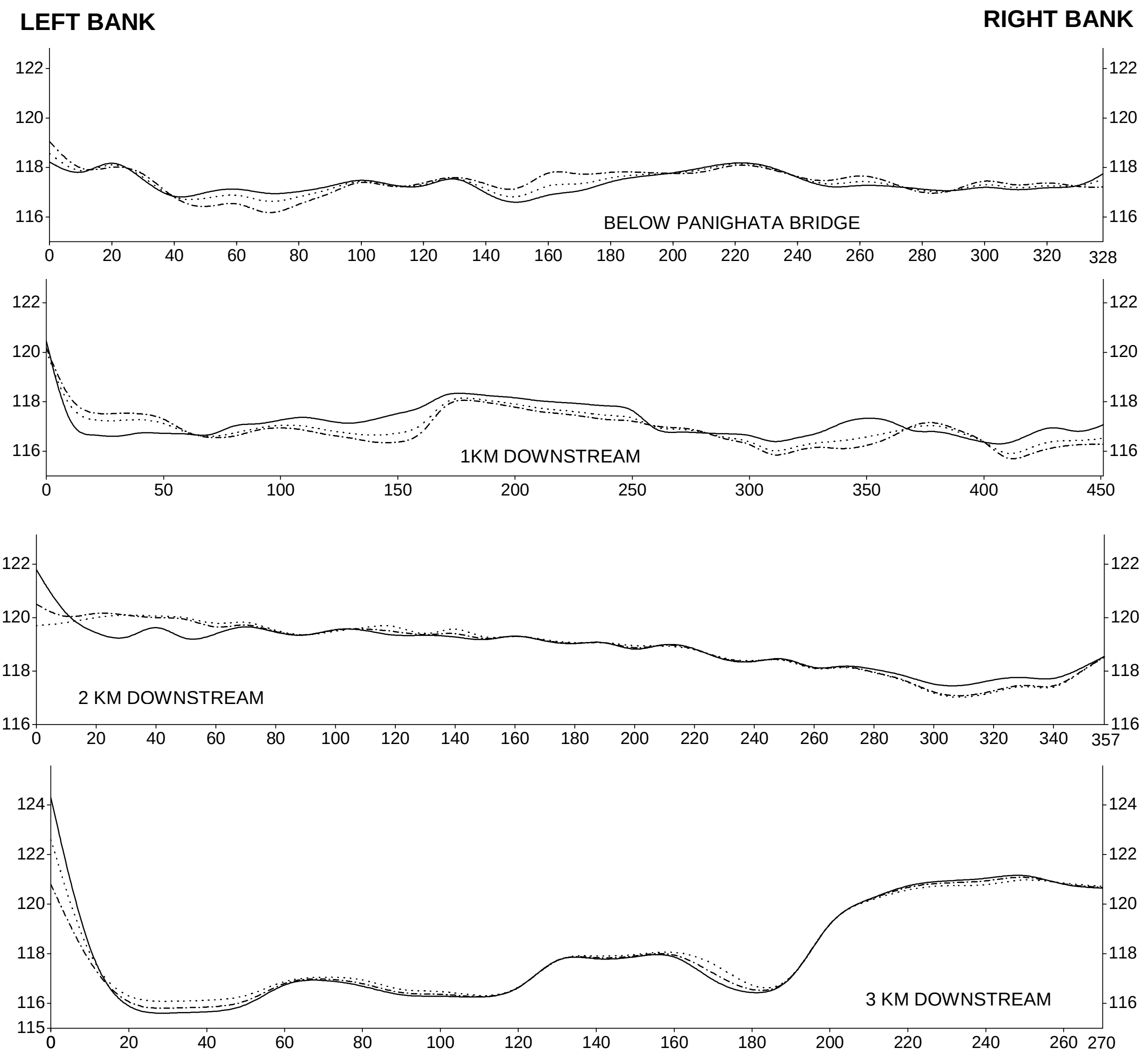
The epirogenic history of the Balason basin revels that the intermitted uplifts of the Himalayas has interrupted the smooth running of a cycle of erosion and thereby has produced a number of sub-cycles along the longitudinal profile of the river which are demarcated by definite break in slopes (300 m, 800 m and 1400 m). Such uplifts have affected the major thrusts zones or morphotectonic belts of the Himalayas and the marked lithological differences may have also paved the way for unequal erosion causing prominence in breaks along the longitudinal profiles (De, 1998).

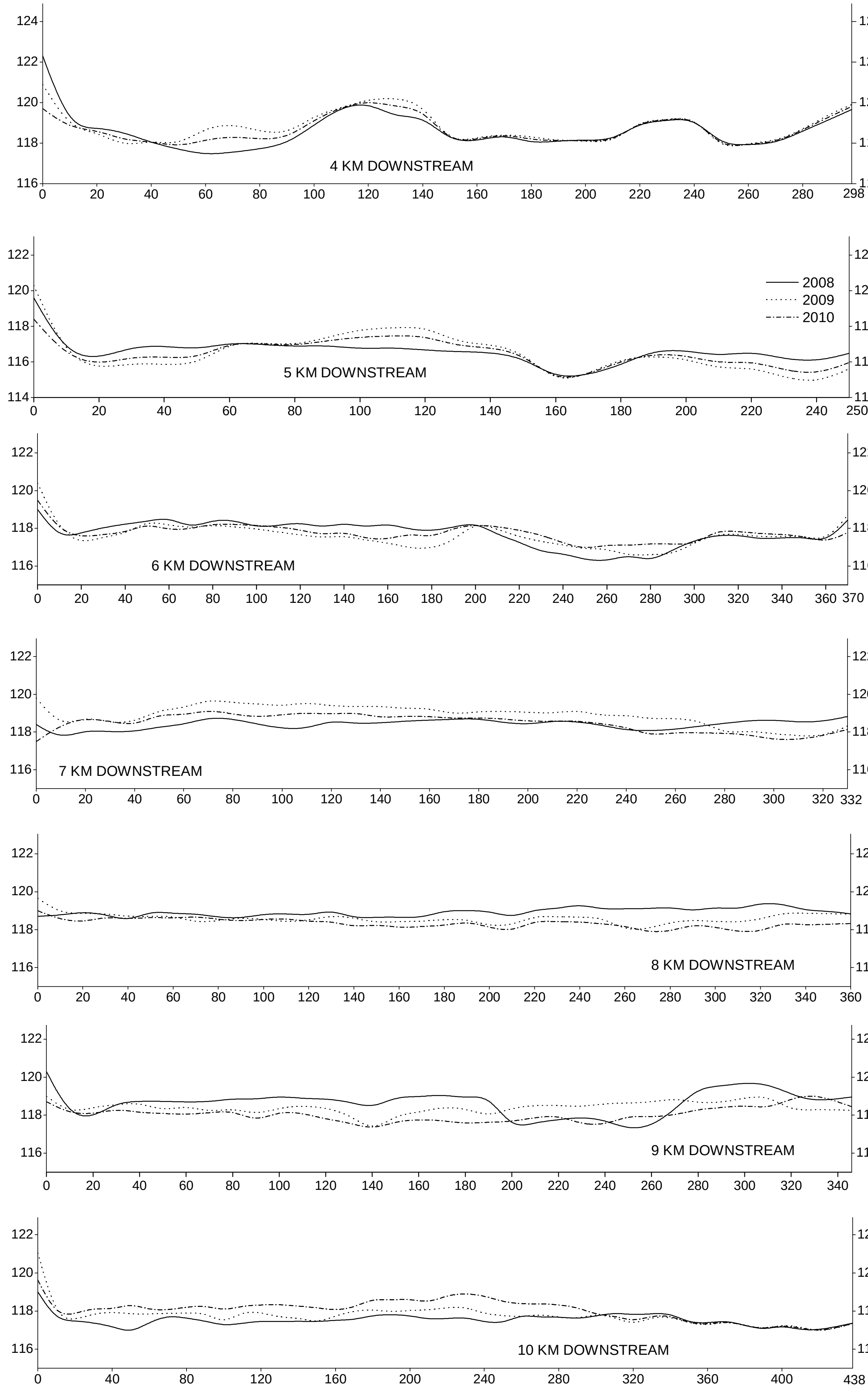
The uppermost portion of the long profiles falling within the Archaean geological structures like Darjeeling gneiss and Daling series has exhibited the steepest slope gradient. Since these structures are composed of very hard metamorphosed rocks like gneiss and schists with occasional slate, phyllites and quartzites and the hardness in the rock out crop has played a role of shearing resistance against erosion. Due to this, the longitudinal profile of the Balason river does not have sufficient power to be flattened enough. The more the rock hardness has decreased with the change of geological structures downstream, the more the gradient of the river have depicted less steepness in the profile. Thus the longitudinal profile has exhibited continuous ups and downs according to the streams ability to erode the bed rocks.

3.2.2 Study of the cross profiles of the lower Balason river

The shape of the cross-section is described through the ratio of channel width to depth. The depth of flow in a channel is directly proportional to the force which the water exerts on the bed and to its ability to transport sediment (Leopold and Wolman, 1957). The cross profiles along the lower course of Balason is typical braiding type with a number of water covered channels that are separated by sand bars, mud-flats of vegetated islands (De, 2010). The width (w) of the cross-sections increases as the river moves downstream with occasional narrowing at few sections due to deposition of bars and also concentration of channel flow over same segments thus increasing channel velocity also. The channel mean depth (d) is also variable, which is largely controlled by frequent changes in bars and flow conditions. The unstable bars and frequent diversions of flow due to its braiding nature and extraction of bed materials from the river bed are also changing the channel mean depth in entire lower course.

In this section, the researcher has studied the cross-sections along the lower course (at 1 km interval) both during pre-monsoon and post-monsoon periods with the help of Dumpy Level from below Panighata bridge (Dudhia Bazar) to Naukaghat bridge with respect to the CWC Bench Mark (119 m). The channel width and depth surveyed (plate 3.2F) are computed and plotted for analysis of channel forms during 2008 – 2010 (figure 3.2).




4 KM DOWNSTREAM
2008
2009
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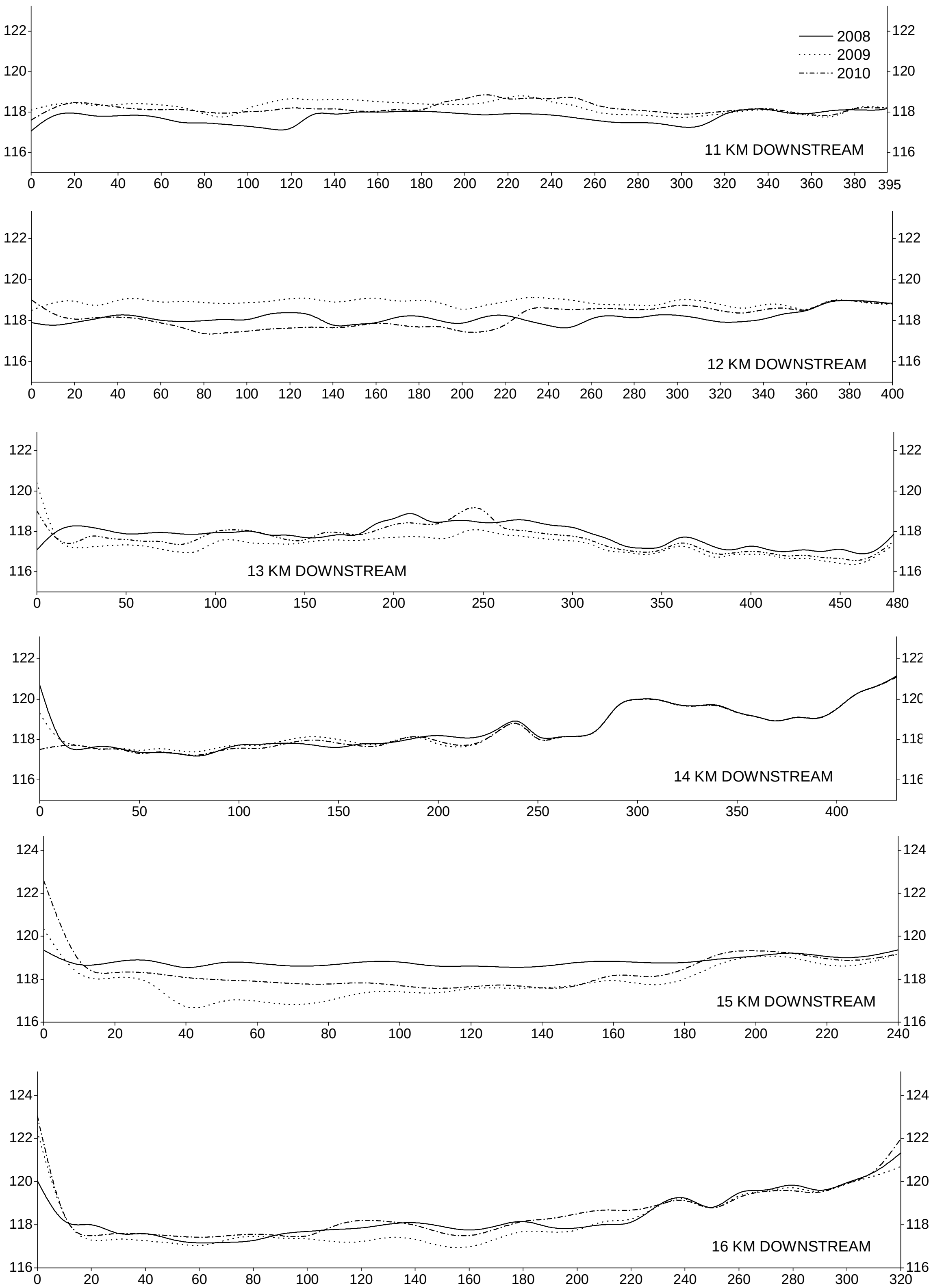
2008
2009
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11 KM DOWNSTREAM
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13 KM DOWNSTREAM
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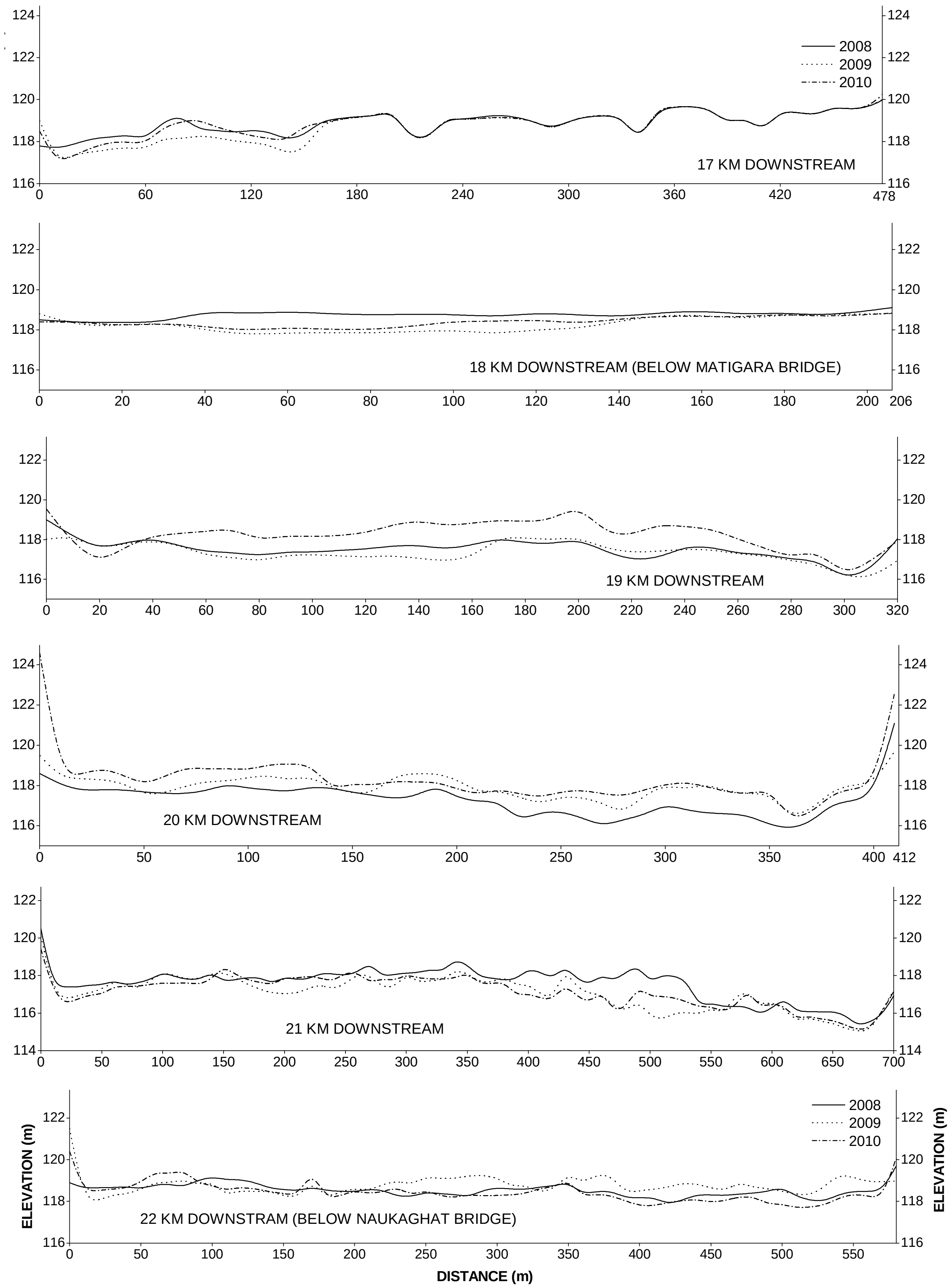
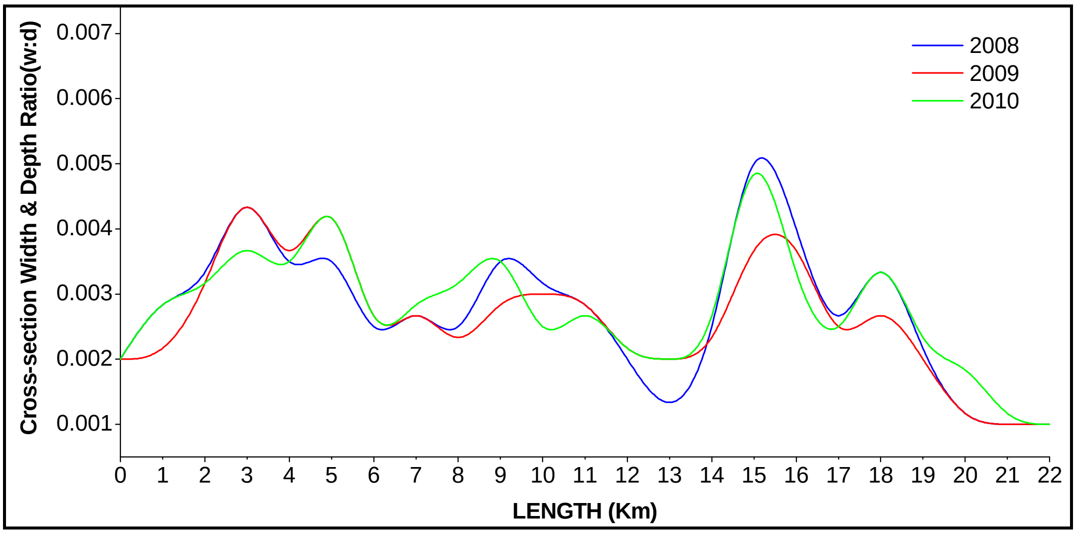
16 KM DOWNSTREAM



(*Based on cross-section survey*)

Figure 3.2 Cross-sections along the lower course of Balason river showing the annual bed elevation during 2008, 2009 and 2010.

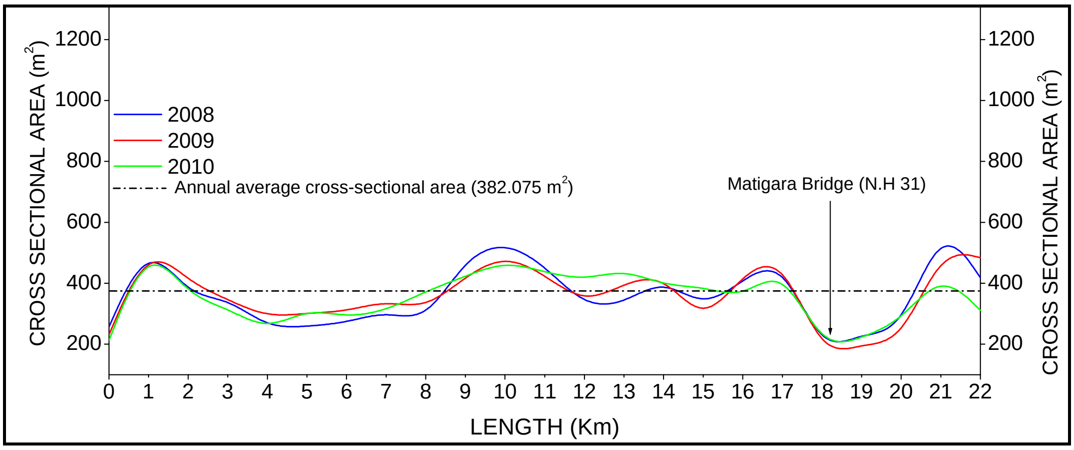
In the surveyed cross-sections along the lower course of Balason river, there is no marked annual changes in its width and mean depth. The width ranges from maximum of 702.600 m (21 km downstream) to minimum of 202 m (below Matigara Bridge) with channel widening at an average rate of 2.100 m (1 km below Panighata bridge), 1.270 m (8 km downstream) to 0.640 m (22 km downstream) during 2008 to 2010. From the surveyed cross-sections, the annual average width varies between 337.833 m (below Panighata Bridge) to 206.333 m (below Matigara bridge) and 580.333 m (below Naukaghat bridge). In case of channel mean depth, the value ranges from 1.530 m (4 km downstream) to 0.380 m (20 km downstream). The annual variation in mean depth is 0.692 m (below Panighata Bridge) to 0.811 m (below Matigara bridge) and 0.697 m (below Naukaghat bridge).



(Computed by the researcher based on cross-section survey)

Figure 3.3 Annual cross-section width and mean depth (***w:d***) along the lower Balason river during 2008-2010 *(Refer Appendix table 3.3).*

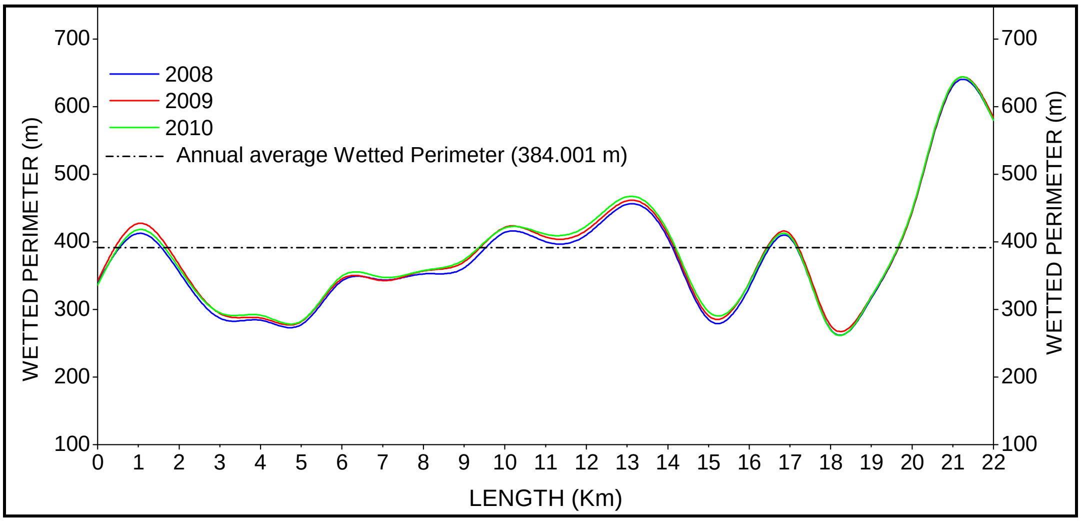
The variations of cross-section width and mean depth ratio (w:d) along the lower Balason river during 2008-2010 (figure 3.3) shows that the value ranges between 0.001 to 0.005. At segments (14 km to 16 km below) where the banks are exposed and also the continuous extraction of bed materials from the river bed as well as adjacent floodplains inducing the frequently shifting of channel flow, thus increasing the width as well as mean depth. But at segments, where channel flow has been concentrated over same portions mostly due to increase in the bar height or reduction in channel competence and where artificial bank protection structures are present, there exists low w:d, since the channel has little scope for widening and also the depth also remains almost the same.



(*Computed by the researcher based on cross-section survey*)

Figure 3.4 Annual trends in cross-sectional Area (m^2) along the lower Balason river during 2008, 2009 and 2010 *(Refer Appendix table 3.1).*

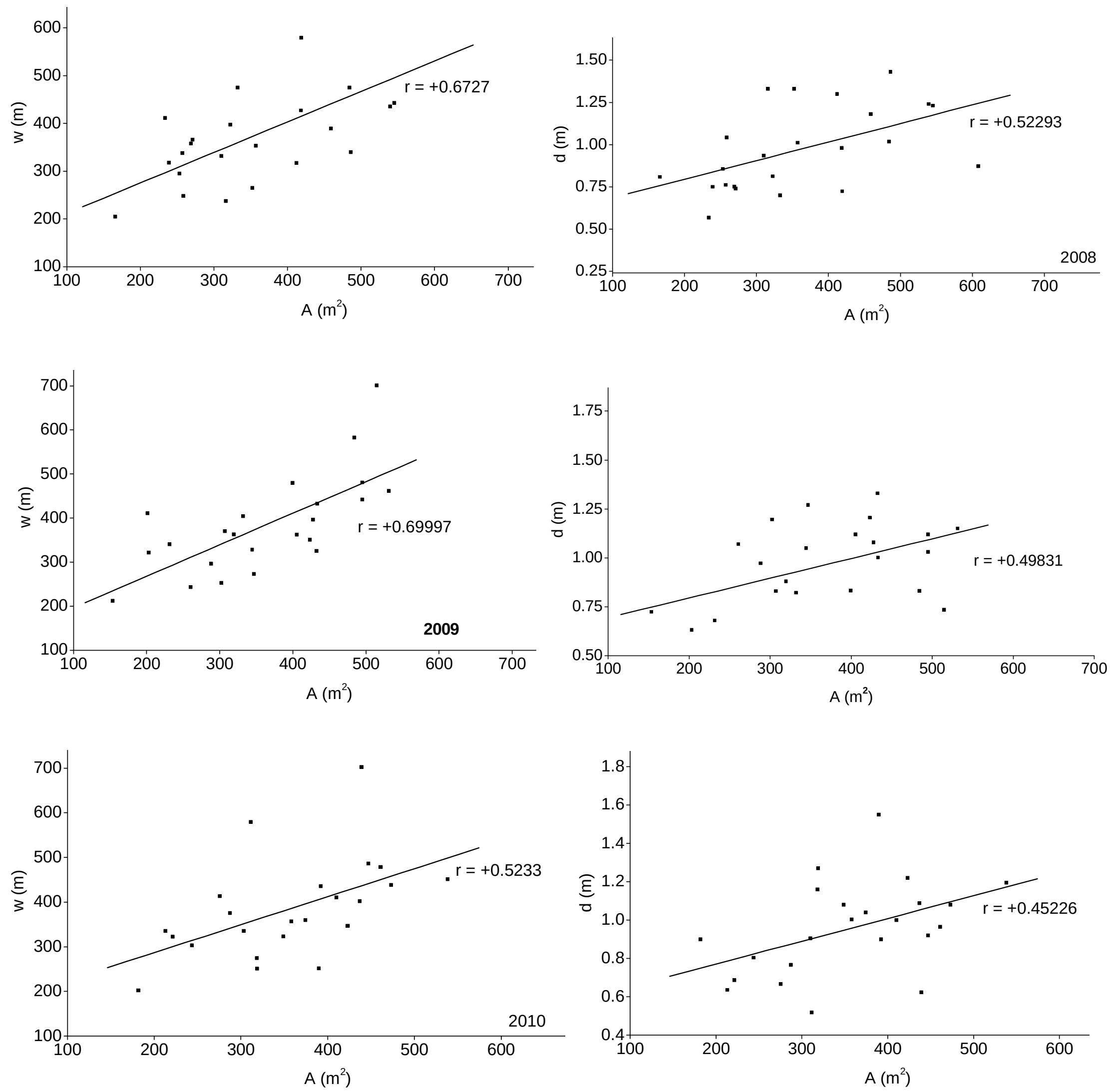
The trend in cross-sectional area along the entire lower Balason river (figure 3.4) reveals that at few segments (3 km to 8 km downstream) the area reduces to from 318.420 m^2 to 269.083 m^2 and also at segments below Matigara bridge (18 km to 20 km downstream) with an area of 153.488 m^2. As compared to the segments with no restrictions in its flow, there exists marked reduction in the cross-sectional area below the bridges (233.939 m^2 below Panighata Bridge and 167.044 m^2 below Matigara Bridge) as channel is being constricted causing retention of flow (plate 3.2A & B) and also narrowing channel width. Moreover, such disturbance has resulted in deposition in the form of channel bars of considerable sizes (Tamang and Mandal, 2010). Hence, the segments (1 km, 2 km and 9 km to 17 km downstream) and also at the confluence with Mahananda (21 km and 22 km downstream), have less disturbances.



(*Computed by the researcher based on cross-section survey*)

Figure 3.5 Annual trends in Wetted Perimeter (m) along the lower Balason river during 2008, 2009 and 2010 *(Refer Appendix table 3.2).*

The wetted perimeter of surveyed cross-sections ranges from 339.552 m (below Panighata Bridge) to 207.955 m (below Matigara Bridge) and 581.728 m (below Naukaghat Bridge). The maximum wetted perimeter (703.848 m) prevails near the confluence with Mahananda river (21 km and 22 km below) and minimum (203.800 m) at 18 km downstream (Matigara Bridge). Along the entire lower course, segments (2 km to 9 km below, 15 km and 18 km downstream) with narrow channel width and divisions of channel flow have reduced its mean depth resulting into lower wetted perimeter (359.423 m to 348.504 m, 246.833 m and 207.955 m respectively). Although, there does not exists any noticeable variations in annual trend of wetted perimeter during 2008 – 2010 (figure 3.5), only at 2 (two) cross-sections (1 km and 2 km downstream), the concentration of main flow over same portions allowing down cutting which in turn increases the channel mean depth (454.317 m and 359.423 m respectively). In other segments, the trend is almost similar with no or slight variations annually.



(*Computed by the researcher based on cross-sections survey*)

Figure 3.6 Correlation of annual average cross-sectional area (A) with its corresponding average width (w) and mean depth (d) along the lower Balason river during 2008-2010.

The analysis of correlation (figure 3.6) between average annual cross-sectional area and its corresponding width (w) along the lower course of Balason river shows that the values of correlation co-efficient (r) varies from +0.6723 in 2008, +0.69997 in 2009 to +0.5233 in 2010. The values of correlations co-efficient (r) with channel mean depth (d) varies from +0.52293 in 2008, +0.49831 in 2008 to 0.45226 in 2010. The result show the decreasing trend annually as the bars condition is changing frequently with splitting of main channel flows, high under cutting at few segments and construction of artificial bank protection structures thus narrowing the cross-section widths. Besides, the unscientific method of extraction of bed materials directly from the river bed is disturbing not only the channel form but resulting into local steeper gradients, thus, increasing stream power and consequent bed erosion (Kondolf, 1994).

3.3 Study of the Hydraulic characteristics of the lower Balason river

Fluvial processes of a river are a dynamic phenomenon controlled by the several factors, some of which are independent in origin and therefore cannot be regulated by the available technologies. The dynamic and random nature of flow can be interpreted in terms of probability and frequency analysis. Balason, an important right bank tributary of Mahananda river is noteworthy for its dynamic fluvial characteristics, sometimes causing devastating floods, erosion and sedimentation, which are primarily controlled by the discharge, bed load and the abrupt changes in the gradient in which the channel adjust itself (Jana and Dutta, 1997). The fluctuating discharge, excessive bed load supply from its upper catchments and highly erodible banks resulted in braided nature with sandy filled bars at lower plain. In its lower course the river bed has been gradually elevated, restricting the free passage to an excessive amount of run-off due to heavy and concentrated rainfall causing flood.

In this section, the researcher has attempted to describe the hydraulic characteristics of lower Balason river for which the analysis of various hydrulic parameters such as discharge (Q), velocity (v), and water level, bed heights and flow characteristics has been calculated. Since several factors affecting river form and processes such as channel shape, slope, roughness, and sediment transport, etc changes frequently, hence, the data on discharge, water level and velocity collected from the CWC Gauging & Discharge (G&D) Site, located at Matigara (N.H 31) has been computed and analyzed on daily basis for both the monsoon and non-monsoon periods from 2008 to 2010 (plate 3.2E). The annual variability of maximum and minimum discharge and water level from 1989 to 2010, analysis of discharge and water level hydrographs and rating curves on daily and monthly basis for 2007 to 2010 and correlation of discharge with water level and velocity have been done to bring out the probable hydrological condition prevailing in lower Balason river. Flow characteristics have been studied with the help of peak flow, flood frequency and return period analysis.

3.3.1 Study of Discharge Variability

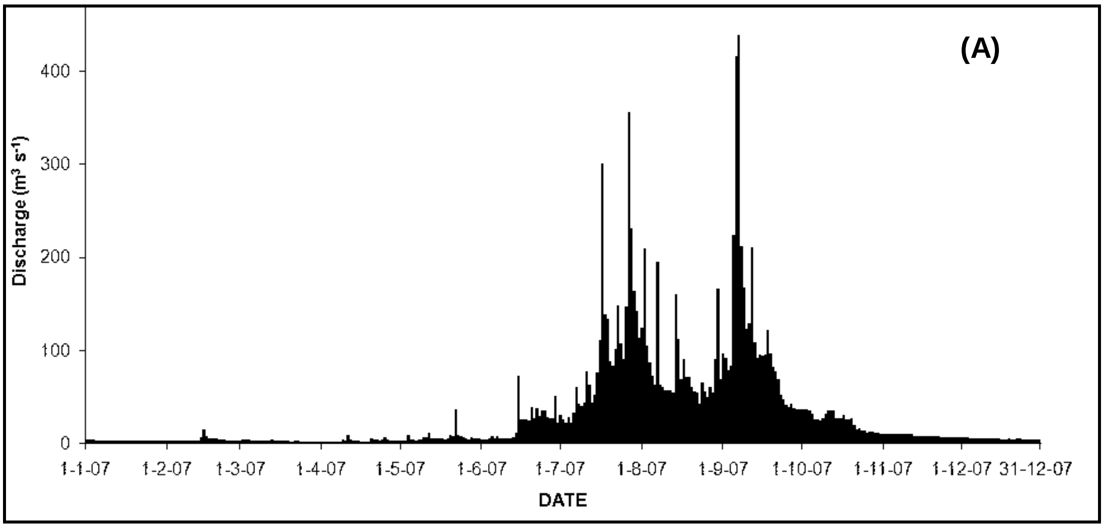
Discharge (Q) is the volume of flow of water per unit time at particular point of a river, expressed in cubic meter per second ($m^3\ s^{-1}$). There exists several methods of measuring the discharge and the methods adopted at a particular gauging site will depend upon the size of the river, the stability of the channel, the variability of the flow and the sediment transport and the length and accuracy of the record required. In this study, the daily mean discharge data (2007-2010) collected from the CWC G&D Site, Matigara has been used which has been calculated by Velocity-Area method.

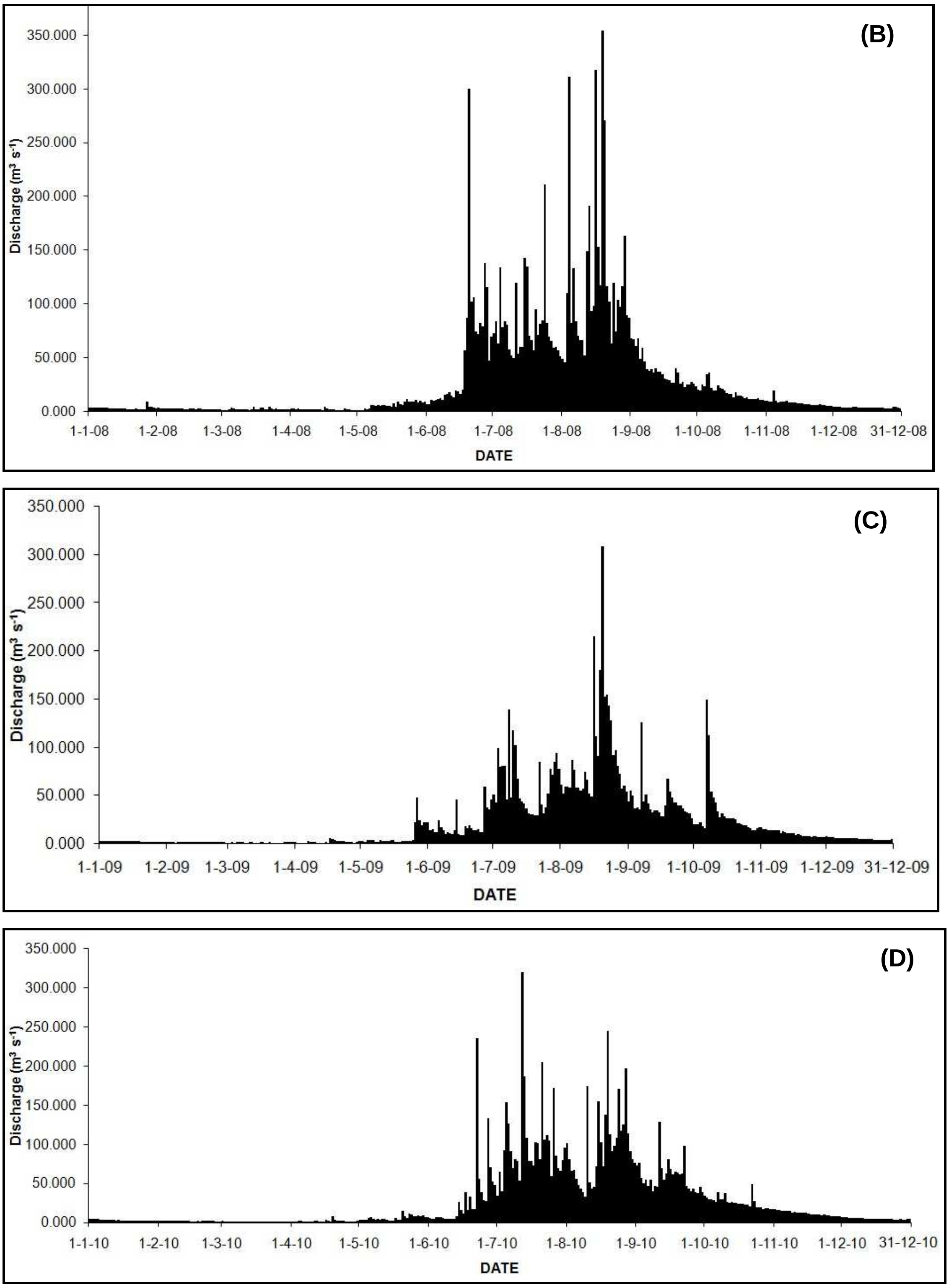
From the analysis of the daily discharge data, it seems that on an average about 90% of the total volume of water is carried through the river during the monsoon period (June to October months) and this is mostly concentrated during high intensity rainfall periods. During 2007 - 2010, the total discharge of Balason river was 11562.554 $m^3\ s^{-1}$, 10580.706 $m^3\ s^{-1}$, 8652.787 $m^3\ s^{-1}$ and 10632.387 $m^3\ s^{-1}$ respectively. Out of the total annual volume of water, 10616.245 $m^3 s^{-1}$, 9720.596 $m^3\ s^{-1}$, 7703.520 $m^3\ s^{-1}$ and 9686.454 $m^3\ s^{-1}$ were contributed during monsoon periods which were 91.82%, 91.87%, 89.03% and 91.10% respectively and the only 946.306 $m^3\ s^{-1}$ (8.18%), 946.306 (8.13%), 949.264 (10.97%) and 936.933 $m^3\ s^{-1}$ (8.90%) were contributed during the non-monsoon periods. Hence it may be said that the river remains active mostly during the monsoon periods.

3.3.1.1 Study of the daily Discharge Q ($m^3\ s^{-1}$) Hydrograph

The daily discharge hydrograph of the Balason river (figure 3.7) reveals that almost every year the river attains the peak flows during monsoon period (June to October) concentrated within a few well defined spells. During 2007, there exist more than 5 peak flows (above 200 $m^3\ s^{-1}$) ranging from the maximum of 439.6 $m^3\ s^{-1}$ on 07-09-2007 to the minimum of 210 $m^3\ s^{-1}$ on 02-08-2007 (figure 3.7 A). In 2008, similar amount of peak flows were noticed but its intensities ranged from 210.800 m^3 s^{-1} 24-07-2008 and maximum of 354.200 m^3 s^{-1} on 19-08-2008 (figure 3.7 B). The occurrences in peak flow were slightly reduced during 2009 and 2010 with 2 and 4 peak flows but its intensities were almost similar to annual peak flow trends (figure 3.7 C & D). The maximum peak discharge was recorded as 309.200 m^3 s^{-1} on 20-09-2009 and the minimum peak of 215.200 m^3 s^{-1} on 16-08-2009. For 2010, the maximum peak discharge was 320.700 m^3 s^{-1} on 12-07-2010 and minimum peak discharge was 204.600 m^3 s^{-1} on 21-07-2010.

Thus, it may be said from the analysis of daily discharge hydrograph of Lower Balason river that there exists few spells of peak discharges during the monsoon period almost every year (2007 to 2010), which directly reflects the nature of monsoon rainfall associated with the number of successive rain-storms. Moreover, the sudden increment in discharge during the late-monsoon period often invites devastating floods along the lower reaches of the river (Lama, 2003) (plate 3.1E & 2C, D).



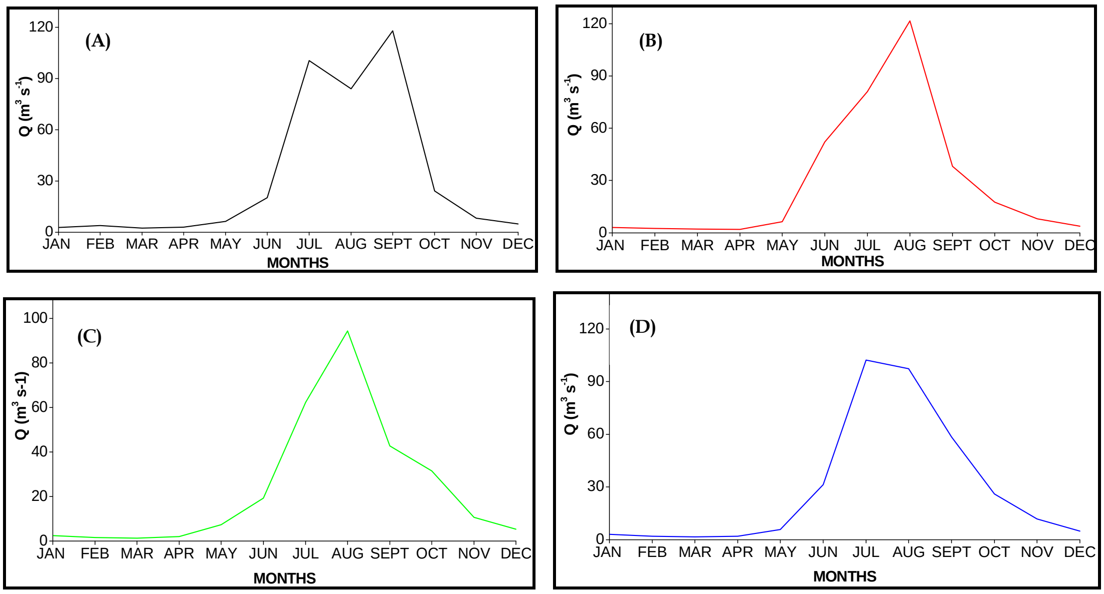


(Source: CWC G&D Site, Matigara)

Figure 3.7 Daily discharge hydrographs of lower Balason river from 2007 to 2010.

3.3.1.2 Study of the mean monthly Discharge Hydrograph

The mean monthly discharge hydrograph (figure 3.8) of lower Balason river during 2007 to 2010 shows some variations in terms of crest, rising and recession of its limb depending upon the channel run-off and infiltration capacity of the watershed (Morisawa, 1968). In 2007, two crests or peaks during the months of July (100.543 $m^3 s^{-1}$) and September (117.892 $m^3 s^{-1}$) could be observed and there exists sudden rising and recession immediately before and after it reaches to the crest (figure 3.8 A). Such condition signifies that the high monsoon rainfall during that period has abruptly increased the river run-off with consequent reduction in its absorption capacity. The situation during 2008 and 2009 was almost similar with only a single crest (August with 121.460 $m^3 s^{-1}$ in 2008 and 94.430 $m^3 s^{-1}$ also in the month of August, 2009) (figure 3.8 B & C). After the crest has been attended, in both the year there is abrupt recession of its limb, signifying the continuous fall in the amount of rainfall in its catchment. In 2010, the trend is slightly different as the hydrograph crest has expanded for two months (July and August) with mean monthly Q of 102.310 $m^3 s^{-1}$ and 97.300 $m^3 s^{-1}$ respectively (figure 3.8 D). Here, the peak Q has been attended in both the months with 320.700 $m^3 s^{-1}$ on 12-07-2010 and 244.900 $m^3 s^{-1}$ on 19-08-2010.



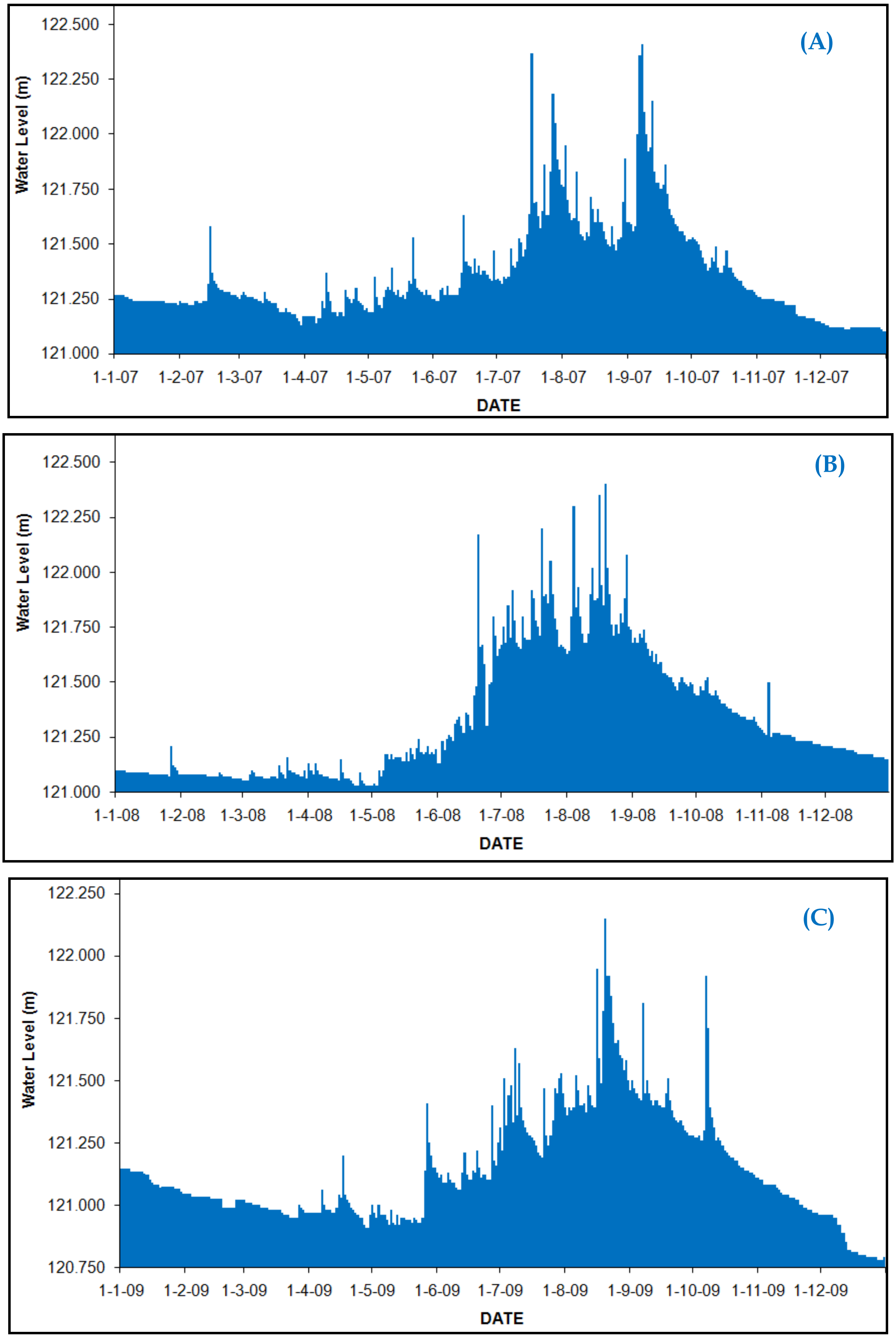
(*Computed by the researcher based on Q data collected from CWC G&D Site, Matigara*)

Figure 3.8 Mean monthly discharge (Q) hydrograph of the lower Balason river for the year 2007 to 2010 *(Refer Appendix table 3.4).*

3.3.2 Study of the Water Level (m) Variability

Water level or river stage is an important concept when analyzing how much water is moving in a stream at any particular moment. Water level is the level of water above some arbitrary point, usually with the zero height being near the river bed and is commonly measured in metre or feet. Similar to discharge, water level is a rainfall dependent hydrological parameter which varies consequent to channel run-off and absorption capacity. In figure 3.9, the daily water level of lower Balason river from 2007 to 2010 has been diagrammatically represented to show the variability throughout the year. The maximum water level usually occurs during monsoon peak flows as the high intensity rainfall over the entire basin area sufficiently allows the surface run-off to add into the river flow through tributaries, gullies and man-made drains.

During 2007, the annual mean water level was 121.359 m with maximum water level of 122.410 m on 07-09-2007 and the minimum of 121.000 m on 30-12-2007 & 31-12-2007. The mean water level during monsoon period was 121.546 m and during non-monsoon period was 121.223 m, so the annual mean water level varied from +0.187 m to -0.136 m. In 2008, the annual mean water level was 121.329 m with maximum water level of 122.400 m on 07-09-2008 and the minimum of 121.030 m on 23-04-2008. The mean water level variation from annual mean water level was +0.297 m (121.608 m) for monsoon period and -0.149 m (121.128 m) for non-monsoon period. For 2009, the mean annual water level was 121.144 m with maximum water level of 122.150 m on 20-08-2019 and minimum water level of 120.780 m on 28-12-2009. The mean water level variation from annual mean water level was +0.203 m (121.347 m) for monsoon period and -0.147 m (120.997 m) for non-monsoon period. During 2010, the annual mean water level was 120.893 m with maximum water level of 121.940 m on 12-07-2010 and the minimum of 120.660 m on 24-03-2010. The mean water level during monsoon period was 121.090 m and during non-monsoon period was 120.760 m, so the annual mean water level varied from +0.197 m to -0.133 m.


(A)
Water Level (m)
122.500
122.250
122.000
121.750
121.500
121.250
121.000
1-1-07
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1-4-07
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1-6-07
1-7-07
1-8-07
1-9-07
1-10-07
1-11-07
1-12-07
DATE
(B)
Water Level (m)
122.500
122.250
122.000
121.750
121.500
121.250
121.000
1-1-08
1-2-08
1-3-08
1-4-08
1-5-08
1-6-08
1-7-08
1-8-08
1-9-08
1-10-08
1-11-08
1-12-08
DATE
(C)
Water Level (m)
122.250
122.000
121.750
121.500
121.250
121.000
120.750
1-1-09
1-2-09
1-3-09
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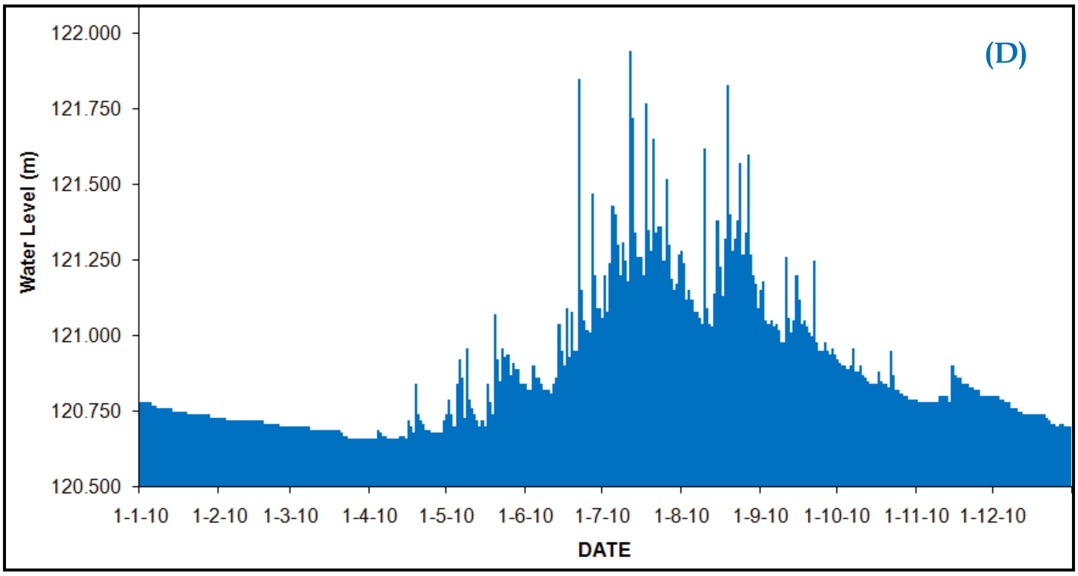


(Source: CWC G&D Site, Matigara)

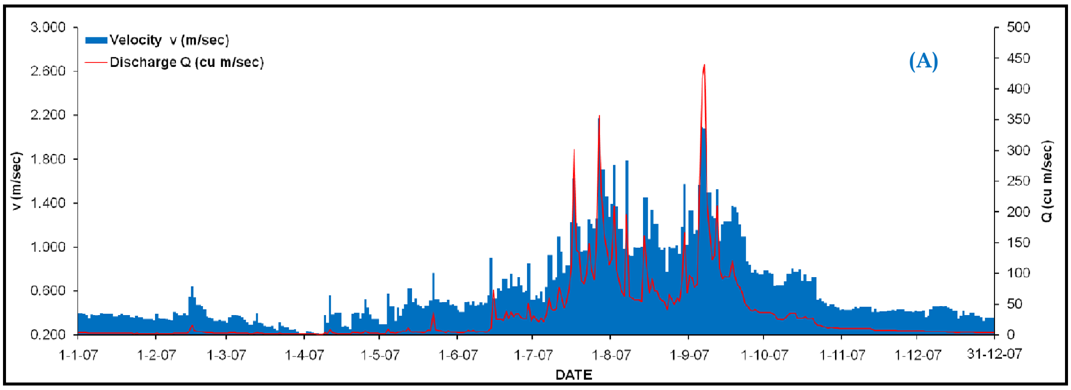
Figure 3.9 Daily Water Level (m) of the lower Balason river during 2007 to 2010.

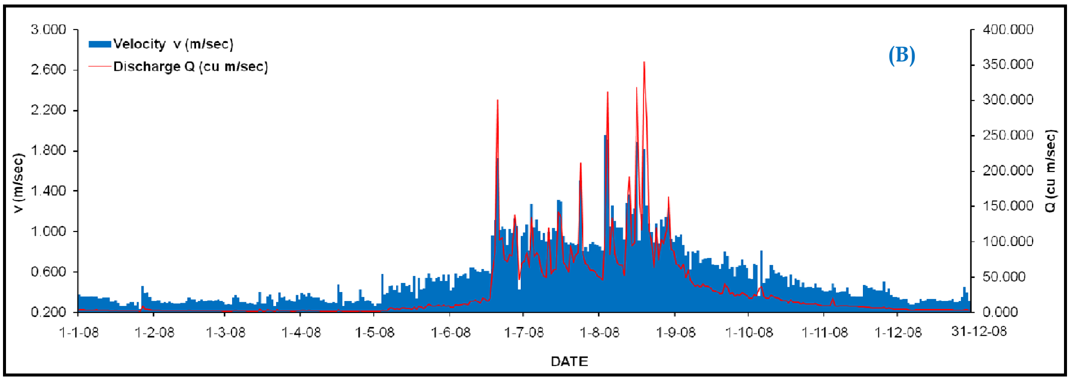
3.3.3 Study of the velocity (m s^{-1}) Variability

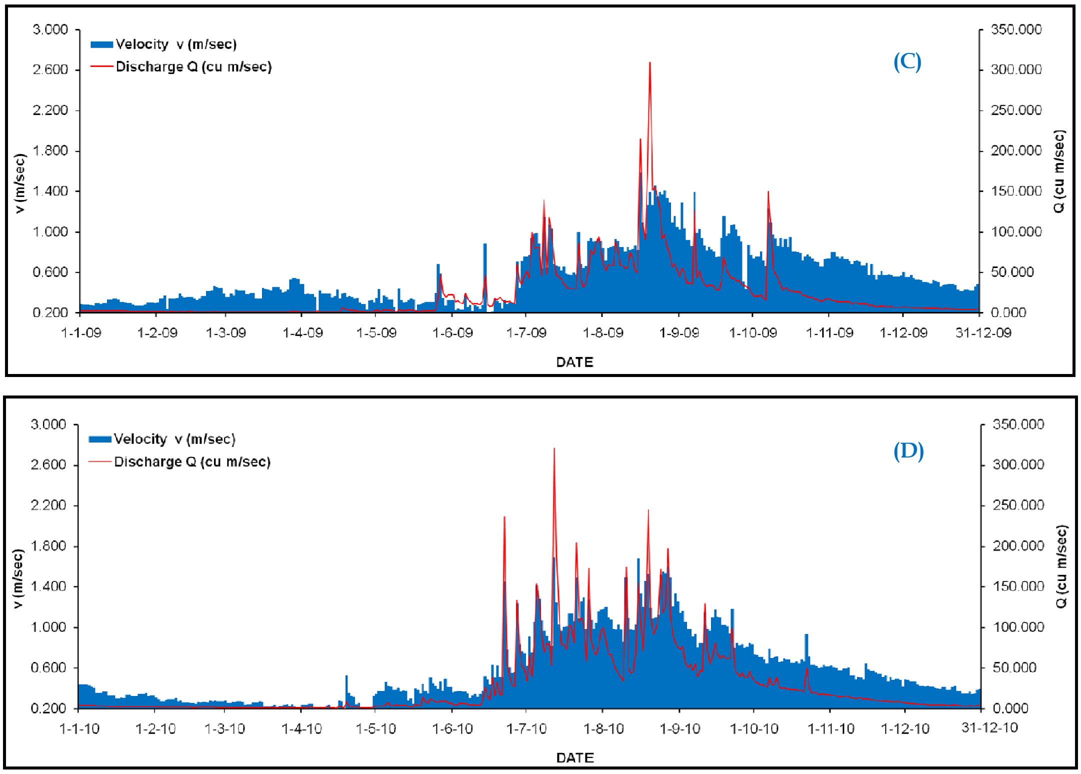
The velocity of a river refers to the rate of water movement, often measured on metres per second. Mean flow velocity increases slightly with distance from the source. It is determined by the efficiency of the river in overcoming friction with the bed and banks (Leopold, 1953). Although velocity appears to be higher in mountain streams than in the lowlands, appearances are deceptive as much of the water in the upper courses particularly close to the bed and banks is almost stationary.

The high rainfall intensities and consequent surface run-off during monsoon period in the upper reaches of Balason river coupled with highly erodible banks has largely incremented the river energy with fluctuating discharge and velocity in its lower reaches. In this section, the daily mean velocity at CWC G&D Site, Matigara has been analyzed to show the variability during 2007 to 2010 (figure 3.10). During 2007, the maximum velocity (v) was 2.171 m s^{-1} on 27-07-2007 and the minimum velocity was 0.204 m s^{-1} on 07-04-2007 with mean annual velocity of 0.623 m s^{-1}. The mean velocity of monsoon period was 0.932 m s^{-1} which was +0.309 m s^{-1} excess from annual mean velocity and the mean velocity of non-monsoon period was 0.390 m s^{-1}

which was -0.233 m s^{-1} deficient. In 2008, the maximum velocity was 1.952 m s^{-1} on 03-08-2008 and the minimum velocity of o.231 m s^{-1} on 26-01-2008 with mean annual velocity of 0.569 m s^{-1}. The mean velocity variability during monsoon (0.855 m s^{-1}) and non-monsoon (0.364 m s^{-1}) period from mean annual velocity was +0.286 m s^{-1} and -0.205 m s^{-1}. For 2009, the maximum velocity was 3.587 m s^{-1} on 16-08-2009 and the minimum velocity was 0.174 m s^{-1} on 09-05-2009 with annual mean velocity of 0.599 m s^{-1}. The mean velocity variability was +0.244 m s^{-1} and -0.176 m s^{-1} during monsoon period with 0.843 m s^{-1} and non-monsoon period with 0.423 m s^{-1}. In 2010, the annual mean velocity was 0.590 m s^{-1} with the maximum velocity of 1.694 m s^{-1} on 12-07-2010 and the minimum velocity of 0.164 m s^{-1} on 10-04-2010. The variability of mean velocity was +0.318 m s^{-1} during monsoon period with 0.908 m s^{-1} mean velocity and -0.237 m s^{-1} during non-monsoon period with 0.353 m s^{-1} of mean velocity.







(Source: CWC G&D Site, Matigara)

Figure 3.10 Daily mean velocity (m s^{-1}) distribution of the lower Balason river during 2007 to 2010.

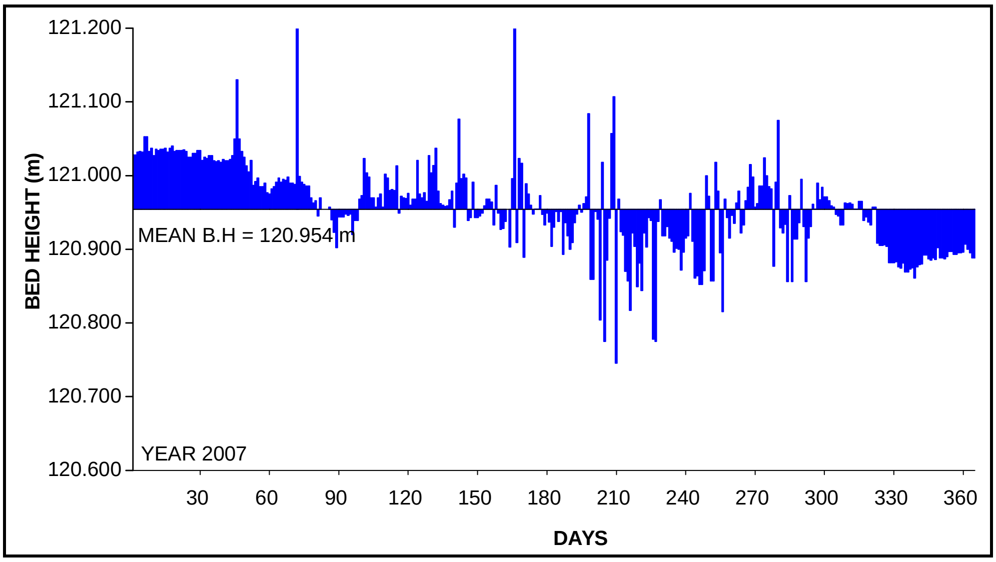
3.3.4 Study of the bed height (m) Variability

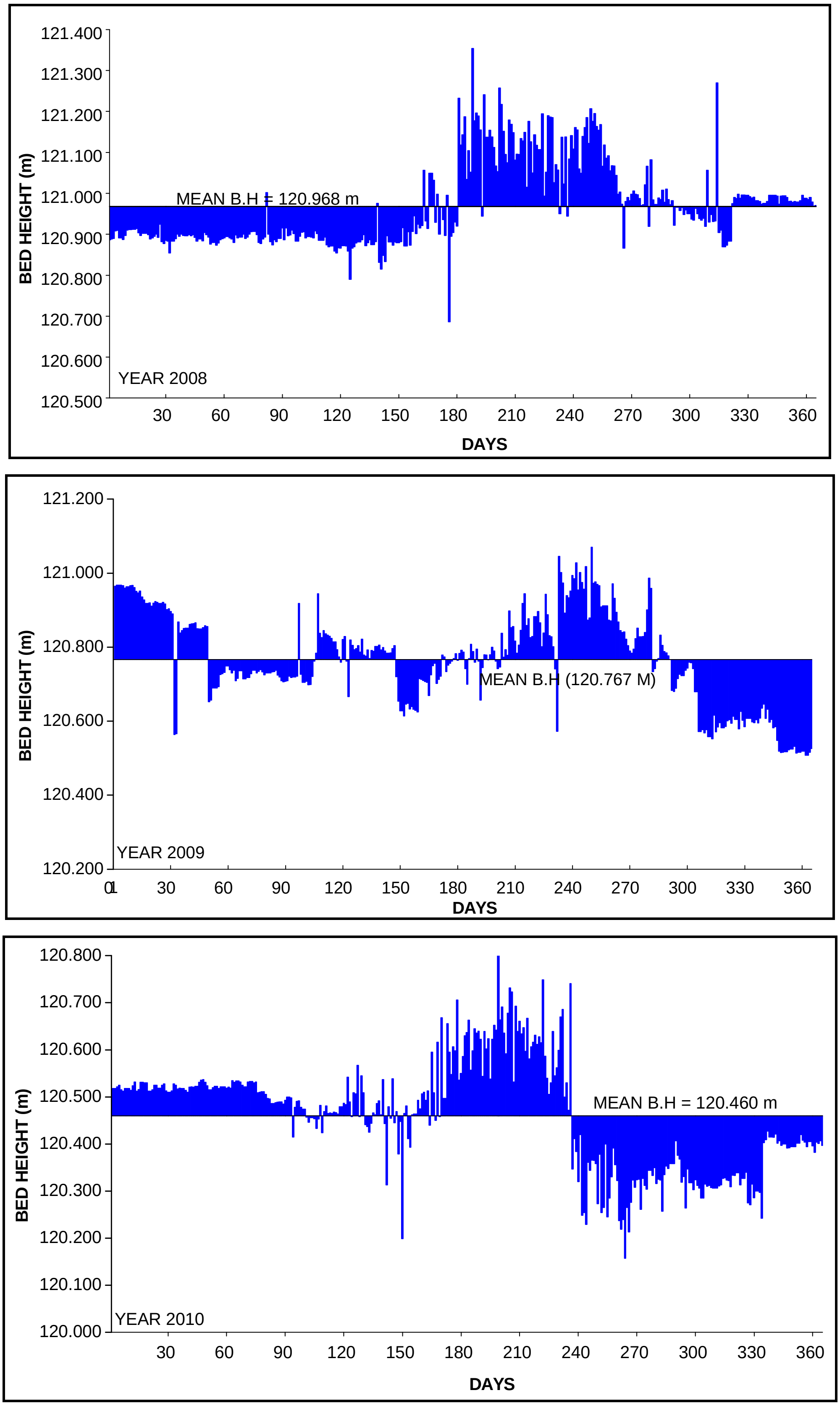
In this section, the researcher has attempted to show the variability of bed height of the lower Balason river which has been calculated from the Water level and Hydraulic Mean Depth (HMD) data collected from CWC G&D Site, Matigara during 2007 to 2010.

Bed Height (m) = *Water Level (m) - Hydraulic Mean Depth (m)*

In figure 3.11, the daily bed heights above and below the annual mean has been plotted to show the variations of bed heights in both monsoon and non-monsoon period from 2007 to 2010. During 2007, the annual mean bed height was 120.954 m with the annual maximum of 121.213 m on 15.06.2007 and the minimum was 120.745 m on 29.07.2007. The mean bed height varied from 120.933 m during monsoon period to 120.969 m during non-monsoon period. In 2008, the annual mean bed height was 120.968 m with the maximum bed height of 121.345 m on 06-07-2008 and minimum bed height of 120.686 m on 24-06-2008. The mean bed height from monsoon period was 121.047 m and for non-monsoon period the mean bed height was 120.913 m. For 2009, the annual mean bed height was 120.767 m with the maximum bed height of 121.072 m on 07-09-2009 and the minimum bed height of 120.508 m on 28-12-2009. The mean bed height varied from 120.813 m during monsoon period to 120.734 m during non-monsoon period. During 2010, the annual mean bed height was 120.460 m with the maximum bed height of 120.898 m on 18-07-2010 and the minimum bed height of 120.213 m on 23-09-2010. The mean bed height varied from 120.465 m during monsoon period to 120.457 m during non-monsoon period.

The variability shows that the trend of increasing or decreasing bed height has no rhythm and almost throughout the year the bed height remains more or less same with only slight increase during monsoon period. The annual mean bed height variation were +0.014 m, -0.201 m and -0.307 from 2007 to 2010 which may be attributed to the bed lowering or incision due to anthropogenic factors rather than natural.



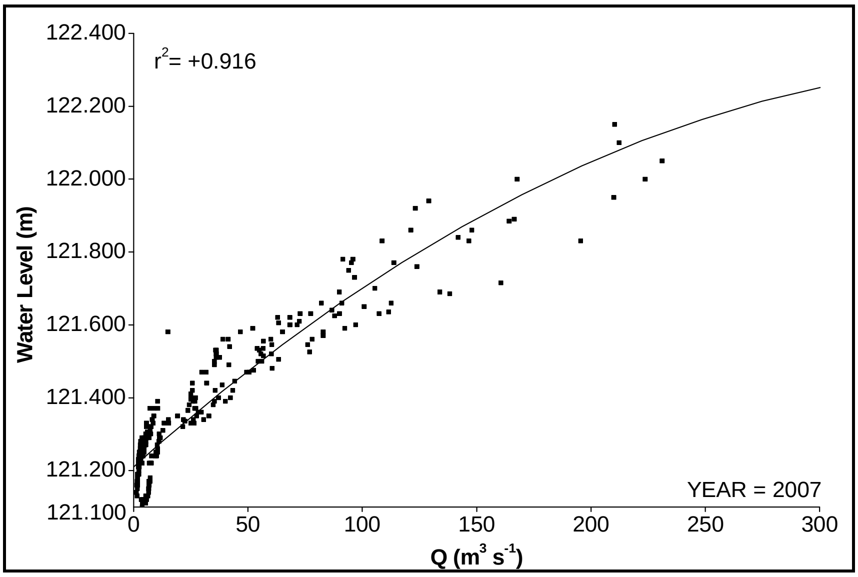


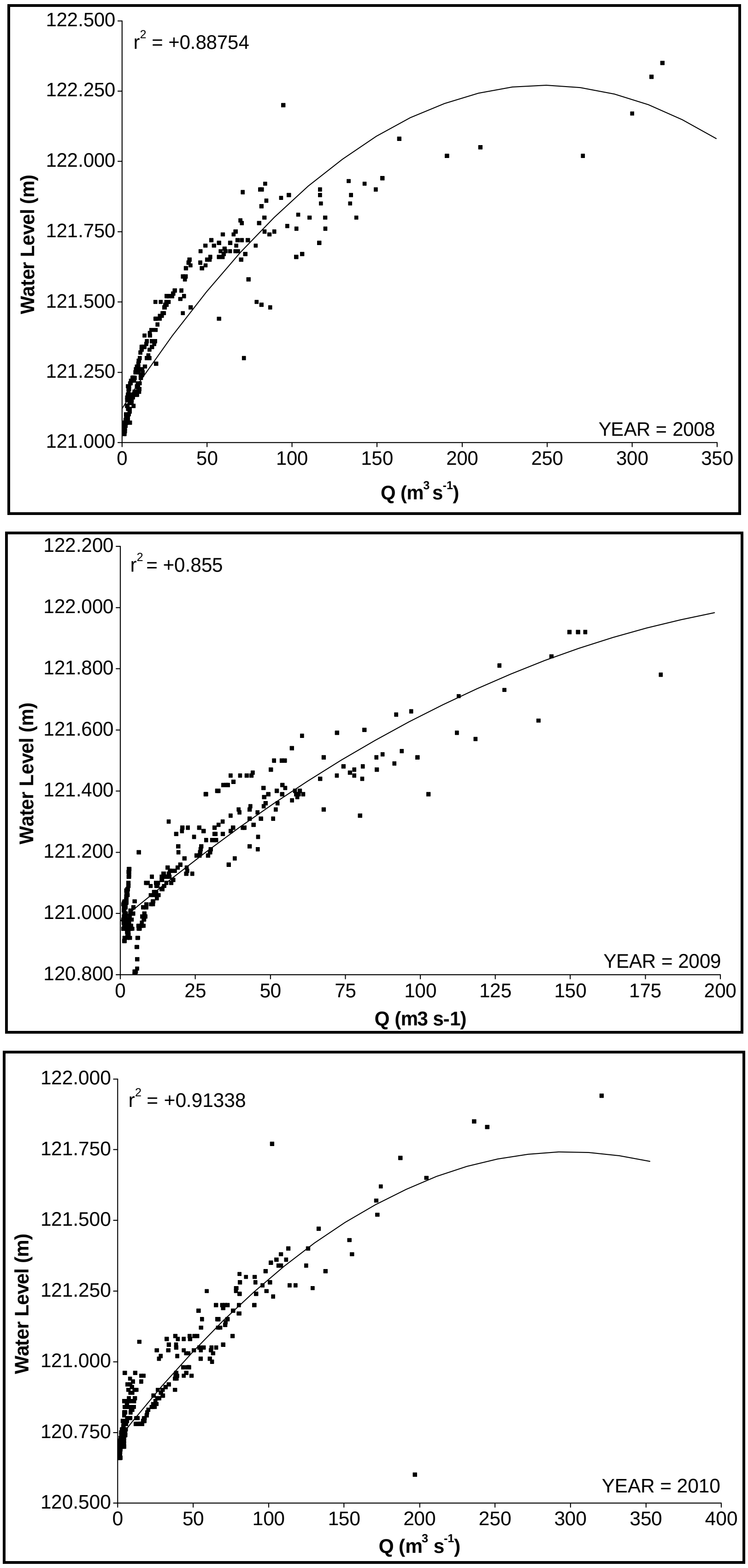
(Computed by the researcher based on data collected from CWC G&D Site, Matigara)

Figure 3.11 Daily bed height (m) distribution of the lower Balason river during 2007 to 2010.

3.3.4 Study of the discharge - water level relationship during 2007 to 2010

To study the relationship between the daily volume of water and corresponding water level at CWC G&D Site, Matigara from 2007 to 2010 the rating curve has been used (figure 3.12). The correlation co-efficient values (r) were 0.916 for 2007, 0.887 for 2008, 0.855 for 2009 and 0.913 for 2010. The values for coefficient of determination (r^2) are calculated 0.852 for 2007 its value will be, followed by 0.759 for 2008, 0.797 for 0.834 for 2010. Thus from these analysis, we may state that the water level or gauge height of lower Balason river has positive correlation with total volume of water passing through the CWC G&D Site, Matigara which is largely dependent up on the rainfall intensities over its upper catchment. Although due to the location of the CWC G&D Site, the actual volume of water does not reach till that point since the river after entering into the lower course adjusts within its wide flood plains composed mainly of sand, silt and gravels (Lama, 2003).



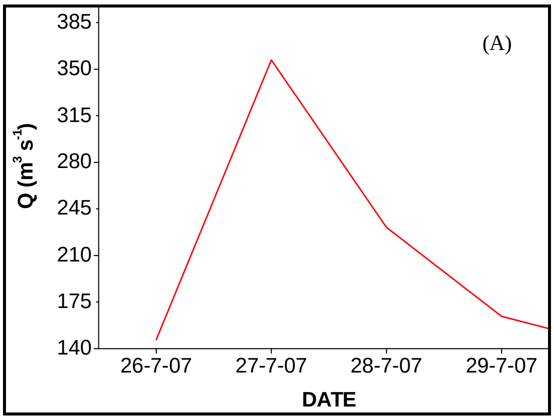


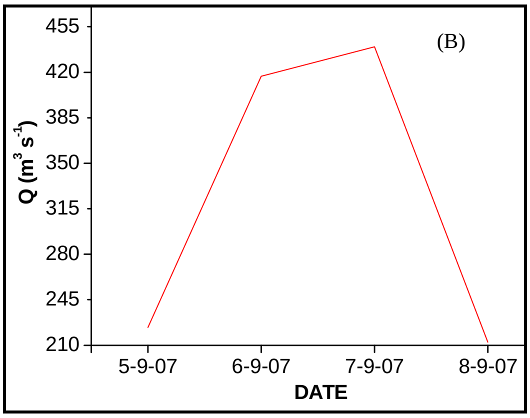
(Computed by the researcher based on data collected from CWC G&D Site, Matigara)

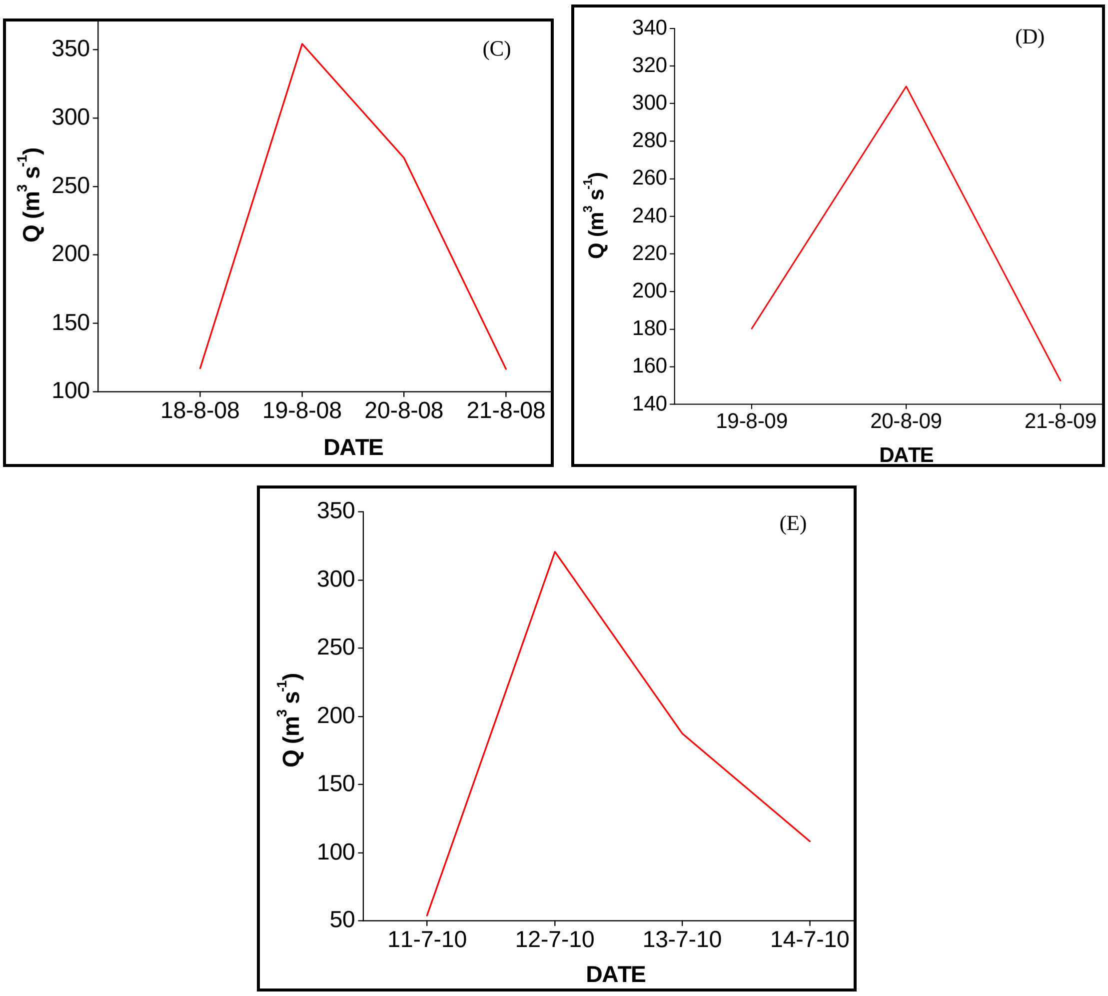
Figure 3.12 Discharge - Water Level Rating curve of the lower Balason river for the year 2007 to 2010.

3.3.5 Study of the Peak flow characteristics of the lower Balason river

With high annual rainfall intensities (2500-3000 mm) in its upper catchments the nature of flow in the lower course of Balason river during monsoon period are coupled with few spells of peak flows inducing floods in its lower reaches. During 2007, the peak flow spell was attained 5 (five) times out of which 2 spells continued for more than a day. The first peak flow spell occurred from 26-07-2007 to 29-07-2009 with maximum peak discharge of 356.700 $m^3\ s^{-1}$ (figure 3.13 A). Another peak flow spell also remained for 4 (four) days from 05-09-2007 to 08-09-2007 with the maximum peak discharge of 439.600 $m^3\ s^{-1}$ (figure 3.13 B). In 2008, only a single peak flow spell could be noticed which occurred from 18-08-2008 to 20-08-2008 with maximum peak discharge of 354.200 $m^3\ s^{-1}$ (figure 3.13 C). During 2009 the peak flow spells occurred during 19-08-2009 to 21-08-2009 with maximum peak discharge of 309.200 $m^3\ s^{-1}$ (figure 3.13 D). In 2010 the peak flow spell occurred during 11-08-2010 to 14-08-2010 with maximum peak discharge 320.700 $m^3\ s^{-1}$ (figure 3.13 E).







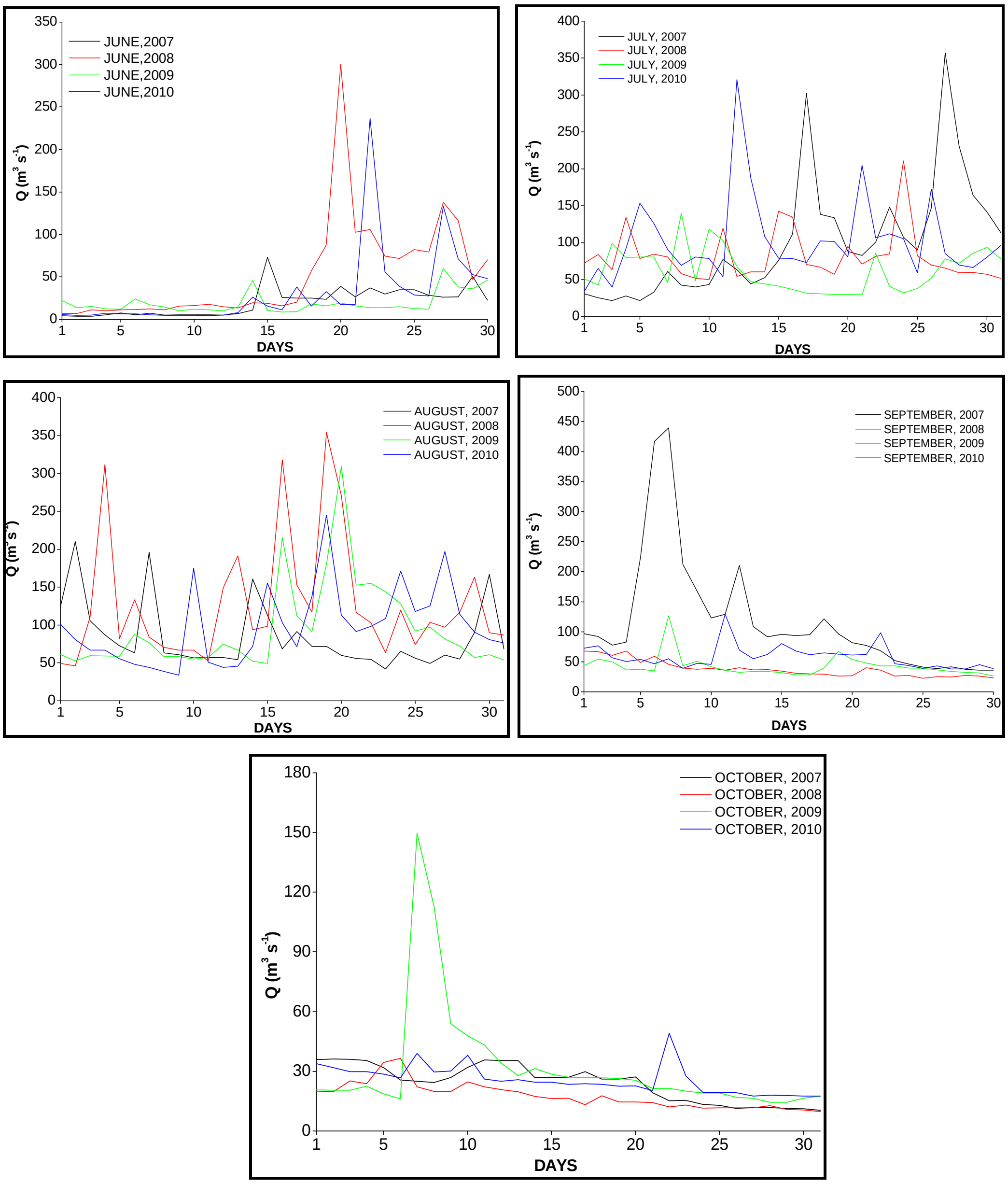
(Computed by the researcher based on data collected from CWC G&D Site, Matigara)

Figure 3.13 Peak flow Hydrographs showing the peak discharge (m^3 s^{-1}) of the lower Balason river for the year 2007 to 2010.

3.3.5.1 Study of the monthly Peak flow characteristics

As it has been mentioned in previous sections that the monsoon period carries more than 90% of the total annual volume of water as the river follows the rainfall pattern, the analysis of the peak flow during this period reveals the formation of short steep rise in discharge and consequent water level due to high flow storage capacity during high intensity rainfall (Starkel and Basu, 2000). Such conditions favours the occurrences of floods in its lower reaches (1998, 2002). During 2007 to 2010, the peak flow characteristic clearly shows the frequent rising and falling of flow discharge within a single monsoon month (figure 3.14). The variation in total discharge in a single month from June to October were 5.26%, 26.96%, 22.52%, 30.59% and 6.48%

respectively of the total annual discharge of 2007. In 2008 the variations were 7.37%, 23.73%, 37.34%, 10.82% and 5.19% respectively of the total annual discharge. The variations in total monthly discharge from annual total discharge were 6.69%, 22.33%, 33.83%, 14.85% and 9.20% respectively during 2009 and 8.81%, 29.83%, 28.37%, 16.54% and 7.53% respectively during 2010. Thus it may be noticed that annual peaks mostly reaches during the month of August showing several peak flows causing channel modifications and floods.



(Computed by the researcher based on data collected from CWC G&D Site, Matigara)

Figure 3.14 Peak monthly discharge ($m^3\ s^{-1}$) during monsoon period (June – October) of the lower Balason river from 2007 to 2010 *(Refer Appendix table 3.5).*

3.3.6 Study of the flood frequency

The procedure involved in interpreting dynamic hydrologic events is known as frequency analysis. There are several methods of frequency analysis and most of them uses the statistical distribution. Flood frequency analysis of the lower Balason river has been attempted in this section in order to estimate the flood of various return period at CWC G&D Site, Matigara. Once a return period-flood magnitude relationship is fitted to a data series, flood magnitude may be worked out of any return periods. For analysis of flood frequency two types of data series are computed, namely, Annual Peak flood series (AP) and Partial Duration series (PD) (Chow, 1964). Annual peak flood series is the highest annual discharge of each year. The major disadvantage of this using this series (AP) for analysis is that the second or third highest events in a particular year may be higher than some of the annual peak floods and still they are totally disregarded in this analysis. Such a disadvantage is remedied by using Partial Duration series (PD) for all the events above a certain threshold value in the analysis, which can be used in this study. All the flood events more than 150 $m^3\ s^{-1}$ magnitudes collected from CWC G&D Site, Matigara has been considered for analysis using partial analysis series.

The extreme value distribution introduced by Gumbel (1941) based on frequency factor (K) has been used for the flood frequency analysis of the lower Balason river in which the general equation used is as follows:

$X = x + K$, where,

X = the flood magnitude of a given return period (T)

x = the mean of the annual peak flood series

K = the frequency factor.

Again, $K = (y_T - y_n) / \delta_n$ where

$y_T = -\ln\ln (T/T-1)$

y_n = Expected mean

δ_n = Standard deviations of reduced extremes to be found from Gumbel's table.

The frequency factor (K) has been determined based on the values obtained from Gumbel's table *(Ref. Appendix B Table 2)*

y_n = 0.5268 and

δ_n = 1.0754

Based on the above equations, the flood discharge of lower Balason river for different return periods has been calculated and given in Table 3.6 A&B for CWC G&D Site, Matigara.

Sl. No	**Year**	**Peak Q (m^3 s^{-1})(X)**	**X-x**	**$(X- x)^2$**	**$(X-x)^3$**
1	1989	378.100	-10.215	104.356	-1066.039
2	1990	415.200	26.885	722.779	19431.579
3	1991	903.800	515.485	265724.317	136976778.560
4	1992	182.600	-205.715	42318.848	-8705641.101
5	1993	251.300	-137.015	18773.235	-2572223.297
6	1994	173.400	-214.915	46188.653	-9926655.269
7	1995	619.600	231.285	53492.541	12371998.023
8	1996	472.000	83.685	7003.103	586051.504
9	1997	312.900	-75.415	5687.491	-428924.703
10	1998	364.700	-23.615	557.690	-13170.096
11	1999	510.800	122.485	15002.464	1837569.968
12	2000	216.400	-171.915	29554.924	-5080948.110
13	2001	315.200	-73.115	5345.870	-390865.693
14	2002	152.000	-236.315	55844.994	-13197035.155
15	2003	1050.000	661.685	437826.438	289702987.413
16	2004	330.300	-58.015	3365.793	-195268.009
17	2005	202.700	-185.615	34453.097	-6395027.254
18	2006	409.700	21.385	457.299	9779.127
19	2007	439.600	51.285	2630.105	134883.719
20	2008	354.200	-34.115	1163.864	-39705.758
21	2009	309.220	-79.095	6256.091	-494828.356
22	2010	320.700	-67.615	4571.850	-309127.695
	Total	**8542.940**			

Mean (x) 388.315

(Computed by the researcher based on data collected from CWC G&D Site, Matigara)

Table 3.6A Details of Annual peak Q of the lower Balason river at CWC G&D Site, Matigara from 1989 to 2010.

The flood frequency analysis based on Gumbel's method show that the return period for the maximum peak Q of 1037.350 $m^3 s^{-1}$ is predicted to be more than 1000 years and also the annual average peak Q (330.903 $m^3 s^{-1}$) is predicted to occur after almost every year which has been clear from the previous sections (3.3.5). Although the above analysis shows the frequency of occurrences of peak Q as a very rare event, but it might not be the actual scenario as the total volume of the water could not always pass through the channel where site for observation is located.

SL. NO	RETURN PERIODS (Year)	y_T	K	Q ($m^3 s^{-1}$) X_T
1	2	0.367	-0.123	375.889
2	10	2.250	1.760	566.337
3	25	3.199	2.709	662.320
4	50	3.902	3.412	733.422
5	100	4.600	4.110	804.018
6	1000	6.907	6.417	1037.350

(Computed by the researcher based on data collected from CWC G&D Site, Matigara)

Table 3.6B The predicted flood discharge (Q) for different return periods based on Gumbel's method.

3.4 Conclusions

The study of the fluvial characteristics of the lower Balason river considering its morphological and hydraulic characteristics shows that the river adjusts within the changing fluvial conditions through the scouring and filling phenomenon but the effects of anthropogenic disturbances like construction of bridges, embankments and artificial bank protection structures could be clearly seen in its form. Besides, the channelization of the river flow due to extraction of bed materials from the river bed and adjacent flood plains and terraces is also largely hampering the morphological characteristics of the river.

The hydraulic nature of the lower Balason river characterised by high rainfall intensities with fluctuating discharge and surface run-off proves that the river is still active in its fluvial processes. Although the low channel flow during non-monsoon period reduces the transporting capacity (plate 3.1B, D & F) but due to frequent outburst of monsoon peak flows increments the channel run-off and capacity inducing varied bed erosion (plate 3.1A & C). The channel flow at lower reaches also migrates frequently abandoning the pervious path. Such act of river is also encouraging the anthropogenic control in the form of bed materials extraction and human encroachment of flood plains and banks.

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Plate 3.1 The monsoon flows above (A) and below (C) Panighata Bridge in the upper piedmont segment, above Matigara bridge (E) in the middle segment and the reduction of channel flow during non-monsoon period over the same places (B, C & D). (Photographs by the Researcher)

Plate 3.2 The constriction of monsoon below bridges at Dudhai bridge (A) and Marigara bridge (B) and its uninterrupted monsoon flows causing inundations (C & D) in the lower segments; the CWC water level measurement site below Matigara bridge (E) and the field measurement of channel depth by the researcher (F).

CHAPTER 4

Sediment Distribution: Nature, Extent and Mechanism

4.1 Introduction

Self-formed streams receive their sediment supply almost entirely from upstream (fluvial) sources, the local bed, and erosion of banks composed of sediment transported under the current transport regime. Stream morphology and sediment sizes are exclusively controlled by the interaction between flow and sediment. Consequently, the streambed does not contain particles larger than that can be moved during the highest floods. The transport of sediments downstream is dependent on the characteristic of the supply catchments (geology, soil, topography, and land use), the type of sediment being released and the hydrology of the river (Ankers et al, 2003).

Coarse material transported by a river (bed load) commonly is moved by rolling, sliding, or bouncing along the channel bed. There is a large amount of uncertainty in the process of calculating annual rates of bed load transport. How much coarse material is moved, how long it remains in motion and how far it moves depends on the size, shape, and packing of the material and the flow characteristics of the river. Downstream movement commonly occurs as irregular bursts of short-distance movement separated by longer periods when the particles remain at rest. Because bed load changes from hour to hour, day to day, and year to year, estimating annual bed load rates is a dynamic process involving careful examination.

The Balason river is noteworthy for its transporting capacity of huge volume of coarse materials as bed load. The catchment characteristics with high rainfall intensities, and decreasing vegetative coverage inducing surface run-off and occasional landslides have incremented the delivery of colluvial masses including big boulders and gravels causing aggradations in middle and lower reaches of the Balason river (Starkel and Basu, 2000) (plate 4.2C). In its lower course, the decrease in the flow velocity of the river with subsequent fall in the gradient and braiding nature, the competency and transportation ceases and the assorted deposition of the load carried by the river begins (plate 4.1A & B).

In this chapter the sediments size, characteristics and its distribution along the lower course of the Balason river have been studied based on the field surveys and analysis of nature, extent and mechanism with the help of data on surface sediment distribution and suspended sediment collected by the researcher from 2008 to 2010 and also recorded at CWC G&D Site, Matigara. Such analysis have been validated and properly interpreted following the literatures available and its relationship with the fluvial characteristics of the lower Balason river.

4.2 Sediment sources

The sediment sources in the Himalayas are widely considered to be the glacial debris and landslides but there are only few data available on the relative contribution of sediments from either source. In some parts of the Himalayas visual observations suggests that glacial debris is the major source materials while in other parts landslides appear to be the major sources (Jhonson and Collins, 1983). Quaternary sediments in the eastern Himalayan foothills un-conformably overlie the Siwalik group of rocks and older metamorphic units like Daling group or Darjeeling Gneiss near the mountain front (Acharrya and Shastry, 1979). Three distinct groups of Quaternary sediments occur in the eastern Himalayan foreland in the Darjeeling and Jalpaiguri districts of West Bengal, India (Chakraborty and Ghosh, 2010). These are: (a) coarse gravely piedmont sediments lying close to the mountain front and at places extending few kilometres inside the mountain valleys; (b) pebbly, coarse to fine sand and mud related to the mega fans and (c) gravel, sand and clay deposited in the modern river valleys (Shukla et al, 2001). The fact that these thick beds overlies the northward dipping Siwalik (Pliocene Pleistocene) strata at the base of the eastern Himalayas indicates that the boulder formation originated sometimes in the Pleistocene after the uplift, lilting and partial denudation of the Siwalik (Basu and Sarkar, 1990). It is thus evident that during the Pleistocene, when the higher parts of the Darjeeling

Himalayas were experiencing widespread glaciations, the Manebhanjyang-Sukhiapokhari-Ghoom range was subject to periglacial conditions. During this period, Balason, the main stream, together with its tributaries Rakthi and Rohini, brought down a great volume of periglacial debris and solifluction materials which eventually were deposited as coalescing alluvial fans at their outlets (Kar, 1962, 1969). Such sediments have become finer grained and more rounded with greater quartz and mica composition as the river settles its load after the erosional threshold ceases. The occurrence of cobbles, gravels and boulders with subordinate amount of sand, silt and some clay in the Balason-Rakti-Rohini fan has been deposited by the intermittent flash floods, stream action, stream floods and mass-movements (Basu and Sarkar, 1990).

4.3 Study of the coarse sediments (>2 mm) in the lower Balason river

The river bed sediment distribution analysis is essential for understanding the hydraulics and other river characteristics such as bed-load transport rate, sediment budget, and habitat description. Accurate sediment sampling can be an important component of identifying changes in bed composition due to varied flow conditions and environmental factors.

In this section, the researcher has attempted the coarse sediment sampling following the Grid sampling method of Wolman (1954) at an interval of 1 km along the lower course of Balason river during pre-monsoon and post monsoon periods from 2008 to 2010. Since the river bed is mostly composed of boulders, gravels and pebbles which are extensively lifted along the entire lower Balason, hence the researcher in this study has considered only a single grid of 1 m^2 over reaches where the bed material extraction has not been carried. Within the grid prepared, the sediments intermediate axis is measured in mm (figure 3.2) and the process is repeated until the desired number of samples have been sampled and measured, with 100 samples being the generally accepted guideline (plate 4.1D, E & F). The obtained sizes were arranged in a frequency distribution table with a Wentworth scale showing only class limits. The mean of all the sample sizes from each grid are further used to represent the mean coarse sediment distribution at each site (1 km interval) along the lower course of the Balason river.

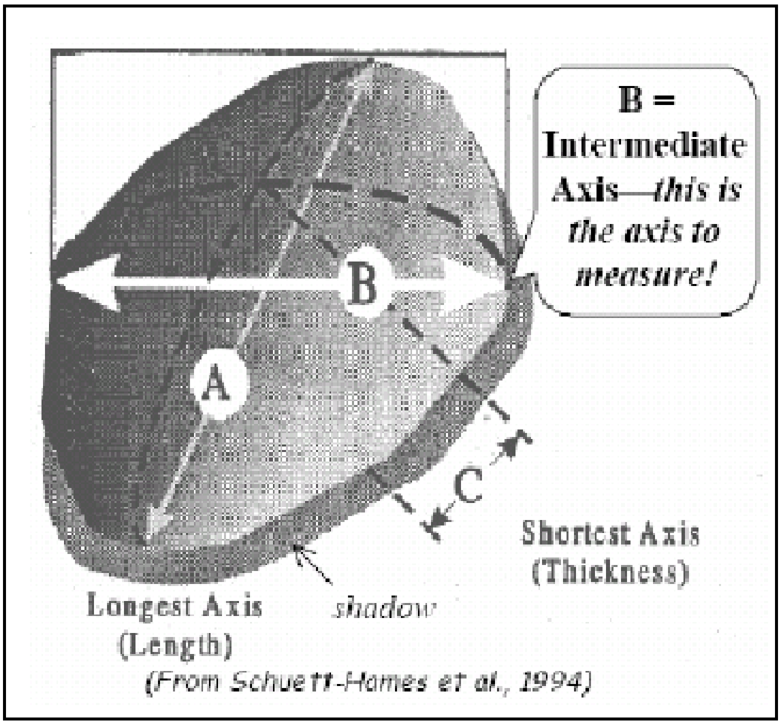
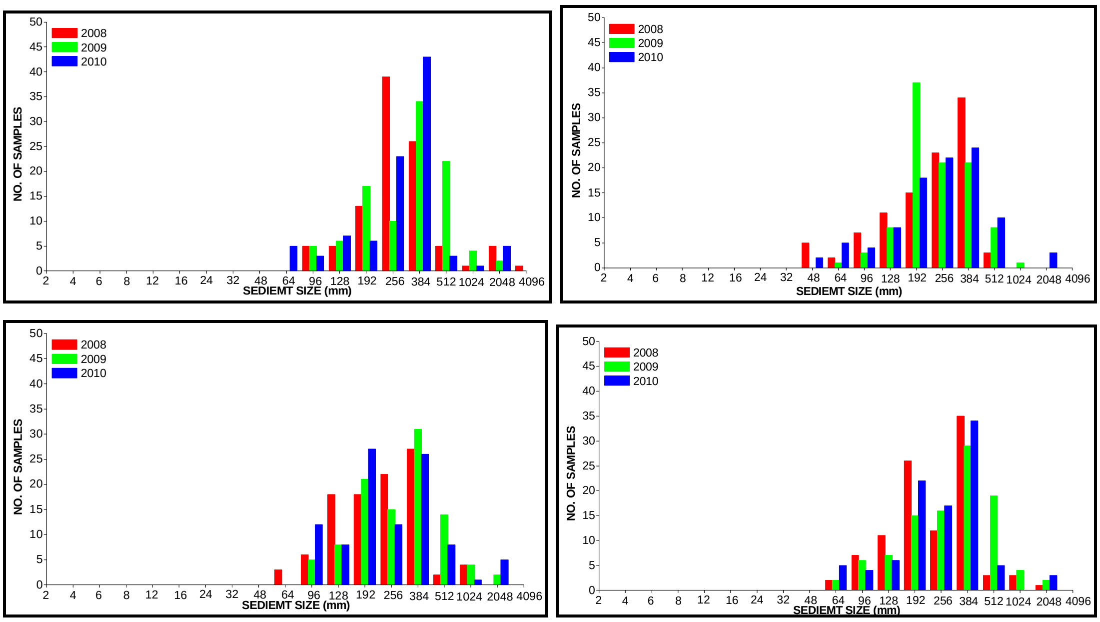
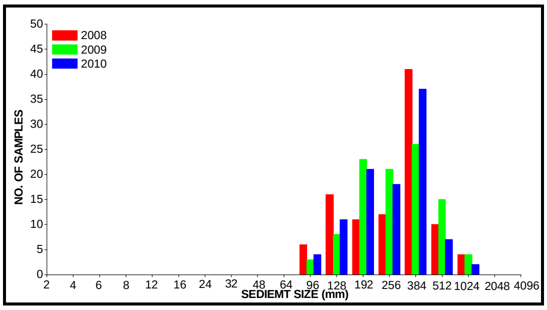


Figure 4.2 The different axis of the pebbles used for measuring its size.

PRE-MONSOON SAMPLING POST-MONSOON SAMPLING

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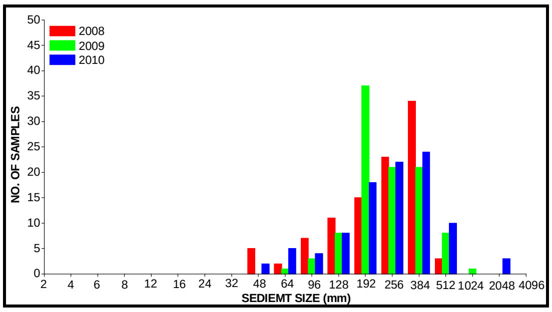
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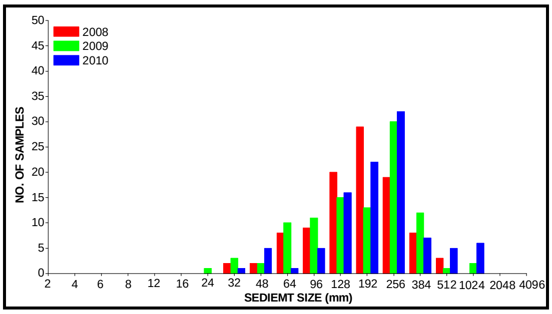
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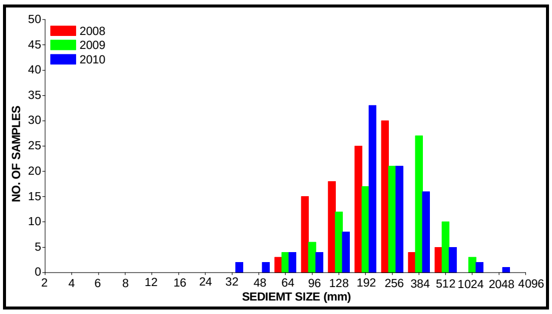
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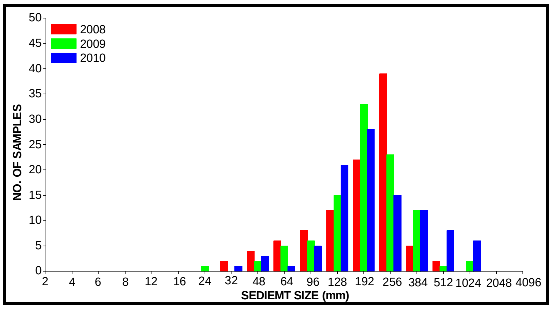
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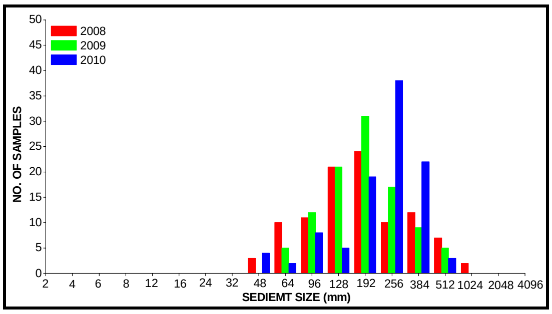
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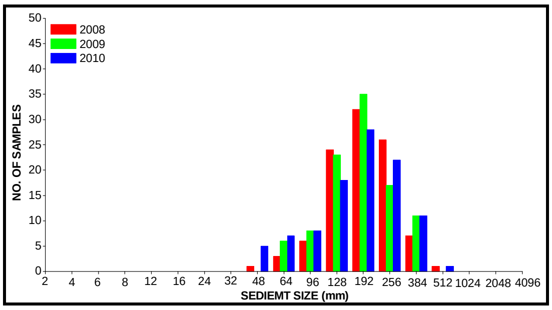
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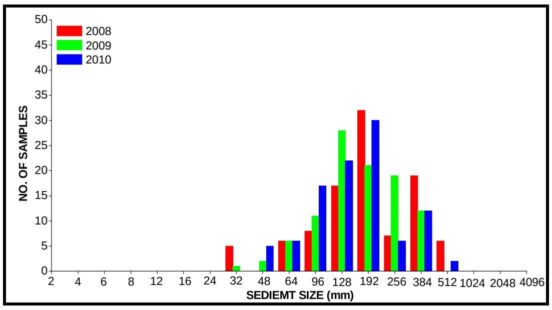
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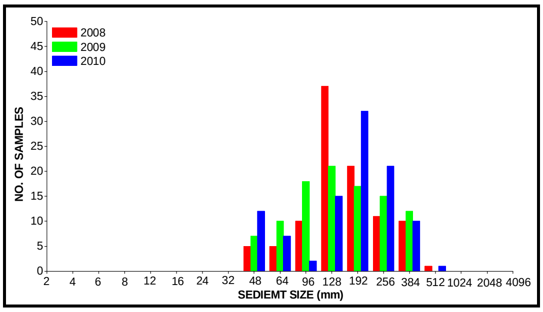
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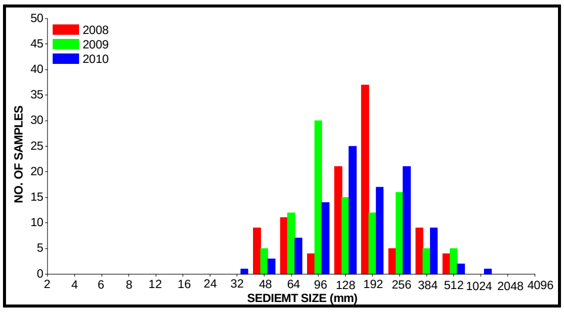
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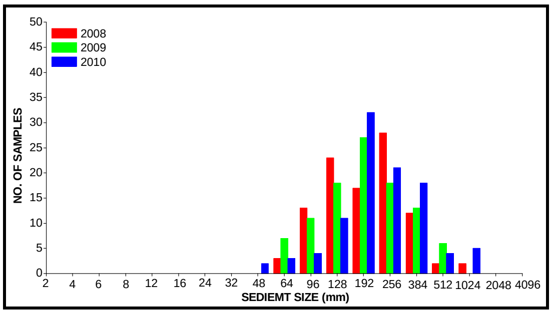
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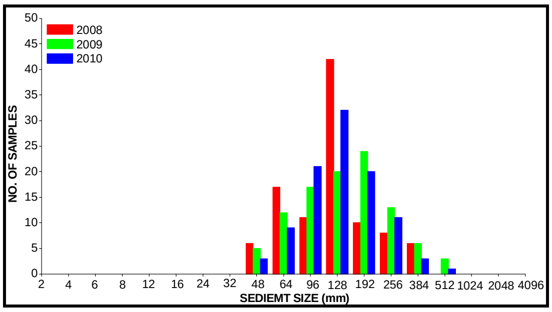
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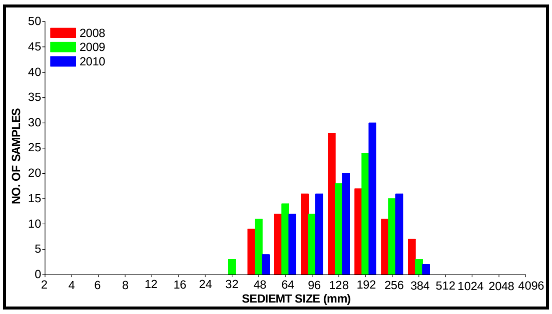
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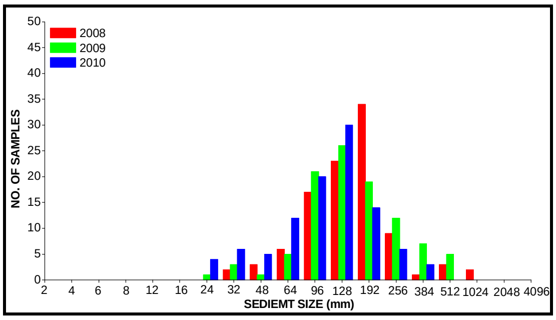
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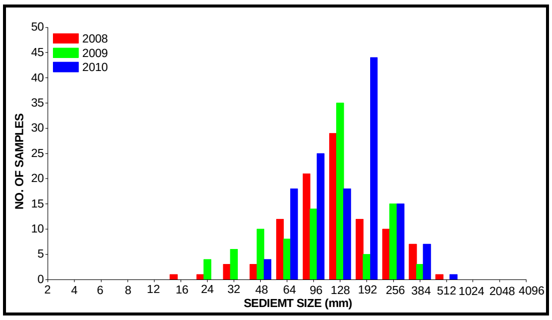
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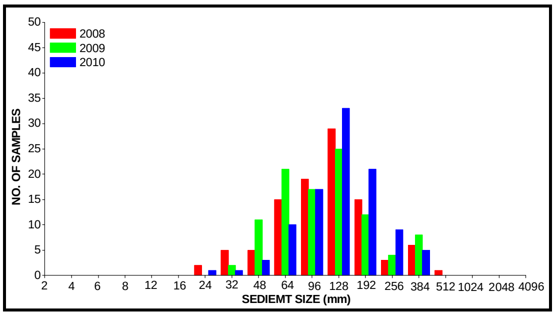
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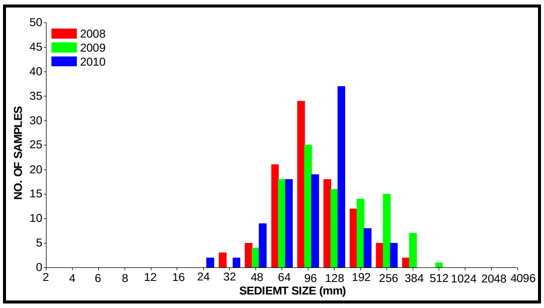
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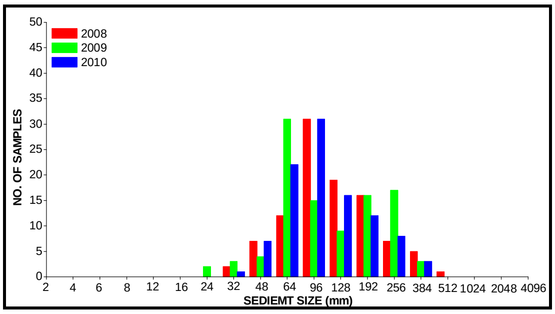
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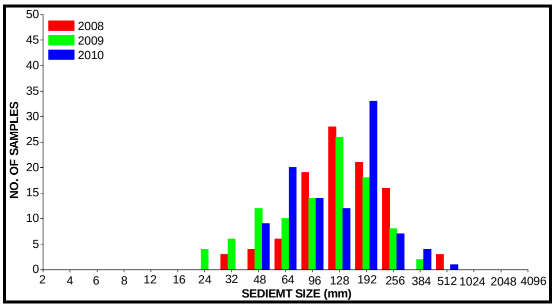
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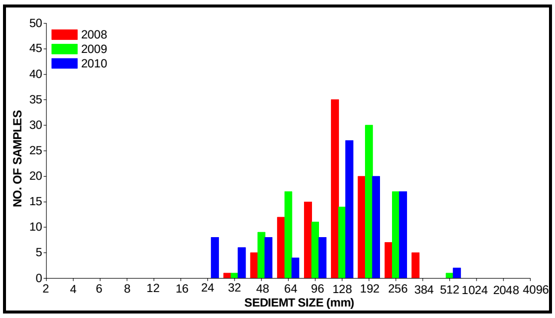
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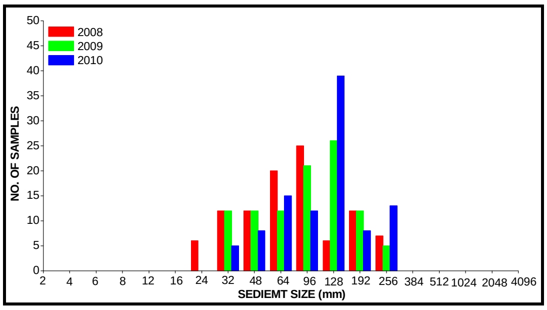
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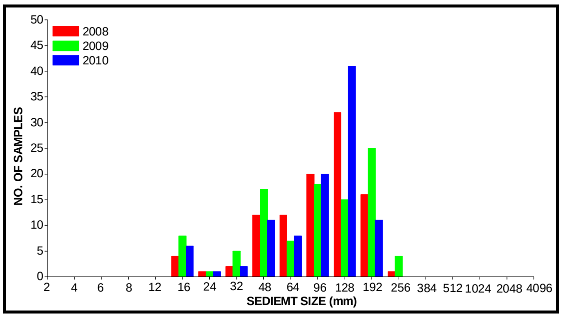
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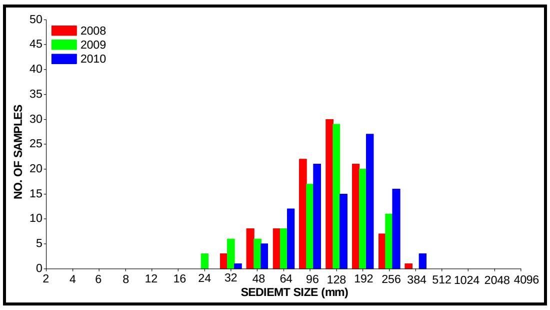
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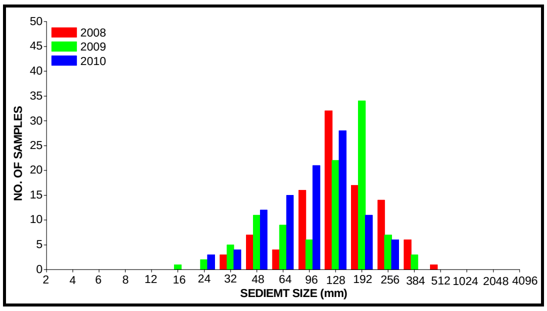
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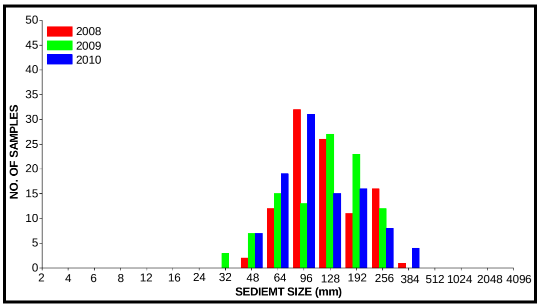
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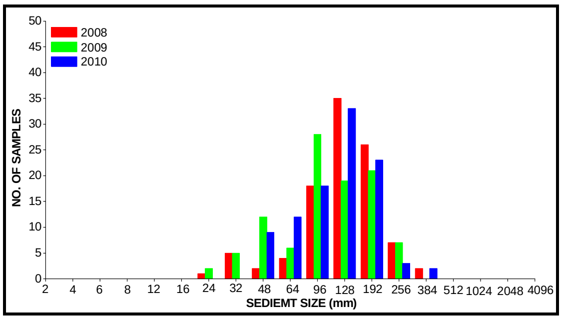
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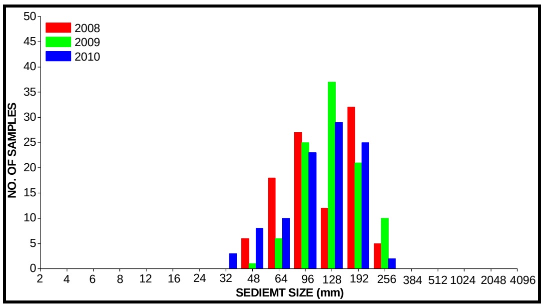
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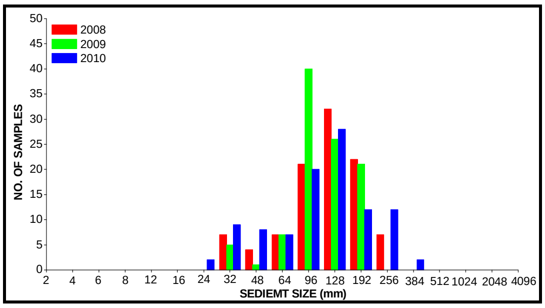
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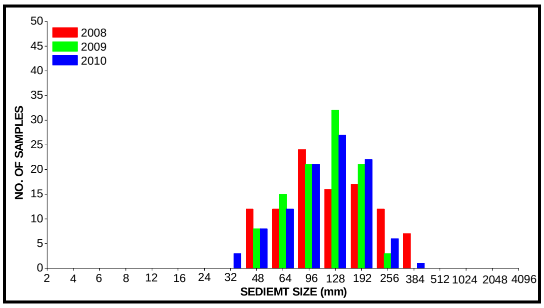
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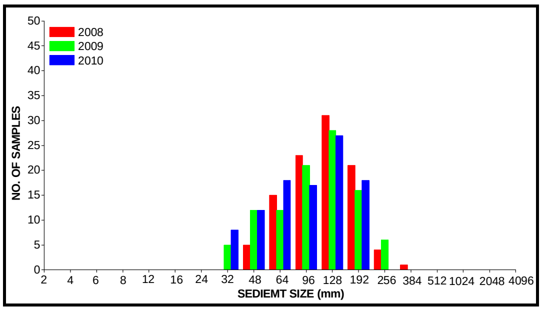
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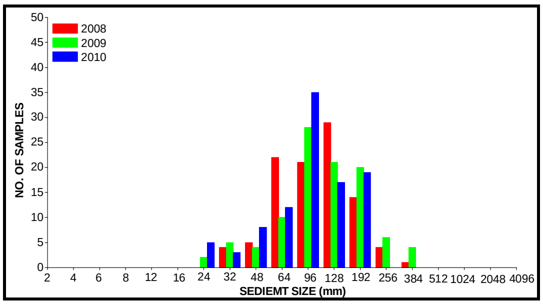
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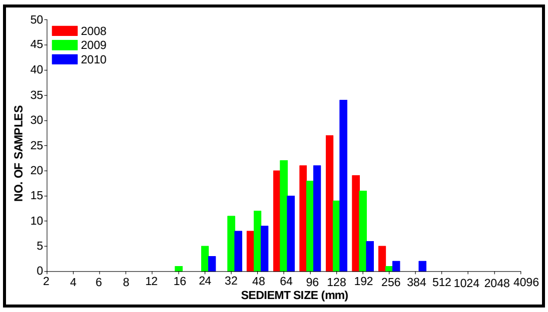
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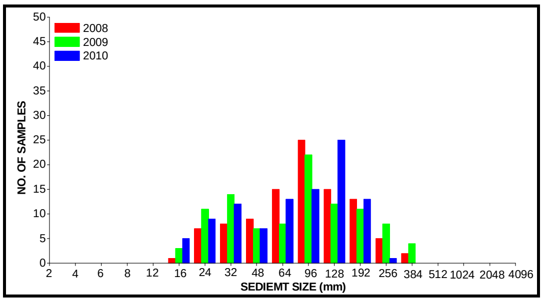
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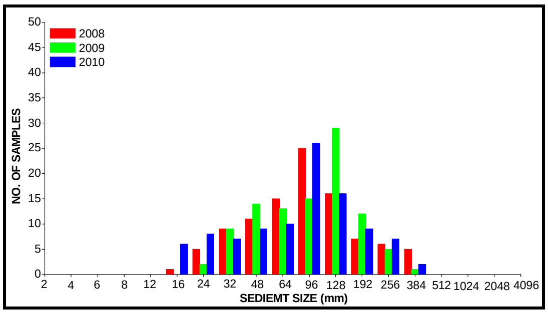
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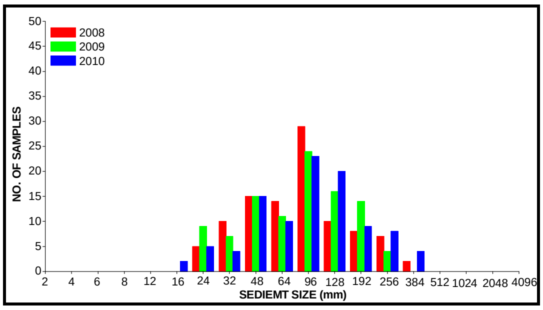
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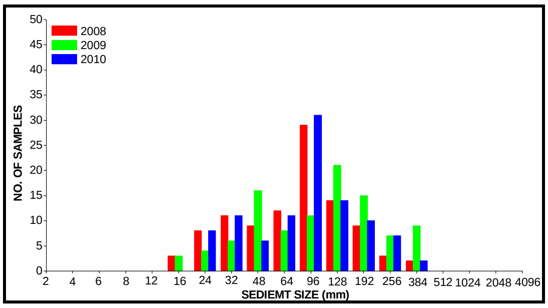
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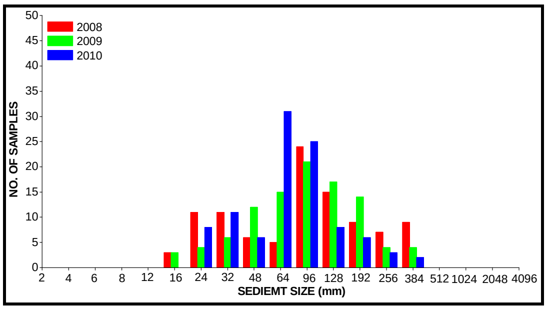
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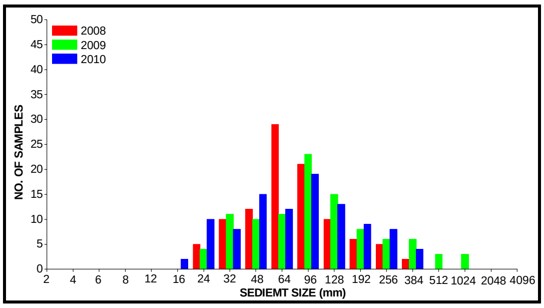
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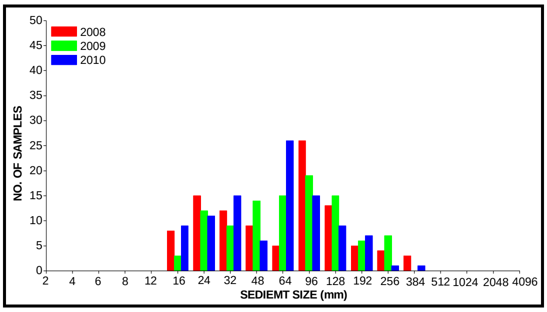
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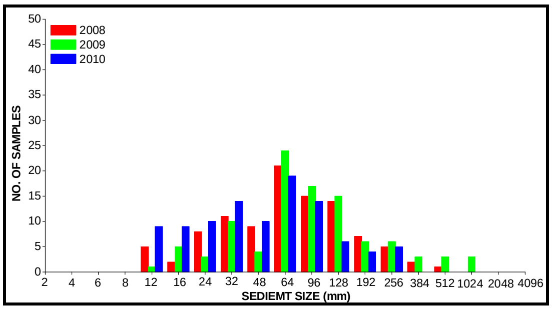
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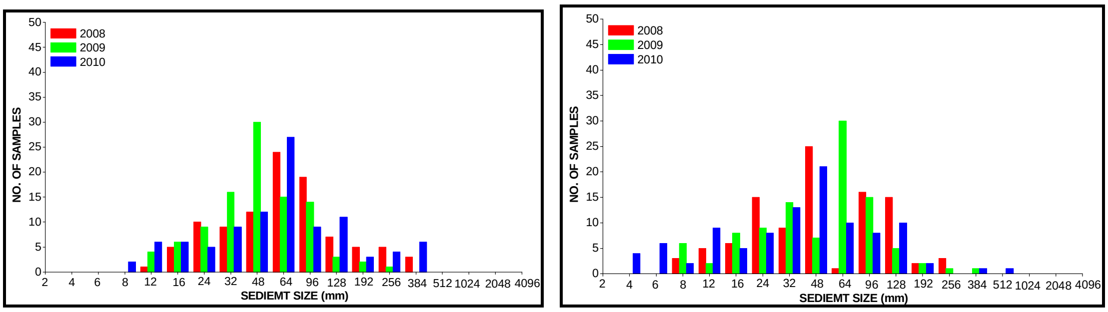


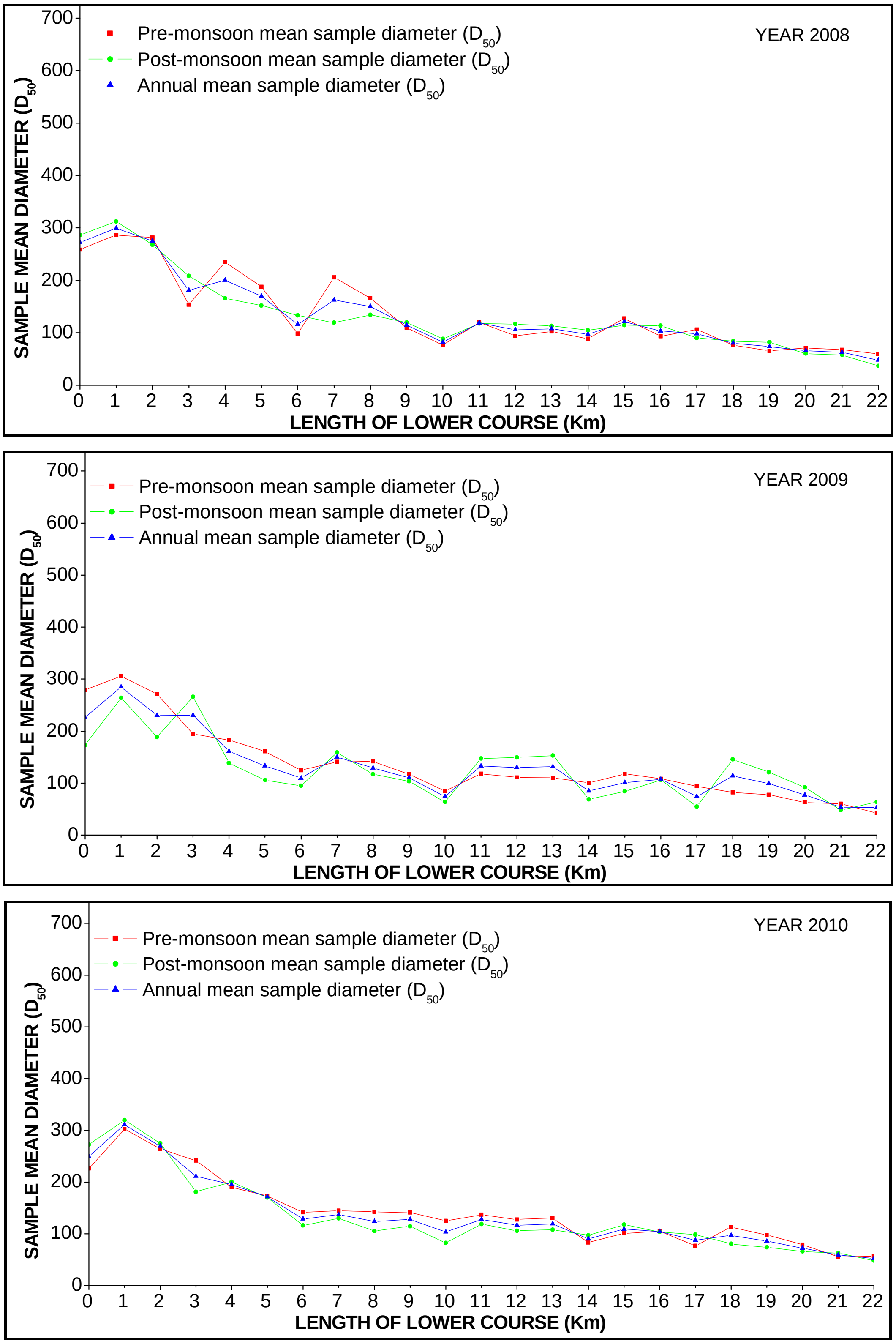
(Based on field survey)

Figure 4.3 The distribution of coarse sediments (>2 mm) at sites (1 km interval) along the lower course of Balason river during 2008 to 2010.

The study of coarse sediments reveals that the sediments ranging from boulders (512 - >4096 mm) in its upper segment, Cobbles (96 – 128 mm) and gravels (12 – 96 mm) in middle segment and sand and silt (2 – 12 mm) are distributed unevenly throughout the lower course of Balason river (figure 4.3). The segments upto 4 km downstream of the Panighata bridge has un-assorted boulders with largest diameter of more than 1.5 m and plenty of medium and small diameter boulders. The presence of such boulders indicates the river's competency to transport sediments from its upper sediment sources as well as the intensity of extreme floods carrying heavy debris flow. Below these segments upto the Matigara Bridge (18 km downstream) the cobbles and gravels (32 – 256 mm) are found in large quantities mixed with coarse sand with medium boulders (512 – 1024 mm). In this segment of the lower Balason river there is maximum extraction of bed materials and due to this the sorting of coarse sediments are also hampered. Mostly the cobbles and gravels are extracted which are river processed and readily available for construction purposes. Although the extent of bank failure in this segment indicates the river's adjustments as the deficit sediment are being added to the river from such exposed banks. In the segment below Matigara bridge till the confluence with Mahananda river the coarse sediments also decreases in size with ample of medium to small gravels (12 – 96 mm). The coarse sand is abundantly available and decrease in the amount of cobbles and gravels reveals that the river starts depositing the finer suspended sediments in the form of sand, silt and clay. Also few boulders (512 – 1024 mm) are scattered along this segment probably brought down during extreme flood time.

4.3.1 Study of the distribution of mean coarse sediments (D_{50}) in the lower Balason river during 2008 to 2010

The analysis of the mean coarse sediments (D_{50}) in each site along the lower course of the Balason river, which has been calculated based on the mean diameter (D_{50}) of the total samples of each grid shows that it ranges from largest 319.323 mm to smallest of 36.755 mm (figure 4.4). The mean coarse sediment for the entire lower Balason river was 134.892 mm, 130.383 mm and 136.728 mm during 2008, 2009 and 2010. The variation of mean coarse sediments in different sites of 1 km interval during pre and post monsoon from the annual D_m shows that the upper segments (up to 8 km below) and segments near Matigara bridge (18 km below) had maximum of 86.356 mm (7 km below, 2008) and minimum of 32.002 mm (18 km below, 2010). Although such changes in D_m could not be directly related to channels annual adjustments but it was noticed that mostly sections with maximum human interferences (boulder lifting activities) shows that the coarse surface sediments are lifted and also bed and bank erosion is prevalent. Hence it could be ascertained that despite of river's own adjustment under human interferences, the competency and sorting of coarse sediments is highly uneven along the lower course of Balason river.



(Computed by the researcher based on field survey)

Figure 4.4 The distribution of the mean sample diameter (D_{50}) of the coarse sediments (>2 mm) at sites (1 km interval) along the lower course of Balason river during 2008 to 2010 *(Refer Appendix C table 4.1, 4.2 and 4.3).*

4.3.2 Study of the relationship between fall or settling velocity ($m\ s^{-1}$) and the distribution of the coarse sediments

Fall or settling velocity is a function of density, shape, size, roundness and surface texture of the sediment particles and specific weight and viscosity of the water and it determines the terminal rate of settling of particles under varied flow condition. This influences the sediment particles mode, rate and distance of transport by shearing forces of the flow (Dietrich, 1982). Considering the coarse sediments as spherical particles, an attempt has been made to estimate the fall velocity of the sampled coarse sediments with respect to its diameter (mm) and water temperature (˚C) along the lower course of Balason river during 2008 to 2010. The formula used for calculation of fall velocity (w) is as follows:

$$\mathbf{w} = \{(4/3)[(gd_m)/C_D]\ [(\gamma_s - \gamma)/\gamma]\}^{1/2} \text{ where}$$

w = fall velocity ($m\ s^{-1}$)

g = gravitational acceleration ($m\ s^{-3}$)

d_m = sediment diameter (mm)

C_D = Drag Coefficient (dimensionless)

γ_s = Specific weight of the particles ($kN\ m^{-3}$)

γ = Specific weight of the water ($kg\ m^{-3}$)

In this estimation of fall velocity ($m\ s^{-1}$) certain parameters has been taken as constant based on hypothetical assumptions provided in several related literatures. The water temperature of 20˚C and the mean flow velocity and depth has been estimated from the data collected from CWC G&D Site. The assumed values considered for these parameters are as follows:

$g = 9.81\ m\ s^{-3}$

$\gamma_s = 26.0\ kN\ m^{-3}$

$\gamma = 9.789\ kN\ m^{-3}$ for 20˚C

$C_D = 24/R + 2$ (Rubey, 1933)

Again, R = Reynolds number of sediment particles has been calculated based on the formula:

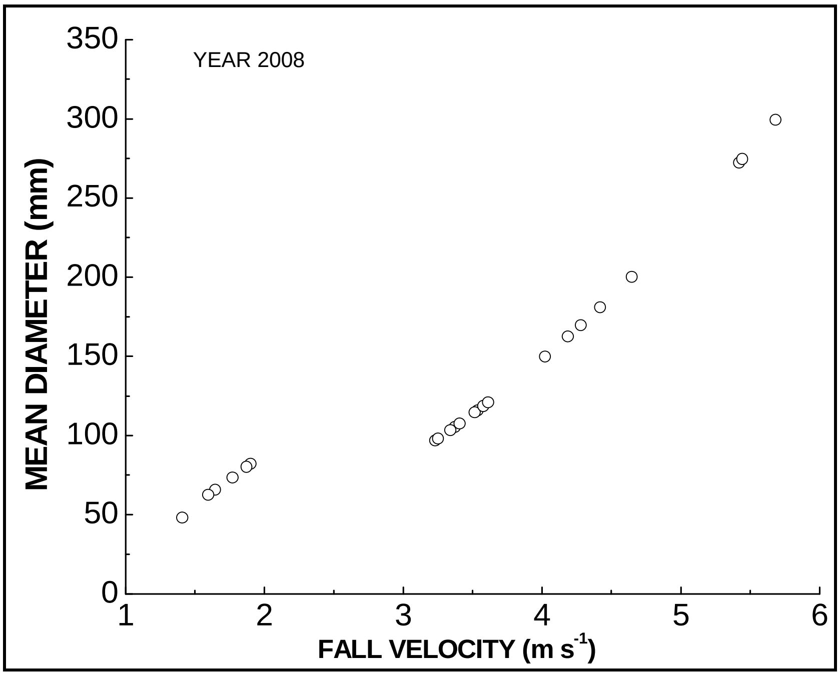
R = *(p*V*h)/μ* where

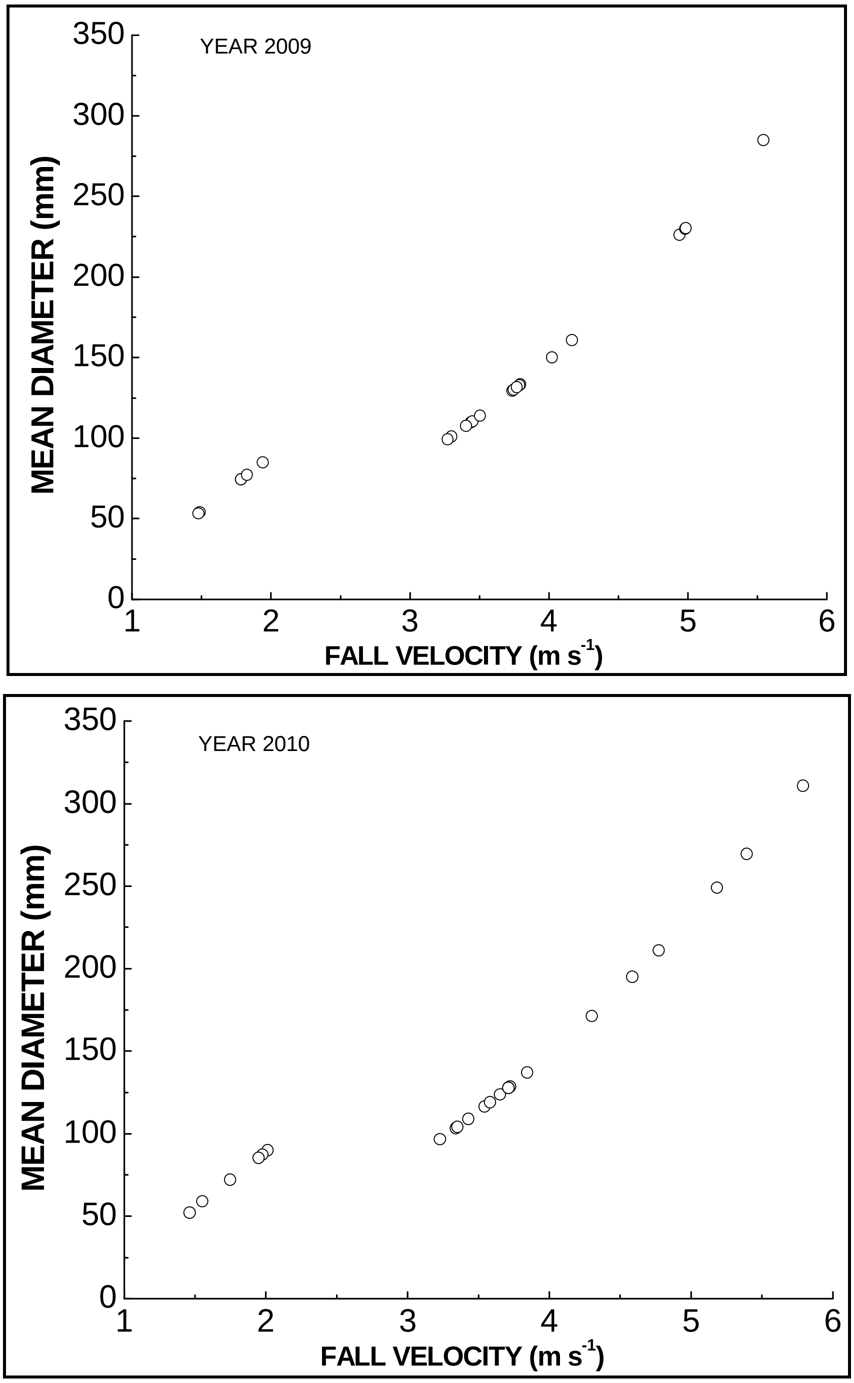
p = Density of the sediment particles (kg m^{-3})

V = Mean flow velocity (m s^{-3})

h = Mean flow depth (m)

The estimated fall or settling velocity (w) revels that the larger sized boulders (> 4096 mm) which are common till sites 3 km below Panighata Bridge may have been transported by the river during extreme flood events as debris flow with fall velocity of more than 20 m s^{-1} *(Refer Appendix B table 4.4, 4.5 and 4.6)* (plate 4.2A & B). Similarly, the medium and smaller sized boulders (256 – 1024 mm) and cobbles (64 – 256 mm) almost available till Matigara Bridge (18 km downstream) may have been transported during flash floods occurring once or twice a decade (Starkel & Basu, 2000) with fall velocity between 5 – 3 m s^{-1}. The remaining sites till the Naukaghat Bridge (22 km downstream) having plenty of gravels and coarse to fine sands may be transported during the annual peak flows from upper segments which are being settled as flow retreats with fall velocity below 2 m s^{-1}.





(Estimated by the researcher based on field survey and hypothetical assumptions)

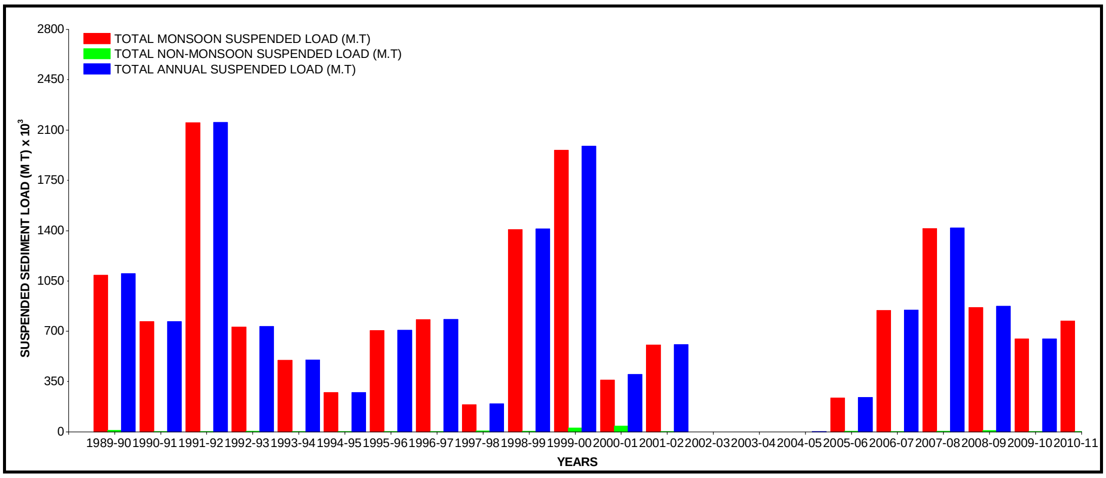
Figure 4.5 The estimated fall or settling velocity (m s^{-1}) of the annual mean coarse sediments (D_{50}) sampled during 2008 to 2010 *(Refer Appendix C table 4.4, 4.5 and 4.6)*

4.4 Study of the Suspended sediments of the lower Balason river

The amount and type of solid particles carried by the river flow shows the relative contribution of the surface run-off and its catchment characteristics

(Morisawa, 1968). The lower Balason river with deforested catchment and high surface run-off brings down huge loads of suspended particles during monsoon periods with its flow in the form of sand, silt and clay which are being deposited on its entire lower course before it mixes with Mahananda river. In this section, the researcher has attempted to calculate the total suspended load (metric tons) based on the data collected from CWC G&D, Matigara (plate 4.2D, E & F). In the analysis of suspended sediment, the particles have been classified on the basis of its grain size, which are as follows:

i. Coarse (coarse to medium sand) with diameter of 2.00 - 0.20 mm
ii. Medium (fine sand) with diameter of 0.02 – 0.075 mm, and
iii. Fine (silt and clay) with diameter <0.075 mm



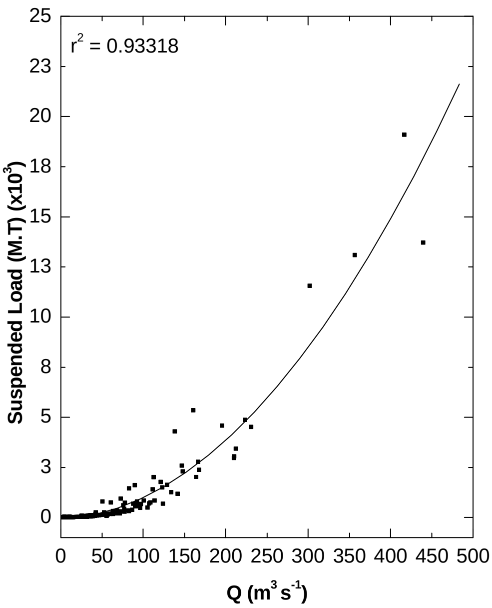
(Computed by the researcher based on data collected from CWC G&D, Matigara)

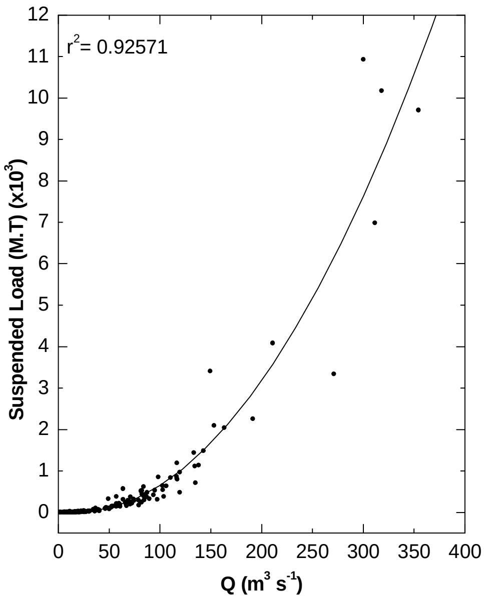
Figure 4.6 The total suspended load (M.T) of lower Balason river from 1989 – 1990 to 2010-2011 *(Refer Appendix C table 4.7).*

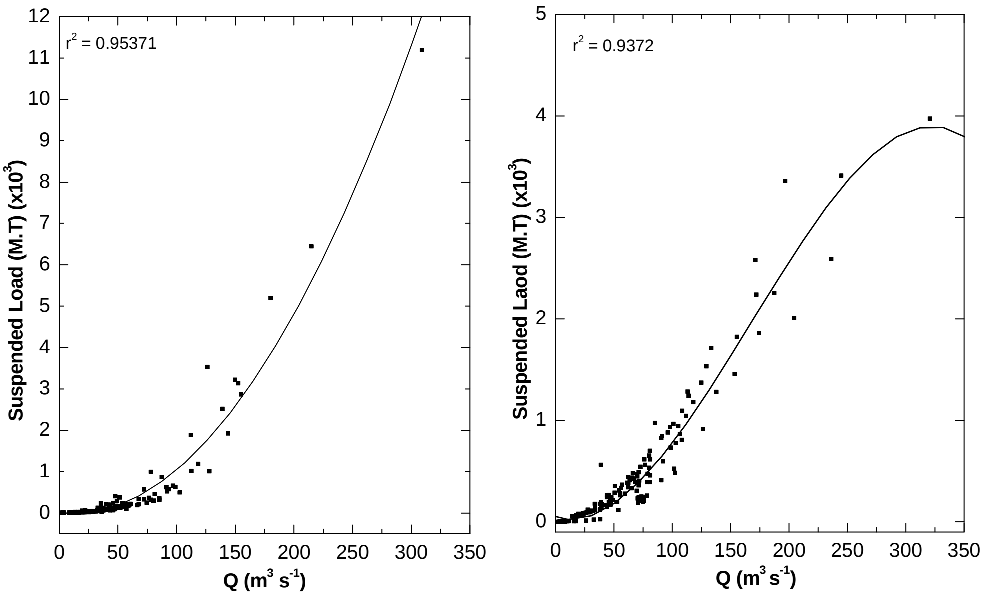
In figure 4.6, the annual total suspended load in metric tons has been estimated along with its proportion during monsoon and non-monsoon periods. It could be clearly seen that the monsoon periods contribute more than 90% of the total annual suspended load carried by the river. The maximum annual suspended load was estimated 2153895 M.T during 1991-92 and the proportion of monsoon suspended load was 2151205 M.T which was 99.88% of the total annual load and for non-monsoon period it was only 2690 M.T. The minimum annual suspended load was estimated 195095 M.T during 1997-98 and the contribution of monsoon suspended load was 188857 M.T which was 96.80% of the annual total and for non-monsoon period it was 6238 M.T. During non-monsoon due to nil to few low intensity rainfall and consequent non occurrence of the surface run-off, the suspended load carried by the river is very minimal. The maximum non-monsoon suspended load was estimated at 38670 M.T during 2000-01 and its contribution to annual total 399448 M.T was 9.68%.

4.4.1 Study of the relationship between discharge (m^3 s^{-1}) and Suspended Sediment Load (M.T) during monsoon period (June – October) of the lower Balason river during 2007 to 2010

Since during monsoon period the suspended load carried by the lower Balason river contributes more than 90% of the total annual load as high rain intensity and consequent high saturation of soil profiles and also high gradient of the bed rocks in its upper catchment accelerates surface as well as sub-surface run-off (Starkel & Basu, 2000). An attempt has been made by the researcher to estimate the relationship with the help of coefficient of correlation between discharge and suspended load during monsoon period from 2007 to 2010.







(Computed by the researcher based on data collected from CWC G&D, Matigara)

Figure 4.7 The coefficient of correlation (r^2) between the total daily suspended load (M.T) and mean discharge (m^3 s^{-1}) during monsoon period during 2007 to 2010.

The relationship between the total daily suspended load (M.T) and mean discharge (Q) during monsoon periods of the lower Balason river are highly correlated as the values of coefficient of correlation (r^2) is 0.93318 in 2007, 0.92571 in 2008, 0.95371 in 2009 and 0.9372 in 2010 (figure 4.7). Such correlation clearly states that during monsoon periods with the increase in discharge due to high intensity rains, river energy also increases and consequently the load of suspended particles in its flow fluctuates thereby incrementing the channel competency.

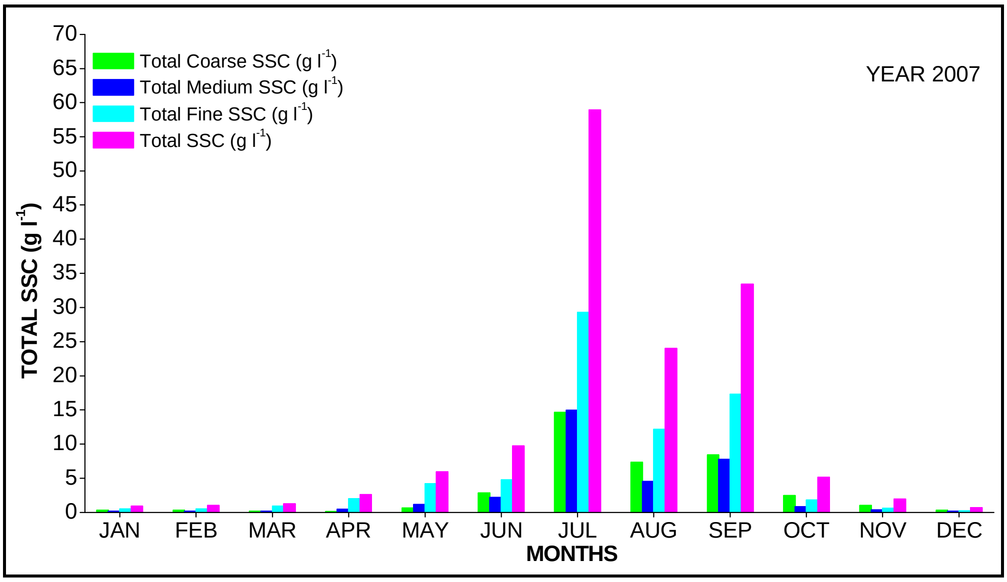
4.4.2 Study of the Suspended Sediment Concentration (g l^{-1}) (SSC) of the lower Balason river during 2007 to 2010

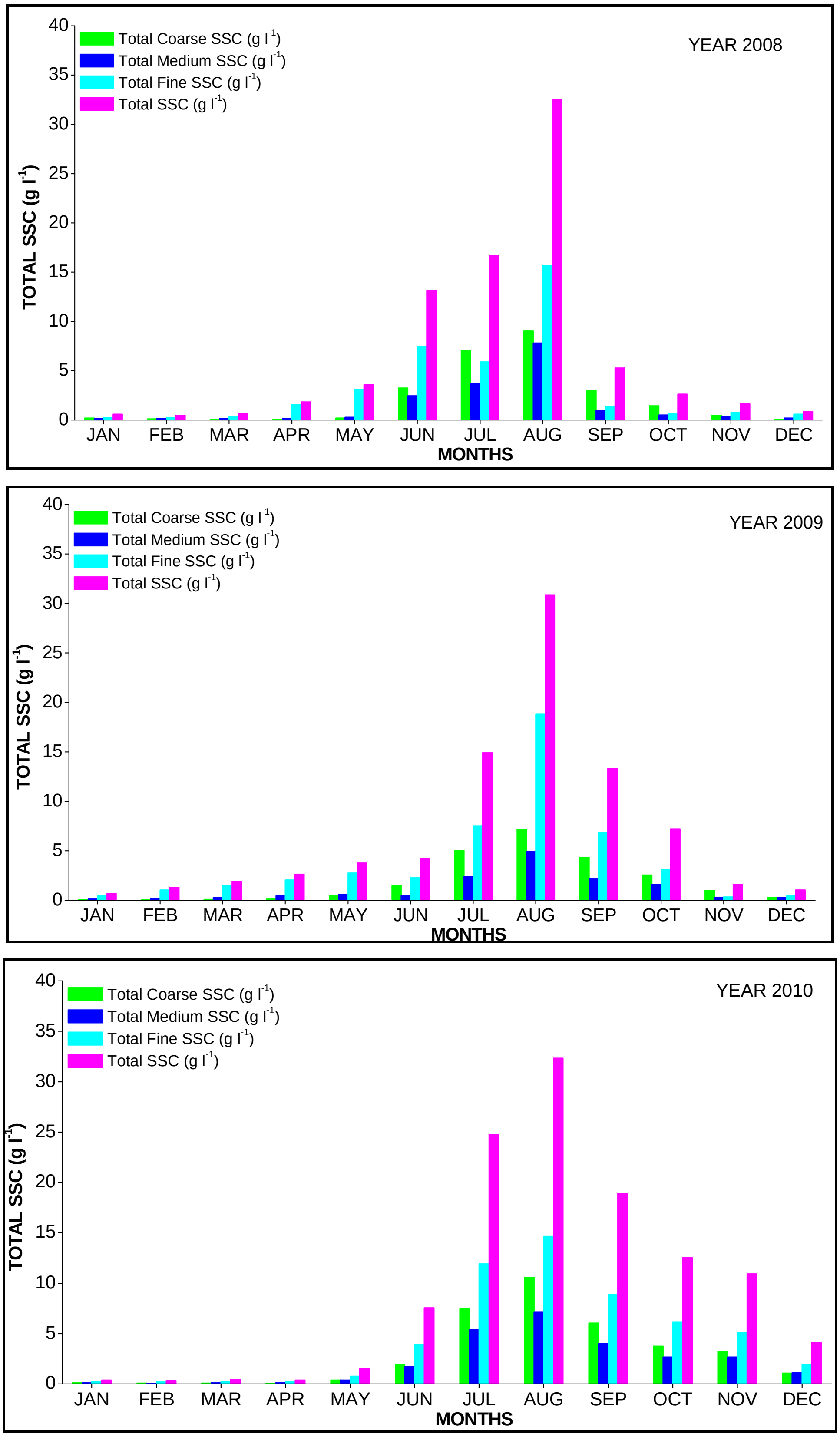
In rivers the concentration of suspended particles depends on the water's flow rate, turbidity, soil erosion, land use changes, impoundment on upstream river and several other factors. The SSC (g l^{-1}) of the lower Balason river shows the overall effects of such factors which greatly contributes to the total SSC. During 2007 to 2010, the estimation of total monthly SSC (figure 4.8) based on the data collected from CWC G&D Site, Matigara reveals that the maximum SSC were 145.671 g l^{-1}, 79.728 g l^{-1}, 83.364 g l^{-1} and 114.098 g l^{-1}. The proportions of coarse, medium and fine particles in total SSC were 28.51%, 21.02% and 50.45% of the total SSC during 2007 - 2010 (Table 4.8). Such grains proportion of suspended load shows the actual competency of the river flow which has been largely controlled by anthropogenic effects, soil erosion, surface runoff etc on the lower Balason river.

YEARS	COARSE (g l^{-1})	MEDIUM (g l^{-1})	FINE (g l^{-1})	TOTAL SSC (g l^{-1})
2007	38.492	32.928	74.179	145.671
2008	24.948	16.871	37.909	79.728
2009	22.556	13.760	47.048	83.364
2010	34.578	25.341	54.179	114.098
MEAN	**120.574**	**88.900**	**213.315**	**422.861**

(Computed by the researcher based on data from CWC G&D Site, Matigara)

Table 4.8 The total monthly SSC (g l^{-1}) of lower Balason river from 2007 to 2010.



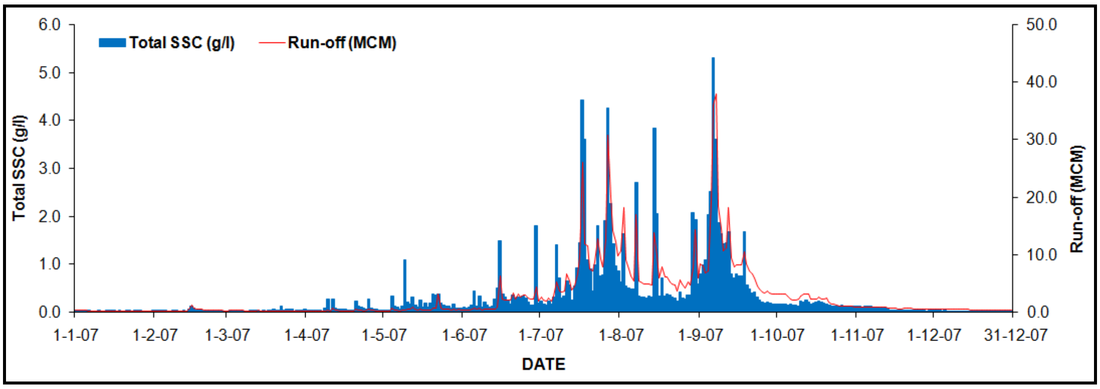


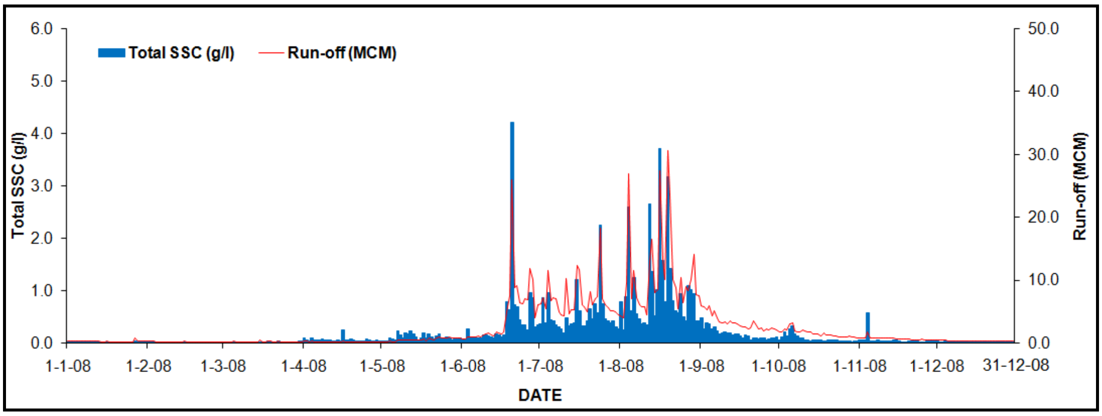
(Computed by the researcher based on data collected from CWC G&D, Matigara)

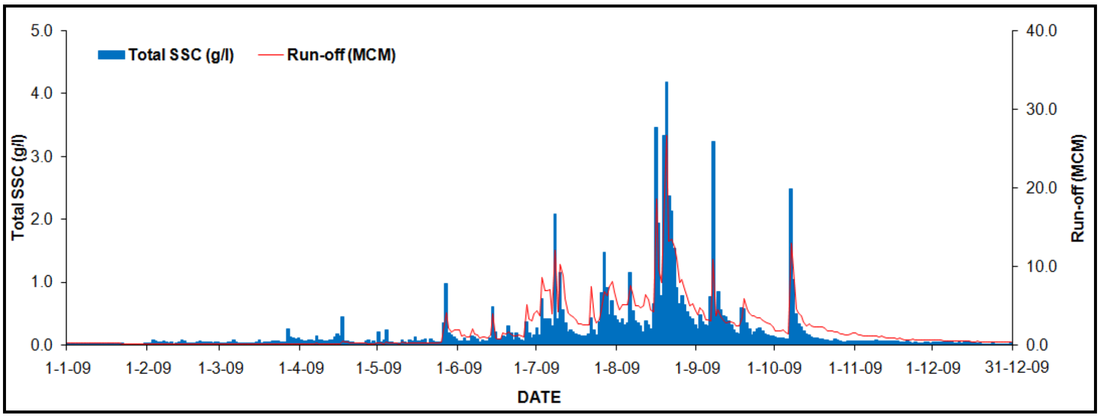
Figure 4.8 The total monthly SSC (g l^{-1}) of lower Balason river from 2007 to 2010 *(Refer Appendix C table 4.8, 4.9, 4.10 and 4.11).*

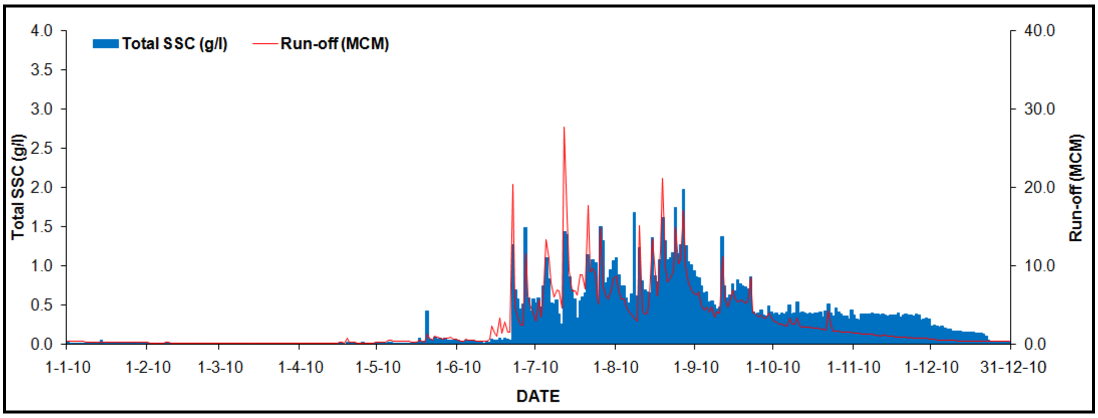
4.4.3 Study of the total Run-off (million m^3) and Suspended Sediment Concentration ($g\ l^{-1}$) of the lower Balason river during 2007 to 2010

The analysis of the daily run-off (million m^3) and SSC ($g\ l^{-1}$) of the lower Balason from 2007 to 2010 has been attempted to shows that the SSC fluctuates with river run-off (figure 4.9). During the monsoon period (June to October) the increase in river discharge causing maximum run-off and consequently high SSC could be noticed. During non-monsoon period (November to May), the SSC also recedes but sometimes late monsoon rainfall largely contributes to the SSC with increase in river discharge and consequent runoff as could be noticed in 2010.









(Computed by the researcher based on data collected from CWC G&D, Matigara)

Figure 4.9 The total daily run-off (million m^3) and SSC ($g\ l^{-1}$) of lower Balason river from 2007 to 2010.

4.5 Study of the daily Suspended Sediment Yield (ha 300 $km^2\ d^{-1}$) of the lower Balason river during 2007 to 2010

Suspended sediment yield (SSY) refers to the rate delivery of eroded soil particles brought down by the river with its flow (Reddy, 2008). An estimate has been made by the researcher in this section about the suspended sediment yield of the lower Balason river based on the sediment run-off date collected from CWC G&D, Matigara during 2007 to 2010 (figure 4.10). In order to estimate SSY, the following formula and parameters has been used:

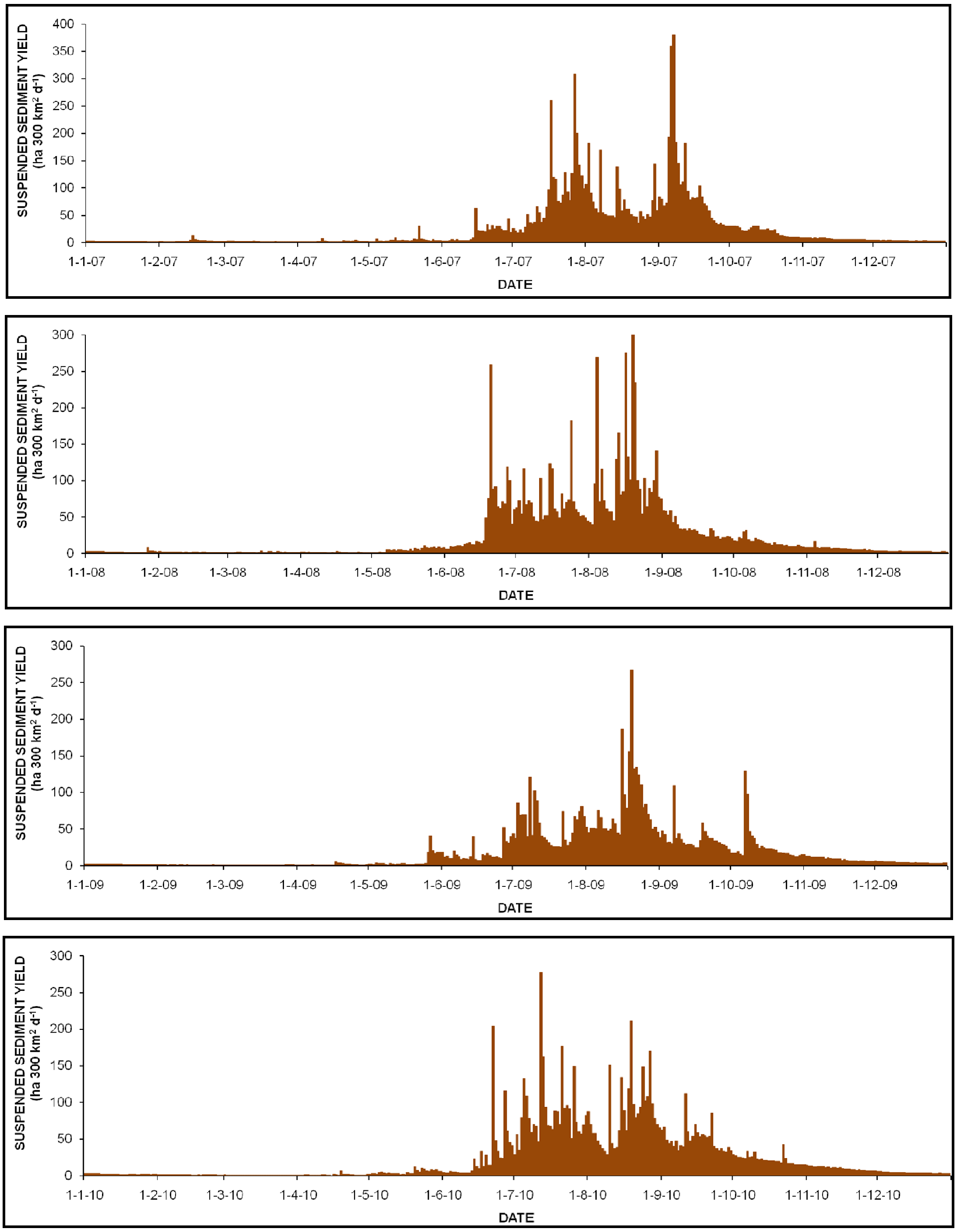
SSY = [(Qs * 300) / (A/300)] where

Qs = Suspended sediment run off (ha m /10^3)

A = Total Basin area (km^2)

Again, Suspended sediment discharge (Qs) has been calculated with the help of following formula

Qs = [(Q * 0.0864)/10] where, Q = discharge ($m^3\ s^{-1}$)



(Estimated by the researcher based on data collected from CWC G&D, Matigara)

Figure 4.10 The total daily suspended sediment yield (ha 300 km^2 d^{-1}) of lower Balason river from 2007 to 2010.

4.6 Conclusions

The analysis of surface coarse sediments and suspended sediments of the lower Balason river and its relation with discharge, run-off and fall or settling velocity reveals that the during hyperconcentrated flows occurring very rarely, the efficiency of sediment delivery by linear erosion and mass movement causes substantial transformations in the channel geometry. The annual flow with normal peak discharge (below 500 $m^3 s^{-1}$) does not greatly results the sediment transportation with only substantial change in sediment distribution. The suspended sediment yield rate also fluctuates with fluctuation in channel flow and surface run-off.

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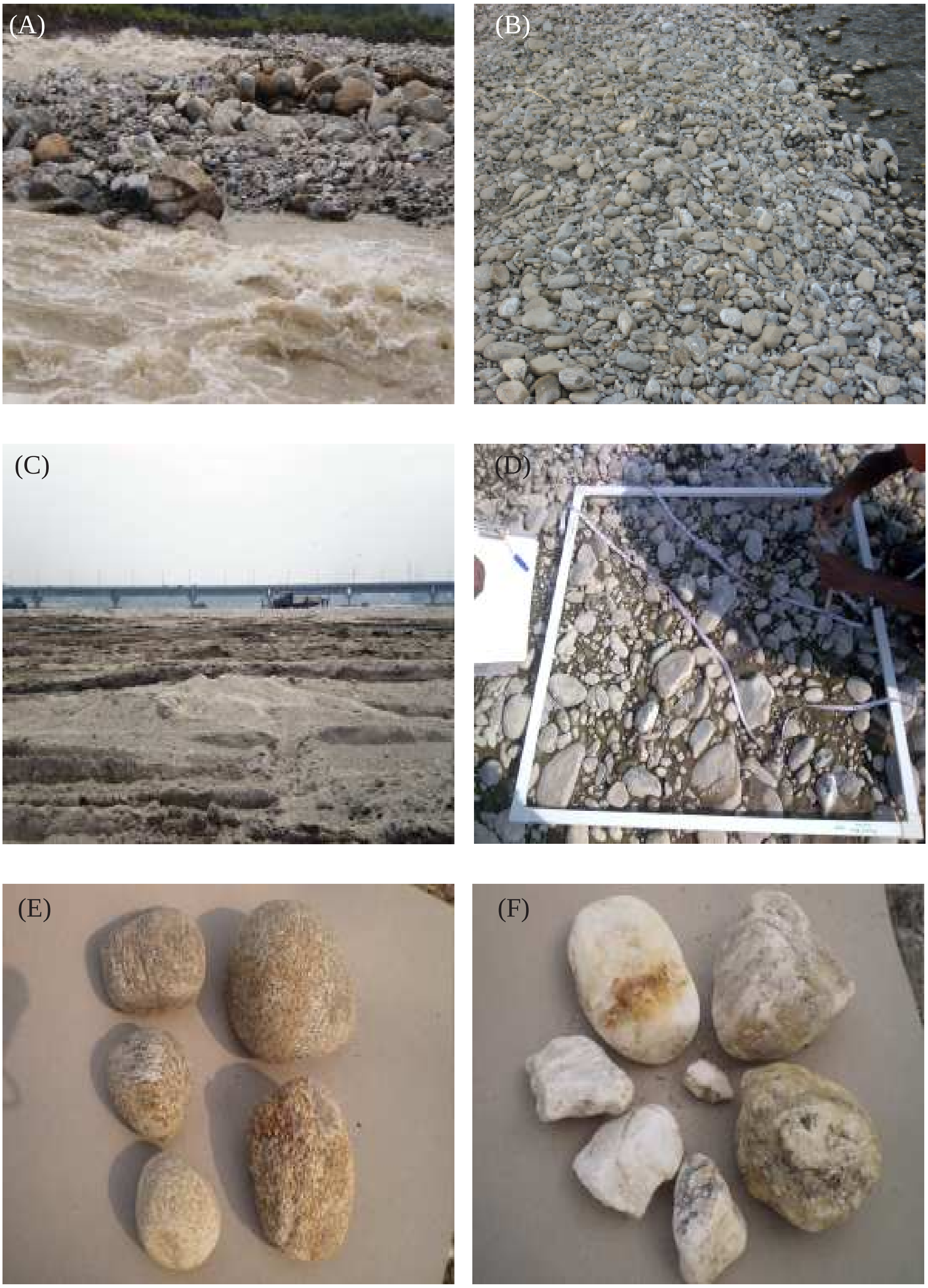


Plate 4.1 The sediment distribution along the lower Balason river starting from unassorted boulders in its upper piedmont segments (A), followed gravels and coarse sand in its middle segments (B) and the finer sediments mostly sand in the lower reaches (C) transported by the river during monsoon flows; grid sampling (D) and samples collected (E & F) for measuring its size (diameter).

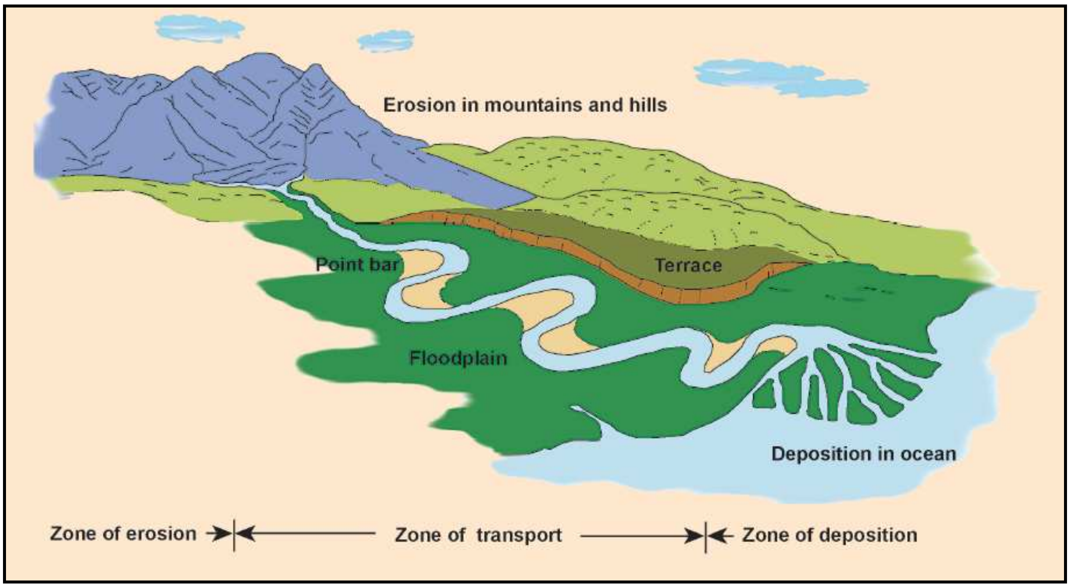
Plate 4.2 The larger boulders in the middle segments brought during extreme flood flows (A & B) scattered over river bed; loose soils in its upper catchment (C) adding suspended load to the river, and the monsoon flows carrying large quantities of suspended load (D, E & F) in the lower Balason river. (Photographs by the Researcher)

CHAPTER 5

Boulder Lifting: An overview

5.1 Introduction

Sand and gravel deposits are the results of the erosion of bedrock and the subsequent transport, abrasion, and deposition of the particles by ice, water, gravity, and wind. The amount of sediments available in rivers and their associated terraces are determined in large part by the geologic, hydrologic, climatic, and anthropogenic characteristics of the area drained by the stream or river.The sediment in the bed of rivers is not a static feature, but is a dynamic feature, in transit through the system during floods. The flux of bed sediment depends on the supply of coarse sediment from the watershed and the transporting power of the river, and transport rates vary over space and time. River sediments are typically of excellent quality because natural river processes eliminate weak materials by abrasion and attrition, and the resulting deposits are durable, rounded, well-sorted, and relatively free of interstitial fine sediment.



(After Langer, 2003 & Kondolf, 1997)

Figure 5.1 Origin, transport and deposition of stream sediments of a river.

Alluvial channels have historically been an attractive source of sand and gravel for a variety of construction activities. The floodplains and terraces are mostly the sites of sediment storage in stream systems and can contain large quantities of boulders, gravels and sands that can be mined economically (Langer, 2003). There are several advantages for the aggregate operators in using river sediment (Kondolf, 1994), such as: (a) the material is already granulated, rounded, well-sorted, and generally clean (lacking cement and weak materials, and relatively free of interstitial fine sediment); (b) the source of material is generally close to destination or to the markets for the product, reducing transportation costs; (c) active channel sediments can be easily extracted (deep quarrying is not necessary), require little processing, and are periodically replaced from upstream during high flow events.

Methods of sediment extraction commonly practiced:

i. **Dry-pit mining**: Pits excavated on dry ephemeral stream beds and exposed channel/point bars.
ii. **Wet-pit mining**: This involves mining below the water level of a perennial channel generally during the lean period. This may involve frequent/ partial or full dewatering of working face.
iii. **Bar skimming or scraping**: Scraping of top portion of the bar deposits are generally undertaken for sustainable mining of sand/gravel grade material.
iv. **Pits on the adjacent floodplain or river terrace**: In this case dry or wet pitting/ mining are involved depending upon geomorphology of the area. Dry pits are located above the water table and wet pits are developed below the groundwater table in the area.

5.2 History of boulder lifting activities in the lower course of Balason river

The extraction of bed materials along the lower Balason river began only after the river shifted its course into the present position, which previously used to be fertile agricultural land with forest cover (as per the old records in SOI topographical maps, cadastral maps, literatures, etc). The loss of agriculture lands forced the local inhabitants to take up extraction of the bed materials as an alternative source of livelihood. Initially, only the large sized gravels and boulders used to be quarried, but as demands increased with time, extraction of other grades of bed materials began. From 1980 onward, when the extraction permits and leases were distributed to the landholders, only large sized gravels and boulders were quarried from the river bed but with increasing demand along with growing population, the process of extraction of other grades of bed materials began.

5.3 Extraction permissions and land ownership

Any extraction from the river bed requires a mining permit and land lease, given on the condition that a minimum royalty at fixed rate be paid to the State Government (table 5.1), even if no actual extraction has taken place in that year. Extraction without a licence is liable to penal action. The process of permits and leases are looked after by the Land & Land Reform Department at each Block and the concerned authority functions under the jurisdiction of sub-division and district mining authority. Illegal mining is punishable by imprisonment for a brief term or a fine or both. This is provided by Rule 21 (Penalties) of the Mines and Mineral (Development & Regulation) Act 1957 (Act 67 of the Indian Parliament) and its amendment up to 2000; and Rule 33 (Penalty) of The West Bengal Minor Minerals Rules, 2002 (Banerjee, 2007). There is also legal provision for the recovery of the mineral and associated royalty.

Name of Minor Minerals	Rate
Boulders/Pebbles/Stones/Sandstone/Gravel	**Rs. 22.00 per cu. m**
Granite (Black)	Rs. 650.00 per cu.m
Granite (coloured)	Rs. 525.00 per cu.m
Ordinary Clay/Fuller’s earth/Brick Earth	Rs. 12.00 per cu.m
Ordinary Sand	**Rs. 22.00 per cu.m**

(Source: Schedule I, rule 20 (1) of the West Bengal Minor Minerals Rules, 2002)

Table 5.1 Rate of Royalty on minor minerals as per the West Bengal Minor Minerals Rules, 2002.

Initially, the lease to land for extraction is given for period of 5 years and it can be renewed to a maximum of 20 years. The period of extraction extends from a few days to a maximum of three months, which may be renewed. The Mining Department is authorised to grant these permits as well as more elaborate, long-term mining leases. During 2008 – 2009, as per the official records of District Land and Land Reform Office, Darjeeling, there are total of 37 Quarry Permits and among these 21 such permit holders are operational at lower course of Balason river bed stretched over the Kurseong and Siliguri sub-division of Darjeeling district (Tamang and Mandal, 2009-10).

5.4 Extent of boulder lifting activities in the lower course of Balason river

Extraction of bed materials along the lower course of Balason river is mostly dependent up on the size, amount and quality of bed materials available. Along the entire stretch (24.13 km) of the lower Balason river, which falls under 4 blocks of Darjeeling district, namely Mirik, Kurseong, Naxalbari and Matigara, the available official records as per District Land & Land Reform Office, Darjeeling, the boulder lifting permits are given to different land holders and extraction volume is mostly size selective depending on the available bed materials.

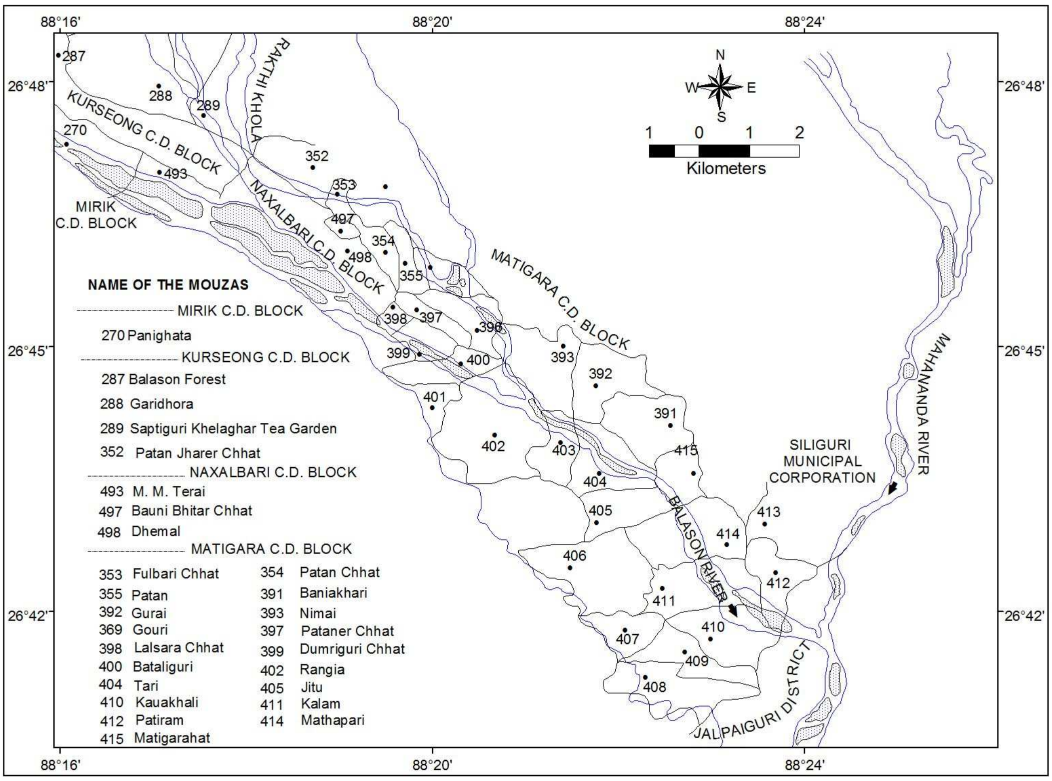
Based on these records as well as the information collected during extensive field surveys, the researcher has divided the whole lower course into 3 important segments (figure 5.3), on the basis of size and quantity of extracted volume from different sites. These are –

1. **SEGMENT 1**: This zone extends up to 8 km downstream from Dudhia Bridge. In this zone, large sized boulder ranging up to 1 m diameter predominates in the upper piedmont area. Here extraction of larger sized gravels and boulders are common (plate 5.1A & B). Such boulders are broken with the help of human muscles in different sizes according to the demand of the market. Mostly the extracted volumes from this zone are used for road (sloping), embankment and bridge construction. The important sites in this zone are Dudhia, Panighata, M. M. Terai, Bauni Bhitar Chhat, Dhemal, Tarabari and Gouri.

YEAR	M. M. TERAI	GOURI	DHEMAL	TOTAL (m^3)
2002	581225	75000	411075	1067300
2003	544925	136025	389767	1070717
2004	24650	498600	127475	650725
2005	35125	43800	251400	330325
2006	238050	91625	113975	443650
2007	10346	152775	110000	273121
2008	163200	334850	193900	691950
2009	754300	671800	905750	2331850
2010	552175	645875	862500	2060550
MEAN (m^3)	**322666.200**	**294483.300**	**373982.400**	**991132**

(Estimated by the researcher based on official records and field surveys)

Table 5.2 Extracted volume (m^3) of bed materials from Segment 1 along the lower course of Balason river.



(Source: Administrative Atlas of West Bengal, 2008)

Figure 5.2 Different mouzas located along the lower course of Balason river.

2. **SEGMENT 2**: This zone with a total length of about 9 km extends up to the Matigara Bridge, where due to gradual decrease in sediment size, boulders ranging from 300 - 50 mm diameter are extracted. In this site huge amount of medium to small sized gravels along with both coarse & fine grained sand are extracted (plate 5.1C & D).The extracted materials are processed both manually at extraction sites and also there are processing centers *(Kasari),* where bed materials are processes into different grades with the help of mechanically operated sieves. Due to the accessibility of NH 31 and also other well connected local roads, this zone has the largest number of extraction sites and also the extracted volume is highest in the whole stretch.

YEAR	TARI	NEMAI	BATALI-GURI	LALSARA CHHAT	PATANER CHHAT	NENTI-CHARA	TOTAL (m^3)
2002	245275	449250	453125	113390	170325	323175	1754540
2003	240425	497413	1044035	94875	1453175	780010	4109933
2004	239775	380775	499675	505550	649050	590900	2865725
2005	685900	544975	501525	251400	203750	128700	2316250
2006	306050	349600	869050	164600	104450	283600	2077350
2007	199227	546875	198400	183230	507149	205675	1840556
2008	326900	647423	1167400	157000	657750	551250	3507724
2009	113560	1345525	1086200	491000	957750	21658	3994035
2010	3393825	1152825	1120500	436600	1529025	19300	7652075
MEAN	**638993**	**657184.600**	**771101.100**	**266405**	**692491.600**	**322696.400**	**3346465**

(Estimated by the researcher based on official records and field surveys)

Table 5.3 Extracted volume (m^3) of bed materials from Segment 2 along the lower course of Balason river.

3. **SEGMENT 3:** In the remaining length of about 7 km, downstream from Matigara Bridge, the extraction of smaller sized gravels, pebbles and sands predominates. In the extraction sites, mostly instream bed materials are extracted manually, which are washed and sieved simultaneously. Along the lower stretch, mostly sand extraction is done on large scale (5.1E & F). The important sites are Jitu, Mathapari, Kalam and Kauakhali.

YEAR	JITU	KALAM	KAUAKHALI	MATHAPARI	TOTAL (m^3)
2002	501440	447617	806885	63925	1819867
2003	516925	690258	305025	1196525	2708733
2004	278253	573750	292800	564700	1709503
2005	648075	394550	331600	237750	1611975
2006	301750	677000	382550	423500	1784800
2007	254150	158350	433350	304125	1149975
2008	249675	527000	1201225	206650	2184550
2009	380175	4353575	502925	100514	5236675
2010	158625	3099175	344250	703925	4305975
MEAN (m^3)	**365452**	**1213475**	**511178.9**	**422401.6**	**2501339**

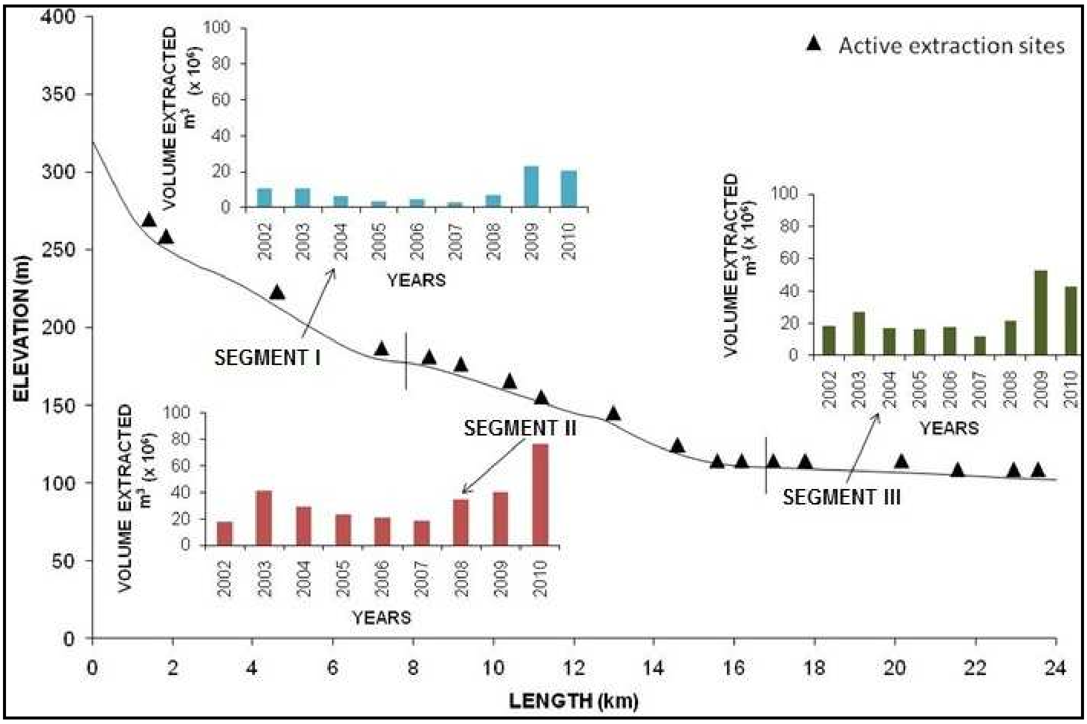
(Estimated by the researcher based on official records and field surveys)

Table 5.4: Extracted volume (m^3) of bed materials from Segment 3 along the lower course of Balason river.

YEAR	SEGMENT 1	SEGMENT 2	SEGMENT 3	TOTAL (m^3)
2002	1067300	1754540	1819867	4641707
2003	1070717	4109933	2708733	7889383
2004	650725	2865725	1709503	5225953
2005	330325	2316250	1611975	4258550
2006	443650	2077350	1784800	4305800
2007	273121	1840556	1149975	3263652
2008	691950	3507724	2184550	6384224
2009	2331850	4015693	5337189	11562560
2010	2060550	7652075	4305975	14018600
MEAN (m^3)	**991123**	**3348872**	**2512507**	**6838937**

(Estimated by the researcher based on official records and field surveys)

Table 5.5 Total extracted volume (m^3) of bed materials from the lower course of Balason river during 2002 - 2010.



(Estimated by the researcher based on official records and field surveys)

Figure 5.3 Total volume of extracted bed materials ($m^3 \times 10^6$) from different sites during 2002 -2010.

5.5 Nature of boulder lifting activities

The construction of well connected transportation networks connecting the rapidly developing Siliguri also arouse the demand for construction materials and due to the nearness and availability of readily available raw materials in the form of bed materials, the lower Balason river has become an important source of readily available construction material. During this process, the development of boulder lifting activities also attracted huge influx of laborers from different parts of North Bengal, South Bengal, Bihar, Assam, Rajasthan, Uttar Pradesh, and Bangladesh. Most of them migrated from Bangladesh during time of independence of Bangladesh in 1971 (Gan, 2008). These undocumented migrants are settled along the river banks in temporary built huts and every family member including small children are engaged in extraction activities. The earning of such labours depends on the volume of materials extracted or the total volume of stones crushed into smaller sizes, as such, extracting 100 cu ft of *Accurate* (gravel sized) fetch Rs. 350 and 100 cu ft of *Bajri* gives Rs. 700.

On the extraction sites, the bed materials are extracted up to 2 m during the dry season and the larger boulders are collected at some selected places which are broken into smaller sizes ranging between 75 to 90 mm diameters (plate 2B & C). Other grades of bed materials supplied are *Accurate, Misali, Metal, Grid, Bajri, 3/4th, 1/4th and chips* from large boulders and mostly coarse and fine sands. During the monsoon period, mostly larger boulders and gravels brought down by the flow are extracted near the banks. Also the instream extractions are carried in lesser extent, as the river becomes inaccessible with increase in channel flow (plate 5.3A & B).

5.5.1 Processing of the extracted bed materials

Along the lower course of Balason river at least 3 processing centers (locally called *kasari*) can be found where the extracted materials are brought from the river bed with the help of trucks at the rate of Rs. 120/- per ton and these materials are processed mechanically with the help of sieve of various sizes fitted at the top and the sieved materials are kept separately according to its sizes (plate 5.2E & F). At Basbari (Khaprail), sieves of 40 mm, 20 mm, 10 mm, 6 mm and 0.75 mm are fitted and according to the workers engaged in this privately operated centre, the obtained product also costs in respect of its size (table 2). The unskilled worker of such centers gets wages of Rs. 90/- per day while the skilled worker gets Rs. 166/- per day.

Sieved size of bed materials (in mm)	Sold at (Rs / Cu.ft)
40 mm	Rs. 12.50
20 mm	Rs. 15.00
10 mm	Rs. 13.00
06 mm	Rs. 6.00
0.75 mm (Grit)	Rs. 8.00
Dust (fine sand)	Rs. 5.00

(Compiled by researcher based on field survey)

Table 5.6 Costs of minor minerals of different sizes produced at *Kasari*.

5.5.2 Transportation of extracted bed materials

After the finished products are ready, they are loaded in trucks of different capacities. These materials are transported not only to adjacent local places but also to the different hilly sub-divisions of Darjeeling district. Usually smaller to medium sized trucks (125-250 cu ft) are used for transportation to surrounding areas, majority of which are supplied to Siliguri, Darjeeling, Jalpaiguri, Islampur, Dalkhola and Raiganj. The far distance supplies are carried by larger trucks (400-1200 cu ft), the maximum being parts of South Bengal, Bihar, Assam, Jharkhand, etc. Thus, the final price of such extracted materials depends on the distance traveled. Beside this, the accessibility of the extraction site also determines the price of the material required. For example, a full truck of 250 cu.ft gravel costs around Rs. 400-500, whereas, the same quantity of gravel in Darjeeling costs not less than Rs.5000-6000. Hence, the price of minor minerals extracted from Balason river, varies with size, grade and distance travelled from source of production.

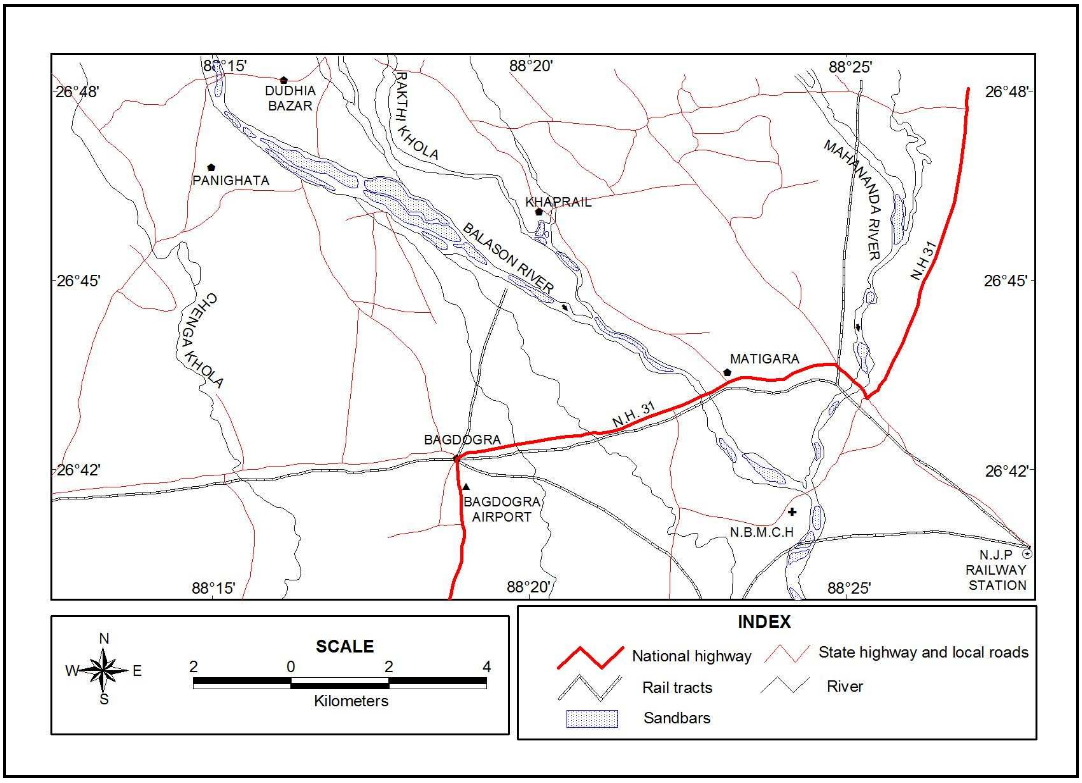


Figure 5.4 Location and connectivity in and around the lower Balason River.

5.6 Conclusions

With rapid development of Siliguri as major urban centre of the region, the extraction of bed materials from Balason river bed is also becoming an important industry providing livelihood to large number of population mostly migrated from adjoining places. The common practice of extracting the bed materials along the lower Balason river is a traditional one with labours still using their physical strength and few tools for extraction process and the extraction process is mostly dependent up on the size, amount and quality of bed materials available (plate 5.3D, E & F). The people dependent upon such activities are not concerned about the ultimate result and with more demand from local markets; illegal mining is a common practice. Hence, the extraction activities are largely hampering the fluvial environment of the region and also the huge influx of migrants is resulting into additional burden over the available resources.

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Plate 5.1 Lifting of larger boulders in the upper piedmont segment (A & B), followed by extraction of gravels in the middle segments (C & D) and sand extraction in the lower segments (E & F) of the lower Balason river. (Photographs by the Researcher)

Plate 5.2 Accumulation of larger boulders and gravels in the upper segments (A & B) mostly used for road sloping; extraction of newly deposited bed materials from the river bed (C & D) in the middle segment and local processing units near Khaprail bazaar (E & F).

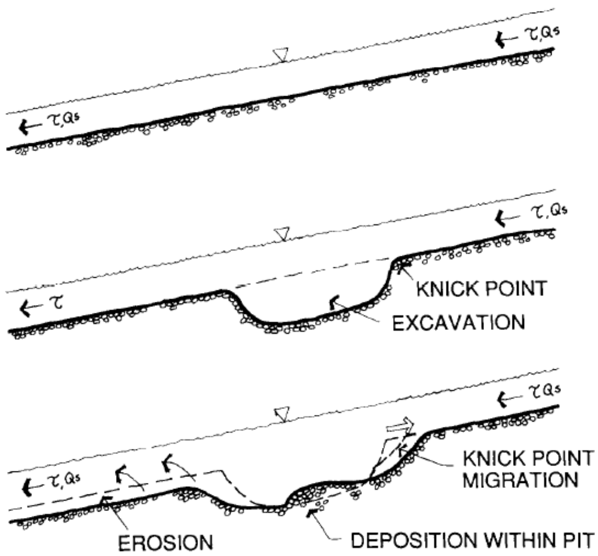
Plate 5.3 The extraction activities during monsoon periods (A & B); cutting of river bed for extracting better quality materials (C); the tools used for extraction process (D, E & F).

CHAPTER 6

Effects of boulder lifting on the fluvial characteristics of the lower Balason basin

6.1 Introduction

The flow regime and sediment transport characteristics of rivers are systematically correlated to temporal and spatial changes in channel geometry and bed material size. The interaction between channel flow, flow regime and sediment transport aid in the determination of channel response to natural or man-induced changes. A stream that is free to develop its own geometry which evolves through time to develop a channel shape, dimension and pattern that reflects a balance between the sediment and water forming the bed and banks. But this balance has been largely affected due to various hydrological and anthropogenic factors which results into changes in the river form and flow characteristics. Among such factors, the extraction of bed materials is also responsible for infringement of its adjustment between the channel geometry and its sediment capacity (Martin-Vide, et al 2010).



(After Kondolf, 1994)

Figure 6.1 The knick point migration and resultant bed erosion causing incision upstream and downstream due to extraction of bed materials.

In general, bed materials extraction from the active river bed may trigger changes in many factors governing fluvial processes, disturb the sediment balance and alter the erosion and sedimentation patterns (Lopez, 2004). If the extraction rate exceeds the potential of the river to backfill the excavated segments, overall river degradation can occur extending for long distances upstream and downstream from the extraction sites.

Rinadli, et.al (2005) have sufficiently documented cases selected from published studies on effects of bed material extraction or sediment mining on alluvial rivers of many rivers of California, USA and some other countries like Italy, France, Spain, New Zealand, etc. Some of such review of cases is as follows:

- Based on Collins and Dunes (1997) and Kondolf (1997), the effects of bed materials extraction on the Cache Creek of California, USA were incision by an average of about 4.6 m with channel widening upto 8.2 m over a 21 year period. Also undermining of all bridges, increase flood capacity, water table lowering with loss in aquifer storage potentials has been noticed.
- Based on Harvey and Schumm (1987), Collin and Dunne (1990) and Kondolf (1997) the effects on Russian rivers were incision by an average of 3.5 m, locally upto 6 m between 1940 and 1972 with exposure of resistant substrates (clay layers); drop of water levels in some wells; death of riparian vegetation; loss of aquifer storage. On Dry Creek of California, local degradation between 1964 and 1984 along the extraction sites were noticed
- Based on Billi and Rinaldi (1997); Rinaldi and Simon (1998); Agnelli, et al (1998), the effects of bed material extraction on Arno River, central Italy were Incision (2 to 5 m on average and up to 9 m) along all alluvial and coastal plain reaches; two phases of incision: minor phase from the beginning of 20th century; second phase from 1945-60 to 1990s along with damage to bridges, bank protections and levees; upstream migration on tributaries; riverbanks instability; loss of groundwater resources; and beach erosion.

- Based on Scott (1973), Bull and Scott (1974); Collins and Dunne (1990), the effects on Tujunga Wash, California were inactive channel captured during a flood (1969) triggering head-ward scour (incision greater than 4 m) and incision downstream due to sediment trapped in the pit along with failure of bridges; lateral instability destroying a long section of highway.
- Based on Uribelarrea, et al (2003), the effects noticed on Jarama River, central Spain were incision upto 4 m; channel narrowing; reduction of area occupied by bars along with damage to bridges and dikes.
- Based on Page and Heerdegen (1985) and Collins and Dunne (1990), the effects of sediment mining noticed on Lower Manawatu River, New Zealand were incision of about 0.25 m between 1967 and 1976 by repeated cross-sections; about 1.1 m from 1964 to 1977 and about 0.5 m from 1972 to 1977 at two gauging stations.

Summarising the above reviews after Rinaldi, et al (2005), the incision followed by damages to bridges and lateral instability are the common effects of bed material extraction. In lower Balason river, such effects has been noticed from the field surveys and which have also been mentioned in the past studies of the same river.

In this chapter, an attempt has been made to highlight the effects of human interferences in the form of boulder lifting activities on the fluvial characteristics of the lower Balason river. For better representation of the prevailing effects, the fluvial characteristic has been sub-divided into morphological and hydraulic characteristics.

6.2 Study of the effects of boulder lifting on the morphological characteristics of the lower Balason river

The morphological characteristic of Balason river in its lower course shows marked variation in bed elevation, which may be attributed to extensive extraction of bed materials not only from the river beds but also from adjacent floodplains and terraces. The extent of extraction increases as the river proceeds downstream and in its middle segment (8 to 18 km downstream) the maximum volume of bed materials are being extracted based on the official records and field observations. In this section, a 4.200 km stretch with maximum bed material extraction in the middle segment (15 to 18 km downstream) has been selected to study the changes in the morphological characteristic (figure 6.2). Cross-sections at every 200 m both during pre-monsoon (March-May) and post-monsoon (November-January) from 2008 to 2010 (figure 6.3) has been done and the annual changes in bed elevation has been properly computed and further analyzed with the help of CWC datum of 119 m.

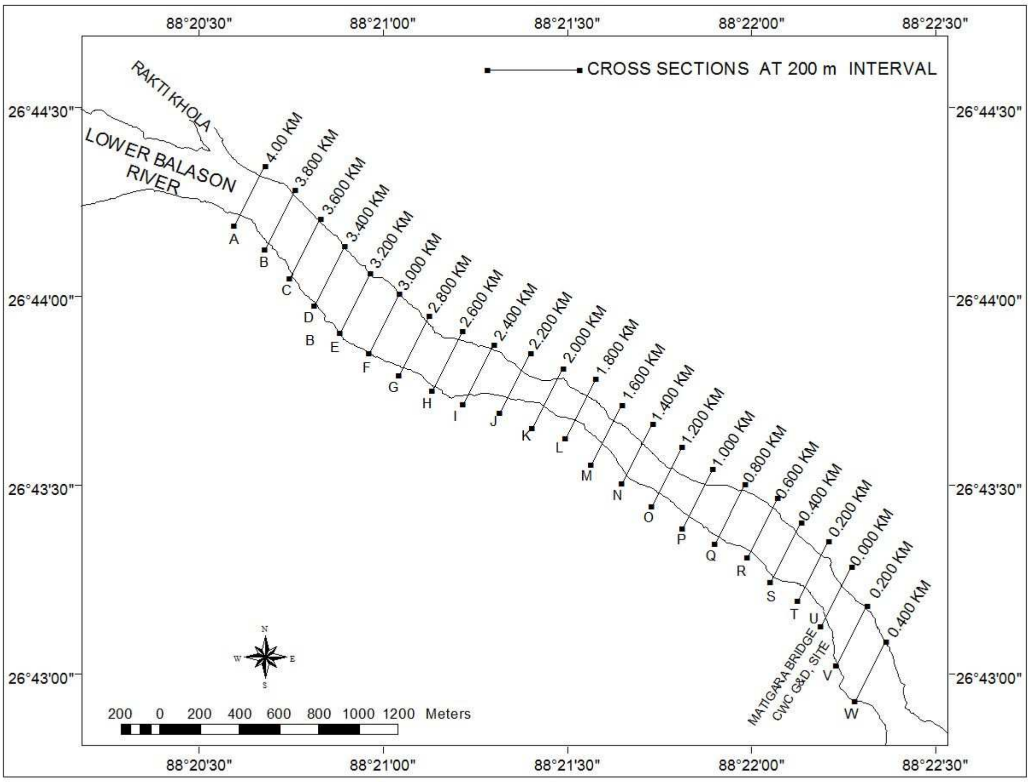
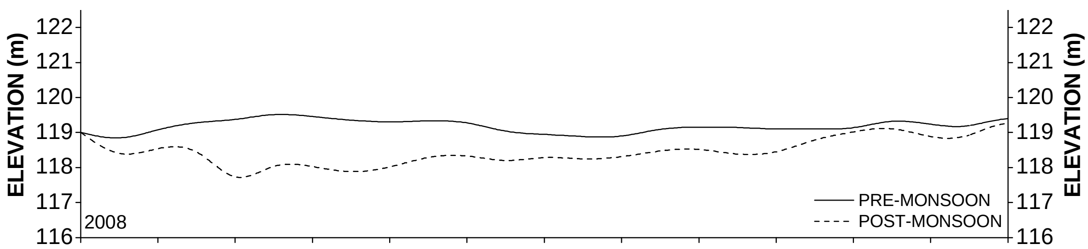
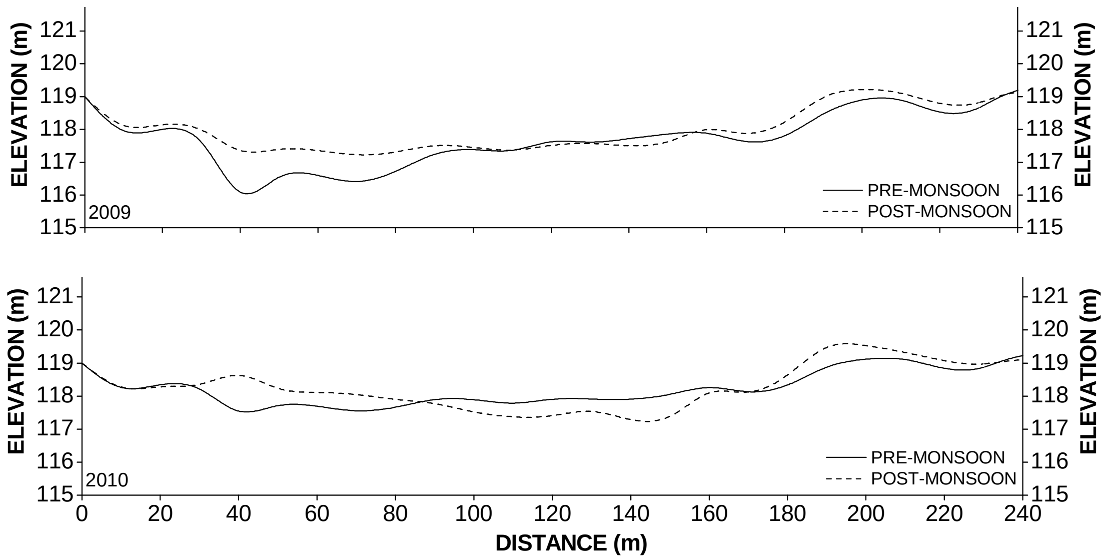


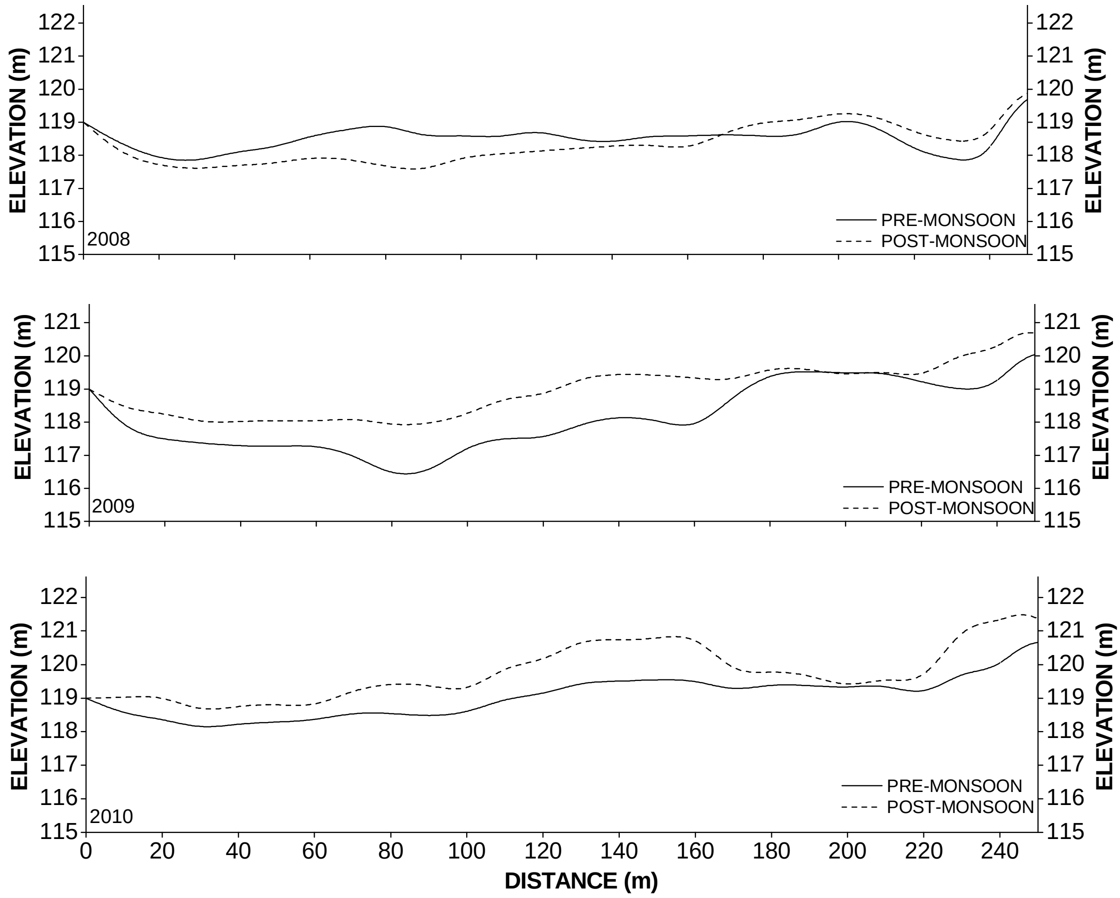
Figure 6.2 Locations of the cross sections at 200 m interval in the middle segment of the lower Balason river.

(A) 4.000 km

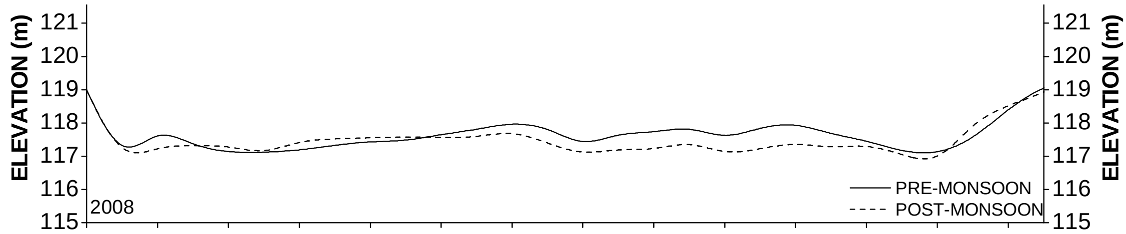


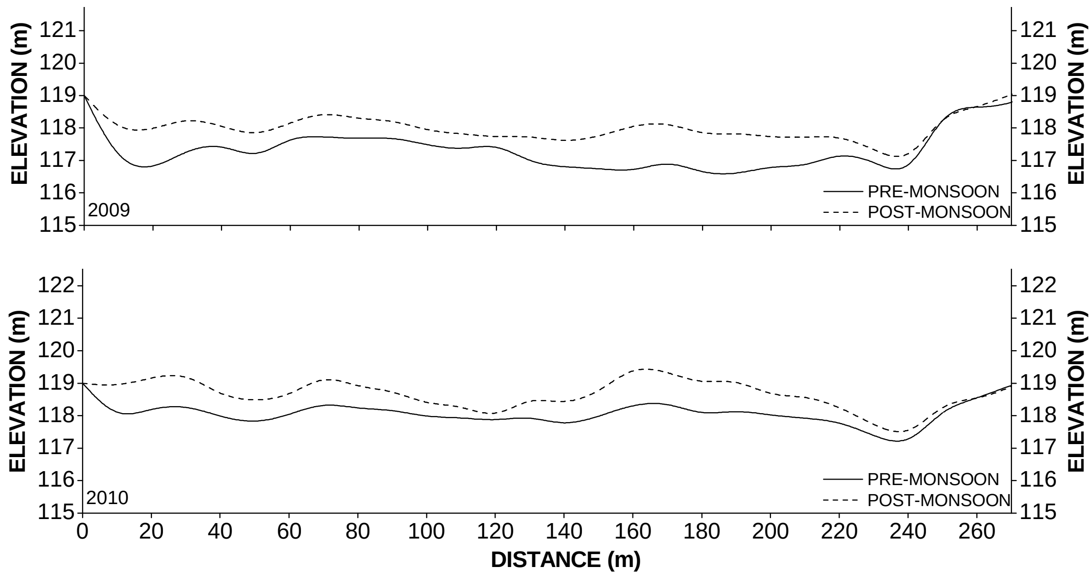


(B) 3.800 km

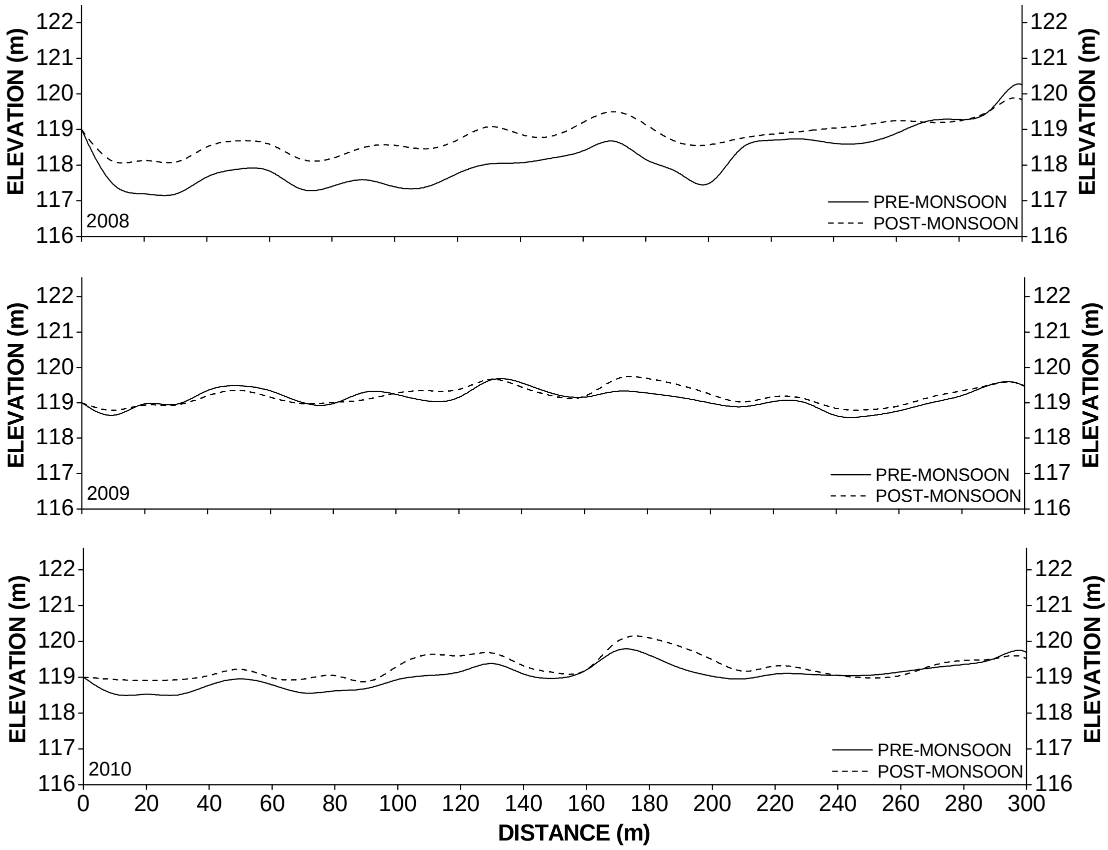


(C) 3.600 km

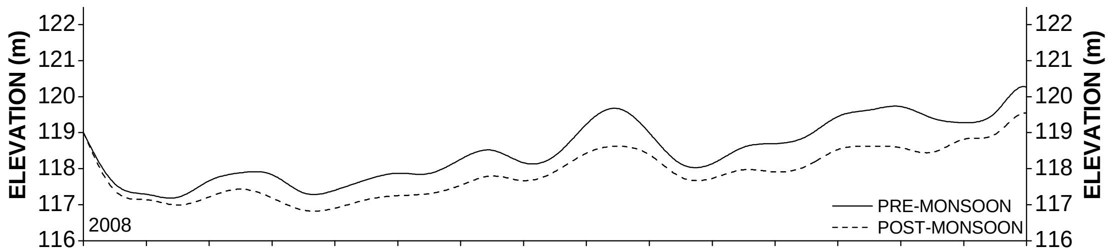


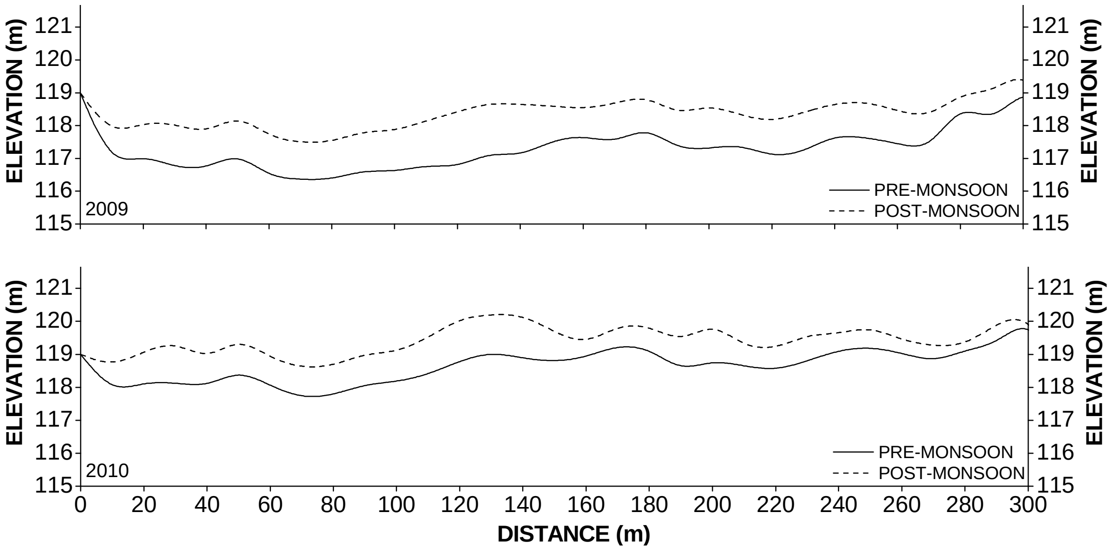


(D) 3.400 km

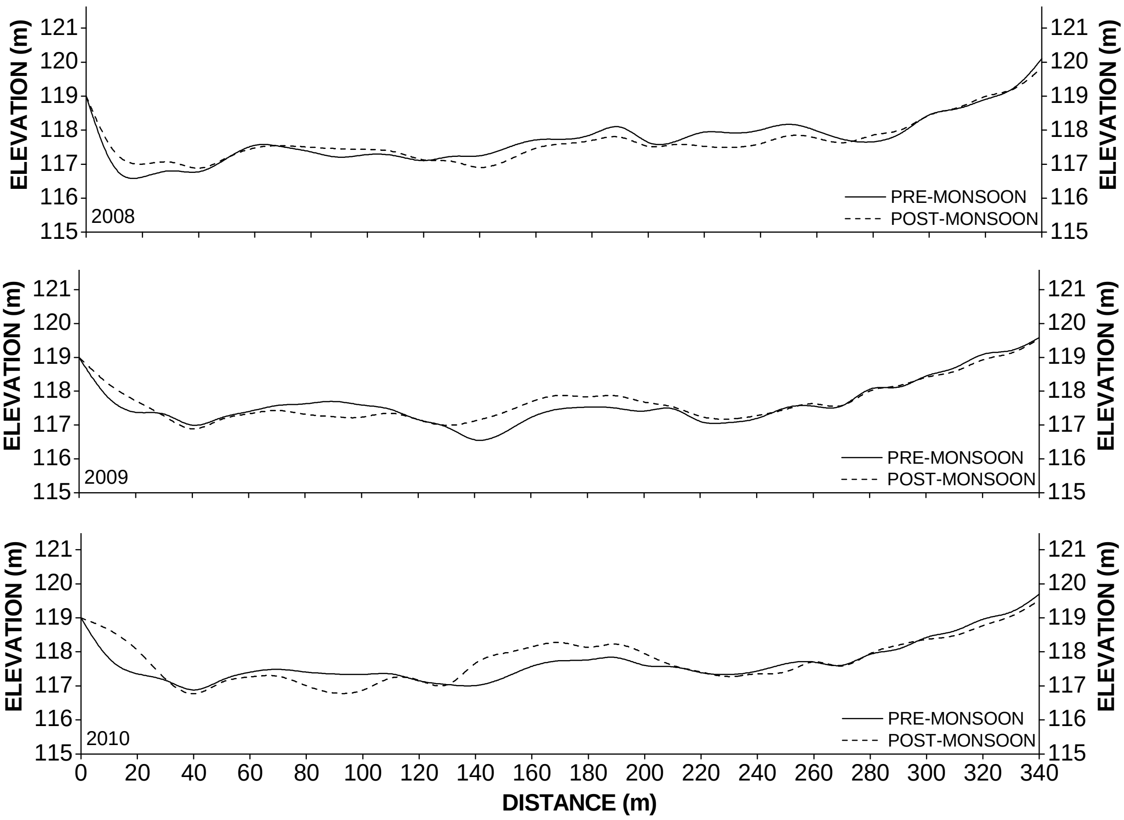


(E) 3.200 km

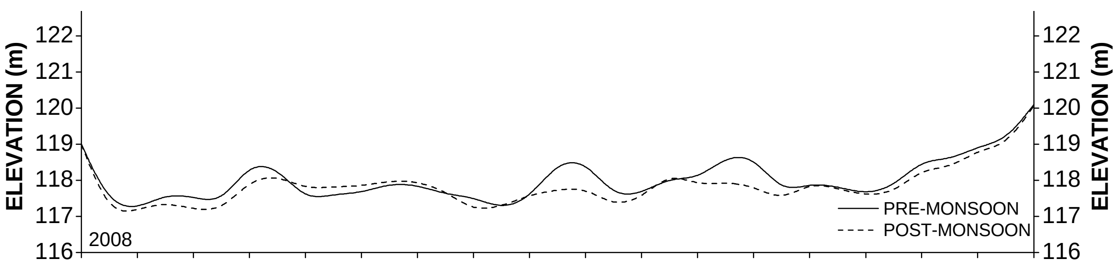


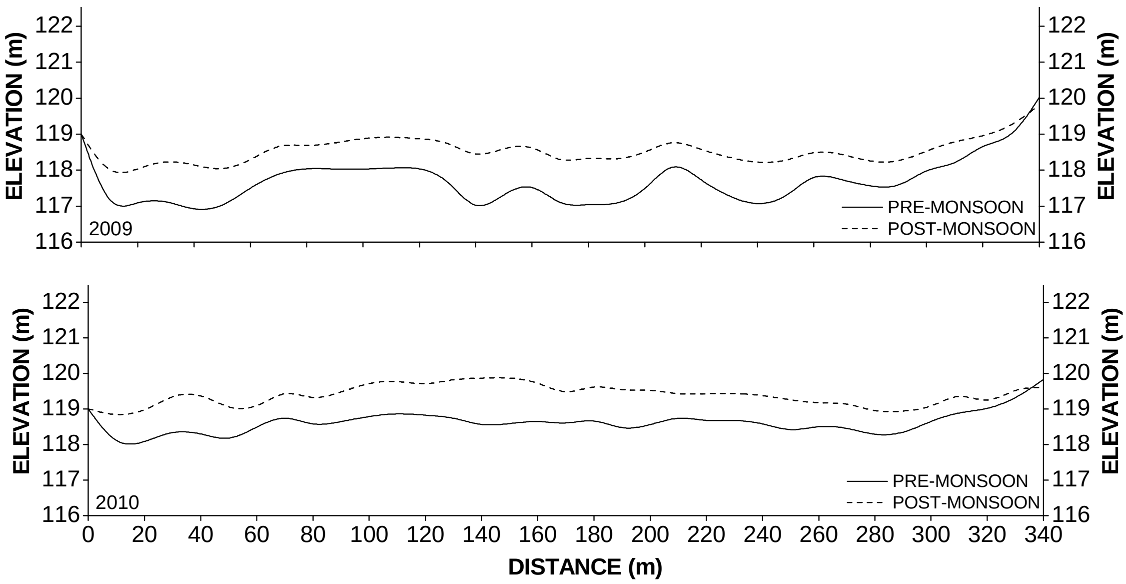


(F) 3.000 km

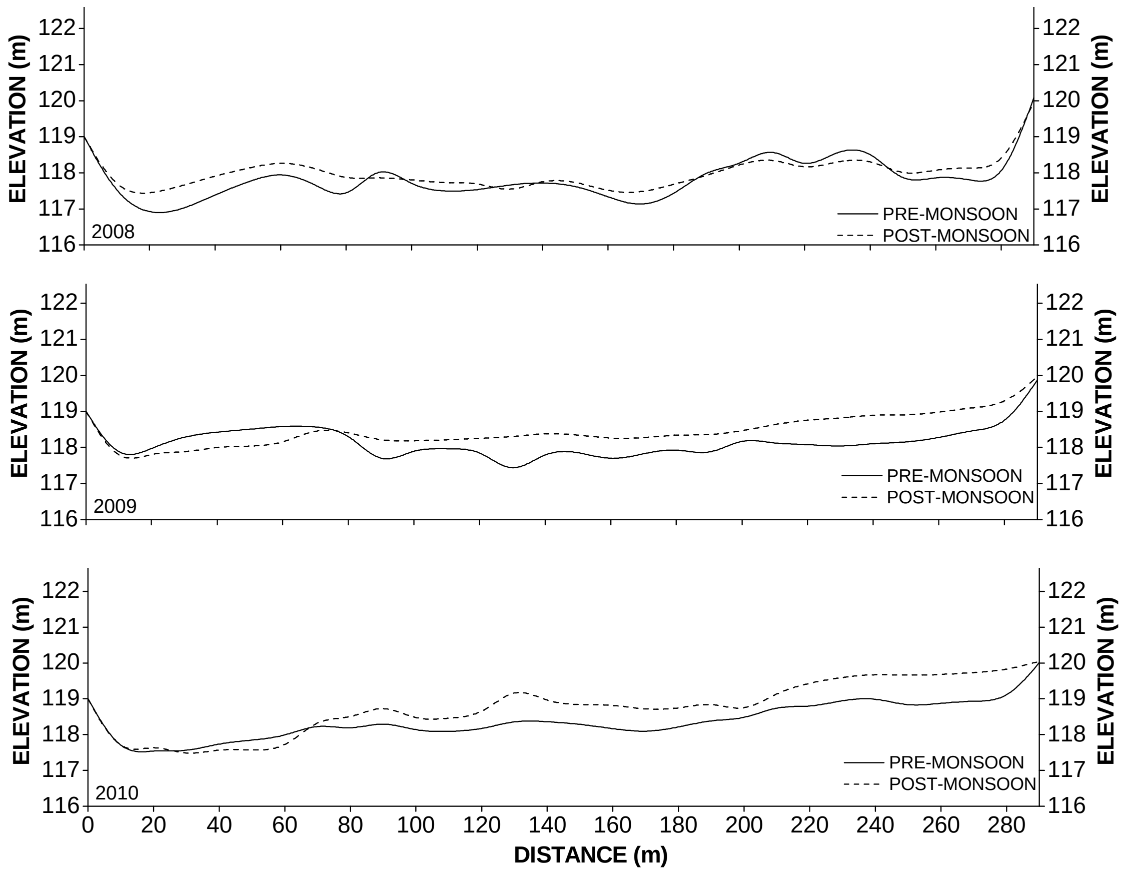


(G) 2.800 km

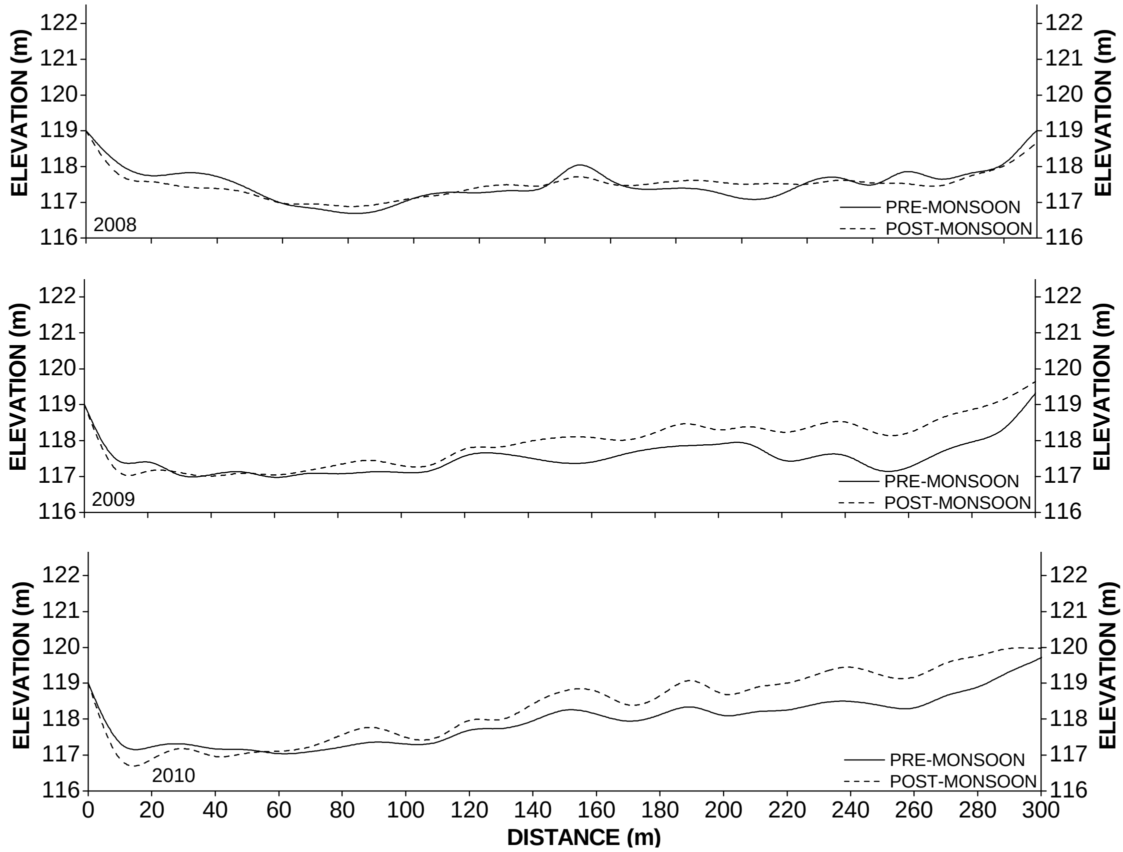



ELEVATION (m)
DISTANCE (m)
2009
2010
PRE-MONSOON
POST-MONSOON

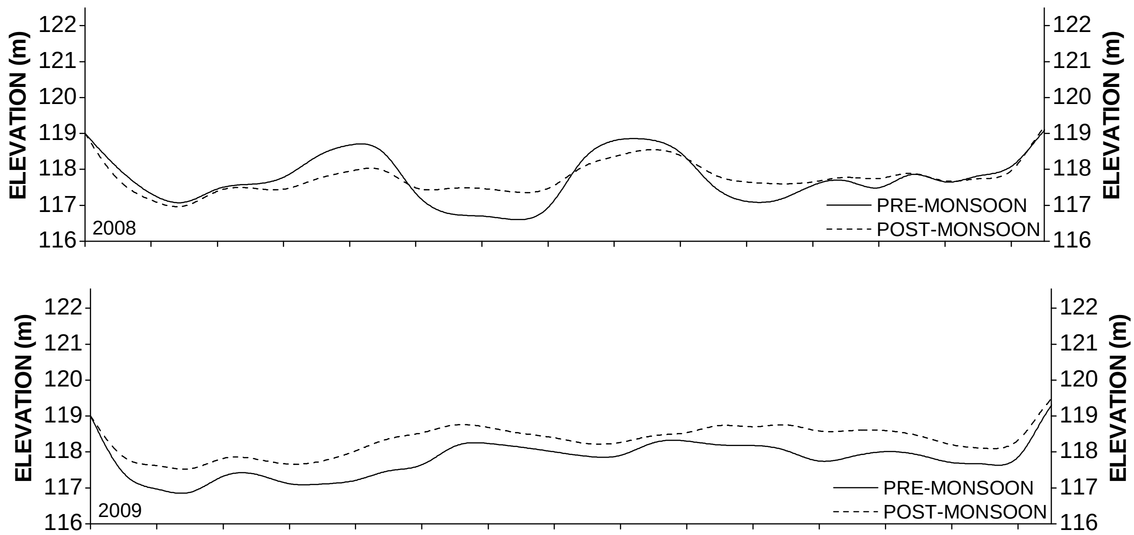
(H) 2.600 km

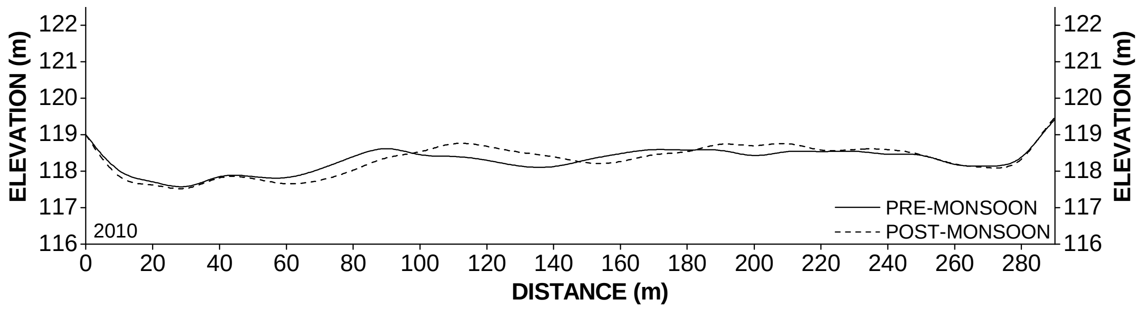

ELEVATION (m)
DISTANCE (m)
2008
2009
2010
PRE-MONSOON
POST-MONSOON

(I) 2.400 km

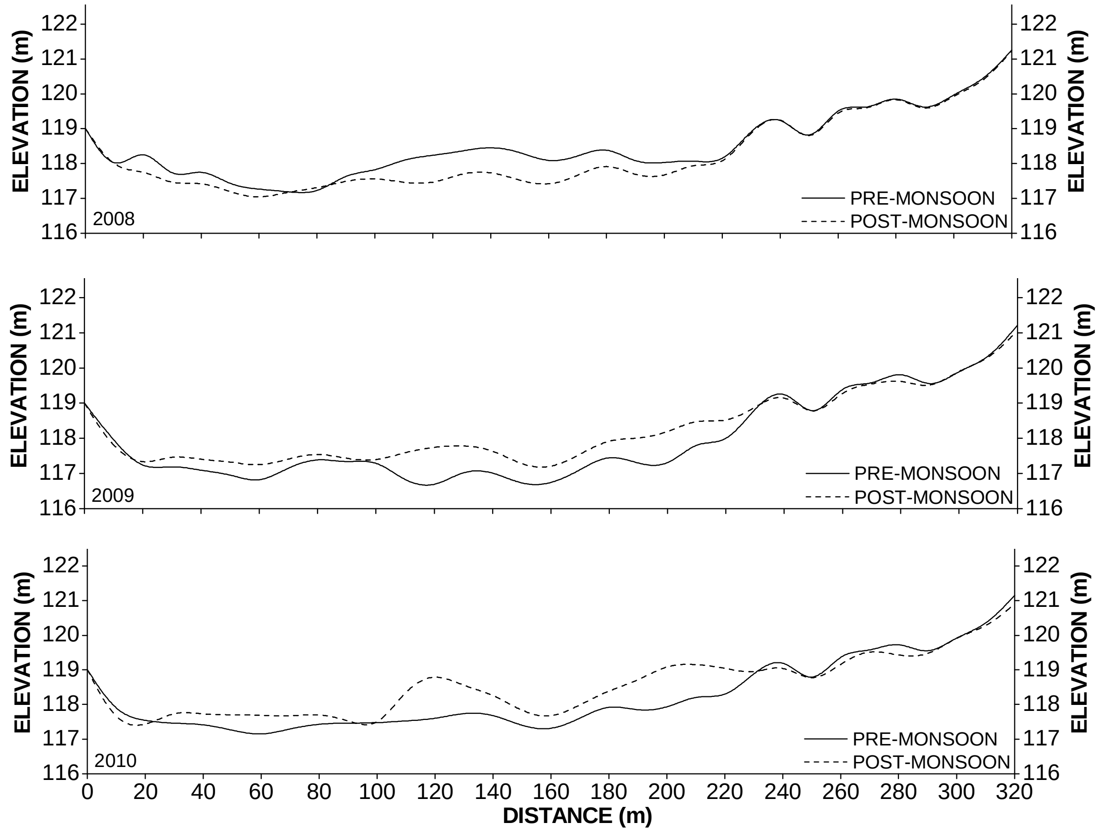


(J) 2.200 km

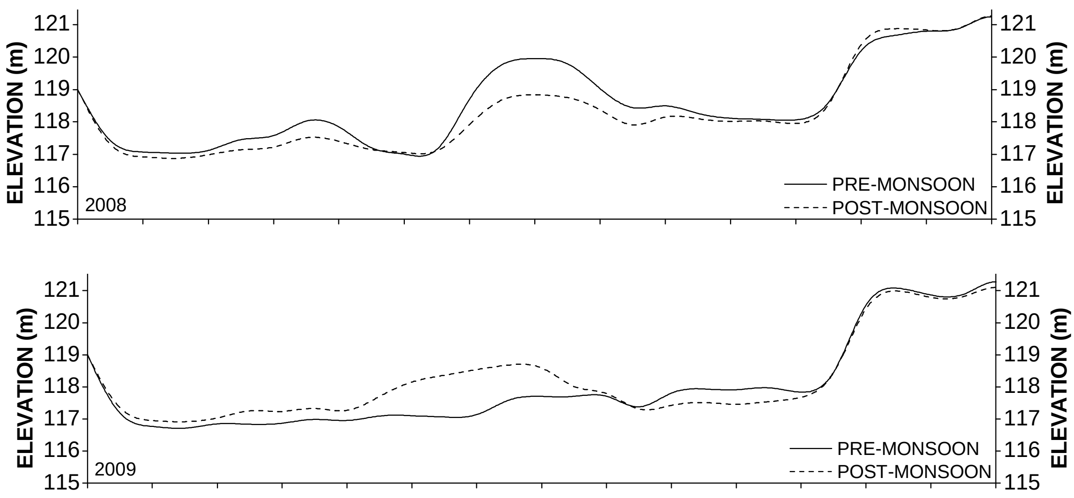


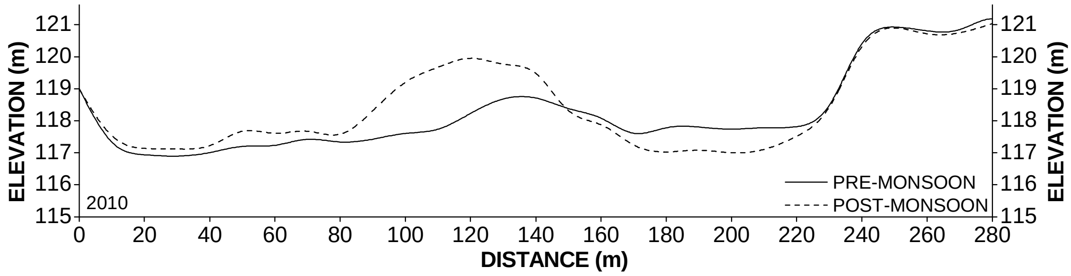


(K) 2.000 km

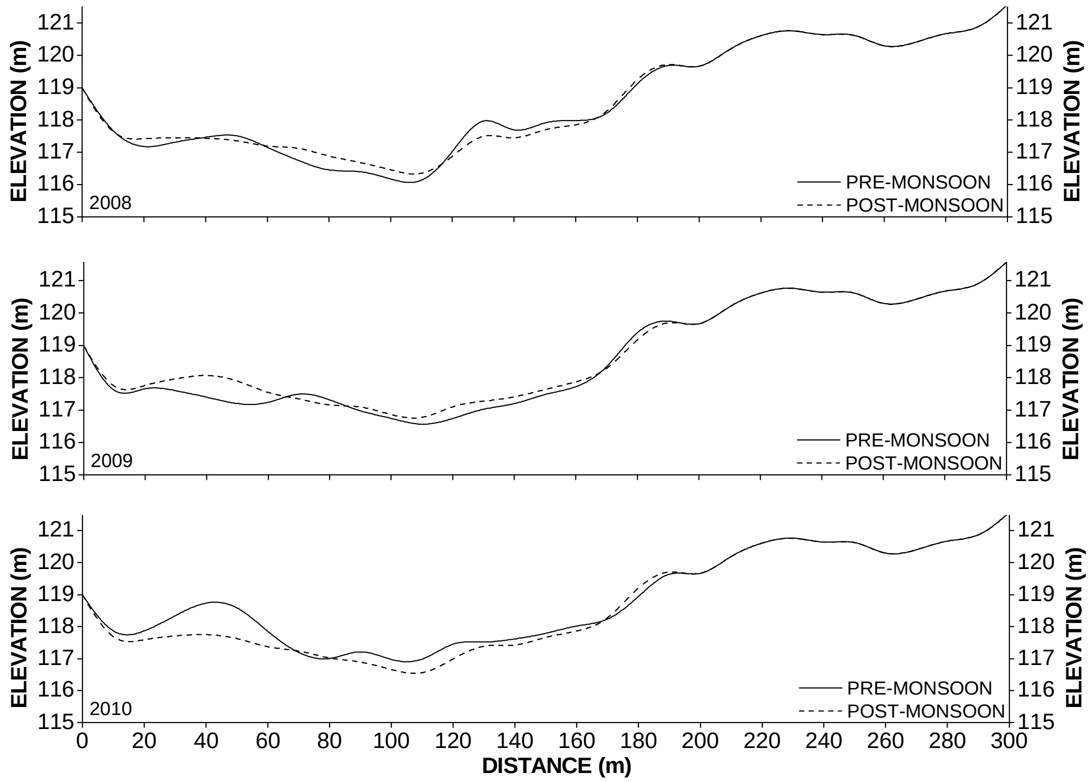


(L) 1.800 km

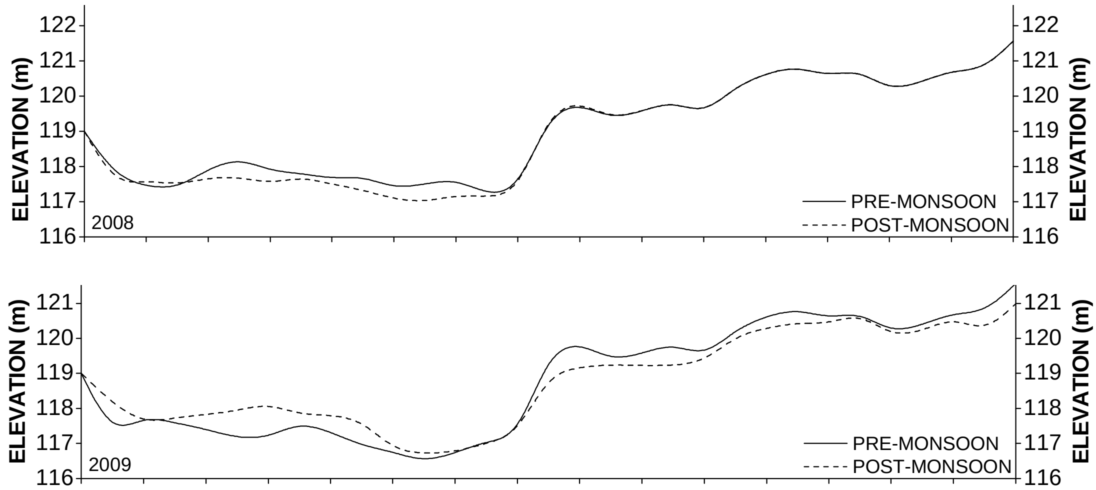


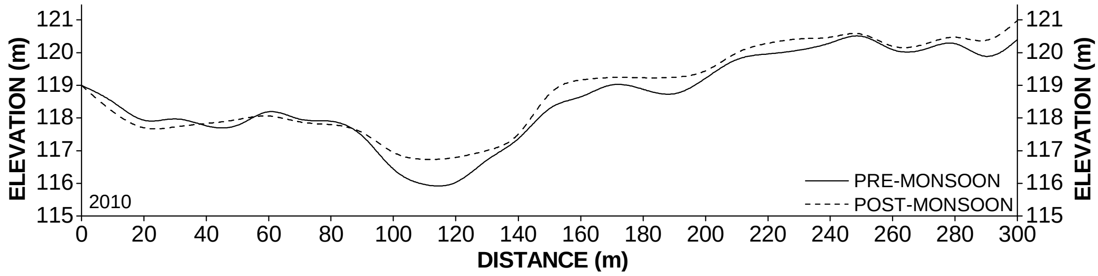


(M) 1.600 km

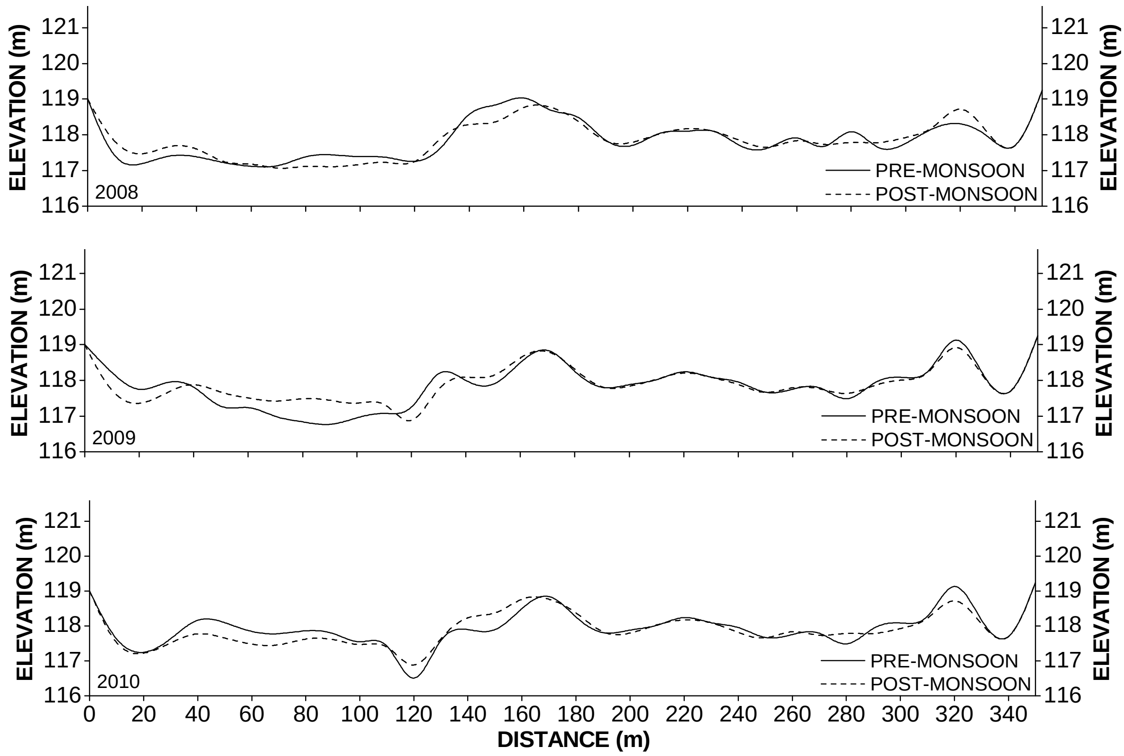


(N) 1.400 km

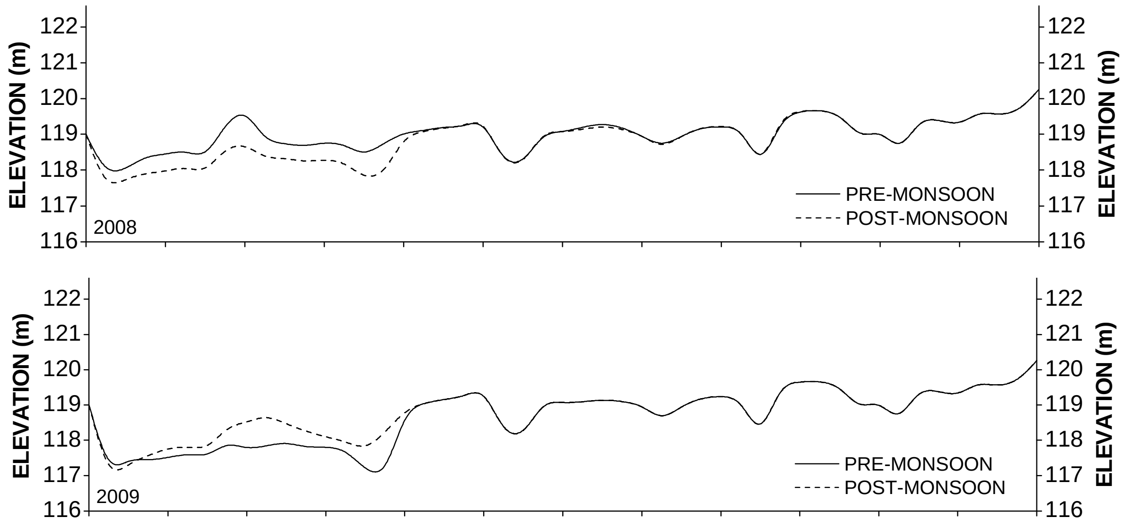


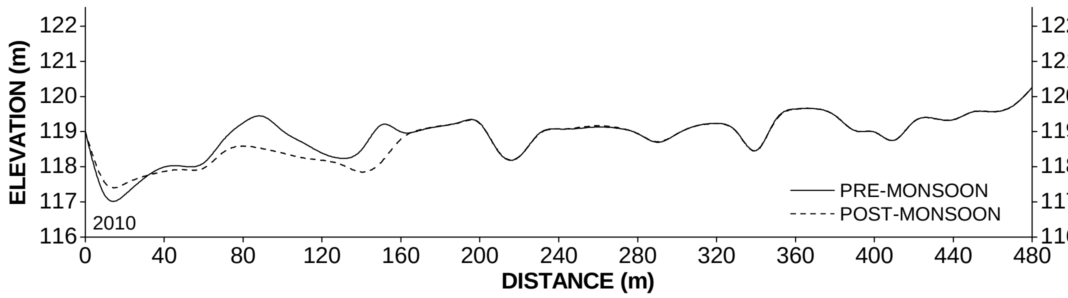


(O) 1.200 km

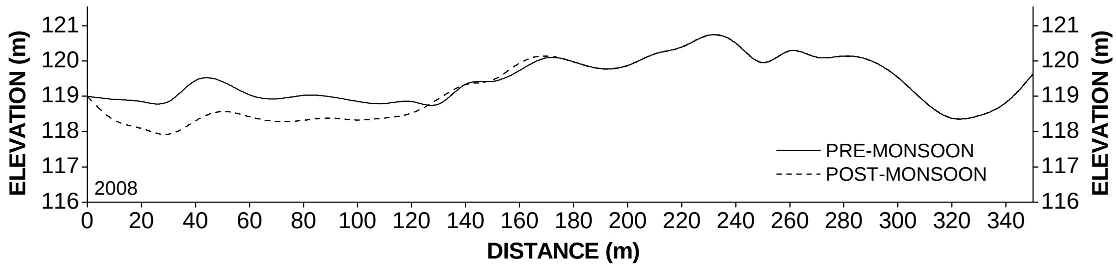


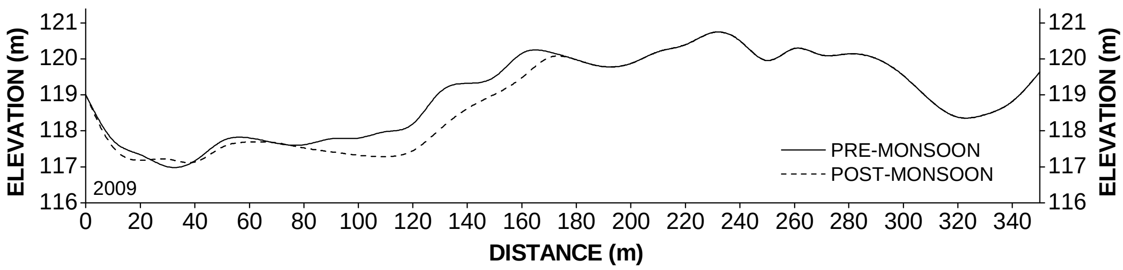
(P) 1.000 km

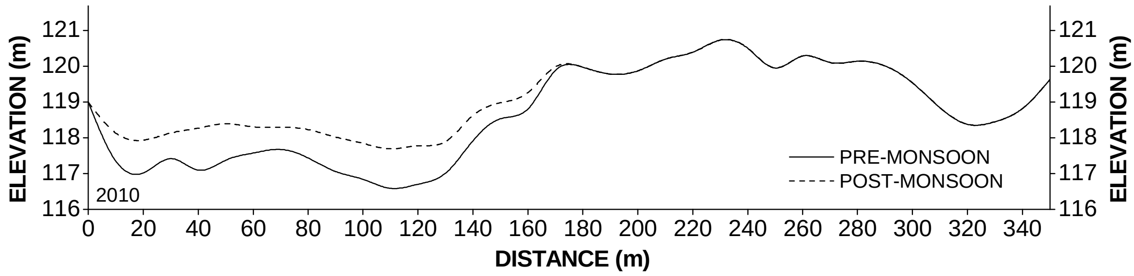




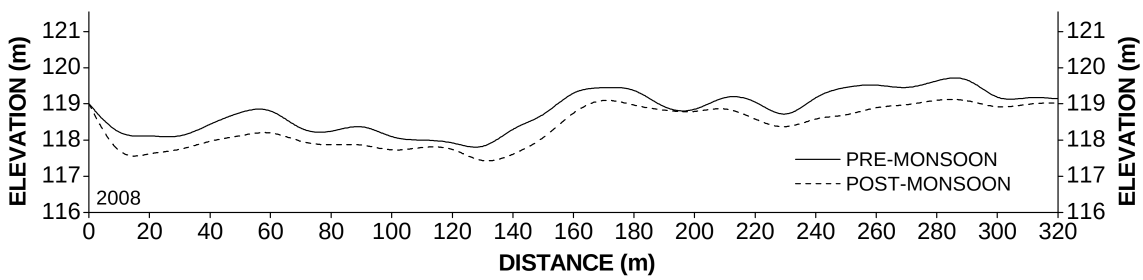
(Q) 0.800 km

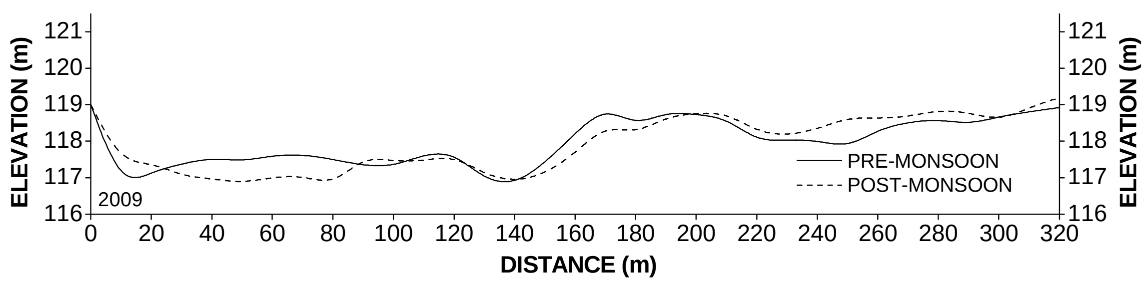


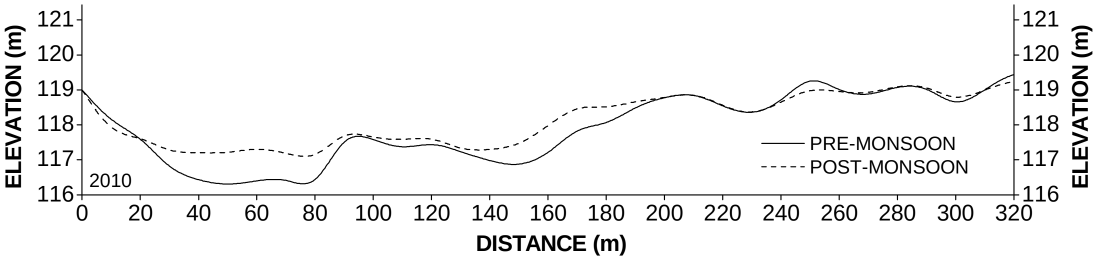




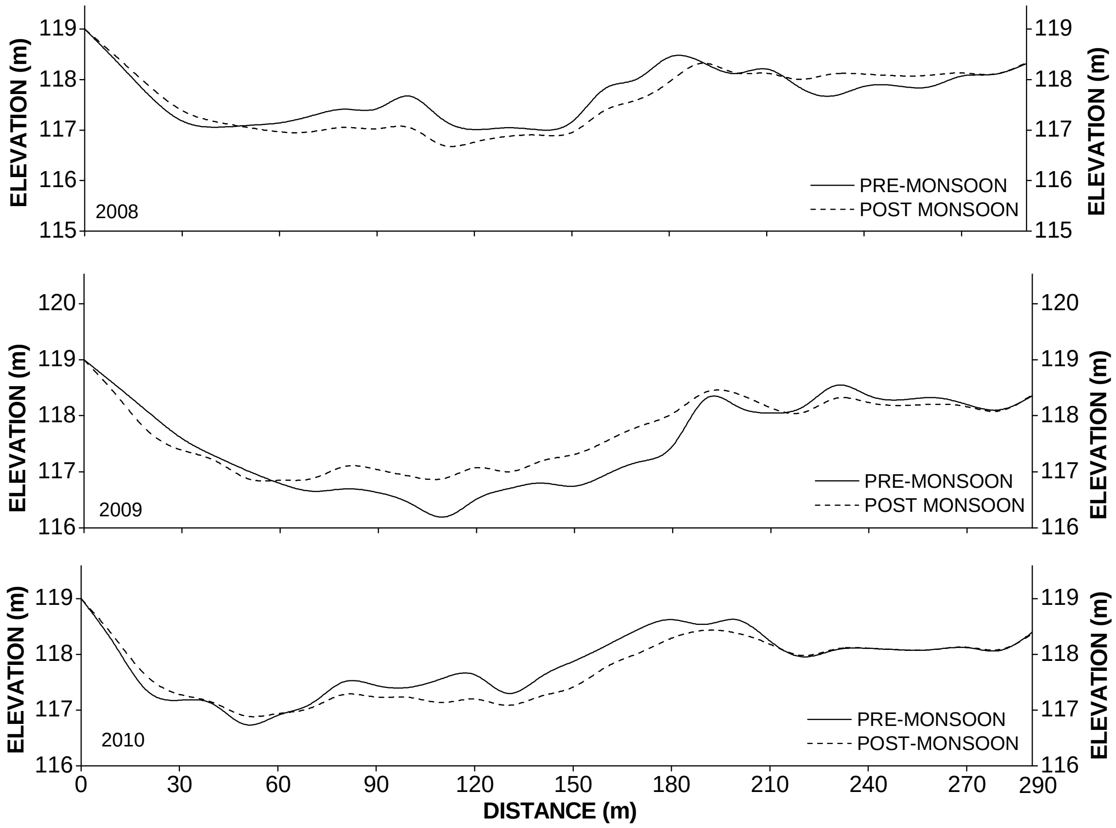
(R) 0.600 km



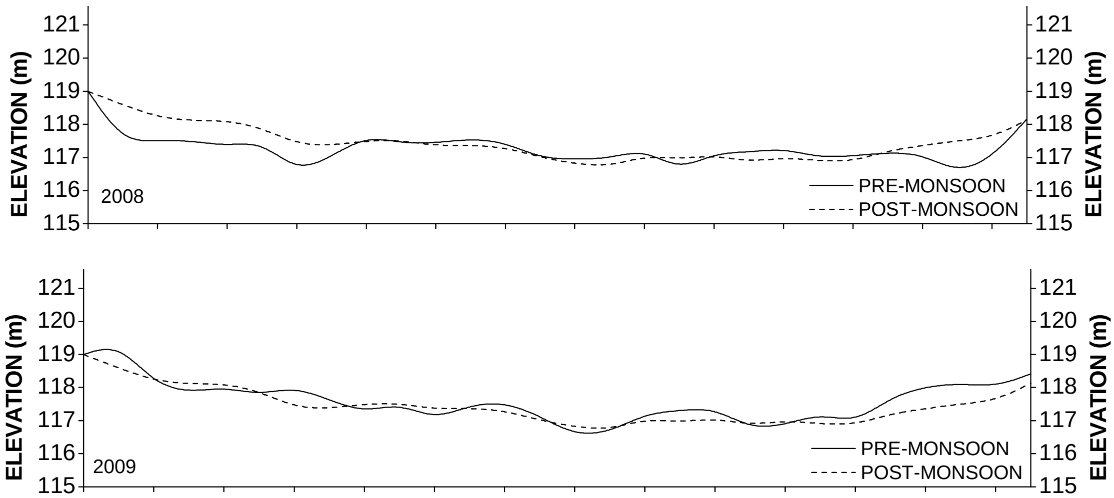


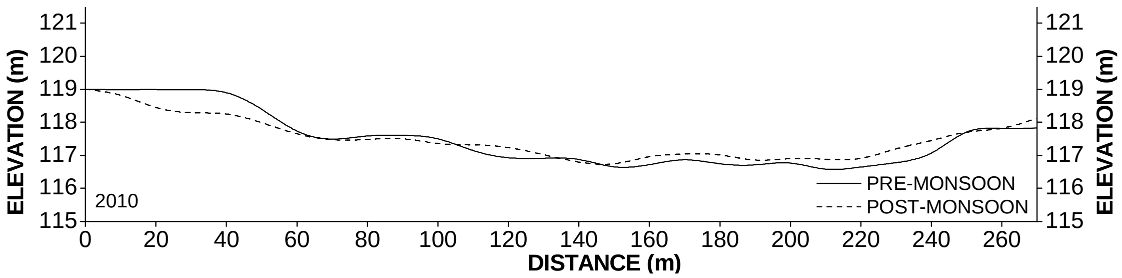


(S) 0.400 km

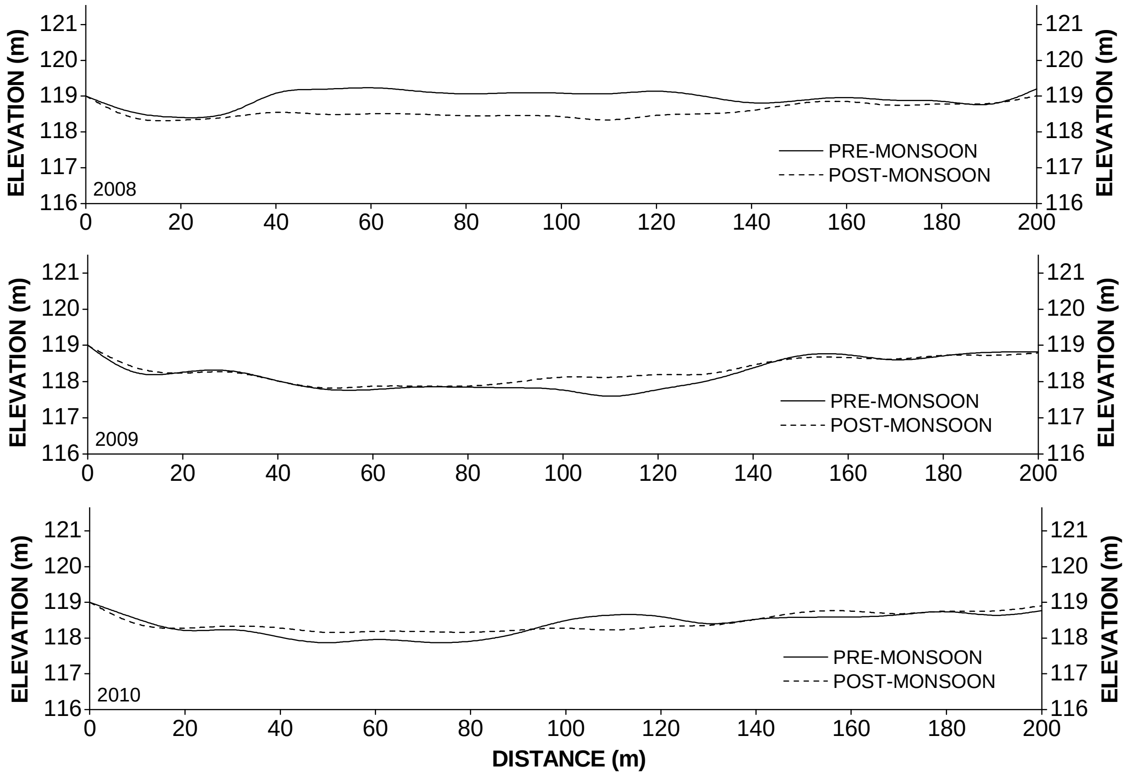


(T) 0.200 km

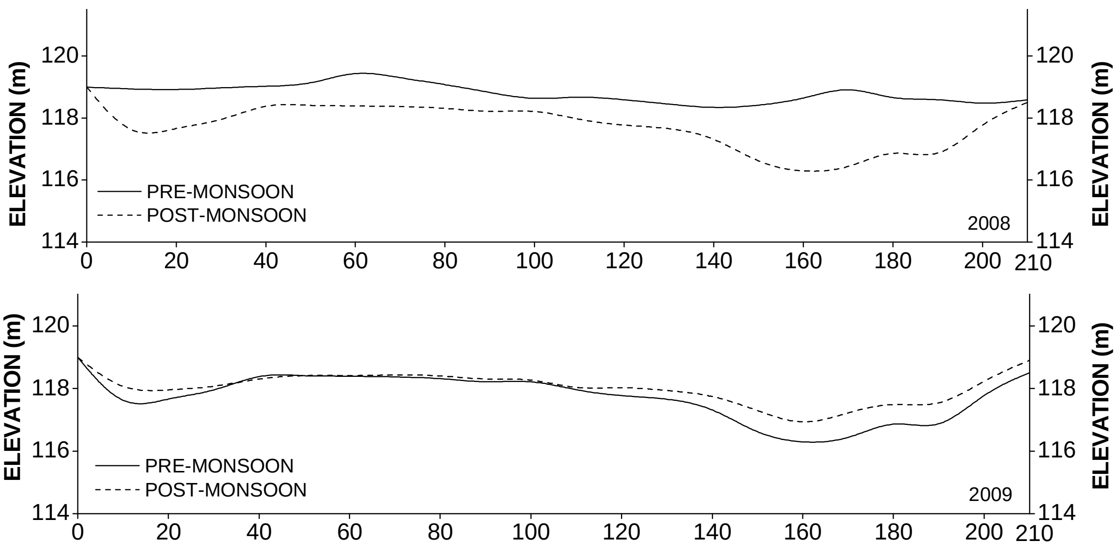


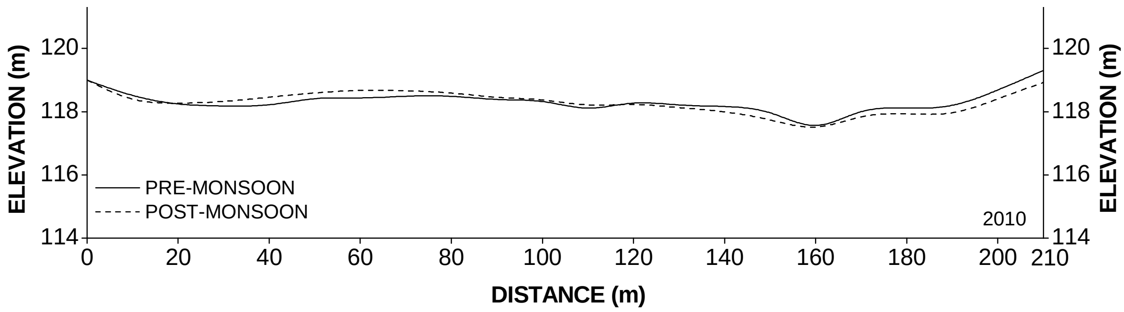


(U) 0.000 km (Below Matigara Bridge)

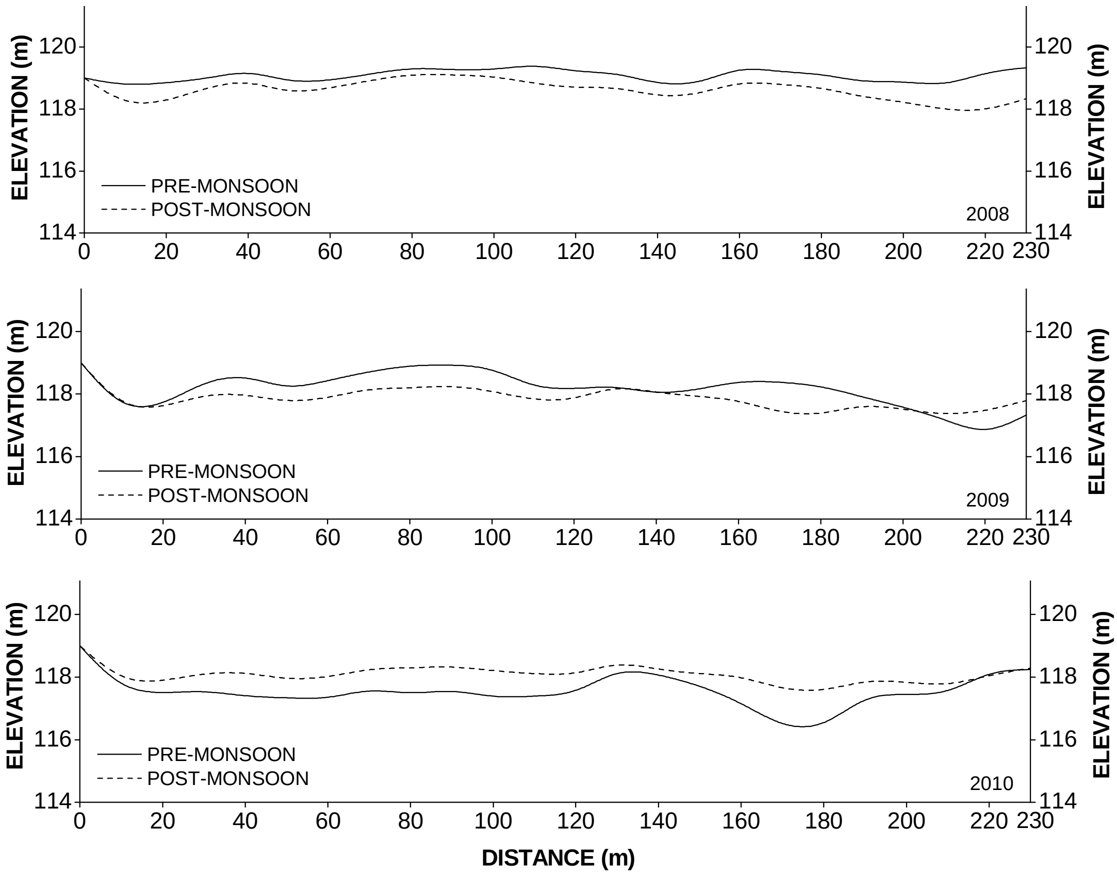


(V) 0.200 km below Matigara Bridge





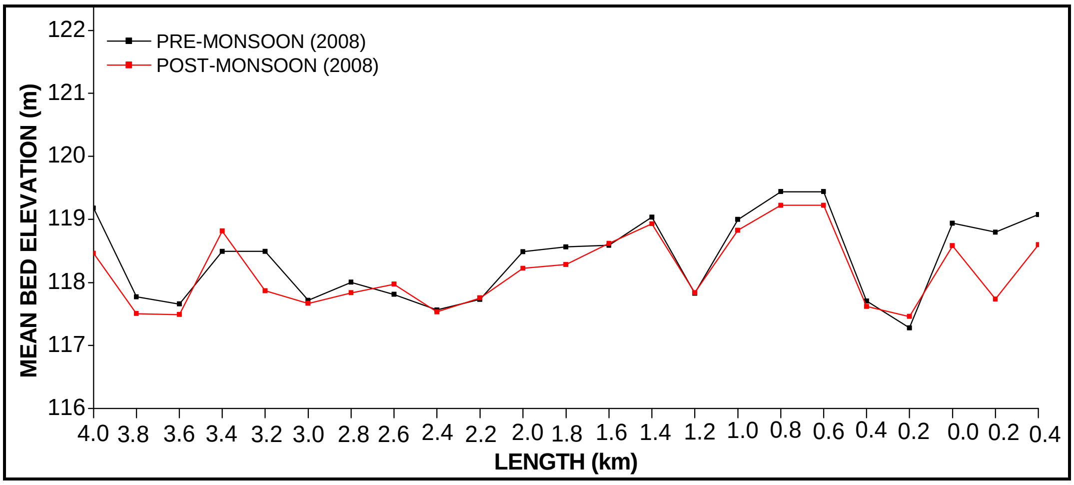
(W) 0.400 km below Matigara Bridge

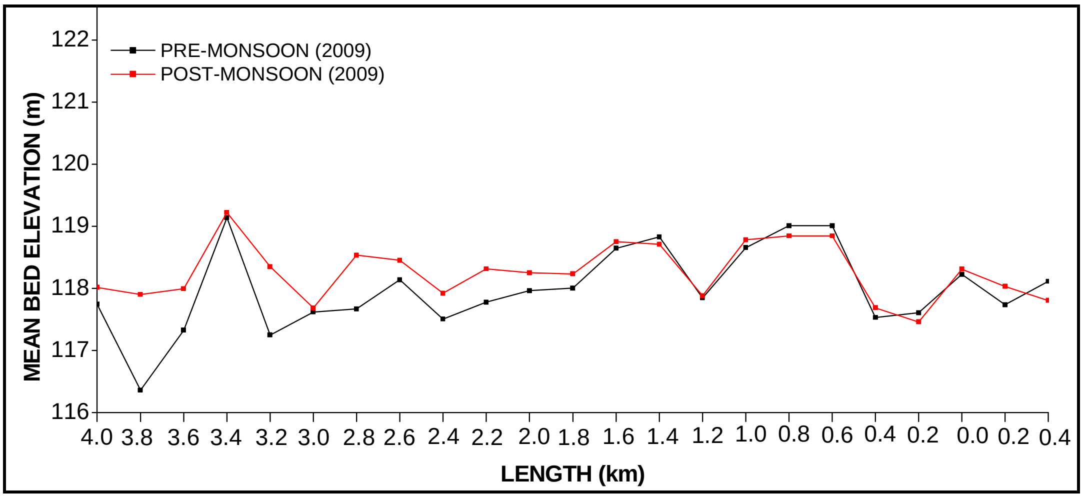


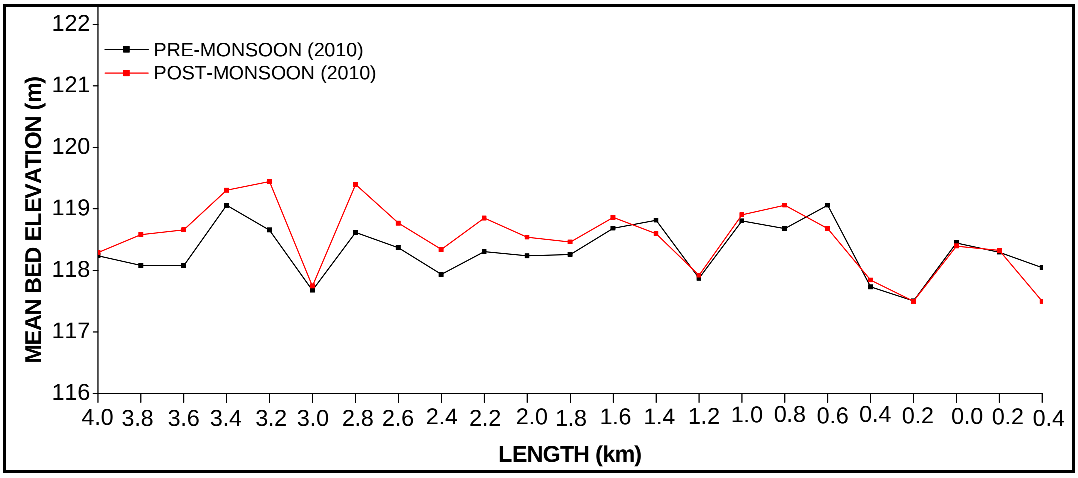
(Based on the cross-section survey)

Figure 6.3 Cross-sections along the selected stretch (4.200 km) at 200 m interval showing the changes in bed elevation during pre-monsoon and post-monsoon condition from 2008 to 2010.

The study of the cross-sections of the selected stretch of the lower Balason river shows that the effect of extraction activities is quite visible on the mean bed elevations. Although there is minimal change in width, but the channel flow remaining concentrated in same portion of the channel has caused narrowing of its cross-section. During 2008 from the pre-monsoon condition, the post-monsoon mean bed elevation lowered to 0.197 m with maximum lowering at 200 m below Matigara bridge (1.062 m) indicating that the replenishment of sediments by the river was not sufficient to fill the extracted volume. The conditions during 2009 and 2010 shows that the post-monsoon mean bed elevation increased to 0.273 m and 0.287 m (figure 6.4) but in some sections the replenishment was not sufficient since the continuous extraction rate has lowered the bed elevation.



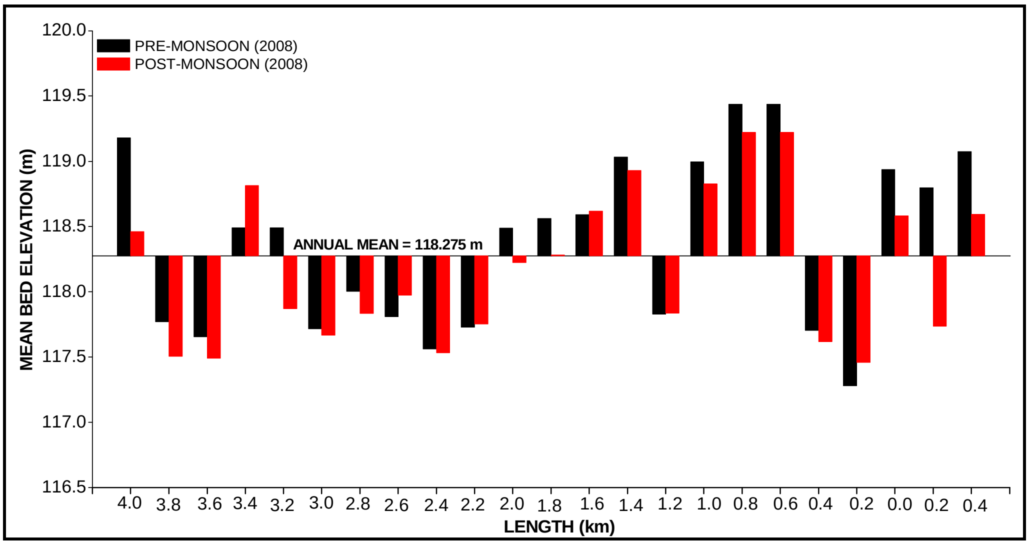


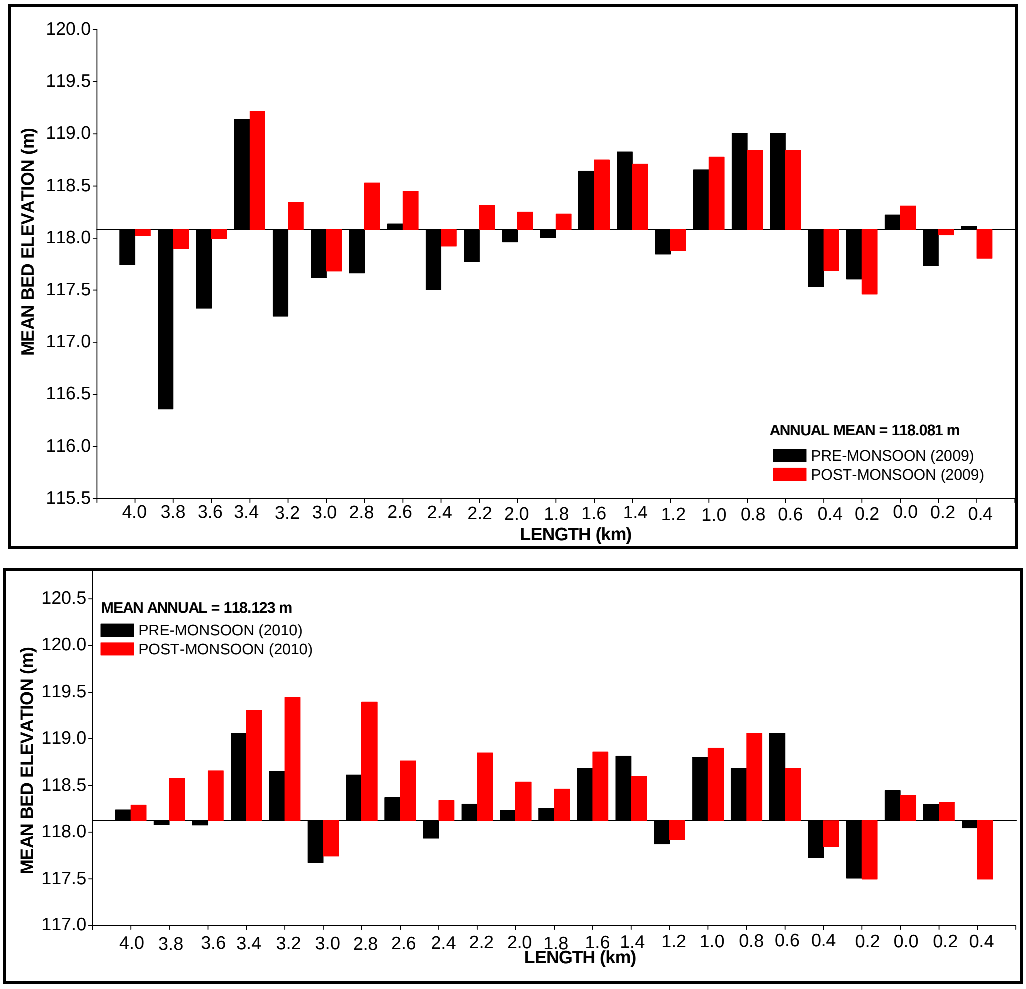


(Computed by the researcher based on the cross section survey)

Figure 6.4 The mean bed elevation (m) during pre-monsoon and post-monsoon from 2008 – 2010.

The mean annual bed elevation also reveals the variability in scouring and filling by the river during the study period. In 2008, the mean bed elevation was 118.275 m which reduced to 118.081 m in 2009 but in 2010 it again increased to 118.123 m (figure 6.5). In 2008, more than 50% of the area experienced scouring resulting mainly due to excessive volume of bed materials extracted from this stretch. But in 2009 and 2010, the filling of the pervious lowered channel bed substantially increased the bed elevation in almost all the sections except some scouring could be noticed in the upper sections (3.800, 3.200 and 0.200 km sections). Such annual changes are highly variable in almost every section of the selected stretch in the lower Balason river.

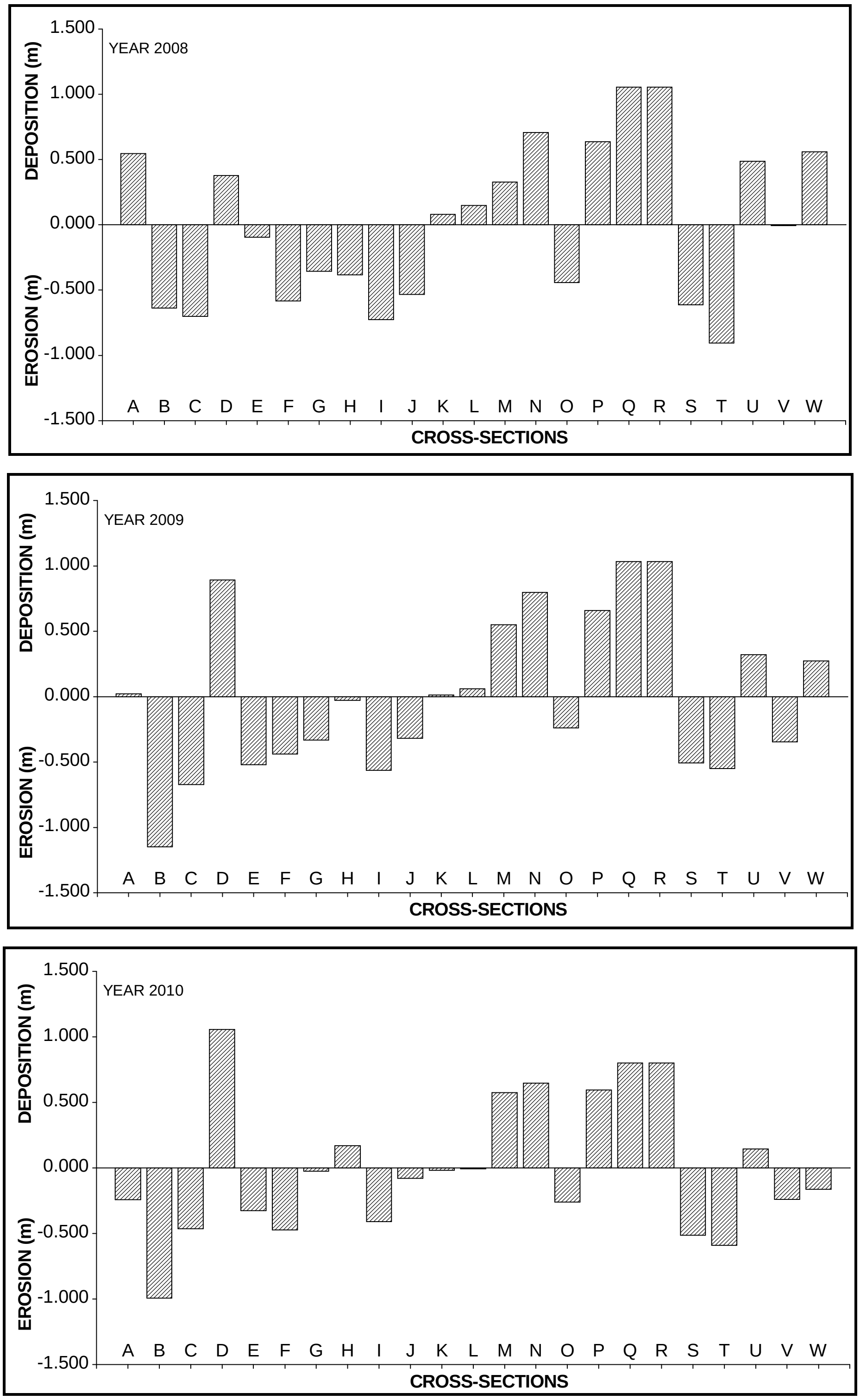




(Computed by the researcher based on the cross section survey)

Figure 6.5 The variability of mean bed elevation (m) during pre-monsoon and post-monsoon from the annual mean bed elevation during 2008 – 2010.

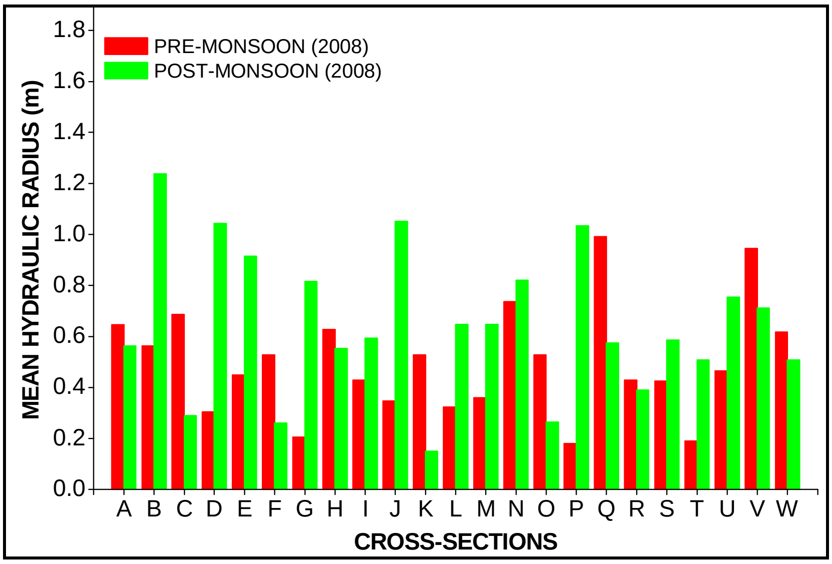
The annual scouring and filling by the river has been maintained to some extent but the bed material extractions have caused bed erosion. The difference of mean bed elevations during pre-monsoon and post-monsoon conditions from annual mean bed elevation reveals that bed erosion has occurred in all three years with maximum of 0.905 m at 0.200 km (cross-section T) in 2008, 1.149 m at 3.800 km (cross-section B) during 2009 and 0.992 m again in the same section in 2010 also (figure 6.6). This clearly indicates that the effect of continuous extraction of bed materials from the same place have been creating extraction pits of more than 2.000 m depth which has increased the channel gradient and consequent bed erosion upstream and downstream of such extraction pits. Also the exposed tree trunks being exposed due to prolonged extraction on the channel bed and adjacent banks are clear indication of bed erosion induced incision (plate 6.2B, C, D & E)

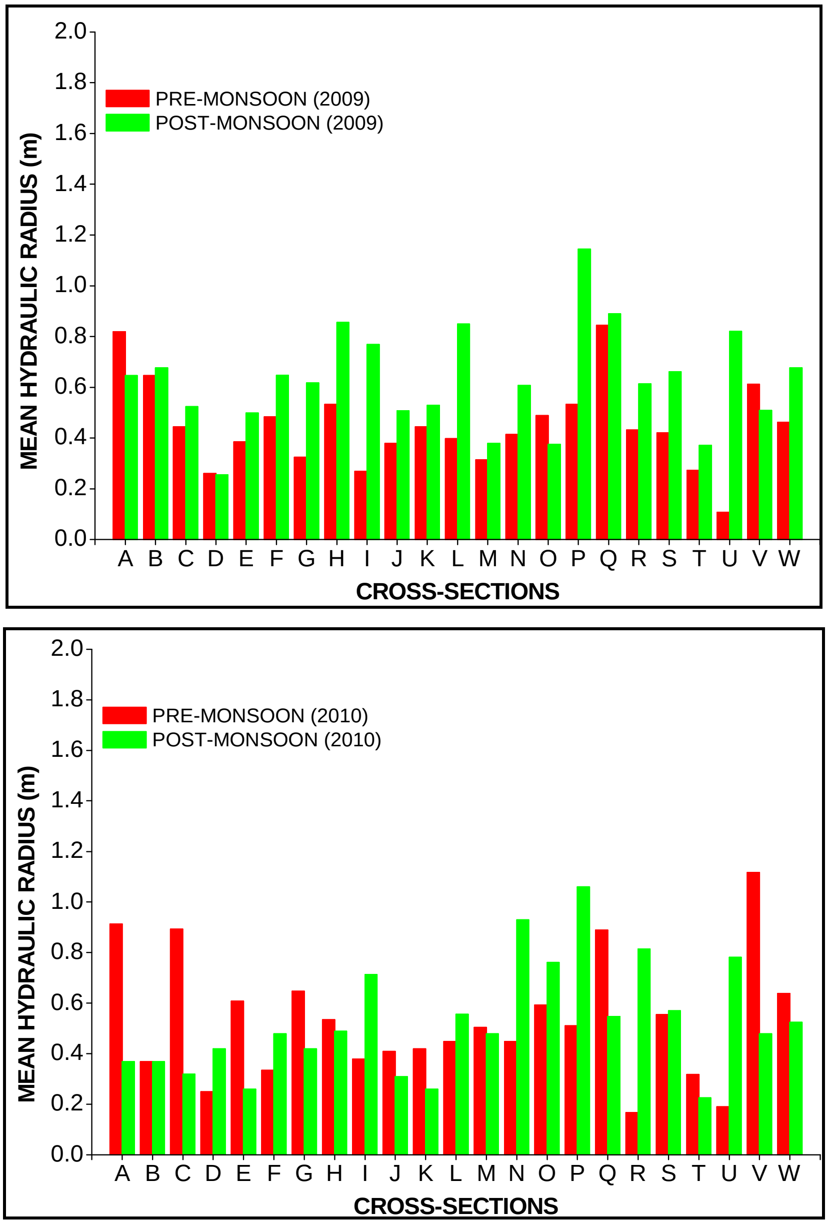


(Computed by the researcher based on the cross section survey)

Figure 6.6 The annual erosion and deposition at surveyed cross-sections during 2008 to 2010.

The study of the mean hydraulic radius also considered as the measure of the efficiency of the channel (Schumm, 1977) supports the fact that at sections with bed erosion, the hydraulic radius is higher compared to the sections with deposition replenishing the extraction volume (figure 6.7). The maximum mean hydraulic radius of 1.238 m was computed for cross-section B (3.800 km) in 2008 which was more than double of the annual mean hydraulic radius (0.574 m) for the entire studied stretch. In 2009, the computed maximum mean hydraulic radius of 1.145 m occurred at cross-section P (1.000 km) with annual mean of 0.537 m. During 2010, the computed maximum mean hydraulic radius further decreased to 1.117 m at cross-section V (0.200 m below Matigara Bridge) with annual mean hydraulic radius of 0.527 m for the entire studied stretch. Thus it reveals that with continuous increase of mean hydraulic radius at few sections has incremented the channel velocity and energy thus inducing bed erosion and increase in channel gradient.

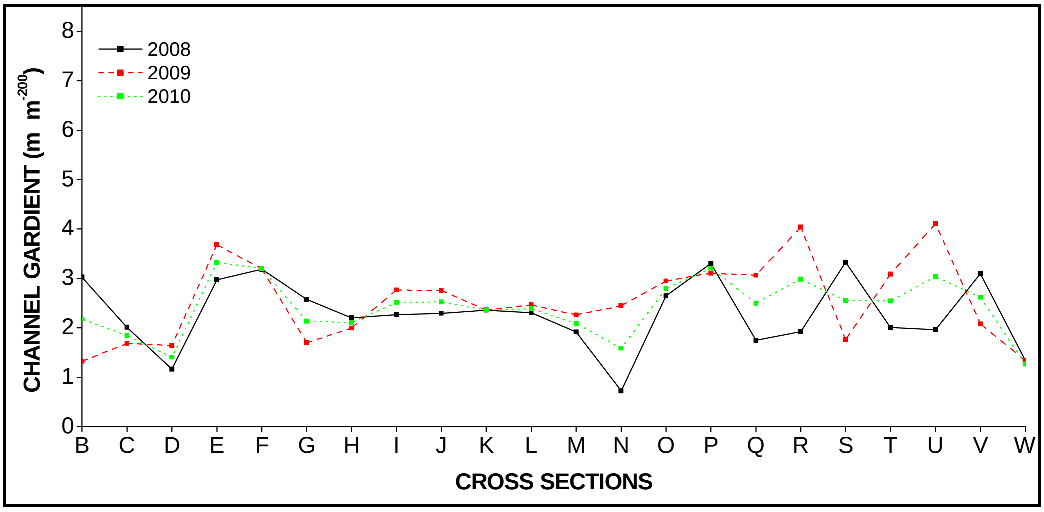




(Computed by the researcher based on the cross section survey)

Figure 6.7 The mean annual hydraulic radius (m) at surveyed cross-sections during pre-monsoon and post-monsoon condition from 2008 – 2010.

The channel gradient variations between the cross sections is an indication to the channel erosion caused due to prolonged bed material extraction from the river bed. The lowering of bed elevations has caused the channel adjustments due to increase in the gradient resulting into increased stream power and consequent bed erosion (Kondolf, 1997). The cross-sections with maximum annual bed erosion (cross-sections B, E, R and U) have steeper gradient which migrates both upstream and downstream annually (figure 6.8) (plate 6.3A). Thus the bed erosion also migrates depending upon the active channel, which is called the *"head cutting or knick point migration"* according to Kondolf (1997) (figure 6.1).



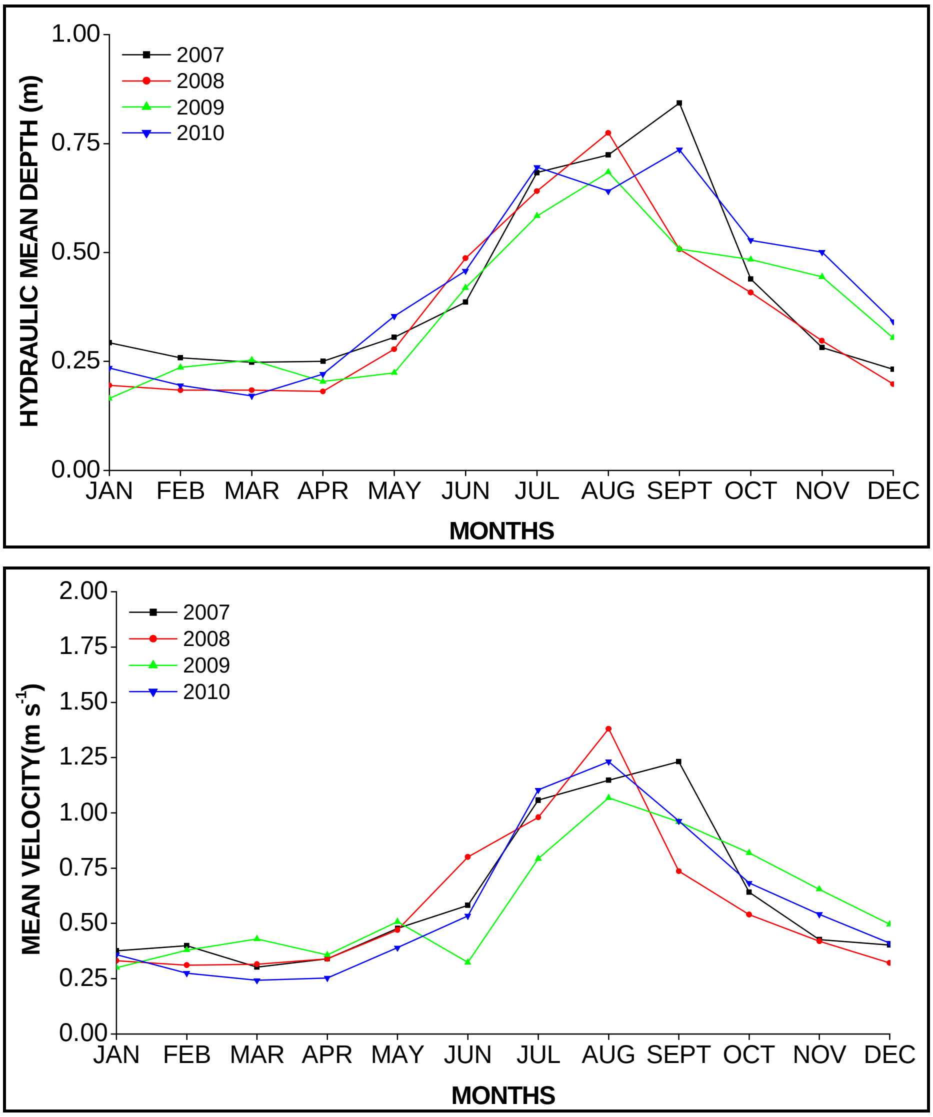
(Computed by the researcher based on the cross section survey)

Figure 6.8 The mean annual channel gradient (m) at surveyed cross-sections during 2008 – 2010 *(Refer Appendix C 6.1).*

6.3 Study of the effects of boulder lifting on the hydraulic characteristics of the lower Balason river

In order to study the effects of boulder lifting activities on the hydraulic characteristics of the lower Balason river, the data of different hydraulic parameters like hydraulic mean depth (m), mean velocity (m s^{-1}) discharge (m^3 s^{-1}) and water level (m) have been collected from CWC G&D, Matigara located within the studied stretch from 2007 to 2010.

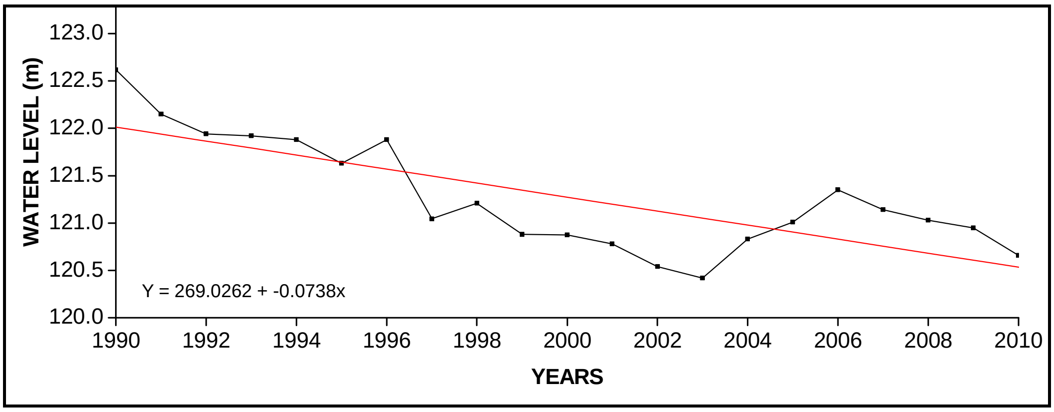
The mean monthly hydraulic mean depth from 2007 to 2010 (figure 6.9 A) reveals that there exists annual trend of replenishment by the river mostly during monsoon periods. From 2007, the mean depth has increased substantially during post-monsoon periods but the condition was opposite during pre-monsoon periods with decrease in mean depth. Such condition indicates that the extent of bed materials was higher during post monsoon period which induced the bed erosion and consequently increased the mean velocity (figure 6.9 B).



(Computed by the researcher based on records of CWC G&D Site, Matigara)

Figure 6.9 The monthly hydraulic mean depth (A) and the monthly mean velocity (B) from 2007– 2010 *(Refer Appendix C table 6.2 & 6.3).*

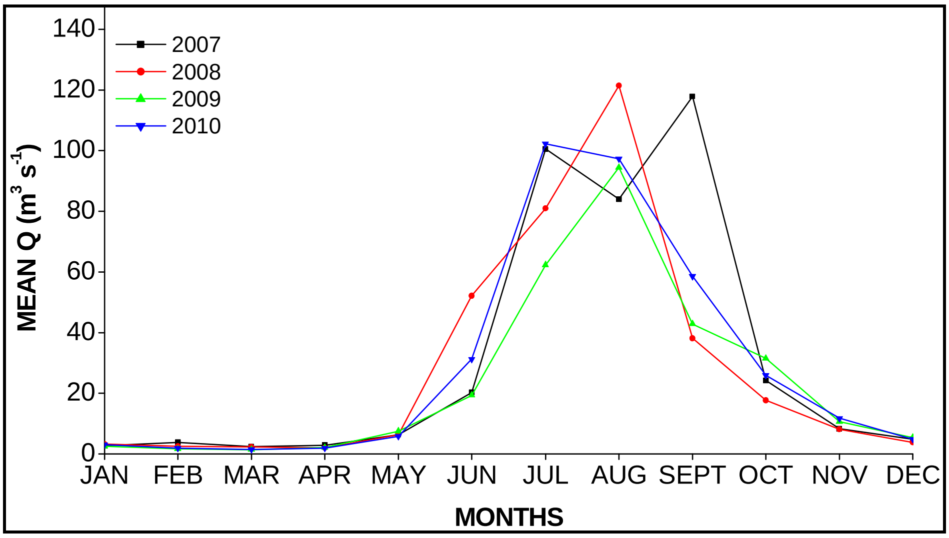
The annual minimum water level (m) from 1990 to 2010 also shows the decreasing trend of the annual water level which is largely responsible due to increase in extraction rate after 2000 (figure 6.10). The extraction of finer bed materials (mostly sand) increases the channel efficiency and ultimately causes incision or bed lowering leaving the coarser materials on the leaving bed (Starkel and Froehlich, 2000).



(Computed by the researcher based on records CWC G&D Site, Matigara)

Figure 6.10 The trend of the annual minimum water level from 1990– 2010.

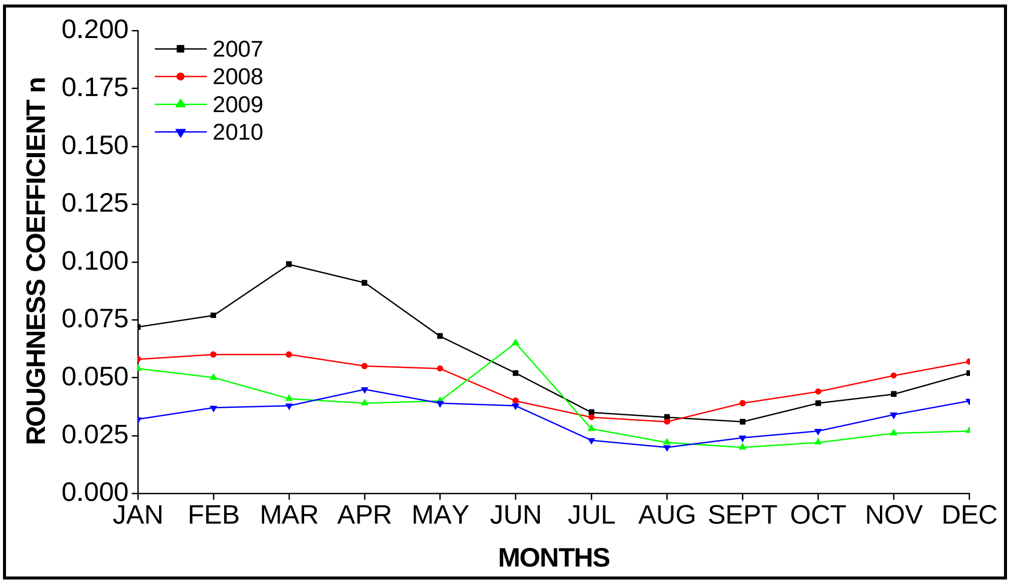
Another effect of bed material extraction in lower Balason river has been noticed on the mean monthly peak discharge from 2007 to 2010 (figure 6.11). The lowering of the bed elevation and occurrences of deep extraction pits reduces the flow retention which attenuates the peak flows but downstream the magnitude of inundation increases resulting into increased flood magnitudes (Rinaldi, 2003).



(Computed by the researcher based on data collected from CWC G&D Site, Matigara)

Figure 6.11 The monthly mean discharge of the lower Balason river from 2007– 2010.

The extensive extraction of bed materials from the lower Balason river has lowered the transport of coarser sediments downstream resulting into deficit of coarser sediments as the extraction pits acts as trap for sediments (Rinaldi et.al, 2005). Thus during high flow only finer sediments are being transported into downstream segments. Such condition has lowered the roughness coefficient (n) of the river bed as could be noticed at CWC G&D Site, Matigara (figure 6.12) during 2007 to 2010.



(Computed by the researcher based on records of CWC G&D Site, Matigara)

Figure 6.12 The monthly mean roughness coefficient of the lower Balason river during 2007– 2010 *(Refer Appendix C table 6.4).*

6.4 Conclusions

The prolonged bed material extraction from the lower Balason river has caused bed erosion which is migrating annually with variations in channel gradient both upstream and downstream of the extraction sites (plate 6.3E & F). The river has been adjusting with changes in its morphology and with maximum coarse materials (gravels and boulders) being extracted from the river bed, the balance between transport capacity and sediment supply is being largely altered. Although the river annually replenish the sediment deficit by scouring and filling but such modifications are largely responsible for under cutting of bridges and embankments (plate 6.1A, B & C). The near-bank extraction has also resulted into diversion of channel flow sometimes abandoning its pervious course (plate 6.1D) and also causing retreat of exposed banks (plate 6.2F).

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Plate 6.1 The undercutting below Dudhia bridge (A); breached embankment during monsoon flow (B) near Tarabai and railway bridge near Matigara damaged (C) during monsoon high flows; the concentration of channel flow during low flows due to frequent under cutting leaving (D); the undermined Matigara bridge piers (E); and remnants of old flood deposited bars in the lower segment (F) of the lower Balason river. (Photographs by the Researcher)

Plate 6.2 Direct extraction from active channel flow by extractors causing bed erosion (A); tree trunks (red circled) being exposed due to prolonged extraction causing incision (B, C, D & E);and near bank extraction diverting channel flow (F) in the lower Balason river.

Plate 6.3 Examples of undercutting and remnants of high raised bars along the upper segments (A) and middle segments (B); destruction of permanent structures built over flood plains (C) and extraction pits and degraded river bed after extraction (D, E & F) in the lower segments of the lower Balason river.

CHAPTER 7

Bank failure and boulder lifting on lower Balason basin

7.1 Introduction

The adjustments of the channel width by mass-wasting and related processes can be represented as an important mechanism of channel response and energy dissipation in alluvial channels (Simon, et al 1999). Under such lateral adjustments, the channel initiates bank failure depending upon the flow energy and shear strength, composition and environmental setting of the banks. This process undercuts the bank base and channel bed adjacent to the banks, thus weakening the shear strength of the bank.

Failure of the banks along the lower Balason river has been noticed as the river undergoes lateral adjustment due to high fluctuating discharge with frequent flow diversions, cohesiveness of the bank materials and anthropogenic effects in the form of human occupancy on the bank and extensive bed material extraction. During monsoon high peak flood flows, sudden outburst of water in the channel increases its shear stress causing failure of the exposed banks annually. Bank line survey using GPS before and after monsoon periods by the researcher and the obtained results when superimposed with past bank conditions from available satellite imageries also shows that the bank failure has been prevalent and is amongst the important modifications by the lower Balason river under increasing human interferences (figure 7.1).

7.2 Study of the bank composition

The banks of the lower Balason river consists of loose unassorted colluvial sediments transported by the river during extreme flood events. Such sediments are being further eroded during annual peak flows by the river and moreover the finer sediments are being added over it through surface run-off thus producing the upward fining tendency (Jana and Dutta, 1995). The vertical distribution of bank materials varies as the river proceeds downstream with larger unassorted sub-angular boulders (1024-4096 mm) mixed with coarse sands and gravels in the upper piedmont segments till 6 km downstream (plate 7.1A). The compactness and cohesiveness is high with ample top soil favoring vegetative growth. The middle segments (till 18 km downstream) mostly consists of medium sized boulders (256-1024 mm), gravels (64-256 mm) mixed with sand. The coarse sand layer with distinct cross bedding thins out to fine sand and the cohesiveness is less as materials come out when plucked (plate 7.1B). The top soil is very thin layered and as such vegetative growth is also less compared to upper piedmont segments. In the lower segments, there exist mostly finer particles with fewer mediums to small sized gravels (12-128 mm). The sand and silts with distinct flood deposit layer are visible on the exposed banks (plate 7.1C). The formation of top soil layer is almost nil and mostly few small grasses grow over the finer sand and silt deposited annually by the river during monsoon flows.

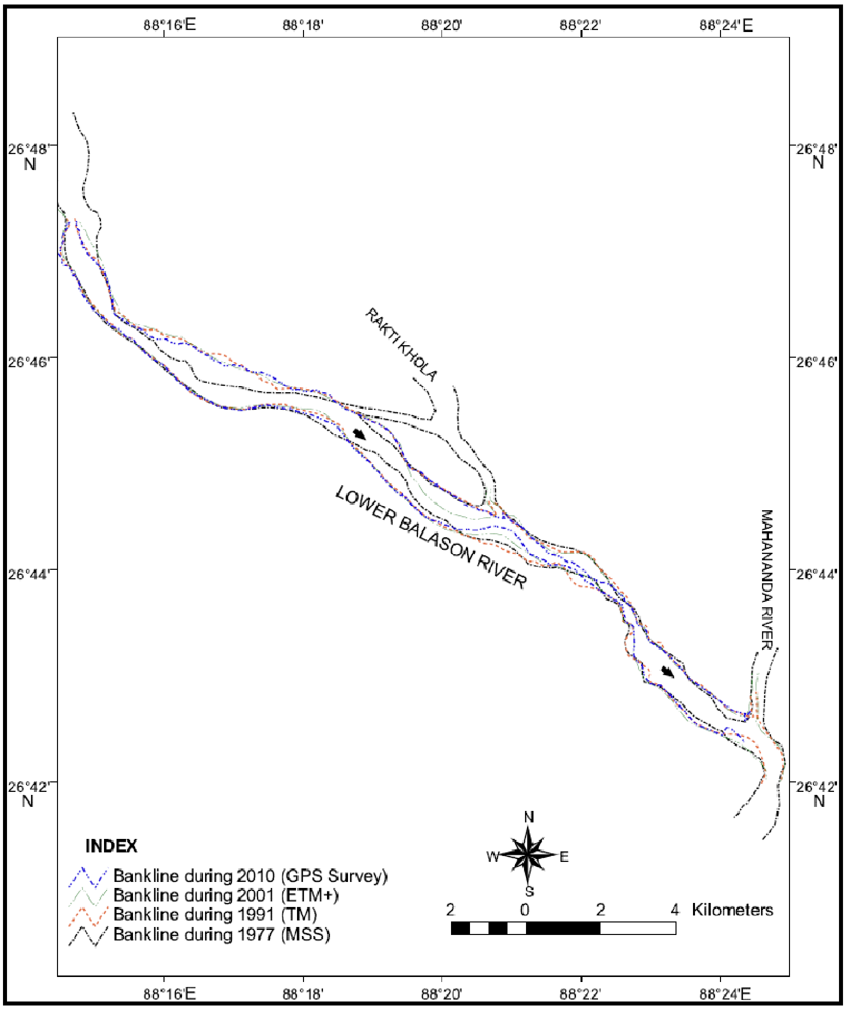

Figure 7.1 The changes in bank line along the lower Balason river from 1977 to 2010.

6.3 Study of the bank heights along the lower Balason river

In the upper piedmont segment (till 6 km downstream), due to high compactness of bank materials and presence of the vegetation growth, the bank heights are quite high ranging between 10-12 m on its right bank and with almost similar compositions the height of its left bank also ranges between 8-10 m (plate 7.1D). The middle segment (till 18 km downstream) is the most failure prone zone with highly instable banks and the bank heights are also highly variable along this segment of the river. On the right bank at few places the bank rises to more than 7 m (plate 7.1E) but the left is quite stable at 3 m height with presence of embankments and human settlements. Along the lower segment (below 18 km downstream) the bank height reduces to 1.5-2 m with very loose sand and silt. Although in this segment the embankments has been constructed on both banks, due to the human occupancies within floodplains near embankments the main channel flow remains mostly near the banks and has raised the bank heights.

7.4 Study of the causes of bank failure in the lower Balason river

The bank failure in lower Balason river is associated with several factors like high rainfall and fluctuating discharge, formation and migration of ephemeral bars near the banks, channel scouring actions, sediment load and energy of the channel flow during monsoon periods. Cohesiveness and configuration of the bank materials, anthropogenic effects in the form of human occupancies near banks and most importantly through extraction of bed materials from the river bed as well as adjacent flood plains and terraces cause such failure.

7.4.1 Study of the natural causes

In the lower Balason river, the in-depth study of the channel morphological and hydraulic characteristics reveals that due to its high peak monsoon discharge with high velocity and sediment load produces the required shear stress to erode its bed and adjacent banks. Frequent diversions of flows towards banks aggravate under cutting and the top exposed bank materials collapses increasing the sediment load of the river. The ephemeral bars near banks which migrates frequently and remains submerged during high flows further pushes the channel flow towards bank base causing undercutting (plate 7.2A & B). Such phenomenon is very common along the right bank of the lower Balason river and due to continuous undercutting by the river, the bank heights have increased substantially and narrowing of the channel width can be noticed. Thus the channel action near the bank base causes scouring of the banks base and the beds. The high monsoon rainfall also lowers the shear strength of the bank materials and cracks on the bank surface can be noticed due to the absence of vegetative cover.

7.4.2 Study of the anthropogenic causes

The construction of houses and roads near banks has further aggravated the failure of exposed banks as the extractors prefer to settle near the banks for easy access to river bed (plate 7.2C). The accumulation of extracted bed materials over banks during monsoon high flows when entering into river bed is not possible. Such overweight undercuts the banks. The human settlements have also reduced the vegetative growth over banks which lead to collapse of bank materials during monsoon downpour. The construction of roads near banks for transporting extracted materials and entry paths used by extractors for entering into the river has also reduced the bank shear strength creating vibrations due to continuous running of heavy trucks laden with extracted bed materials. In few places it has been noticed that the bank materials are directly extracted from bank base as well as from the bank surface (plate 7.2F). Such acts along with extensive lowering of river bed due to extensive bed material extraction during non-monsoon periods together have been largely responsible for the existing condition of banks along the lower Balason river.

7.5 Study of the types of bank failure in the lower Balason river

During the study of the extent and nature of bank failure in the lower Balason river the researcher has noticed some variations in the type of failure of banks with undercutting and rotational slips being common in upper piedmont and middle segments of the river but along the lower segments mostly the block slumping of bank materials occurs.

7.5.1 Undercutting or undermining

This type of failure of banks caused due to impinging high velocity channel monsoon flow which results in slumping of bank materials (Shrestha, 2007) have been noticed mostly at concave bends along the upper piedmont segments of the lower Balason river. The banks at such bends are almost at right angle and undercut has formed holes with deposits of upper loose bank materials at the base of the bank (plate 7.3D).

7.5.2 Rotational slips

The right banks at some places in the middle segments with compact clay deposits and the top loose gravels and sands has created rotational slip of upper bank materials. This is largely due to the imbalance between accumulation of dry loose materials on top face and under cutting by channel flow at the bank base. The frequent use of overbank surface due to human occupancies and running of trucks have caused slips of loose materials at the base (plate 7.3E).

7.5.3 Block slumping

In the lower segment (20 km downstream), the bank is composed of loose finer materials with few gravels. Here human settlements within floodplains near embankments and channel flow at bank base have triggered the mass slumping of loose top materials. The top grass covered blocks of banks at bank base can be noticed at many places along this segment of the lower Balason river (plate 7.3F).

7.6 Study of bank failure rate at selected sites

For better understanding of the processes of bank failure in lower Balason river, two stretches with severe bank failure along the right bank of 1 km each in the middle segment (2 km above Matigara Bridge) has been surveyed and studied in detail. The bank failure rates were recorded following the planimetric resurvey method (Lawler, et al 2001) by which the distance of bank top has to be measured from selected permanent structures. For measuring the failure rates the points at every 200 m were marked and the distance of bank top from the nearest permanent structures (houses, roads, house fencing and trees) within 50 m were measured during pre-monsoon period and post-monsoon period in order to get the annual rate of bank failure.

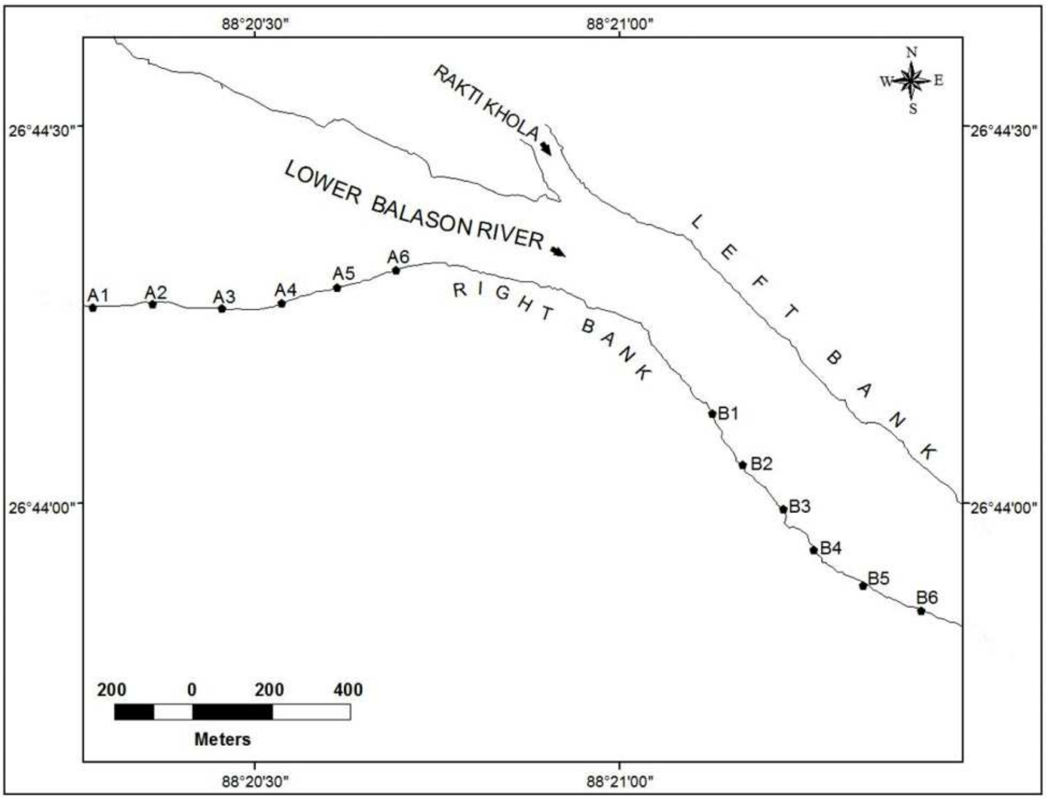

Figure 7.2 Location of the stretch and points considered for measuring the bank failure rates.

The stretches along right bank is composed of unassorted large to medium sized boulders (256-1024 mm), gravels (24-128 mm) and coarse sand in the middle and lower layers with occasional layer of silt and clay at the middle portions (plate 13B). The top soil is very thin with few grasses followed by layer of coarse sands and smaller gravels (4 – 32 mm). The bed height at this stretch varies from 2.500 to 3.100 m at stretch A (till 1 km downstream) and from 4.650 to 7.000 m in stretch B (plate 7.3C). Although at this stretch channel flows at bank base have undercut the bank, the construction of roads and housed, less vegetative cover on bank top and the extraction of bank materials near bank base as well as over bank surface are responsible for decreasing bank heights and consequent failure (plate 7.2C).

The distance measurement of bank top from the nearest pre-selected permanent structures within 50 m during pre and post monsoon condition from 2008 to 2010 (table 7.1) shows that at stretches having less vegetative growth on top of the bank and scouring at the bank base resulting under cutting, the bank failure was higher with maximum of 1.480 measured during 2010 at A5 and 1.335 m measured at B2 during 2008. The nearness of human settlements and roads has also affected the bank conditions and annual retreat of bank has been noticed (A3, A4 and A5). Moreover, near-bank extraction of bed materials has resulted in diversion of channel towards the bank during high discharge thus increasing the bank undercutting and consequent failure in stretch B (B2 and B3). But at this stretch it can be noticed that failure has gradually decreased (B4, B5 and B6) due to substantial increase in vegetative cover on bank top.

POINTS	P. STRUCTURE	PRE08	POST08	PRE09	POST09	PRE10	POST10
A1	ROAD CULVERT	38.715	37.500	37.500	37.395	37.395	36.350
A2	HOUSE	41.240	41.045	41.045	40.940	40.940	40.330
A3	HOUSE	26.115	24.950	24.950	24.920	24.920	24.280
A4	HOUSE	24.570	23.225	23.225	23.105	23.105	21.990
A5	HOUSE FENCE	30.030	28.550	28.550	27.690	27.690	27.515
A6	HOUSE	43.560	43.475	43.475	43.240	43.240	43.105
B1	HOUSE	12.380	12.310	12.310	12.115	12.115	11.960
B2	HOUSE	10.805	9.470	9.470	9.220	9.220	8.840
B3	HOUSE FENCE	22.460	22.350	22.350	21.940	21.940	20.650
B4	TREE	19.225	19.100	19.100	18.895	18.895	18.670
B5	HOUSE	15.240	15.220	15.220	15.045	15.045	14.440
B6	TREE	9.250	9.200	9.200	8.985	8.985	8.985

(Based on field records by the researcher)

Table 7.1 The distance (m) of bank top at different points from the pre-selected permanent structures during per-monsoon (PRE) and post-monsoon (POST) survey from 2008 to 2010

On the basis of the bank top distance measurements, it can be said that along the stretches surveyed on right bank of the lower Balason river, the banks are eroding at an average rate of 0.615 m for stretch A and 0.319 m at stretch B and at 0.467 m for the entire stretch of 2 km (table 7.2). The variation of failure rate in this two stretches is largely due to the bank composition, the extent of under cutting and the extraction of bed materials.

POINTS	2008	2009	2010	AVERAGE	AVERAGE

A1	1.215	0.105	1.045	0.788	
A2	0.195	0.105	0.610	0.303	
A3	1.165	0.030	0.640	0.612	**0.615**
A4	1.345	0.120	1.115	0.860	
A5	1.480	0.860	0.585	0.975	
A6	0.085	0.235	0.135	0.152	
B1	0.070	0.195	0.155	0.140	
B2	1.335	0.250	0.380	0.655	
B3	0.110	0.410	1.290	0.603	**0.319**
B4	0.125	0.205	0.225	0.185	
B5	0.020	0.175	0.605	0.267	
B6	0.050	0.150	0.000	0.067	
AVERAGE (m)	**0.600**	**0.237**	**0.565**	**0.467**	

(Computed by the researcher based on field records)

Table 7.2 The annual failure rate (m) at different cross-sections from the pre-selected permanent structures from 2008 to 2010.

7.7 Conclusions

The study of the nature and extent of the bank failure along the lower Balason river revels that the right bank is more failure prone compared to its left bank in the upper and middle segments but in its lower segments (near the confluence) failure have been noticed on the left bank. This has been largely due to frequent diversion of channel flows depending on the monsoon peak flows causing scouring and under cutting at bank base, the extent of human occupancies and extraction of bed materials which are largely triggering the rate of bank failure. The failure of exposed banks are acting as local sediment sources for the river and due to continuous bank failure at few stretches, the finer sediments are being carried away by the river during monsoon flows. Such suspended loads are being deposited in the lower segments causing siltation near its confluence.

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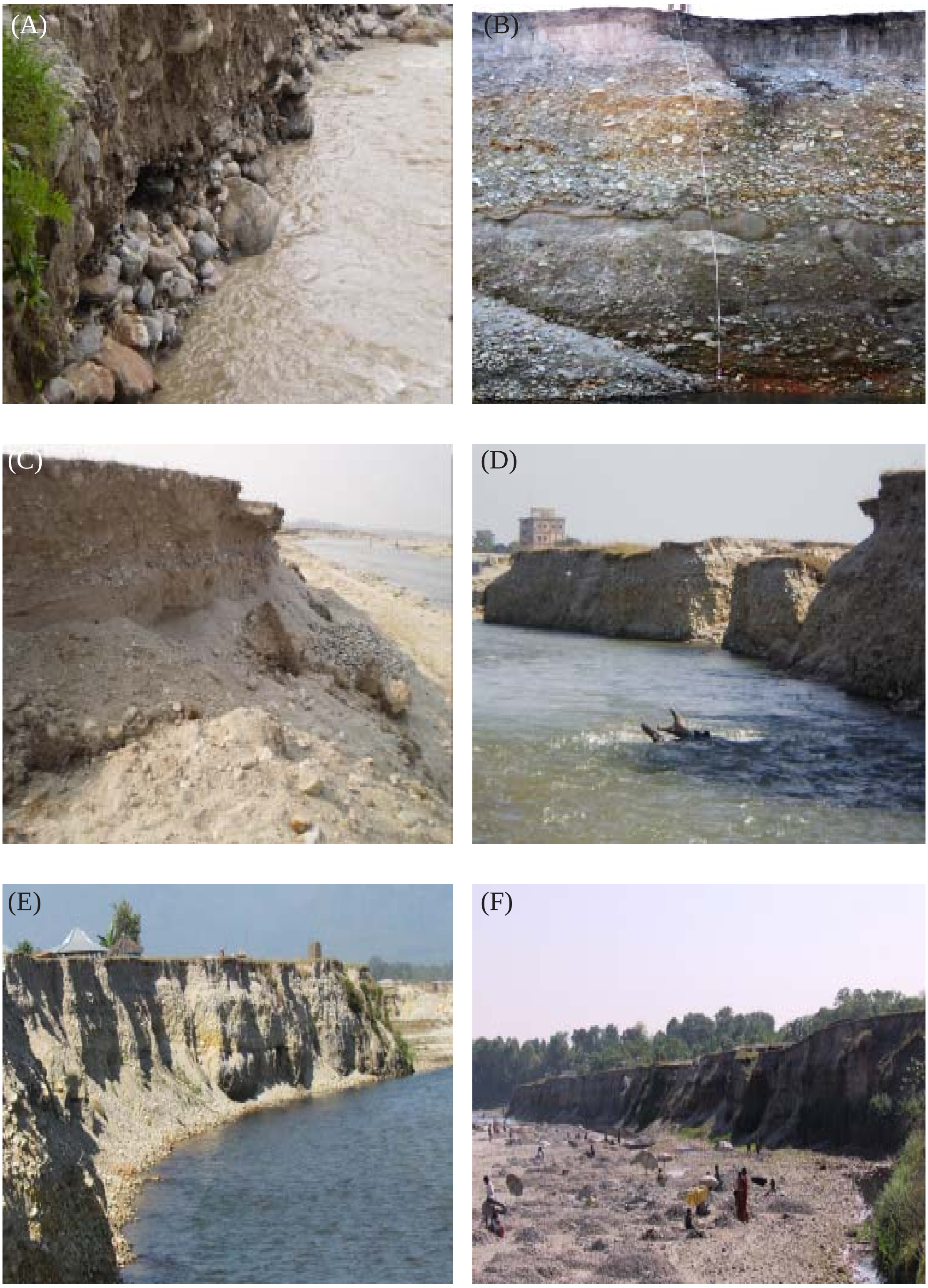

Plate 7.1 The bank compositions with larger sized boulders and thick top soil layer in upper piedmont segment (A), medium sized unassorted boulders and gravels mixed with coarse sand with very thin top soil layer in the middle segment (B), medium sized gravels with lots of sand in the lower segment (C), concentration of channel flows near bank base in middle segment (D) & (E), and, extraction of bed materials near the exposed banks in the middle segment of the lower Balason river (F).

Plate 7.2 Channel flows during monsoon period undercutting bank base (A) & (B), human occupancies near retreating banks in the middle segment (C) and lower sement (D), accumulation of extracted bed materilas over banks during monsoon period (E) and extraction of bank materilas from bank top (F) in the lower Balason river.

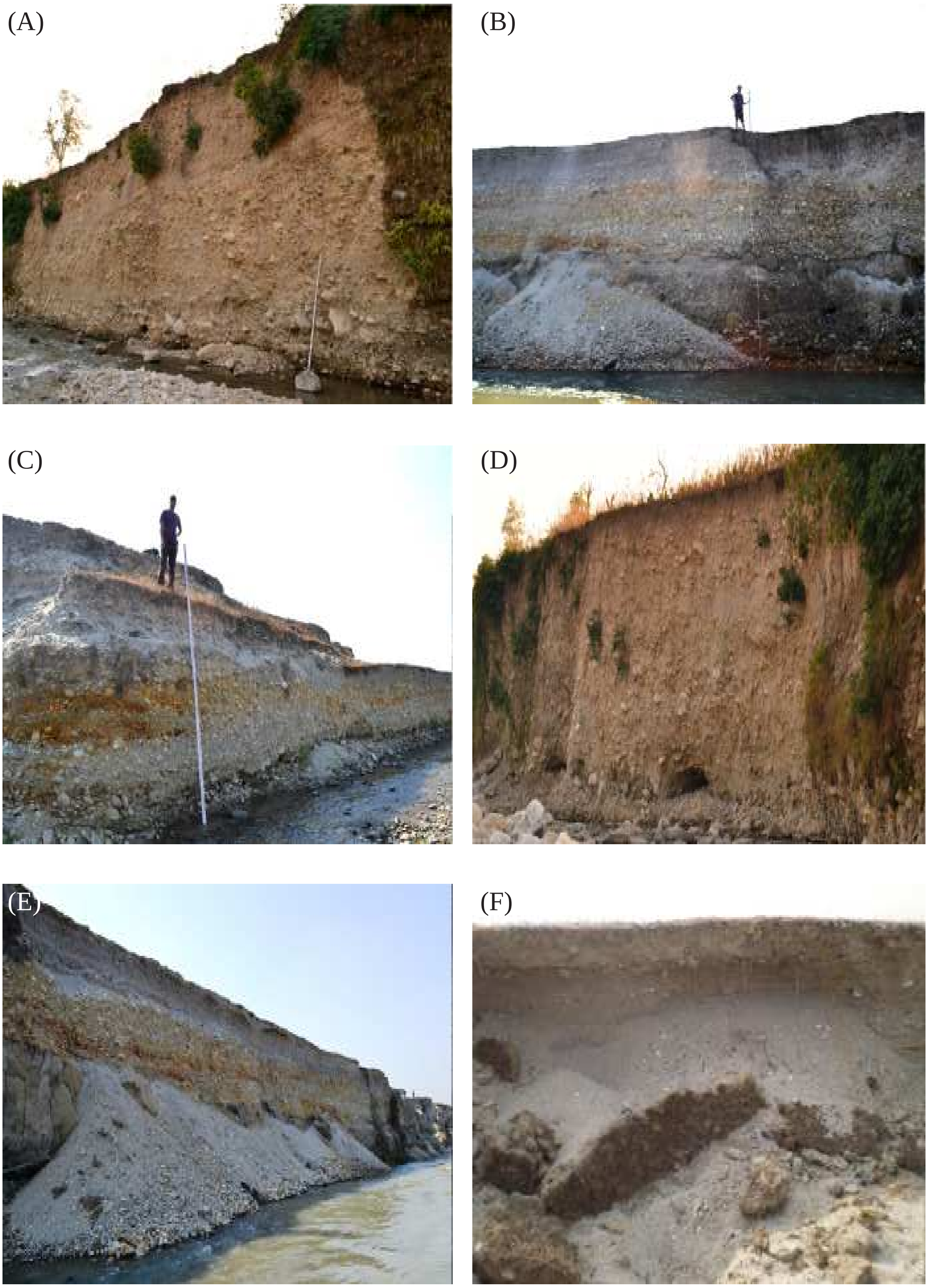

Plate 7.3 Bank heights ranging between10 - 12 m in upper piedmont segment (A) and more than 7 m in the middle segment (B) & (C) of the lowert Balason river. The undercutting of banks forming holes at base common in the upper piedmont segment (D), rotational slips accumulating the loose bank materials at the base common in the middle segment (E) and slumping of bank tops common in the lower segments (F) of the lower Balason river. (Photographs by the researcher)

CHAPTER 8

Remedial measures and recommendations

8.1 Introduction

Natural restoration or human reclamation of the stream-side environment is a complicated process, and involves many other human changes in addition to those related to in-stream extraction. Understanding design approach can turn features perceived by the public as being undesirable (mines and pits) into something desirable. Forward-looking extraction operators who employ modern technology and work within natural restrictions can create a second use of mined-out sand and gravel an operation that often equal or exceeds the value of the pre-mined land use (Langer, 2003).

There are some general relationships between environmental effects, the location of extraction site, water table, the depth of the extraction and the plan form of the river. These relationships can be used as a general guide for the design of in-stream and near-stream bed material extraction. All other things being equal:

i. Extraction of bed materials that does not penetrate the water table and is located away from an active stream channel should cause little or no change to the natural hydrologic processes unless the stream captures the pit during high flood periods. The exception is that changes in evapotranspiration, recharge and runoff may create minor changes to the ground water system, which may in turn affect stream flow.
ii. Limiting extraction of material in floodplains to an elevation above the water table generally disturbs more surface area than allowing extraction of material below the water table.
iii. In-stream extraction of bed materials from below the water level of a stream generally causes more changes to the natural hydrologic processes than limiting extraction to a reference point above the water level.

iv. In-stream extraction of gravel below the deepest part of the channel (thalweg) generally causes more changes to the natural hydrologic processes than limiting extraction to a reference point above the thalweg.
v. Extraction of bed materials from a small straight channel with a narrow floodplain generally will have greater effects on the natural hydrologic processes than extractions on a braided channel with a wide floodplain.
vi. Extracting of bed materials from a large river or stream will generally create less effect than extracting the same amount of material from a smaller river or stream.

8.2 Appropriate bed material extraction methods

Kondolf, et al (2001) summarized several methods of sand and gravel extraction operations as below:

1. Bar scalping or skimming: Bar scalping or skimming is extraction of sand and gravel from the surface of bars. This method generally requires that surface irregularities be smoothed out and that the extracted material be limited to what could be taken above an imaginary line sloping upwards and away from the water from a specified level above the river's water surface at the time of extraction (typically 0.3 to 0.6 m). Bar scalping is commonly repeated year after year. To maintain the hydraulic control provided to upstream by the riffle head, the preferred method of bar scalping is generally to leave the top one-third (approximately) of the bar undisturbed allowing extraction only from the downstream two-thirds.

2. Dry-Pit Channel Extraction: Dry-pit channel mines are pits excavated within the active channel on dry intermittent or ephemeral stream beds with conventional bulldozers, scrapers and loaders. Dry pits are often left with abrupt upstream margins, from which head cuts are likely to propagate upstream.

3. Wet-Pit Channel Extraction: Wet-pit extraction involves extraction of a pit in the active channel below the surface water in a perennial stream or below the alluvial groundwater table, requiring the use of a dragline or hydraulic excavator to extract sand and gravel from below the water surface. In areas such as low terraces, some glacio-fluvial deposits, and some ephemeral streambeds, sand and gravel extraction may penetrate the water table and may be mined wet or dry. In some geologic settings, wet pits can be made dry by collecting the groundwater in drains in the floor of the pit and pumping the water out of the pit.

4. Bar Extraction: A pit is excavated at the downstream end of the bar as a source of aggregate and as a site to trap sand and gravel. Upon completion, the pit may be connected to the channel at its downstream end to provide side channel habitat. On the Russian river and California recent proposals for bar extraction include leaving the bar margins untouched and extraction from the interior of the downstream part of the bar, but above the water surface, a variant intermediate between bar scalping and bar extraction is recommended.

5. In-stream Gravel Traps: Sand or “bed load traps” have been used to reduce sand in downstream channels for habitat enhancement in Michigan. Such traps can also be potential sources of commercial aggregate, provided the amounts so collected are sufficient to be economically exploited. One advantage of the traps as a method for harvesting sand and gravel are the concentration of extraction effects at one site, where heavy equipment can remove sand and gravel without impacting riparian vegetation or natural channel features. Sand and gravel can be removed year after year from the bed load trap. An idealized trap has short dikes to create a constriction downstream and to hold the resultant higher stages. Sand and gravel are removed from the downstream end of the deposit, and a grade control structure at the upstream end of the trap prevents head cutting upstream from the extraction. There are no hydraulic effects upstream due to the extraction because the engineered constriction is the hydraulic control during high flows. The concentrated flow scours a deep pool immediately downstream from the constriction, which may be important habitat in aggrading reaches where pool formation is limited by deposition.

8.3 Ministry of Environment & Forest, India stipulated the following recommendations on extraction of minor minerals/ construction materials (Banerjee, 2007):

- Extraction Lease (ML) area should be demarcated on the ground with pucca pillars.
- For river sand extraction, area should be clearly specified for extraction operations in the region. The area should be properly surveyed and mapped with the help of GPS to assign geo-coordinates and accordingly erect boundary pillars so as to avoid illegal unscientific extraction.
- Within the ML area, if any forest land exists, it should be distinctly shown on the map along with coordinates.
- While considering the sanction of ML area, due attention should be paid to the presence of any National park/sanctuary/ecologically sensitive landscape. In such cases order of the Hon'ble Supreme Court should be strictly followed.
- For extraction lease within 10 km of the National Park/Sanctuary, recommendation/ permission of National Board of Wild Life (NBWL) have to be obtained as per the Hon'ble Supreme Court order in I.A. No. 460/2004.
- Site-specific plans with eco-restoration should be considered/ implemented.

8.4 Prohibition of bed materials extraction operation without permit or extraction lease (as per the West Bengal Minor Minerals Rules, 2002, Schedule V):

- No extraction of minerals shall be allowed within 200 m of both sides of any river bridge or culvert over any waterway or from any embankment and structural works of the irrigation and waterways department.
- No extraction operation shall be allowed within a distance of 200 m from any hydraulic structure, reservoir, bridge, canal, road and other public works or buildings.

- No extraction operation shall be done within a distance of 5 km of a barrage axis or dam of a river. The distance is to be reckoned across an imaginary line parallel to the barrage or dam axis as the case may be.
- In the districts of Darjeeling and Jalpaiguri, the extraction of boulders and sand shall only be made from the central one-third of the river-bed; provided that where the width of the river is 30 m or less, the extraction of the said minerals shall not be made except with the permission in writing from the Irrigation and Waterways department.
- No tree shall be felled and removed and no public easement shall be interfered with except with the written consent of the issuing Authority in this respect and he may attach such conditions to his consent as he thinks fit, and the conditions shall be binding on the permit-holders.

8.5 Geo-scientific considerations as suggested by Geological Survey of India to be taken into account for extraction of river bed materials:

- Abandoned stream channels on terrace and inactive floodplains may be preferred rather than active channels and their deltas and floodplains. Replenishment of ground water has to be ensured if excessive pumping out of water is required during extraction.
- Extraction below subterranean water level should be avoided as a safeguard against environmental contamination and over exploitation of resources.
- Large rivers and streams whose periodic sediment replenishment capacity are larger, may be preferred than smaller rivers.
- Segments of braided river system should be used preferably falling within the lateral migration area of the river regime that enhances the feasibility of sediment replenishment.
- Extraction at the concave side of the river channel should be avoided to prevent bank erosion. Similarly meandering segment of a river should be selected for extraction in such a way as to avoid natural eroding banks and to promote extraction on naturally building (aggrading) meander components.

- Scraping of sediment bars above the water flow level in the lean period may be preferred for sustainable extraction.
- It is to be noted that the environmental issues related to extraction of minerals including riverbed sand extraction should clearly state the size of mine leasehold area, mine lease period, mine plan and mine closure plan, along with mine reclamation and rehabilitation strategies, depth of extraction and period of extraction operations, particularly in case of river bed extraction.
- The Piedmont Zone (bhabbar area) particularly in the Himalayan foothills, where riverbed material is mined, and this sandy- gravelly track constitute excellent conduits and hold the greater potential for ground water recharge. Extraction in such areas should be preferred in locations selected away from the channel bank stretches. Areas where channel banks are not well defined, particularly in the braided river system, midstream areas should be selected for extraction of riverbed materials for minimizing adverse effects on flow regime and in-stream habitat.
- Extraction of gravelly sand from the riverbed should be restricted to a maximum depth of 3 m from the surface. For surface extraction operations beyond this depth of 3 m (10 feet), it is imperative to adopt quarrying in a systematic bench- like disposition, which is generally not feasible in riverbed extraction. Hence, for safety and sustainability restriction of extraction of riverbed material to maximum depth of 3 m is recommended.
- Extraction of riverbed material should also take cognizance of the location of the active channel bank. It should be located sufficiently away, preferably more than 3 m away (inwards), from such river banks to minimize effects on river bank erosion and avoid consequent channel migration.
- Continued riverbed material extraction in a given segment of the river will induce seasonal scouring and intensify the erosion activity within the channel. This will have an adverse effect not only within the extraction area but also both in upstream and downstream of the river course. Hazardous effects of such scouring and enhanced erosion due to

riverbed extraction should be evaluated periodically and avoided for sustainable extraction activities.

- Mineral processing in case of riverbed extraction of the sandy gravelly material may consist of simple washing to remove clay and silt area. It may involve crushing, grinding and separation of valueless rock fragments from the desirable material. The volume of such waste material may range from 10 to 90%. Therefore, such huge quantities of mine wastes should be dumped into artificially created/mined out pits. Where such tailings/waste materials are very fine grained, they may act as a source of dust when dry. Therefore, such disposal of wastes should be properly stabilized and vegetated to prevent their erosion by winds.
- Identification of river stretches and their demarcation for extraction must be completed prior to extraction for sustainable development.
- The extraction pits should be backfilled where warranted and area should be suitably landscaped to prevent environmental degradation.
- Extraction generally has a huge effect on the irrigation and drinking water resources. These attributes should be clearly evaluated for short-term as well as long-term remediation.

8.6 Recommendations for regulation of sediment extraction from active channels based on the concept of "Redline" method (After Castro, et al 2006):

The *"Redline"* method is used to regulate maximum channel disturbance, and indirectly limit extraction quantities. Redlines define an initial extraction surface (i.e., elevation, slope, area) with vertical and horizontal offsets from the banks and the low flow channel. In subsequent years, only the aggregate that is replenished above the redline surface is allowed to be extracted. During wet years, deposition above the Redline can be voluminous, while during dry years there may not be any deposition. One advantage of the redline management method is that it can allow for varying climatic and sediment transport events. It can tie sediment extraction more closely to the natural hydrologic and sediment cycles than can simply allocating via sediment budget. However, local sediment depletion can occur when only the redline method is used for regulating extraction in large-scale sediment production areas. In effect, a consistently applied redline regulation imposes a localized sediment budget approach to managing extraction, but it can allow for extracting 100% of the incoming load, which can significantly reduce sediment supply to downstream habitat.

The purpose of defining a Redline is simply to limit sediment removal to control gross degradation of the streambed. Unless applied judiciously, with relatively large vertical and horizontal offsets from the low flow channel, redline methods do not maintain a positive sediment budget so that downstream habitats receive coarse sediment input and in-channel geomorphic features continue contributing to ecosystem health. Additionally, the Redline method can result in expansive areas that are flat and devoid of vegetation. As flows increase in the fall and early winter, these areas are quickly inundated and can just as rapidly dry up as storm driven flows recede, potentially resulting in fish stranding.

8.7 Recommendations for bed material extraction from river bed

In spite of several adverse morphological, ecological and environmental effects of extraction of bed materials from alluvial channels, such effects are seldom taken into account in the decisions concerning sediment extraction which is largely due to:

- Poor knowledge of the effects among river managers, reflecting insufficient documentation of such effects in the hitherto published literature;
- Ignoring the environmental costs of extraction in cost-benefit analysis, which makes active channels much more profitable source of sediment compared to other alternatives, and
- Considering the evaluation of potential effects of extraction as an unnecessarily expensive and time-consuming procedure.

a) ***Extraction permit based on measured annual replenishment:*** The use of the concept of annual replenishment protects long-term channel stability as well as aquatic and riparian habitat by extracting a volume sustainable by watershed processes. It is important to develop a system to allocate the total estimated annual replenishment between all of the extractors. However, the use of monitoring data is essential in measuring when actual replenishment occurs.

b) ***Establish an absolute elevation below which no extraction may occur (minimum enveloped level or Redline):*** The absolute elevation below which no extraction could occur or "redline" could be surveyed on a site-specific basis in order to avoid effects such as under cutting below bridges and to avoid vegetation effects associated with down cutting due to excessive removal of bed materials. An extraction site can be determined after setting the deposition level at 1 m above natural channel thalweg elevation.

c) ***Bar skimming:*** If extraction is limited to the downstream end of the bar with a riparian buffer on both the channel and hill slope (or floodplain) side, bar skimming would minimize effects. In addition, direct disturbance of the substrate in the low flow channel should be avoided. Trenching on bars may be beneficial in the future if the river becomes severely aggraded, flat, shallow and braided. Trenching of bars may initially effects smaller area of riparian habitat than skimming - as a result of extraction deeper rather than shallow skimming of a large area. However, over the long-term, the upstream and downstream effects of a trench on the bar or in the channel may offset any short-term benefit derived from this method.

d) ***Extraction of bed materials from the downstream portion of the bar:*** Retaining the upstream one to two thirds of the bar and riparian vegetation while extraction from the downstream third of the bar is accepted as a method to promote channel stability and protect the narrow width of the low flow channel necessary for fish. Bed materials would be again deposited in the excavated downstream one to two thirds of the bar (or downstream of the widest point of the bar) where an eddy would form during sediment transporting flows. In contrast, if extraction occurs on the entire bar after removing existing riparian vegetation, there is a greater potential for widening and braiding of the low flow channel.

e) ***Deliberate activities to minimize disturbance:*** In-stream extraction activities should be concentrated or localized to a few bars rather than spread out over entire river bed. This localization of extraction will minimize the area of disturbance of upstream and downstream effects.

f) ***Long-term monitoring program****:* Long term monitoring of changes in bed elevation and channel morphology upstream and downstream of the extraction sites will provide data to which will be helpful in determination of extraction trends.

g) ***Retaining vegetation buffer at edges of water and against river bank:*** Riparian vegetation performs several functions essential to the proper maintenance of geomorphic and biological processes in rivers. It shields river banks and bars from erosion and also the riparian vegetation including roots and downed trees works as a filter against sediment inputs.

h) ***Maintaining annual status and trends report:*** The report on review of permitted extraction quantities along with progress of the monitoring program as well as improved estimates of replenishment should be formulated. The report should also document changes in bed elevation, channel morphology and hydraulic characteristics of the river. The report should also include records of extraction volumes permitted and location of extraction sites with recommendations for reclamation, if needed should be documented.

8.8 Conclusions

Many of the effects associated with bed material extraction are not easy to quantify, however, an overall assessment should be under taken based on the river adjustment of its fluvio-geomorphic characteristics. Such an integrated assessment of a river's sensitivity to modifications will help resource management decisions including protection of the fluvial environment so that the boulder lifting activities does not jeopardise the sustainability of other appropriate river users and values. This could be possible by devising and executing a long term management plan with proper understanding and management of sediments at basin level and a wider application of the available scientific knowledge, particularly of fluvial geomorphology and hydraulics.

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Plate 8.1 Protection of bridge piers from undercutting below Dudhia bridge (A); reconstruction of railway bridge near Matigara (B); protection of embankments (C, D & E); temporarily diversion of channel flows during monsoon period (F).

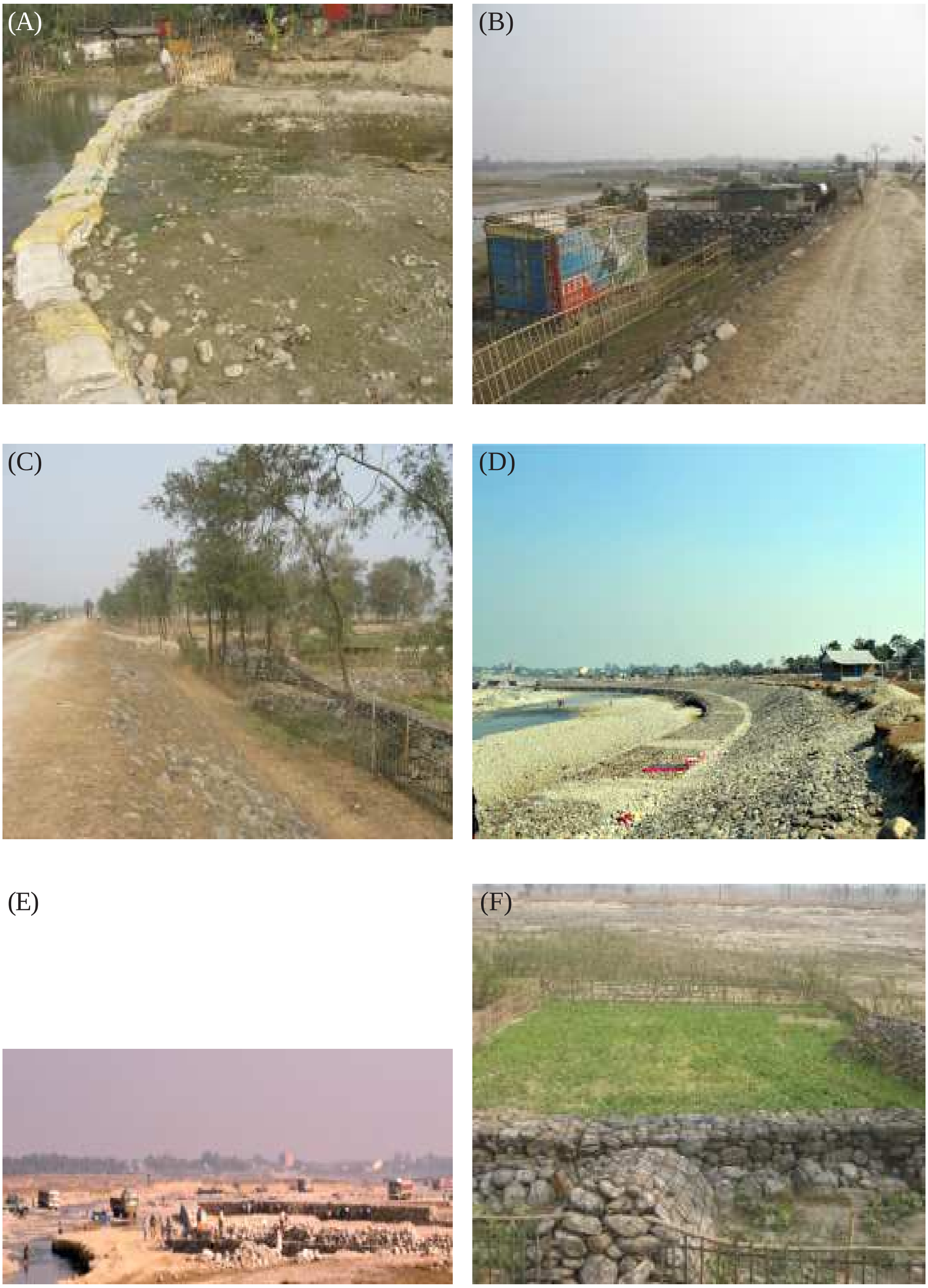

Plate 8.2 Channel flow diversion using sand bags to protect low floodplain settlements (A); construction of boulders filled embankments protection (B, D & E) with plantation of trees (C) and use of sand deposits below embankments for agricultural purposes (F). (Photographs by the Researcher)

CHAPTER 9

Conclusions

The Balason river with the monsoon regime characterized by high rainfall and consequent high flows facilitates transport of million tons of sediment load from its upper catchments. The physical set up of the Balason basin reveals that it is a geologically young and fragile region with intensely metamorphosed rocks like gneiss, schists, phyllites, etc, which are highly weathered, fractured and jointed, vulnerable to slope instability. The basin does not follow the law of absolute relief and slope frequency distribution which indicates the youth stage of the basin. The climatic characteristic also shows wide variation which is largely dependent on the altitude. The drastic reduction of the natural forests, combined with the high annual rainfall in most part of the basin, makes the area highly vulnerable to soil erosion and landslides, reducing the soil fertility.

The fluvial characteristics of the lower Balason basin shows that the river adjusts within the changing fluvial conditions through the scouring and filling phenomenon but the effects of anthropogenic disturbances like construction of bridges, embankments and artificial bank protection structures could be clearly seen in its form. Besides, the channelization of the river flow due to extraction of bed materials from the river bed and adjacent flood plains and terraces is also largely hampering the morphological characteristics of the river. The low channel flow during non-monsoon period reduces the transporting capacity but due to frequent outburst of monsoon peak flows increments the channel run-off and capacity inducing varied bed erosion. The channel flow at lower reaches also migrates frequently abandoning the pervious path. Such act of river is also encouraging the anthropogenic control in the form of bed materials extraction and human encroachment of flood plains and banks.

The analysis of surface coarse sediments and suspended sediments of the lower Balason river and its relation with discharge, run-off and fall or settling velocity reveals that the during hyperconcentrated flows occurring very rarely, the efficiency of sediment delivery by linear erosion and mass movement causes substantial transformations in the channel geometry. The annual flow with normal peak discharge (below 500 $m^3 s^{-1}$) does not greatly results the sediment transportation with only substantial change in sediment distribution.

The causes and extent of the bank failure along the lower Balason river revels that the right bank is more instable compared to its left bank in the upper and middle segments but in its lower segments (near the confluence) failure have been noticed on the left bank. This has been largely due to frequent diversion of channel flows depending on the monsoon peak flows causing scouring and under cutting at bank base, the extent of human occupancies and extraction of bed materials which are largely triggering the rate of bank failure. The failure of exposed banks are also acting as local sediment sources for the river and due to continuous bank failure at few stretches, the finer sediments are being carried away by the river during monsoon flows. Such suspended loads are being deposited in the lower segments causing siltation near its confluence.

Presently, the extent and intensity of bed material extraction in the lower Balason river have taken such a dimension that it needs immediate check to reduce the associated effects on its form and processes. The problem though seems local, proper management is very much essential both in the lower course as well as the upper catchments of the Balason river. The continuous extraction inducing lowering of bed elevations and resultant bed erosion and also lifting specified size gravels and leaving behind the smaller one thus disrupting the sediment transportation and distribution have resulted into head ward erosion which is being transformed into its upper segments beyond the margins of the lower plains. The adjustment by the river in the form of scouring and filling have also resulted into undercutting below bridges and embankments due to narrow channel width causing retention of flows. The destruction of permanent structures as it happened on 18th August, 2009, when the two piers of Railway Bridge near Matigara over the river bed was uprooted damaging the whole bridge is one of the effects of river's adjustment under changing fluvial characteristics.

The prolonged bed material extraction from the lower Balason river has caused bed erosion which is migrating annually with variations in channel gradient both upstream and downstream of the extraction sites. Also the river has been adjusting with changes in its morphology and with maximum coarse materials (gravels and boulders) being extracted from the river bed, the balance between transport capacity and sediment supply is being largely disturbed. Although the river annually replenish the sediment deficit by scouring and filling but such modifications are largely responsible for under cutting of bridges and embankments. The near-bank extraction has also resulted into diversion of channel flow sometimes abandoning its pervious course and also causing retreat of exposed banks. Besides, the increasing human interferences along with bed material extraction activities have consequently degraded the fluvial characteristics of the lower Balason river and alterations in its form, roughness and cross-sections altogether have influenced the flow characteristics, morphology and sediment transport and distribution.

Although the State Govt. has formulated different provisions under *The West Bengal Minor Minerals rules, 2002 and The West Bengal Minerals (Prevention of Illegal Mining, transportation and Storage) Rules, 2002, along with the Mines and Minerals (Development and Regulation) Act, 1957*, but the people involved upon such activities seems to be absolutely little concerned with its environmental effects. The implementation of the above rules has not taken place due to callousness of the concerned authority and the role played by the permit-holders as middle man. The workers engaged in direct extraction activities are mostly deprived as they cannot bargain for the better wages and hence illegal extraction is a common practice and unchecked. Even extractions below the bridges and embankments although prohibited by laws are a common practice. Human settlements near the banks and adjacent flood plains for easy access to river bed and also construction of roads near banks for transportation of extracted bed materials have reduced the vegetation thus triggering the exposed banks to retreat further.

In spite of various detrimental effects of bed material extraction, if a river is aggrading, extraction of bed material may in some cases also have positive effects for flood-control purposes, channel stability and restoration. Hence in order to reduce the negative effects of bed material extraction, detail understanding of its fluvial characteristics is very much essential which would help in the better implementation of its reclamation. Thus the concerned authorities should implement proper long term management plan to reduce the effects of bed material extraction on the already degrading lower Balason river.

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APPENDIX A

<u>List of publications:</u>

1. *Quarrying activities along the lower Balason river in Darjeeling District, West Bengal* – Lakpa Tamang, **Indian Journal of Spatial sciences** (EISSN 2249 – 4316), 4, 2013, pp. 1-8.
2. *Balason River: An important source of natural aggregates in the Darjeeling sub-Himalayas* – Lakpa Tamang and Sonam Lama, In Chaudhari, S. and Dulal C. R., (ed.) **Resource management: Human and Natural, perspective on North-East region** (ISBN 978-81-87891-47-5), Readers Services, Kolkata, 2012, pp. 328-339.
3. *Human interferences and channel response along the lower Balason river in Darjeeling district, West Bengal* – Lakpa Tamang, **The Indian Journal of Landscape Systems and Ecological Studies** (ISSN 0971 4170), 35, 1, 2012, pp. 115-122.
4. Regulations for Extraction of Bed Material from the river: A management perspective - Lakpa Tamang and Deepak kr. Mandal, In Sarkar, S. (ed.) **Disaster: Perception and Mitigation, SAP-DRS Monograph 2** (ISBN 978-81-921692-1-7), 2012, pp. 118 – 129.
5. *Bed material extraction and its effects on fluvial characteristic in Lower Balason river in Darjeeling District, West Bengal* - Lakpa Tamang & Deepak Kr. Mandal, **Geo-Analysts** (ISSN 2294 - 2909), 1, 2, 2011, pp. 49-54.
6. *Changing fluvial characteristics of the lower course of Balason river, West Bengal* – Lakpa Tamang & Deepak Kr. Mandal, **Geographical Review of India** (ISSN 0375 – 6386), 72, 1, 2010, pp. 10-19.
7. *Quarrying of Minor minerals and associated economic prospects – A case study of Balason river* – Lakpa Tamang & Bishal Chettri, **Salesian Journal of Humanities & Social Sciences** (ISSN 0976 – 1861), Special

Issue on Mountain Economy: Resources, sustainability and Governance, 2, 2, 2011, pp. 151 – 158.

8. *Human induced activities: An Anthropogenic threats to Balason Watershed in Darjeeling District, West Bengal* – Lakpa Tamang & Deepak Kumar Mandal, In Sarkar, S. (ed.) **Geo-hazards in Sub-Himalayan North Bengal, SAP-DRS Monograph 1** (ISBN ISBN 978-81-921692-0), 2011, University Press, University of North Bengal, pp. 143-148.
9. *Bed Material Extraction induced Morphological modifications along the lower course of the Balason River* - Lakpa Tamang & Deepak Kr. Mandal, **Geographical Review of India** (ISSN 0375 – 6386) (*in press*).

APPENDIX B

CROSS-SECTION NO: **SITE:**

DATE:

POINTS	DISTANCE (m)	READINGS			RISE	FALL	REDUCED LEVEL (m)	REMARKS
		B.S	IS	F.S				

Table 1 Sample field sheet used for the cross-section survey.

SAMPLING NO: *DATE:*
LOCATION: *TIME:*

SEDIMENT TYPE	PARTICLE SIZE (in mm)	TOTAL
Sand and Silt	< 2	
	2 – 4	
	4 – 6	
	8 – 12	
Gravels	12 – 16	
	16 -24	
	24 – 32	
	32 – 48	
	48 – 64	
	64 – 96	
Cobbles	96 – 128	
	128 – 192	
	192 – 256	
	256 – 384	
	384 – 512	
Boulders	512 – 1024	
	1024 – 2048	
	2048 - 4096	
	> 4096	

Table 2 Sample field sheet used for the sampling coarse surface sediments.

Temp. (°C)	Density ρ (kg/m^3)	Specific weight γ (N/m^3)	Dynamic viscosity μ (N × s/m^2)	Kinematic viscosity ν (m^2/s)
0	1,000	9,810	1.79×10^{-3}	1.79×10^{-6}
5	1,000	9,810	1.51×10^{-3}	1.51×10^{-6}
10	1,000	9,810	1.31×10^{-3}	1.31×10^{-6}
15	999	9,800	1.14×10^{-3}	1.14×10^{-6}
20	998	9,790	1.00×10^{-3}	1.00×10^{-6}
25	997	9,781	8.91×10^{-4}	8.94×10^{-7}
30	996	9,771	7.97×10^{-4}	8.00×10^{-7}
35	994	9,751	7.20×10^{-4}	7.25×10^{-7}
40	992	9,732	6.53×10^{-4}	6.58×10^{-7}
50	988	9,693	5.47×10^{-4}	5.53×10^{-7}
60	983	9,643	4.66×10^{-4}	4.74×10^{-7}
70	978	9,594	4.04×10^{-4}	4.13×10^{-7}
80	972	9,535	3.54×10^{-4}	3.64×10^{-7}
90	965	9,467	3.15×10^{-4}	3.26×10^{-7}
100	958	9,398	2.82×10^{-4}	2.94×10^{-7}
(°F)	(slug/ft^3)	(lb/ft^3)	(lb × s/ft^2)	(ft^2/s)
40	1.94	62.43	3.23×10^{-5}	1.66×10^{-5}
50	1.94	62.40	2.73×10^{-5}	1.41×10^{-5}
60	1.94	62.37	2.36×10^{-5}	1.22×10^{-5}
70	1.94	62.30	2.05×10^{-5}	1.06×10^{-5}
80	1.93	62.22	1.80×10^{-5}	0.930×10^{-5}
100	1.93	62.00	1.42×10^{-5}	0.739×10^{-5}
120	1.92	61.72	1.17×10^{-5}	0.609×10^{-5}
140	1.91	61.38	0.981×10^{-5}	0.514×10^{-5}
160	1.90	61.00	0.838×10^{-5}	0.442×10^{-5}
180	1.88	60.58	0.726×10^{-5}	0.385×10^{-5}
200	1.87	60.12	0.637×10^{-5}	0.341×10^{-5}
212	1.86	59.83	0.593×10^{-5}	0.319×10^{-5}

(Source: Julien, 2001)

Table 3 Approximate physical properties of clear water at atmospheric pressure

N (number of years)	y_n	σ_n	N	y_n	σ_n
10	0.4952	0.9497	65	0.5536	1.1803
15	0.5128	1.0206	70	0.5548	1.1854
20	0.5236	1.0620	75	0.5559	1.1898
25	0.5309	1.0915	80	0.5569	1.1938
30	0.5362	1.1124	85	0.5578	1.1973
35	0.5403	1.1285	90	0.5589	1.2007
40	0.5436	1.1413	95	0.5593	1.2038
45	0.5463	1.1518	100	0.5600	1.2065
50	0.5465	1.1607	200	0.5672	1.2359
55	0.5504	1.1681	500	0.5724	1.2588
60	0.5521	1.1747	1000	0.5745	1.2685

Table 4 The Value of y_n with respect to N (number of years) in Gumbel's method.

APPENDIX C

Months	Northern Uplands		Southern lowlands		Basin (as a whole)	
	Rainfall (mm)	Temp (℃)	Rainfall (mm)	Temp (℃)	Rainfall (mm)	Temp (℃)
January	140.500	10.53	198.500	17.26	169.500	13.90
February	199.600	12.09	211.900	19.60	205.800	15.85
March	489.600	15.56	528.800	23.45	509.200	19.51
April	1089.800	18.62	1295.600	26.27	1192.700	22.45
May	3143.200	19.50	2288.000	27.60	2715.600	23.55
June	3624.600	20.72	3984.300	29.19	4304.500	24.96
July	4454.900	21.71	4203.200	28.12	4629.100	24.92
August	3748.100	21.88	4911.500	28.81	3329.800	25.35
September	2498.400	19.94	3203.500	27.35	2101.000	23.65
October	1422.300	18.36	1463.200	26.65	1442.800	22.51
November	249.200	15.23	355.500	23.02	302.400	19.31
December	63.900	11.92	144.000	19.11	104.00	15.52
Mean	**1760.342**	**17.18**	**1899.000**	**24.70**	**1750.533**	**20.96**

(Source: Tea Gardens record collected during 2000 to 2010)

Table 2.1 Total monthly Rainfall (mm) and average monthly Temperature (˚C) distribution in the Balason basin.

SITES	2008	2009	2010
0 KM (BELOW PANIGHATA BRIDGE)	257.218	231.540	213.060
1 KM DOWNSTREAM	545.087	531.300	538.494
2 KM DOWNSTREAM	356.883	405.440	358.071
3 KM DOWNSTREAM	352.450	346.71	318.420
4 KM DOWNSTREAM	253.405	288.198	243.612
5 KM DOWNSTREAM	258.664	302.335	318.770
6 KM DOWNSTREAM	270.840	307.100	287.250
7 KM DOWNSTREAM	310.088	344.400	310.088
8 KM DOWNSTREAM	269.083	314.440	374.400
9 KM DOWNSTREAM	486.200	423.306	423.096

10 KM DOWNSTREAM	539.400	495.040	473.040
11 KM DOWNSTREAM	459.02	427.716	437.05
12 KM DOWNSTREAM	322.500	332.088	410.000
13 KM DOWNSTREAM	332.500	399.590	447.028
14 KM DOWNSTREAM	418.460	433.165	391.996
15 KM DOWNSTREAM	316.008	260.545	389.825
16 KM DOWNSTREAM	412.100	432.649	348.84
17 KM DOWNSTREAM	484.161	495.018	461.100
18 KM (BELOW MATIGARA BRIDGE)	165.845	153.488	181.800
19 KM DOWNSTREAM	238.950	203.125	221.214
20 KM DOWNSTREAM	233.732	201.292	275.471
21 KM DOWNSTREAM	608.236	514.657	438.964
22 KM (BELOW NAUKAGHAT BRIDGE)	418.964	484.141	311.502
MEAN AREA (m^2)	**361.294**	**326.056**	**355.352**

(*Source: cross-section survey*)

Table 3.1 Annual cross sectional Area (m^2) along the lower Balason river during 2008, 2009 and 2010.

SITES	2008	2009	2010
0 KM (BELOW PANIGHATA BRIDGE)	339.522	341.860	336.272
1 KM DOWNSTREAM	445.262	464.300	453.388
2 KM DOWNSTREAM	355.022	364.240	359.006
3 KM DOWNSTREAM	267.660	275.540	276.820
4 KM DOWNSTREAM	296.718	298.444	304.608
5 KM DOWNSTREAM	250.068	255.309	253.5400
6 KM DOWNSTREAM	367.4800	371.660	376.523
7 KM DOWNSTREAM	333.868	330.100	336.810
8 KM DOWNSTREAM	359.802	364.7600	362.060

9 KM DOWNSTREAM	342.860	353.412	359.802
10 KM DOWNSTREAM	437.480	444.240	440.160
11 KM DOWNSTREAM	391.360	398.558	403.876
12 KM DOWNSTREAM	398.626	405.644	412.000
13 KM DOWNSTREAM	476.400	481.366	487.740
14 KM DOWNSTREAM	428.960	434.304	437.400
15 KM DOWNSTREAM	240.260	245.640	254.600
16 KM DOWNSTREAM	319.600	327.960	325.160
17 KM DOWNSTREAM	477.636	482.660	480.230
18 KM (BELOW MATIGARA BRIDGE)	206.618	213.448	203.800
19 KM DOWNSTREAM	320.100	322.664	323.374
20 KM DOWNSTREAM	412.636	411.780	414.334
21 KM DOWNSTREAM	698.147	701.969	703.848
22 KM (BELOW NAUKAGHAT BRIDGE)	580.846	584.262	580.076
MEAN WETTED PERIMETER (m)	**380.301**	**385.831**	**386.323**

(Source: cross-section survey)

Table 3.2 Annual cross section wetted perimeter (m) along the lower Balason river during 2008, 2009 and 2010.

SITES	2008	2009	2010
0 KM (BELOW PANIGHATA BRIDGE)	0.004	0.004	0.004
1 KM DOWNSTREAM	0.004	0.004	0.004
2 KM DOWNSTREAM	0.004	0.004	0.004
3 KM DOWNSTREAM	0.004	0.004	0.004
4 KM DOWNSTREAM	0.004	0.004	0.004
5 KM DOWNSTREAM	0.004	0.004	0.004
6 KM DOWNSTREAM	0.004	0.004	0.004
7 KM DOWNSTREAM	0.004	0.004	0.004
8 KM DOWNSTREAM	0.003	0.003	0.003
9 KM DOWNSTREAM	0.003	0.003	0.003

10 KM DOWNSTREAM	0.003	0.003	0.003
11 KM DOWNSTREAM	0.003	0.003	0.003
12 KM DOWNSTREAM	0.003	0.003	0.003
13 KM DOWNSTREAM	0.003	0.003	0.003
14 KM DOWNSTREAM	0.003	0.003	0.003
15 KM DOWNSTREAM	0.003	0.003	0.003
16 KM DOWNSTREAM	0.003	0.003	0.003
17 KM DOWNSTREAM	0.003	0.003	0.003
18 KM (BELOW MATIGARA BRIDGE)	0.003	0.003	0.003
19 KM DOWNSTREAM	0.003	0.003	0.003
20 KM DOWNSTREAM	0.003	0.003	0.003
21 KM DOWNSTREAM	0.002	0.002	0.002
22 KM (BELOW NAUKAGHAT BRIDGE)	0.002	0.002	0.002
MEAN ANNUAL GRADIENT (m/Km)	**0.003**	**0.003**	**0.003**

(Source: cross-section survey)

Table 3.3 Annual cross-section width and mean depth (***w:d***) along the lower Balason river during 2008-2010.

MONTHS	**2007**	**2008**	**2009**	**2010**
JANUARY	2.670	3.189	2.520	3.025
FEBRUARY	3.871	2.492	1.687	1.911
MARCH	2.425	2.302	1.356	1.456
APRIL	2.873	2.026	2.067	1.956
MAY	6.316	6.346	7.477	5.862
JUNE	20.285	52.154	19.310	31.234
JULY	100.543	81.000	62.360	102.310
AUGUST	84.009	127.46	94.430	97.300
SEPTEMBER	117.892	38.162	42.860	58.610
OCTOBER	24.187	17.710	31.550	25.900
NOVEMBER	8.280	8.054	10.640	11.740
DECEMBER	4.825	3.823	5.356	4.897

MEAN ANNUAL	**31.515**	**28.727**	**23.468**	**28.850**

(Source: CWC G&D Site, Matigara)

Table 3.4 Mean monthly discharge (Q) hydrograph of the lower Balason river for the year 2007 to 2010.

JUNE

YEAR	TOTAL Q ($m^3 s^{-1}$)	MEAN Q ($m^3 s^{-1}$)	MAX Q ($m^3 s^{-1}$)	MIN Q ($m^3 s^{-1}$)
2007	608.555	20.285	72.890	3.682
2008	780.376	52.152	300.000	6.818
2009	579.296	19.310	59.870	8.620
2010	937.009	31.234	236.300	4.343
ANNUAL MEAN	**726.309**	**30.745**	**167.265**	**5.866**

JULY

YEAR	TOTAL Q ($m^3 s^{-1}$)	MEAN Q ($m^3 s^{-1}$)	MAX Q ($m^3 s^{-1}$)	MIN Q ($m^3 s^{-1}$)
2007	3116.820	100.543	356.700	21.560
2008	2511.000	81.000	210.800	49.980
2009	1933.260	62.363	139.400	29.310
2010	3171.700	102.313	320.700	33.910
ANNUAL MEAN	**2683.195**	**86.555**	**256.900**	**33.690**

AUGUST

YEAR	TOTAL Q ($m^3 s^{-1}$)	MEAN Q ($m^3 s^{-1}$)	MAX Q ($m^3 s^{-1}$)	MIN Q ($m^3 s^{-1}$)

007	2604.280	84.009	210.000	41.800
2008	3951.110	127.455	354.200	46.040
2009	2927.370	94.431	309.200	49.300
2010	3016.510	97.307	244.900	33.540
ANNUAL MEAN	**3124.818**	**100.800**	**279.575**	**42.670**

SEPTEMBER

YEAR	TOTAL Q (m^3 s^{-1})	MEAN Q (m^3 s^{-1})	MAX Q (m^3 s^{-1})	MIN Q (m^3 s^{-1})
2007	3536.740	117.891	439.600	36.230
2008	1144.860	38.162	68.200	22.850
2009	1285.790	42.850	126.400	26.250
2010	1758.290	58.610	129.300	38.030
ANNUAL MEAN	**1931.420**	**64.381**	**190.875**	**30.840**

OCTOBER

YEAR	TOTAL Q (m^3 s^{-1})	MEAN Q (m^3 s^{-1})	MAX Q (m^3 s^{-1})	MIN Q (m^3 s^{-1})
2007	749.810	24.187	36.220	10.400
2008	549.070	17.712	36.500	9.870

2009	978.040	31.550	149.700	14.450
2010	803.000	25.90323	49.040	17.530
ANNUAL MEAN	**769.980**	**24.838**	**67.865**	**13.062**

(Source: CWC G&D Site, Matigara)

Table 3.5 Peak monthly discharge (m^3 s^{-1}) during monsoon period (June – October) of the lower Balason river from 2007 to 2010

SITES	Mean sediment (D_{50}) (mm)	Largest sediment (mm)	Smallest sediment (mm)
0 km (Panighata Bridge)	272.249	1450.000	93.980
1 km Downstream	299.323	4207.300	62.230
2 km Downstream	274.673	2612.140	55.880
3 km Downstream	180.944	640.080	58.420
4 km Downstream	200.119	650.240	36.830
5 km Downstream	169.719	443.230	38.100
6 km Downstream	115.905	530.860	33.020
7 km Downstream	162.448	429.260	39.370
8 km Downstream	149.937	410.210	40.640
9 km Downstream	114.530	330.200	30.400
10 km Downstream	82.163	406.400	38.100
11 km Downstream	118.629	436.880	35.560
12 km Downstream	105.378	195.580	27.940
13 km Downstream	107.553	251.460	23.100
14 km Downstream	96.793	325.120	45.720
15 km Downstream	120.930	358.140	23.020
16 km Downstream	103.345	317.500	13.970
17 km Downstream	97.960	241.300	5.080
18 km (Matigara Bridge)	80.197	647.700	10.400
19 km Downstream	73.518	246.380	9.240

20 km Downstream	65.628	198.120	11.210
21 km Downstream	62.547	284.480	4.870
22 km (Naukaghat Bridge)	48.038	78.740	6.220
MEAN	**134.892**	**682.231**	**32.317**

(Source: Based on field survey)

Table 4.1 The size (diameter in mm) distribution of sampled coarse sediments in different sites during 2008.

SITES	Mean sediment (D_{50}) (mm)	Largest sediment (mm)	Smallest sediment (mm)
0 km (Panighata Bridge)	226.140	1352.800	99.060
1 km Downstream	284.792	4759.460	82.550
2 km Downstream	229.930	2832.100	74.930
3 km Downstream	230.265	482.600	82.550
4 km Downstream	160.752	441.960	66.040
5 km Downstream	133.389	472.440	41.910
6 km Downstream	109.593	505.460	31.750
7 km Downstream	149.994	590.550	36.830
8 km Downstream	129.420	444.500	37.200
9 km Downstream	110.288	298.450	21.400
10 km Downstream	74.409	439.420	31.750
11 km Downstream	132.884	495.300	38.100
12 km Downstream	130.095	312.420	25.400
13 km Downstream	131.589	259.080	40.640
14 km Downstream	84.894	223.520	35.030
15 km Downstream	100.917	228.600	33.020
16 km Downstream	107.442	309.880	11.430
17 km Downstream	74.425	299.720	7.620
18 km (Matigara Bridge)	113.875	292.100	10.254
19 km Downstream	99.227	218.440	12.700
20 km Downstream	77.286	193.040	8.410
21 km Downstream	53.998	199.390	12.700
22 km (Naukaghat Bridge)	53.198	157.480	6.510

MEAN	130.383	687.335	36.860

(Source: Based on field survey)

Table 4.2 The size (diameter in mm) distribution of sampled coarse sediments in different sites during 2009.

SITES	Mean sediment (D_{50}) (mm)	Largest sediment (mm)	Smallest sediment (mm)
0 km (Panighata Bridge)	249.033	1384.300	83.820
1 km Downstream	310.746	4328.200	58.420
2 km Downstream	269.440	2850.600	53.340
3 km Downstream	211.113	779.780	62.230
4 km Downstream	194.936	723.900	53.880
5 km Downstream	171.326	417.830	50.800
6 km Downstream	128.472	406.400	52.070
7 km Downstream	136.982	444.500	43.180
8 km Downstream	123.642	393.700	32.520
9 km Downstream	127.689	346.710	33.200
10 km Downstream	103.414	419.100	35.560
11 km Downstream	127.651	386.080	27.940
12 km Downstream	116.329	248.920	12.700
13 km Downstream	118.889	304.800	27.940
14 km Downstream	89.836	309.880	35.560
15 km Downstream	108.955	609.600	33.640
16 km Downstream	104.109	269.240	20.574
17 km Downstream	87.220	322.580	15.240
18 km (Matigara Bridge)	96.548	332.740	20.320
19 km Downstream	85.363	299.720	11.620
20 km Downstream	72.121	201.300	14.200
21 km Downstream	58.910	114.300	12.700
22 km (Naukaghat Bridge)	52.029	236.220	4.230
MEAN	**136.728**	**701.322**	**34.595**

(Source: Based on field survey)

Table 4.3 The size (diameter in mm) distribution of sampled coarse sediments in different sites during 2010.

SITES (2008)	Mean Fall Velocity (m s^{-1})	Maximum Fall Velocity (m s^{-1})	Minimum Fall Velocity (m s^{-1})
0 km (Panighata Bridge)	5.420	12.509	2.047
1 km Downstream	5.683	21.307	1.596
2 km Downstream	5.444	16.789	1.517
3 km Downstream	4.419	8.311	1.549
4 km Downstream	4.647	8.377	1.260
5 km Downstream	4.280	6.916	1.278
6 km Downstream	3.537	7.569	1.201
7 km Downstream	4.187	6.806	1.297
8 km Downstream	4.022	6.653	1.314
9 km Downstream	3.516	5.969	1.152
10 km Downstream	1.901	6.622	1.271
11 km Downstream	3.578	6.867	1.233
12 km Downstream	3.372	4.594	1.111
13 km Downstream	3.407	5.209	1.02
14 km Downstream	3.232	5.923	1.376
15 km Downstream	3.612	6.217	1.021
16 km Downstream	3.339	5.853	0.851
17 km Downstream	3.251	5.103	0.523
18 km (Matigara Bridge)	1.872	8.360	0.750
19 km Downstream	1.770	5.156	0.706
20 km Downstream	1.646	4.624	0.778
21 km Downstream	1.596	5.541	0.512
22 km (Naukaghat Bridge)	1.409	1.850	0.579
MEAN	**3.441**	**7.527**	**1.128**

(Source: Based on field survey and hypothetical assumptions)

Table 4.4 The estimated fall or settling velocity (m s^{-1}) for different sites on the basis of the diameter (mm) of the largest, mean and smallest coarse sediments sampled during 2008.

SITES (2009)	Mean Fall Velocity (m s^{-1})	Maximum Fall Velocity (m s^{-1})	Minimum Fall Velocity (m s^{-1})
0 km (Panighata Bridge)	4.940	12.082	2.117
1 km Downstream	5.544	22.663	1.883
2 km Downstream	4.981	17.482	1.770
3 km Downstream	4.985	7.216	1.883
4 km Downstream	4.165	6.906	1.641
5 km Downstream	3.794	7.140	1.332
6 km Downstream	3.439	7.385	1.181
7 km Downstream	4.023	7.983	1.260
8 km Downstream	3.737	6.926	1.265
9 km Downstream	3.450	5.675	0.989
10 km Downstream	1.784	5.675	1.174
11 km Downstream	3.787	7.311	1.271
12 km Downstream	3.747	5.806	1.065
13 km Downstream	3.768	5.287	1.306
14 km Downstream	1.942	4.911	1.225
15 km Downstream	3.300	4.967	1.195
16 km Downstream	3.405	5.783	0.785
17 km Downstream	1.784	5.688	0.641
18 km (Matigara Bridge)	3.505	5.614	0.744
19 km Downstream	3.272	4.855	0.823
20 km Downstream	1.828	4.564	0.674
21 km Downstream	1.489	4.639	0.823
22 km (Naukaghat Bridge)	1.478	4.122	0.593
MEAN	**3.398**	**7.421**	**1.202**

(Source: Based on field survey and hypothetical assumptions)

Table 4.5 The estimated fall or settling velocity (m s^{-1}) for different sites on the basis of the diameter (mm) of the largest, medium and smallest coarse sediments sampled during 2009.

SITES (2010)	Mean Fall Velocity (m s^{-1})	Maximum Fall Velocity (m s^{-1})	Minimum Fall Velocity (m s^{-1})
0 km (Panighata Bridge)	5.184	12.222	1.902
1 km Downstream	5.791	21.612	1.5490
2 km Downstream	5.392	17.539	1.4839
3 km Downstream	4.773	9.173	1.596
4 km Downstream	4.586	8.839	1.490
5 km Downstream	4.300	6.714	1.450
6 km Downstream	3.723	6.622	1.467
7 km Downstream	3.845	6.925	1.349
8 km Downstream	3.653	6.517	1.193
9 km Downstream	3.711	6.116	1.1974
10 km Downstream	3.341	6.725	1.233
11 km Downstream	3.711	6.455	1.111
12 km Downstream	3.543	5.183	0.82
13 km Downstream	3.582	5.735	1.110
14 km Downstream	2.013	5.783	1.233
15 km Downstream	3.429	8.111	1.204
16 km Downstream	3.352	5.390	0.972
17 km Downstream	1.976	5.900	0.877
18 km (Matigara Bridge)	3.228	5.992	0.968
19 km Downstream	1.948	5.687	0.791
20 km Downstream	1.749	4.661	0.856
21 km Downstream	1.551	3.512	0.823
22 km (Naukaghat Bridge)	1.463	5.049	0.478
MEAN	**3.471**	**7.672**	**1.1806**

(Source: Based on field survey and hypothetical assumptions)

Table 4.6 The estimated fall or settling velocity (m s^{-1}) for different sites on the basis of the diameter (mm) of the largest, medium and smallest coarse sediments sampled during 2010.

Year	Monsoon (M.T.)	Non-Monsoon (M.T.)	Annual Load (M.T.)
1989-90	1090285	10470	1100755
1990-91	765896	2249	768144
1991-92	2151205	2690	2153895
1992-93	729635	4118	733753
1993-94	497544	1923	499468
1994-95	271728	865	272593
1995-96	705552	1708	707260
1996-97	780863	1557	782419
1997-98	188857	6238	195095
1998-99	1408099	4264	1412363
1999-00	1960629	26845	1987475
2000-01	360778	38670	399448
2001-02	605038	829	605867
2002-03	N/A	2409	2409
2003-04	1970925	N/A	1970925
2004-05	N/A	1203	1203
2005-05	235651	3425	239076
2006-07	845134	2290	847424
2007-08	1415210	3141	1418351
2008-09	866143	7701	873844
2009-10	645217	1968	647185
2010-11	770561	1989	772550
MEAN	**796319.33**	**3102.43**	**835977.36**

(Source: CWC G&D Site, Matigara)

Table 4.7 The total suspended load (M.T) of lower Balason river from 1989 – 1990 to 2010-2011.

MONTHS	Coarse (g l^{-1})	Medium (g l^{-1})	Fine (g l^{-1})	TOTAL (g l^{-1})
JANANUARY	0.279	0.190	0.474	0.943
FEBRUARY	0.279	0.190	0.474	1.015
MARCH	0.163	0.190	0.930	1.283
APRIL	0.136	0.439	2.031	2.606
MAY	0.648	1.125	4.186	5.959
JUNE	2.817	2.176	4.748	9.741
JULY	14.661	14.982	29.275	58.918
AUGUST	7.336	4.520	12.165	24.021
SEPTEMBER	8.409	7.751	17.295	33.455
OCTOBER	2.475	0.837	1.810	5.122
NOVEMBER	0.999	0.368	0.572	1.939
DECEMBER	0.290	0.160	0.219	0.669
TOTAL (g l^{-1})	**38.492**	**32.928**	**74.179**	**145.671**

(Source: Based on CWC G&D Site, Matigara)

Table 4.8 The total monthly SSC (g l^{-1}) of lower Balason river during 2007.

MONTHS	Coarse (g l^{-1})	Medium (g l^{-1})	Fine (g l^{-1})	TOTAL (g l^{-1})
JANANUARY	0.196	0.150	0.253	0.599
FEBRUARY	0.106	0.136	0.229	0.471
MARCH	0.097	0.152	0.361	0.610
APRIL	0.085	0.146	1.585	1.816
MAY	0.181	0.280	3.097	3.558
JUNE	3.227	2.46	7.447	13.134
JULY	7.061	3.718	5.881	16.660
AUGUST	9.001	7.803	15.682	32.486
SEPTEMBER	2.991	0.938	1.326	5.255

OCTOBER	1.424	0.510	0.689	2.623
NOVEMBER	0.489	0.386	0.765	1.640
DECEMBER	0.090	0.192	0.594	0.876
TOTAL (g l^{-1})	**24.948**	**16.871**	**37.909**	**79.728**

(Source: Based on CWC G&D Site, Matigara)

Table 4.9 The total monthly SSC (g l^{-1}) of lower Balason river during 2008.

MONTHS	Coarse (g l^{-1})	Medium (g l^{-1})	Fine (g l^{-1})	TOTAL (g l^{-1})
JANANUARY	0.077	0.142	0.448	0.667
FEBRUARY	0.082	0.179	1.019	1.280
MARCH	0.122	0.280	1.489	1.891
APRIL	0.143	0.439	2.042	2.624
MAY	0.419	0.602	2.725	3.746
JUNE	1.454	0.492	2.260	4.206
JULY	5.007	2.374	7.526	14.907
AUGUST	7.129	4.915	18.841	30.885
SEPTEMBER	4.324	2.177	6.816	13.317
OCTOBER	2.547	1.578	3.074	7.199
NOVEMBER	0.980	0.300	0.329	1.609
DECEMBER	0.272	0.282	0.479	1.033
TOTAL (g l^{-1})	**22.556**	**13.760**	**47.048**	**83.364**

(Source: Based on CWC G&D Site, Matigara)

Table 4.10 The total monthly SSC (g l^{-1}) of lower Balason river during 2009.

MONTHS	Coarse (g l^{-1})	Medium (g l^{-1})	Fine (g l^{-1})	TOTAL (g l^{-1})
JANANUARY	0.086	0.085	0.198	0.369
FEBRUARY	0.073	0.061	0.191	0.325

MARCH	0.065	0.091	0.254	0.41
APRIL	0.055	0.097	0.217	0.369
MAY	0.379	0.379	0.758	1.516
JUNE	1.904	1.694	3.937	7.535
JULY	7.455	5.389	11.928	24.772
AUGUST	10.557	7.121	14.658	32.336
SEPTEMBER	6.029	4.014	8.903	18.946
OCTOBER	3.727	2.653	6.127	12.507
NOVEMBER	3.192	2.668	5.066	10.926
DECEMBER	1.056	1.089	1.942	4.087
TOTAL (g l^{-1})	**34.578**	**25.341**	**54.179**	**114.098**

(Source: Based on CWC G&D Site, Matigara)

Table 4.11 The total monthly SSC (g l^{-1}) of lower Balason river during 2010.

CROSS-SECTIONS	2008	2009	2010	MEAN
B (3.8OO km)	3.027	1.322	2.177	2.175
C (3.600 km)	2.008	1.687	1.848	1.848
D (3.400 km)	1.166	1.645	1.406	1.406
E (3.200 km)	2.976	3.681	3.326	3.328
F (3.000 km)	3.187	3.192	3.197	3.192
G (2.800 km)	2.577	1.697	2.137	2.137
H (2.600 km)	2.207	1.996	2.102	2.102
I (2.400 km)	2.267	2.766	2.517	2.517
J (2.200 km)	2.292	2.757	2.527	2.525
K (2.000 km)	2.357	2.362	2.357	2.359
L (1.800 km)	2.307	2.467	2.387	2.387
M (1.600 km)	1.918	2.262	2.088	2.089
N (1.400 km)	0.726	2.446	1.586	1.586
O (1.200 km)	2.646	2.946	2.796	2.796
P (1.000 km)	3.302	3.106	3.207	3.205

Q (0.800 km)	1.747	3.065	2.496	2.436
R (0.600 km)	1.921	4.040	2.987	2.983
S (0.400 km)	3.327	1.766	2.547	2.547
T (0.200 km)	2.007	3.085	2.546	2.546
U (Matigara Bridge)	1.966	4.107	3.037	3.037
V (0.200 km below)	3.098	2.078	2.618	2.598
W (0.400 km below)	1.339	1.337	1.268	1.315
MEAN	**2.289**	**2.537**	**2.416**	**2.414**

(Source: Based on cross-section survey)

Table 6.1 The channel gradient (m m^{200}) at surveyed cross-sections during 2008-2010.

MONTHS	2007	2008	2009	2010
JANUARY	0.293	0.195	0.165	0.235
FEBRUARY	0.258	0.184	0.236	0.195
MARCH	0.248	0.184	0.253	0.171
APRIL	0.250	0.181	0.204	0.221
MAY	0.305	0.278	0.224	0.354
JUNE	0.386	0.487	0.419	0.458
JULY	0.683	0.641	0.584	0.696
AUGUST	0.724	0.774	0.684	0.641
SEPTEMBER	0.843	0.507	0.508	0.736
OCTOBER	0.439	0.408	0.484	0.528
NOVEMBER	0.282	0.297	0.444	0.501
DECEMBER	0.232	0.198	0.304	0.342
MEAN	**0.412**	**0.361**	**0.376**	**0.423**

(Source: Based on CWC G&D Site, Matigara)

Table 6.2 The monthly hydraulic mean depth (m) from 2007-2010.

MONTHS	2007	2008	2009	2010
JANUARY	0.376	0.331	0.300	0.359
FEBRUARY	0.399	0.311	0.379	0.275
MARCH	0.302	0.316	0.429	0.243
APRIL	0.340	0.340	0.358	0.253
MAY	0.477	0.470	0.507	0.390
JUNE	0.582	0.801	0.324	0.534
JULY	1.058	0.980	0.793	1.104
AUGUST	1.148	1.380	1.068	1.232
SEPTEMBER	1.232	0.736	0.959	0.964
OCTOBER	0.641	0.540	0.818	0.682
NOVEMBER	0.427	0.419	0.655	0.541
DECEMBER	0.403	0.322	0.496	0.411
MEAN	**0.615**	**0.579**	**0.591**	**0.582**

(Source: Based on CWC G&D Site, Matigara)

Table 6.3 The monthly mean velocity (m s^{-1}) from 2007-2010.

MONTHS(2007)	Mean Q (m^3 s^{-1})	Mean Manning n
JANUARY	2.670	0.072
FEBRUARY	3.871	0.077
MARCH	2.425	0.099
APRIL	2.873	0.091
MAY	6.316	0.068
JUNE	20.285	0.052
JULY	100.543	0.035
AUGUST	84.009	0.033
SEPTEMBER	117.892	0.031
OCTOBER	24.187	0.039
NOVEMBER	8.280	0.043
DECEMBER	4.825	0.052
MEAN ANNUAL	**31.515**	**0.058**

MONTHS(2008)	Mean Q ($m^3 s^{-1}$)	Mean Manning n
JANUARY	3.189	0.058
FEBRUARY	2.492	0.060
MARCH	2.302	0.060
APRIL	2.026	0.055
MAY	6.346	0.054
JUNE	52.154	0.040
JULY	81.000	0.033
AUGUST	127.46	0.031
SEPTEMBER	38.162	0.039
OCTOBER	17.710	0.044
NOVEMBER	8.054	0.051
DECEMBER	3.823	0.057
MEAN ANNUAL	**28.727**	**0.049**

MONTHS(2009)	Mean Q ($m^3 s^{-1}$)	Mean Manning n
JANUARY	2.520	0.054
FEBRUARY	1.687	0.050
MARCH	1.356	0.041
APRIL	2.067	0.039
MAY	7.477	0.040
JUNE	19.310	0.065
JULY	62.360	0.028
AUGUST	94.430	0.022
SEPTEMBER	42.860	0.020
OCTOBER	31.550	0.022
NOVEMBER	10.640	0.026
DECEMBER	5.356	0.027
MEAN ANNUAL	**23.468**	**0.036**

MONTHS(2010)	Mean Q ($m^3 s^{-1}$)	Mean Manning n
JANUARY	3.025	0.032
FEBRUARY	1.911	0.037
MARCH	1.456	0.038
APRIL	1.956	0.045
MAY	5.862	0.039
JUNE	31.234	0.038
JULY	102.310	0.023
AUGUST	97.300	0.020
SEPTEMBER	58.610	0.024
OCTOBER	25.900	0.027
NOVEMBER	11.740	0.034
DECEMBER	4.897	0.040
MEAN ANNUAL	**28.850**	**0.033**

(Source: Based on CWC G&D Site, Matigara)

Table 6.4 The monthly mean Discharge ($m^3 s^{-1}$) and mean Manning's n from 2007-2010.

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