Two Years
Post Graduate Degree Programme (CBCS) in Geography
Semester – IV

Paper Code: GEO/DSE/FG/T-421

Fluvial Geomorphology-IV: HAZARDS, ISSUES AND MANAGEMENT

(Special Paper)

Self Learning Material

Directorate of Open and Distance Learning (DODL)
University of Kalyani
Kalyani, Nadia
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Director's Message

Satisfying the varied needs of distance learners, overcoming the obstacle of distance and reaching the unreached students are the threefold functions catered by Open and Distance Learning (ODL) systems. The onus lies on writers, editors, production professionals and other personnel involved in the process to overcome the challenges inherent to curriculum design and production of relevant Self Learning Materials (SLMs). At the University of Kalyani a dedicated team under the able guidance of the Hon'ble Vice-Chancellor has invested its best efforts, professionally and in keeping with the demands of Post Graduate CBCS Programmes in Distance Mode to devise a self-sufficient curriculum for each course offered by the Directorate of Open and Distance Learning (DODL), University of Kalyani.

Development of printed SLMs for students admitted to the DODL within a limited time to cater to the academic requirements of the Course as per standards set by Distance Education Bureau of the University Grants Commission, New Delhi, India under Open and Distance Mode UGC Regulations, 2020 had been our endeavour. We are happy to have achieved our goal.

Utmost care and precision have been ensured in the development of the SLMs, making them useful to the learners, besides avoiding errors as far as practicable. Further suggestions from the stakeholders in this would be welcome.

During the production-process of the SLMs, the team continuously received positive stimulations and feedback from Professor (Dr.) Amalendu Bhunia, Hon'ble Vice- Chancellor, University of Kalyani, who kindly accorded directions, encouragements and suggestions, offered constructive criticism to develop it within proper requirements. We gracefully, acknowledge his inspiration and guidance.

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Their persistent and co-ordinated efforts have resulted in the compilation of comprehensive, learner-friendly, flexible texts that meet the curriculum requirements of the Post Graduate Programme through Distance Mode.

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Director
Directorate of Open and Distance Learning
University of Kalyani

Syllabus

Semester –IV

Paper Code: GEO/DSE/FG/T-421

FLUVIAL GEOMORPHOLOGY-IV: HAZARDS, ISSUES AND MANAGEMENT

(SPECIAL PAPER)

Internal Evaluation/ Assessment – 10; Examination/Report/ Viva Voce – 40 (Semester end Examination); Credit – 4; Marks -50

Unit-01	Fluvial hazards: nature and types
Unit-02	Floods: types, causes, spatial nature, behaviour, effects, and risk analysis
Unit-03	Riverbank erosion: causes and effects
Unit-04	Riverbank erosion in West Bengal: problems and management
Unit-05	Channel modification: requirements, processes, and effects
Unit-06	Management of river discharge at Farakka Barrage and related issues
Unit-07	Rivers as a resource in West Bengal, their sustainable management
Unit-08	Floodplain management: strategies and principles
Unit-09	Watershed management: need and significance
Unit-10	Integrated River Basin Management: approaches and principles
Unit-11	Tista Megafan processes, landforms and hazards
Unit-12	Sundarban processes, landforms and hazards

Contents

INTRODUCTION:

This specialized paper delves into the complex interactions between rivers, landscapes, and human activities, emphasizing the understanding and management of fluvial hazards.

LEARNING OBJECTIVES

- By the end of this course, you will:
- Understand the processes and factors contributing to fluvial hazards.
- Identify and analyze the impacts of fluvial hazards on landscapes and communities.
- Evaluate management strategies for mitigating fluvial hazards.
- Develop skills in hazard assessment, mapping, and risk communication.

ASSESSMENT OF PRIOR KNOWLEDGE

- Before beginning this course, it is beneficial to review your understanding of:
- Basic principles of fluvial geomorphology.
- Types and causes of riverine hazards.
- Tools and techniques used in hazard assessment and management.

LEARNING ACTIVITIES

- Throughout this course, you will engage in various learning activities, including:
- Lectures covering theoretical concepts and case studies.
- Field visits to observe and analyze fluvial processes.
- Hands-on exercises in hazard mapping and risk assessment.
- Group discussions and presentations on key topics.

FEEDBACK OF LEARNING ACTIVITIES

Regular discussions and feedback sessions will be conducted to address any concerns and enhance your understanding of the subject matter.

UNIT-1: FLUVIAL HAZARDS: NATURE AND TYPES

Flood peaks are generated in river channels by a variety of causes (see Figure 7.13). Most river floods result directly or indi rectly from climatological events such as excessively heavy and/or excessively pro longed rainfall. In cold winter areas, where snowfall accumulates, substantial flooding usually occurs during the melt season in spring and early summer, particularly when melt rates are high. Floods may also result from the effects of rain falling on an already decaying and melting snowpack. An addi tional cause of flooding in cold winter areasis the sudden collapse of ice jams, formed during the break-up of river ice Some of the most devastating floods occur in tropical regions due to the inten sity of the rainfall experienced there. One recent tragic example is the Pakistan flood ing in 2010, when there were unusually intense monsoon rains attributed to La Niña (see Chapter 2). Heavy rainfalls of more than 200 mm were recorded in the Indus headwaters areas in the N of Pakistan during a 4-day period in July 2010. The resultant flooding left 20% of country under water; 2.6M ha of cultivated land were devastated and over 2000 people killed (see Smith, 2013). Temperate areas can suffer from extreme floods too, although generally with few fatalities. For example it is only just over a 100 years ago that the centre of Paris was flooded with extensive damage to property, but no loss of life (Jackson, 2010). Hydrologists are concerned to know the rarity of such events, and often use flood frequency analysis of past data. There are many excellent engineering and statistical books detailing the frequency analyses of floods and droughts. Instead this section touches on aspects that the hydrologist may need to consider interpreting the results of such techniques. A flood return period or flood interval is the probability that a flood of a given size (or bigger) may occur in any year. Hydrologists may refer to a 100-year flood, which can be misleading to the layman. It does not mean it will occur once every 100 years, and certainly does not mean that after one has occurred there will be no further flooding of that magnitude for another 99 years. Rather, that it is the average time interval betweenyears containing such a flood, i.e. there is 1% probability (p = reciprocal of the return period) that such a flood occurs in any one year. Following such a flood, the probabil ity of a similar flood occurring in the fol lowing year remains 1%. Due to the com mon misunderstandings caused by time-dependent terms such as ‘period’ or ‘inter val’, many hydrologists prefer the terms flood ‘risk’ or ‘probability’. Flood frequency analyses commonly make several assumptions that should be verified: a. The data are homogeneous, i.e. the catchment has not undergone changes (such as land use), and neither has the climate. It is also assumed that the observed floods will come from the same ‘population’ as other potentially larger floods. If there are subsequent floods produced by entirely different mechanisms (for example tropical cyclones in an area where temperate storms are the norm), then using data from the normal events to predict flood risk in the future will miss these outliers, b. The length of record and hence the sample size should be sufficiently large to encompass some major floods and not be restricted to a period of unusu ally flood rich or flood poor years, c. It is dangerous to extrapolate too far beyond the record length – perhaps twice the length of the data set. d. Estimation is only as good as the quality of data available; the measure ments of extreme floods are of particular importance, but may be the least accurate.

An excellent discussion of the potential pitfalls of flood frequency estimation is provided by Reed (2002). Historic flood markers can provide val uable additional information about flood risk and a context for current conditions, but must be treated with caution. Channel dimensions may have changed, and obsta cles such as bridges and mills may have been added or removed. There are also descriptive records of past floods (and droughts) from local community and church records as well as agricultural har vest records (e.g. Stratton, 1978). Flood intensifying factors As the lower part of Figure 7.13 shows, f loods may be modified by a number offactors. These can operate either to ame liorate or to intensify flooding although, for the sake of brevity, only the latter func tion is considered in this discussion. For example, river floods may be intensified by factors associated either with the catch ment itself or with the drainage network and stream channels. Most of these oper ate to increase the volume of quickflow and to speed up its movement. Few of these factors operate either uni-direction ally or independently. Area, for example, is fundamentally important in the sense that the larger the catchment, the greater is the f lood produced from a catchment-wide rainfall event. However, when a storm cov ers only part of the catchment, the attenu ation of the resulting flood hydrograph, as it moves through the channel network to the outlet, is greater in a large catchment than in a small one. Again, basin shape and the pattern of the drainage network combine to influence the size and shape of f lood peaks at the basin outlet as was shown in Figure 7.8. Some of the most complex relationships, those between the variable basin factors, have a significant influence on three important hydrological variables, i.e. water storage, infiltration, and transmissibility. Water storage in the soil and deeper subsurface layers may affect both the tim ing and magnitude of flood response to precipitation, with low storage often result ing in rapid and intensified flooding. High infiltration values allow much of the pre cipitation to be absorbed by the soil surface and may thereby reduce catchment flood response, depending on the extent and growth of areas of saturation overland flow and on subsurface transmissibility; lowinfiltration values encourage infiltra tion-excess overland flow leading to rapid increases in channel discharge (see also Section 7.4). Urbanisation will generally intensify f lood peaks downstream due to the large areas of impermeable surfaces and also the urban storm sewer network removing run off from these surfaces. Some rural activi ties may be similar to urban changes by replacing soil water storage and slower subsurface flows by overland flow. The most extreme cases are soil loss by erosion, which may result from the removal of pro tective vegetation, and soil crusting caus ing a change from subsurface flow to rapid overland flow. Channel changes can take a number of forms; they may be farmland drainage to aid crops, which can unintentionally alter the rate at which water reaches the stream network and so influence flow regimes downstream (Robinson and Rycroft, 1999). Or they can be deliberate interventions such as channel dredging to increase the carrying capacity of a stream to reduce local overbank flooding. The removal of flood plain storage may simply move the problem further downstream, the extent of which depends on the design flood capacity of the scheme (Sear et al, 2000). Spatial patterns of flooding Although floods at any location in a river system are a function of the floods generated in the catchment upstream of that point, the relationship between flood behaviour in headwater catchments, and the flood behaviour of the entire river basin is often complex. The downstream flood hydrograph differs from the upstream hydrograph forthe same event, partly because of lag and routing effects, partly because of the changing nature of the basin geology, physiography and climate from headwaters to outlet, and partly because of scale effects. Scale effects are important in relation to both catchment conditions and precipitation inputs, and frequently restrict our ability to generalise from existing flood data and to predict flood occurrence and distribution. The fact that flood peak discharges tend to increase downstream when measured absolutely (i.e. m3s-1) but decrease downstream when expressed as specific discharge (i.e. m3s km-2) may in part reflect steeper slopes and higher rainfall inheadwater areas, but there is also a mismatch between the scales of catchment and precipitation event. Large catchments normally have a lower specific discharge than small catchments partly because they may be only partly covered by a flood-producing storm, while smaller catchment areas may be completely covered (see Section 2.6.3), thereby generating high specific flood discharges. From the preceding discussions of runoff processes and flooding, one might expect the flood-producing potential of each river basin and sub-catchment to be distinctively different. However there is some evidence of a spatial dimension toriver flooding on a scale larger than that of a river basin. This can be illustrated for the UK, by an index of flood potential, the median annual flood (Figure 7.14). The pattern of isopleths drawn through the QMED values shows a marked gradient from specific discharges exceeding 1.50 m3s-1km-2 in the north and west to values well below 0.25 m3s-1km-2 in the south and east. It should be noted that the comparatively low values of flood flow per unit area over south eastern England may be misleading in the sense that they are, to some extent, compensated by the large area of the catchments concerned. The highest instantaneous gauged discharge for the Thames at Kingston (9,950 km2), for example, is about 900 m3s-1 (Terry Marsh, pers comm., 2016), exceeding that of 663 m3s-1 for the Tees at Broken Scar (820 km2) and 830 m3s-1 for the Clyde at Blairston (1,700 km2). The Flood Studies Report (NERC, 1975) generalised the relationship between mean annual flood (QBAR) and the flood of a given return period (QT) for defined geographic regions by a Growth Factor, by which the mean annual flood value is multiplied to obtain approximate values of floods having specified return periods. Subsequent analyses of European data (Beran et al, 1984) confirmed that, in areas having the same flood-producing mechanism, it is possible to 'pool' or average flood frequency curves to produce inter- as well as intra-national comparisons. The Flood Estimation Handbook (FEH), which succeeded the Flood Studies Report in the UK, adopts a more sophisticated approach in relating flood hydrology to catchment characteristics. This is achievedlargely by using indicators such as stream length, stream density and slope gradient which can be derived from digital terrain models and other increasingly accessible digitised and gridded data which was not available at the time of the earlier report (Stewart et al, 2015). In Britain, flood risk maps have been produced showing the 1% (1 in 100 years) and 0.1% (1 in 1000) chance of inundation each year for England and Wales (see http:// watermaps.environment-agency.gov.uk/ and 0.5% (1 in 200 years) for Scotland (http://www.sepa.org.uk/environment/ water/flooding/flood-maps). In the USA the Federal Emergency Management Agency (FEMA) produces similar maps showing areas at flood risk (http://www.newfloodmap.com/). (Ward).

UNIT-2: FLOODS: TYPES, CAUSES, SPATIAL NATURE, BEHAVIOUR, EFFECTS, AND RISK ANALYSIS

Although the flow regime shows seasonal variations in river flow, it does not provide detailed information on the magnitude (size) and frequency of floods and droughts. Floods are of most interest here because they are capable of carrying out large amounts of geo morphological work and are thus significant in shaping the channel. The term ‘flood’ is hard to define. In general terms, a flood is a relatively high flow that exceeds the capacity of the channel. While more frequent flows are confined within the channel, periodic high flows overtop the banks and spill out onto the surrounding floodplain. Significant here is the bankfull discharge (Qb), defined as ‘that discharge at which the channel is completely full’ (Knighton, 1998). Although these definitions may sound straightforward enough, it is actually quite difficult to define bankfull discharge in the field because the height of the banks varies, even over short distances. This means that overtopping of the banks does not occur simultaneously at all points along the channel. Floodplain relief can be quite variable, with variations of between 1.7 m and 3.3 m observed on three Welsh floodplains (Lewin and Manton, 1975). Along the Alabama River, United States, flooding has been observed to occur more frequently at the apexes of actively migrating meander bends. This is associated with the development of floodplain features called levees. These are raised ridges that form along the banks when material is deposited during overbank flows (see Figure 8.9). Levee development is impeded at actively migrating bends because the deposits are eroded as the channel migrates. Levees are better developed (higher) along less actively migrating sections of channel, where flooding occurs less frequently (Harvey and Schumm, 1994).

Flood magnitude and frequency Floods of different sizes are defined in terms of high water levels or discharges that exceed certain arbitrary limits. The height of the water level in a river is called its stage. For a given river, there is a relationship between the size of a flood (in terms of its maximum stage or dis charge) and the frequency with which it occurs. Floods of different sizes do not occur with the same regularity: large floods are rarer than smaller floods. In other words, the larger the flood, the less often it can be expected to occur. Floods are therefore defined in terms of their mag nitude (size) and frequency (how often a flood of a given size can be expected to occur).

You have probably heard reference to the ‘twenty-year flood’ or the ‘100-year flood’. This return periodis an estimate of how often a flood of a given size can be expected to occur and, since less frequent floods are more extreme, the 100-year event would be bigger than the twenty-year flood. The return period (T) can also be expressed as a prob ability (P) by taking the inverse of the return period, i.e.: Using this, the probability of a 100-year flood taking place in any one year can be calculated as

0.01 (i.e. 1 per cent), and for the twenty-year flood, 0.05 (5 per cent). The probability that a flood with a particular return period will occur is the same every year and does not depend how long it was since a flood of this size last occurred – the twenty-year does not occur like clockwork every twenty years. However, if a period of several years is considered, the likelihood of a given flood occurring during this time increases. For example, if someone bought a house on the 100 year floodplain and lived there for thirty years, the probability of that property being flooded in any one year would be 0.01. This increases to 0.3 (probability × number of years), or 30 per cent, for the thirty-year period. Box 3.2 explains how return periods are estimated. As with any odds, flood probabilities are estimates, and a number of under lying assumptions are made when deriving them. It is assumed that runoff is randomly distributed through time and that the data set holds a representative sample of these random events. Estimates are therefore more reliable when a longer record is available, since a larger number of flood events will be included in it. Another assumption is that there are no long-term trends in the data, which is not the case when climate change is occurring.

The frequency of bankfull discharge Although bedrock channels are mainly influenced by high magnitude flows, those formed in alluvium can be adjusted by a much greater range of flows (see Chapter 1, pp. 5–6). This is reflected by the morphology and size of alluvial channels. Over the years, much research has focused on the bankfull discharge (defined above), since it represents a distinct morphological discontinuity between in-bank and overbank flows. Leopold and Wolman (1957) suggested that the channel cross-section is adjusted to accommodate a discharge that recurs with a certain return period. From an examination of active floodplain rivers, they found that the bankfull discharge had a return period of between one and two years. This is corroborated by later observations made for stable alluvial rivers (for example, Andrews, 1980; Carling, 1988). However, the concept of a universal return period for bankfull dis charge that can be applied to all rivers is controversial. Williams (1978) observed wide variations in the frequency of bankfull discharge, which ranged from 1.01 to 32 years, and concluded that this was too variable to assume a uniform return period for all rivers. Even along the same river, there can be marked variations in the frequency of bankfull discharge (Pickup and Warner, 1976). The concept of a uniform frequency for bankfull dis charge assumes that all channels are ‘in regime’. This means that the morphological characteristics of a given channel, such as size, fluctuate around a mean condition over the time scale considered (Pickup and Reiger, 1979). This is not true for all rivers and there are many examples of non-regime, or disequilibrium, channels. An example would be where channel incision is taking place through erosion of the channel bed. This results in a deeper channel, which requires a larger, and therefore less frequent, discharge to fill it. The Gila River in Arizona, United States, was greatly enlarged when past events had led to large floods. The enlarged channel is not adjusted to the contemporary flow regime, which means that the bankfull discharge for the enlarged channel has a much lower frequency (Stevens et al., 1975). The material forming the bed and banks is also significant. In cases where the bound ary is very erodible, the bankfull discharge may simply reflect the most recent flood event (Pickup and Warner, 1976).

The geomorphological effectivenes of floods Given that many rivers exceed their channel capacity and flood on a fairly regular basis, it would not be unreasonable to ask why they do not shape channels that are large enough to convey all the flows supplied to them. While it is true that high-magnitude events lead to significant changes in channel morphology, the com parative rarity of these large floods must also be taken into account. The cumulative effect of smaller, more frequent floods can also be significant in shaping the channel. The effectiveness of any given discharge over a period of time is therefore something of a compromise between its size and how often it occurs. The basic question is: are a number of smaller floods as effective as one large flood? This concept is explored further in Box 3.3.

Regional flood frequency curves The flood frequency–magnitude relationship differs between regions. Despite the low annual rainfall in dry land environments, precipitation can be highly variable and the twelve largest floods ever recorded in the United States all occurred in semi-arid or arid areas (Costa, 1987). During flash floods, such as the one shown in Colour Plate 14, floodwaters rapidly inundate the dry channel. Not all dryland rivers are prone to flash flooding however, and there is considerable variation in the size, type and duration of flooding. Regional flood frequency curves are shown in Figure 3.4. The return period is plotted on the horizontal axis using a logarithmic scale, with the relative flood magnitude on the vertical axis. A relative flood magnitude has been used to allow comparison between floods for a number of rivers in different regions. Because these all drain different areas, a direct compari son of flood magnitudes would not be very meaningful. Instead, for each river included in the analysis, the ratio between the magnitude of each flood on record and a low magnitude 'reference flow' – the mean annual flood – has been used. This is defined in Box 3.2 and has a return period of 2.33 years (i.e. the flow that will be equalled or exceeded on average once every 2.33 years2). The steepness of each curve reflects the variability of the flow, with arid zone rivers showing a much greater increase in relative flood magnitude at higher return periods. This reflects the extreme flow variability observed in these rivers and has important implications for the morphology of dryland channels, as will be seen in later chapters.

Reconstructing past floods Palaeoflood hydrology is a new and developing area of hydrology and geomorphology, which reconstructs past flood events in order to extend the flow record. Due to problems associated with monitoring major floods and the relatively short duration of most gauged records, extreme floods are very rare in the observational record. By reconstructing palaeofloods, the flood record can be extended, allowing increased accuracy in the estimation of floods for risk analysis (Box 3.2). Evidence of past flood events is provided by geological indicators such as flood deposits, silt lines and erosion lines along the channel and valley walls (Benito et al., 2004). Historical records are also used and include documents, chronicles and flood marks inscribed on bridges and buildings. Using this evidence, it is possible to determine the size of the largest flood events over periods of time ranging from decades to thousands of years (Benito et al., 2004). As well as identifying the largest floods, evidence of floods above or below above specified flow stages can also be reconstructed (Stedinger and Baker, 1987). Although time-consuming, it is possible to reconstruct a complete record, chronicling the largest flood, together with the size and number of intermediate palaeofloods (Benito et al., 2004). Chapter 9 discusses some of the techniques that are used in reconstructing past flood events.(Charlton, 2008).

UNIT-3: RIVERBANK EROSION: CAUSES AND EFFECTS

The morphology of bedrock channels is mainly influenced by processes of erosion because the supply of sediment is often limited. Three types of erosion are significant: block quarrying, abrasion and corrosion. Block quarrying is the dominant process (Hancock et al., 1998) and involves the removal of blocks of rockfrom the bed of the channel by drag and lift forces. The size of the quarried blocks can be considerable. Tinkler (1993) reports blocks of sandstone 1.2 m × 1.45 m × 0.11 m and 1.0 m × 0.5 m × 0.05 m being removed from the bed of Twenty Mile Creek, Niagara Peninsula, Ontario, dur ing normal winter flows, when the flow depth was less than 0.4 m. Before blocks can be entrained by the flow, a certain amount of 'preparation' is required to loosen them. Sub aerial weathering and other weakening processes play an important role in this. Weakening processes described by Hancock et al. (1998) include the bashing of exposed slabs by particles carried in the load and a previously undocumented process termed 'wedging', which leads to the enlargement of cracks in the bedrock substrate. This is thought to occur when small bedload particles are able to enter cracks that are momentarily widened by fluid forces. The particles then become very firmly lodged and prevent the crack from narrowing again. As time progresses, further widening of the crack can be sus tained as larger particles fall into it, and may ultimately lead to block detachment. Under conditions of very high flow velocity, sudden changes in pressure can generateshock waves that weaken the bed by the process of cavitation. This effect is caused by the sudden collapse of vapour pockets within the flow (Knighton, 1998). Abrasion is the process by which the channel bound ary is scratched, ground and polished by particles carried in the flow. Erosion is often concentrated where there are weaknesses and irregularities in the rock bed, which allow abrasion to take place at an accelerated rate. This can lead to the development of potholes, deep circular scour features that often form in bedrock reaches. Once a pothole starts to develop, the flow is affected, focusing further erosion. Any coarse material that collects in the pothole is swirled around by the flow, deepening and enlarging it, and literally drills down into the channel bed. Over time potholes may coalesce, leading to a lowering of the bed elevation. Plate 7.1 shows how potholes have contributed to bed lowering near the site of a waterfall. Scouring by finer material carried by the flow, such as sand, leads to the development of sculpted forms. These include flutes and ripple-like features, which reflect structures within the flow (Plate 7.2). These are commonly observed on the crests of large boulders and other protrusions into the flow, whereflow separation takes place and fine sediment is decou pled from the flow (Hancock et al., 1998). The rock boundary may also be polished by fine material carried in suspension. Bedrock channels formed in soluble rock are also sus ceptible to erosion by corrosion, especially where the presence of joints and bedding planes allows solutional enlargement. Solutional features such as scallops may also be seen. These spoon-shaped hollows often cover the walls of cave streamways. Their length is related to the formative flow velocity, ranging from a few millimetres (relatively fast flow) to several metres (relatively slow). Although the actual processes of erosion operate at a small scale, their effects can be seen over scales ranging from millimetres to kilometres. There are several con trols on rates of erosion, which influence the processes described above. These include micro-scale (millimetres to centimetres) variations in the rock structure, the larger scale effects of bedding, joints and fractures, and basin-scale influences such as regional geology and base level history (Wohl, 1998).

BANK EROSION IN ALLUVIAL CHANNELS

Processes of bank erosion are important in the develop ment and evolution of different channel forms, while the migration of river channels across their floodplains involves a combination of bank erosion and deposition. Bank erosion can also create management problems when bridges, buildings and roads are undermined or destroyed. Large volumes of sediment can be generated, leading to problems of aggradation further downstream. Land disputes may also arise where boundaries lie along actively migrating river channels. Rather than being a process in itself, bank erosion is brought about by a number of different processes which can be considered in three groups: 1 Pre-weakening processes such as repeated cycles of wet ting and drying, which ‘prepare’ the bank for erosion. 2 Fluvial processes, where individual particles and aggregates are removed by direct entrainment. 3 Processes of mass failure, which include the collapse, slumping or sliding of bank material into the channel. Bank material that has been detached remains at the base of the bank until it is broken down in-situ or entrained and transported downstream. A balance exists between the rate of sediment accumulation and its rate of removal, which acts as an important control on rates of bank erosion (Carson and Kirkby, 1972). If material accumulates at the base of the bank at a faster rate than it is removed then, to a certain extent, the bank is protected from further erosion. When the opposite situation applies, with bank material being removed faster than it accumulates, bank erosion will continue, sometimes at an increased rate. A third possibility is that rates of supply are the same as rates of removal. The relative rates of accumulation and removal are dependent on the available stream power and the controls on bank erosion discussed below.

Bank materials and weakening processes

The moisture content of the bank is significant, particularly for cohesive bank materials whose strength varies with the level of saturation. A certain amount of water is held in the pores, against the force of gravity, by matric suction forces. These result from surface tension effects, and a negative pore water pressure (less than atmospheric) develops when the soil is not completely saturated. As the soil dries, the strength of the matric suction forces increases as all but the smallest pores are emptied. These forces can be considerable and several authors have observed an increase in the resistance of the bank material to erosion at high matric suctions. However, it has also been suggested that desiccation can lead to higher rates of bank retreat, because the shrink ing of clay particles causes cracking and shedding of loose material at the bank surface. The process of slaking occurs when banks are rapidly immersed by floodwaters and air becomes trapped and compressed within the pores. The resultant pressure causes material to become dislodged (Thorne and Osman, 1988). At high flows, banks may become satu rated with water from the channel. Saturation also occurs when there is a rise in the water table or during prolonged rainfall. Under these conditions a positive pore water pressure exists between the grains. This weak ens the cohesive forces, acting as a lubricant and reducing inter-granular friction.

During cold conditions, the growth of lenses, wedges, and crystals of ice can significantly reduce resistance to erosion, especially where freeze–thaw cycles occur. In temperate regions, the growth of ice needles occurs during moderately sub-zero tempera tures. These are elongated crystals of ice that start to grow as the temperature of the air in contact with the bank decreases, growing in the direction of cooling (into the bank). The crystals often lift and incorporate material which then moves downslope or remains as a 'sediment drape' when the ice melts (Lawler, 1988). In colder regions, where rivers freeze over in winter, can tilevers of ice can cause significant damage (Church and Miles, 1982). Where permafrost exists, thermo erosion niches are cut into frozen banks by the relatively warm water in the channel. While not a process in itself, the presence of vegetation influences the resistance to bank erosion in various ways. Root networks are particularly important and veg etated banks tend to have a more open structure and be better drained. Vegetation also acts to bind the soil together and increase the shear strength of the bank material. Unlike soil, roots have a very high tensile strength, which means that they are able to resist ten sion (stretching forces).

Bank erosion by fluvial processes

For any given situation the relative importance of direct entrainment and mass failure is mainly determined by the composition of the bank, although other factors can also be important. Banks composed of sand and coarser particles are non-cohesive and this material is usually detached grain by grain. Although cohesive forces do not exist between the particles, movement is resisted by inter-particle friction and the packing structures holding the grain in place. However, the selective entrainment of finer sands and gravels often leads to a weakening of the overall structure, which may lead to collapse. In the case of cohesive banks, it tends to be aggregates and crumbs that are detached rather than individual particles. The weakening processes described above are of great importance in assisting fluid forces to detach and entrain aggregates. Once entrained into the main flow, aggregates tend to disintegrate fairly rapidly. Bank failure mechanisms Bank failure occurs when bank material becomes unstable and falls or slides to the base of the bank. There are several types of failure, and different failure mechanisms are observed for cohesive and non-cohesive bank mate rials. Also important are bank height, bank angle, moisture content and the effects of vegetation. There are some similarities between bank failure mechanisms and the processes of mass wasting discussed in Chapter 4 (pp. 39–42). The stability of banks is determined by the balance between the shear stress exerted by the down-slope component of gravity (driving force) and shear strength of the bank material (resisting force). In cohesive banks, failure occurs across a failure plane, the surface within the bank across which shear stress exceeds shear strength. Failure planes can be almost planar (flat) or curved. One of the most common types of failure is illustrated in Figure 7.1(a) and occurs where banks are low, steep and composed of cohesive material. Typically the failure surface is almost planar and vertical, parallel to the bank surface (Plate 7.3, see also Colour Plate 3). Where bank angles are less steep, the failure plane is usually curved and located deep within the bank (Figure 7.1b). Cohesive banks are often most susceptible to failure after a flood wave has passed, when the saturated banks are no longer supported by the pressure of flow in the channel. Non-cohesive banks tend to fail along shallow slip sur faces (Figure 7.1c). Mixed banks are common, typically with fine cohesive sediment overlying non-cohesive material (Plate 7.4). Undercutting of the non-cohesive material by fluvial processes leads to instability of the overlying material. This can cause various types of bank instability, including the cantilever failure illustrated in Figure 7.1(d). (Charlton).

UNIT-4: RIVERBANK EROSION IN WEST BENGAL: PROBLEMS AND MANAGEMENT

Physical geography mostly studies earth surface phenomena as natural processes. However, human geography seeks to explain the surface phenomena as the interaction of the physical and socioeconomic processes. There are clear differences between these two types of processes. Although most physical phenomena are easily understood by physical laws, complex, fuzzy, often non-linear processes at multiple spatio-temporal scales are also prevalent in the physical world (Richards, 2002). However, the complexity of social phenomena is quite different and strikingly present in human society and often interpreted as the processes of social interaction in relation to physical processes (Grundmann & Stehr, 2007). Considering these differences, the state of art of bank erosion research in the Bengal Delta is focused on the physical processes with a universal notion and social interactions with the particularistic form. There is indeed a considerable difference between the study of riverbank erosion of the western and eastern worlds (Wantzen, 2022). In the Western world, more than 90% population lives in cities, where riverbank erosion is no more a risk. Rivers within or at the periphery of the cities are tamed. It is also found in the larger cities of the Eastern world, but most of the people of Asia and Africa are settled along the river course. The agrarian economy is at the base of such people. Therefore, bank erosion and related hazards scape are integral parts of the state of the art of erosion research for the rivers of Asia and Africa including the Bengal Delta (Paul et al., 2020). Bank erosion in the Bengal Delta is thus an ideal consideration in exploring bank erosion-related dynamics from a humanistic approach. Therefore, the present investigation has a specific focus on bank erosion and its impact on the economy and society within the study area. The study area is marked by the channel oscillation of the Ganga, Bhagirathi-Hooghly, Padma, Meghna, Jamuna, and Brahmaputra river systems. For example, the Bhagirathi River in West Bengal oscillates within a belt of 5–15 km with a revisit period of around 200–250 years as per historical records (Islam, 2016). In the study area, agriculture, fishing, and animal husbandry have faced an extreme level of marginalization due to channel shifting and bank erosion. In a nutshell, the economy of the study area has been drastically affected due to the severity of bank erosion as well as dismantling other sociocultural processes. In this regard, thousands of extremely marginalized people have been investigated intensively to bring out an alternative solution to this problem. In the study area, palaeochannels, pastures, or chars can be used as common property resources (CPRs) which have a higher potential to support the economy against bank erosion hazards (Islam, 2016). This CPRs management may act as the immediate substitution for a land-based economy. At the same time, a non-land-based economy has a high potential to absorb the shock of hazards which is deeply investigated in this research work. Apart from in-situ adjustment, ex-situ adjustment very common in the study area in terms of migration has been analysed through process and outcomes in the sequel to stabilize the economy against the hazard.

Present Study: Needs and Focus The study of environmental hazards is important from the very inception of civilization. Humans prefer to settle in those areas which are less hazardous. Development of settlement in safe locations is not only found in ancient, medieval periods but also in modern days. In recent decades, hazard study is becoming more and more important due to the increase in population and built-up environment in the hazard-prone areas which are intensifying hazards. Prosperous human civilization has developed on the riverside because of hydrological and agroecological perspectives (Adedeji, 2011). Ancient civilizations like Indus Valley Civilization, and Mesopotamia, are examples of river-based civilizations (Zhang et al., 2015). Nowadays more than 70% population lives in flood plains and the deltas of the rivers (Global Centre on Adaptation, 2021). Rivers by nature oscillate and swing across the flood plains and deltas from one position to another. This channel oscillation induces hazardous conditions by eroding land, and settlement and thus destabilizes the livelihood of the people around the intensive bank erosion sites. In an urban area, a river is bound by engineering structures and hence channel migration is forcefully stopped to secure the urban livelihood. But in a rural set-up river is relatively unbound and so likely oscillation of rivers damages livelihood. Therefore, rural people are the most victims of channel migration and bank erosion. The mighty river system in the Bengal Delta with huge monsoon spells and a large population pressure altogether makes this unique. Though some researchers (e.g., Haque, 1998; Hutton & Haque, 2004; Islam, 2016) have uttered a few specific issues related to riverbank erosion problems in the states of West Bengal and Bangladesh, a comprehensive understanding of the present erosion scenario, management strategies, and future risk estimation is the need of the hour. The analysis undertaken in this book is attempted at two levels: (1) intensive field-based investigation carried out mainly in the eastern part of the Bengal Delta (i.e., West Bengal) and (2) general portrayal of the bank erosion scenario carried out for the eastern part of the Bengal Delta (i.e., Bangladesh) mainly based on the literature, secondary data, maps, and images. For intensive field-based investigation, severe bank erosion-prone area, i.e., lower stretch of the Bhagirathi River located in the inter-confluence zone formed by the river Ajay marking the northern limit of the study area and the river Jalangi marking the southern limit where the river Bhagirathi gives a way to the river Hooghly (Fig. 2.5) is particularly focused. Furthermore, to portray the riverbank erosion as a socio-spatial process, a typical study area design is figured out. With the increase of distance from the river bank, the impact of bank erosion becomes gradually feeble. To assess this spatial variability of bank erosion hazard, three tiers around the left bank of the river have been taken into consideration. Tier-1 villages are located adjacent to the river Bhagirathi, i.e., up to 1.5 km from the left bank of the river, tier-2 lies in the middle strip between 1.5–3.0 km and tier-3 is located far away from the bank, i.e., beyond 3 km (Fig. 2.5). It is observed that there are both intra-zonal variation and inter-zonal variation while correlating bank erosion with society. Generally, it can be said that there is a strong correlation between bank erosion and society for the mouzas adjacent to the river Bhagirathi (tier-1), feeble correlation for the farthest villages (tier-3), and moderate for the middle strip (tier-2). Therefore, a socio-spatial symbiosis is clearly depicted. Hence in tier-1 or in the active erosion-prone areas, four representative villages from four C.D. Blocks of Nadia district adjacent to the river Bhagirathi have been selected. These four villages are (1) Matiari of C.D. Block Kaliganj, (2) Akandanga of C.D. Block Nakashipara, (3) Rukunpur of C.D. Block Krishnagar II, and (4) Ganjadanga of C.D. Block Nabadwip. The intensity of erosion for Akandanga is moderate, Ganjadanga is characterized by high erosion and Rukunpur and Matiari are conspicuous by their severity of erosion. In the very high erosion (severe) belt two villages, i.e., Rukunpur and Matiari have been taken to assess whether the severity of erosion is the only cause of the degree of victimization. Rukunpur is basically an agricultural area whereas Matiari once had a dual economy through agriculture and the brass metal industry has now deviated from a land-based economy to a brass metal industry. In tier-2, another one village, i.e., CharKashthasali adjacent to Ganjadanga has been taken. Char-Kashthasali is showing a feeble correlation between bank erosion and social vulnerability because it has a minimum land loss. In tier-3, virtually no village has experienced bank erosion at all. But for the interlinking of the rural economy, some villages in this belt have had an indirect impact on their life and livelihood by the severity of bank erosion for the nearby villages. Sujanpur is a representative village of this kind located near Rukunpur.

The primary data for carrying out the work have been collected from a field survey taking 782 sample households on a random basis from the six selected villages viz. Matiari, Akandanga, Rukunpur, Ganjadanga, Char-Kashthasali, and Sujanpur. For the collection of household data, random sampling has been applied for its inherent virtue of being unbiased because of more or less homogeneity of the population. For determining sample size, first, a pilot survey was conducted to ascertain the target population, i.e., the erosion victims of the villages. The results derived through the pilot survey establish that there are 61%, 69%, 83%, 100%, and 35% land-losing households of the total households in Matiari, Akandanga, Rukunpur, Ganjadanga, and Char-Kashthasali respectively while no land-loss is reported in Sujanpur village. The sample size has been determined according to the formula (Eq. 2.1) propounded by the Department of Economic and Social Affairs (2005):

$$nh = \left(z^2\right)\ (r)\ (1-r)\ (f)\ (k)/(p)\ (n)\ \left(e^2\right)$$

where nh is the sample size to be selected; z is the level of confidence desired (95% here); r is an estimate of a key indicator to be measured by the survey; f is the sample design effect assumed to be 2.0 (default value); k is a multiplier of non-response (1.1 here); p is the proportion of the total population accounted for by the target population and upon which the parameter r is based; n is the average household size (number of persons per household); and e is the margin of error (0.01 here) to be attained.

Using the above formula a statistically significant sample size of 725 erosion victim households (362 households in Matiari, 88 in Akandanga, 152 Rukunpur, 72 in Ganjadanga, and 51 in Char-Kashthasali) while another 57 non-erosion victim households from Sujanpur were chosen for final interview in the study area to ascertain the economic change and livelihood vulnerability as discussed in Chap. 6. However, to unfold bank erosion-induced social hazards, tier-1 villages viz. Matiari, Akandanga, Rukunpur, and Ganjadanga have been taken into consideration. Sample households have been chosen according to two criteria of land loss – (a) households greater than 90% land loss and (b) households greater than 6 bighas land loss. In the study villages, almost all the households are victims of bank erosion but the families who have lost their lion's share of agricultural land are not only economically exhausted but socially and psychologically ruined also. So those families are taken as samples to study the impact of bank erosion on society. Following this method the number of respondents interviewed for social analysis (Chap. 7) from Matiari, Akandanga, Rukunpur, and Ganjadanga is 122, 19, 62, and 20 respectively out of the total erosion victim households of 362, 88, 152, and 78 (Table S2.1) chosen according to Eq. 2.1. Therefore, this book will unearth various perspectives of bank erosion research: (1) bank erosion as a natural process, (2) bank erosion as a human-induced process, (3) dynamics of geomorphic landscapes in relation to riverbank erosion, (4) economic and (5) social impacts of river bank erosion and (6) the management of bank erosion with an indication of (7) future bank erosion scenario. This integrated attempt will establish a discourse on riverbank erosion as a science that will help the academician, researchers, planners, and stakeholders of the Bengal Delta in particular and other areas of the world in general.

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UNIT-5: CHANNEL MODIFICATION: REQUIREMENTS, PROCESSES, AND EFFECTS

Why rivers are engineered Human settlements have long been located along river channels, which provide a supply of water and power, fertile floodplain soils, fisheries and a potential means of navigation. Rivers can also be hazardous and many urban areas are increasingly at risk from flooding as they expand onto floodplains. This risk is further increased by larger flood peaks associated with land use change within the drainage basin – upstream deforestation, land drainage and urban development can all significantly increase flood peaks further downstream. Flood control works involve artificially increasing the channel cross-section, constructing flood embankments, straightening channels and removing vegetation and other obstacles. More recent techniques include theconstruction of flood diversion channels and flood storage reservoirs. Many lowland rivers are maintained for navigation; these include the Rhine, Danube, Mississippi, Missouri, Ohio and Arkansas. The aim is to maintain a minimum depth of water along the navigable length of the river by means of dredging, removal of shoals and other obstacles and river training (see below). Weirs and locks are also used to extend the navigable length, providing a minimum depth for larger vessels at all times, despite natural variations in discharge. Increased industrialisation and urbanisation place growing demands on water supply systems. The world’s largest cities consume water at a rate that is exceeded only by the flow of a few major rivers. Meeting these demands involves constructing dams to store and regulate flow. It is also necessary to integrate supply from a number of different surface and subsurface sources, which can involve transferring water over large distances in river channels, pipelines and canals. On a global scale, the largest demand comes from irrigated agriculture in arid and semi-arid environments. Advances in irrigation technology allowed a huge expansion in the total irrigated area during the Green Revolution of the 1960s. This was also the decade that saw the construction of the greatest number of dams, the scale of which had been increasing since the construction of the Hoover Dam in 1935. By 1986 there were 39,000 large dams over 15 m in height (International Commission on Large Dams (ICOLD), 1988) and today few of the world’s major rivers are unregulated. In the second part of the twentieth century there was a growing trend towards multi-purpose dams, whose roles include water supply, flood control and hydroelectric power generation. Channel modifications are often involved in land reclamation and the drainage of wetlands and low lying areas. Many channels in lowland areas have been deepened and straightened to convey the increased vol ume of water resulting from the installation of field drains. Local modifications are also made to channels where channel instability might cause problems, for example, to prevent bank erosion at the site of bridges and other structures. Channelisation and flow regulation Channelisation is the modification of natural river channels for the purposes of navigation, flood control, land drainage and erosion control (Brookes, 1988). Re-sectioning and realignment Re-sectioning describes the modification of the channel cross-section to provide adequate depth for navigation and to increase the channel capacity for land drainage and flood control. This may involve the removal of a few bars or shoals, or deepening all, or part, of the cross section. Some channels may be enlarged further by widening. Depending on the size of the channel and the purpose of the engineering works, re-sectioning is carriedout using dredging, or by means of river training. Realignment involves the straightening of river channels for purposes of navigation and flood control. It is also carried out where channels share the valley with roads and railways, to reduce the number of bridges that have to be constructed. In navigable rivers with a high natural sinuosity, the removal of meanders greatly reduces the distance that has to be travelled by vessels moving up and downstream. However, the increase in gradient can lead to instability as a result of increased stream power in the straightened section. Increased erosion in this section can lead to problems of deposition further downstream. Dredging Dredging is the removal of sediment from the bed of the channel for flood control and to maintain or deepen existing navigation channels. It is also carried out when sand and gravel are mined from the river bed. Dredging has been carried out for thousands of years and was practiced by the Egyptians, Sumerians, Chinese and Romans, by means of mass labour and manual tools (Petersen, 1986). Over time, developments in dredging technology and mechanisation have enabled these operations to be carried out at increasing scales. In smaller, non-navigable channels, dredging is carried out from the bank using a dragline or bulldozer. Bank-side vegetation is often removed to enable access. In larger channels, the dredger is mounted on a floatingplatform. Mechanical dredgers remove material by lifting it from the bed in a bucket or dipper, whereas hydraulic dredgers use suction pumps to remove mate rial, via a pipeline, to a disposal site. Rotating cutter heads and explosives are used to remove resistant bed sediment and bedrock outcrops. Dredging for channel maintenance has to be carried out on a regular basis, at considerable cost. This is because it treats the problem (sediment accumulation) rather than its causes (sediment sources). Excessive mining of sediment from the river bed can lead to serious problems of erosion, both upstream and downstream from the site (p. 67). Snagging and clearing Flow resistance in the channel is increased by woody debris (fallen trees, logs, branches), large rocks and urban debris. In-channel debris presents additional hazards to navigation and may threaten bridges and other structures. The purpose of snagging and clearing is to remove this material, and these operations are usually part of the routine maintenance carried out every few years on many engineered channels. Trees and bushes at the edge of the channel may also be cleared at the same time. This is because bank-side vegetation can increase resistance to high flows, reducing velocity and potentially increasing the flood risk. Other reasons for removing vegetation are to allow access and to reduce the amount of woody debris entering the channel. As with dredging, snagging has to be carried out on an ongoing basis. Levees and embankments Levees are artificial embankments which are built along side or close to the channel margins of lowland rivers. Their purpose is to increase the channel capacity at high flows and protect the surrounding floodplain from inundation. Levees are found extensively along many major rivers, including the Nile and Mississippi. Traditionally, levees have been constructed of earth, and many still are. In urban areas, where the potential human and economic losses are greater, levees and floodwalls are usually made of concrete. It is not feasible in economic or practical terms to construct levees that would contain all the floods that could possibly occur. Levees are therefore built to withstand a certain design flood, such as the twenty-year event. If this flow is exceeded the levees will be overtopped. The depth of flow contained within the levees is greater than it would be if no levees were present and water was able to inundate the floodplain. Since shear stress increases with flow depth (see Box 6.1), increased erosion of the channel bed is possible. Bank protection Banks are protected using various types of revetments and resistant lining materials. Revetments provide armouring, in the form of loose rocks and boulders, or container systems, such as wire baskets filled with rock (gabions). Banks can also be lined with concrete, asphalt, paving slabs or, where the engineered cross section is rectangular, using vertical sheet steel piling. Plate 10.1 shows a heavily engineered urban channel which has been lined with concrete to prevent erosion. Lining a channel with concrete can lower the resistance to flow, possibly leading to problems of scour further downstream. For larger rivers, banks can be protected by laying down mattresses of concrete slabs connected by tough steel cables. This method has been extensively used along the lower Mississippi river, United States. Spur dykes or groynes can be used to protect banks by deflecting flow away from vulnerable zones. They are built at an angle from the bank and are constructed from various materials, including stone, boulders, earth, gabions or pile. Thousands of stone spur dykes have been constructed along the lower Mississippi (Plate 10.2). Bed protection Armouring is often used to protect the channel bed from erosion. In-channel grade control structures can also be installed. These are of two basic types: sills and weirs. Sills are low, submerged structures, which are built at right angles to the direction of flow. They provide local fixed points that control the channel bed slope and water surface elevation to prevent degradation and headcutting. Weirs act as hydraulic controls, dissipating excess energy and reducing the energy slope(Plate 10.1). Protecting the bed from erosion reduces the available load and may lead to scour further down stream by sediment-hungry water. River training River training techniques have been used since as long ago as the late sixteenth century on the Yellow River in China (Przedwojski et al., 1995). In Europe, aggrading glacially fed braided channels were among the first to be ‘corrected’. One of the earliest and most successful examples was the work carried out on the Alpine Rhine (Switzerland) in the early nineteenth century. Before then, the active braided channel had occupied a width of several kilometres. High rates of channel migration combined with frequent flooding meant that the floodplain could not be fully utilised. There was also a high incidence of waterborne disease, including malaria. The main idea behind the works was to ‘train’ the river to flow in a deeper channel, reducing the incidence of flooding. This was achieved by confining the flow to a straight, single channel, using embankments and groynes to encourage deposition at the channel edges and to stabilise the channel in one position. Flow was concentrated along the centre of the channel, leading todeepening and an increase in channel capacity. This allowed floodwater and sediment to be rapidly trans ported downstream. By 1845, 12.5 million ha of the floodplain marsh had been drained, allowing increased rates of agricultural production

(Downs and Gregory, 2004). Today the area is intensively cultivated. Extensive training works have been carried out on many other rivers, including the Rhone, Danube and Mississippi. Spur dykes were constructed along the lower Mississippi to encourage deposition at the edge of the channel (Plate 10.2). This concentrates erosion of the channel bed, allowing the depth of the shipping channel to be maintained. In order to protect the opposite bank from erosion, it was necessary to install bank protection in the form of extensive concrete mattresses. Bed degra dation is controlled using fixed weirs and sills (see above). Structures can also be installed to alter flow patterns on a more localised scale. Dam construction Dams are constructed for power generation, flood control, and for supplying water to irrigation schemes and urban centres. Today, very few large rivers remain unregulated, and the global volume of water stored in reservoirs now exceeds the volume of flow along rivers (Brierley and Fryirs, 2005). The scale of dams varies, from relatively small structures on tributaries to large dams that exceed 15 m in height. Gregory (1995) esti mates that over 200 large dams are completed each year. However, there has been a decline in the rate of dam building in the industrialised world because many potential dam sites have now been developed. Flow regulation dramatically alters the flow and sediment regimes. Flood peaks are reduced in magnitude and most of the sediment load is trapped in the reservoir behind the dam. Downstream from hydroelectric powerstations there are often rapid fluctuations in discharge. Inter-basin transfers involve the movement of water across drainage divides, with the result that there is a net gain to some river systems and a net loss from others. Emplacement of locks and weirs The Rhine, Mississippi and Arkansas rivers have all been canalised to ensure a minimum depth of water for ship ping and to increase the navigable channel further upstream. Canalisation involves installing dams across the channel to create a series of slackwater pools. Sluice gates, weirs and other control structures regulate the flow of water and vessels pass up and downstream through locks or, occasionally, ship lifts.

ENVIRONMENTAL DEGRADATION

Human activity has led to the environmental degradation of numerous river systems. The fragmentation of river systems by dams, weirs and other structures seriously disrupts the natural functioning of physical and ecological processes. Together with declining water quality, this leads to a dramatic reduction in species diversity. The effects of human activity result in direct and indirect impacts on river systems. Indirect impacts are brought about by changes within the drainage basin that affect the flow and sediment regimes. Examples include deforestation, changing agricultural practices, urbanisation, mining and road construction. Direct impacts result from dam construction and channelisation, where modifications are made to the channel itself. Basin-scale impacts The basin-scale impacts of human activity on fluvial systems have been considered in Chapters 4, 5 and 9, which referred to deforestation, agriculture, mining and urbanisation. Deforestation, associated with agricultural development, has affected river systems for thousands of years. However, there has been an acceleration in the development of land and water resources over the last 100 to 500 years. Across much of Western Europe the intensity of agricultural production increased dramatically after the Second World War. This intensification has included changes from grazing to arable land, the clearance and cultivation of riparian zones and increases in stocking densities. This has often increased the supply of fine sediment to river channels, leading to problems of siltation. Agrochemicals such as pesticides, herbicides and fertilisers have all increased pollution from agricultural runoff. Municipal sewage, industrial effluents and urban runoff also contribute to water pollution. With increasing urbanisation and the move to a more industrialised society, the floodplains of major rivers in Europe and elsewhere are changing from agricultural to urban land use. This affects the flood hydrograph, increasing peak flows and necessitating further flood protection works. At the same time, because a greater proportion of incoming rainfall is rapidly diverted to rivers via drains, gutters and sewers, there is a reduction in groundwater recharge rates. Impacts of dams Changes to the flow regime One of the most profound influences is the alteration of the flow regime by dams and other flow control structures. The life histories of many species have evolved in response to natural flow regimes. As you have seen in previous chapters, flow affects all aspects of the physical habitat, including the shape and size of the channel, the spacing of riffle and pool habitats and nature of the channel substrate. Even at small scales, variations in velocity and shear stress across the channel bed affect the distribution of plants and macro-invertebrates within the channel. For most fish species, the timing of life events such as reproduction and spawning can be linked to the flow regime. The timing of rising flows are important for fish that move out onto the floodplain to spawn. Other triggers include day length and tempera ture. Under an altered flow regime, these may no longer be synchronised with natural variations in flow. The impacts of flow regulation on a given river sys tem are dependent on several factors, including the number and size of dams, the distance downstream from an impoundment and the proportion of the upstream drainage basin area that is regulated. Further downstream, the effects of flow regulation may bereduced to some extent by unregulated tributaries joining the main channel. The type of operation, for example hydroelectric power generation, is also significant. One of the main impacts is the reduction in flood peaks, which play a vital role in the life cycle of many species. Irrigation schemes can even result in a reversal of the flow regime, when seasonal flood flows are impounded and later released to water crops during dry months. Downstream from hydroelectric plants the flow can vary considerably in just a few hours, as electricity is generated to meet daily fluctuations in energy demand. Such releases can have a serious impact on the tempera ture regime. During relatively warm conditions, water released from the base of a dam originates from the cooler depths of the reservoir. This can result in severe thermal shocks to fish and other species downstream from the dam. In July 1976 high mortalities occurred among grayling (a fish species) in the River Ain, a tributary of the Rhône, because of twice-daily releases of cold water from upstream reservoirs (Bravard and Petts, 1996). Seasonally modified temperature regimes also affect life cycle patterns and coldwater releases have been found to delay spawning by up to thirty days in some fish species (Zhong and Power, 1996). In the Western world, inter-basin transfers are becoming more common as most potential dam sites have now been developed. This involves diverting water from one drainage basin to another, via a pipeline or canal, to enhance flow in the receiving drainage basin for water supply or irrigation. Downstream from the abstraction point, a ‘compensation flow’ is released into the channel to meet the needs of downstream users, and to provide sufficient water to dilute sewage and industrial effluents that are discharged into the channel. However, this is usually much less than the natural flow and may not be sufficient to meet environmental needs. In dryland environments, the receiving river can be transformed from an ephemeral to a perennial channel. This is the case with the Great Fish River in South Africa, which has changed from a series of unconnected pools in the dry season to a perennial river as a result of the Orange–Fish inter-basin transfer. Such transfers have major implications for existing plant and animal communities that have evolved to a highly variable flow regime. In fact, non-native ‘exotic’ species may thrive under the new flow regime. Regulation of flows in some Australian rivers is thought to favour nonnative carp and mosquitofish (Bunn and Arthington, 2002). Despite precautions, exotic organisms, including parasites, bacteria and fish, are often unintentionally transferred between basins via connecting pipelines. This is how Orange River fish have made their way into the Great Fish River in South Africa. Reduced connectivity Longitudinal connectivity is greatly disrupted by dams, locks and weirs. In many cases migratory pathways are blocked, even by relatively small structures. Migratory species including shad, lamphrey and eels have disappeared from the Rhône in France (Bunn and Arthington, 2002). Fish ladders are often installed at the site of dams to allow fish to bypass the dam by swimming up through a flight of pools. For various reasons these structures are not always successful, mean ing that reduced numbers of fish are able to make the journey upstream. Lateral connectivity is reduced by the dramatic reduction in the frequency, extent and duration of over bank events. Bravard and Petts (1996) cite the case of the Volga where the duration of floodplain inundation has decreased, from fifty to seventy, to ten to fifteen days a year, since flow regulation began. This has had a major impact on fish populations, since a minimum of forty days is needed for the growth and development of juvenile fish before their descent to the Caspian Sea. A reduction in flood inundation also threatens wetland areas, particularly where land drainage is carried out. The Macquarie Marshes in eastern Australia, a wetland reserve for birds, has been reduced to between 40–50 per cent of its original size by flow diversions and weirs (Kingsford and Thomas, 1995). Lateral connectivity is further reduced by levees and embankments and artificially deepened channels (see below). Vertical transfers are also affected, since recharge of the underlying alluvial aquifer takes place when floodwaters inundate the floodplain. Reduced rates of aquifer recharge lead to a drop in groundwater levels, further contributing to the drying out of wetland areas.

Impacts of channelisation Instability problems Channelisation programmes have significantly modified tens of thousands of kilometres of river channels (Brookes, 1985). These modifications often lead to instability within the engineered reach and in the reaches upstream and downstream from it. Changes to the channel slope, width, depth or roughness all affect channel hydraulics. Feedback mechanisms lead to adjustments as the channel tries to find a new equilibrium. For example, in a channel that has been enlarged for flood control, there will be a reduction in velocity and unit stream power at low flows. This will result in deposition along the reach, meaning that the channel has to be re-dredged on a regular basis to maintain its capacity. Modifications to the channel slope, made by creating artificial cutoffs, gravel mining or dredging, can have the most dramatic effects because of the resultant increase in stream power. Incision often occurs upstream from the artificially steepened reach. Erosion is concentrated at the break in slope between the gentler upstream reach and steeper engineered reach. Upstream incision then takes place as a series of headcuts migrate upstream, although the rate of incision decreases in an upstream direction. In severe cases, banks become unstable, resulting in collapse and channel widening. Bridges and other structures can also be undermined. The additional sediment that is produced causes further problems of aggradation downstream. Major instability problems resulted from the removal of sixteen meander bends along the lower Mississippi between 1929 and 1942. It shortened the channel by 220 km and led to excessive channel erosion, necessitating further intervention. Prior to the installation of bank protection on a massive scale, erosion was removing 900,000 m3 of bank material a year (Bravard and Petts, 1996). Upstream degradation has also led to extensive deposition in the engineered reach, in the form of bars. Geomorphological response times vary, being dependent on the type of work carried out, and the extent to which unit stream power, sediment supply and vegetation cover are affected. In some cases it may take up to 1,000 years for the channel to reach a new equilibrium form (Brierley and Fryirs, 2005). Ecological impacts The abundance and diversity of different species tends to be greatly reduced in engineered channels as a result of limited connectivity and habitat availability (Figure 10.2). Dredging and snagging remove geomorphic structures such as riffles, pools and bars, and disturb the structure of bed sediment. The uniformity of engineered channels provides little variety, affecting the viability of certain species. This is particularly true of concrete-lined channels, which have very little ecological value. During high flows, stream velocities may be higher than some species can withstand. Deepened channels and levees increase channel capacity, greatly concentrating high flows. Opportunities for shelter are reduced within the channel, and levees prevent access to calmer waters on the floodplain. Water temperatures can increase to intolerable levels during low flows. Enlarged channels may not provide a sufficient depth of flow, a problem that is exacerbated by the removal of pools and the shading effects of riparian vegetation. Aesthetic impacts As well as affecting the morphology and behaviour of river channels, channel engineering works often have a negative impact on the appearance and amenity value of the channel. Part of what makes natural rivers pleasing to look at is the amount of variety one can observe, even over a short distance. Variations in depth, velocity, slope and sediment size, associated with forms like riffles and pools, bends, bars, rapids, trees and other vegetation, all combine to create an interesting environment. By contrast, engineered reaches can be very monotonous in appearance, with their straight channels and uniform cross-section, cut off from the adjacent floodplain by embankments and levees. A heavily engineered channel like the one shown in Plate 10.3 resembles little more than an open drain. This particular example is to be found hidden beneath the multiple flyovers of Birmingham’s famous Spaghetti Junction in England. However, many more examples can seen in parks and residential areas. They do little to enhance the urban environment and have no amenity value (Charlton).

UNIT-6: MANAGEMENT OF RIVER DISCHARGE AT FARAKKA BARRAGE AND RELATED ISSUES

Farakka Barrage Project with its headquarter at Farakka in Murshidabad district of West Bengal is a subordinate office under the Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti. The Farakka Barrage Project Authority was set up in 1961 with the mandate to execute and thereafter operate and maintain the Farakka Barrage Project Complex. The project construction commenced in 1961 and the project was commissioned and dedicated to the Nation in May 1975.

The Farakka Barrage Project was designed to serve the need of preservation and maintenance of the Kolkata Port by improving the regime and navigability of the Bhagirathi-Hoogly river system. In addition to this, now the project has been serving other purposes such as water supply to power plants of NTPC Ltd, Farakka (2100MW) and WBPDC Sagardighi (1600MW); provides rail-cum-road communication link between North-Eastern Region and Eastern part of the country; regulation of water to Bangladesh as per Indo-Bangladesh Treaty-1996 on sharing of Ganga Water at Farakka; fresh water supply to Kolkata city and en-route cities, etc.

The Farakka Barrage Project organization has been assigned the work for operation and maintenance of the following principal components of the Project:

1. **Farakka Barrage:** The main barrage has a length of 2,245 m with 109 Gates having 18.30 m span. The design discharge of the barrage is 76,500 cumecs across the mighty Ganga river at Farakka in Murshidabad. Gates numbered 1 to 24 are under sluice gates with a height of 7.93 m and gates numbered 25 to 109 are spillway gates with a height of 6.40 m. And protection works of barrage in the upstream and the downstream of the barrage near to the gates.
2. **Head Regulator**: At the upstream of the barrage on its right bank, the head regulator was constructed with 11 gates of 12.19 m span. The head regulator controls the diversion of 40,000 cusecs of Ganga water into the Feeder Canal.
3. **Feeder Canal**: The length of the Feeder canal is 38.38 km which originates in the upstream of the barrage to carry a discharge of 40,000 cusecs into the river Bhagirathi-Hooghly mainly for the preservation of Kolkata Port. The Bhagirathi Ganga waterway is the National Waterway No.1 for the inland transport facilities from Allahabad to Kolkata operated by IWAI. The Feeder canal has several cross-drainage structures for irrigation, communication, and removal of drainage congestion. It has around 17 jetties for ferry service, 2 road cum rail bridges, 2 road bridges, 3 inlets, 1 syphon and 2 drainage regulators.
4. **Navigational Lock at Farakka**: In order to facilitate the navigation vessel from Ganga to Bhagirathi via Feeder canal, a navigational lock is provided having a width 25.15 m and length 180.7 m along with two giant gates of dimensions 25.15 m x 12.6 m on the upstream and 25.15 m x 10.52 m in the downstream. Floating caisson type emergency gates are provided to carry the repair works and other facilities such as jetties, shelter basin, gauges,

ladders hooks, floating mooring bitts, fixtures, fenders, bollards etc. have also been provided to aid the navigation smoothly. The navigational lock has been now transferred to IWAI in the year 2018 for their operational requirement.

5. **Jangipur Barrage**: It has been constructed across the river Bhagirathi near its off take from the river Ganga. The main function of Jangipur barrage is to regulate the flow of Ganga water into the Bhagirathi and vice versa. It has 15 gates of 12.20 m span. A navigational lock on bypass channel alongside of Jangipur barrage was also constructed.
6. **Guide Bunds and Afflux Bunds**: In order to maintain the safety of the barrages, four guide bunds are provided along both the banks at Farakka and Jangipur. The Left Afflux Bund (LAB) with inspection road is 34 km long along with several regulators across rivers at Pagla, Tutianala, Nimjala, Bhagirathi and Kalindri. The Right Afflux Bund (RAB) is 10 km long. The Left bank protection works on the upstream of the barrage is carried out for the protection of riverbanks and thickly populated villages close to the embankment.
7. **Township**: A large township is maintained by the Farakka Barrage Project which consists of residential and non-residential buildings at Farakka and two other townships at Jangipur and Khejuriaghat.
8. **School & Hospital**: A higher secondary school and hospital with bed capacity of 40 is maintained by the Farakka Barrage Project for the welfare and health care of employees including CISF Personnel working for the scheme.
9. **Ferry Services**: At various locations of Feeder Canal, ferry services are provided for communication of villagers residing on both sides of canal banks.

   Anti-erosion Works: Protection works against bank/bed erosion of river Ganga is being executed along the bank of river Ganga up to 12.5 km upstream and 6.9 km downstream of the Farakka Barrage. Anti-erosion works are also executed along the feeder canal.
10. **Maintenance of Road Bridge**: The renovation and maintenance of PSC Road Bridge includes replacement of damaged portion of super structure and sub structure, bearings, surfacing, road marking, bridge lighting, etc.
11. **Other Hydraulic Structures**: The organization also looks after other appurtenant structures such as Pagla regulator, Bhagirathi regulator, Kalindi regulator, Maha Pagla regulator, Bansloi regulator,Bagmari syphon, etc (FARAKKA BARRAGE PROJECT, FARAKKA, 2024).

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UNIT-7: RIVERS AS A RESOURCE IN WEST BENGAL, THEIR SUSTAINABLE MANAGEMENT

PHYSIOGRAPHIC DIVISIONS

West Bengal is the only state of India that extends from the Himalaya to the Bay of Bengal. A large portion of the state occupies the transitional zones between the Himalayas in the north and the Chhotanagpur plateau in the west to the plains of the Ganga-Brahmaputra delta (GBD) in the southern and eastern sections (Fig. 1). Broadly, West Bengal has nine major physiographic units: (I) the Himalayas, (II) the sub-Himalayan alluvial fans, (III) the Barind uplands, (IV) the degenerated eastern fringes of the Chhotanagpur plateau, (V) the plateaufringe palaeodeltas resembling subdued fans at present, (VI) the primarily non-tidal upper Ganga delta, (VII) the tidal and reclaimed lower Ganga delta, (VIII) the tidally inundated lower Ganga delta occupied by the Sundarban mangroves and (IX) the Medinipur coastal plains primarily contributed by the Subarnarekha river. Each of these regions are represented by different sets of geological characteristics (Fig. 2), hydrology and surface water attributes (Fig. 3), detailed in Table 1. The state's land use pattern (Fig. 4), flood inundation (Fig 5) and water availability (Fig. 6) are also closely related to its physical divisions.

GEOLOGY AND DRAINAGE EVOLUTION

The western extremity of West Bengal evolved as the coastal part of the northeastern Indian craton that broke loose from the Gondwanaland in Early Cretaceous (133 Ma BP) and started to drift northwards (Lawver et al. 1985). East-flowing rivers formed coalescing deltas on the continental shelf—the Bengal basin—that continued to prograde into the sea till the formation of the wider Ganga delta, much later (Niyogi, 1975; Agarwal and Mitra, 1991). At present these rivers are represented by the east-flowing rivers of West Bengal: the Mayurakshi, the Ajay, the Damodar, the Rupnarayan and the Kangsabati-Haldi (Fig. 3). The Damodar is by far the largest among them and occupies a coal-bearing aulacogen that formed as a part of the tri-junctions that separated India from Antarctica. India's hard collision with Tibet in the Middle Eocene (44 Ma BP), initiated the rise of the Himalaya (Curray et al. 1982; Chen et al. 1993). The molasse deposited in a foreland basin at the uplifting mountain's southern edge started to get elevated into the Siwaliks from Middle Miocene (c. 15 Ma BP). However, owing to erosion and subsequent southward thrusting of the lower Himalayas over the erosional gap, the Siwalik ranges formed a re-entrant in West Bengal (Heim and Gansser, 1939) and does not exist east of the Tista valley (Nakata, 1972). Consequently, the mountain streams of northern West Bengal mostly drain the southern flanks of the lower Himalaya instead of the Siwaliks. The Tista and the Amo Chu-Torsa are notable exceptions as they emanate from the edge of the Tibetan plateau and drain through the higher Himalaya. They follow structural anticlines probably formed by unloading and antedate the rise of the Himalaya (Montgomery and Stolar, 2006; Gerrard, 2008). The Himalayan rivers, as they emerged out of the mountain, formed prominent alluvial fans that grade southward into the plains of the Ganga-Brahmaputra Delta (GBD). Thus, both the south-flowing and the east-flowing rivers of West Bengal formed fan systems. The western fan system, known by the name of Rarh plains in its lateritic west, is markedly diminutive in comparison to the active fans of the north that border one of the highest and rainiest mountains of the world. Contemporary to the India–Tibet hard collision, the Bengal basin acquired its eastern boundary in the form of the IndoBurman ranges. The basin has three tectonic provinces (Alam et al. 2003): the shelf region (underlain by continental crust), the deeper basin region (underlain by oceanic crust) and the folded flysch sediments of the arc-trench accretionary prism — the Chittagong–Tripura Fold Belt (CTFB). Of these, the plains of West Bengal occupy mostly the shelf area, the edge of which is demarcated by the shelf-slope boundary known as the 'Hinge Zone' (Fig. 2). All subsequent sedimentation from the east-flowing plateau rivers as well as the Ganga took place on this platform. The Bengal basin is the cradle of the GBD, of which the western 20% is included in West Bengal. The western and northern boundaries of the delta are surrounded by the crystallines of the Chhotanagpur plateau, the Rajmahal hills and the Meghalaya plateau, all of which were parts of the Gondwanaland. Its eastern boundary is delineated by Neogene sedimentaries of the CTFB. Over the land, the GBD is enclosed by highlands on all three sides excluding a short 125-km extent in the north—the Rajmahal-Garo Gap (RGG)—that links the region to the 1,625,000-km2 provenance of the Ganga and the Brahmaputra rivers. The GBD originated with the opening of the RGG in the Pliocene (5.2–1.64 Ma BP; Alam, 1989; Khan, 1991) or Pleistocene (1.64–0.01 Ma BP: Auden, 1949). It acquired its present form during the latest Holocene as the sea level neared its current position following the midHolocene transgression (Goodbred and Kuehl, 2000), by throwing successive accretionary lobes towards the east (Allison et al. 2003; Sarkar et al. 2009). Mostly contributed by the Bhagirathi, its palaeodistributaries and western tributaries from the Chhotanagpur plateau, the West Bengal region is long considered as the oldest part of the GBD (Bagchi, 1944; Niyogi, 1975). The evolution of geology and drainage of West Bengal has largely shaped its groundwater potential (Fig. 2), with the largest yields occurring in the alluvial eastern and mid-northern regions and the lowest yields confined to the western plateaus and northern hills. The plateau-fringes and the Damodar aulacogen represent zones of moderate yield prospect. DRAINAGE AND DISCHARGE CHARACTERISTICS Because of its elongated orientation and transverse alignment to most of the rivers, only six of its 22 drainage basins fall completely within the political boundary of West Bengal. The state is largely a recipient of run-off generated outside. Basins of three major rivers share West Bengal: the Ganga (81% of area), the Brahmaputra (12%), and the Subarnarekha (4%); two small coastal basins constitute the reminder (3%). Following the regime characteristics of monsoon climate, discharge of these rivers show sharp increase between June and September compared to that in the lean season. For example, 89% of the discharge of the Ganga at Farakka is contributed by the monsoons (SCoWR-LSS, 2014). Gauge heights of some of the state's major rivers often increase by more than 10 m and culminate into floods. While all the rivers receive copious amount of water during the monsoons, there is a pattern in the fluctuation of discharge, indicated in the inset stage diagrams of Fig. 3. Based on their origin and the terrains over which they flow, the rivers of the states can conveniently be divided into six major types, as described below Himalaya and Northern Fan Rivers The Himalaya gets the maximum amount of rainfall in the state, up to 6,000 mm per year (Fig. 6A). The rivers originating from the Himalaya and draining the northern fans are mostly shallow and braided. However, some channels, like the Murti and Upper Jaldhaka that traverse over uplifted blocks have confined courses (Guha et al. 2007). The large 8,638 and 3,805 km2 hinterland catchments of the snow-fed Tista and Amo ChuTorsa largely overshadow the water and sediment contribution from other rivers of this region (Starkel et al. 2008). The Tista megafan is roughly bounded by the Mahananda and the Tista itself. The western part of the fan is largely abandoned at present (Chakraborty and Ghosh, 2010) and this partly explains the eastward orientation of some of the rivers of Jalpaiguri district towards the Brahmaputra. With exceptions of the Tista, Jaldhaka and Torsa, most rivers of this region drain small and mid-sized hinterland basins of 4–500 km2 and are extremely responsive to storm rainfall. Here, the rise and fall of discharges are characteristically sharp and get superposed on the gauge height of the major rivers like the Tista (Fig. 3A). Starkel et al. (2008) estimated the mean annual discharge of the Jaldhaka and Torsa to be 230 and 225 cumecs respectively. For the Tista it is estimated at 608 cumecs (ORNL-DAAC, 2010). This, however, can shoot up to as high as 5,000 (Jaldhaka, 4 Aug 2000) and 19,800 (Tista, 2 Oct 1968) cumecs during floods caused by intense storms or glacial lake outburst. Aided by a slope of ~0.1° in the upper fan area, duration of floods generally does not continue here for more than three to four days at a stretch. Most of these rivers are actively aggrading their valleys by 6–19 cm yr–1 during the last three decades due to clustering of extreme events (Starkel and Sarkar, 2002; Prokop and Sarkar, 2012) besides deforestation and mining activities (Starkel et al. 2008). These facts, combined with extension of human habitation into the river corridors culminate into recurrence of floods in this area. The northern 'neck' of West Bengal, represented by the Uttar Dinajpur district falls completely within the Tista megafan but benefits from abandonment of the western fan and is free from floods (Fig 5). In West Bengal, the distal end of the fan terminates at the northern edge of the Ganga plains where the gradient falls close to 0.001° leading to formation of wetlands as the water brought down by the fans encounter the levee system of the Ganga. This region is locally known as the Tal country. At the eastern lower end of the Tista megafan, a small part of the Barind upland occurs within West Bengal. Formed of impervious clays on the surface, the region generates a large amount of storm runoff reflected by fluctuating stream discharge and gauge level (Fig. 3C) not unlike other rivers of the abandoned fans (Fig. 3B). Tangan, Punarbhaba and Atrai are the three misfit rivers that used to carry the discharge of the Tista into the Ganga system up to 1787, when an avulsion towards the Brahmaputra occurred during a flood event (Fergusson, 1863). Western Plateau Rivers The eastern fringe of the Chhotanagpur plateau, represented by Puruliya and parts of Bankura districts, are the only parts in West Bengal apart from the Himalaya that are underlain by hard rocks. Known for its draught-proneness (Fig. 5), the area is mostly drained by the tributaries of the Subarnarekha, Kangsabati-Haldi and Dwarakeshwar. The 333-km2 Ajodhya hills form the only contiguous hilly region in the area apart from the 468-km2 Dalma range and its adjacent highlands towards the south. Flash floods from the typical 6th-order basins of the hills are common during the monsoons. These floods typically affect the structures built across the channels. Western Fan Rivers Eight major streams drain this region. Among these, four rivers emanate from the Chhotanagpur plateau and are now largely regulated by controlled release from reservoirs. For example, the average annual discharge of the mid-sized Damodar, with a catchment area of 22,000 km2 , is 387 cumecs (Rao, 1979). This sharply peaks at 1,038 cumecs in August (ORNL-DAAC, 2010). Induction of the Damodar Valley Corporation dams on tributaries of the Damodar reduced its peak discharge by 67% to 78% (Bhattacharyya, 2011). Rao (1979) estimated that the other major rivers that drain into the Bhagirathi-Hugli — the Mayurakshi-Dwarka, Ajoy, Rupnarayan and Kangsabati-Haldi — contribute a combined mean annual discharge of 558 cumecs. The flood in the lower parts of the western plateau rivers are now mostly caused by monsoon rains in the uncontrolled parts of the catchment (Sen, 1985) that get stagnated at the lower edge of the western palaeodelta complex where the gradient of the rivers become very low and the channels, at places, flow parallel to the levees of the Bhagirathi-Hugli for some distance. Small and regional rivers like the Kaliaghai, with highly fluctuating storm discharges, also contribute to it (Fig. 3H). Upper Ganga Delta Rivers Sourced from a partly snow-bound catchment area of 1,008,500 km2 , the Ganga has an average annual discharge of 11,811 cumecs at Farakka (MoWR-GoI, 2014) and is least susceptible to short term fluctuations (Fig. 3D) that characterise the rivers with small catchment areas, which are highly responsive to storm discharges (Fig. 3B, C, H). Flow of the rivers of the upper Ganga delta are mostly dependent on the contributions from the Ganga. The principal of the Ganga distributaries, the Bhagirathi-Hugli, receives its entire headwater supply from the Farakka barrage project. Since 1975, the project diverts an average discharge of 1,046 cumecs from the Ganga into it through a 38-km feeder canal (SCoWR-LSS, 2014). Consequently, the upper part of the Bhagirathi-Hugli exhibits very little monthly variation in discharge (Fig. 3E). The two rivers that fall into the Bhagirathi-Hugli from its east are the Bhairab-Jalangi and the Mathabhanga-Churni. Neither of these receives any water from the Ganga during the nonmonsoon months, due to sedimentation at off-take points and are maintained mostly by groundwater. Average annual and peak discharge (September) of Churni are estimated at 60 and 156 cumecs respectively and are characteristically not much different from those of the Jalangi (Fig. 3F). In contrast to this, augmented by the Farakka barrage and the tributaries that flow into it, the peak discharge of the Bhagirathi-Hugli varied between 1,736 (1979) and 4,409 (1971) cumecs during 1971– 1985 at Purbasthali, 5 km north of its confluence with the Jalangi (Parua, 2010). The other major river of the upper delta, the Ichhamati, branches off from the Churni and closely follows the IndiaBangladesh border up to the sea. The uppermost reaches of the river remain completely dry during the lean season and receive water only during the monsoons. Its lower stretch, however, is tidally maintained as are all major estuaries and minor creeks of the lower Ganga delta (Fig. 3G). Lower Ganga Delta Rivers The position of the Ganga delta at the apex of the Bay of Bengal led to development of large tidal amplitudes in its coastal part, ranging from 4.32 at the mouth through 6.73 m in the interior areas (Chatterjee et al. 2013). This sets up movement of enormous tidal prisms into its interior areas twice daily, in turn maintaining six large estuaries and an intricate network of creeks and intervening mangrove islands, collectively known as the Sundarban. The peak flood and ebb discharges at the mouth of its westernmost Hugli estuary amount to 260,000 and 109,000 cumecs respectively (McDowell and O'Connor, 1977). Apart from the Hugli, only the easternmost Hariabhanga possesses any sizable link to the upcountry rivers — the Ichhamati and the Kulti Gang that drain the middle part of the upper Ganga delta including Kolkata (Fig. 3). Since the late 18th century, about 56% of the Indian Sundarban is now reclaimed by placing embankments in the island margins and by blocking tidal creeks that irreversibly transformed them into elongated water bodies. Elevations of most of the reclaimed islands remain below the levels of spring tides and storm surges, making them extremely prone to flooding due to breach or overtopping of the embankments. Medinipur Coastal Rivers This coastal region is drained by four main inlets, of which the principal ones are the Pichhabani and the Rasulpur. Tidally active, these rivers mostly carry regional drainage of a 2,432-km2 catchment between the Kangsabati-Haldi and the Subarnarekha.

WETLAND CHARACTERISTICS

Permanent inland water bodies constitute 6% of the total geographical area of West Bengal. However, during the monsoons, their area increases almost to 12%. Among these, 66% are formed naturally and the rest are anthropogenically created (SAC and IESWM, 2010). Broadly, the wetlands of the state may be classified into inland and coastal types. The inland natural wetlands mostly include rivers (9%), palaeochannels and backswamps in all forms and shapes (18%). The large reservoirs (3%), tanks, ponds and aquaculture sites (17%) constitute the anthropogenic components. The Sundarban mangroves (39%) comprise the largest part of the coastal wetlands while the remainder is shared by brackish water fishery and salt pans. The district-wise distribution of wetlands of West Bengal is shown in Fig. 4 (inset). The types of wetlands found in different physiographic zones of the state are described in Table 1.

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UNIT-8: FLOODPLAIN MANAGEMENT: STRATEGIES AND PRINCIPLES

River management should involve resource utilization without deterio ration of the natural basis (Mellquist, 1992), a concept promoted in the Brundtland Report (1987). In practice, river management involves import ant choices (Boon, 1992). First, for rivers that are essentially pristine, there is an overwhelming case for preservation. The challenge is to allow natural changes within fluvial hydrosystems (those caused by floods, droughts, erosion and sedimentation - and variations in the frequency and duration of these processes with changing weather patterns) whilst protecting the river from artificial influences. In most cases, however, the pressures for land and water development, and the resulting problems of waste disposal, will require management to limit artificial changes within the catchment and to mitigate the impacts of human actions. Secondly, at the other extreme are rivers or sectors that have become so severely degraded that in the short and medium terms the only management option is to accept dereliction. This realization is necessary to direct resources not only to high quality rivers and sectors deserving protection but also to those that have a fair chance of being improved by the third option, restoration. For preservation and restoration to be effective, management must address (a) catchment-scale issues, i.e. the flows (quantity and quality) and sediment loads (Chapters 2 and 3), and (b) local (sector-scale) issues concerning channel dynamics, especially lateral erosion and deposition (Chapters 4 and 5). Particular attention must be given to the maintenanceof connectivity (a) between sectors, (b) between the different functional units of the hydrosystem and (c) between surface and subsurface environ ments (Chapter 9) and to the nature of ecological successions (Chapter 10). Management options must also be evaluated in the context of the historical legacy of human impacts throughout the drainage basin (Chapter 11). The cumulative effects of human impacts have been particularly severe in Western Europe (Petts et al., 1989b). In summary: 1. Catchment land-use changes have altered the hydrological and sediment transport regimes, and the form and amount of allogenic organic matter entering water courses; 2. Impoundments created by dams, weirs and locks, have transformed the fundamental instream hydraulics; 3. Water is abstracted for domestic and industrial supplies (often to be returned to the same river as waste water but sometimes transported long distances by inter-basin transfers) and for irrigation agriculture - a truly consumptive use (water being 'lost' by evapotranspiration); 4. Industrial, urban and agricultural pollution has led to the accumulation of contaminants in sediments, plants and animals, with concentrations being increased along food chains; 5. Channels have been engineered for navigation and flood control; 6. The linkage between the channel and its floodplain, with its network of channels and backwaters, has been decoupled by regulation; 7. Important changes of the riparian zone, notably the removal of import ant 'buffer' strips of riparian trees, has resulted from river develop ments for navigation, from land drainage and agricultural expansion; 8. Floodplains have been developed for urban and industrial uses. This historic legacy of land and river development is important not only because it highlights the causes of ecological degradation along rivers but also because it identifies constraints to restoration. In most cases, management cannot restore pristine rivers, rather the objective is to enhance the ecological diversity of the remaining river corridor. The term rehabilitation is used in this situation. In rehabilitation, particular emphasis should be placed on encouraging and expanding relict populations/communities once their habitat requirements are known. Where a population is struggling, but surviving, data gathered on the relicts will be of great assistance in defining the requirements of a rehabilitation programme. In any case, river rehabilitationcan not be achieved passively; the cessation of a particular use and abandonment of the river or floodplain is unlikely to prove successful. 'Management' involves the maintenance of some artificial condition (Mellquist, 1992). The protection or rehabilitation of a river requires active management that not only involves manipulation of the environment andcontrols on the abundance and distribution of animals and plants, but also imposes and administers controls on human actions. This concluding chapter summarizes the values of fluvial hydrosys terns for ecologically sound - or, at least, ecologically sensitive - environ mental management and then examines the applicability of the fluvial hydrosysterns approach for the rehabilitation of large alluvial rivers.

12.2 RATIONALE FOR RIVER REHABILITATION

The rationale for rehabilitating fluvial hydrosysterns relates especially to their values for biological conservation and, in a socioeconomic context, for enhancing the quality of life and increasing the potential for wealth creation. The World Conservation Strategy (IUCN, 1980) embodies the primary objectives: • To maintain essential ecological processes and life-support systems; • To preserve genetic diversity; and • To ensure sustainable utilization of species and ecosystems. The strategy focuses on the long-term benefits of biological conservation to humans, emphasizing that nature conservation does not imply the neglect of issues affecting human welfare. River corridors are particularly important in biological conservation for five reasons: • They have high biological diversity; • They have high biological productivity; • They contain refuge habitats; . • They include refugia from the preindustrial period; and • They are sources for species dispersal. The particular value of river corridors is illustrated by the study of Knopf et al. (1988) who show that although riparian habitat occupies less than 1 % of the western North American landscape, it provides habitat for more species of bird than all other habitats combined. The second dimension to the rationale for river rehabilitation is that river corridors have a range of socioeconomic values related to their commercial and recreational potential (e.g. fishing, hunting, boating) and their high visual quality (petts, 1990). Green and Tunstall (1992) showed that river corridors are particularly attractive for casual recreation, receiving more local visits and drawing visitors from a larger area, than does the average small park. The public are attracted to river corridors that are (a) unpolluted, (b) quiet, rich in flora and fauna, and form attractive landscapes; and (c) have basic facilities such as toilets and paths, reflect ing important public concerns for the safety of children and general public health. Public perception of a healthy environment is important.

For example, the return of salmon (Salmo salar) to the River Taff in Wales is considered to have considerable importance, regardless of any fishery value, because salmon are symbols of clean water (Mawle, 1991). Follow ing a long history of severe degradation caused by gross pollution, a breeding salmon population in the Taff would be a clear demonstration of improved quality.

12.3 THE SCIENTIFIC BASIS

The scientific basis of river rehabilitation is centred on the need to develop models to predict the ecological impacts of human activities, including rehabilitation measures! This requires integration of knowledge from three areas of study and from three levels of investigation. Studies of hydrology, geomorphology and ecology must be fully integrated to develop applicable models of ecosystem, habitat, community and species responses. Information is required on structural relationships and dynamic interactions at three levels of scientific analysis: 1. Functional studies which seek to explain the spatial distribution of, and interdependence between, species, communities and habitat patches; 2. Historical; and 3. Palaeoenvironmental studies which seek to understand the ways that species, communities and habitats change in response to human impacts and climate change, respectively; and to establish the former 'natural' characteristics of fluvial hydrosystems. The first level of analysis is concerned with understanding short-term process dynamics (e.g. carbon spiralling, trophic interactions, chemical exchanges between water and sediment, etc.) and with describing spatial relationships between individuals, species, communities and habitat pat ches. Functional studies are important for determining the 'technological' basis for restoration, that is providing the scientific knowledge necessary to define management processes: • Selection of species, communities and/or habitat characteristics as targets for management; • Introduction (e.g. fish stocking, reintroduction of otter (Lutralutra), introducing gravel to create bars, etc.); • Elimination (e.g. culling to control population numbers, controls on invasive plants, etc.); • Control of key fluxes (e.g. water levels, nutrient supply, primary pro duction, siltation, etc); and • Controlled disturbance (e.g. river-bank or woodland clearance to rejuvenate succession, artificial 'floods' to scour channels or inundate riparian wetlands).

The second and third levels define the context within which rehabilitation programmes must be set. The most productive approach to reconstruct ing the sequence of changes experienced by fluvial hydrosystems over historic and palaeoenvironmental time-scales is inductive (Thomes, 1987), in which the direction of investigation is the reverse of the direction of causation (Figure 12.1). The use of a deductive method is prohibited by the complexity of physical, chemical and biological dynamics and their interactions. Information on the physical and biological characteristics of rivers in the past can be derived for a number of specific time periods from maps, plans, photographs and documents, and from landforms and strati graphie units dated by tree-ring analysis, archaeological evidence etc, Studies of sediment cores from cut-off channels, including granulometry, geochemistry, pollen, diatoms, and invertebrates, can be especially useful. With the inductive method, field observations, evidence of former bio logical populations (Levell), fluvial sediments and landforms (Level 2) are used to make inferences about the process dynamics of the environment (Level 3). Historical studies benefit in most cases from more or less detailed documentary evidence concerning the precise nature andtiming of anthropogenic changes (Level 4). Application of the inductive method to analyse historical changes along large alluvial rivers is developed by Petts et al. (1989b), and exemplified for the Rhone by Amoros et al. (1987b) and for the Trent by Petts et al. (1992).

12.3.1 THE FLUVIAL HYDROSYSTEM APPROACH

A fluvial hydrosystem perspective provides a practical approach for ecologically sensitive river management by classifying rivers as a sequence of sectors of variable length from less than 1 km to 50 km or more. Each sector is defined by four sets of criteria, each including artificial influences: 1. Inputs derived from the catchment and routed through the channel network upstream. The fluvial hydrosystem is seen as a component of the drainage basin within which the primary controls are climate, geology, relief, and vegetation (land use); 2. Internal structural controls within the sector including slope and degree of lateral confinement (by valley sides, river terraces, woodland and channel engineering structures), etc.; 3. Internal process dynamics within the sector such as influent or effluent flow conditions, nutrient spiralling dimensions, and morphological dynamics (aggradation and incision), etc.; and 4 Downstream structural controls which effectively control baselevel for the adjacent sector upstream, including bedrock controls, channel behaviour (aggradation and incision) and artificial controls such as weirs and bridges. Each sector comprises a characteristic range of physical habitats. These are the the fundamental units (Chapters 1 and 5) and their different successional stages (Chapter 10); in ecological terms they determine the biotope and biocoenosis of each elementary river landform. Figure 12.2 summarizes the biological features of three functional sectors having different physical characteristics. The figure emphasizes the importance of (a) lateral and vertical connectivity (Chapters 7, 8 and 9) and (b) channel erosion and deposition, which rejuvenates successions and sus tains a range of successional stages as well as a diverse range of habitat patches (e.g. gravel bars, sandy levees, backswamps and ponds; Chapter 5). Greatest diversity and productivity occur in hydrosystems character ized by a moderate degree of channel instability. In highly mobile braided channels, ecological successions are truncated and production limited by the morphological instability and high frequency of disturbance.

12.3.2 PRINCIPLES FOR ECOLOGICALLY SENSfI1VE RIVER MANAGEMENT

The applicability of this fluvial hydrosystem perspective in river manage ment is justified by three important principles. The first principle is that each sector must be viewed in the context of its catchment. The flow regime, the water quality and the sediment loads within a sector are dependent on catchment conditions upstream. Whereas sector-scale management actions can yield important and immediate benefits, in the longer term, successful rehabilitation requires catchment management and planning. The second principle is that rivers must be viewed as systems in dynamic equilibrium. Within each sector a quasi-equilibrium condition may be defined involving hydrological, geomorphological and ecological inter actions. Each sector can be described by a more or less complex arrangement of aquatic, semiaquatic and terrestrial patches. The patches will be of different type (defined primarily by morphological, sedimentological, and vegetational criteria) and different age (reflected by successional criteria for each type). The arrangement of patches within the sector changes over time in response to successional processes and disturbance (by erosion and deposition). Thus, the optimal areas for particular fauna shift to different parts of a sector in response to the build-up of sediments (Bayley, 1991). Over a time-scale of 10-100 years the spatial arrangement of patches may change, but the composition of patches within each sector will remain relatively stable, about an average condition. The third principle is that lateral exchanges play an important role in sustain ing the functioning of river sectors. The role of the ecotone concept (Chapter 9) in river management is to focus attention on the transitional zone, or dynamic boundary, at the land-water interface. Traditionally, manage ment has focused on patches. Conservation has been concerned primarily with the preservation of species within patches by defining more or less artificial boundaries around them. River margins are determined primarily by hydrological variations and geomorphological disturbance, and are highly sensitive to external controls. The ecotone concept empha sizes (a) the importance of river margins for sustaining the functional characteristics of the fluvial hydrosystem and (b) the role of hydrological and geomorphological dynamics in sustaining the structural and functional characteristics of the river margins. 12.4 OPTIONS FOR MANAGING FLUVIAL HYDROSYSTEMS Management must be based on the best available science (Calow and Petts, 1992, 1994). Despite the long history of scientific endeavour models of fluvial hydrosystems remain imprecise and a precautionary approach must be used when applying apparently 'scientifically sound' tools and approaches. Whilst acknowledging the limitations of our knowledge, enough scientific information is available to begin to address most of the immediate problems. The fluvial hydrosystem approach provides a framework to structure the consideration of the management options. At one end of the spectrum, management to protect a pristine river from development may require non-use of a natural resource - implicitly accepting that non-use is an acceptable form of use. In some cases, the protection of a river from hydropower development, for example, may be seen as a trade-off, the preservation of one being acceptable because of the intensive development of another (e.g.Ledec and Goodland, 1988). At the other end of the spectrum, river management is required to limit or mitigate the impacts of water division for power generation, domestic supply or irrigation, the complete alteration of a river's hydrological and water-quality regimes by large-scale impoundments, or the controlleddischarge of waste waters. On a smaller scale, management must con sider options for minimizing the adverse ecological effects of removing channel bed sediment to improve navigation, weed cutting for flood control, 'protecting' a river bank to prevent erosion, embanking to pre vent floodplain inundation, or removing riparian vegetation to improve access. There are five general groups of options for river rehabilitation: 1. Water quality improvements involving point and non-point pollution controls; 2. Manipulating river flows; 3. Structural modifications to improve instream, riparian and floodplain habitats; 4. Biological controls, such as vegetation planting or control of invasive weeds, and fish stocking or selective fishing; and 5. Controls on human access and activities. In general terms, the first two require catchment management and the last three relate to management plans at the sector scale. In any case, management plans must seek to achieve the best practicable solution to a problem by considering all reasonable combinations of options. 12.4.1 WATER QUALI1Y That at least a tolerable water quality exists, or can be achieved and sustained is a prerequisite for the success of any rehabilitation pro gramme (Dobbs and Zabel, 1994). Proposed water-quality standards for fisheries in England and Wales are given in Table 12.1. Considerable lengths of river throughout Europe remain unsuitable for physical andbiological rehabilitation because of inadequate water quality. For example, in England and Wales in 1990, fish were absent or occurred only sporadically along nearly 4500 km of main river, representing about 12.5% of the total length of main river. Since the mid 1960s advances in water-treatment technology, higher standards and better monitoring (Parr, 1994) have decreased the input of labile organics from sewage works and improved industrial effluent discharges. On the River Trent in Nottingham, for example, between 1964 and 1984, biological oxygen demand fell from 15 mg 1-1 to less than 4 mg 1-1 (Brewin and Martin, 1988). Despite improvements in the quality of point-source discharges, on most rivers current problems relate to non-point sources and to the high frequency of pollution incidents. Further progress in water-treatment technology and stronger legislation are required if the full potential of river rehabilitation is to be realized. 12.4.2 DISCHARGE The influence of hydrology involves both water-level (frequency and duration of inundation or dewatering) and water volume (frequency of floods and duration of 'normal', and extreme, low flows). The allocation of water resources to maintain an 'ecolOgically acceptable' flow regime (e.g. Figure 12.3) is vital for river rehabilitation but also a source of major conflict, not only between water users but also between the different objectives for rehabilitation (Stalnaker, 1994; Petts and Maddock, 1994). (a) Minimum flows The maintenance of minimum flows has become a major problem because of abstractions, interbasin transfers and water-storage projects. Along rivers affected by artificially low flows, the implementation of control rules to maintain flows has demonstrated ecological value. Weisberg et al. (1990) for example, demonstrated the value of maintaining summer minimum flows reducing the dewatered area of channel bed, increasing flow velocities and diversifying instream hydraulic conditions for benthic invertebrates. A physical habitat stimulation model (PHABSIM) has been developed to provide a hydraulic framework for describing lotic ecosystems in a way that can be used to predict the effects of water resources develop ment on the habitat of aquatic biota (Stalnaker, 1994). PHABSIM uses relationships between a species of interest and a range of variables describing instream habitat (e.g. velocity). It is assumed that each species exhibits discrete and quantifiable preferences which can be described as habitat suitability curves. The model simulates the area of suitable habitat within a representative or critical reach, providing a single compositevalue of habitat for a reach composed of a number of cells, or microhabi tats, of different depths, velocities and channel character (substrate and cover). Examples of the applicahon of PHABSIM in the UK are given by Petts and Maddock (1994) and Petts et al. (1995). (b) High flows In rivers regulated by dams, an important option exists for rehabilitation, that is the programmed release of a predetermined discharge, for a given duration. Such releases can be used to maintain a desired channel condition and to sustain riparian and floodplain environments. Channel maintenance flows (Reiser et al., 1989) serve the function of natural high flows: maintain channel geometry, flush fine sediments and control vegetation growth. One method of determining the characteristics of channel maintenance flows is to utilize historic streamflow records to develop statistical relationships between a hydrological parameter, such as flow frequency or duration, and the observed flow at which adequate flushing is achieved. Three examples are the 1.5 year flood (often taken to approximate the 'bankfull discharge'), the 5th percentile flow duration, and 200% of the average annual flow). Attention must also be given to the timing of flows in relation to the life-history requirements of aquatic biota (Chapters 7, 8 and 9).

Overbank flows that inundate and disturb riparian and floodplain areas are required to maintain the range of habitat patches that comprise the river corridor (Chapters 5, 9 and 10). The maintenance and control of water level is particularly important to conserve and rehabilitate flood plain wetlands and woodlands (e.g. Bren, 1988; Dister et al., 1990). Model ling approaches to measure riparian response to altered flow regimes have been initiated by Stromberg and Patten (1990). Water level manipulation may be achieved by using gated or ungated weirs, but these alter the instream flow conditions. Where weirs are in place, and are required to maintain the river for navigation or hydro power production, water-level regulation may provide an important tool for maintaining or enhancing fish and wildlife resources. Such an approach is being developed, for example, for navigation pools and associated floodplains of the Upper Mississippi System (Lubinski et al., 1991). The advantage of this approach is to allow a high level of manage ment at the sector scale.

12.4.3 HABITAT CONTROLS

A variety of habitats is one of the most important conditions for the existence of well-balanced aquatic communities. Habitat simplification, resulting from river regulation, diminishes the number and diversity of species. Rehabilitation involves the diversification of habitat whilst sustaining other user needs (e.g. erosion control: Jaeggi, 1989; Hey, 1994). A range of design alternatives has been employed (e.g. Brookes, 1989; Swales, 1989; Kern, 1992; Larsen, 1994) including tree planting, instream devices to provide cover, artificial riffles, different channel geometries and realignment to create meanders. Functional research is continuing to elaborate the importance of physical habitats for biota. For example, in conflict with traditional river management practices which seek to remove fallen trees and coarse organic debris from streams and rivers, recent research has demonstrated the biological importance of coarse woody debris in streams and along river margins (Gregory and Davis, 1992; Gurnell et al., 1995). This illustrates the applicability of continuing functional research to river management, in this case emphasizing the ecological value of rehabilitating a river's natural budget of coarse organic debris. A case study of strategies for conserving the fish fauna of the Danube (Schiemer and Waidbacher, 1992) illustrates the practical approaches that may be applied to river management. They identify the first priority as the maintenance and improvement of the remaining free-flowing sectors of the river by: • Increasing the morphological diversity of the river bed near the banks;Increasing the area inundated at low flood levels; and • Re-activating the links between the river and floodplain backwaters by opening upstream connections at mean water level. Although there are few post-rehabilitation appraisals at this time, many studies have demonstrated the link between physical habitat diversity and biotic diversity. In one recent post-project appraisal, the ecological benefits of instream habitat diversification have been given support. Jungwirth et al. (1992) demonstrated the correlation between variance of maximum depths, as a measure of habitat structure, with the number and diversity of fish species. On the fifth-order River Melk, Austria, enhanced habitat diversity by creating shallow water lagoons, marginal gravel bars and riffles resulted in an increase in the number of fish species from 10 to 19, a threefold increase of fish density and biomass, an increase in the annual production of 0+ fish, and an increase in the number of benthic invertebrate taxa from 202 to 272. The newly created riparian habitat provided important refuge habitats during floods, places for hatching and emerging, and nursery grounds for younger benthic instars and fish fry. 12.4.4 BIOLOGICAL CONTROLS The control of animal and plant populations is often necessary to achieve rehabilitation objectives, both to sustain populations of some species and also to prevent overpopulation of other species particularly favoured by a management regime. Vegetation control is a common practice (e.g. Wade, 1994). Management of unwanted plants includes mechanical, chemical and other controls, different river conditions dictating the type of vegetation control to be applied. Planting is also practised, especially to protect river banks from erosion by boat wash, for example, along the River Thames (Hemphill and Bramley, 1989). Without sustained manage ment, forest expansion from fragmented woods into formerly cultivated land, for example, is typically dominated by monopolistic species and an impoverished flora (Pautou and Decainps, 1985). Fish culture is an ancient pursuit and fish stocking remains a wide spread practice (Dodge and Mack, 1994). In reviewing the main conservation options for managing freshwater fish resources in Britain, including the conservation of threatened species, Maitland and Lyle (1992) identified stock transfer, together with improved legislation to prevent the introduction of potential harmful species, as particularly useful. One task of river rehabilitation is to introduce or enhance species which may quickly become adapted to that particular system. The trans fer of adult salmon from overstocked areas to underutilized parts of the same system has also been advocated with the advantage that theprogeny will be of 'wild quality' compared with the juveniles produced from hatcheries and released into streams. The stocked race will not be directly analogous to the original race, but it will be a race that adapts well to the contemporary river conditions. It is vital that stock type should be matched as closely as possible, both physically and biologically, to the 'new' river (Thorpe, 1988). 12.4.5 CONIROLS ON HUMAN ACTIVTI1ES Overfishing can be a major problem in some river fisheries, but controls on catches, access (especially seasonal restrictions and controls on the numbers of fishers), and fishing methods have been found successful (Petts et al., 1989b). Similarly, controls on riparian land uses (such as grazing and access for recreation) may need to be controlled to restore riparian vegetation successfully (Risser and Harris, 1989). Grazing retire ment can have particular benefits for remnant areas of native vegetation and Armour et al. (1991) highlight the value of grazing controls in riparian areas for fish habitat. On the floodplain of the River Seine, grazing of the marshes and wet grasslands by animals adapted to this type of environment, such as Highland Cattle and Carmargue horses, has stabilized the ecological succession and prevented the development of shrubs and trees, thereby sustaining the diversity of wetland patches (Lecomte and Neveu, 1986).

12.5 CATCHMENT MANAGEMENT

Some of the major impacts causing ecological changes within a sector of a river relate to catchment land use practices, influencing runoff and water quality, and river management (e.g. dams, removal of coarse woody debris) in remote sectors upstream or downstream. For example, for restoring migratory fish stocks, catchment management is necessary because sector-scale management, even if target habitats - such as spawn ing areas - are defined and given special protection, would be inade quate. The obvious example is Atlantic Salmon (Salmo salar) which has quite specific environmental requirements (Table 12.2). Inadequate dis charges or water quality at any point along a river may severly constrain opportunities for rehabilitation as would the impedence to free passage caused by weirs, dams and impoundments.

Buffer zones

Buffer zones along channels in headwater catchments can play an import ant role in reducing the pollution of watercourses. Riparian buffer zones act as a filter for particulates and storage for solutes between the hillslope and the river channel (Large and Petts, 1994). The primary retention processes involved are: • Interception of sediment-bound nutrients, especially phosphorus, and other contaminants, such as pesticides, transported by surface runoff; • Uptake by vegetation or microbes of soluble nutrients (particularly nitrate); and • Association of solutes with organic and inorganic soil particles. In temperate zones, organic riparian soils can significantly reduce the concentration of nutrients in groundwater, as long as the root zone is not bypassed by deep groundwater flow or pipe drainage.

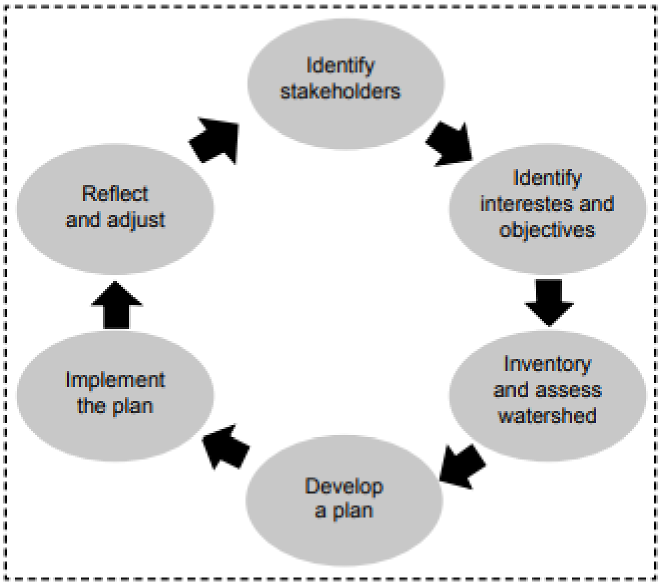
12.5.2 CONSERVATION CORRIOORS

The importance of river corridors for nature conservation is well established (Naiman and Decamps, 1990; Boon et al.,1992). Corridors not only provide ecotonal habitats between the terrestrial and aquatic ecosystems, they also provide a network of routeways through a drainage basin. A restored river corridor should: • Provide sufficient space for species; • Be sufficient to protect habitat quality and wildlife from adverse impacts of adjacent land uses; andHave adequate connectivity to allow freedom of movement through out the available stream network. Most mammal, reptile and amphibian species have been shown to con centrate within 60 m of a river bank (Brinson et al., 1981). Van der Hoek (1987) recommended a 150 m-wide buffer zone to improve groundwater quality, improve floristic diversity and to protect vulnerable and rare plant species but even 5-15 m riparian strips can provide valuable habitat for fauna (e.g. Budd et al., 1987). Floodplain management need not create simple corridors. A bead-like form can have considerable value, with large areas linked by narrow connections (Large and Petts, 1994). Brinson et al. (1981), for example, suggest that 5-6 ha habitat 'islands' can support near-maximum bird diversity. However, where there are important allu vial aquifers and groundwater flow has a major influence on the habitat patch mosaic, a larger buffer zone may be required. 12.6 CONCLUSION Scientifically based approaches and tools are needed to limit impacts of river and catchment development; to mitigate the effects of river regulation, abstraction or waste disposal where such actions are accepted as necessary for socioeconomic development; and to rehabilitate degraded rivers by stimulating and enhancing natural recovery processes. How ever, in reality the attainment of these aims is constrained by the goals of socioeconomic development. It is necessary therefore to make a pragmatic choice of the best practicable environmental option (Royal Com mission, 1976, 1989; Petts, 1990a). Importantly, such an approach recognizes the time-limited nature of decisions, flexibility in management being important so that the 'best' option can be revised once new knowl edge is available. The analysis of fluvial hydrosystems provides an approach with space and time-scales appropriate for management, which emphasizes the important relationships between hydrology, geomorphology and ecology. It presents a framework for applying scientific knowledge to the ecologically sound development of water and land resources within river corridors. The management of river sectors provides a pragmatic approach to river rehabilitation. The application of the fluvial hydrosystem approach to the integrated management of all river sectors throughout a drainage network offers the potential for developing catchment management with clear benefits, not only for nature conservation, but also for all river users (G. E. Petts and C. Amoros).

UNIT-9: WATERSHED MANAGEMENT: NEED AND SIGNIFICANCE

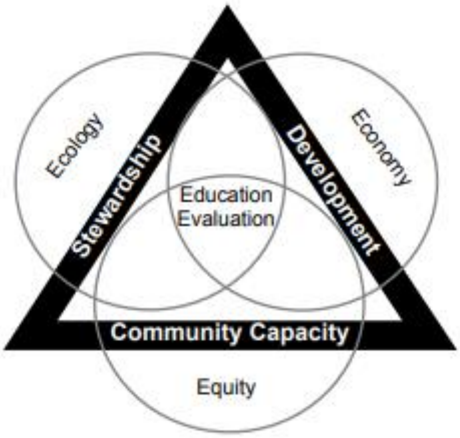
Increasing land degradation in the world with degradation moving at a quicker speed in the developing countries has become a serious problem threatening soil and water resources (Bartarya 1991, Sidle 2000, Sadeghi et al. 2004). During the last few decades, natural resources worldwide have faced some serious degradation problems such as soil erosion, sedimentation, wind erosion, water scarcity and pollution, groundwater overexploitation, land use changes, overgrazing in the rangelands, soil salinity, forest fire, flooding and wetlands loss (Bartarya 1991, Sidle 2000). Finding scientifically appropriate, practically feasible, environmentally friendly, technically sound, economically efficient, developmentally sustainable and socially acceptable solutions are therefore vital for the successful and persistent management of diminishing resources. "A watershed is a complex and dynamic bio-physical system which is identified as planning and management unit. Hence, considering all technical, socio-economical, physical, ecological and organizational dimensions is essential for proper planning and management processes. Due to complex interactions among different aspects of the watershed, application of an integrated management approach is inevitable to coordinate study aspects" (California Department of Conservation 2015). A watershed is also a hydrological and biophysical response unit, and a holistic ecosystem in terms of the materials, energy, and information present. The watershed not only is a useful unit for physical analyses, it can also be a suitable socioeconomic-political unit for management planning and implementation. In essence, a watershed is a basic organizing unit to manage resources. Watershed management is faced with complex problems that are characterized by uncertainty and change. Watershed management is an ever-evolving practice involving the management of land, water, biota, and other resources in a defined area for ecological, social, and economic purposes (Wang et al. 2016). It studies the relevant characteristics of a watershed aimed at the sustainable distribution of its resources and the process of creating and implementing plans, programs, and projects to sustain and enhance watershed functions affecting the plant, animal, and human communities within the watershed boundary (California Department of Conservation 2015). In 2015, some 17 Sustainable Development Goals (www.un.org) were designated to be achieved as the 2030 Agenda for Sustainable Development none of which can be adopted without an integrated and adaptive watershed management. This can be planned in different zones of the watersheds namely headwaters (upstream), transfer zone (midstream) and depositional zone (downstream) as an occurrence that changes the pattern of all that follows, moving the flow of events toward a different outcome and simply called the "watershed event" (California Department of Conservation 2015). This is in the same vein as the United Nations; which has committed to focus on water for a decade (2018–2028) to advance sustainable development of water (www. un.org). Integrated and systematic management of the watershed is one of the vital approaches to develop sustainably (Sadoddin et al. 2016, Raum 2018). It leads to the effective utilization of natural resources, alleviates poverty, improves sustainable livelihoods, and increases collaboration among the various stakeholders particularly in undeveloped countries. To sustainably utilize available resources and meet the fulfillment of human needs as well as restore the ecosystem balance to mitigate poverty, conserve the Earth and ascertain prosperity for all as part of a new sustainable development agenda in 21st century, new breath of air has to be blown into existing programs and projects at the watershed scale. Otherwise, all accessible and even available resources will have thoroughly perished resulting in an irreversible situation, including tragic famine and cannibalism at the end. This problem is far more serious in developing countries where higher demands exist on one side and low technology and technical knowledge are available (World Bank 2008) on the other side. To address these issues, some important and developing strategies have been discussed for the integrated management of the watershed through incorporating various techniques and using indigenous knowledge.

In summary, integrated watershed management is the process of creating and implementing plans, programs, and projects to sustain and enhance watershed functions that provide the goods, services, and values desired by the community affected by the conditions within a watershed boundary. The management is integrated and complex, including components inside (e.g., upstream, midstream, downstream) and outside the watershed, affecting both man-made and natural factors. There is a general belief that the future watershed management will need to account for the management of limited resources for ever-increasing demand and greed of the humans by employing technological advancements and holistic, cross-disciplinary approaches (Wang et al. 2016). It certainly ensures for watersheds continue to efficiently and successfully perform essential ecosystem services and serve their ecological and socio-economic services. Optimizing Land Use Utilization Considering conflicts upon very limited resources among different sectors with an ever-increasing demand at the watershed scale is necessary in the 21st century for satisfying the inhabitant's demand (Pastori et al. 2017, Tajbakhsh et al. 2018, Wu 2018). Otherwise, more transient benefits reach a particular sector resulting in the diminishing of other particles of the ecosystem and ultimately making it vulnerable to introducing driving forces. It virtually leads to degradation of the watershed and the consequent lower productivity, and further subsequent overexploitation of the resources to compensate insufficient production. Optimization as an act, process, or methodology of the decision making process as fully, perfect, functional and efficient as possible is therefore needed for effectively managing the valuable watershed assets and improving the ecosystem services (Guo et al. 2016, Li and Ma 2017). Despite the plethora of literature existing on the optimization field of different resources management (Sadeghi et al. 2009, Liu et al. 2015, Ma and Zhao 2015, Pastori et al. 2015, Tajbakhsh et al. 2018, Wu 2018), frequent application of this applied mathematical approach in the management of the watershed as a necessary approach for resources management in the developing world is still lacking. However, the application of linear programming as a basic method for many other optimization programs has been reported for the optimization of watershed management using associated software. A specific study on the optimization of land use allocation to orchard, range, irrigated and dry farming land uses has been reported by Sadeghi et al. (2009) using linear programming to minimize soil erosion and to maximize the economic return within the Birmvand Watershed in Kermanshah Province, Iran. Solving the multi-objectives linear optimization problem developed for the study watershed; revealed that the amount of soil erosion and benefit could respectively reduce and increase by 7.9% and 18.6%, in the case of implementing optimal allocation of the land use in the study. It is therefore an approach that can be applicable for the resources management of the watershed (Kaim et al. 2018). Monitoring based Watershed Management Understanding hydrologic behaviors and assessing the influence of land use and land cover change in the hydrologic response of different watersheds is important for watershed researchers and management in the 21st century (Paule-Mercado et al. 2018). Assessment of watershed behavior is intended to provide a better understanding and awareness of hydrologic behaviors of the watershed system. So that monitoring the health of watersheds is a critical precursor to the adaptive resources management on a watershed basis (Hazbavi et al. 2018a and b). Hence, continuous monitoring of the watersheds behavior in response to various anthropogenic and natural driving triggers helps adopt an integrated and adaptive management strategy in different scales (Hazbavi and Sadeghi 2017, Hazbavi et al. 2018a and b). Monitoring of the watershed health is hence considered to be one of the main stages of adaptive management and the main components of the watershed management plan as shown in Fig. 1. Developing better methods for analyzing and assessing cumulative watershed effects is considered to be the other challenges in the 21st century (Sidle 2000). That is why; ascription of anthropogenic and natural effects on watershed degradation is also needed.



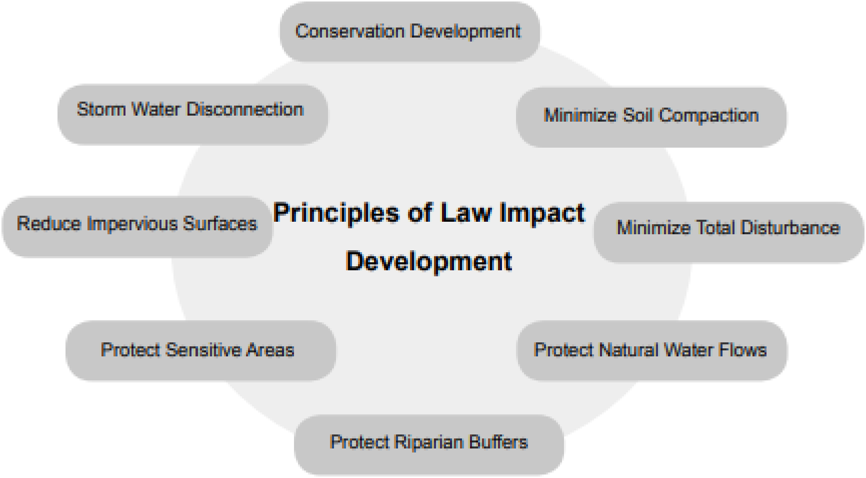
Components of watershed adaptive management plan (After www.conservation.ca.gov).

Concepts and definition Despite existence of the concept of watershed management for millennia (Wang et al. 2016), the management of watershed resources has not been successfully achieved. Such that almost half of the countries in the world have low to very low access to fresh water; owing in part to population growth resulting in increasing constraints on the land, water, and other natural resources availability. Therefore, the scarcity of fresh water supply, contamination of agricultural land, and polluted streams are affecting millions of lives (Wang et al. 2016). It clearly verifies the necessity of a new definition for watershed management to comprehensively and suitably satisfy man's ever-increasing demands, and appropriately and sustainably conserve the environment. Such a definition will certainly be fulfilled using a system's approach to sustainable development as proposed by Flint in 2015 (www.eeeee.net/watershed.htm). Therefore there should be a heartfelt belief that the current policies affecting civilization today and the Earth for generations yet to come. There should be another belief that we cannot independently alter or modify one element of a natural system without expecting changes elsewhere. We therefore need to think like a watershed because acting sustainably requires concurrent multi-dimensional thinking in such way to cover both the temporal and spatial for various sectors concerning the economy, society and environment. Accordingly an adaptive watershed management is a decision-making process which effectively integrates both short and long-term economic, environmental and social concerns (Flint 2006). Adaptive watershed management is cored on Five E's including Ecology, Economy, Equity, Education and Evaluation as shown in Fig. 2; leading and encouraging the development of interdisciplinary



Five E' Unlimited in watershed management (After www.eeeee.net/watershed.htm)

adaptive, and integrally-informed understanding of social-ecological systems at the watershed level. The knowledge is then transferred to various stakeholders to facilitate collaboration among the different stakeholders and stewards. Adaptive management can be amalgamated with integrated and comprehensive management helping to cope with the uncertainties dealing with the management of complicated and dynamic systems of the watershed. Basically, adaptive management gives several suggestions for handling of the governing complexity on the watershed system. It is achieved by learning from the watershed outcomes while doing and working with the system. It ultimately leads to a proper adoption of managerial approaches and adjustment of future strategies accordingly. In order to get access to a successful adaptive management, an insight goal based monitoring and consequent evaluations are needed. Forthcoming strategies for the adaptive management of the watershed need to be persistently improved by learning from the pre-implemented policies. Self-evaluation to identify mistakes, flexibility in decisions, appropriate regulations to rectify mistakes, time dedication and financial investments in reducing the biases from the main goals are therefore a necessary need for the adaptive watershed management (Allan et al. 2008, Raadgever et al. 2008, Porzecanski et al. 2012). Low impact development Low impact development practices as a cost effective practice of land development approach strives to mimic the pre-development conditions of a watershed (Ahiablame and Shakya 2016, Xu et al. 2018) and can be used to mitigate risks in watersheds, adaptively. The low impact development strategy has attracted growing attention as an important, efficient and more reliable method for the management of urban watersheds with a focus on flood mitigation (Ahiablame and Shakya 2016, Hu et al. 2017, Xu et al. 2018). The findings verified effective roles of low impact development practices for flood inundation mitigation at the watershed scale. Basically, the low impact development approach for storm water control is shaped based on the eight main elements represented in Fig. 3. Water-Energy-Food nexus To adaptively manage the watersheds, other new approaches such as the Water-Energy-Food (WEF) nexus can also be adopted, since the objective of watershed management can be achieved by the application of interdisciplinary and professional approaches through establishing a dynamic and optimal balance in supply and demand resources and consumption. The WEF nexus has been initially introduced in the world as an adaptive management approach to reduce the vulnerability to climate change and human impact in terms of the security



Main principles of low impact development measures for storm water management (After Vermont Green Infrastructure Initiative 2018).

challenges of water, energy, and food (Endo et al. 2015, Rasul and Sharma 2016). The WEF nexus focuses on the interdependency of water, energy, and food security to be explicitly identified in the decision making process (Mohtar et al. 2015). By definition, the nexus consists of basic concepts for the dynamics of the water, energy and food inter-relationship (Smajgl et al. 2016) water or food security. Current frameworks are partial as they largely represent a water-centric perspective. Our hypothesis is that a dynamic nexus framework that attempts to equally weight sectoral objectives provides a new paradigm for diagnosis and investigation. Dynamic refers here to explicitly understanding or a diagnosis of an important discussion in agricultural land use in watersheds, presents several challenges within the WEF nexus at the local and global scales (Gulati and Pahuja 2015). While considering other important chapters of the watershed system such as soil there is a need to allow the comprehensive management of the watershed in an adaptive manner (Lal et al. 2017). Actually, to consider the nexus approach with a sufficient concentration on the soil is essential as the foundation of the future of mankind. It is therefore a long way ahead in the future to provide meaningful concepts of the WEF nexus at the watershed scale. It is due to the complexities in the dynamic components of the watershed system. In light of the evidence, most of the literature on WEF and its various editions exist in Central, South, Southeast and East at 38%; and North America (USA, Mexico and Canada) with another 31%. It clearly verifies that more necessary efforts need to be made in other regions with a further focus in the developing countries where such approaches are needed to harmonize the inter-relationship amongst the important chapters of soil, water, energy and food.

Best co-management of the watershed Conservation of available and accessible resources and making a balance amongst the ecosystem components is essential to target the goals of the developmental plan. Hence, it is designed in order to recognize that the natural resources are the mutual assets of the society. If such an approach is governed, all different categories of people can receive mutual benefits and have co-responsibility for its use and management. Towards this, empowerment and deliberated participation, capability strengthening as well as awareness and encouragement are important for decision making on watershed management. It eventually leads to a balanced conservation and use, short term and long term benefits for the stakeholders.

Establishing a government sector, non-government organization, local community and academia network is also supposed to be an actual social driving force (Chanya et al. 2014). Best management practices (BMPs) are famous and effective approaches applied to ameliorate hydrological and fluvial behaviors of the watersheds (Strauch et al. 2013, Loperfido et al. 2014). Despite the long-term performance of the BMPs, they can help improve the decision support systems for creating competent strategies for watershed management projects (Liu et al. 2018) in sustainable and adaptive manner. BMPs widely remain an important solution at the local and regional-scale to mitigate water quantity and quality issues. Such that, the BMPs tries to handle issues in a very soft manner with the least intervention in the natural system. In particular, the watershed-wide application of the distributed BMPs improved hydrological behavior of the system. Integrated planning of storm water management system, protected riparian buffers and forest land cover with suburban development in the distributed-BMP watershed which enabled multi-purpose use of land, that provided an aesthetic value and green-space, community gathering points, and wildlife habitat in addition to an individual hydrologic storm water treatment (Loperfido et al. 2014). Different features of a watershed include soil and water utilization and conservation, water rights, and the overall planning and utilization of watersheds. Many stakeholders viz. landowners, land use organizations, foresters, ranchers, environmentalists, governmental agencies, and communities all play an integral part in watershed management. Once all stockholders and individuals think like a watershed and become aware of the benefits of proper thinking, they are often hands-on in the different stages of watershed management programs. They then favorably contribute in the planning, decision-making, implementation, restoration, maintenance, monitoring and even evaluation processes. It will eventually help reduce conflicts, increase commitment to the essential actions to fulfill environmental aims, improve economic and social situations of the stockholders and ultimately lead to sustainable life and development (Flint 2006). A new cooperative watershed management methodology is designed for developing equitable and efficient BMPs with the participation of all main stakeholders. The approach intended to control watershed outputs and to improve the socio-economic status of the watershed, considering villagers, legislation and executive stakeholders with conflicting interests (Adhami et al. 2018). Toward this goal, a powerful compromising like game theory can be used for analyzing strategies amongst the various demands in order to achieve cooperative decision-making in the sub-watershed and Best Co-Management Practices BCMPs prioritization. The collaborative management is a vast ranged-effort to participate in information collecting, decision-making and an accomplishment of projects (Bryson et al. 2013) and helps decision-makers resolve complex society-environment dilemmas (Leys and Vanclay 2011) at the watershed scale. A collaborative watershed management is a process, which includes relevant stakeholders to watershed resources in decision-making to achieve ecosystemoriented goals, such as water quality improvement, soil conservation and pollution control (Ucler et al. 2015, Thomas 2017). Conclusion There are many conflicting issues dealing with watershed ecosystems in the 21st century none of which can be simply ignored. The necessity of considering the ecosystem balance on one side and the growing demands of communities as the main driving forces on the system on another side make it somehow difficult to achieve sustainable development. Adopting appropriate approaches such as adaptive management, co-best management practices and optimal scenarios may therefore be as practical approaches in the current century. These approaches hopefully guarantee the cautious utilization of the available resources in a way to restore natural potentials and conserve them for future generations. However, continuous monitoring of the watershed systems to evaluate the outcome behaviors and accordingly adapt our attitudes in the proper direction is essentially needed. Obviously, more attention and considerations along with insight investigations are required in developing countries where the degradation of various resources is drastically accelerated (Sadeghi, 2020).

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UNIT-10: INTEGRATED RIVER BASIN MANAGEMENT: APPROACHES AND PRINCIPLES

During the ancient period, village boundaries were decided upon on the watershed basis by the expert farmers in the villages. Such boundaries were socially acceptable to all the members of the system. Such age-old village boundaries are fixed at the common point of the drainage system in between the two villages. Watershed based planning of resource management has generated a wide appreciation in India, particularly for assured dividends. The concept of maintaining an ecological balance embedded in the watershed programme has also started getting attention in different sections of the society. As the entire process of agricultural development depends on the status of water resources, the watershed with its distinct hydrological boundary is considered ideal for taking on a developmental programme. Planning and designing soil and water conservation structures such as bunds, waterways, overflow hydraulic structures, water harvesting tanks, etc., are carried out considering the expected rate and amount of runoff and flood volumes. This helps in reducing soil and nutrient loss, top fertile soil removal, improved in situ soil moisture and ultimately to improve crop productivity. Watershed development is fundamentally focused on conservation, regeneration and the judicious use of all the resources; both natural (land, water, plants, animals) as well as human components within the watershed area (Shinde 2014). Watershed management seeks to bring about the best possible balance in the environment between natural resources and man/ animals (Mani 2005). Since it is the man who is chiefly responsible for the degradation of the environment thus regeneration and conservation can only be possible by promoting, awakening and ensuring the participation of the people who inhabit the watershed vicinities. Watershed management is defined as the integrated use, regulation and development of the water and land resources of a watershed in order to accomplish the sustainable use of land, aqua and flora. The emphasis is on soil and water conservation on the watershed basis. Integrated watershed management involves working on the natural and human resources in a watershed in accordance with the social, political, economic and institutional factors that operate within the watershed (Hufschmidt 1991).

Principles of Watershed Management The main principles of watershed management under Mahnot and Singh 1993, are: i) Utilizing the land according to its capability. ii) Maintaining adequate vegetative cover on the soil for controlling soil erosion, mainly during the rainy season. iii) Conserving the maximum possible rainwater at the place where it falls, on arable land by contour farming. iv) Draining out the excess water with a safe velocity to avoid soil erosion and storing it in ponds for future use. v) Preventing erosion in gullies and increasing ground water recharge by putting in nullah bunds and gully plugs at suitable intervals. Multiple Use Concept in Watershed Management A multiple use perspective is required to achieve sustained and integrated watershed management, particularly in those areas, where a large rural population depends upon a variety of resources produced in upland watersheds. It may be noted that much of the intensive farming, grazing, and timber harvesting that take places in most of the areas is leading to watershed degradation, loss of biodiversity and adverse downstream impacts. Watershed inhabitants in many areas practice multiple use, which involves the production of goods that they require such as food, fiber, fuel and fodder. Most of the development activities are closely associated to the development and use of water resources. Thus, multiple use is being practiced on various watersheds, but whether multiple use is being properly managed for upland and downstream inhabitants is a matter of concern. The main aim of multiple use management is to manage a natural resource mixture for the most beneficial combination at both present and future uses. It is not necessary that every watershed is managed for all possible natural resource products simultaneously. Instead, most of the watersheds are utilized for various natural resource products depending on levels of supplies and demand. Multiple uses can be accomplished by one or more of the following options (Brooks et al. 1997): i) Concurrent and continuous use of several natural resource products obtainable on a particular watershed requiring the production of several goods and services from the same area. ii) Alternating or rotating the use of various natural resource products on a watershed. iii) Geographic separation of uses or use combinations, so that multiple use is accomplished across a mosaic of land management units on a watershed, with any use to which it is most suited.

It is important that effective multiple use management should accommodate to the extent possible the full spectrum of today’s requirements while providing for tomorrow’s needs. Types of multiple use management There are two types of multiple use management viz. resource oriented and area oriented. Resource oriented multiple use management represents the alternative uses of one or more natural resources. For instance, timber can be managed for lumber, fuel wood and pulp. Such management depends upon the knowledge of interrelationships-showing how the management of one natural resource affects other uses of the same resources or how one use of a natural resource affects other uses of the same resource. Resource oriented multiple use management needs thorough the understanding of the production capacities of natural resources. Area oriented multiple use management represents the production of a mix of products and amenities from a particular area. It is important that area-oriented multiple use should consider the physical, biological, economic and social factors related to resource product development in a given area. Area oriented multiple use gets the information required to describe resource potentials from resource oriented multiple uses and then relates this to the dynamics of local, regional and national demands. Brooks et al. (1997) show multiple resources from the land area that results in several products (Table 1). It may be noted that area oriented multiple use management is not necessarily intended to replace other forms of land management but to complement them.

Integrated Watershed Management Approach Integrated watershed management approach focuses on the assimilation of various technologies within the natural boundaries of a drainage area for optimum development of land, water, and vegetation to meet the fundamental needs of people and animals in a sustainable manner (Wani and Garg 2009). It orients to enhance the standard of living of the common people (Wani and Garg 2009) by increasing his earning capacity by offering all facilities required for optimum production (Singh 2000). In order to accomplish various objectives of integrated watershed management, various strategies are worked out simultaneously like land and water conservation practices, water harvesting in ponds and recharging of groundwater for increasing water resources potential and stress on crop diversification, use of an improved variety of seeds, integrated nutrient management and integrated pest management practices, etc. (Wani and Garg 2009). Soil and Rainwater Management Practices Soil and water conservation measures are aimed at management of rainwater, soil and vegetation resources in a manner that perceptible changes with regard to water resources development take place in the watershed so as to increase land productivity on a sustainable basis (Arora 2006). Not only should the surface water storage increase as a result of soil water conservation interventions, but increased ground water recharge should take place. Some of the effective and feasible soil and water conservation practices either indigenously followed or adopted through technological interventions in watershed programmes by the farmers of the Shivalik foothills in north-western Himalayas includes field bunding, pre-monsoon ploughing, terracing, contour trenching, earthing-up in maize, straw and soil mulching and tillage management (Arora et al. 2006, Arora and Hadda 2003). Socio-Economic Development The watershed development programme in agricultural and forest catchment's aims in soil and water conservation result in several ecological benefits viz. reduction in soil loss, development of vegetative cover, fodder production, increase in crop yields, wasteland development, etc. This in turn results in the economic development of resource poor rural communities in the region, as indicated through increased availability of fuel, fodder and commercial grass, employment generation and economic analysis. Productivity and income generation Watershed management programmes will not be self-sustainable, if improvement in productivity and generation of additional income does not commensurate with investment. Increased biomass and fodder production resulting from integrated management of watershed helps to change the composition of livestock to more economical animals and reduced seasonal migration of herds due to assured fodder supply during the year. The harvested rainwater in small storage tanks/ structures/farm ponds can be effectively utilized for supplemental irrigation during lean periods to boost crop production. Water harvesting structures proved to be economically viable, environmentally sound and socially acceptable (Samra 2002).

Bio-Industrial Watershed Management Approach The term bio-industrial connotes two meanings. Firstly, bio highlights the human-centered development that the project promotes. Through agricultural inputs and social interventions, the watershed community remains at the center of the program. As their on-farm efficiency and profitability increases, their social standing is expected to do the same. Secondly, the word industrial points toward the enhancement of livelihoods and the development of a more diversified economy in the village. Beyond the promotion of on-farm livelihoods, need to garner off-farm and non-farm livelihoods for the sake of enhancing income security (McGhghy 2012). Bio-industrial Watershed Management is watershed management plus processing industries for value addition of agricultural products before marketing them. This is the way to make the presently profitless farming in India, to be profitable (Bali 2005). Special bio-industrial zones need to be marked and infrastructure developed. First, soil and water conservation measures have to be applied. After that, the small watershed unit must be provided with assured agricultural knowledge and inputs availability. Bio-processing industries, owned preferably by the farmers, have to be developed. Natural resources are then developed by developing land, water and vegetation. A financial system of loans and subsidies must support each bio-industrial watershed. The tenants' rights have to be secured. Bio-industrial Extension personnel must be available to do the running about for each bio-industrial watershed. Farming is supported financially by all enlightened governments. Farm prices are kept low to reduce poverty. But this works unfairly for the farmers. That is why most governments subsidize farming to the tune of 30 or 40 per cent. In France, subsidies touch 80 per cent. Subsidized farming keeps food prices low and helps eradicate poverty. There are three major components of the bio-industrial watershed management, i.e., resource conservation, sustainable biomass production and processing of produce. Resource conservation in bio-industrial watershed Soil and water conservation, within bio-industrial watersheds, is vital for rain fed agriculture. Every drop of rain has to be conserved. Soils are poor and shallow. Land is sloping and water runs off quickly. Land is to be protected with contour bunds which will level the land over time. Water harvesting has to be developed. The ephemeral streams around provide an opportunity for farm ponds which can give life-saving water. It is here that the watershed management would meet its toughest challenge. It is here that the need is the greatest, that small quantities of produce must be processed and converted into high value nutritive products which will bring good money to the farmers who must be a partner in the processing industry. Watershed programmes act as pivot to agricultural growth and development in rain fed areas.

Sustainable production of biomass in bio-industrial watersheds Bio-industrial Watershed Management would be meaningful when marketable produce is available from different crops in quantity and quality. If what is produced is all consumed, there would hardly be any scope for processing and marketing for extra money in the pocket of the poor growers (Bali 2005). Present crop yields are low while the potential is high. This is a boon in a way. We shall have scope to expand the yield and cater to the food needs of the future high population. Those countries which have already achieved the peak productivity would not have such potential. But the crop yields must improve quickly. China has only two-thirds of the area under agriculture compared to India, but her food production is double of India's. Wheat and rice constitute about three-fourth of the food grain production in the country, but the productivity of both these crops is lower than other countries and also below the world average. Other countries have two to three times the yields achieved in India. There is tremendous scope of increase of productivity and total food production in our country. The need is for water harvesting and management, including rainwater management, and further intensification of application of science, technology and inputs. All said and done, population control is a major area of attention. India cannot afford to multiply indefinitely. There is a school of thought which says health and education facilities are the best contraceptive. But there is a place for direct intervention also. India's programmes are on the right path. Only the speed needs to be enhanced so that poverty is reduced within a stated time frame. Rural poverty comes in the way of the effective adoption of agricultural technologies available from research. The only way seems to be adoption of the Bio-industrial model of rural development in which processing is an essential step and which is bound to increase incomes and eradicate rural poverty. Processing, value addition, storage and marketing The foregoing efforts in the increase of productivity and market surpluses will make it possible to introduce processing of the watershed produce as an essential component of the watershed development and management programme. Strategies are needed for value addition to the products by supporting approaches such as structural mechanism, non-structural mechanisms and institutional approach (Cosgrove and Loucks 2015). Bio-industrial Watershed Management would be the ideal vehicle to take industries to agriculture and the rural people. Bio-Industrial Watershed Opportunities in Hilly Region There are many plus points to the mountains. Good climate and attractions for the tourists, an appropriate niche for horticulture of a great variety, rich biodiversity, medicinal and aromatic plants, animals well-adapted to the terrain, cooperative people, and a haven for future organic farming and food processing industries which can lift people from poverty to prosperity. People in and around the watershed are convinced for linkages between watershed conservation status and downstream hydrological benefits and the users to pay for the existing services, examples like the watershed protection, bio-prospecting and ecotourism (Tognetti et al. 2005). Regenerating watersheds in a holistic manner (watershed development) helps in revitalizing the ecosystem, the base of food sources and addressing biodiversity and sustainability concerns. There is plenty of potential for clean hydroelectricity, especially in hilly tracts and thanks to the Tehri Dam and other mini-hydroelectric projects. Even tiny projects can be installed on the old abandoned watermill sites and the new sites as well. Almost all the hill states of India are abound in the potential for cash crops like saffron, flowers, off season vegetables, vegetable seeds, mushrooms, honey, silk, wools (including the fine Angora rabbit wool), bamboo and other bio-products on which rural industries can be based. The need is there for holistic development on the watershed basis. If only agricultural production is pursued there will be the serious consequences of erosion and biodiversity disappearance affecting the future generations. In Morocco, the Sebou watershed is one of the most populated geographical zones and this watershed is equipped in various industries. Two hundred units are installed in the watershed and are mainly represented by oil factories, sugar factories, tanneries, paper factory, textile units, etc., using conserved water and providing livelihoods (Jaghror et al. 2013). In the Ethiopian watershed, industries gave impetus to improved watershed management adopting, different soil and water conservation practices, and rehabilitation of watershed through afforestation, community woodlots development and construction of micro and small-scale irrigation projects (Hoben 1995, Gebremedhin et al. 2003). Agriculture alone is not paying, much less so in the hilly watersheds. There is an urgent need for agriculture plus industry to add value to the produce of plants and animals. In the words of Prof. M.S. Swaminathan, we have to integrate Ecology, Economics, Employment and Equity. Contract Farming and Bio-Industrial Watershed Management Contract farming comes close to the bio-industrial watershed model, if the whole watershed is taken for resource conservation, development and raw material production with distinct objectives: (a) ensuring regular supply of raw materials (b) avoiding incidences of distress sale (c) promoting cultivation of process able varieties of farm produce (d) preventing wastage of surplus farm produce and increasing its shelf life through processing, and (e) commercializing agriculture through contract farming.

Way Forward for Bio-Industrial Watersheds There is a need to take certain initiatives in the watershed programmes in the near future to make Bio-industrial watershed a reality (Bali 2005). Strengthening processing and value addition Bio-industrial Watershed Management has the potential of ushering in a Bioindustrial Revolution in the Rural Areas, eradicating poverty. Processing components may, therefore, be added to all the current watershed programmes and the existing guidelines may be suitably amended to enable the change. Department of bio-industrial watershed management Existing Watershed Organizations in the States may be re-organized in order to establish a strong Department of Bio-industrial Watershed Management, to make Bio-industrial Rural Revolution a reality. Bio-industrial watershed management coordination council Bio-industrial Watershed Management would require close coordination between the Ministries of Rural Development, Agriculture and Food Processing Industries. A Bio-industrial Watershed Management Council may, therefore, be set up bringing all the concerned Ministries together. Bio-industrial watershed research and training institute Bio-industrial Watershed Model with its union with a number of departments and organizations and with a multiplicity of disciplines, needs a separate Bio-industrial Watershed Management Research Institute. In the meantime, existing research establishments should take up definite studies of the Bio-industrial Watershed Problems of different regions and different socio-economic conditions. However efficient the organization which is built up for demonstration and propagandas be, unless that organization is based on the solid foundation provided by research, it will merely be a house built on sand. It is hence important that we pay attention to strengthening the research and development infrastructure essential for sustainable food security in an era of climate change (Swaminathan 2010). Food security and environmental degradation are two of the main challenges facing humanity in the twenty-first century (Lal 2000). Protecting and strengthening watershed ecosystems is one of the main strategies Extension Agricultural Extension should contain a wing on Bio-industrial watersheds. The Extension agencies should convey knowledge of various assistance schemes for the rural bio-industries. There should also be the link between rural entrepreneurs and the sources of processing technologies like the CSIR. Processing vital for perishable produce of watershed villages At present hardly 2% of fruits and vegetables are processed. In order to save the profitable horticultural produce, and increase rural incomes, this proportion must be brought up to 25% within 5 years. Credit and Insurance The agriculture and industry combination in the Bio-industrial watersheds need access to easy credit and also crop insurance. Farmers suffer for want of extensive insurance coverage, and commit suicide when caught in the debt trap. Special credit facilities will have to be set up to promote the system. Present facilities are neither adequate nor easily accessible to the rural people. Credit and insurance cover for the crop and stored produce is essential for the success of the Bio-industrial Watershed Management Movement. Marketing Marketing is crucial for the success of the Bio-indstrial Watershed Movement. Existing marketing structure may, therefore, be reviewed to make it more effective in bringing the bulk of the profits of processing to the primary growers. Monitoring and evaluation Monitoring of physical parameters is not enough. We must monitor whether poverty in the rural areas has been alleviated if not eradicated. Evaluation should similarly ascertain the improvement in the real incomes of the villagers, specially the deprived sections of the society. Encouraging self help groups and NGOs A rural individual is weak in economic power. Grouping under various systems is necessary. Whether it is the Cooperative, Corporate Body, Self Help Group or any other institution depends upon the local conditions and choice of the people. Genuine NGOs can play an important role in pushing forward the Bio-industrial Management Movement.

Reaching the unreached The whole purpose of bringing industry to join with agriculture is to help the poor, deprived and the unreached sections of the society. Unless the profits of industrial processing of bio-produce are derived by the upstream growers also, poverty shall persist. The role of Government and the NGOs should be as facilitators to bring genuine Bio-industrial benefits to the rural people to bring about a Rural Bio-industrial Revolution, comparable to the Industrial Revolution of the Nineteenth Century, which never reached India. Conclusions Soil and water conservation practices are essential components of watershed development programme. If properly implemented through farmers' participatory approach, the soil and water conservation practices in agricultural catchments, shall enable the farmers to optimize their crop yields and also rehabilitate the erosion prone degraded lands. To make agriculture a profit giving venture in rain fed and hilly areas, on which young men would build their livelihood willingly, a processing industry; would have to be added to agriculture on the pattern of the Bio-industrial Watershed Management. The approach of watershed with agricultural and rural development activities should be converged into the bioindustrial watershed for synergy effect. Watershed Programmes of India will yield the desired results only when they are converted into Bio-industrial Watershed Programmes (Arora, 2020).

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UNIT-11: TISTA MEGAFAN PROCESSES, LANDFORMS AND HAZARDS

The Tista is the main river draining the Sikkim Himalaya (Fig. 1). It takes its source at an elevation of 5320 m close to the SikkimeTibet border and flows southward for 200 km before crossing the Himalayan mountain front at 150 m elevation. Within the foreland, the river currently runs along the eastern edge of the megafan it has built and joins the Jamuna (the downstream continuation of the Brahmaputra) as a large braided tributary in Bangladesh. The total length of the river is about 400 km. 2.1. The Tista megafan and hinterland terraces The Tista megafan extends over 16,500 km2 from its apex at the Himalayan mountain front down to the confluence of the Tista and Jamuna/Brahmaputra Rivers (Fig. 1). The megafan shows a radiating drainage pattern; historical records suggest that major avulsion events have affected the megafan in the last centuries (Chakraborty and Ghosh, 2010), similar to the better-known examples described from the adjacent Kosi megafan (Wells and Dorr, 1987; Sinha, 2009; Chakraborty et al., 2010). Historical maps show that the Tista River was a small plains-fed channel flowing into the Brahmaputra prior to 1787, while the Sikkim Himalaya was drained by the western Mahananda, Atrai and Karatoya Rivers (Fig. 1), which are tributaries of the Ganges (Bristow, 1999). Archaeological excavations demonstrate that these rivers constituted large navigable channels until the 11th century AD (Chakrabarti, 2001; Goswami, 1948). Chakraborty and Ghosh (2010) used satellite imagery to map ancient and modern radial drainage systems, and distinguished three depositional lobes in the megafan (Fig. 1). They proposed a relative chronology of these lobes based on inferred truncating relationships of the drainage systems and elevation profiles derived from a digital-elevation model, but did not report any absolute ages. They considered that the eastern distal lobe, drained by the modern Tista River (lobe 1 in Fig. 1), was the first to have been built. A small western lobe (named lobe 1A by these authors) would have developed contemporaneously. The river would subsequently have shifted westward to form the main western lobe (lobe 2 in Fig. 1). Finally, the river switched eastward again to build the smaller lobe 3, which forms the proximal lobe of the megafan. The modern Tista River has incised up to ~40 m within this proximal lobe of the megafan, from the mountain front to ~25 km southward. The western and eastern distal lobes of the megafan are less incised, up to ~8 m. The sedimentology of the proximal and medial parts of the Tista megafan is dominated by sandy sheet braided-stream deposits. In the distal parts, low-energy sand-mud channel deposits dominate with a downstream increase of floodplain marsh or lake deposits (Chakraborty and Ghosh, 2010). Coarse material is restricted to a 1-m thick layer in the fan apex, in contrast to the adjacent Kosi megafan where it is more common (Sinha et al., 2014) and the modern Tista riverbed, which is composed mostly of gravel. Quaternary fluvial cut-and-fill terraces are also developed on both banks of the Tista River in the Sikkim Himalaya north of the town of Rangpo (Fig. 1). They correspond to material deposited by braided river channels, debris flows and hyperconcentrated flows, and have been incised several tens of meters by the Tista River (Meetei et al., 2007). Unpaired terraces have also been described along the Rangit River, the main west-bank tributary of the Tista, north of the town of Jorethang (Fig. 1; Mukul, 2010). These terraces appear to be restricted to the region between the Main Central Thrust and the Main Boundary Thrust (in the so-called Tista halfwindow; Mukul, 2010).

2.2. Structure and active tectonics

The Himalayan mountain front in West Bengal, as elsewhere, is delimited by the active Main Frontal Thrust (MFT), which accommodates present-day convergence at rates of 15e17 mm yr1 (Vernant et al., 2014). Paleoseismological studies have found indications for major historical earthquakes on the MFT, with magnitudes that may have exceeded Mw 8.0, in West Bengal (30 km east of the Tista River outlet; Kumar et al., 2010; Mishra et al., 2016), eastern Nepal (Sapkota et al., 2013) and Bhutan (Berthet et al., 2014). The Matiali alluvial fan, just east of the Tista megafan, has clearly been affected by surface deformation associated with thrusting on the MFT (Kar et al., 2014), but the MFT projects laterally to north of the apex of the Tista fan and no clear deformation features have been reported on the Tista megafan apex. Although the topography of the Indo-Gangetic and Brahmaputra plains is very smooth due to the presence of an up to 6-km thick alluvial sediment fill, three inherited subsurface basement ridges have been mapped under the sediments (Rao, 1973). They are interpreted as relict horsts, bounded by long-lived, multiply reactivated crustal-scale faults that affected the Indian plate from Precambrian times onward. Surface-geological data combined with aeromagnetic, gravity and seismic surveys have established the location of the ridges and constrained their size and depth below the plains (Valdiya, 1976; Gahalaut and Kundu, 2012; Godin and Harris, 2014). These mainly north-south trending basement ridges may act as lateral barriers to the ruptures of major Himalayan earthquakes (Gahalaut and Kundu, 2012) and appear to guide transverse tectonic features within the Himalaya (Dasgupta et al., 1987; Godin and Harris, 2014). They have also been suggested to guide neotectonic deformation in the Indo-Gangetic plains, which may control local incision of alluvial fans and the oblique course of many Himalayan rivers in the foreland (Pati et al., 2011). The Tista megafan is located above the easternmost of these buried basement ridges, the so-called Munger-Saharsa Ridge (Gahalaut and Kundu, 2012; Godin and Harris, 2014). Minor historical seismicity has been registered in the fan and around it (Gahalaut and Kundu, 2012). To the southeast, the Shillong Plateau is bounded by active faults that have generated historical earthquakes with magnitudes up to Mw 8.1 (e.g., Bilham and England, 2001). Recent GPS data suggest that the Shillong Plateau is rotating clockwise with respect to the Indian plate, inducing minor active deformation in the Tista megafan region (Vernant et al., 2014). 2.3. Climate and hydrology The seasonal monsoon dominates climatic variability in the study area on timescales from the annual cycle to glacialinterglacial cycles. Average modern precipitation for the entire mountainous catchment of the Tista River is 1870 mm yr1 (Bookhagen and Burbank, 2006, 2010). This amount reaches nearly 3000 mm yr1 in southeastern Sikkim and decreases to less than 1000 mm yr1 in northern Sikkim. In the alluvial plain, precipitation increases toward the mountain belt: near the apex of the megafan, average precipitation reaches 4070 mm yr1 (reference:

Anderson Bridge Gauge Station; Fig. 1) while it oscillates between 1000 and nearly 2000 mm yr1 in its distal parts. The Tista River exhibits high seasonal flow variability that causes inundation of floodplains during the monsoon and low-flow conditions in the dry season. Two gauge stations inform about the average annual discharge between 1965 and 1975 (predamming period) along the Tista River (Fig. 1). Around 80 km downstream from the mountain front, at the Anderson Bridge gauge, the river has a yearly-average discharge of 609 m3 s 1 , with monthly-average discharge varying between 130 m3 s 1 in the dry season and 1500 m3 s 1 during the monsoon. In Bangladesh, upstream of the confluence with the Jamuna/Brahmaputra River, the Kaunia gauge station records a yearly-average discharge of 896 m3 s 1 for the Tista River, with monthly-average discharge exceeding 2000 m3 s 1 during the monsoon and dropping to 125 m3 s 1 in the dry season (data from the SAGE Global River Discharge Database; http://www.sage.wisc.edu/riverdata/). As no major tributaries join the Tista River between these two gauge stations, the significant increase of river discharge may be due to groundwater recharge (but note that the data for the two stations only partly overlap in time and inter-annual variability is large). Prell and Kutzbach (1987) discussed the nature of variability in the South Asia summer monsoon over the past 150 ka. They showed that monsoon precipitation in South Asia was reduced during the Last Glacial Maximum (LGM, ~20 ka) relative to the Marine Isotope Stage 3 (MIS-3, 60 to 27 ka), as a consequence of lower northern-hemisphere insolation. However, some authors suggest that the increase of moisture transport to the Himalayan mountain belt at the end of MIS-3 led to an increase in precipitation accumulated as snow at high altitudes (e.g., Bush, 2004). These conditions may have allowed glaciers to grow in the Himalaya, causing a local LGM early in the last glacial cycle (Owen et al., 2002; Owen, 2009). Tsukamoto et al. (2002) dated glacial sediments on the Nepali flank of the Kanchenjunga massif that record glacier expansion at 20e21 ka, suggesting that the local LGM in the study area was synchronous with the global northern-hemisphere LGM. Hydrological changes during the LGM were significant, with a strongly reduced monsoon leading to lower continental runoff (Cullen, 1981; Duplessy, 1982; Herzschuh, 2006; Kudrass et al., 2001) and reduced sediment supply to the Bay of Bengal (Goodbred, 2003; Weber et al., 1997). Other strong monsoonal precipitation episodes are described during the early Holocene period of maximum insolation between 6 and 8, 9.5e10, and 10.5e11 ka (Prell and Kutzbach, 1987; Clemens et al., 1991; Gasse et al., 1996; Overpeck et al., 1996; Schulz et al., 1998; Enzel et al., 1999). The Holocene glacier expansions recorded in the Kanchenjunga massif at 8e10 and 5e6 ka by Tsukamoto et al. (2002) may be related to higher precipitation during these periods.

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UNIT-12: SUNDARBAN PROCESSES, LANDFORMS AND HAZARDS

Located at the northern apex of the Bay of Bengal, the Ganga–Brahmaputra delta (GBD) is the world's largest both in terms of land area (15,000 km2 36) and yearly discharge of sediments (~109 t a –1). The delta is contributed by a combined catchment area of 1.6 × 106 km2 37 , drained 38 by many small to medium sized peripheral streams that emanate from the surrounding 39 uplands apart from the Ganga and the Brahmaputra.

The GBD, of which Sundarban forms the coastal part, is bordered by highlands on all three 48 sides barring a 125-km-wide passage that links the region to its northern provenance. This is 49 known as the Rajmahal–Garo Gap (RGG), a worn-down saddle of the Indian craton between 50 the Rajmahal and the Garo hills (Fig. 1). Besides the RGG, the northern and eastern 51 boundaries of the delta are defined by the crystallines of the Meghalaya plateau, the Rajmahal 52 hills and the Chhotanagpur plateau, all of which were parts of the Gondwanaland up to the 53 Jurassic. The eastern boundary of the delta is delineated by the Neogene sedimentaries of 54 Chittagong–Tripura Fold Belt (CTFB). 55 The subaerial and subaqueous parts of the GBD can be seen as integral parts of the Bengal 56 Depositional System that stretches from south of the Himalaya to the distal edge of the Bay of 57 Bengal (Curray, 2014). Its deltaic components include • a higher-gradient fan delta in the 58 north, characterised by vertically and laterally migrating sand-dominated braidbelts; • a lower59 gradient fluvio-tidal section in the southeast which is building into the sea with comparatively 60 stable channels; and • a fluvially abandoned tidal section in the southwest that is accreting 61 vertically but also declining irreversibly in certain sections (Wilson and Goodbred, 2015).

The current orientation of the Ganga–Padma–Lower Meghna river diagonally divides the 63 GBD into two parts. The southwestern portion, along with southern coastline of the delta 64 between the Hugli and the Baleswar estuaries, is primarily contributed by the distributaries of 65 the Ganga system—active or dissipated. Its 200-km littoral stretch constitutes about 47% of 66 the GBD coastline and harbours the largest contiguous mangrove forests of the world—the 67 Sundarban. 68 This article first reviews the evolution of the Sundarban region as a part of the Bengal basin 69 and the GBD. It then discusses the main natural and anthropogenic forcings working on the 70 area and how the region is responding to them. 71 2. EVOLUTION OF THE DELTA 72 The cradle of the GBD is the Bengal basin — a structural depression filled up by the rivers 73 during the last ~150 Ma. The evolution of the basin was controlled by a series of tectonic and 74 sedimentation phases related to plate movement, palaeoclimate and eustasy. 75 2.1 Cretaceous-Tertiary evolution 76 India detached from the eastern Gondwanaland and started drifting northwards during Early– 77 Late Cretaceous, c. 133–93 Ma BP (Fig. 2A) (Lawver et al., 1985). The northern and western 78 parts of the Bengal basin took shape on the continental shelf that skirted this newly formed 79 subcontinent (Fig. 2B). Deltas began to accrete on the shelf and continued to prograde till 80 they merged with the materials brought down by the Ganga and the Brahmaputra in the

81 Quaternary (Niyogi, 1975; Agarwal and Mitra, 1991). These palaeodeltas now resemble a 82 coalescing fan system of the western tributaries of the Bhagirathi–Hugli river. About 50 Ma 83 later, in Early Eocene, India collided with the Tibetan mainland and the rise of the Himalaya 84 was initiated (Curray et al., 1982; Chen et al., 1993). At about 44 Ma BP (Mid Eocene), the 85 Indian plate added a counter-clockwise orientation to the post-collision movement as a sequel 86 to the opening of the Arabian sea (Fowler, 1990). Due to the shape of the northeastern edge of 87 the Indian continent and this rotational movement, the subduction in the Indo-Burmese sector 88 progressed obliquely (Fig. 2C) and the remnant ocean basin between eastern India and Burma 89 was subjected to a 'zipper-like' closure from north to south (Biswas and Agrawal, 1992). 90 Sediments from Burma are first detected in the Bengal basin in the Early Miocene (Steckler et 91 al., 2008). This signals acquiring of a continental boundary to its east. As the oceanic part of 92 the Indian plate continued to slide under the Burma platelet, the eastern sector of the Bengal 93 basin changed to a subduction-related mountain building area and evolved into the 94 Chittagong–Tripura Fold Belt (CTFB). 95 In this way, the Bengal basin traversed some 70 degrees of latitude (~7,700 km) from its 96 original pre-drift locality. It witnessed transformation from an open continental shelf-slope 97 setting of a drifting continent into a miogeosynclinal foredeep at the foot of a young folded 98 mountain that now defines its eastern boundary. Earthquakes continue to originate in the 99 eastern section of the basin since the historical times, indicating tectonic adjustments (Nandy, 100 1986; Steckler et al., 2008). The channel avulsion patterns of eastern portion of the delta are 101 largely steered by tectonics (Reitz et al., 2015). As Morgan and McIntire (1959:335) 102 observed, 'active, Recent faults of the magnitude present in the Bengal Basin are unusual'. 103 Three tectonic provinces are distinguishable in the Bengal basin (Alam, et al., 2003): (1) the 104 shelf region, underlain by continental crust; (2) the deeper basin region, underlain by oceanic 105 crust and (3) the folded sediments of the arc-trench accretionary prism — the CTFB. The 106 GBD and the Sundarban essentially rest on the first two of these. The principal features and 107 events pertaining to the basin are summarised in Table 1 and Fig. 3A and 3B.

2.2 Quaternary evolution 128 Accretion of the modern GBD was initiated with the opening of the RGG in the Pliocene 129 (Alam, 1989; Khan, 1991) or Pleistocene (Auden, 1949). At the inception of the Quaternary, 130 while the main GBD was gradually being accreted by the Ganga and the Brahmaputra from 131 north and along the central section through the RGG, smaller peripheral streams were 132 simultaneously contributing sediments along the basin boundary. Despite the fact that the 133 depth of the Mio-Pliocene surface does not vary appreciably along the same latitude between 134 the eastern and western edges of the Bengal basin (Khan, 1991), deltaic progradation had 135 probably been more prominent in the western basin margin, compared to the east owing to the 136 comparatively larger size of the rivers. 137 The Pleistocene is marked for fluctuations in global temperature that brought four cool glacial 138 stages and the intervening warm interglacials. Intrinsically linked to the global hydrological 139 cycle, the cool (warm) epochs caused worldwide fall (rise) in the secular mean sea level. The 140 latest glaciation ended about 15~12 ka BP, establishing the onset of the Holocene. The GBD, 141 like all modern deltas of the world, was primarily shaped during this period. Therefore, events 142 of the Holocene constitute a crucial part in its evolutionary history. 143 2.2.1 Holocene Sea-Level curve 144 The Holocene secular man sea level (MSL)/time curves provided by different workers connote a quick rise at ~10 mm a –1 145 between 15 ka and 6 ka, which slowed down to 0.5 & 0.1– 0.2 mm a –1 146 during the last 6 ka & 3 ka respectively (Pugh, 2004). This means that the MSL 147 had almost reached its present position some 6 ka BP after which it is rising slowly. The fast 148 rate of MSL rise during the early Holocene caused worldwide inundation of low-lying coastal 149 areas. Estimations of these rates for the GBD are summarised in Table 2 and Fig. 4.

It is important to note that although evidence of land subsidence is common in the Sundarban 156 (Blanford, 1864; Gastrell, 1868:26–28; Fawcus, 1927; Haque and Alam, 1997), some of the 157 above studies did not consider this appreciably. Compared to other large deltas, the general 158 dominance of silts and sands over clays significantly prevents autocompaction in the GBD 159 sediments (Goodbred and Kuehl, 2000a, Kuehl, et al., 2005). Tectonics is regionally capable of initiating channel avulsion in GBD (Reitz et al., 2015) and is also a cause of the 2–4 mm a– 160 1 161 subsidence estimated for its central and coastal parts (Goodbred and Kuehl, 2000a). For the western Sundarban, Stanley and Hait (2000) estimated subsidence up to 5 mm a–1 162 against sediment accumulation of up to 7 mm a–1 163 . For shorter time span, Hanebuth et al. (2013) dated 164 mangrove roots and archaeological remains from the Khulna Sundarban and estimated subsidence of 5.7 mm a–1 and 4.1 ± 1.1 mm a–1 165 for the last 360 a and 300 a, respectively. This

may be compared with the available subsidence rate of ~3 mm a–1 166 from short-term GPS 167 measurements near Patuakhali at the coastal delta, east of the Sundarban (Reitz et al., 2015). 168 2.2.2 Holocene evolution The ~8,500 km3 169 Holocene sequence in the Bengal basin varies from c. 15 m over the eastern 170 platform (Tectonic Province-1) to some 90 m in the deeper basin areas (Tectonic Province-2) 171 (Allison, et al., 2003; Goodbred et al., 2014). The broad framework of evolution of the GBD 172 is outlined in the following sections based mainly on Goodbred and Kuehl (2000a) and 173 Goodbred (2003). Table 3, Fig. 5 and Fig. 6 provide summaries of the changing scenarios. 174 THE LOWSTAND SCENARIO (24–18 ka BP): The glacial lowstand was at its maximum (Fig. 175 5A). Exposed laterised uplands and incised valleys, often containing lag gravels, were 176 widespread. River discharges were low, probably insignificant, compared to the present. MSL 177 was some 100 m lower than the present. About 80–100-km wide stretch of continental shelf 178 became exposed off the GBD to subaerial processes (Niyogi, 1972; Alam, 1989), and may 179 have extended up to the shelf break (Cochran, 1990). Existence of cut and fill channels on the 180 shelf area supports this observation (Saxena et al., 1982). At this time, salinity of the northern 181 Bay of Bengal was at least 4‰ higher than the present due to absence of freshwater discharge 182 (Cullen, 1981). 183 ONSET OF WARMING (15 ka BP): The upper part of the submarine Bengal fan started receiving 184 fresh sediment input, indicating onset of climatic warming and strengthening of the summer 185 monsoon and increase in discharge levels. The accumulation rate at the submarine Bengal fan 186 off the GBD greatly increased up to about 11 ka BP when the rising MSL submerged large 187 areas of the delta that transferred the depocentre landwards with extensive development of 188 floodplains. Since ~12 ka BP, the valleys incised during the lowstand were started to fill up 189 with sands (Facies-II of Table 2). 190 DELTA DEVELOPMENT COMMENCED (11.5–10 ka BP): By 11.5 ka BP, intensity of the sothwest 191 monsoon became significantly higher, which shot up sediment discharge at least 2.5-times of 192 their present level. The incised river valleys started to fill-up with sand (Fig. 5B) (Goodbred 193 and Kuehl, 2000b). However, a high rate of sedimentation at the Bengal fan connotes that the 194 incipient GBD was incapable of accommodating a large part of the load it received. A couple 195 of wood fragments and a shell, found below and ~10 m above the low-stand laterite horizon 196 respectively, were dated ~14 ka BP and ~ 9.9 ka BP by Umitsu, 1993 (Fig. 4). This indicates 197 that the delta growth must had started at about 10~11 ka BP. At this time the Bengal fan 198 sedimentation also recorded a sharp decline indicating shift of the depocentre to on-shore 199 localities. The MSL rose to –45 m, submerged a large part of the basin and started to trap 200 sediments that initiated the development of the modern GBD system. In the southern basin, 201 20–25 m-thick fine Lower Delta Mud facies (Facies-III of Table 2) covered most of the 202 lowstand laterised surfaces (Facies-I) in a near-shore mangrove-dominated depositional 203 environment. In northern parts of the basin, clean Sand sequences (Facies-II), associated with 204 fluvial channels, continued to be deposited in the central valleys. 205 DELTA DEVELOPMENT DURING RAPID RISE OF SEA LEVEL (11–9/7.5 ka BP): The delta continued 206 to agrade as the huge sediment load of the Ganga–Brahmaputra system largely compensated 207 the rise in the MSL. This scenario, matched in few areas of the world (Kuehl et al., 2005), persisted as the MSL rose to –15 or –10 m at the end of this period at ~10 mm a –1 208 . Continuous 209 subsidence of the Sylhet basin repeatedly altered the hydraulic gradient of the Mymensingh 210 corridor between the Meghalaya plateau and the morphotectonic Madhupur terrace. Filling-up 211 of the basin makes the passage between the Barind and Madhupur terraces—the one currently 212 followed by the Brahmaputra river—comparatively steeper; but only up to the point when 213 subsidence of the Sylhet basin alters it to the Mymensingh passage's favour. Consequently, the Brahmaputra switched its course at least five times in the Holocene between these two 215 corridors (Goodbred and Kuehl, 2000a; Heroy et al., 2003). Deposition of Fine Mud facies in 216 the northeastern Sylhet basin started only after 9 ka BP, indicating that after this time the E), and discharging its|217 Brahmaputra was following its western course (Avulsion-I: W 218 sediments directly into the sea, until ~7.5 ka BP. This, although starved the subsiding Sylhet 219 basin from filling-up, supported the maintenance of shoreline stability of the delta front at the 220 time of rapid rise in MSL.

MAXIMUM HOLOCENE TRANSGRESSION AND DELTA PROGRADATION THEREAFTER (7.5–5 ka 231 BP): The rate of SL rise slowed around 7.5 ka BP and the maximum landward limit of 232 inundation was achieved in the western part of the basin (Fig. 5C). This had brought the delta 233 coast ‘in line with an arc that swung across from south of Calcutta almost to Dhaka and then 234 more closely followed the present coast to the southeast’ (Alam, 1989:137). The delta 235 transformed from an aggradational (on-lapping, vertically accreting) to progradational (off236 lapping, horizontally accreting) system and the main depocentre started to migrate seaward 237 (Goswami and Chakrabarti, 1987; Chakrabarti, 1995). Extensive dispersal of sands started on 238 the coastal plain as the upstream alluvial valleys were topped up. This laid the Muddy Sand 239 deposits onto the mangrove-dominated coastal plains (Facies-IV of Table 3). A muddy 240 submarine delta begun to take shape at about 7.5 ka BP as well and that made GBD a 241 compound entity with clearly defined subaerial and sub-aqueous components. The Muddy 242 Sand deposits (Facies-IV) can be viewed as the topset beds to both the components (Fig. 6). 243 The growth of the delta clinoform continued and the western delta approached its present 244 extent by ~5 ka BP. This also heralded the formation of coastal peat layers and abandonment 245 and eastward migration of the active Ganga distributaries, leading to the formation of the 246 Sundarban area. 247 Between 7.5 ka and 6 ka BP, the Brahmaputra returned to its eastern course to the Sylhet basin that started to rapidly fill up at > 20 mm a–1 E). This was also the time□248 (Avulsion-II: W 249 when maximum Holocene transgression was achieved in the eastern delta, some 1 to 2 ka 250 after the western part. Between 6 ka and 5 ka BP, as the Sylhet basin sediments indicate, the E). With this|251 Brahmaputra switched its course again and returned west (Avulsion-III: W 252 change, the river probably joined the Ganga, now migrated eastward, for the first time in 253 Holocene (at ~5 ka). By mid-Holocene, the antecedent lowstand valleys of the major streams 254 like the Ganga, the Brahmaputra and the Meghna were mostly filled-up and the rivers started 255 to avulse and migrate freely across the floodplains much like today (Goodbred et al., 2014).

E). In fact, the paths of the Ganga and the|into its modern channel (Avulsion-V: W 271 Brahmaputra swung across the central part of the delta for the major part of the Holocene. In 272 certain localities, provenance of the sediments brought down by the rivers indicated two to six 273 switchings between the two rivers (Heroy et al., 2003). In the coastal GBD, clay mineralogy, elemental traces and 14 274 C chronology indicate a younging 275 trend towards the east in four overlapping phases (Allison et al., 2003). The westernmost part of 276 the coastal delta—comprising whole of the 24 Parganas Sundarban—was accreted during 5–2.5 ka BP (lobe G1 of Fig. 7). This observation is consistent with l4 277 C dating of samples from 70 a (Gupta,±278 Namkhana (+2.25 MSL) and Gangasagar (0.9 m bgl) that indicated dates of 3,170 20 a (Chakrabarti, 1991) respectively. It also agrees with suggestions that the±279 1981) and 2,900 280 evolution of the Sundarban part of the GBD commenced after 5 ka BP (Umitsu, 1987) or during 281 4.5–3.2 ka BP (Banerjee and Sen, 1987). The delta growth then shifted east in phases that 282 lasted 4–1.8 ka BP.

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