Chapter 2
Rivers-Structure and Functions

Abstract Rivers are the corridors connecting the terrestrial environment to the ocean realm. They play an important role in the sustenance of life systems of nature. As a geological agent, rivers carve out distinct suite of geomorphic features on the surface of the Earth. But human interventions consequent to economic developments in the past few decades have imposed tremendous pressure on rivers. As a result, most of the rivers in the world, especially the small rivers, have been altered to levels, often beyond their natural resilience capability. The present chapter gives a brief presentation of the river environment with special reference to its ecological and geological functions. River sediment characteristics, channel processes, classifications of rivers, and some of the classic concepts in riverine studies are also given in the chapter.

Keywords River ecosystem · Geological work of rivers · River sediments · Concepts in riverine studies

2.1 Introduction

Apart from being a crucial ecosystem linking the land and ocean systems, rivers serve as a prominent geological agent in tropical and subtropical regions. Running water is the most pervasive agent of erosion in nature. Under the influence of the force of gravity, rivers sculpture Earth's surface into distinct landforms (Leopold et al. 1964). The most striking example is the Grand Canyon that has been carved down by running water through a process that took millions of years. Like erosion of land, rivers play a major role in the transfer of materials from terrestrial environment to ocean realm (Lal 1977).

Milliman and Meade (1983) computed that 12–13 $\times$ 10^9 tons of suspended sediments are supplied to the world oceans annually by rivers and further 1–2 $\times$ 10^9 tons are supplied as bed load and flood water discharges. However, all sediments borne off by rivers seldom reach the sea as a considerable portion is

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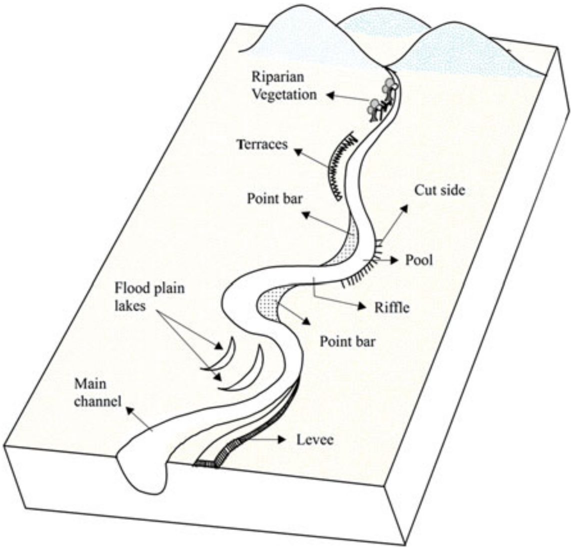

Fig. 2.1 Gross features of a river along the master channel

detained in the onland part of the fluvial system. Flowing water is the main agent responsible for the creation of physical habitat in a river environment (FAO 1998). Rivers create, destroy, and re-create distinct landforms and habitats through erosion, deposition, or a combination of these two. A low order stream in the uplands is usually erosional. This reach will essentially be composed of boulders, cobbles, and other coarser sediments, whereas the higher order rivers in the lowland contain sediments of silt-sand grades that are deposited in the form of bars, point bars, islands, natural levees, etc. A river system comprises the whole river corridor—the river channel, riparian zone, floodplain, and alluvial aquifer. Figure 2.1 depicts the gross features of a river along its master channel. Sand and gravel deposits constitute an integral part of this fluvial hydrosystem, which make it permeable to exchange of water between the corridors. In addition to this, sand and gravel dominant sediment substratum within river channels offer a conducive environment for many psammophilic organisms in the river environment. As the course of a river changes from upstream to downstream, the habitat and the communities in the environment would also vary. It is now well understood that the effects of alterations and perturbations in one stretch can be transferred into the downstream stretches located far from the source of the problem, inflicting the consequences at a distance (Jeffries and Mills 1990).

Despite its importance in supporting the life and greenery of the basin environment, rivers have been widely exploited by humans for natural resources—both living and nonliving, without understanding much the ecosystem functions (Naiman 1992; Naiman et al. 1995; Naiman and Bilby 1998). Studies reveal that man has changed the nature of many of the world rivers by controlling their floods, constructing large impoundments (Ittekkot and Lanne 1991), over exploiting the resources (Kitetu and Rowan 1997; Macfarlane and Mitchell 2003) and using rivers for disposal of wastes (Haslam 1990).

2.2 The River Ecosystem

River ecology deals mainly with the energy transformation, nutrient turnover, and storage and processing of organic matter. Rivers are basically heterotrophic as a substantial proportion of the biotic energy that drives stream communities is organic matter derived from allochthonous sources. Many aquatic plants, invertebrates, and fishes have adapted to fill a specific niche. Within most rivers, the pattern of flow variation, and its ramifications in terms of substrate stability and water quality, is the dominant factor controlling species distributions. Elwood et al. (1983) showed that lotic (pertaining to running water) ecosystems are longitudinally interdependent and that energy processing depends on the retention and cycling of nutrients by biological communities in upstream areas. From a biological point of view, flowing water has a number of advantages over still water. It constantly gets mixed up by turbulence providing nutrients, exchange of respiratory gasses, and removal of wastes. Lotic water is fundamental for the downstream and lateral movement of plants and animals. However, the character of flow changes from the headwaters to the river mouth, which in turn leads to a characteristic zonation in the riverine biological community. Biological community of a river ecosystem includes a variety of plants and animals. Producers in aquatic systems include diatoms, blue green algae, and water moss. Nymphs of dragon flies, may flies and stone flies, beetles, snails, fishes, etc. are the common consumers in river ecosystems. Some plants and animals can withstand the rapid flow of hill streams. Other species of plants and animals can live only in slow moving waters. Some species of fishes move to hill streams as they need crystal clear water to breed. The rising turbidity due to indiscriminate scooping of river bed materials for various purposes is an adverse condition for the existence of such fishes. In highly flooded rivers, recession of the annual flood delivers high levels of dissolved organic carbon and detritus (wood, leaves, seeds, etc.) to the main channel. This lateral connectivity is very important for sustaining the biological integrity of large rivers with well developed floodplains.

Riparian and instream vegetations are the integral components of the river ecosystems. The riparian vegetation plays an important role in sustaining the vitality of rivers. It is a source of organic matter, which forms an important source of energy in most of the river ecosystems. Further, the woody debris in aquatic ecosystems is an important habitat and spawning site for many aquatic animals. They not only play a pivotal role in stabilizing river banks from erosion, but also act as travel corridors for wild animals that connects with other ecosystems

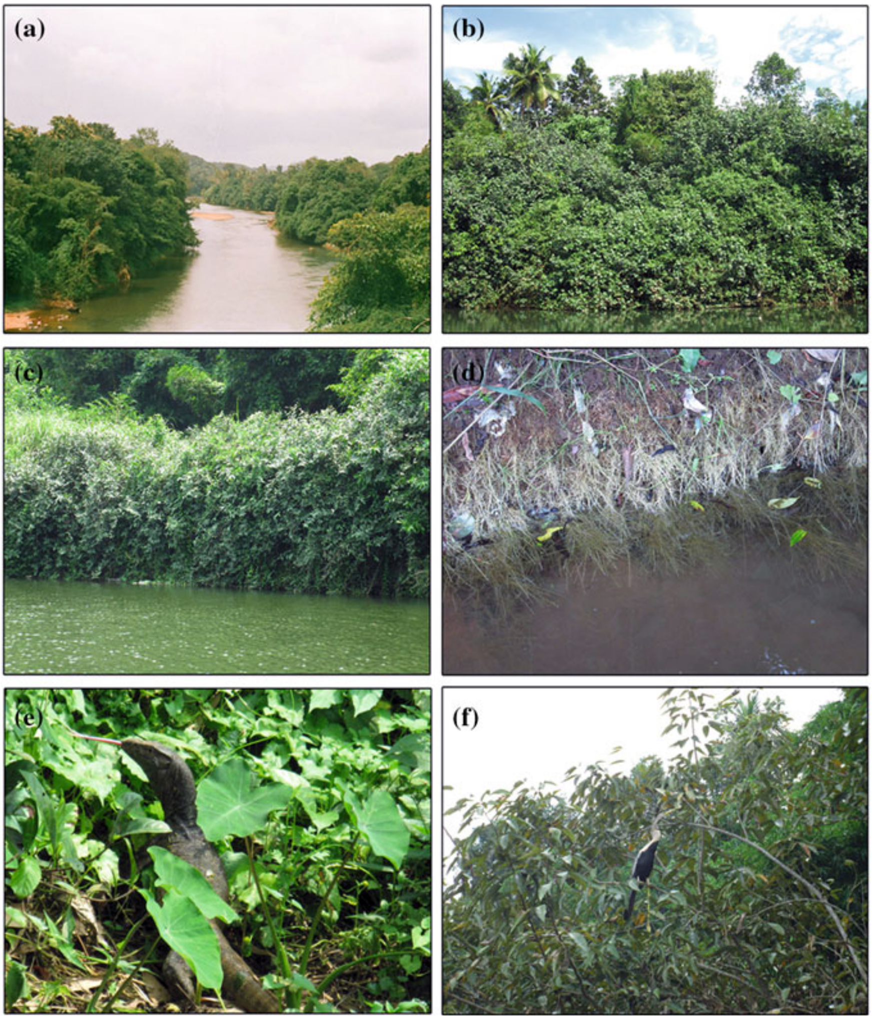

Plate 2.1 Functions of riparian vegetation. **a** Dense riparian vegetation along the banks of river forms a protective sheath; **b** Riparian vegetation and its canopy not only protect river banks but also regulate water flow during high flow regime; **c** Bio-shielding of river banks by creepers; **d** Profuse development of roots of certain riparian plants (*Ochreinauclea missionis*) creates a blanket on river banks and thus rescue them from failure incidences/erosion; **e** and **f** The riparian vegetation provides habitat to many animals like Monitor lizard and birds

(Plate 2.1). The riparian environment hosts many ecologically significant and economically important plants (Plate 2.2). They offer shade and shelter to a variety of organisms including rare and endangered ones.

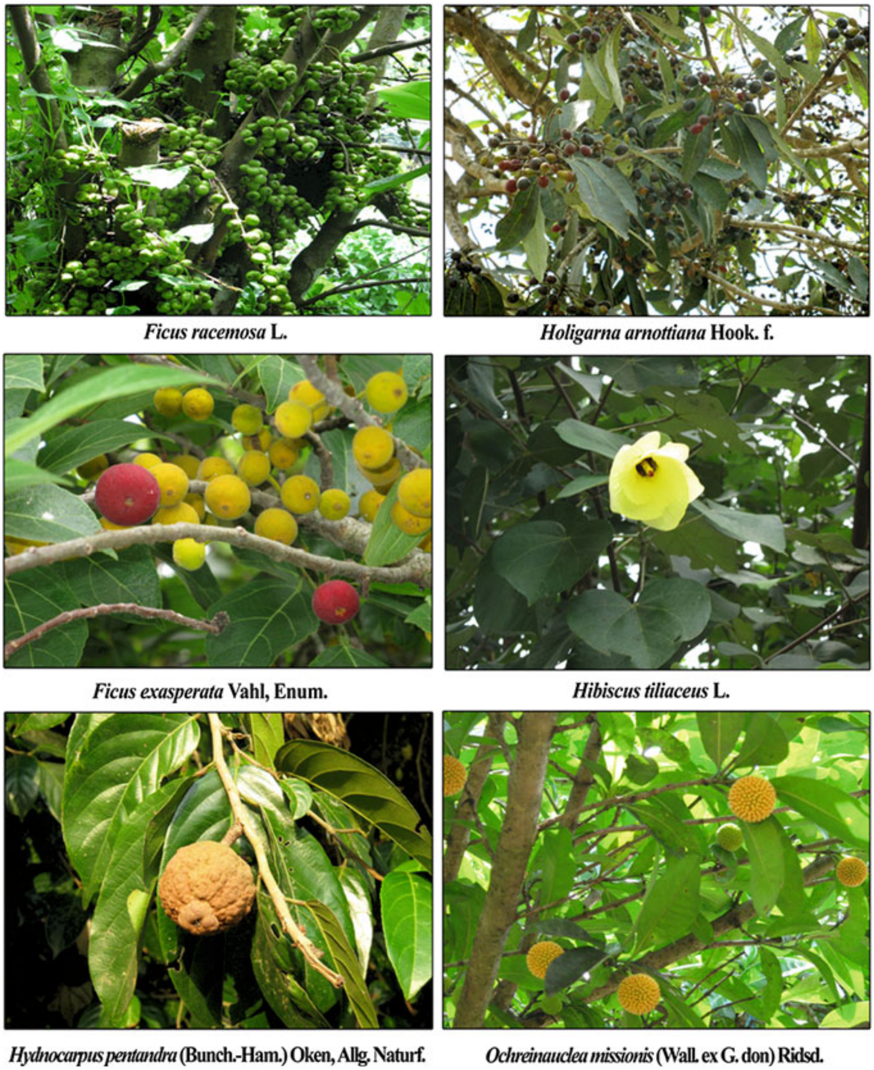

Plate 2.2 Some of the common riparian plants in the small rivers in the southwest coast of India

2.3 Geological Work of Rivers

The water flowing through a river could erode the land over which it flows, transport sediments that are formed by weathering and erosion, and finally deposit the transported materials, under favorable conditions into discrete landforms. According to Schumm (1977), an idealized river system can be divided broadly into three zones—(i) production zone or a zone of sediment erosion, (ii) zone of

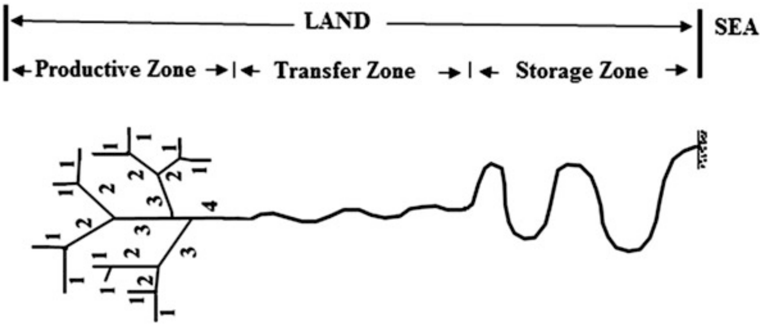

Fig. 2.2 The three primary zones of a river (after Schumm 1977)

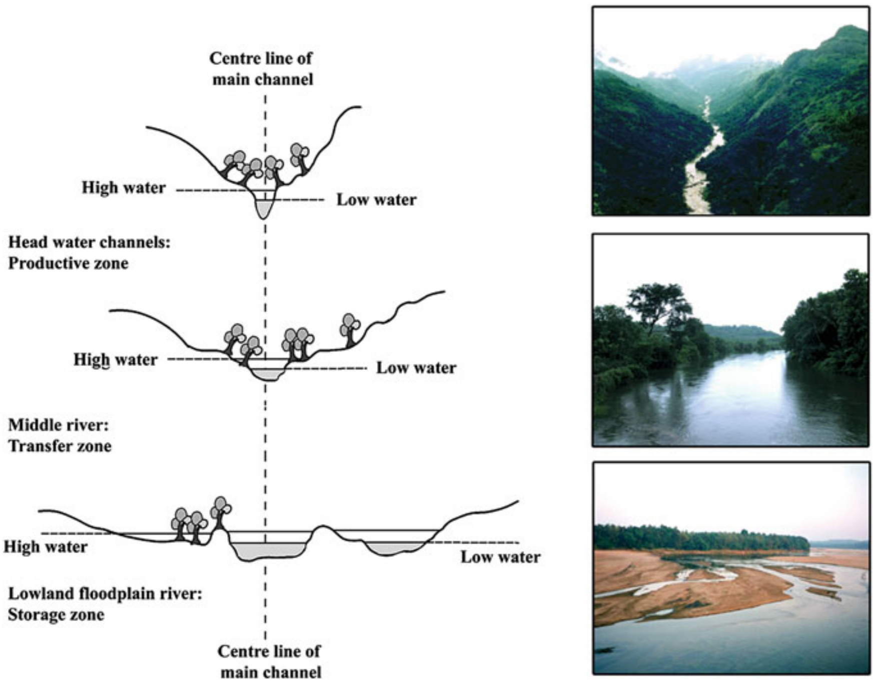

Fig. 2.3 Cross profiles of a river in the production, transfer and storage zones along with field evidences from the respective zones

sediment transfer, and (iii) a zone of deposition (Fig. 2.2). Figure 2.3 depicts cross profiles of a river in production, transfer, and storage zones along with field evidences from the respective zones.

The production zone will be steep, rapidly eroding head waters, whereas in transport zone the sediment is moved without net gain or loss. The transported materials will be deposited in the storage zone of the river under favorable conditions. The rate of erosion varies widely both spatially and temporarily. For example, the Appalachian mountains (North America) are eroded at about 0.01 mm/year (Leopold et al. 1964), the southern Alps of Newzealand at about 11 mm/year (Griffiths and McSaveney 1983), and southern central Range of Taiwan over 20 mm/year. The work of rivers is of considerable importance in land sculpturing. The entire processes involved in the geological work of rivers can be divided into three distinct processes, such as (a) erosion (hydraulic action, abrasion, attrition, and solution), (b) transportation (bedload, saltation, suspension, and dissolved forms), and (c) deposition (as fluvial landforms). Of these processes, the first process brings about degradation of the terrain, while deposition causes aggradation at suitable sites under favorable conditions. In the upper course of a river, processes are dominated by sediment production and incision of the channel into the landscape. The process of erosion becomes very conspicuous in excavating or downcutting the valley floor. The size of the sediment transported in any segment of the river is dependent on the geology of the basin as well as the distance of the segment from the source. The amount of sediment load carried depends on the size of the material, discharge, slope, and channel and catchment characteristics. When there is reduction in the discharge or in the slope of equilibrium, the same cannot transport the material supplied to it. Hence the stream deposits its excess materials in the form of floodplains, alluvial fans, deltas, etc., depending on the size and specific gravity of the material.

2.4 River Sediments and Channel Processes

River sediments comprise a spectrum of particle sizes such as boulder, cobble, pebble, granule, sand, silt, and clay (Lane 1947). Among these, the largest particles commonly occur in upland channels where the terrain gradient is the highest, while finer entities are enriched progressively downstream due to sediment sorting based on size and specific gravity (Blatt et al. 1972). Lower channel gradients in the lowlands favor deposition of small-sized particles and help floodplain development (Kondolf 1997). However, in the lower reaches, smaller tributaries can often contribute coarser particles to the mainstream. Table 2.1 shows the classification of sediment particles used widely by engineers and ecologists (Garde and Ranga Raju 1985; Jeffries and Miller 1990). Plate 2.3 shows the river bed characteristics of small rivers in the southwestern coast of India.

Collins and Dunne (1989) recognized three sediment delivery processes such as (1) mass wasting on hill slope, (2) hill slope erosion, and (3) erosion of channel bed and banks. Mass wasting includes landslides and soil creep, and occurs when gravity moves soil into the river channels. Hill slope erosion occurs when precipitation intensity exceeds the absorption capacity of soil and generates overland

Table 2.1 Grade scale for size terms applied for clastic sediments

Range in mm	Class name	Range in mm	Class name
4,096–2,048	Very large boulders	1/2–1/4	Medium sand
2,048–1,024	Large boulders	1/4–1/8	Fine sand
1,024–512	Medium boulders	1/8–1/16	Very fine sand
512–256	Small boulders	1/16–1/32	Coarse silt
256–128	Large cobbles	1/32–1/64	Medium silt
128–64	Small cobbles	1/64–1/128	Fine silt
64–32	Very coarse gravel	1/128–1/256	Very fine silt
32–16	Coarse gravel	1/256–1/512	Coarse clay
16–8	Medium gravel	1/512–1/1,024	Medium clay
8–4	Fine gravel	1/1,024–1/2,048	Fine clay
4–2	Very fine gravel	1/2,048–1/4,096	Very fine clay
2–1	Very coarse sand		
1–1/2	Coarse sand		

Source Lane 1947

flow. Stream channels and floodplains are built up and maintained by erosion and deposition of sediments during high stream flows (Whiting 1998). In relatively undisturbed river systems at its mature phase, gradual erosion of outside bends of meanders and deposition of eroded materials on inside bends cause an imperceptible shifting of channels within its floodplain. This form of stability is called dynamic equilibrium (Heede 1986). Although river flows and sediment loads vary annually or even seasonally, sediment balance and channel stability occur over the long-term. Instabilities introduced by human activities like deforestation, sand and gravel mining, and other activities, and natural processes like extreme precipitation, forest fires, and other events can cause channel bed and banks to become net sources of sediment.

2.5 River Classification

The classification of rivers are complicated by both longitudinal and lateral linkages, by changes that occur in the physical features over time, and by boundaries between apparent patches that are often indistinct. Davis (1899) divided rivers into three classes based on relative stages of channel developments—youthful, mature, and old age. River classification systems based on qualitative and descriptive delineations were developed by Melton (1957) and Matthes (1956). Broadly, two types of river classifications exist in literature—(1) physical and (2) biotic. Most classifications are based on characteristics of biota (Huet 1954; Hawkins et al. 1993) or valley types (Thornbury 1969) or fluvial features (Galay et al. 1973; Mollard 1973), but a few are based on other characteristics like levee formations (Culbertson et al. 1967) and floodplain types (Nanson and Croke 1992).

Plate 2.3 River bed materials. **a** and **b** Cobble bed river reach; **c** Rocky river bed; **d** Pebble bed—a close view; **e** Pebble bed showing patches of well sorted, fine to very fine sand deposited from bottom suspension due to obstruction by vegetation in the river bed; **f** Sand deposit in the storage zone

Another important classification proposed by Milliman and Syvitski (1992) is based on headwater elevation of rivers. They classified rivers as high mountain (headwater elevation >3,000 m amsl), mountainous (1,000–3,000 m amsl), upland (500–1,000 m amsl), lowland (100–500 m amsl) and coastal plain (<100 m amsl) rivers. The quality of river water was also considered, in some cases, for classifying rivers (Sioli 1950; Furch and Junk 1997). Based on this, the rivers are classified as black water rivers, white water rivers, and clear water rivers. A black water river is one with a deep, slow moving channel that flows through forested swamps and wetlands. The black color of river water is attributed to leaching of tannins from decayed leaves of adjoining vegetated lands. Black water rivers are seen in Amazonia, Orinoco basin, Southern and Northern United States. Negro river is the largest black water river in the world, and is one of the largest Amazonian tributaries. The white water rivers are muddy in color due to their high sediment content, while clear water rivers drain areas where there is little erosion. Based on the flow characteristics /water availability, rivers are classified into three—(1) ephemeral, (2) intermediate, and (3) perennial. Ephemeral rivers are those that do not flow continuously throughout the year. Such rivers are common in semi-arid and desert regions. Intermediate rivers are those that carry water almost throughout the year and dry up in extreme droughts. Some rivers flow throughout the year even in extreme droughts and are called perennial rivers.

2.6 Concepts in Riverine Studies

Ecological studies of river systems have made many advances during 1980s and 1990s, and several new paradigms such as the river continuum and nutrient spiraling concepts have emerged during this period. The following section deals with a brief account of the various classic concepts of riverine studies.

2.6.1 River Continuum Concept

The river continuum concept was developed by Vannote et al. (1980). The concept was developed from the idea that river systems, from headwaters to the mouth, present a continuous gradient of physical conditions. This gradient provides the physical template upon which the biotic communities and their associated processes developed. As a result, one would expect to observe recognizable patterns in the community structure and input, transport, utilization, and storage of organic matter. It proposes that energy inputs will change in a longitudinal direction, in relation to channel size, degree of shading, light penetration, and so on. And, the relative importance of functional feeding groups will change in tandem.

2.6.2 Nutrient Spiraling Concept

Webster (1975) and Webster and Patten (1979) proposed nutrient spiraling as a mechanism to account for the apparent ability of stream ecosystems to withstand and recover from disturbance. The term spiraling refers to the spatially dependent cycling of nutrients and the processing (i.e., oxidation and conditioning) of organic matter in lotic ecosystems. In effect, the nutrient spiraling concept provides both a conceptual and quantitative framework for describing the temporal and spatial dynamics of nutrients and organic matter in flowing waters. It also allows the structural and functional aspects of the biotic communities that enhance the retention and utilization of nutrients and organic matter to be interpreted in terms of ecosystem productivity and stability. Later Wallace et al. (1977) applied the idea in describing the role of filter feeders in streams. Newbold and his colleagues developed mathematical models at Oak Ridge National Laboratories to explain this concept (Newbold et al. 1981; 1982a, b; Elwood et al. 1983). These collective studies are termed as the nutrient spiraling concept.

2.6.3 Flood Pulse Concept

This concept was developed by Junk et al. (1989). The principal driving force behind the existence, productivity, and interaction of the diverse biota in river—floodplain systems is the flood pulse. A spectrum of geomorphological and hydrological conditions produces flood pulses, which ranges from unpredictable to predictable and from short to long duration. Short and generally unpredictable flood pulses occur in headwater streams and in streams heavily modified by human activities, whereas long duration and generally predictable floods occur in larger rivers. The net result is that the biota and the associated system level processes reflect the characteristics of the flood regime. Its basis is that the pulsing of river discharge—the flood pulse—is the major force controlling biota in river floodplains, and that lateral exchange between the river channel and its floodplains is more important in determining nutrient and carbon supply in lower reaches than longitudinal connections (Fig. 2.2).

2.7 Human Interventions

The dynamics of river systems are affected greatly by human interventions either within the catchment or directly within the river corridor (Petts and Calow 1996). River regulation by dams, diversions, channelization, and other physical controls, resource extraction including sand and gravel, etc., has significantly altered majority of the world rivers. The physical, chemical, and biological characteristics of rivers suffer from these effects. In addition to directly altering river flow, anthropogenic activities transform the landscape through which the river flows. Erosion delivers more sediment to river channel, with detrimental effects on the instream habitat. Removal of riparian vegetation leads to rise in temperature of overlying waters, shift from heterotrophy to autotrophy, reduced bank stability, and loss of the natural capacity to prevent sediments and nutrients from reaching

Plate 2.4 Environmental degradation caused by human interventions: **a** Disposal of solid waste into river channel is a common practice in many rivers; **b** Encroachment on a river channel; **c** and **d** Removal of riparian vegetation for sand mining and agricultural activities

river channels. Anthropogenic activities also enhance the quantity of chemical wastes entering in rivers, both from agricultural and urban sources.

Human impacts on river ecosystems may vary in character, and the way in which they are mitigated or resolved depends on whether they are 'planned' or 'unplanned' (Plate 2.4). 'Planned impacts' are usually direct and quickly felt effects, such as land use changes or in-channel changes by construction and /or mining activities. Clearing of forest cover on slopes close to channel margins may increase the quantity and speed of overland flow. Construction of bridges and check dams modifies local flow behavior in channels, causing scour of adjacent bed and bank sediments. Construction of large impoundments as well as large-scale riverbed mining is the most radical form of human impacts (Elliott and Parker 1997; Hadley and Emmett 1998 and Kondolf 1997). Although this form of intervention can exert long-term effects, most of them are, in principle, reversible, or at least amenable to mitigation. Channel works can be removed or redesigned; land use change can be reversed. 'Unplanned effects' are usually delayed in their onset, and are often more difficult to identify, and may be cumulative. Protection and restoration of rivers from anthropogenic disturbances is the need of the hour. Rivers have considerable ability to recover from 'pulse events', such as chemical inputs from an accidental spill or a point source. Unfortunately, threats like sand and gravel mining, channelization and other forms of regulations /modifications that affect morphological character of rivers are essentially continuous, or 'press events'. These require much more effort to address, and one hopes that the principles of ecology and geomorphology will be considered /viewed seriously while designing conservation and management strategies of these life-sustaining systems.

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