Chapter 9
Riparian Ecotones: An Important Derivative for Managing River Pollution

Shikha Sharma, Madhoolika Agrawal, and Arijit Roy

9.1 Introduction

The rivers around the world have been attempted with technological know how while addressing the issues of water pollution. Recently, Rowinski et al. (2018) suggested for nature-based solutions (NBS), a solution which mimics nature while restoring the degrading rivers. The NBS emphasises over the role and importance of riparian vegetation in improving the water quality. The importance of establishing the riparian ecotones for maintaining the water quality has been emphasised since the 1980s (Roberts and Krishnaswami 1982; Sirenko 1981).

The word "riparian" has been defined variedly in the literature and has been associated with variable suffixes. However, riparian vegetation in most simplistic manner designates to the vegetation flanking the riverbank. These vegetation are the diversified ecosystem encompassing the distinct biological diversity, capable of bringing physiochemical and biological changes in the environment (Tabacchi et al. 2000) and are also proving to be efficient solutions for scrubbing harmful pollutants entering the river (Rowinski et al. 2018).

Several researchers via both field and laboratory experiments have established that vegetation along the riverbank has shown equal or better performance than grey infrastructure employed for improving the river water quality (Rowinski et al. 2018; Liquete et al. 2016; Gonzalez et al. 2015). On the broad scale, the vegetation in the riparian ecotone reduces the impact of pollutants on the river environment by acting as a barrier trapping and breaking down the pollutants or sometimes even processing

S. Sharma · A. Roy (✉)
Indian Institute of Remote Sensing, Indian Space Organisation, Dehradun, India
e-mail: arijitroy@iirs.gov.in

M. Agrawal
Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, Uttar Pradesh, India

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them into other less toxic compounds within the ecotone before the runoff reaches the water body (Rowinski et al. 2018). These systems have been explored in terms of the removal efficiency of pollutants such as nitrogen (N), phosphorus (P) and sediment. Most of the researches pertaining to the role of riparian vegetation in reducing pollutants from river water are confined to the countries of Europe and North America (Vidon et al. 2019) with minimal work being reported from India.

The present scenario of rivers in India demands a research outlook to the role of riparian vegetation as NBS for Indian rivers, as these systems lie at the crossroads of the biosphere, hydrosphere, lithosphere, atmosphere and anthrosphere and are an important part of riverine systems, serving multiple socioecological functions (Dufour et al. 2019; Naiman et al. 2005).

9.2 Defining the Word "Riparian"

The word riparian has a lingual derivation from the Latin word "riparius," meaning from "bank" (https://www.merriam-webster.com/). The origin of this word dates back to the mid-nineteenth century. The initial usage of the term was notably legal rather than scientific. The legal usage of the term dates back to the 1800s confined to political boundaries of the USA for describing the property of citizens adjacent to stream or river (Klett 2002; Baker 2002). However, on the scientific background, it is difficult to trace as to when did the scientists first adopted the term "riparian". Baker (2002) states that this term started appearing in scientific literature since the 1970s. Later during the 1980s, several scientists, agencies and the public were seen managing the riparian areas; thus it was during this decade which an effort was made to define this term; consequently, this decade was seen with conceptualising what "riparian" actually is, and the year 1985 was termed as "the year of the riparian" (Anderson 1987).

In literature the word "riparian" has not been defined as a single entity but in association with various suffixes such as riparian area, riparian zone, riparian reserve, riparian system, riparian ecosystem, riparian corridor and riparian ecotone. Verry et al. (2004) stated that the meanings of all the suffixes are more or less similar. Among the suffixes used, the most common ones are riparian zone and riparian buffer zone. Both of these suffixes have been intermittently used by the researchers, Wegner (1999) puts forth the difference between these two words, explaining that "buffer" is used with riparian as suffix during measurement of the important function of this transition zone, i.e. to shield the rivers/streams from the anthropogenic influences. The differentiation of Wegner (1999) points towards the importance of these areas/zones. Other than these suffixes, the word "riparian zone" has also been synonymously used as stream corridor, river corridor, ribbons of life, riparian woodlands, riparian forests, riparian buffer zones, riparian strips, riparian zones, alluvial floodplains, etc. (Zaimes et al. 2010). This addition of varied suffixes and synonymous usage of the word "riparian" perplexes the researcher as to what to add to riparian while defining it in river science. To make it a little simpler, Ilhardt et al.

(2000) and Verry et al. (2004) suggested to add the term "ecotone" with riparian, because it is not an ecosystem rather a part of the two ecosystems. Thus, it can be stated that in the legacy of the use of varied suffixes the suffix "ecotone" goes much in compliance.

Along with the variability related to the use of suffixes and synonyms against the word riparian, a large amount of variability can also be seen in defining the word "riparian". There is no universally accepted definition of the term riparian by the scientific or regulatory community (Zaimes et al. 2007). The term "riparian" has been defined like a tailor-made approach by the researchers of varied disciplines so far, with each of them emphasising according to their disciplines.

9.2.1 Criteria of Defining "Riparian" in Literature so Far

The definition of the word "riparian" has seen a progression from legal aspect to scientific; since the 1980s, several researchers have added different aspects of varied scientific disciplines subsequently seeing a progression.

1. Legal – The term has been used by the US government, in policy and regulations related to water law. The term was used basically to protect the area near the water bodies from anthropogenic activities. Further these zones were considered both hydrologically and ecologically important (FEMAT 1993; Parrott et al. 1997; NRCS 2002).
2. Hydrologic – The authors have defined riparian zone in connection with the river flows indicating towards an area close to the river (Bren 1993; Malanson 1993; Osterkamp 2008; Lovett and Price 1999).
3. Ecology (vegetation) – The word "riparian" has been used over the years by several ecologists to define the vegetated strip near the river (Narumalani et al. 1997; Gregory et al. 1991; Martin et al. 1999).
4. Edaphic – The scientists used an approach defining riparian areas on the basis of soil water availability (Naiman et al. 1993; Naiman and Decamps 1997; Ledesma et al. 2018).

Over the period of time, several authors have attempted to comprehensively discuss the progression and variability in defining the riparian areas. To be mentioned are review papers by Verry et al. (2004), Naiman et al. (2005), Clerici et al. (2011) and Dufour et al. (2019). Baker (2002) asserted that no one definition satisfies more than two to three disciplines, as every researcher emphasises the subject matter while defining the riparian. According to Verry et al. (2004) "the concept of riparian must tie definition, delineation and resource data aggregation together into a logical sequence", and defining "riparian" must include geomorphology, ecology and species association (Verry et al. 2004; Dufour et al. 2019).

The vast array of riparian definitions ranges from simplest to complex, further to structural and functional type. The simplest form of defining the word riparian is considering it as a transition zone, while complexity arises when considering it as the ecotone, wherein the biotic and abiotic interactions are taking place. The simplest definition of riparian comes from Gregory (1991) "as the transition zone, an interface between terrestrial aquatic ecosystems". However, much before Gregory et al. (1991), Lowrance et al. (1985) included organisms while defining riparian and defined riparian as an ecosystem having the complex assemblage of organisms and their environment existing adjacent to and near flowing water. Adding to the definition of riparian was the water extension, which led Naiman and Decamps (1997) to define riparian as a stream channel between the low and high water marks and that portion of the terrestrial landscape from the high water mark towards the upland where vegetation may be influenced by elevated water tables or flooding and by the ability of the soils to hold water. Adding to it is the recent definition by a soil scientist Ledesma et al. (2018) who defined riparian as "the area between the edge of the stream and characteristic transition between organic and mineral soils". The most complicated definition comes by Ilhardt et al. (2000) as 3D ecotones wherein interaction between terrestrial and aquatic ecosystems exists; this area extends from groundwater to over the canopy top, beyond the floodplains, near to the slopes, draining water also having lateral connections with terrestrial ecosystem along the water course, and the width of the zone may vary accordingly.

A review by Dufour et al. (2019) comprehensively categorises riparian definition into functional and structural type. The structural definition defines the riparian from topographical perspectives, whereas functional approach defines considering the interactions between two systems, viz. aquatic and terrestrial, in terms of hydrological, morphological, chemical and biological processes. The authors suggest that most of the definitions of riparian use a functional approach. Defining the riparian areas from structural perspective puts forth the geomorphological perspective of riparian zone which deals with various fluvial features and landforms formed by river deposits (Dufour et al. 2019). Dufour et al. (2019) emphasised that structural approach is more used in delineating the riparian extent.

The diversified definition and suffixes of the word riparian still perplex researchers, so it is important to come on one common note, thus accepting ecotone as suffix to the word riparian and definition by Ilhardt et al. (2000), which not only considers the biotic and abiotic interactions but also gives the spatial dimension to the riparian ecotone, thus defining it completely. So further in the chapter, the authors will be referring to riparian areas as riparian ecotone.

9.3 Components and Characteristics of Riparian Ecotone

Riparian ecotone, being the transition zone between the terrestrial and aquatic ecosystems, comprises of the two important components, viz. land and water. Further, talking in terms of ecology, this transition zones contain both abiotic (soil and water) and biotic (organisms from microscopic to macroscopic fauna and flora) components. These are thus the basic components of riparian areas; however, each river has its unique riparian ecotone with their distinct geomorphology and ecology.

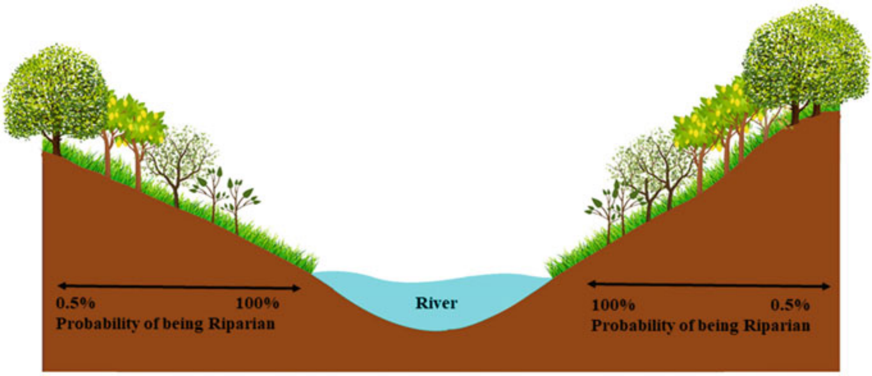

Fig. 9.1 Probability of area to be a riparian ecotone. (Source Ilhardt et al. 2000)

However, in the literature, the riparian ecotone has mostly been discussed in terms of vegetation type, and it is the vegetation which is of importance and mainly researched and discussed. However, Zaimes et al. (2010) ascertain that the riparian ecotone possesses the following common characteristics:

1. The land along the river or fluvial system comprising of distinct vegetation type influencing and being influenced by the various physicochemical and biological interactions between the vegetation, land and water.
2. This ecotone sometime is encompassed within the floodplain or sometime may extend beyond it. However, Ilhardt (2000) stated that the frequency of designating an area to be riparian decreases with distance from the fluvial system (Fig. 9.1).
3. These are the areas through which surface and subsurface hydrology connects water bodies with their adjacent uplands.
4. These areas are distinguished from upland areas via distinct physicochemical, biological and ecological processes and biota.
5. These areas have a distinct mosaic of vegetated patches having different physiognomy, structure and composition.
6. These areas are characterised by varied land use features changing in accordance to the human population.
7. These areas witness local variability in the physical conditions such as flow velocity (flood and drought), water level, etc.

The important thing to note is that areas cannot be categorised or undergo zonation or have similar characteristics at global level because their characteristic features can change in accordance with the region.

9.4 Functions of Riparian Ecotone

Though having characteristics and distinct features, the riparian ecotone delivers an important role in both the terrestrial and aquatic ecosystems, which remains homogenous across the globe. These ecotones play an important role in physical, biological and ecological functions (Klapproth and Johnson 2009), adding to the importance of interactions taking place in this zone between soil, water and biotic communities. The functions of riparian ecotone are dependent on the land use features comprising the riparian ecotone. All over the globe, these regions are experiencing the transformation from natural vegetation to agriculture and subsequently to human habitations (Sharma et al. 2016). However, the role, importance or function of riparian ecotone is discussed and researched mostly in terms of natural vegetation. Certain basic functions of riparian areas are as stated below.

9.4.1 Bank Stabilisation

The vegetation cover over soil has already been known to hold the soil, thus playing the prominent role in the conservation of the top soil. A similar kind of role has been reported long back during the 1980s for establishing the importance of vegetation near rivers towards riverbank stabilisation (Omernik et al. 1981; Smith 1992; Arthington et al. 1997; Townsend and Douglas 2000). Riparian vegetation has shown to play an important role in protecting the river shorelines from damage caused to soil during heavy flows such as runoff from upland or downpours (EPA 2010). Riparian vegetation mediates their input by armouring stream banks against erosion, storing runoff, trapping sediment and transforming nutrients (Omernik et al. 1981; Smith 1992; Osborne and Kovacic 1993; Arthington et al. 1997; Townsend and Douglas 2000) (Fig. 9.2).

The mechanism by which riparian area does is slowing the flow of water, thus ensuring that sediments settle out before they reach the water course (Montgomery et al., 1996). In a naturally vegetated riparian ecotone, floodwater overshoots from the bank and spreads out the broad floodplain, thus reducing the energy of the water (https://www.nrcs.usda.gov/). As floodwater flows through a vegetated area, the plants resist the flow and dissipate the energy, increasing the time available for water to infiltrate into the soil and be stored for use by plants (https://www.nrcs.usda.gov/). The roots of the plants increase the riverbank cohesiveness adding a tensile strength which enables the riverbank soil to resists shear stresses (Castelle and Johnson 2000). Thus, de-voiding the fluvial system from its natural vegetation can have adverse effects on the stability of its bank (Fig. 9.2).

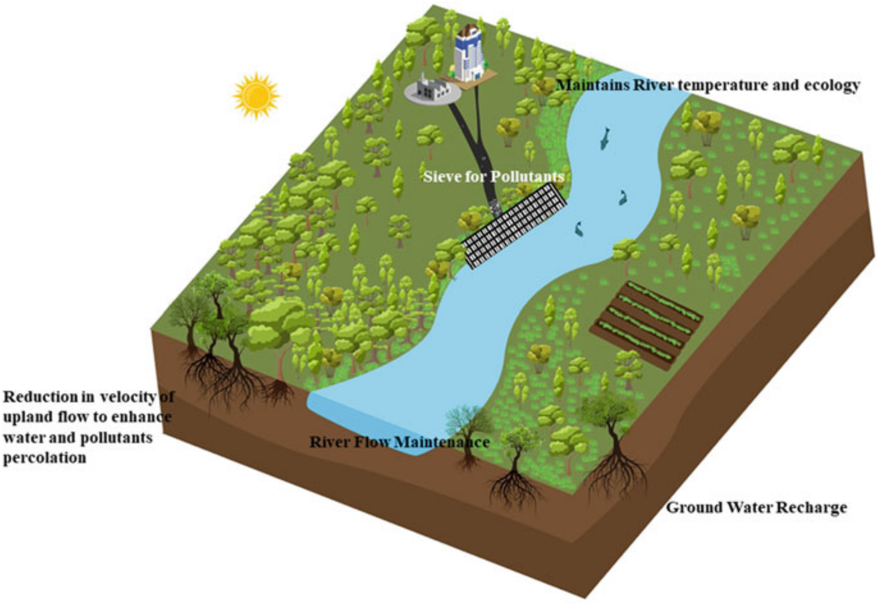

Fig. 9.2 Functions of riparian ecotone

9.4.2 Filtration

The riparian ecotone acts as filter for the river; Pinay et al. (2018) have termed it as a "skin for the river". The water draining downwards via riparian ecotone undergoes natural filtration process for the absorption and adsorption of sediments, pollutants, etc. The process of filtration takes place by the vegetation (Luke et al. 2007) and microbial fauna present in the riparian ecotone (Silvan et al. 2002; Palviainen et al. 2004). The vegetation present in the riparian ecotone decreases the export of suspended solids by reducing the velocity of overland flow and thus enhancing water infiltration into soil leading to particle sedimentation (Gundersen et al. 2010). The sedimentation rate depends on flow velocity, particle size and particle density (Gundersen et al. 2010) (Fig. 9.2).

The pollutants such as compounds of nitrogen, phosphorus, potassium, calcium, magnesium, etc. are adsorbed by the plant root system and used as source of nutrients for growth (Mayer et al. 2007). Recently riparian ecotones have also been reported as the carbon pool (Forster et al. 2007). The soil C concentration is largely dependent on soil moisture, and riparian ecotone having high moisture content serves to hold greater carbon per unit area as compared to upland forests (Forster et al. 2007). Thus riparian ecotone comprising of vegetation acts as nutrient sink and sediment entrapment owing to the uptake and sorption processes, thus playing an important role in the protection of river water quality (Fig. 9.2).

9.4.3 Flow Regulation and Groundwater Recharge

The riparian vegetation affects the river flow and is termed as safety valve of the watershed (gov.mb.ca). The reason for designating riparian ecotone as safety valve is the vegetation, which slows the water flow, thus reducing the intensity of flood further downstream of the river channel. This not only controls flood but also the upland water flow into the river, thus maintaining the river flow. Hydrologically, riparian ecotones are considered as discharge areas through which water flows before reaching surface water (Gundersen et al. 2010) (Fig. 9.2).

These areas are often characterised by a high groundwater table and superficial subsurface flow created by groundwater exfiltration (Gundersen et al. 2010). As the vegetation slows down the water velocity, it in turn increases the retention time of water in this zone enhancing the groundwater potential of that region (Swanson et al. 2017). The reduction in the speed of water allows increase in absorption of water into the soil, thus replenishing groundwater reserves (Swanson et al. 2017). The percolation down into the ground is also dependent on soil types of the region. The silt texture of the soil acts as a sponge to aid in groundwater recharge and underground storage. Not only this, the water stored in the ground seeps into the river through lateral connectivity during lean season, thus maintaining river flow throughout the season (https://www.nrcs.usda.gov/). Riparian vegetation in the riparian ecotone is thus important to maintain the river flow, prevent flood and recharge the groundwater (Fig. 9.2).

9.4.4 Maintaining River Channel Environment

The riparian vegetation has proved to play a crucial role in maintaining the river environment, viz. river water temperature and organic-inorganic inputs into the river. The types of vegetation affect the intensity of light reaching the river water; the dense canopy lowers the river water, whereas the open canopy raises the river water (Garner et al. 2017) (Fig. 9.2).

Maintaining the river temperature is essential to prevent the faster rate of chemical speciation subsequently leading to rise in pollutant levels in the river water. The temperature also influences the dissolved oxygen content of the river. The optimised temperature of river water is also essential for the biological activity of the river diversity. The autochthonous input from the vegetation near the river plays an essential role in the river biotic life. Organic matter from riparian ecotones, such as leaves, twigs, logs and stems that fall from the buffer into the water, are the main source of food for aquatic macroinvertebrates (Mayer et al. 2006). The debris or wood from vegetation traps additional leaf litter and wood. Macroinvertebrates use the wood as habitat, living inside the wood, under residual bark and on surfaces that protrude out of the water (Mayer et al. 2006) (Fig. 9.2).

9.5 Riparian Vegetation as Pollutants Scrubber

9.5.1 Ecology of Vegetation

Plant ecology is a wholesome branch of ecological sciences studying how plants interact with their abiotic and biotic environment. These interactions vary in terms of type of species dominating a particular region. The riparian plants acquiring a different physical habitat have altogether different ecological attributes. In order to understand how riparian plants maintain the water quality of the river, it is very important to understand the riparian plant ecology. The likelihood that a particular riparian vegetation type will occur in a given watershed depends on the ecological tolerances of the component plant species and their adaptations for specific hydrogeomorphic conditions, along with water availability, anaerobic soils, surface characteristics and flood disturbance regimes (Steiger et al. 2005). The functionality of riparian vegetation in controlling the water pollutant is dependent over the structural physiological traits of vegetation such as size, form, growth rate, longevity and litter quality (Dosskey et al. 2010). Not only the type but age of vegetation can also play an important role in pollutant removal as the efficiency of the plants declines with age.

The riparian plants vary from region to region so is the ecology; thus, it becomes essential to study the kind of riparian vegetation harbouring the bank of the rivers (Fig. 9.3). Internationally there have been numerous studies both in field and in laboratory to analyse the riparian vegetation for their composition and potency to remove pollutants. The vegetation types analysed are grass riparian ecotone and forested riparian ecotone. Parkyn (2004) reported that most of the researchers have studied the efficiencies of vegetated filter strips of rank paddock grasses. However, in Indian context, the riparian vegetation is studied mostly in terms of determining floristic composition of the species, and very few emphasised their role in removing pollutants. The riparian vegetation reported is diversified across the rivers from plain to mountains (Fig. 9.3). The species reported from plains are *Prosopis* sp., *Acacia* sp., *Azadirachta* sp. and *Jatropha* sp., along the river Yamuna in the floodplain (Jha et al. 2010), whereas *Rhododendron* sp., *Quercus* sp., *Woodfordia* sp., *Oxalis* sp., *Tridax* sp., etc. have been reported from Bhilangna River (tributary of river Bhagirathi) of the Himalayan region.

9.5.2 Mechanism of Pollutant Removal

The plants have their own mechanism and processes for removal of the pollutants, and both above and below ground biomass structure determine the effects of vegetation on river water quality (Dosskey et al. 2010). The riparian vegetation is a community with high productivity resulting in higher nutrient uptake from soil and groundwater via its own growth. Long back in 1985, it has been established that the

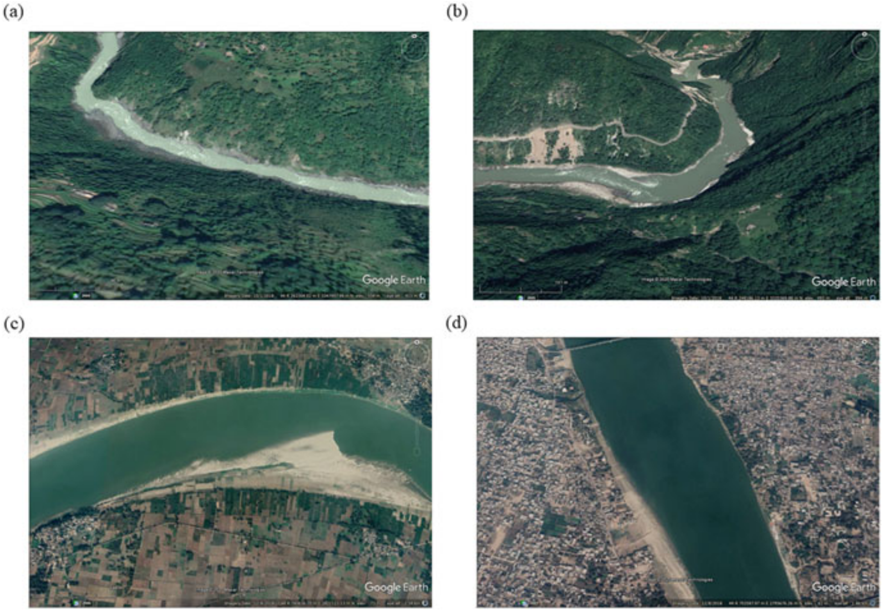

Fig. 9.3 Ecology of riparian vegetation in different regions of Indian river basins. (**a**) Dense vegetation of river Bhagirathi in the hills. (**b**) Dense vegetation of river Ganga in foothills. (**c**) Agricultural practice in the riparian ecotone of river Ganga in plains. (**d**) Human habitation harbouring the riparian ecotone of river Ganga in plains

vegetation near the river or in a watershed spreads and divides the upland flow, thus reducing the velocity (Clinnick 1985) and consequently enhancing the infiltration (Norris 1993). Osborne and Kovacic (1993) explained that major mechanisms involved in the removal of pollutants in the riparian ecotones are physical retention, plant uptake, dilution and chemical transformation.

The riparian vegetation both directly and indirectly improves the water quality (Tabacchi et al. 2000). The shoots and plant litter (above ground biomass) have direct interactions with precipitation and surface runoff in riparian zone (Dosskey et al. 2010), whereas the root systems have indirect interactions with water seeping inside the soil as groundwater (Dosskey et al. 2010). The plants also supplement food in the form of organic matter to autotrophs, which play an important role in transforming the substance dissolved in upland flow, thus contributing in enhancing water quality of the region (Tabacchi et al. 2000).

The stems and litter in the vegetated strip provide resistance to flow of river water via increasing hydraulic roughness (Parkyn 2004; Dosskey et al. 2010). This hydraulic roughness lowers the flow velocity and sediment transport capacity of surface runoff, thus increasing the contact time of water (Parkyn 2004) leading to enhancement of deposition and infiltration of particulates (Gharabaghi et al. 2002). The pollutants which are soluble infiltrate into the ground, and those insoluble deposit above ground (Gharabaghi et al. 2002). Along with this, the root activity, viz. growth and decay, followed by the activity of plant microfauna also increases the soil permeability by creating pores via which water carrying pollutants percolate down (Cardoso et al. 2013). Thus, the more the hydraulic roughness of the riparian ecotone, more will be the infiltration, and less will be the tendency of the surface runoff to input sediments and pollutants into the river.

Among the varied processes of pollutant removal, the absorption by the roots is predominantly researched. The plant roots have been associated with supplying the majority of nutrients to the shoots mostly phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S) and some other non-nutrients such as Cd, Cr, Hg, Ni, Pb, As, Se, B, Cs and Sr (White and Brown 2010). Many researchers have also reported plants as the important contributors in solubilising pesticides, volatile organic compounds (benzene, trichloroethylene and toluene) and selenium and organo-mercury compounds (Lin et al. 2008; Juraske et al. 2008). But in the water quality studies, the chemical entities of much concern are N and P, K and metals. Not only plant roots but shoots too play an important role in nutrient management. The plant leaves and foliage intercept and evaporate the considerable amount of rainfall and prevent it from reaching the soil (Tabacchi et al. 2000), thus working at canopy level. Further several researchers have established that vegetation increases evapotranspiration from watersheds (Trimble et al. 1987) and riparian zones (Cleverly et al. 2006; Kellogg et al. 2008).

Other than the role of live plant parts, litter too plays an important role in pollutant scrubbing. The plant litter being rich in organic matter retains the pollutants dissolved in percolating water via processes such as ionic attraction, hydrogen-ligand bonding, etc. (Dosskey et al. 2010). There have been report that agricultural pesticides and endocrine disruptors have high binding affinity to soil organic matter and undergo immobilisation (Yamamoto et al. 2003) which can be further degraded by soil microbial fauna. Further the indirect form of pollutant removal by plant is also done by activating the microbes, which switch to alternative electron acceptors such as nitrate, sulphate and oxidised iron and manganese compounds during limited supply of oxygen, thus supporting further decomposition of these compounds (Hill 2000). The riparian soil is often reported with limited oxygen conditions because the decomposition of plant detritus consumes the limited supply of oxygen in wet and saturated soil (Zaimes et al. 2007). The second indirect role includes the activity of organisms such as mycorrhizal fungi or root symbiotic sites. The symbiotic association in plants is associated with increase in the nutrient uptake efficiency by enhancing the volume and surface interaction between the plant and physical environment (Tabacchi et al. 2000).

9.5.3 Types of Riparian Vegetation and Their Pollutant Removal Capacity

There are two most prominent types of vegetation studied in the riparian ecotone, viz. grasses and forest, with their type varying from region to region. The two predominant vegetation types have different roles in the pollutant removal. The grass riparian ecotones are capable of filtering sediments and pollutants associated with sediments such as phosphorus and nitrogen (Parkyn 2004). Further there are reports that grass riparian ecotones are less effective in the removal of soluble nutrients such as nitrate, ammonia and dissolved phosphorus and nitrate removal is greater in forested buffers compared to grasses (Parkyn 2004).

The role of riparian buffer strips in relation to nitrogen has been well studied (Peterjohn and Correll 1984; Daniels and Gilliam 1996). There is a large variability in the removal efficiency of N ranging from 20 to 100% (Valkama et al. 2019). The removal of N and P via vegetation in the riparian ecotone varies widely, and it is difficult to predict (Hoffmann et al. 2009) as the hydrological regimes controlling the biogeochemical processes in the riparian zone change along the river continuum (Hoffmann et al. 2009). None of the riparian ecotone vegetation types, viz. grass or forested, are much effective in reducing concentration of dissolved phosphorus (Parkyn 2004). In most of the research monitoring, the effectiveness of buffer zones for their pollutant removal capacity has focused on vegetated filter strips (VFS) (Parkyn 2004).

Riparian forest reduces the nitrate input into the river via the uptake by plant roots (Silvan et al. 2002; Palviainen et al. 2004), retention to soil and utilisation by the microbes (Silvan et al. 2002; Palviainen et al. 2004), also via gaseous N fluxes from soil to the atmosphere (Silvan et al. 2002). The different fractions of nitrogen, viz. ammonium, nitrate and dissolved organic nitrogen, undergo transformation in the soil for their effective utilisation and assimilation. The riparian forest decreases the concentration of ammonium and dissolved organic nitrogen in surface runoff more than nitrate (Kokkonen et al. 2006).

During the 1980s and 1990s, the mechanism of phosphorus removal by riparian buffers has been studied by several researchers. The mechanisms explained are deposition of phosphorus attached with sediment, settling of particulate phosphorus and adsorption of dissolved phosphorus by clay particles in particular clay containing high levels of aluminium and iron (Reddy et al. 1999). Further there are reports of phosphorus reduction via uptake from understory vegetation and microorganisms (Silvan et al. 2004).

9.6 Other Attributes of Riparian Ecotone Affecting the Pollutant Removal Efficiency

The knowledge of the hydrogeomorphic regimes has been ascertained as the key limitation in the management and restoration of degraded riparian ecotones (Shaw and Cooper 2008). The study of riparian system as a whole requires an understanding of the geomorphic structures and processes that form the bed sediments and maintain flow pathways through them. Further Engelhardt et al. (2012) suggested that it is important to ascertain the relationship between watershed lithology, geomorphology and riparian vegetation for the development, management and restoration of riparian vegetation. Thus, the hydrogeomorphology of the watershed also plays an important role in the pollutant removal activities of the riparian ecotones.

9.6.1 Geomorphology of the Riparian Ecotone

There are various geomorphological attributes associated with riparian ecotone. Morphologically the riparian ecotones differ from other upland features as they receive drainage from large contributing areas, characterised by shallow groundwater table and relatively low slope gradients. The literature suggests that geomorphological attributes affect the pollutant removal functionality of riparian ecotone in two ways: (1) direct and (2) indirect. Certain features, viz. sediment size, sediment load, slope, soil structure, subsurface drainage pattern, etc., of the riparian ecotone affect the pollutant removal, posing direct affect. Indirect effects include the structure, type and distribution of riparian vegetation, which in turn are determined by the geomorphological traits of the region.

The geomorphology of the watershed regulates the movement of both water and sediment, through watershed into the channel and via channel network (Engelhardt et al. 2012). The capacity of riparian ecotone to remove pollutants increases if the flow across the watershed is not canalised rather distributed across wide areas (Polyakov et al. 2005). Further, the slope of the zone is also an important determinant of pollutant trapping efficiency of the ecotone (Jin and Römkens 2001). Another topographic feature of importance in determining the buffering capacity of riparian ecotone is convergence factor, which is the ratio of active area of the riparian buffer to the total area (Polykov et al. 2005). Active area of the riparian buffer according to Polykov et al. 2005 "is the portion of buffer through which runoff flow from the upslope occurs". A low convergence value is indicative of dissected relief, gully and steep valley floors, and higher values (value close to 1) indicate towards plain conditions (Polykov et al. 2005).

The riparian soil-holding capacity, soil type, soil water content, soil particle size and soil aggregate density affect the pollutant removal capacity of the buffer (Munoz-Carpena et al. 1999). The properties of riparian ecotone to trap sediment decrease with reduction in sediment size (Lee et al. 2003). If the riparian ecotone is

Fig. 9.4 Development of river island of the river Ganga (geomorphological feature) and variations in ecology of riparian vegetation

formed of coarse-grained alluvial sediments, it allows complex microbial assemblage and metazoan biota (Huggenberger et al. 1998). It is the three processes, viz. erosion, transportation and deposition, which determine the structure of fluvial forms and hydrogeological properties, thus governing the connectivity between surrounding landscape to the drainage network (Huggenberger et al. 1998). The morphological attributes, viz. length, gradient and shape of the runoff area and that of upstream of riparian ecotone, affect the pollutant removal capacity (Norris 1993). For example, in a convex slope, the upland flow is faster than the concave slope (Norris 1993).

Recently, Pinay et al. (2018) stated that along the river continuum, we could determine three distinct geomorphic characteristics, viz. in the headwater, in the middle reaches and in the lower reaches. These physical or geologic features control the distribution of grain sizes as well as successional dynamics and structure of vegetation communities along the river continuum (Gregory et al. 1991). The headwaters, which are steep, have constrained valleys with high erosional rate and less formation of geological features resulting in minimal riparian vegetation development; in the middle reaches, the slope is comparatively less steep and transports minimum sediment leading to formation of river island and sediment deposition offering sites for generation of riparian vegetation (Pinay et al. 2018). Depositional reaches in the lowland valleys with very fine unstable sediment deposits are important for the development of riparian vegetation (Pinay et al. 2018) (Fig. 9.4).

Several basin properties influence vegetation types because they pose a direct influence on flood regime and water availability. In a study conducted by Engelhardt et al. (2012) in 18 upland watersheds of central Nevada, USA, the following morphometric parameters were studied, viz. watershed area, watershed length, total stream length, drainage density, Shreve magnitude, relief, ruggedness, relief ration, relative stream power, watershed shape and hypsometric integral. Engelhardt et al. (2012) ascertained that composition of riparian ecotone is a function of those geomorphological characteristics of watershed which influence flood regimes, sediment transport and water availability also inclusive of hypsometric integral, relative stream power and topographic relief. It was observed that riparian vegetation distribution and composition were determined by both geologic and morphometric variables. Bedrock lithology is also an important feature determining the riparian vegetation composition.

9.6.2 Hydrology of the Riparian Ecotone

Among the several abiotic (e.g. water chemistry, light and wind) and biotic (e.g. competition, invasive species; see in the succeeding paragraphs) factors that influence riparian vegetation processes, fluvial hydrodynamics (i.e. flow and flood regime and related processes) plays a significant role in all plant life stages, i.e. dispersal, colonisation, recruitment, growth, succession and mortality (Solari et al. 2016). Successful riparian plants often adopt a combination of adaptive strategies during different life stages in order to ensure their survival (e.g. high dispersal rates, adaptations to resist stress and vegetative reproduction; Camporeale et al. 2013).

Norris, 1993, stated that "effectiveness of riparian buffer ecotone depends upon the rate of flow of surface water, hydraulic conductivity and holding capacity of the buffer zone soil". The water or upland flow which passes through the watershed via riparian ecotone exhibits variable random forcing over the vegetation among which the important one is flow variability (Vesipa et al. 2017). The river stage and velocity affect the riparian environment. The variability in the flow regime of the river affects the riparian vegetation from its establishment to its death. The river flow of ample magnitude is needed to remove the vegetation already harbouring the riverbank (Holanda et al. 2005) and further depositing the fresh sediments for the recruitment of new seeds of plants.

The rivers also are known to be associated with the phenomenon of hydrochory. For hydrochory to take place, it is essential that the river shows fluctuations in its flows (Greet et al. 2011). The rise and fall of the river are essential for collection and deposition of seeds (Vesipa et al. 2017). Certain hydraulic conditions such as Froude, Reynolds and Shield number associated with river hydrographs determine the number of seeds scoured or deposited. Other than the recruitment of seeds, the flow of the river also plays an important role in determining whether the seed will germinate and grow into an adult (Fraaije et al. 2015). Both the sudden decline and sudden rise in river water affect the growth of the seedling.

These river flows are also associated with effects on the adult vegetation in their life stage (Garssen et al. 2015). The river flow affects the age and spatial distribution of populations (Mosner et al. 2011). River flow fluctuations affect the stratigraphy of riverbanks (Merritt et al. 2010). The variability in river flow is also responsible for transport of nutrients and salts which are required for the sustenance of vegetation (Asaeda and Rashid 2014). Thus, river flow is the important driver of riparian vegetation.

9.7 Conclusions

The riparian vegetation is turning as one of the natural means of maintaining the river water quality with recently their importance being more emphasised over technical solutions of combating river pollution. The word "riparian" and the suffixes used with it have been associated with the inherent variability. The literature suggests the inherent variability in definitions of the word "riparian" and the suffixes used. The definition of the term and its usage have evolved from legal to scientific, with each branch of science defining it in its own way. The author suggests that the definition given by Ilhardt et al. (2000) is more complete and should be universally used henceforth; further, the most appropriate suffix to explain the functionality of riparian areas is "ecotone," given by Ilhardt et al. (2000).

These areas are to be looked as of utmost importance because of their important role in maintaining the fluvial landscape. The researchers have emphasised over their role in stabilising the riverbank, in filtering the pollutants, in regulating the river flow and groundwater recharge and also for maintaining the river ecosystem. These functions of riparian ecotone are dependent on the type of vegetation harbouring the riverbank. Most of the researches have been done to see the effectiveness of grass and forest riparian ecotone with sediments, nitrate and phosphorus as pollutants. The literature suggests a few studies from India being cited in the context of laying the importance of riparian ecotone, thus requiring directives to research the Indian river from riparian ecotone perspective and including it in river management plans.

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