
11 The Ecohydrological Approach as a Tool for Managing Water Quality in Large South American Rivers

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Introduction

The ecohydrological approach (Zalewski *et al.*, 1997) stems from our understanding that aquatic ecosystems contain intrinsic water purification systems wherein physical, biological and chemical processes interact to maintain water quantity and quality within ranges acceptable to the majority of organisms. These intrinsic services of water purification function to some extent throughout river corridors, but they tend to be accentuated in specific features such as riparian zones, wetlands and flood plains. Ecohydrologists strongly believe that by improving our understanding of natural water purification processes, humans can make use of these features as explicit tools in larger water management programmes, serving to complement and enhance engineering plans. This improved understanding would also enable humans to better preserve critical ecosystem components and to ensure that they continue to fulfil their ecological roles.

In this chapter the utility of the ecohydrological approach to managing water quality in large neo-tropical river basins is examined. Ecohydrology should play an expanded, and in some cases commanding, role in water quality management in the humid tropics. Severe economic problems in most tropical countries preclude the widespread installation of expensive water supply and waste treatment systems. What money is available from international aid agencies is targeted for high-priority urban areas and water-starved areas on the margins of the tropics and in other developing nations. Vast areas of the more humid tropics must rely on low-cost water management systems that make rational and complementary use of the inherent assimilation capacity of riverine ecosystems. Fortunately, large portions of Earth's major tropical river basins retain more or less natural hydrological cycles and geomorphological features. These areas are especially favourable for making an ecohydrological approach the primary approach to water quality management.

This chapter presents an overview of the condition of Earth's large tropical rivers. It then reviews the intrinsic water-purifying capacity of river systems and presents an example of this capacity in the Amazon basin. In the final section it discusses the integration of an ecohydrological approach into tropical water management programmes.

The Condition of Earth's Large Tropical Rivers and Limitations to Their Management

Earth's most intense and persistent band of rainfall encircles the globe at the equator, bathing much of the tropics in abundant fresh water. Consequently, several of the planet's great rivers are born in this region. Earth's largest river, the Amazon, follows the equator eastward across the South American continent, draining the largest remaining track of tropical rainforest and discharging nearly 20% of all continental freshwater runoff into the western Atlantic ocean (Table 11.1 and Fig. 11.1). In Africa, the Congo river collects a full one-third of that continent's runoff and delivers it into the eastern Atlantic ocean. Across Asia,

Table 11.1. Major rivers of the tropics.

River basin	Basin area ($\times 10^6$ km ²) ^a	Average discharge (km ³ /year) ^b	Countries traversed ^a
Amazon	6144	6300	Brazil, Peru, Bolivia, Colombia, Ecuador, Venezuela, Guyana
Congo	3807	1250	Congo, Central African Republic, Angola, Zambia, Tanzania, Cameroon, Burundi, Rwanda
Orinoco	954	1100	Venezuela, Colombia
Mekong	806	470	China, Laos, Myanmar, Thailand, Cambodia, Vietnam
Magdalena	264	237	Colombia
Zambezi	1332	223	Zambia, Angola, Zimbabwe, Tanzania, Mozambique, Malawi, Botswana, Namibia
Niger	2262	192	Mali, Nigeria, Niger, Algeria, Guinea, Chad, Cameroon, Burkina Faso, Benin, Côte d'Ivoire, Chad
São Francisco	618	97	Brazil
Nile	3255	30	Sudan, Ethiopia, Egypt, Uganda, Burundi, Tanzania, Kenya, Congo, Rwanda, Eritrea
Fly	61 ^b	77	Papua New Guinea
Purari	31 ^b	77	Papua New Guinea

Sources: ^aWorld Resources (1998); ^bMilliman and Meade (1983).

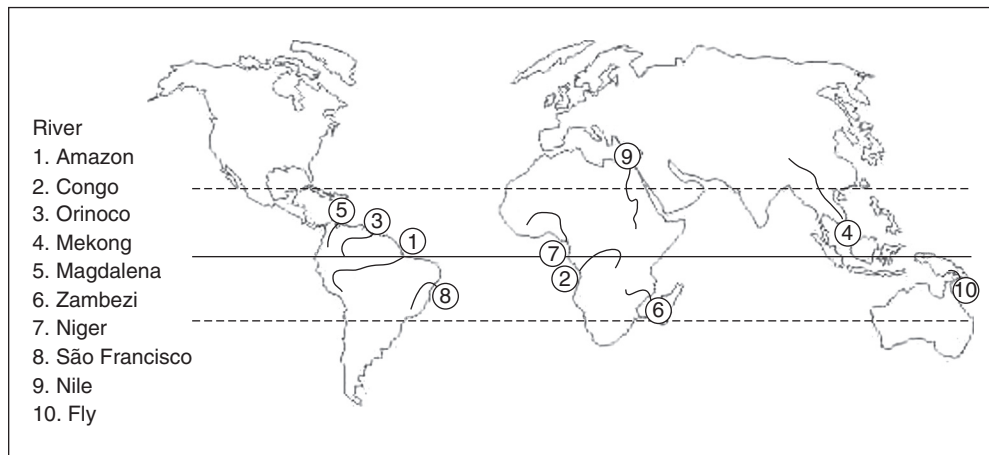


Fig. 11.1. World map showing the locations of the major tropical rivers discussed in the chapter.

where no continental landmass lies on the equator, the countless smaller rivers of the region's island nations exhibit the highest water yields on the planet, and deliver these waters and entrained sediments to the Indian and western Pacific oceans.

In contrast to the humid landscapes through which these rivers flow, other large tropical rivers such as the Zambezi, Niger, Orinoco and São Francisco pass through more arid landscapes characterized by vast savannahs or even deserts. As a special case, the Nile river flows as a singular source of water through one of the most arid parts of the planet, making possible all life within its valley. The Mekong river is interesting in that it presents the reverse case of the Nile, originating on the arid Mongolian Plateau and descending into the humid landscape of Indochina. In all, the rivers listed in Table 11.1 account for 32% of total continental freshwater runoff.

The diversity of life and other natural features in tropical river basins is truly remarkable. While the rainforests of Amazonia, the Congo and South-East Asia occupy little more than 7% of Earth's land surface, they are home to more than half of its species (Wilson, 1988). This phenomenal biodiversity extends into the rivers as well. In the Amazon, approximately 1700 fish species have been described so far, and Goulding *et al.* (1996) estimate that the total fish species diversity will approach 3000. The Amazon river also contains many curiously unique species such as the pink dolphin (*Inia geoffrensis*), piranha (Subfamily Serrasalminae) and giant river turtle (*Podocnemis expansa*).

Over the coming decades, more than 90% of population growth is expected to occur in the tropics. Currently, the human populations occupying tropical river basins vary greatly in density and the extent to which they have altered the river basins (Table 11.2). Population densities are highest in the Magdalena and Zambezi and lowest in the Amazon. Population densities in all of these river basins, however, are low when compared with major European basins such as the Rhine

Table 11.2. Population, land use and environmental conditions in selected large tropical rivers. (From World Resources, 1998.)

River basin	Population density (/km ²)	Land use			Original forest loss (%)	Arid area (%)	Wetlands area (%)	Protected area (%)
		Cropland (%)	Forest (%)	Developed (%)				
Amazon	4.3	14.9	72.9	0.5	13.2	4.0	8.3	7.0
Congo	14.5	7.8	43.4	–	45.9	0.0	9.0	4.7
Orinoco	13.1	18.8	49.6	2.8	22.5	8.5	15.3	23.7
Mekong	77.6	37.9	41.5	2.2	69.2	0.0	8.7	5.4
Magdalena	78.8	38.6	36.6	10.0	87.5	7.2	0.2	4.0
Zambezi	17.7	20.4	4.1	–	43.1	8.7	7.6	7.7
Niger	31.2	5.0	0.3	1.1	95.9	65.4	4.1	4.9
São Francisco	17.6	61.4	0.8	2.4	64.4	32.0	9.7	0.5
Nile	42.7	10.3	2.0	1.1	92.1	67.4	6.1	4.4

(304 people/km²) and the Danube (103 people/km²). The Nile and Niger basins have seen the greatest reduction in their original forest cover, but all basins with the possible exception of the Amazon suffer from severe deforestation. Of course the Amazon basin is currently undergoing rapid deforestation, and its percentage forest loss is expected to increase incrementally over the coming years. Percentage cropland is relatively low in each catchment, with the exception of the São Francisco basin. The Magdalena is the most developed from an urban and industrial standpoint.

A common denominator in nearly all tropical river basins is poverty. From the standpoint of water resources management, poverty may be seen as a crippling obstacle in tropical basins. The average per capita gross national product of all countries listed in Table 11.1 is US\$837. Arranged according to continent, average per capita gross national products are US\$1892 in South America, US\$569 in Africa and US\$897 in South-East Asia (World Resources, 1998). Significant national investments in water resources have therefore been minimal historically, and they are likely to remain low for the foreseeable future. Nearly all capital for major water works projects has come from international financial aid, which is now at a 50-year low. At least 18 of the countries making up the major tropical river basins are classified as 'severely indebted' by the World Bank (1999) and another five are classified as 'moderately indebted'.

A second common denominator between these tropical basins is a direct and generally unbuffered dependence of the local populations on water and other aquatic resources from the river systems. Although data are not available basin by basin, local people take their drinking water from nearby streams and rivers and consume it with little or no form of treatment. Similarly, human and other wastes are commonly disposed of in rivers without treatment. The effects of poor waste-disposal practices and drinking untreated water are reflected in health statistics from countries of the region. In 16 of the countries for which data are available, 21% of rural children below 5 years of age suffer from chronic

diarrhoea (World Resources, 1998). Individual country data range from 13% in Brazil and Egypt to 29% in Kenya. Of the countries considered, Egypt and Brazil are the two in which the greatest percentage of rural households have piped water, 50% and 13%, respectively. On average, only 8% of rural households in the remaining countries have piped water. Cases of children's diarrhoea are not much better in urban parts of these countries (average 19%). In fact, in Bolivia and Côte d'Ivoire there are more documented cases of diarrhoea among urban children than rural children. Inadequate systems for human waste disposal explain much of this poor urban health. Only 32% of urban households in these countries are connected to sewer systems.

The area of large-scale water infrastructure that has received the greatest investment in tropical countries is irrigation and hydropower. Considerable international financing has gone towards the construction of dams to provide for these services. At least 15 major dams (greater than 1000 MW installed capacity) and countless small-scale projects have been constructed in the major tropical basins (Gleick, 1993). In Brazil, a full 95% of the country's electricity comes from hydropower, and the majority of the country's untapped potential lies in the Amazon. Brazil thus has ambitious plans to develop an additional 25 dams in this region. These plans are complicated, however, by the exceedingly low elevation and flat relief of the Amazon. The Balbina Dam, for example, forms a reservoir covering 2300 km² but generating only 250 MW of electricity (Smith *et al.*, 1995). This generation efficiency of 2 kW/ha of reservoir is extremely low and means that large areas of rainforest must be flooded to generate modest amounts of electricity. During the construction of the Tucuruí Dam in the Amazon, between 20,000 and 30,000 people had to be relocated. With respect to water for irrigation, reservoirs built in tropical river basins generally service only small percentages of land under cultivation. With the exception of Egypt, where 100% of cultivated land is irrigated, other tropical African nations generally apply irrigation waters to less than 5% of their cultivated lands. Although slightly higher, the same may be said for percentages of cultivated land irrigated in South America. In Indochina, between 4% and 52% of cultivated land is irrigated. Thus, water subject to expensive and engineering-intensive management schemes in tropical basins may be said to play a generally small role in overall regional water use.

The quality of water in large tropical river basins is not well known. Dismal health statistics from throughout the region suggest that water quality is poor in most urban and many rural locations. According to the findings of the First Assessment of Global Freshwater Quality published by the World Health Organization and United Nations Environment Programme (Meybeck *et al.*, 1989), organic matter in the form of domestic sewage, municipal wastes and effluents from agricultural industries makes up the most ubiquitous source of water pollution. Organic pollution is made worse by the presence of pathogens. Indeed, in the Amazon basin, alarmingly high bacterial concentrations occur in the La Paz river as it exits the city of La Paz, Bolivia, and extending more than 40 km downstream (Ohno *et al.*, 1997). This bacterial contamination has been linked to a high incidence of diarrhoeal disease in the city of La Paz. The Oropouche virus has been detected near the city of Iquitos in the lowland Amazon of Peru and

was found to be transmitted to the population of the city and surrounding areas (Watts *et al.*, 1997). High levels of organic pollutants in tributaries of the Niger river are attributed to runoff from agricultural fields and animal lots (Nwokedi and Obodo, 1993).

Throughout the tropics, inappropriate land management practices and over-exploitation contribute to increased erosion and elevated sediment loads in streams and rivers. The extent of degradation of water quality from erosion is variable and not well known. Large sections of land within the São Francisco, Niger and Nile river basins have been classified as being at very high risk of erosion and desertification. Parts of these basins already show evidence of severe erosion (Seager, 1990). In the more humid basins of the tropics, widespread erosion is less prevalent and generally not a problem so long as an adequate litter and vegetation layer stabilizes the soil (Bruijnzeel, 1990). There are, however, more localized occurrences of severe erosion when the protective layer is absent and when extreme precipitation events occur. The consequences of additional erosion include siltation of reservoirs, possible damage to other engineering infrastructures, smothering of aquatic habitats, and diminished water quality for drinking and other domestic uses. Sediments may also have associated chemical contaminants, which when dissolved or desorbed further degrade water quality.

Contaminants such as pesticides, petroleum products and heavy metals also pollute tropical river basins, but generally in a more localized form. Mining activities in the Papuan highlands have contaminated sediments of the Fly river with copper, lead and zinc (Baker and Harris, 1991). Soltan *et al.* (1996) also reported high levels of lead in sediments above the High Aswan dam on the Nile river. This lead is largely attributed to the gasoline spills from the 200 ships and 300 boats operating on that section of the river. Oil spills have been reported in oil-producing areas throughout the tropics and, although there are undoubtedly been several disastrous spills, there are few quantitative data on which to quantify the impacts of these spills. Pesticide use is generally low throughout the large tropical river basins, as is the use of artificial fertilizers. This is especially true in Africa and South America, and less so in Asia. The explanation for low agrochemical use is largely economical, as poverty within these nations limits the purchase of these products.

Based on the preceding paragraphs, the general condition of large tropical river basins may be summarized as follows. Climatically, geologically and biologically they are extremely diverse, ranging from high-yield rivers draining young terrain covered by dense tropical rainforest to low-yield rivers draining ancient terrain covered by savannahs or deserts. However, they share a common set of problems, which are linked to poverty and a dependence on outside capital to finance large engineering operations. They are also similar in that they contain large rural populations in intimate contact with river water and whose numbers are expected to grow exponentially over the coming decades. In general, water management schemes are simple and controlled by the end users (not large water supply and waste treatment infrastructures). The most prolific contamination problems take the form of excess organic waste, pathogens and sediment. These seemingly low-grade problems are accentuated by a lack of

proper water treatment prior to domestic consumption. Occasional more severe contamination occurs from pesticides, heavy metals and petroleum wastes in areas of industrial activity and hydrocarbon exploration. Expensive and highly engineered solutions to water resource problems are not practical today, and are unlikely to become practical for several decades.

Ecohydrology and Riverine Ecosystem Resistance and Resilience

Riverine ecosystems possess an intrinsic capacity to regulate flows and quality of water passing through them. This capacity stems from finely tuned ecohydrological interactions between organisms, water and the river's material load. Interactions are biological, physical or chemical in nature, and in concert they lend resistance, resilience and adaptability to riverine ecosystems. Consequently, riverine ecosystems are able to withstand frequent low-magnitude disturbances (i.e. storms, small landslides), recover from less frequent high-magnitude disturbances (i.e. hurricanes, major landslides), and constantly adapt to changing short-term and long-term environmental variables. These disturbance regimes, and the river's response to them, are natural components of healthy riverine ecosystems (Naiman *et al.*, 1992).

In general, riparian zones and wetlands are the most important natural components of riverine ecosystems regulating the quantity and quality of water entering from uplands. Together they function as effective buffers against extreme flooding and excess sediment loads linked to runoff from the landscape. In developed areas, they are also effective buffers against excess erosion, nutrient inputs and contaminant runoff from agricultural fields, pastures and residential areas (Haycock *et al.*, 1997). Riparian zones and wetlands are most effective in the headwater portions of watersheds, where flow is distributed among a large number of smaller streams. In downstream portions of rivers and streams, water quality and fluxes are regulated by riverine wetlands and flood plains. These drainage-system components also dampen extreme runoff events and effectively strip sediments and excess nutrients from river water. A final ecosystem component which is less well understood but potentially quite important is the hyporheic zone underlying and adjoining river and stream channels (Bencala, 1993). River water maintains a direct hydraulic connection to pore waters of the sediments composing the river bed. Depending on the physical properties of the bed sediments and the geometry of the river channel, river water may repeatedly move from the river channel to underlying sediments in a coupled form of downstream flow.

The following sections provide an overview of the ecohydrological processes operating in each of these ecosystem components. Emphasis is placed on the buffering capacities of these processes and ultimately to their potential role as tools of water resource management in tropical landscapes. The great majority of material presented here comes from outside the tropics due to a lack of tropical data. In a separate section it is integrated with a specific example from the tropics.

Riparian zone processes

Riparian zones border streams, rivers, lakes and wetlands and are characterized by plant species associations that are more tolerant of a shallow water table and frequent flooding. Although their geomorphological setting may vary greatly, they commonly occur in valley bottoms and are thus more level than surrounding hill slopes. Their soils are commonly waterlogged and anoxic, creating a chemical environment that is distinct from the drier, more aerated upland soils. Frequent disturbances within the riparian zone also tend to select for fast-growing plant species. Across the landscape, riparian zones act as natural barriers between aquatic environments and terrestrial uplands. In this setting, their qualities of low relief topography, anoxic soil columns and fast-growing species make riparian zones effective traps for particulate and dissolved material moving from terrestrial to aquatic environments.

Riparian zones are capable of removing sediment, nutrients, acidity and toxic chemicals from runoff waters. These removals result from processes of sedimentation/trapping, binding/sorption, plant uptake and denitrification/organic breakdown. Each of these processes is commonly accentuated in riparian zones. Forested and grass riparian zones in the south-eastern coastal zone of the USA have been shown to remove 80–90% of sediment in runoff from adjoining croplands (Cooper *et al.*, 1987; Gilliam, 1994). Here, riparian vegetation slowed the flow of runoff waters, thereby decreasing energy levels and promoting sedimentation. Riparian vegetation also promotes increased infiltration, which captures runoff waters and retains sediments. Riparian zones exhibit a marked capability to remove excess nitrate from runoff waters. Even in agricultural settings where groundwater nitrate levels may exceed 700 μM , riparian zones have been shown to reduce nitrate concentrations by as much as 90% (Jacobs and Gilliam, 1985; Haycock and Pinay, 1993). Nitrate is removed through a combination of plant uptake and microbe-mediated denitrification. Both mechanisms are effective means of cleansing runoff waters, but denitrification is more useful in that it completely expels the excess nitrate from the ecosystem as N_2 gas. Nitrate taken up by plants is only temporarily stored in plant tissue and may be released again to soils and groundwater. Plants may facilitate the denitrification process, however, by taking up nitrate from deeper groundwater and delivering it to surface soils via litterfall (Hanson *et al.*, 1994). Denitrification potentials tend to be greater in surface soils because of abundant organic carbon, which acts as the electron donor in the reduction reaction.

The retention of phosphate in riparian zones is much less predictable than retention of nitrate (Uusi-Kämpf *et al.*, 1997). Phosphate concentrations are regulated by plant uptake and partitioning reactions with soil mineral surfaces and are only indirectly impacted by oxidation–reduction reactions. Under most natural conditions in upland areas, subsurface waters are oxic and phosphate is relatively immobile. In riparian zones anoxic conditions frequently prevail. Anoxic conditions favour the reduction and dissolution of iron oxides and consequently the liberation of sorbed phosphate. Hence, under natural conditions riparian zones may act as a source for soluble phosphorus. Several investigators have shown, however, that riparian zones may strip phosphate from contaminated

runoff waters. Madison *et al.* (1992) documented a 90–99% reduction in phosphate concentrations in runoff waters passing through a grass riparian buffer strip during simulated storms. Dillaha *et al.* (1989) similarly documented a 69–83% reduction in phosphate concentrations in agricultural runoff from a Virginia catchment. With regard to particulate phosphorus associated with sediments, retention is proportional to the quantity of sediments retained and the concentration of phosphorus in those sediments. As indicated previously, riparian zones are effective at retaining sediments and thus effective at retaining particulate phosphorus.

Pesticides washed from agricultural fields are a growing problem in aquatic ecosystems. Little research has been completed to date on the effectiveness of riparian zones in retaining pesticides, but early data from France provide some encouragement. Gril *et al.* (1997) reported that grass buffer strips reduced concentrations of lindane by 72–100%, atrazine by 44–100%, isoproturon-IPU by 75–99% and diflufenican-DFF by 68–97%. Pesticides are stripped from runoff waters via adsorption on to soil particles. The pesticides can then be broken down by soil microbes to eliminate them completely from the system. Riparian zones assist in this process by slowing the flow rate of runoff waters and allowing additional time for sorption reactions to take place. The effectiveness of riparian zones at retaining other contaminants such as organic wastes and pathogens is still very unclear (Coyne *et al.*, 1995).

Wetland and flood plain processes

Wetlands are widely distributed in river basins and may or may not be in direct hydraulic connection to the surficial drainage system. This discussion is only concerned with wetlands that have some superficial hydraulic connection with the river system, and the term 'wetland' is used to refer to those areas that are saturated on an inter-annual time scale. The term 'flood plains' refers to depositional plains running along the margin of river and stream channels, which are flooded sporadically and most often seasonally. Each of these systems possesses ecohydrological conditions that are distinct from the river and stream channels, and each exhibits a certain capacity for buffering river and stream water against the ill effects of upstream contamination and flood events.

Small wetlands in the headwater portions of watersheds act as buffers against contaminated runoff in a manner much like that of riparian forests and grass strips. In fact, small fringing wetlands are commonly integrated into riparian zones and interact closely with riparian vegetation, soils and groundwaters. These wetlands collect fast-moving runoff waters and facilitate the deposition of entrained sediments. They also harbour aquatic vegetation and macrophytes that take up excess nutrients from runoff waters. While deposition of sediment has potential for long-term storage, nutrient uptake by vegetation is generally of short-term duration (Reddy *et al.*, 1999), especially when taken up by rapidly turning over species. Longer-term storage occurs when nutrients are taken up into wetland trees. Mitsch *et al.* (1979) reported, however, that phosphorus uptake by cypress trees amounted to only 10% of the total phosphorus uptake in

an Illinois wetland. Hence it is likely that in other wetlands too only a small portion of nutrients are taken up into long-term storage pools. Headwater wetlands may also develop pockets of anoxia that support nitrate removal via denitrification (Groffman, 1994). On a river basin scale, Whigham *et al.* (1988) have suggested that sediment and nutrient retention in headwater areas should be proportional to the area covered by wetlands, but conclusive data to support this suggestion are still lacking.

Sediments and dissolved contaminants that penetrate or bypass headwater buffer zones move downstream and into larger sections of the river system. During high water phases of the river's hydrograph, some fraction of river water may move laterally out of the channel and into flood plains and riverine wetlands. Sediment and contaminant concentrations often increase during the early rising limb of river hydrographs. Thus it is likely that flood plains will receive significant pulses of these materials when they are initially inundated. The efficiency with which flood plains and riverine wetlands act as buffers depends on a number of hydraulic and biological variables. As with other ecosystem components presented in this section, flood plains and riverine wetlands slow the flow rate of river waters and thus decrease its sediment-carrying capacity and increase its interaction time with biota and sediment/soil surfaces. Sediment deposition is generally the most important long-term mechanism for retaining nutrients in river systems. In 17 riverine wetlands, Johnston (1991) reported rates of particulate nitrogen and phosphorus retention as high as 15 g/m²/year and 1.5 g/m²/year, respectively. In a riverine wetland in Wisconsin, Klopatek (1978) reported nitrogen and phosphorus uptake rates by vegetation of 20.8 g/m²/year and 5.3 g/m²/year, respectively. However, 74% and 62% of this nitrogen was returned to the water column through leaching and litterfall. An even larger percentage may have been returned through longer-term decay processes.

In-channel and hyporheic processes

In addition to buffer zones upstream and adjacent to river channels, rivers possess a certain capacity within their own channels to mitigate levels of sediments and contaminants that have come from upstream areas. The processes are similar to those discussed previously and include sediment deposition in areas of slow-moving water, plant uptake of excess nutrients, and sorption-decomposition of organic wastes. Exchange with the hyporheic zone is suggested to increase with increasing river size (Hill, 1997), provided geomorphological features (i.e. permeability and river bed topography) of the river are such that exchange is facilitated. Within the river bed sediments and hyporheic zone, denitrification and other anaerobic processes may be important.

Again the bulk of our current understanding relates to excess nutrient levels. In-channel aquatic vegetation has been reported to take up between 40 and 75% of nitrate input from upstream areas (Cooper and Cooke, 1984; Jansson *et al.*, 1994), but of course much of this nitrogen is later returned to the aquatic system. Periphyton and microorganisms can take up significant amounts of phosphorus (Newbold *et al.*, 1983), but rapid turnover rates in these biological

pools leads to only short-term storage in any single location. With all of these biological pools, however, only a small percentage of organic material enters refractory pools and is stored long-term (Gachter and Meyer, 1993).

Whole-stream experimental methods applied in the south-eastern USA have demonstrated that phosphate uptake is significantly greater in streams with greater hyporheic flow (Mulholland *et al.*, 1997). Two streams investigated were similar in many physical characteristics but differed in their ratios of surface to subsurface water volumes. One stream contained a hyporheic zone 1.5 times the volume of the stream channel, while the other contained a hyporheic zone only 0.1 times the volume of the stream channel. Consequently, water residence times were considerably higher in the stream containing greater hyporheic flow. This greater residence time is thought to be the main factor facilitating greater mass uptake rates of phosphate. Phosphate was taken up in the hyporheic-influenced stream at a rate nearly twice that of the more channelized stream (Mulholland *et al.*, 1997). Hyporheic zone processes have been shown to be quite variable in terms of nitrogen retention. Studies by Triska *et al.* (1989) and Jones *et al.* (1995) have reported a net increase in stream nitrate concentrations as a result of hyporheic processes. While it is likely that denitrification consumed some fraction of nitrate in the subsurface of these systems, this loss was more than compensated for by subsequent nitrification of ammonium liberated from decomposing organic matter.

In a review of in-channel and hyporheic retention of nutrients in lowland agricultural streams, Hill (1997) cited examples of nitrate removal that ranged from 1 to 68% of annual nitrate loading. Summer low flow retention reached as high as 76% in one Canadian stream. Hill indicated that water residence time in the stream reach was the single most important factor in determining efficiency of nitrate retention. In the same review, Hill (1997) cited examples of phosphorus removal that ranged from 20 to 92% during summer low flow. Annual removal efficiencies were presented for only one study, and those ranged from 56–59% of total phosphate loading to <5% of total phosphorus loading. Because phosphorus is generally most abundant in particulate form, sediment entrainment during occasional storm events may quickly erase gains in phosphorus retention made during low water periods. Hill (1997) indicated, however, that both nitrogen and phosphorus retention increase with increasing water temperature.

The Amazon Basin

Studies of buffering processes in riparian zones, wetlands and river channels of the tropics are exceedingly rare. While limited, investigations in the Amazon basin of Brazil may provide the most comprehensive understanding currently available on buffering processes within a large tropical river basin. Research in the Amazon has touched on the effectiveness of riparian buffers, flood plain processes and in-channel microbial activities.

In a small catchment from the central Amazon basin, Williams *et al.* (1997) evaluated the effects of deforestation on a nearby stream. They found that NO_3^- , NH_4^+ , Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , Al, Fe, Mn and dissolved organic carbon

all increased in concentration in soil water filtering through a 'cut and burnt' experimental plot. They further found that overland flow had elevated concentrations of these same ions as well as PO_4^{3-} , total dissolved phosphorus, total dissolved nitrogen, dissolved inorganic carbon and dissolved silicon. Concentrations of several of these ions were observed to increase in stream water as well, but the authors noted a significant reduction in sediment loads and NO_3^- as surface and ground waters passed through the vegetated riparian zone. In fact, sediment was completely retained in the riparian zone, and it was only in areas without riparian buffers that stream sediment concentrations increased (Williams and Melack, 1997). Thus the maintenance of riparian buffer strips along rivers and streams of the region should provide an effective shield against excess sediment and nutrient runoff from agricultural fields and pastures. As these are the dominant forms of land use in the region, riparian buffer strips will serve as the most important regional tool for surface water control.

In the Amazon basin more than 90% of all sediment transported by the river originates in the Andes mountain range. Approximately 1400 Mt/year enters the river's mainstem, from which about 200 Mt/year, or 14%, are deposited on the river's flood plain and within its channel (Dunne *et al.*, 1998). In the river water entering the flood plain, greater than 90% of suspended sediment was deposited, leading to increased water clarity and increased phytoplankton growth (Engle and Melack, 1993) (Fig. 11.2). Dramatic decreases in dissolved nutrients were also observed as river water moved across the flood plain. In addition to cleansing river flood waters, these flood plains provide habitat and food for many of the most important commercial and non-commercial fish species in the Amazon basin (Goulding *et al.*, 1996). They are thus essential centres of protein production for the region's inhabitants.

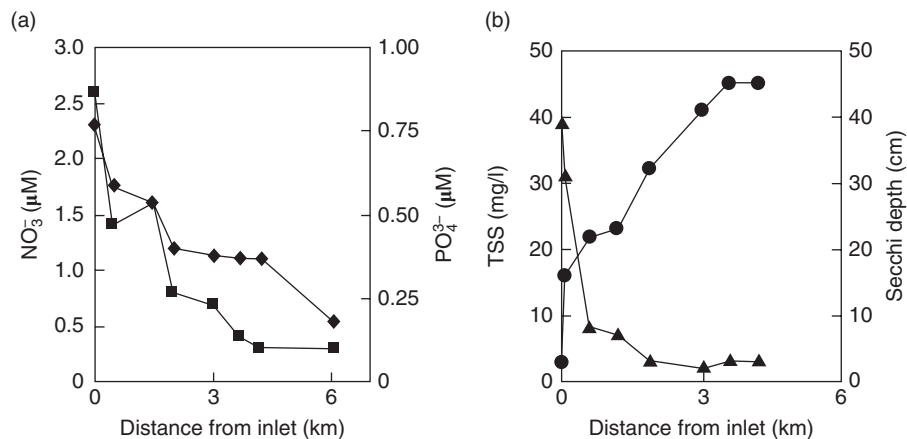


Fig. 11.2. Plots illustrating the decreasing levels of (a) nutrients (\blacksquare , NO_3^- ; \blacklozenge , PO_4^{3-}) and (b) sediments (\blacktriangle , total suspended solids (TSS)) in river waters passing through a flood plain lake of the Amazon river. Increasing water clarity reported as Secchi depth (\bullet) is also shown (b). (Adapted from Engle and Melack, 1993.)

In the mainstem river channel, available organic matter limits bacterial metabolism. Amon and Benner (1996) found microbial respiration rates to increase by a factor of 3, rising from 0.49 to 1.76 $\mu\text{M O}_2/\text{h}$, when glucose was added to the sample. Integrated across the width and depth of the river channel, these authors calculated a current consumption rate of 13.0 mmol C/m²/h. Under conditions of greater carbon availability, this rate could rise to near 40 mmol C/m²/h. Assuming an untapped consumption rate of 27 mmol C/m²/h over the 2-week travel time of water along the Amazon mainstem, the river could potentially process an additional 200 grams of organic matter per square metre of river. Given the extremely large size of the mainstem river (3–5 km wide), this rate translates to nearly 1 Mt of organic matter consumed per metre of river length. Thus the Amazon mainstem has an enormous potential for processing organic wastes discharged into it, but it is not advisable to rely on this internal cleansing potential to control organic pollution.

Integrating Ecohydrological Principles into Tropical River Management

The suite of ecosystem components and processes described in this chapter constitute the most basic and intrinsic mechanisms for maintaining the environmental integrity of river systems. Riparian zones, wetlands, flood plains and in-channel/hyporheic zones effectively regulate water fluxes and quality, thereby maintaining appropriate habitat for aquatic organisms, supplying consistent quantities of clean water for human needs, and delivering needed nutrients and organic matter to unpolluted estuary zones. While intact, these ecosystem components significantly increase the river's tolerance of both natural and anthropogenic disturbances. These ecosystem components might be viewed as the river's immune system – its 'intrinsic purification systems' (IPSS).

But how can these natural riverine components be integrated into official water management actions and policies, and what function might they realistically serve in river management plans? To some extent IPSS have already been recognized in international agreements. The 1992 International Conference on Water and the Environment, in Dublin, Ireland, made clear references to the importance of land–water linkages and 'ecosystem integrity' in achieving water resource management goals. These references were amplified and further articulated in subsequent conferences such as the 1992 United Nations Conference on Environment and Development (the Earth Summit) in Rio de Janeiro, the 1994 Summit of the Americas in Miami, the 1995 Pan-American Conference on Health and Environment in Sustainable Development in Washington, DC and the 1996 Summit Conference on Sustainable Development in Santa Cruz, Bolivia.

In the midst of this new global focus on more holistic approaches to water management, the World Bank articulated its own new approach to guide lending for water resource projects (World Bank, 1993). Recognizing past failures brought by an over-centralized approach and insufficient account of environmental concerns, the Bank's new policy called for the preparation of comprehensive national strategies that incorporate policy reforms, institutional adaptation, capacity building,

and environmental protection and restoration. Explicit attention was given in the policy to:

incentives and programs. . . to improve land management practices and to restore, then protect, environmental resources in floodplains and wetlands [with the aim of] reducing pollution, soil erosion, waterlogging, and flood runoff. . . with non-structural measures that are less costly, yet no less effective. . . (p. 61)

The plan also referred to wetlands and riverine flood plains as:

biophysical filters [that] safeguard biological diversity and conserve water resources (pp. 74–75)

Ecuador is one of many countries that have worked directly with the Bank to develop a national strategy that is in accordance with the new guidelines (CNRH, 1998). It is important to note that both the Bank policy and resulting national strategies call for a national prioritization of problems within each country and a global prioritization of the countries and regions with the most urgent needs across the globe.

While the importance of protecting riparian zones, wetlands and flood plains is now routinely acknowledged in the text of national and international water policies, the role of IPSs could be expanded such that they are employed explicitly as tools in water resource management. In urban and industrial areas, IPSs should be viewed as a crucial set of controls to fortify nearby aquatic systems and increase the likelihood that other, engineering-based controls will achieve water quality goals. Amplifying the chances that more technically complicated management activities will succeed is a wise strategy, which is why it is the guiding principle within the Ecohydrology Programme of the United Nations Educational, Scientific and Cultural Organization (Zalewski *et al.*, 1997). In rural areas, IPSs may serve as a main means of controlling surface water quality in conjunction with simple drinking water treatment and waste treatment systems (e.g. solar latrines). Other simple engineering systems in rural areas may be designed to interact with IPSs. For example, sewage from small communities can be piped into wetlands designated for the purpose of cleaning the wastewater prior to discharge to an adjoining river. Of course, in this example the value of the wetland as an IPS must be weighed against other services (e.g. fish nursery habitat) that may be lost as a result of sewage inputs.

It is beyond the scope of this chapter to propose a detailed plan for the incorporation of IPSs into river management plans in the tropics. Specific plans are likely to vary greatly in their details, just as environmental, social and economic conditions vary between the individual river basins. A few guidelines that may be widely applicable are explained here.

- 1.** IPSs should be explicitly identified in water policies and plans as tools should be used towards maintaining water quality and reducing flood hazards. Wherever possible, the services of IPSs should be quantified to justify, from an economic standpoint, the preservation of these ecosystem components. Other services of intact IPSs should also be considered in the calculation of economic value. These may include nursery habitat for juvenile commercial fish, habitat for plants and

animals that are harvested in the wild, and touristic value. Other less tangible values such as non-commercial biodiversity and ecosystem integrity should also be considered.

2. IPSs should not be viewed as independent and stand-alone solutions to water quality management problems. They should be viewed as a fundamental component of more multifaceted solutions, which should include additional systems to treat water for domestic supply and treat wastes prior to disposal. Wherever possible, the varied components should be interconnected to form a continuum of water quality management solutions. In urban and industrial situations, IPSs will play a smaller, but still important, role in management activities, while in rural situations IPSs may play a major role, even serving as the sole management tool outside individual supply and waste treatment systems in households.

3. Natural riparian zones, wetlands and flood plains are the most economical and best adapted tools to employ in water quality management plans. They need not be purchased and they are already perfectly placed in the natural hydrological pathways of the basin. Natural IPSs also provide additional services and hold greater intangible values, as listed in item 1 above. However, in basins that have already been subjected to widespread anthropogenic disturbance, it may be necessary to rehabilitate IPSs and perhaps to even construct artificial buffer systems. Artificial buffers, when properly managed, may also be used in multiple ways such as recreation, low-intensity agroforestry in the case of riparian zones, and aquaculture in the case of wetlands and flood plains. In situations where contaminant loads are unusually high, such as near mines or petroleum exploration sites, it may also be prudent to construct artificial buffer systems to enhance the capabilities of IPSs.

4. Special attention should be given to the maintenance of IPSs in headwater portions of tropical river basins. This is especially true in humid areas of high relief that are likely to be sensitive to flash flooding and mass wasting.

5. The effective use of riparian zones, wetlands and flood plains in rural water quality management plans will require the complete and voluntary participation of local communities and landholders. Local people should play a leading role in developing plans to employ IPSs, such that they share a sense of ownership of the plan. This will not only increase the likelihood of compliance among the population; it will also foster a mechanism for community-driven enforcement when individuals do not comply. Long-term community participation will perhaps be best accomplished through the formation of basin committees composed of respected local community elders, leaders and normal individuals.

6. IPSs should be incorporated into formal management plans, but ideally they will also be incorporated into cultural norms of commonsense resource management. In rural situations they are tools that nearly every landowner can make use of with no need for outside investment or expertise. If the utility of IPSs can be instilled into cultural norms, IPSs are likely to be employed in water resource management with or without formal management plans. In order to bring about this change in cultural perception, the multiple services of IPSs must be demonstrated to local communities through education programmes and example projects. Financing of these programmes in the tropics will likely require a degree of initial external financial support, but the financial benefits from protected water

quality, diminished health problems and sustained aquatic food production would far outweigh the initial investment. This would serve as a perfect example of the power of education to bring about long-term and self-sustained financial and societal benefits.

Concluding Remarks

Abundant investigative evidence from ecohydrological and other research demonstrates that riparian zones, wetlands and flood plains act as efficient 'intrinsic purification systems' in aquatic environments. Although data are lacking in the tropics, it is apparent that these IPSs also provide essential services to natural tropical ecosystems and have potential for mitigating contamination from human activities. In the impoverished river basins of the tropics, IPSs have special importance in controlling surface water quality given that more costly, engineering-based controls are not economically feasible today, nor are likely to be feasible on a wide scale for the foreseeable future. As the World Bank has recommended, water problems should be prioritized within, and among, the nations of the developing world, and the bulk of international financial aid should go towards solving the most urgent problems. On a much wider scale, however, the water quality needs of countries within the large tropical basins will be best served by conserving and rehabilitating IPSs and explicitly incorporating these systems into water management plans that also call for appropriate technologies of treatment for water supply and liquid wastes. The time to implement these regional actions is now.

On a longer timescale, the effective use of IPSs in water quality management requires that we develop a more thorough and quantitative understanding of how these systems function, what their real capacities are for processing a wide range of contaminants, and their tolerances and limitations. We must develop techniques to better integrate these natural features into human resource systems. At the same time, however, we must understand how and to what extent their use as water quality buffers impinges upon the other services they provide to ecosystems, such as critical habitat to terrestrial and aquatic organisms and corridors for animal migrations. Thus, there is a profound need for continued research which is applied and objective-driven. This need for research should in no way diminish the need for quick action to preserve and rehabilitate IPSs today.

Water problems facing the Earth's great tropical river basins are multifaceted and complicated in ways not well understood in the temperate zones. Creative and region-specific solutions must be developed, and these solutions must, even more than in the North, involve local people. One benefit, however, of the slow pace of development in the tropics is that tropical river basins tend to preserve more of their original ecosystem components than large rivers in the temperate zones. As one aspect of the move towards creative solutions in this region, the intrinsic water purification capabilities of these rivers should be recognized and more importantly put into service.