CHAPTER 11

THE APPLICATION OF ECOHYDROLOGICAL PRINCIPLES FOR BETTER WATER RESOURCES MANAGEMENT IN SOUTH AMERICA

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Clean surface water is fundamental to the health and welfare of South Americans and to the preservation of the continent's stunning natural ecosystems. The majority of water for domestic and industrial use in South America is taken from surface sources, while groundwater is important in arid regions and in some more industrialized agricultural areas to the south. Overall the continent is estimated to have 13 400 km^3 in renewable water supplies, with 21% of this flowing annually in rivers. Total annual withdrawals were estimated at 166 km^3 in 1995, with 60% going to agriculture, 20% going to domestic use, and the remainder going to industrial and other uses. South Americans also rely on surface waters for food. Recent estimates place the annual freshwater fish harvest at nearly 400 000 metric tonnes (WRI, 1998).

Currently, people in South America have unequal access to what the United Nations defines as improved drinking water and sanitation services (WHO/UNICEF, 2002). Urban inhabitants' access to improved drinking water ranges from 85% in Venezuela to 99% in Chile. However, for rural inhabitants these values fall to 70% and 58%, respectively. Suriname is reported to have the lowest percentage of rural inhabitants with access to improved drinking water (50%), while Uruguay has the highest (93%). Closely related to the issue of clean drinking water is the availability of improved sanitation services. The lowest availability of sanitation services for urban inhabitants is reported for Venezuela (71%), while the highest is for Chile (97%). As with improved drinking water, the availability of sanitation services tends to drop for rural inhabitants, with the minimum reported for Brazil (43%) and the maximum for Chile (97%).

The condition and future of South America's surface water quality are strongly influenced by the interaction of the region's social and economic systems with its natural resource base. This chapter will devote considerable attention to the natural resource and ecohydrological aspects of the problem, but it is important to highlight certain socio-economic factors that will undoubtedly play a role in determining management options. The countries of South America may be classified as developing nations and as such they have relatively few financial resources to address water quality management problems (Table 11.1). Only Argentina and Uruguay have *per capita* gross national products (GNP) above the world average of US$5020 and all are well below the average (US$26 440) GNP of the high-income OECD member states (World Bank, 2001). Pressing problems reflected in population growth, illiteracy, unacceptable infant mortality rates, and high external debt will continue to be top priorities for expenditure in these nations. Water resource management themes that relate directly to economic development, such as dams and irrigation works, are also likely to be priorities. However, management of *in situ* water quality in surface waters, used to support natural ecosystems, protect artisan fisheries, and reduce the occurrence of waterborne illness among rural peoples, is not likely to garner much financial support in the coming years, nor is it likely to make its way onto any national priority action lists.

Table 11.1 Demographic and economic data for South American countries for 1999. Data from World Bank (2001)*.

	Total population (millions)	Urban population (% of total)	Infant mortality rate†	Overall budget deficit‡	GNP *per capita*, Atlas method (1999 US$)
Argentina	36.6	89.6	18.4	–1.49	7550
Bolivia	8.1	61.9	58.8	–2.27	990
Brazil	168	80.72	32.2	–7.34	4350
Chile	15	85.44	9.98	–1.47	4630
Colombia	41.5	73.48	22.76	–7	2170
Ecuador	12.4	64.3	28.4	-	1360
Guyana	0.85	37.64	56.8	-	760
Paraguay	5.4	55.28	23.8	-	1560
Peru	25.2	72.42	39.2	–2.09	2130
Uruguay	3.3	91.04	14.5	–3.72	6220
Venezuela, RB	23.7	86.62	20.2	–2.27	3680

*Relevant data for French Guiana and Suriname were not available.

†Per 1000 live births.

‡Including grants (% of GDP). Budget deficit data from Argentina are from 1998 and for Brazil are from 1997.

In this chapter I present an ecohydrological approach to surface water quality management that I believe is viable given both the needs and limitations in South America. The premise for this approach is that rivers and wetlands, especially natural rivers and wetlands, possess a strong capacity for self purification that can be explicitly incorporated into water management programmes. Processes to eliminate organic wastes, strip excess nutrients, filter sediments, neutralize acidity, and reduce metal concentrations are intrinsic to free-flowing rivers with intact biological communities. Many of these processes have been noted in the preceding chapters of this book, and I will draw on those examples. Ironically, the very socio-economic problems that hamper water quality management today also precluded widespread development and intensive resource use in many South American basins historically. Consequently, South American rivers and wetlands remain in a more natural state than many of their northern counterparts and exhibit stronger self-purification capacities.

SOUTH AMERICAN DRAINAGE SYSTEMS AND WATER RESOURCES

By world standards South America has abundant available water resources, although as indicated in the introduction the safety of these resources varies between countries and social groups. South America's *per capita* water availability is 38 000 m^3 $year^{-1}$ (Gleick, 2000). That is twice the availability of water in North and Central America and nearly an order of magnitude higher than the availability of water in Europe and Asia. South America's 10 largest river basins account for 70% of the total continental area and an even greater percentage of the continent's runoff (Fig. 11.1, Table 11.2). The Amazon is the world's largest basin and alone accounts for 35% of the continent's area and nearly 70% of its total runoff.

South America contains diverse landscapes resulting from the wide range of latitude (12°N–55°S) and elevation (0–6959 m a.s.l.) found on the continent. The continent's largest basins, the Amazon, Paraná, and Orinoco, each include varied terrain but distinctions are

Fig. 11.1 South America's major river basins and wetlands.

evident. The Amazon and Orinoco rivers drain large tracts of rainforest and tropical savannas, and both are fed by mountain rivers from the eastern flank of the Andes cordillera. The Paraná River, by contrast, drains the vast plains and grasslands of the Gran Chaco and the

Table 11.2 Details on the characteristics and condition of South America's major river basins.

River basin	Area (km^2)	Average discharge ($m^3 s^{-1}$)*	Populat'n density (ind. km^{-2})	No. of fish species	Percent wetland	Percent arid	Percent forest	Percent crop-land	Percent grass-land†	Deforest. rate/loss‡	Eroded area (%)
Amazon	6 144 727	175 000 (205 000)	4	3000	8	4	73	15	10	5/13	1
Chubut	182 631	-	2	-	0	61	25	1	67	-/28	0
Magdalena	263 858	7 500 (6 840)	79	149	0	7	37	39	13	26/88	10
Orinoco	953 598	30 000 (35 000)	13	318	15	9	50	19	27	12/23	2
Paraná	2 582 672	18 000 (19 200)	23	355	11	10	12	45	39	18/71	4
Parnaíba	322 823	825	10	90	19	42	5	52	40	14/27	1
Río Colorado	402 956	-	10	-	2	71	1	10	71	-/100	0
São Francisco	617 812	2 900 (2 800)	18	-	10	32	1	61	33	9/64	1
Tocantins	764 183	11 000	6	-	19	0	9	63	27	10/50	2
Uruguay	297 199	5 000	25	160	4	0	7	44	45	12/92	20

Primary source: Revenga *et al.* 1998. A dash (-) is shown where data are unavailable.

*Discharge data from Oki *et al.* (1995), (and Meybeck (1988)).

†Percent grassland includes both grasslands and shrublands.

‡Deforestation values are reported as annual percent deforestation rate on the left and total percent of forest lost on the right.

coastal hills of central Brazil, including the metropolis of São Paulo. The next largest basins, the Tocantins and São Francisco, are both predominantly north-flowing rivers that drain the eastern extension of Brazil. The Chubut, Colorado, and Parnaíba rivers drain more arid parts of the continent; though their basins are large, their discharges are relatively small. The Uruguay River drains the humid chaco between the Paraná and the Atlantic coast, and the Magdalena River drains the moist central valleys of the northern Andes.

The data in Table 11.2 reveal something of the degree of development and intensity of human impacts in these major river basins. Of the major basins the Magdalena is most densely populated, with multiple large cities including Bogotá, Cali, and Medellin. The Magdalena also exhibits the highest rate of deforestation, with 88% of the basin already deforested. The Uruguay basin is the second most densely populated and nearly completely deforested. The basins of the São Francisco, Colorado, and Parnaíba also exhibit significant levels of alteration. The Paraná basin has lost 71% of its original forest, 45% of its area is under cultivation, and along with the Uruguay basin its population density is second highest on the continent. The least impacted rivers on the continent are the Amazon, Orinoco, and Chubut. The great extent and relative inaccessibility of the Amazon and Orinoco no doubt contribute to their less-impacted condition, while similar remoteness and an inhospitable climate likely explain the low intensity of human activity in the Chubut.

Expansive lowlands are characteristic of South America's largest river basins. Approximately 50% of the Amazon basin's 6 million km^2 are below 200 m elevation. In fact, one can travel more than 5000 km up the Amazon River and remain below 200 m a.s.l.! One can also travel thousands of kilometres up the Paraná and Orinoco rivers before rising above the 200 m contour line. The combination of broad lowlands and significant rainfall creates ideal conditions for the formation of large wetlands. Aselmann & Crutzen (1989) estimated that 1.52 million km^2 of freshwater wetlands occur in South America, but this number is highly conservative. Junk (1993) estimated that nearly 2 million km^2 of wetlands occur in the tropical portion of South America alone, including everything from the massive flood plains along major rivers to narrow fringing wetlands in low-order stream segments. The most significant of these are the seasonally-flooded wetlands of the mainstem Amazon River in Brazil (~300 000 km^2), the seasonal savanna wetlands of eastern Bolivia (~150 000 km^2), and the Pantanal wetland (~140 000 km^2), which lies mostly in Brazil. The Pantanal in particular is regarded as one of the largest and most pristine contiguous wetlands in the world. Considerable international attention is focused on the Pantanal today as conservationists and national agencies work to prevent damage by encroaching development (Swarts, 2000).

Another distinctive and globally important freshwater environment of South America is the endorheic basin of Lake Titicaca, which covers an area of approximately 56 000 km^2 (Montes de Oca, 1989). At 3800 m a.s.l. this large lake and its associated wetlands is the only significant body of freshwater on the arid Bolivian altiplano. As such it hosts a number of endemic fish species and provides important habitat for Andean migratory birds. The lake is now feeling the effects of uncontrolled sewage discharges from the Peruvian city of Puno and other industrial and mining waste discharges.

With some exceptions water may be considered to be abundant in South America, and consequently the main factor limiting water availability in many areas is water quality rather than quantity. In the next section I present select data to illustrate the types of contamination impacting South American surface waters. It will become apparent that the most widespread water quality problems are those that ecohydrological processes can effectively address provided that the self-purification capacity of rivers and wetlands is not compromised by human alterations.

THE CURRENT QUALITY OF SOUTH AMERICA'S SURFACE WATERS

As might be expected, water quality in South American rivers and wetlands ranges from absolutely pristine to dangerously poor. While data are limited, it is clear that the most polluted waters occur in and downstream of major population centres, and pollution levels tend to be more intense in smaller rivers where dilution is less effective. The Bogota and La Paz rivers are prime examples, as they are virtually lifeless immediately downstream of the cities that share their names. By contrast, the mainstem sections of the continent's largest rivers, the Amazon, Orinoco, and Paraná, have very high water quality.

Currently it is impossible to present a truly comprehensive assessment of water quality in South America. Existing data are relatively few and thinly scattered in the scientific literature, obscure reports of national agencies, and student theses from South American universities. Of the 715 monitoring stations contained in the United Nations' Global Environment Monitoring System Freshwater Quality Programme (GEMS/WATER), only 50 (or 7%) are from South America. By contrast, South America accounts for more than 20% of recharge and runoff from the continents (WRI, 1998). UNESCO's International Hydrology Programme has an effort underway in South America to compile data on water quality, but this effort has thus far produced no publicly available results. Consequently, in the following sections I will simply highlight the predominant forms of water contamination in South America.

Organic wastes

The most widespread contamination problem is organic waste entering water bodies in the form of untreated sewage and industrial discharges. Presently less than 20% of industrial and domestic waste water is treated prior to discharge in Latin America (CEPIS, 2001). Martinelli *et al.* (2002) describe a severe example of organic contamination in the Piracicaba River, which drains more than 10 000 km^2 of the Brazilian State of São Paulo (Fig. 9.1 in Martinelli *et al.*, 2002) and ultimately empties into the Paraná River. This basin is among the most economically advanced areas of South America, with 7000 industries that account for nearly 10% of the entire Brazilian gross national product. Despite the relative affluence of this basin and its cities, the Piracicaba River receives 84% of the raw sewage and 10% of the untreated industrial effluents generated in the basin. This amounts to approximately 150 t of biochemical oxygen demand (BOD) per day, as well as unknown quantities of metals, salts, and suspended solids. Consequently, this river which was once renowned for its fish and mussel diversity is now biologically barren, with some sections exhibiting pollution so extreme as to eliminate nearly all aquatic life.

In Colombia, the Institute for Hydrology, Meteorology and Environmental Studies (IDEAM) maintains a network of 26 water quality monitoring stations in the vicinity of the cities of Bogotá and Pasto. Near Bogotá, 10 stations lie in the META river basin, which flows into the Orinoco, and 12 stations lie in the headwaters of the Magdalena River basin. The four stations located near Pasto lie in the headwaters of the Patia River basin, which flows westward into the Pacific ocean. By far the dominant form of contamination in these rivers is excess organic matter from domestic discharges. During October 2000, dissolved oxygen deficits reached 100% at two stations passing through heavily urbanized areas (IDEAM, 2000). Deficits of greater than 25% were reported in an additional four stations. Several stations within this monitoring network also reported medium to high values of turbidity, chemical oxygen demand, NH_3, and NO_3. Nationwide in Colombia, an estimated

690 kt of BOD and 1500 kt of suspended solids were discharged into the country's surface waters during 1996 (Rodrigo *et al.*, 1998). Of these national totals, 76% of BOD discharges and 93% total suspended solids discharges are thought to derive from domestic sources, with the remainder coming from industrial and agricultural sources. It should be noted that inputs of BOD from domesticated animals is not considered, but may amount to an additional 2000 kt or more of BOD per year.

Pathogens

Inputs of organic wastes, which give rise to BOD may also introduce pathogens. Illnesses related to poor water quality are the number one health problem in rural South America. During a series of health surveys conducted between 1990 and 1995, 31% of urban children less than 5 years old in Bolivia were found to be suffering from diarrhea. In rural areas the number was 28% (WRI, 1998). High frequencies of diarrhea among rural and urban children were also reported in Brazil (17%, 13%), Colombia (16%, 17%), and Peru (16%, 22%). In the La Paz River of Bolivia, the high incidence of diarrhea has been directly linked to high bacterial concentrations, which persist for more than 40 km downstream of the city (Ohno *et al.*, 1997). Many more alarming forms of viral contamination may also be observed, such as the Oropouche virus detected near the city of Iquitos in the lowland Amazon of Peru. This virus was found to be transmitted to the population of the city and surrounding areas (Watts *et al.*, 1997). In a survey of households in the rural Pachitea basin of central Peru, Aparicio Alcázar (1999) found that greater than 50% of households reported some form of health problem linked to water. Hospitals in the two towns within the basin recorded a total of 8125 cases of illness related to water between January and October 1998 (Aparicio Alcázar, 1999). Acute diarrhea was the most commonly reported illness (4172 cases) along with other helminchic infections (intestinal worms—3578 cases), but 62 cases of viral hepatitis and 18 cases of cholera were also reported. Pathogens in water are especially troubling because dilution does not reduce their potency. A single pathogenic organism can cause illness.

Nutrients

Eutrophication of surface waters has been reported in many parts of South America. Most problems are reported in lake and reservoir systems receiving significant inputs of raw sewage from nearby urban areas (Ceballos *et al.*, 1998). Estuarine waters along urbanized coasts are also sometimes heavily impacted (Braga *et al.*, 2000; Huszar *et al.*, 1998). Problems of eutrophication in rivers have been reported mainly in highly developed areas such as the Piracicaba basin (Martinelli *et al.*, 2002). Concerns about excess nutrient concentrations have also been expressed in field studies from the upper São Francisco basin of southeastern Brazil (Galdean *et al.*, 2000) and the lower portion of the Chubut (Sastre *et al.*, 1998). Modelling studies from the agricultural region of Chile's Central Valley also suggest a real potential for eutrophication (Donoso *et al.*, 1999). The threat of stream and river eutrophication exists throughout the heavily agricultural regions of Chile, Argentina, and Brazil, where fertilizer use continues to rise. By contrast, nutrient levels in the Amazon, Orinoco, and Paraná river systems appear unaffected by anthropogenic processes operating in their basins. Hamilton (2002) notes that nutrient levels in the Paraná River are even lower than those in the Amazon and Orinoco and suggests that greater river–flood-plain exchange in the Paraná may explain the difference.

Sediments

Natural suspended sediment concentrations vary enormously in South American river systems, mainly as a function of basin relief and climate. Virtually no data are available, however, to document anthropogenically driven changes in suspended sediment concentrations. Some of the highest natural sediment loads have been found in rivers draining the Andean cordillera. Guyot *et al.* (1995) reported average suspended sediment concentrations in excess of 10 000 mg l^{-1} for multiple high gradient rivers in the Bolivian Andes, while downstream concentrations in the Madera basin of the Brazilian Amazon were more commonly between 10 and 500 mg l^{-1}. In the Magdalena River Restrepo & Kjerfve (2000) reported mean sediment concentrations of 670 mg l^{-1} during rising water and 420 mg l^{-1} during falling water.

The lack of data to indicate increased sediment loads in South American rivers is somewhat surprising given the considerable attention given to erosion on the continent. Table 11.2 indicates significant areas of eroded lands in the Uruguay and Magdalena river basins. Small basin studies in the Brazilian Amazon (Williams *et al.*, 1997), the Peruvian Amazon (Alegre & Rao, 1996), French Guyana (Fritsch & Sarrailh, 1986), and the basaltic plateaux of southern Brazil (Dos Reis Castro *et al.*, 1999) have all documented increased erosion resulting from deforestation and agriculture. In the bauxite mining area of the Río Trombetas, initial research has also documented the reductions in bottom habitat and reductions in water column photosynthesis due to influxes of mining tailings (Callisto *et al.*, 1998; Roland *et al.*, 1997). A good source of indirect data on changing sediment loads is sediment accumulation rates determined using ^{210}Pb. At least two studies have documented increased sedimentation rates in basins undergoing large-scale development. Forsberg *et al.* (1989) reported that, following the construction of highway BR-364 in 1961 along the Jamari River in Rondonia, Brazil, sedimentation rates increased exponentially in Lago Paca near the river's mouth. By the end of 1985 sedimentation rates had increased 10-fold. Godoy *et al.* (1998) also made use of ^{210}Pb to document increased sediment fluxes in the Taquari River, which flows into the Pantanal.

Metals

In mineral-rich zones of the Andean cordillera where mining is common, surface waters receive sometimes alarming levels of metals and acidity. Near critical situations have also been reported in high Andean lakes (Roca, 1995). Metal contamination from mining operations generally affects smaller rivers at higher altitudes. Resulting problems include harmful levels of heavy metals, increased sediment loads, and acidification. Roca (1995) also reports that agricultural soils have been contaminated with heavy metals by irrigation waters drawn from contaminated rivers. More than 21 000 ha of farmland are said to have been contaminated using irrigation waters from the Mantaro River. This medium-sized river draining the high Peruvian Amazon is one of the country's most polluted water bodies.

There have been few reports of significant levels of metal contamination in larger rivers. A case in point is the Paraíba do Sul River (55 400 km^2 basin) in Brazil, which flows from São Paulo and across the States of Rio de Janeiro and Minas Gerais (Fig. 10.1 in Carvalho & Torres, 2002). Like the Piracicaba River mentioned above, the Paraíba do Sul receives large quantities of untreated (or incompletely treated) waste waters from domestic, industrial, and agricultural sources. However, unlike the Piracicaba, contamination of the Paraíba do Sul River has not risen to such ecologically destructive levels (Carvalho & Torres, 2002). Isolated occurrences of organic contaminants such as PCBs and DDT have been detected downstream of heavily populated areas. Likewise, unacceptably high levels of heavy metals like cadmium (>15 ppm) have been detected in bed sediments adjacent to industrial sites (Torres, 1992), but metal concentrations tend to decrease rapidly downstream to values of less than 1 ppm. Similarly, metal concentrations in sediments across the entire lower portion of the basin contain only low levels of heavy metals.

Trace metal concentrations in the largest South American rivers are generally near background levels despite sometimes significant influxes of industrial effluents. There are certainly no indications of contamination in the mainstem sections of the Amazon and Orinoco rivers, and even in the more highly impacted Paraná system mainstem metal concentrations are low (Facetti *et al.*, 1998). In the much more industrialized tributaries near the mouth of the Paraná and along the southern margin of the Río de la Plata estuary, concentrations are higher but still not alarmingly high (Villar *et al.*, 1998). A significant individual source of contamination to the Río de la Plata estuary is the Reconquista River, which drains 1670 km^2 of the Buenos Aires province. This river suffers from strong hypoxia near its mouth and carries the effluent of many industrial sites (Castañé *et al.*, 1998). The Magdalena River contains the highest metal concentrations of the large South American rivers, which is not surprising given the intensity of human activity within its basin. Perdomo *et al.* (1998) reported concentrations of Cd, Cu, Ni, and Zn in sediments of the lower Magdalena that exceeded international standards; other areas of concern were identified nearly a decade earlier by HIMAT-INGEOMINAS (1991).

Mercury

Without a doubt the most publicized water quality issue in the Amazon during recent years is mercury contamination. Martinelli *et al.* (1988) were among the first to raise this issue in the scientific literature and to tie it to gold mining operations in the Amazon. More recently investigators have shown that naturally high concentrations of mercury occur in Amazon soils as a result of long-term, low-level inputs from volcanism and other atmospheric sources (Roulet & Lucotte, 1995). Consequently, even in remote portions of the river basin erosion of adjacent soils may lead to elevated mercury concentrations in river waters (Maurice-Bourgoin *et al.*, 2000). In the Madera sub-basin of the Bolivian Amazon, levels of mercury in river water are elevated through both natural and anthropogenic processes. Recent investigations there have found that mercury is accumulating in fish tissue and has been reported at concentrations more than 4-times higher than the World Health Organization's (WHO) suggested limit of 0.5 mg g^{-1} (Maurice-Bourgoin & Quiroga, 2002). The highest levels were reported for piscivorous species (2.304 mg g^{-1} for *Pseudoplatystoma tigrinum*). As a result of the biomagnification of this metal, even higher levels of mercury were found in the hair of humans living along the river who ate abundant fish. It is interesting to note that mercury levels in the hair of gold miners (who burned mercury but seldom ate fish) were a factor of 4–20 below those of fish-eating riparian inhabitants (Maurice-Bourgoin & Quiroga, 2002). Even higher concentrations of mercury have been reported in the hair of fishermen and their families from the Tapajós basin in the Brazilian Amazon (Malm *et al.*, 1995) and around the Tucuruí reservoir in the Tocantins basin of the Brazilian State of Pará (Leino & Lodenius, 1995).

The question of what factors control the location of Hg contamination in Amazon fish and the people who eat them, is made more intriguing by the work of Silva-Forsberg *et al.* (1999), who reported that Hg concentrations in fish and people correlated more with the pH and dissolved organic carbon (DOC) concentration of river waters, than its proximity to gold-mining operations. These findings highlight the positive influence of DOC in mobilizing mercury through complexation and the negative influence of pH in inhibiting methylation and bioaccumulation of mercury.

Mercury contamination is certainly not a problem unique to the Amazon. Problems of elevated mercury in fish have also been reported from the flood plain of the Paraná River (Moraes *et al.*, 1997), and Hylander *et al.* (1994) reported mercury levels above WHO guidelines in the Alto Pantanal region. These authors also noted the correlation of mercury levels with DOC and pH. Higher trophic level fish from the Magdalena River system were also found to contain mercury concentrations in excess of WHO guidelines (Olivero *et al.*, 1998), but concentrations decreased in the same species collected from downstream marsh systems (Olivero *et al.*, 1997).

NATURAL ATTENUATION IN RIVER AND WETLAND SYSTEMS

The waste removal capacities of rivers and wetlands have been recognized from the very beginning of human civilization, and consequently these water bodies have forever been the receptacles of our wastes. The most immediate advantage of a river was its flow, which transported wastes from the dumping point, but dilution also quickly reduced liquid waste concentrations, ideally to levels that were harmless to aquatic organisms and downstream human communities. The use of dilution as a means of reducing contamination has remained fixed in the minds of waste managers and even the general public, as evidenced in the popular rhyme "dilution is the solution to pollution". Dilution is fundamental to quickly reducing contaminant levels in rivers, but there are also a number of ecohydrological processes that work to reduce or eliminate contaminants. I will highlight several processes useful in water quality management by presenting three examples of forms of contamination that affect South American river basins and wetlands: (a) organic wastes and associated nutrient releases, (b) excess sediment loads, and (c) metal wastes.

Processes reducing organic matter and nutrient levels

Many South American rivers are net heterotrophic and therefore rely on inputs of organic matter (OM) from upstream to fuel downstream productivity. In these rivers bacteria and fungi form the base of the food chain, and higher trophic levels are adapted to feeding on these organisms. Mayorga & Aufdenkampe (2002) cite rates of community respiration in the rivers of the Amazon basin that range from 0.2 to 2 mmol C l^{-1} h^{-1}. Amon & Benner (1996) go further and, based on glucose-addition experiments, show that respiration rates may be increased by more than three-fold. From this perspective, modest increases in non-pathogenic OM concentrations should not negatively impact riverine food webs, as the additional OM will be rapidly processed into heterotrophic organisms.

In addition to uptake and oxidation by organisms, or more likely prior to it, OM may be stripped out of river water by physical processes such as adsorption onto suspended or bed sediment surfaces, especially the surfaces of Al and Fe oxides. In the presence of certain substances, organic matter may also coagulate and settle out of the water column. Mounier *et al.* (2002) report a loss of 20×10^6 t $year^{-1}$ of organic matter along the mainstem of the Amazon River between the mouth of the Río Negro and the city of Obidos. These losses were observed only at low water stages, however, and removal processes were far less efficient during high water. Particulate forms of organic matter may also be trapped by filtration through bank and bed sediments (just as with fine sediment grains). These various processes serve to immobilize organic matter, which may be subsequently decomposed by benthic fungi and bacteria.

Decomposition of excess organic matter is accompanied by the mineralization of potentially limiting nutrients like nitrogen and phosphorus. In small excess amounts, these nutrients are likely to be taken up by microorganisms or by plants living along the banks of the river. Phosphate is very effectively sorbed onto mineral surfaces and is generally maintained at low levels in tropical rivers. Elevated levels of nitrate may be reduced through denitrification reactions in anoxic bed and bank sediments, or within the anoxic zones that may form in accumulations of organic litter behind obstacles such as fallen trees. Engle & Melack (1993) reported on the efficiency of nutrient uptake from river water on the Amazon flood plain. Water entering the lake at its upstream connection to the river had NO_3^- and PO_4^{3-} concentrations of approximately 7 and 2 mM, respectively. By contrast water being returned to the river 3 km downstream had NO_3^- and PO_4^{3-} concentrations well below 1 mM.

In oligotrophic (or nutrient poor) water bodies, the extra nutrients released from decomposing organic matter may fuel increased rates of productivity. In British Columbia, Canada, oligotrophic lakes have been fertilized with nitrogen and phosphorus for more than two decades to enhance lake productivity and to therefore increase the survival rate of juvenile sockeye salmon (Stockner & Macisaac, 1996). As a result juvenile survival rates increased two-fold and average smolt weight increased by greater than 60%.

Intact riparian forests have been shown to be especially effective buffers in protecting against excess nutrient levels in rivers (Haycock *et al.*, 1997). These forests are most effective at stripping sediments and nutrients from waters flowing from upland sources, but Triska *et al.* (1989) demonstrated that nitrate could be stripped from rivers waters flowing in a hyporheic zone that extends beneath adjacent riparian forest. McClain *et al.* (1994) and Williams *et al.* (1997) reported efficient removal of inorganic nitrogen from runoff waters beneath riparian forest in the central Amazon basin, but otherwise very little work on riparian zones as buffers has been carried out in South America. Nothing is know as yet about their capacity to eliminate higher nitrogen fluxes.

Again the processes operating in rivers to eliminate organic matter and nutrients are identical to those employed in many water treatment systems, including filtration, coagulation, sedimentation, and sorption. The decomposition of organic matter by microorganisms in the river may also be viewed as a sort of bioreactor.

Processes reducing sediment loads in rivers

Sediments entering rivers will initially be partitioned according to dominant size classes and the level of turbulence of the river flow. Large sediment grains will be deposited near the point of erosion, while finer grain sizes will be carried further downstream. Suspended sediments may initially reduce water quality and riverine productivity by limiting light penetration. However, free-flowing rivers that are properly graded contain varying levels of turbulence that serve to strip out excess sediments. In smaller mountainous river systems, riffle and pool structures develop, with pools serving as sinks for excess sediments derived from upstream. Similarly, larger meandering rivers develop low-turbulence zones on the inside curve of meanders, which also serve as sediment sinks. Sedimentation is a commonly applied technique in water treatment facilities, and the process of sedimentation in rivers is fundamentally the same. Furthermore, finer sediments will be filtered from water passing through bank or bed sediments, again emulating processes operating in sand filtration systems or water treatment plants.

Wetlands are very efficient sediment traps with strong ecohydrological ramifications because very often aquatic vegetation in wetlands acts to slow water flow and promote sedimentation. Hamilton (2002) highlights the decisive role of Pantanal wetlands in reducing sediment loads carried by upstream rivers and delivering nearly sediment-free waters to the Paraguay River downstream. Engle & Melack (1993) also reported a dramatic decrease in sediment loads as Amazon River water moved onto the flood plain. Water flowing onto the flood plain contained nearly 150 mg l^{-1} of total suspended solids (TSS), while flood-plain water flowing back into the river 3 km downstream contained less than 10 mg l^{-1} TSS. While both depositional and erosional processes operate on the flood plains of South America's major rivers, deposition likely dominates. Dunne *et al.* (1998) calculated the exchanges of sediment between the mainstem Amazon and its flood plain along a 2010-km reach of the river. They noted an accumulation of sediment along the reach at a rate of 209 (±167) Mt $year^{-1}$, and calculated a net transfer of sediment to the flood plain amounting to 500 Mt $year^{-1}$.

Processes neutralizing acids and stripping metals from river systems

The reduced forms of elements (e.g. Fe and S) that typically weather from mining slag heaps are rapidly oxidized upon interaction with meteoric waters. These oxidation processes generally liberate H^+ ions and therefore drive pH down to more acidic levels. Levels of pH below 2 have been recorded in mine runoff, with correspondingly high concentrations of metals (Förstner & Wittmann, 1983). The sensitivity of rivers to acidification depends on acid buffering capacity, or alkalinity. Acid buffering capacity increases in rivers as a function of carbonate ion concentrations (CO_3^{2-} and HCO_3^-). Thus, rivers draining basins containing carbonate rocks generally have higher acid buffering capacity and are better able to neutralize acid drainage waters.

The effectiveness of ecohydrological processes in reducing metal contamination depends on both the metal considered and even the form (oxidation state) of individual metals. For example, the oxidized form of chromium, Cr(VI), is highly mobile and toxic in aquatic systems, while the more reduced from, Cr(III), is less mobile and less toxic (NAS, 2000). In fact, Cr(III) precipitates from solution at pHs above 5 and is thus rendered harmless. Many microorganisms reduce Cr(VI) to Cr(III), but they all rely on the presence of environmental conditions that favour this reduction. In other words, this reaction is likely to take place only in anoxic zones within the river bed, wetland, or flood-plain sediments, within riparian soils, or within accumulations of organic debris.

Microorganisms will also concentrate metals in their tissues and thereby strip them from solution. These metals may then be passed to higher trophic levels, they may be remineralized when the organisms decompose, or under certain conditions they may be stored in deposited sediments. If deposited in anoxic environments, these metals may be reduced to less mobile forms that can be more or less permanently removed from the system. Konhauser & Fyfe (1993) found 17 trace metals that had been concentrated in the tissue of benthic diatoms from some of the large tributaries of the Amazon River system. For Ti and Zr concentration factors exceeded 1 million, while Hg was concentrated by a factor of roughly 1000. Given such efficient concentration from aqueous phases, it is easy to understand why microorganisms are increasingly used in mining operations to concentrate metals leached from ores.

Thus water purification processes such as dilution, filtration, sedimentation, acid-base reactions and pH buffering, redox reactions (oxidation and reduction), precipitation and dissolution, complexation/coagulation, chemical sorption, hydrolysis, and plant uptake all occur naturally in river and wetland systems, and when properly quantified may be used as effective tools in the management of water quality.

INTEGRATING ECOHYDROLOGICAL PRINCIPLES INTO MANAGEMENT PLANS

The management of water resources is a complex subject that responds to and emerges from a number of international agreements and national and state laws. Specific management actions are generally divided between multiple governmental agencies, with varying levels of interaction with nongovernmental organizations and citizen groups. Management plans may be also highly engineered and strongly regulated in the case of urban areas or they may be essentially non-existent in the very remote rural areas still common on the South American continent. The preceding sections have reviewed the water quality problems in South American surface waters and shown how ecohydrological processes function to counteract them. How, then, can these natural processes be integrated into the heterogeneous mix of management plans and actions that operate on the continent? The answer, I suggest, is to first formally recognize natural processes (e.g. dilution, filtration, sedimentation, oxidation, etc.) as explicit tools in water management plans and then to prescribe management actions that seek to preserve and even enhance these processes. Management actions are likely to be primarily conservation and restoration oriented, where upon development or destruction of crucial components of natural systems (e.g. riparian zones, natural channel forms, fringing wetlands, etc.) are prohibited and restoration of already degraded systems is ordered. They may also be procedural as with maintaining a degree of natural flow variability in highly regulated river regimes (Poff *et al.*, 1997). Focus must be placed on conserving and restoring the integrity of aquatic systems within an overall plan that is consistent with the development goals of the given river basin.

The effort to gain formal recognition of natural processes as explicit tools in water management will require a rather dramatic change in perspective and may be best introduced to South American countries through international agreements. The governments of South America have been very receptive to the visions of water management proclaimed in major international agreements. The 1992 International Conference on Water and the Environment, held in Dublin, Ireland, called for multiple changes in the way water resources were managed. Most notably it advocated the use of river basins as the geographic unit of management and called for a decentralization of decision-making through the establishment of committees composed of government and nongovernment representatives within each river basin. These concepts 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. Subsequently, several nations (perhaps most notably Brazil; ANA, 2001) in South America revised their national plans to incorporate these concepts.

There is already considerable attention being given to the maintenance of ecological integrity in water management planning at the international level. The commission report of the recently prepared World Water Vision (WWC, 2001) makes the point eloquently. “There are those who see water only by use: water for municipalities, for industry, for irrigation, for the environment, as though the last were a competing use, not an inherent part of maintaining the entire ecological system on which all water services depend.” This and other international statements make the point clearly, but the required follow-up actions remain vague and water resource managers in different countries struggle with the question of how to reconcile conservation of ecological integrity with concrete management actions. It is here where I believe it is imperative to revise the language to refer to specific components of intact ecosystems as tools of water management. In this way riparian zones, wetlands, and channel forms may be explicitly incorporated into management plans and managed with the same concrete purpose as waste-water treatment plants, holding ponds, and other more traditional “tools” of water resources management. This task is made easier in South America because water, by law, remains the property of the state, and in many countries there is a fiscal buffer along the edges of rivers that must remain undeveloped.

Another valuable outcome of the formalization of ecohydrological processes in water quality management plans is that it generates management tools in remote rural settings that have little or no engineering infrastructure and are unlikely to see any in the coming years. Even in these remote settings organized water quality management is essential and best achieved through the formation of basin committees. By recognizing riparian zones, wetlands, and natural channel forms as management tools, these rural committees will be able to develop concrete plans that take into consideration the quantity and configuration of these intrinsic water purification systems. Rural communities should recognize that they have at their disposal an assemblage of highly effective water purification services that are virtually free and already perfectly positioned in the hydrological system. The specific management actions required to implement the developed plans will also illuminate the individual responsibilities of institutions and households in the basins.

At the level of implementation, the conservation of ecohydrological processes clearly should not be viewed as an independent and stand-alone solution to water quality management problems. Natural ecohydrological processes should be viewed as a fundamental component of more multifaceted solutions, including additional systems to treat water for domestic supply and to 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 areas, ecohydrological processes should be maintained 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 and a guiding principle within the UNESCO Ecohydrology Programme (Zalewski *et al.*, 1997). In rural areas, natural ecohydrological processes may be recognized as primary tools for controlling surface water quality in conjunction with simple drinking water treatment and waste treatment systems (e.g. solar latrines). Small rural communities may even construct simple engineering systems to interact with natural components of river basins that are hot spots of ecohydrological processes. For example, sewage from small communities may be piped into wetlands designated for the purpose of cleaning the waste water prior to discharge to an adjoining river. Of course, in this example the value of the wetland as a waste-water purification system must be weighed against other services (e.g. fish nursery habitat) which may be lost as a result of sewage inputs.

It is clear that the effective use of ecohydrological processes in water quality management plans (especially in rural areas) will require the complete and voluntary participation of local communities and landholders. As recommended by the World Water Council and other international initiatives, local people should play a leading role in developing water quality management so 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 by ensuring that respected local community leaders, elders, and normal individuals serve on basin committees.

Finally, I do not wish to suggest that South American water managers, in viewing natural ecosystem components as tools, lose sight of the broader ecosystem services provided by riparian zones, wetlands, and channel forms. Many services related to fisheries, transportation, tourism, and other intangible benefits stem from intact river and wetland systems. These too must be weighed in management decisions.

CONCLUDING REMARKS

Although research to date has shown that many ecohydrological processes act to purify natural waters in South America, virtually no studies have specifically addressed the utility of these processes in actually mitigating pollution inputs. Water managers require solid information on the specific capabilities of the tools at there disposal. What processes are effective against which kinds of pollution? Where exactly in the system (i.e. in which landscape features) are these processes most efficient? What is the throughput of water in these features (e.g. riparian zones or wetlands)? What are the concentration and flow thresholds where the efficiency of these processes drop off or where other services are compromised? How do efficiencies and thresholds vary with season and time? There are also considerations that must be addressed regarding the economic trade-offs of conserving landscape features for water quality management instead of developing them for other purposes. A great deal of research remains to be done.

Chapters in this book have illuminated a variety of good research that touches upon these needs, but these studies were originally mounted with other goals in mind such as simple system characterizations or academically-driven research questions on natural ecological processes. Real progress on the employment of ecohydrological understanding for improved water quality management will require coordinated and focused research into the questions posed above. To be successful, this research must combine the expertise of ecologists, hydrologists, and water quality and sanitary engineers. With its expansive surface water systems and relatively low degree of disturbance, South America is an ideal region in which to develop and apply ecohydrological approaches to water quality management.

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