Proceedings of H04, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013 (IAHS Publ. 359, 2013).

Water resources in South America: sources and supply, pollutants and perspectives

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Abstract South America has the largest availability of water resources both per capita and per area. However, the continent also hosts some of the world's regions with the highest water scarcity. Compared to the attention to water quantity, water quality is a much more silent threat. It is increasing rapidly under the pressure of increasing urbanization and vigorous economic growth, especially in highly water demanding industries such as mining and agriculture. We review the major drivers of water quality deterioration in South America and the interaction with water availability. Despite its complexity, some geographical patterns can be identified, relating to the agricultural dominated southeast of the continent, the Andes in the west, and the Amazonian basin. Potential threats to water quality and aquatic ecosystem integrity are identified from both diffuse and point sources, originating from large-scale land-use conversion, intensification of agriculture, and expanding industrial activities such as mining and hydropower.

Key words South America; water quality; mining; agriculture; sediment

INTRODUCTION

South America is arguably the most diverse continent in terms of water resources. It hosts the largest river on Earth (the Amazon), the driest place on Earth (the Atacama Desert), and the longest mountain chain (the Andes). The geographical diversity results in extreme gradients in water availability and quality. Most of the north and northeast of the continent, including the Amazon and Orinoco basins and the Colombian and Ecuadorian Pacific coast, receive abundant precipitation while being relatively scarcely populated (Sansó & Guenni, 1999; Marengo, 2009; Urrutia & Vuille, 2009). At the other end of the spectrum, the Pacific coast of Peru and north and central Chile is densely populated yet receives little or no precipitation, except during El Niño events (Wang & Fiedler, 2006). Major economic activities occur here, including water-intensive agriculture and mineral extraction. In this region, water availability is a major constraint to socio-economic development. The southeast of the continent, including the south of Brazil, Uruguay, Paraguay and Argentina, is characterised by large-scale agriculture and livestock rearing, as well as increasing urbanization and intensification of economic activities. This region is mostly semi-arid, with its climate variability and thus water availability influenced by the South American monsoon system (Marengo *et al.*, 2010). Lastly, the highlands of the Andes pose significant challenges to water management, because of the topographic barriers and the impact of local precipitation gradients (Viviroli *et al.*, 2011). Regions of severe water scarcity exist, especially where high population densities and economic activity (e.g. cities such as Bogotá, Quito, La Paz) interlock with small river basins, erratic weather patterns and dwindling natural storage in wetlands and glaciers (Buytaert & De Bièvre, 2012).

Water quality issues interact with these patterns of water availability. Similarly, strong gradients in water quality can be found, which are often related to the topography, land use and economic activity. In the Andes, chemical water quality issues may superimpose on the naturally high sediment loads, which are often aggravated by agricultural practices. This poses severe problems for water extraction and use, in particular hydropower production (Finer & Jenkins, 2012). Locally, high concentrations of heavy metals may be found in groundwater resources, mainly due to geological settings. In the humid tropics, issues of oxygen depletion and water quality degradation may occur in pools and disconnected river branches. However, major problems with water quality are associated with human activities and pollution. In the remainder of this paper, we review the current trends in water availability and quality, and the main sources of pollution.

TRENDS IN WATER SUPPLY AND DEMAND

Supply

Major changes in water availability over recent decades have been caused by large-scale land-use changes. The largest of these is undoubtedly deforestation in the Amazon plains. It is hypothesised that these changes have affected local atmospheric circulation systems, with impacts on the precipitation patterns and amounts in the region influenced by the South American monsoon system (Spracklen *et al.*, 2012). More directly, changes in land-use and especially deforestation tend to affect runoff behaviour and often lead to an accelerated hydrological response with decreasing base flows, even if the total water yield of the affected catchment increases (Bruijnzeel, 2004). Of note is the large-scale deforestation of the slopes of the tropical Andes. These regions historically hosted extensive regions of cloud forests, which are known for their exceptionally high water yield caused by the interception of cloud moisture, and low evapotranspiration.

More recently, climate change is affecting precipitation patterns. Although observations are scarce and often do not support conclusive historic regional trends, some large-scale patterns emerge from global circulation model projections. On a continental level, a region of increasing precipitation covers the Ecuadorian and Peruvian coast, the Andes region and south Amazonia. It is flanked by a regional decrease of precipitation over the Caribbean coast and northeast Amazonia and the Chilean and Bolivian highlands (Boulanger *et al.*, 2006; IPCC, 2007; Urrutia & Vuille, 2009). The regions of increasing (decreasing) precipitation coincide roughly with the current regions of high (low) water availability, thus highlighting the risk for increased future water scarcity.

Demand

A major driver of water-related issues in South America is related to the fast increase of water demand, underpinned by rapid economic and demographic growths rates. For 2011, demographic growth averaged 1.1% over the entire continent (ECLAC, 2012) but strong geographical differences exist (Table 1). Yet, more important than the regional differences is the general trend towards urbanization. Several major cities in the continent are consistently growing faster than the national average (Table 1), thus putting severe pressure on often underdeveloped water capture and distribution systems. This often leads to water shortages, as well as water quality degradation because of the use of suboptimal water sources and contamination in the distribution system.

In addition to demographic growth, South American economic growth has focused strongly on industries that are, at the same time, highly water intensive and polluting, in particular agriculture and mining. Overall, agriculture consumes around 70% of available water resources in South America, well in agreement with the global average. Locally, agriculture has an even higher share of net water withdrawal, as shown in Fig. 1 for the southern subregion, where domestic use and industry have a relatively low annual consumption. Water requirements for hydropower and mining might represent an important share of gross water resource requirements, but have a negligible net consumption rate according to Aquastat (FAO, 2000). Hotspots of pressure on gross water resources from industrial activities include the Peruvian coast (agriculture), the tropical Andes (mining), the northern Chile and Bolivia (mining), southern and eastern Brazil, Uruguay, Paraguay and Argentina (agriculture) and the Brazilian Amazon (mining), where hydropower production is related to aluminium processing.

Table 1 Exponential growth rates of representative South American countries and major cities. Data source: national statistics institutes of the respective countries.

Country	Population (million)	Growth rate (%)	City	Growth rate (%)
Colombia	46.30	1.35	Bogota	1.82
Ecuador	13.77	2.10	Quito	2.42
Peru	29.50	1.55	Lima	2.00
Bolivia	10.03	2.82	La Paz	2.36
Brazil	199.32	0.86	Sao Paolo	0.76

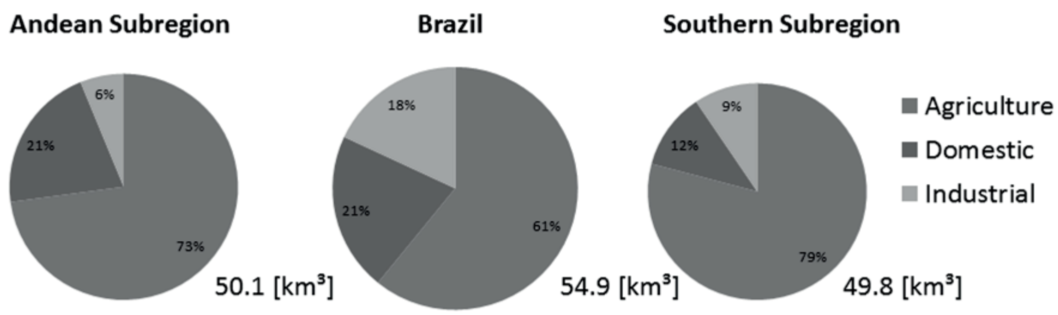

Fig. 1 Water withdrawal in South America by sectors. Andean sub-region comprises Bolivia, Colombia, Ecuador, Peru and Venezuela, and Southern sub-region Argentina, Chile, Paraguay and Uruguay. Circles are scaled to total water use (data source: FAO, 2000).

WATER QUALITY AND THREATS

Diffuse sources

While for many catchments in developed countries diffuse pollution is the dominant pollution pathway, for developing countries in South America it can be assumed that point sources are more important (Ometo *et al.*, 2000). However, this very general pattern is likely changing, especially in those countries of South America where agricultural production is on the rise. Countries such as Brazil, Argentina, Uruguay and Paraguay have emerged to become some of the world's top nations of agricultural production, especially for soybean, maize and sugarcane. Two aspects need to be considered, i.e. intensification of land that is already cultivated, and land-use change from formerly natural vegetation to cropland or pasture.

Associated with the intensification of agriculture is the use of large amounts of agrochemicals for production, such as fertilizers (N and P leading to eutrophication of surface waters, NO_3^- and NO_2^- impacting drinking water quality) and pesticides. However, despite the increasing intensification, many agricultural systems in South America still display negative nutrient balances because fertilization is lower than the harvested export (Portela *et al.*, 2009). Observed nitrogen exports, for example, are currently less than from intensive production systems in North America or Europe (Portela *et al.*, 2009). As this kind of non-sustainable production is only possible as long as soil organic matter pools are sufficient, it can be assumed that in the long-term, increasing fertilizer inputs are required to counterbalance soil organic matter depletion. Pesticide application is a growing problem especially in agriculture that relies on glyphosate tolerant genetically modified organisms (GMO) grown with direct seeding techniques. Nowadays, almost the entire soybean production of Argentina is based on such GMO (Vera *et al.*, 2009). In addition to the direct toxicological effect of pesticides in surface waters, glyphosate contains phosphorous in concentrations potentially increasing eutrophication (Vera *et al.*, 2009).

Apart from changes in the most well-known biome of South America, i.e. the Amazon rainforest, dramatic land-use changes have been occurring during the past two decades in the Cerrado savannah biome that borders the Amazon to the south. Natural vegetation is mainly converted to pasture and cropland. Impacts on water quality are manifold, including likely increases in nutrient inputs, but also stream morphological changes leading to physical stress (Gücker *et al.*, 2009). Associated with these land-use changes are nutrient losses through conversion (Da Silva *et al.*, 2007) and additional nutrient inputs through industrialized agricultural production (Zeilhofer *et al.*, 2006). Often associated with land-use change is the establishment of additional point sources: sewage from increased population growth and resulting urbanization (Zeilhofer *et al.*, 2006); installation of feedlots where nutrient enriched water potentially leaches to the groundwater or where surface runoff promotes erosion and pollutes surface water bodies with nutrients or faecal microorganisms (Chagas *et al.*, 2007; García *et al.*, 2012); wastewater from industrial complexes that process food, feed or biofuel (Gunkel *et al.*, 2007).

The gross impact of agricultural production systems in the Andes is less intensive, as a larger share is attributable to subsistence farming. Excluded from this general classification are intensive irrigation systems and aquaculture. Irrigation agriculture is gaining more and more importance, dominating on the western slopes of the Andes. Effects on water quality mainly occur on the local- to regional-scale due to the size of irrigation structures. Ribbe *et al*. (2008) further noted in their Chilean case study that "*nitrate concentrations … do not reach alarming levels yet, the impact of irrigation agriculture on surface water quality is obvious and makes a case for introduction best management practices to avoid aggravation of contamination*". Aquaculture is a likely polluter as in many cases as effluents from fish ponds are directly discharged into stream ecosystems without treatment (Schenone *et al.*, 2011). However, given the layout of such farms, they should be seen as point, rather than diffuse sources, and are discussed in more detail in the following section.

Point sources

As a major driver of the economic growth of the continent, industrial activity has expanded rapidly, and with it the pressures on the local environment. Most of these are common to emerging economies worldwide and are typically aggravated by the lack of adequate legislation, and poor institutionalisation and enforcement of legislation. However, some industries are particularly relevant in South America and therefore merit further attention.

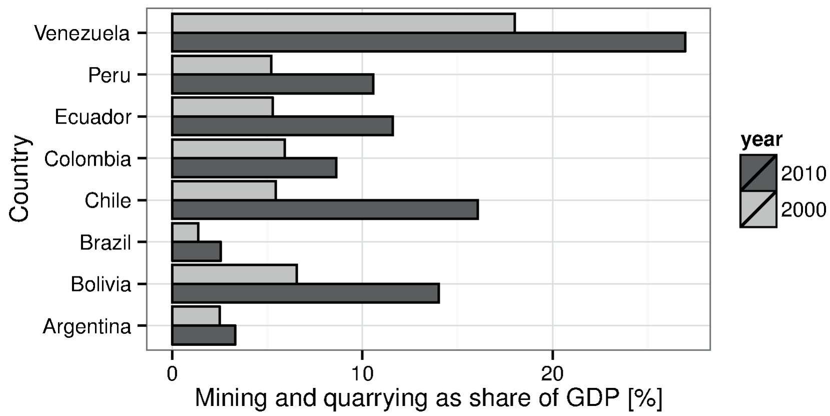

Fig. 2 Mining as a share of gross domestic product (GDP) in representative Latin American countries for the years 2000 and 2010 (data source: CEPALSTAT, 2013).

The biggest such industry is mining, accounting for over 10% of GDP in countries such as Venezuela, Ecuador, Bolivia, Venezuela and Chile (Fig. 2). In 2010, Chile and Peru were, respectively, the largest and second largest mine producer of copper, while Peru also features in the top five of the world's largest producers of silver (2nd), lead (4th) and gold (5th) (Brown *et al.*, 2012). While social conflicts about mining activities typically focus on water use by mines (e.g. Bebbington *et al.*, 2008), such issues are strongly related to water quality. Most of this water is released back into the environment as grey water, contaminated with heavy metals and other waste products, as well as chemicals used in the extraction process.

Although specific studies are scarce, Smolders *et al*. (2003) studied the levels of lead, cadmium, copper, and zinc in water, filtered water, sediment, and chironomid larvae from the upper Pilcomayo River in Bolivia, which is affected by drainage water from mine tailings from the Potosi area. They found concentrations of these heavy metals up to 1000 times above the local background levels. At the same time, strong reductions were found in the diversity of the benthic macroinvertebrate community. Further downstream, the degree of contamination was much lower because of dilution of both water and natural sediments. Yet, the introduction of the flotation process in the mining industry around 1985 could be detected in sediment cores from the Ibibobo floodplain, in the form of a sudden increase of heavy metal concentrations.

Contamination by chemicals used in the extraction process is particularly problematic in the case of informal gold mining, which uses large amounts of mercury. Especially in Peru, where informal gold mining is particularly prevalent in the headwaters of the Amazon basin, it is estimated that 95% of the total mercury import is used in artificial gold mining (Swenson *et al.*, 2011). Although very little official information is available, the fact that such mining typically occurs along streams and rivers because of the occurrence of deposits and the availability of water required for extraction, suggests that much of the consumed mercury is released in surface waters. The recent increase in the gold price has stimulated these informal mining activities, which is reflected in the growing import of mercury in Peru (Fig. 3).

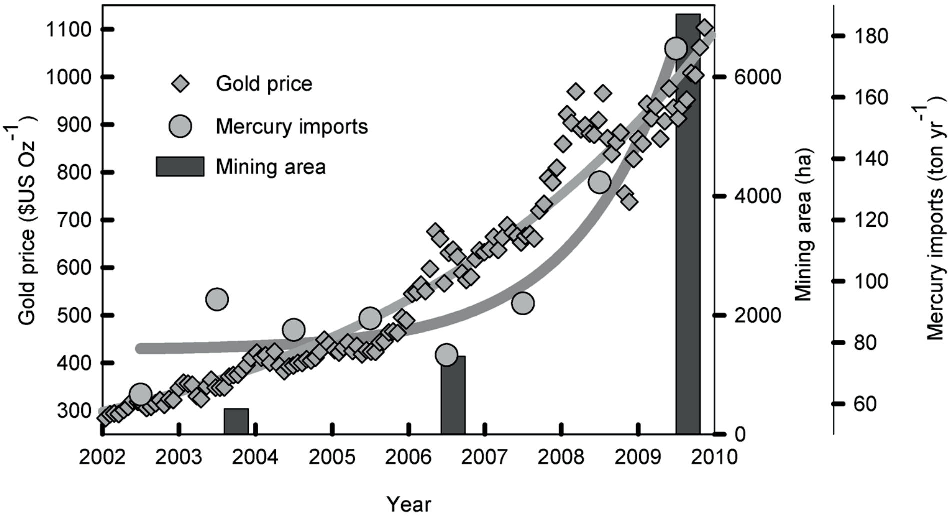

Fig. 3 Temporal dynamics of the international gold price, annual mercury imports in Peru, and forest conversion to mining area in the Madre de Dios region, south Peru (Swenson *et al.*, 2011).

While the direct effects of mercury contamination on health are well described, the occurrence of small-scale gold mining in the Amazon may have additional, indirect health risks because of a potential link with malaria occurrence. Crompton *et al.* (2002) found an association between reported history of malaria and reported past exposure to mercury in gold mining in the Brazilian Amazon in populations at risk of being exposed to mercury through direct contact with the mining process and/or through fish consumption.

Another industry with potentially large impacts on water quality is aquaculture. The practice is widespread in the upper Andes, where small-scale subsistence fishing is gradually being replaced by larger fish farms. Only a few native species have commercial value, of which the Argentinean pejerrey (*Odontesthes bonariensis*) is the most widespread, and is now also produced in Brazil, Uruguay, Bolivia, Chile and Peru, for instance in Lake Titicaca. In most countries, the introduced brown trout and rainbow trout are the most important (Petr, 2003). From a water quality perspective, a disadvantage of this type of aquaculture is its location in the mountain headwaters, such that potential contamination (e.g. nutrients and fertilizers) may propagate downstream. However, very little research has been reported in the scientific literature.

Of a much larger scale is the salmon aquaculture in southern Chile, which only started two decades ago but nowadays represents a US$3 billion-a-year industry. Although the impacts on local hydrology have thus far received little attention in the scientific literature, there is increasing concern about water pollution and loss of biodiversity.

Lastly, an economic activity that has seen a spectacular increase over the last decades is Brazil's biofuel industry. Brazil is the second largest ethanol producer and the largest producer of sugarcane in the world. Ethanol is mostly produced via biological fermentation and distillation (Smeets *et al.*, 2008; La Rovere *et al.*, 2011). Although the process of fermentation does not produce significant amounts of toxic pollutants, effluents from sugarcane distilleries typically contains high loads of organic matter, leading to a high BOD, as well as high temperatures. However, the release of effluents into the environment is being reduced through closed circuit systems, or the use of effluents for combined irrigation and fertilization (*fertigation*) of sugarcane fields.

In addition to industrial growth, the dramatic growth of megacities entails specific issues of both clean water supply and pollution, especially in view of the rapid population growth and urbanization (Table 1). Although the issue of water supply for cities is receiving increasing attention (e.g. McDonald *et al*., 2011), evidence of the impact of raw wastewater injection into the peri-urban environment of South American cities is still very scarce and anecdotal (e.g. Pompeu *et al*., 2005). Nevertheless, it is generally considered to be a significant threat to coastal and freshwater ecosystems, as well as food security and human health (Corcoran *et al*., 2010).

The impact of reservoirs

The increasing number of large reservoirs has a further impact on water quality and stream ecology, especially in the Amazon. Compared to globally-installed reservoir capacity, South America has a medium position (Fig. 4). If numbers of reservoirs are considered, the average installed storage capacity amounts >2.2 km^3, while the average for other world regions is 0.8 km^3. Reservoirs are mainly built for irrigation purposes and hydropower generation, according to many public descriptions of reservoirs. This somehow contradicts data provided by the Global Reservoir and Dam (GRanD) Database, from which Lehner *et al*. (2011) derived a map that hardly shows any irrigation use of reservoirs in South America.

Dams dramatically change upstream and downstream sedimentation loads (Syvitski *et al*., 2005). Thereby they alter longitudinal distribution of nutrients, change longitudinal temperature patterns and heavily impact stream ecology (Baxter, 1977). Further, Poff *et al*. (2007) compared regulated *versus* unregulated rivers across a large range of ecosystems in the USA, and concluded that seasonal and inter-annual streamflow was severely homogenized with an overall dampening effect on natural streamflow dynamics, despite a reduction of the native diversity of aquatic flora and fauna. A similar investigation is lacking for South America, but it can be concluded that the same ecological processes and disturbances observed in the USA are likely to be happening in South America. The impact on biodiversity might be even more dramatic here, given for example the large fish diversity observed in many tropical rivers of the Amazon and other biodiversity hotspots of the Neotropics (Junk, 2007).

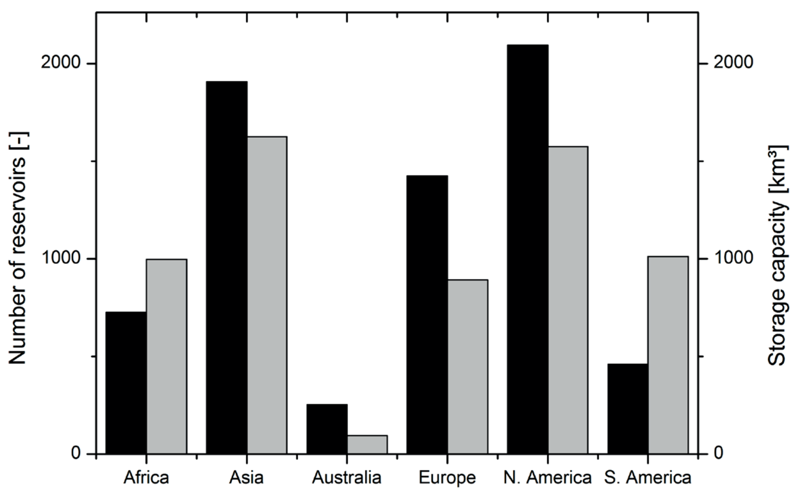

Fig. 4 Number of installed reservoirs and storage capacity across world regions (data extracted from Lehner *et al*., 2011).

CONCLUSIONS

The geographical diversity and complexity of the South American continent gives rise to a large variety of potential threats to water availability and quality. While water quantity is mainly under pressure from a strongly increasing demand and long-term changes in weather patterns, water quality is a much more diverse issue. With regard to diffuse pollution sources, we identify the large-scale land-use changes from the Amazon basin, and the intensification of agricultural activities in the fertile, semi-arid continental plains of South Brazil, Argentina, Paraguay and Uruguay as important drivers of change that need further scientific attention. However, on a smaller scale, intensification of agricultural activities in the Andes and Amazon may also interact with a rapidly increasing demand, thus aggravating current shortages and creating potential future conflicts.

Point sources of pollution are strongly related to the vigorous socio-economic development of the region. Large cities are typically growing faster than the hinterland, thus creating hotspots for both water demand and wastewater production. In terms of industrial activities, the mining industry is a major driver of growth. Several countries in South America are among the world's biggest exporters of oil and metals, and in all of them the industry has experienced double-digit growth in the last decade. Yet, assessing the potential impact on local water quality and aquatic ecosystems remains a major scientific challenge. Other expanding industries that pose a potential threat to water quality are aquaculture and biofuel production.

Lastly, especially in the Andean area, the interest in hydropower as a clean energy source drives a continued increase in the number of large reservoirs. These reservoirs alter longitudinal distribution of nutrients, change longitudinal temperature patterns and impact stream ecology in ways that are often still very poorly understood.

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