Acta Limnologica Brasiliensia

Publication of the Brazilian Association of Limnology

Thematic Section: Opinions about Aquatic Ecology in a Changing World

Acta Limnologica Brasiliensia, 2020, vol. 32, e106
https://doi.org/10.1590/S2179-975X3220
ISSN 2179-975X on-line version

Freshwater ecosystems of Mainland Ecuador: diversity, issues and perspectives

Ecossistemas aquáticos do Equador Continental: diversidade, problemas e perspectivas

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Cite as: Celi, J.E. and Villamarín, F. Freshwater ecosystems of Mainland Ecuador: diversity, issues and perspectives. *Acta Limnologica Brasiliensia*, 2020, vol. 32, e106.

Abstract: Ecuador is one of the smallest and most densely populated countries in South America. In spite of this, it is also one of the 17 megadiverse countries worldwide and home to the largest number of species per unit area. Most aquatic ecosystems in mainland Ecuador have historically faced strong environmental pressures because the country's economy has been based on the exploitation and trade of raw materials and agricultural products at a very high environmental cost. In this review, we provide a broad overview of the diversity of freshwater ecosystems and fish in mainland Ecuador. We address broadly current and historical threats to these ecosystems, including pollution due to oil extraction, mining activities, agriculture and the disruption of hydrological connectivity caused by hydroelectric dams. Despite these problems, we show some examples of promising initiatives at the local and national levels to address this situation.

Keywords: freshwater diversity; environmental degradation; water policies; participatory management.

Resumo: O Equador é um dos países de menor tamanho e o mais densamente povoado da América do Sul. Apesar disso, é também um dos 17 países megadiversos do mundo e abriga o maior número de espécies por unidade de área. A maioria dos ecossistemas aquáticos no Equador continental tem historicamente enfrentado fortes pressões ambientais devido ao fato de que a economia do país tem sido baseada na exploração e comercialização de matérias-primas e produtos agrícolas a um custo ambiental muito alto. No presente trabalho, apresentamos uma visão geral da diversidade de ecossistemas e peixes de água doce do Equador continental. Também, revisamos de maneira ampla as ameaças mais prementes a esses ecossistemas, incluindo a poluição devido à extração de petróleo, mineração e agricultura, e a crescente perturbação da conectividade hidrológica causada por represas hidrelétricas. Apesar dos graves problemas ambientais, fornecemos exemplos de iniciativas promissoras atualmente em andamento nos níveis local e nacional para reverter essa situação.

Palavras-chave: diversidade de água doce; degradação ambiental; políticas hídricas; gestão participativa.

1. Introduction

Ecuador is one of the smallest and most densely populated countries in South America, with almost 68 inhabitants per km^2 (United-Nations, 2017). It is also one of 17 megadiverse countries worldwide and holds the largest number of species per unit area (Sierra et al., 2002). Ecuador's overwhelming diversity of species and ecosystems is partly determined by its geographic and climatic conditions. In this review, we give an overview of the diversity of freshwater ecosystems and fish in mainland Ecuador. We also broadly review the most pressing threats these ecosystems face, including pollution due to oil extraction, mining and agriculture and the ever-growing disruption of hydrological connectivity caused by hydroelectric dams. Despite the severe environmental problems, we provide examples of promising initiatives that are under way at the local and national levels that may contribute to revert this situation.

2. Freshwater Ecosystems and Fish Diversity

Watersheds in mainland Ecuador drain multiple types of terrestrial ecosystems and have unique hydrological and geochemical conditions. These characteristics result from a combination of topographical, climatic and spatial arrangements, but also from geological processes mainly driven by the uplift of the Andes some 10.5 million years ago (Albert et al., 2006). Ecuador ranges from sea level to 6267 m a.s.l., and over time has experienced many volcanic, tectonic and climatic phenomena (such as glaciations) that have shaped the terrain and produced multiple types of aquatic environments.

The Andes separate mainland Ecuador into two major hydrographic regions: the western (Coastal) and the eastern (Amazonian) watersheds. The southwestern part of the country shows a pronounced climatic seasonality with frequent droughts caused by the cold Humboldt marine current. On the other hand, the northwestern lowlands are influenced by the warm Equatorial Current that leads to more humid conditions (Conroy et al., 2009; Vuille et al., 2000). At mid-elevation, on both sides of the Andes, air masses that cross the lowland plains collide with the mountains and cause very high levels of rainfall (Insel et al. 2010). These climatic conditions cause an extremely heterogeneous spatial and temporal distribution of discharge across the country (Auerbach et al., 2016).

Ecuador's watersheds drain waters collected along the whole elevation gradient of the Andes in both the Eastern and Coastal Cordilleras. In western Ecuador, nine main hydrographic units occur from north to south: Mira-Mataje, Santiago-Cayapas, Esmeraldas, the Coastal Cordillera watersheds, Guayas, Cañar-Jubones, Santa Rosa, Puyango, and Catamayo-Chira. Of these, the Guayas River Basin is the largest coastal watershed (34,500 km^2) and holds almost 25% of the country's population (Villacís and Carrillo 2011), concentrated mainly in Guayaquil City. Along their course, tributaries of the coastal basins cross multiple types of mountain, cloud, dry and humid lowland forests and vast wetland areas. These tributaries constitute important sources of water and provide other ecosystem services for local inhabitants (Raes et al., 2015).

In the highlands, basins drain extensive crops and developed areas, including Quito, the country's capital, and many other smaller cities. These highlands are predominantly covered by the *paramo* ecosystem, which lies between the tree and the permanent-snow lines. This ecosystem maintains, purifies and supplies water to main Andean cities and villages (Farley and Bremer, 2017), and it is sprinkled by hundreds of lagoons of volcanic and glacial origin (Steinitz-Kannan, 1997).

On the eastern side of the Andes, Amazonian watersheds occupy 52% of Ecuador's territory and drain extensive and diverse landscapes along the Putumayo, Napo, Pastaza, Santiago and Mayo-Chinchipe River Basins. These rivers that originate in the mountains, including some isolated snow-capped Amazonian volcanoes, pass through wild and deep canyons, and then open up in large alluvial fans and floodplains at the beginning of the lowlands (Custode & Sourdat, 1986). Extensive floodplains occur along the course of large Amazonian rivers. For instance, the Napo River Basin – the largest basin within Ecuadorian territory – is fringed by multiple types of flooded environments. Among these, permanently-flooded *Mauritia* palm swamps, seasonally-flooded forests, lagoons periodically flooded by white waters (sediment- and nutrient-rich Andean waters) and black waters (nutrient-poor and rich in dissolved organic matter) are common (Celi, 2014).

The Ecuadorian Amazon lies on top of ancient marine sediments, and at the foot of both ancient and modern mountain systems. The chemistry of the waters that flow through these rock formations is extremely diverse, and together with the large altitudinal gradient, play a major role in the diversity and distribution of aquatic species, including fish (Celi, 2005).

Overall, Neotropical freshwater fishes exhibit pronounced altitudinal variability on species richness, with maximum diversity at lower altitudes (Albert & Reis, 2011). Diversity of strictly freshwater fishes in mainland Ecuador reaches 824 species (Jiménez-Prado et al., 2015), which represents almost 16% of all South American freshwater fish diversity (Reis et al., 2016). Ecuador occupies four different freshwater ecoregions in tropical South America (sensu Abell et al., 2008), three of which (FEOW 312, 313, 316) belong to the Amazon basin, the largest and most diverse freshwater basin in the world (Reis et al., 2016). Almost 75% of Ecuadorian freshwater fishes are concentrated in its Amazonian freshwaters. Commercially important fish species include the Paiche (*Arapaima* sp.) - the world's largest scaled freshwater fish-, the Paco (*Colossoma macropomum*), and long-distance migratory species of the orders Characiformes (i.e., *Prochilodus nigricans*, *Brycon spp.*) and Siluriformes (i.e., family Pimelodidae). Many of the latter undertake basin-wide spawning migrations from lowland Amazon to the foothills of the Andes, including eastern Ecuador. The most remarkable of these is the catfish *Brachyplatystoma rousseauxi*, which carries out the longest strictly freshwater fish migrations in the world (Barthem et al., 2017).

On the other hand, freshwater fish diversity from the northwest Pacific basin complex (FEOW 301, sensu Abell et al., 2008), that encompasses all Ecuadorian western basins, is relatively species-poor but with a very high degree of endemism (Reis et al., 2016). Important species inhabiting these basins includes the Chame (*Dormitator latifrons*), which is an important food resource for rural and urban inhabitants in the Coastal Plains of Ecuador.

3. Main Environmental Issues

Unfortunately, populations of most commercially important fish species in Ecuador have been severely affected in some places, or are rapidly decreasing due to pollution, habitat destruction, hydrological disruption, harmful fishing practices and invasive species (Cumberlidge et al., 2009). For instance, in the Misahuallí River basin located in the piedmont of the Amazon basin, the Sábalo or Jandia (*Brycon* spp.) and Bocachico (*Prochilodus nigricans*) were so abundant a few years ago that several individuals could be captured with a single multi-hook (Fabian Rivadeneyra pers. com.). These species were so important in people's diet that a traditional festival, *Jandia warmi*, was established in an indigenous community to commemorate the seasonal arrival of these fish (Celi et al., 2016). Currently, these species are very scarce in the basin and even the persistence of the festivity is at risk of disappearing. Overall, the scarcity of fish is common in many of the rivers and streams of the Amazon and the Coast of Ecuador frequently due to unsustainable fishing practices including the use of chlorine and explosives. This problem is exacerbated by the invasion of exotic species including tilapia (*Oreochromis niloticus*) in the lowlands (Zambrano et al., 2006) and rainbow trout (*Onchorynchus mykiss*) in the highlands (Vimos et al., 2015).

However, the heart of large-scale environmental problems in Ecuador resides on the fact that the country's economy has been historically based on the exploitation and trade of raw materials and agricultural products at a very high environmental cost. For instance, the pollution caused by the oil industry since the end of the 1960s has been very severe in the Amazon, even within protected areas (Kimerling & Henriksen, 1991). Oil spills have been very common, especially in water bodies near oil fields, wells and pipelines. In the late 1970s, crude oil used to be purposely spilled on Amazon roads to settle dust, which was then transported by the rain to surrounding rivers and floodplains (Felipe Campos, pers. comm.). Chronic pollution in the northern part of the Ecuadorian Amazon affected many aquatic species and caused health problems in people living near the contaminated environments (Hurtig & San Sebastián, 2002, 2004; San Sebastián et al., 2001). High concentrations of metals associated to oil activities and agrochemicals have been found in soil and water in this region (Barraza et al., 2018). Harmful practices undertaken by oil companies have led to a long-term lawsuit brought by local inhabitants against Chevron-Texaco (Kimberling, 2005).

Gold mining activities have polluted waters draining both the eastern and the western watersheds of the Andes (i.e., Santiago and Puyango Rivers, respectively) – the latter basin is shared with Peru. The most common effects caused by mining activities are the discharge of cyanide, mercury, and metal-rich tailings into the water (Tarras-Wahlberg et al., 2001). Although the use of mercury is currently prohibited, its cumulative effects still persist in the ecosystem and are often manifested in the reduction of the abundance and richness of organisms inhabiting the waterbodies (Calle et al., 2018). The central and southern Ecuadorian Andes hold the country's largest gold and copper deposits (Warnaars & Bebbington ,2014). Today, both large- and small-scale mining activities are currently being undertaken in Ecuador, whether under governmental concessions or illegal operations. Although the first are said to be conducted following rigorous pollution control measures, strong impacts are caused due to the overwhelming size of the operations. For instance, operations in the Condor Cordillera in southeast Ecuador move massive amounts of materials that affect pristine and extremely biodiverse ecosystems, including rivers. On the other hand, the impacts of small-scale, artisanal operations are related to the inefficient and primitive techniques used that lack water pollution control (Tarras-Wahlberg et al., 2000) and habitat restoration measures.

Pesticides and fertilizers currently pollute many rivers across extensive agricultural areas of the country. Pollution comes mostly from agricultural crops, including banana, rice, African palm and ornamental flowers (Suarez-Lopez et al., 2017; Deknock et al., 2019). Untreated organic and industrial waste that originates in the majority of the country's urban and rural population centers, farming facilities (e.g., livestock, swine, poultry, fish), and textile and tannery industries cause extensive and cumulative impacts along rivers. Long stretches of rivers that cross large cities collect untreated sewage, industrial and rain waters that drain the streets and thus affect extensive basin areas. Treatment of urban and industrial wastewater is almost non-existent in Ecuador. In 2006, wastewater treatment service reached only 5% of all the municipalities (Ecuador, 2006); a decade later only 7% of sewage waters are reported to be treated before returning to water courses (CEPAL, 2017).

These pollution problems are exacerbated by the conversion of native ecosystems into agricultural and urban areas (Farley, 2007), and especially by the deforestation of high-slope terrains or riparian zones where erosion is very high and causes sedimentation and aggradation (decreased depth and widening of rivers) (Vanacker et al., 2014). Among the consequences of these changes in rivers are the loss of habitat of many aquatic species, the decrease in water quality, and the reduction of the residence time of water in the watercourse (Vanacker et al., 2015). It is likely that the generalized decrease in the flow of the rivers, perceived by many population groups in Ecuador, is due to changes in land use, and also to the extraction of material for infrastructure development (Celi, pers. obs.). This is causing hydraulic changes and negative effects on the watersheds water balance. In simple terms, the water that flows through rivers stays on the continent for shorter periods of time and reaches the ocean more rapidly. This makes aquatic environments (e.g., pools, rapids) more homogeneous and unsuitable for many species. The reduction in the effectiveness of hydraulic controls in rivers may increase the chances and severity of floods to downstream populations (Hurtado Pidal et al., 2017).

Finally, hydrological disruption caused by the construction of hydropower dams is one of the main problems currently facing aquatic ecosystems in mainland Ecuador. Governmental programs aimed to shifting the energy matrix from fossil fuels to renewable energy sources have led to the steady increase of hydropower infrastructure during the last decade (Ponce-Jara et al., 2018). The electricity generation capacity currently fully covers the country's demand (Ponce-Jara et al., 2018) and it is therefore unnecessary to install additional infrastructure. In spite of this, at least 64 new dams on Andean rivers in the Ecuadorian Amazon basin are proposed to be installed in the next years (Anderson et al., 2018). Additionally, there is a project proposed to be installed near the mouth of the mainstem Napo River in Peru (Mazan Hydropower Dam), which would isolate the lowland Amazon from most part of the upstream river network (Anderson et al., 2018). Hydrological disruption caused by dams in the Andean Amazon region is responsible for a list of environmental problems, including reductions in downstream sediment and nutrient supply, changes in the downstream flood pulse, changes in upstream and downstream fish yields, reservoir siltation, greenhouse gas emissions, and mercury contamination (Forsberg et al., 2017).

4. Policies and Perspectives

Despite the severe problems summarized above, not all is doom and gloom and several promising initiatives have been taking place at the local and national levels to revert this situation. Ecuador's Constitution, approved in 2008, determines that Nature has its own rights, and healthy and safe ecosystems for human populations are therefore guaranteed (Asamblea-Constituyente, 2008). The Water Law dictates that water sources and riverbanks must be protected, that hydrobiological connectivity must be maintained, and that flows must keep their natural variability (Ecuador, 2014). This legal structure paves the way to more sustainable practices.

With this in mind, the Quito Water Fund - FONAG and other municipal firms, including ETAPA in Cuenca, are developing mixed initiatives to support the conservation of water resources on which cities depend (Kauffman, 2014). FONAG, for example, has supported the restoration of eroded hillsides and wetlands that had previously been drained for grazing (Jumbo et al., 2017). It has also encouraged the removal of cattle from Quito's water production areas. Recently, together with national philanthropists, FONAG created the Ponce - Paluguillo National Water Protection Area, the first of its kind in the country. Similar initiatives have been undertaken at the municipal and community levels in various sectors of the country (Raes et al., 2015; Wunder & Albán, 2008). In addition to promoting the conservation of water recharge zones, management practices that favor the integrated use of water and aquatic resources should be established.

Social movements, indigenous organizations and NGOs have stood up against the proliferation of mining and oil operations in protected areas and indigenous territories across Ecuador. Recently, a group of Cofán people granted in court the end of mining operations on their lands (Paz Cardona, 2019). In 2018, the Constitutional Court of Ecuador ordered Chevron to pay $9.5 billion in compensation for environmental damage caused between 1964 and 1990 (Mongabay, 2018). Although the threats from extractive operations are still widespread, these examples highlight the importance of people´s organization to demand the Government the implementation of more sustainable practices that honor Ecuador's Constitution.

A model of participatory and integrated management of water and aquatic resources at the level of watersheds is essential (Halbe et al., 2013). Approaches to social, transboundary basins, in which the role of all components of the hydrological cycle are analyzed are useful to define improved practices for water harvesting, alternatives of treatment and reuse, sensible designs and activities of conservation and management of species (Giordano & Shah, 2014). The decentralized autonomous government of Tungurahua, in the Andean highlands, is a good example of citizen participation, based on a parliamentary system. This "Water Parliament" recognizes the transversal and fundamental role of water in the management of natural resources and generates the necessary conditions among the different actors in order to coordinate actions and create policies that lead to the sustainable use of water (Paltán, 2014). Interest groups influence the planning of the different levels of governance, aimed to the reduction of inequalities, the conservation of water resources and the reduction of pollution. The ultimate goal of this group is improving people´s quality of life.

In this context, close and coordinated work with the irrigation boards is fundamental, in such a way that the provision of water resources is organized and ensured both for the local inhabitants and for the needs of the ecosystems (Llerena Cepeda et al., 2017). There are stretches of rivers in arid or semi-arid Andean basins that dry completely due to the excessive extraction of water for irrigation or consumption without considering environmental flows. This has serious implications for the ecosystems and inhabitants downstream. In this sense, a review of the order of priority of resources in the Water Law in which the ecosystems have priority, may guarantee the health of the ecosystems and the water and food security of all the inhabitants of the basins (Ecuador, 2014). Furthermore, the implementation of ancestral practices for soil and water conservation of, including plowing along contour lines, replacing exotic plants that absorb large quantities of water with native ones that produce water, promoting infiltration in rural and urban areas, and optimizing the use of water in general are improvements that must be achieved (Dewulf et al., 2005).

A few years ago, the Ecuadorian government took a step forward toward the transformation of the production matrix. This has caused an intensification of resource extraction in the short term to support the transition to a 'knowledge-based' economy in the longer term (Purcell et al., 2017). As mentioned above, although the former option has leveraged environmental degradation, some progressive decisions have been taken as well. For instance, one of the most important of those was the institutionalization and strengthening of public universities with a strong focus on the generation of environmental knowledge.

There is much to be done to conserve water and the unique aquatic ecosystems of the wonderful and diverse Ecuador. The recipes are diverse and include participatory proposals with a long-term vision, encompassing both traditional knowledge and scientific and technological advances. An integrative and adaptive focus will facilitate the best use of natural resources, the conservation of biodiversity, and the improvement of people's quality of life. Negative changes are occurring so rapid and profoundly that action needs to be taken in a timely manner. Otherwise, the risk of losing the great diversity of Ecuador is impendent.

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Received: 01 March 2019
Accepted: 13 October 2020

Associate Editors: André Megali Amado, Joyce Andreia dos Santos, Rafael Marques Almeida, Simone Jaqueline Cardoso.