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Provisional chapter

Linkages between Water and Forests in South American Watersheds under Restoration

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Abstract

Water security is threatened by the rapid growth of the human population in areas where there were native forests before coupled with climate change scenarios. One of the main elements which ensures water security is water stored in soil, which is fundamental for maintaining ecohydrological processes at the watershed scale under forest land-use change. In South America, aiming to restore and recover changing catchment areas, best management practices (BMP) have been widely proposed as a strategy for water-forest resource sustainability. Based on forest evapotranspiration demand, this chapter presents fundamental concepts related to soil-water-forest cycles, watershed restoration, and case studies of BMPs in South American watersheds (e.g., Brazilian and Colombian projects for watershed conservation or restoration). It has become clear that there is an opportunity in setting baseline data and quantifying the effectiveness of these BMPs. By using ecohydrological monitoring and suitable indicators of these BMPs in the long term, an integrated understanding of water-forest relationships is needed. Furthermore, the more successful watershed management projects are, the more effective decision-making regarding BMP linking water and forests is.

Keywords: water yield, watershed restoration, hydrological services, ecohydrological processes, South America

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1. Introduction

There is no life without water. Before the earliest writing systems evolved, humans were hunters and food gatherers. Then, with the onset of the Neolithic revolution, humans started settling alongside rivers and developed into early state civilizations, often referred to as "hydraulic civilizations." During the late Holocene, in Latin America, the Maya and Inca empires developed ancient water systems based on empirical observations. Urban civilization replaced small villages with towns and cities, and agriculture progressively took the place of native forests. However, new concerns arose in dealing with the multiple uses of water resources. On one hand, an evolution of public and industrial water supply systems was needed for human well-being. On the other hand, the development of such technologies, as well as other anthropogenic impacts, made ecosystems even more vulnerable than they already were.

Since the mid-twentieth century, rapid human population growth, technological development, and rising resource consumption have increased water pollution and scarcity. The *Food and Agriculture Organization* (FAO) of the United Nations [1] estimates that there will be a need to increase the global food production by 60% to feed more than 9 billion people foreseen to live in the world by 2050. The human impact on Earth seems to reflect a new period in the geological time scale: the so-called Anthropocene [2]. Waters et al. [3] summarized the key markers of functional changes due to anthropogenic actions, which are indicative of the Anthropocene, for example, biotic changes, which include species invasions and accelerated extinction. Furthermore, human-induced stressors are altering freshwater, marine, and terrestrial ecosystems in an unparallelled way [4].

The water cycle connects the abiotic environment with the bio- and anthropospheres, thereby leading the distribution of life on Earth [5]. In turn, freshwater ecosystems have been recognized among the most threatened ecosystems in the world from at least 20 years ago [6–9]. At least 10,000–20,000 freshwater species are already extinct or at risk, with loss rates comparable to those of the late Pleistocene–Holocene succession. Overexploitation and habitat loss trends are pushing Earth to the sixth mass extinction process [3]. It has been shown that 65% of Earth's river discharge and associated habitats are moderately to highly threatened [10].

In his pioneering work, Tansley [11] proposed the term "ecosystem," encompassing abiotic and biotic factors, as well as their functional and structural relationships. Moreover, terrestrial ecosystems influence freshwater by moving and modifying flows through a series of ecohydrological processes. The relationships among ecohydrological processes are strongly nonlinear (see [12–15]; also called geo-bio-hydrologic processes by [16]). This ecohydrological processes in both aquatic and terrestrial ecosystems provide benefits for humans, which are called ecosystem services [17, 18]. Various authors (i.e., [19–23]) have defined ecohydrological processes when relating ecological aspects of the hydrological cycle. For example, by the time correlation of the variable fraction of flooded areas with the duration of flood pulse can better integrate both the nutrient cycling and the river flow as part of a local biogeochemical cycle.

In the scope of this chapter, linked to water resources, three classes of ecosystem services, *provisioning*, *regulating*, and *supporting* and their links, are presented. All these types of ecosystem services have been progressively damaged by anthropogenic pressures:

- *Provisioning services* involve the production of renewable resources (e.g., freshwater, food, and extraction of pharmaceutical and cosmetic products from biota; [18]).
- *Regulating services* are those that indicate benefits arising from regulating ecological processes and, hence, lessen environmental change (e.g., climate regulation, water regulation throughout attenuation of hydrologic extremes such as floods and droughts, disease control; [18, 24]).
- *Supporting services* are the cycles of transformation of energy and mass at ecosystems, and they are the basis for providing other ecosystem services (such as nutrient cycles, soil formation; [18]).

Land-use/land-cover (LULC) changes due to anthropic activities are the main threats to the ecosystem regime shifts. Unbalanced water flows, biodiversity losses, and interruption of nitrogen, phosphorus, and other biogeochemical cycles deplete ecosystem services on large scales [17, 25]. Considering these significant changes, we need to understand how the ecohydrological processes work, if we want to develop better policies on watershed management [26].

The quantity and quality of water resources of each headwater are related to geology, topography, soil type, climate, type and amount of vegetal cover, and to the degree and type of anthropic activity in the watershed. Watershed restoration provides a variety of goods and services for humans and nature, including regulating water and ecosystem flows, improving water quality, reducing sediment loads, and affecting pollination and biodiversity.

The *ecosystem-based adaptation* (EbA) concept emerged at the beginning of the 2010 to mitigate the impacts of the climate change and anthropic activities. EbA means *the use of biodiversity and ecosystem services to help people adapt to the adverse effects of climate change*. This concept was defined by the Convention on Biological Diversity in the 10th Conference of the Parties [27]. Protecting ecosystem services is essential to promote watershed-scale sustainability to decrease ecosystems′ and people's vulnerability, as well as increase their resilience to global change impacts [28, 29]. The *watersheds restoration in South America* can be achieved through projects of payment for ecosystem services (PES) since PES projects are considered a method of EbA [30].

Neither integrated quali-quantitative analysis nor combined indicators of human-ecosystem appropriation of freshwater resources have been established in Brazilian basin plans [31, 32]. On the one hand, among these indicators, we highlight the water footprint—WF [33, 34]. It encompasses gray, blue, and green portions of water into a unique indicator to evaluate sustainability arising from water resource pollution and consumption. For sustainable water allocation planning, river plans must be built based on accurate data on actual water availability per basin, taking into account (i) water needs for humans, (ii) environmental water requirements, and (iii) the basin's ability to assimilate pollution [34]. On the other hand, we suggest the study of forest-climate-water interactions as a hydraulic analogy since changes in forest cover can alter precipitation at regional scales [25].

2. A water-forest interface through hydraulic analogy

To address water-forest restoration perspectives, it is worth studying the water-forest system. It can be shown as a transpiration system which is analogously analyzed as any other closed system that transports fluids, for example, a pipeline. **Figure 1** indicates, from a hydraulic similarity, the energy grade line concept applied to liquid and vapor phases of the system. Because of low velocities, velocity head is neglected due to laminar flow. Energy is required to (1) extract water, (2) transport water through the soil, (3) transport it through the plant, (4) vaporize water, and (5) transport water into the atmosphere. All these energy phases have losses. In **Figure 1**, the change in the point-to-point energy level gives the head losses and energy sources. Flow direction is toward the negative energy gradient. Accounting for the head losses through the liquid phase of the transpiration process, the total frictional head loss is.

$$h_f = h_s + h_r + h_x + h_l, \tag{1}$$

in which h is the dissipated head with the subscripts "s," "r," and "x" and "l" refers to the soil, root, xylem, and the leaf components, respectively. These subscripts will designate the same flow components when used hereafter with other hydraulic terms. Assuming that the flow is laminar, Darcy's flow (qDarcy = k·h/L) and continuity equation (Q = qDarcy·a) may be applied to each component of flow in the liquid phase. For any given hydraulic component, *qDarcy* is the velocity, *k* is the hydraulic conductivity, *L* is the length toward the flow directs, *a* is the cross-sectional area to the flow, and *Q* is the total flow rate. If the expression h = Q/a · L/k is substituted into each component, it yields the hydraulic factors that affect transpiration in the liquid phase.

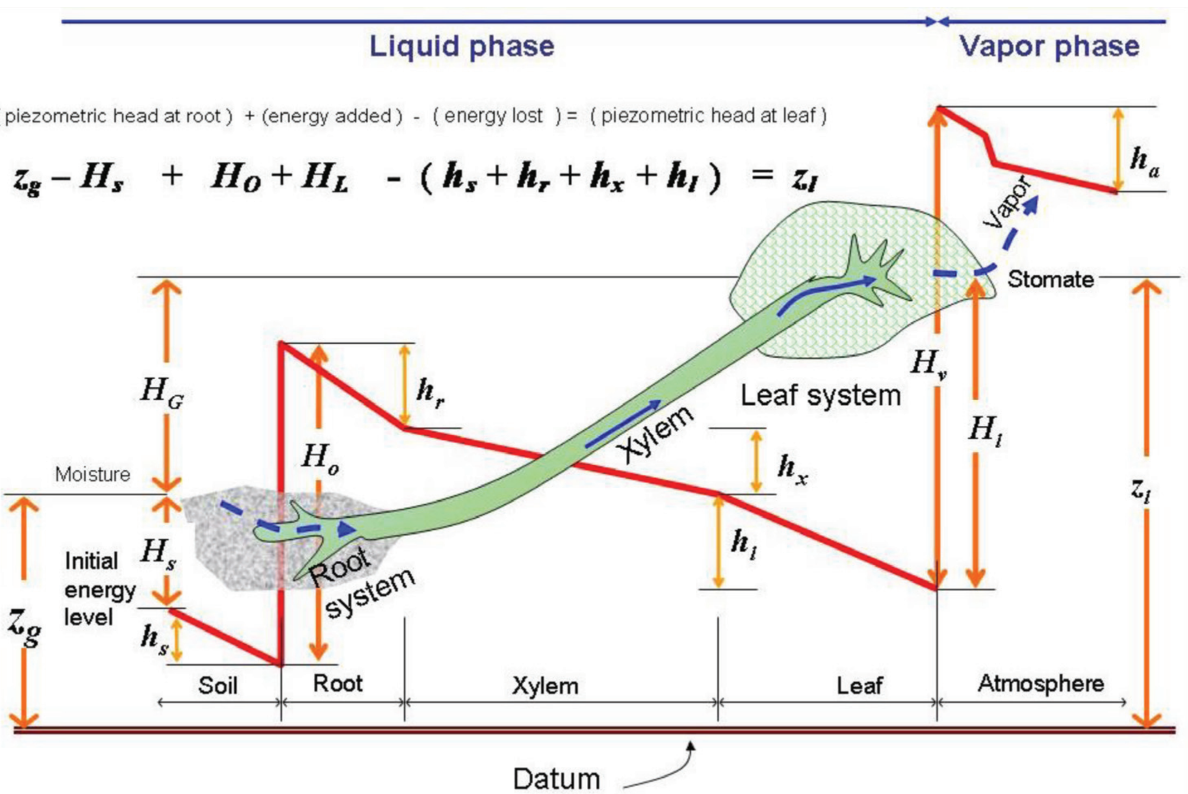


Figure 1. Hypothetical energy grade line in the transpiration process for condition $h_f = H_f$ (adapted from [35]; Ross and Salisbury [36]; and Stewart et al. [37]). See explanation in the text.

$$h_f = Q \cdot \left[\frac{L_s}{a_s k_s} + \frac{L_r}{a_r k_r} + \frac{L_x}{a_x k_x} + \frac{L_l}{a_l k_l} \right] \tag{2}$$

The terms within brackets in Eq. (2) are resistance terms and could be replaced as *Rs* for the soil's resistance and *Rp* for the plant's resistance, as follows:

$$R_s = \frac{L_s}{a_s k_s} \tag{3}$$

$$R_p = \frac{L_r}{a_r k_r} + \frac{L_x}{a_x k_x} + \frac{L_l}{a_l k_l} \tag{4}$$

in which *Rs* and *Rp* are the equivalent hydraulic resistances of the soil and plant, respectively. *Rs* is dependent on the soil moisture content and the type of soil, and *Rp* depends on the type of the plant and the stage of growth that includes the extent of the root system development. From Eq. (2), a more simplified equation is obtained:

Figure 2. The 12 major river basins in Brazil. Source: [38].

$$Q = \frac{h_f}{R_s + R_p}, \tag{5}$$

which states that the flow rate that is delivered in the liquid phase is dependent on the ratio of the total head available and the hydraulic resistances of the soil (depending on water content) and the plant (depending on the vegetation type and growth phase). Eq. (5) shows that the lower the value for *Rp* and the more head, *hf*, that can be developed, the more drought resistant the plant is.

It should be mentioned that the vertical distance between the plant-conduit and the energy grade line (*EGL*) represents the pressure head because the velocity head is negligible. Furthermore, the water-forest cycle shown in **Figure 2** is the key element for restoration and conservation measures, such as BMPs, in different spatiotemporal scales and under several scenarios of climate and land-use changes explained in the following sections.

3. Water resource conservation strategies for South American watersheds: Examples from Brazilian watersheds

Brazil is the largest South American country and is the fifth largest country in the world (both geographically and in population). It presents 87% of urban population and most of the population lives near the Atlantic coast in the east [39]. Due to Brazil's large area (8.5 million km^2), each region presents different meteorological patterns and biomes. Moreover, several river basins were selected for hydropower production, representing ca. 87% of all the energy demand in Brazil [40].

3.1. Hydrometeorological aspects of Brazilian watersheds

The hydrological and meteorological characteristics of the major Brazilian river basins, some of them for hydropower generation, are presented in **Table 1** and **Figures 2 and 3**.

A mixture of climate zones characterizes Brazil [41]. These climate zones can be divided into (1) atmospheric circulation; (2) thermic regions, which are related to the monthly extreme temperatures; and (3) categories related to droughts (**Figure 3**).

The Amazon river basin (3,870,000 km^2) occupies around 45% of the Brazilian territory. The mean flow in the region corresponds to 74% of the national flow in Brazil (179.516 m^3/s). In spite of its abundance of water, just a minor part of the Brazilian population lives in this region, with a demographic density of 2.51 hab./km^2 (10 times less than the national mean), and the water demand is very reduced, as it is only 3% of the national water demand [38].

The Paraná river basin (879,873 km^2), which occupies 10% of the Brazilian territory and includes the metropolitan regions of Sao Paulo and Curitiba, represents the most economically developed region in Brazil and has a high population density, approximately 69.7 hab./km^2. It presents the highest water resource demand in the country, near 31% of the national demand.

River basin	Drainage area (km^2)	Mean precipitation (mm/year)	Mean discharge (m^3/s)	Specific discharge (L/s/km^2)	Evapotranspiration (mm/year)	Native vegetation cover (%)
Major Brazilian river basin regions						
Amazon	3,870,000	2205	132,145	34.1	1128	85
East Atlantic	388,160	1018	1484	3.8	897	35
Western Northeast Atlantic	274,300	1700	2608	9.5	1400	48
Eastern Northeast Atlantic	286,800	1052	774	2.7	967	50
Southeast Atlantic	214,629	1401	3167	14.8	936	31
Southern Atlantic	187,552	1644	4055	21.6	962	39
Paraguay	363,446	1359	2359	6.5	1154	58
Parana	879,873	1543	11,831	13.4	1119	16
Parnaiba	333,056	1064	767	2.3	991	75
São Francisco	638,466	1003	2846	4	862	53
Tocantins-Araguaia	920,000	1774	13,779	15	1302	53
Uruguay	274,300	1623	4103	15	1151	31
Selected strategic river basins for hydropower generation in Southeast Brazil						
Cantareira	2279	1475	35	15	988	26
Emborcação	29,076	1485	456	16	991	29
Três Marias	51,576	1404	657	13	1003	20
Furnas	52,197	1484	905	17	937	19
Mascarenhas	71,649	1238	890	12	847	19

Table 1. Hydrometeorological aspects of the major Brazilian river basin regions and selected watersheds draining to strategic reservoirs for hydropower in Southeastern Brazil.

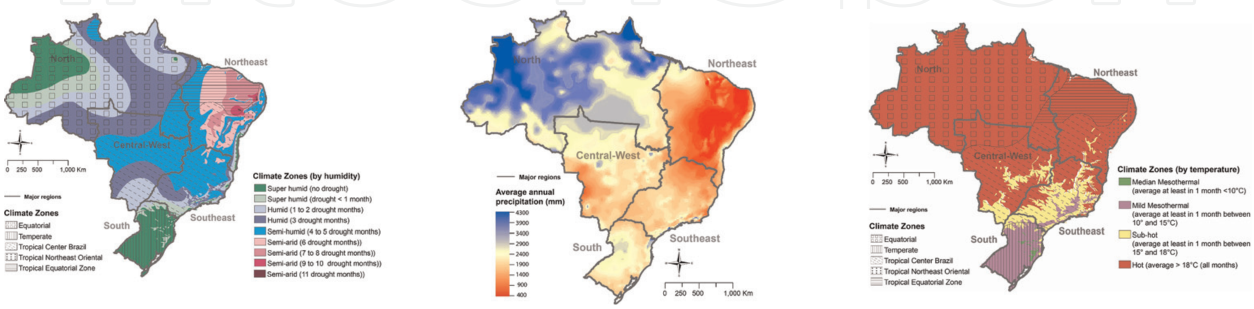


Figure 3. The complex blend of climate zones by average annual precipitation, humidity, and temperature in Brazil. Source: Bressiani et al. [42]. Reproduced with the permission of the authors.

However, the mean flow in the region represents only 6.6% of the national flow [38]. This fact reveals the imbalance in the distribution of the water resources in the country. The Amazon region also presents the higher pluviometric index of the country, 25% higher than the national mean. This occurs because the Amazon river basin is located in a hot and humid climate region, classified as equatorial (**Figure 3**). This region is characterized by the presence of equatorial air masses, of the continental type, by the action of the intertropical convergence zone (ICZ), formed by the convergence of trade winds [43].

In contrast, the *Atlântico Leste* river basin (388,160 km^2), the *Atlântico Nordeste Oriental* (286,800 km^2), Parnaíba (333,056 km^2), and Sao Francisco (638,466 km^2), present minor annual mean precipitations, as a consequence of hot and dry climates, with sparse and irregular rains and a mean rainfall of 500 mm per year [43].

Regarding vegetation, most of the Amazon river basin is covered by its native vegetation, consisting of the Amazon (approximately 87% of its original cover), the "Cerrado," or Savannah (approximately 60% of the original vegetation). On the other hand, the Paraná is the basin which presents the smallest area covered by native vegetation proportionally. In comparison to the original area, only 18% of Savannah and 15% Atlantic Forest biomes remain. The Uruguay (274,300 km^2) and *Atlântico Sudeste* river basins also drastically reduced their native vegetal cover, as shown in **Table 1**.

Table 1 also provides data of the drainage area of important reservoirs for the Southeast region of Brazil. The Cantareira Water Supply System (2300 km^2), hereafter referred to as the Cantareira System, encompasses 1000 hm^3 of reservoirs and is the main source of water supply for the metropolitan region of Sao Paulo and Campinas [38]. This region (**Figures 4** and **5**) was severely affected by the water crisis in 2013–2015, which brought water supply problems to the metropolitan region of Sao Paulo and Campinas and hydroelectric power generation concerns throughout the country [44–48].

Regarding **Table 1**, drainage areas of reservoirs Emborcação, Três Marias, Furnas, and Mascarenhas, which are essential for hydroelectric power generation, irrigation, and water supply, have less than 30% of native forest cover [40]. The Emborcaçao reservoir is the most affected with high deforestation rates (only 6% of the original cover remains). On the other hand, the Cantareira System, considered with the lowest deforestation rate, only has 33% of native Atlantic Forest, partially due to watershed restoration programs (see [29]).

3.2. Biomes in Brazil

Brazil is the country with the highest biodiversity of vegetation in the world. There are more than 55,000 cataloged plant species of an estimated total ranging between 350,000 and 550,000 [49]. A significant part of this biodiversity is found in the Atlantic Forest, a biome that stands out for its high levels of richness, endemism, and devastation. Despite having 20,000 species of vascular plants [50], of which between 7000 and 8000 are endemic [51], only 11% of the Brazilian Atlantic Forest still remains [52]. Since Brazil's colonization, the Atlantic Forest deforestation has narrowed the delivery of ecosystem services. This progressive devastation

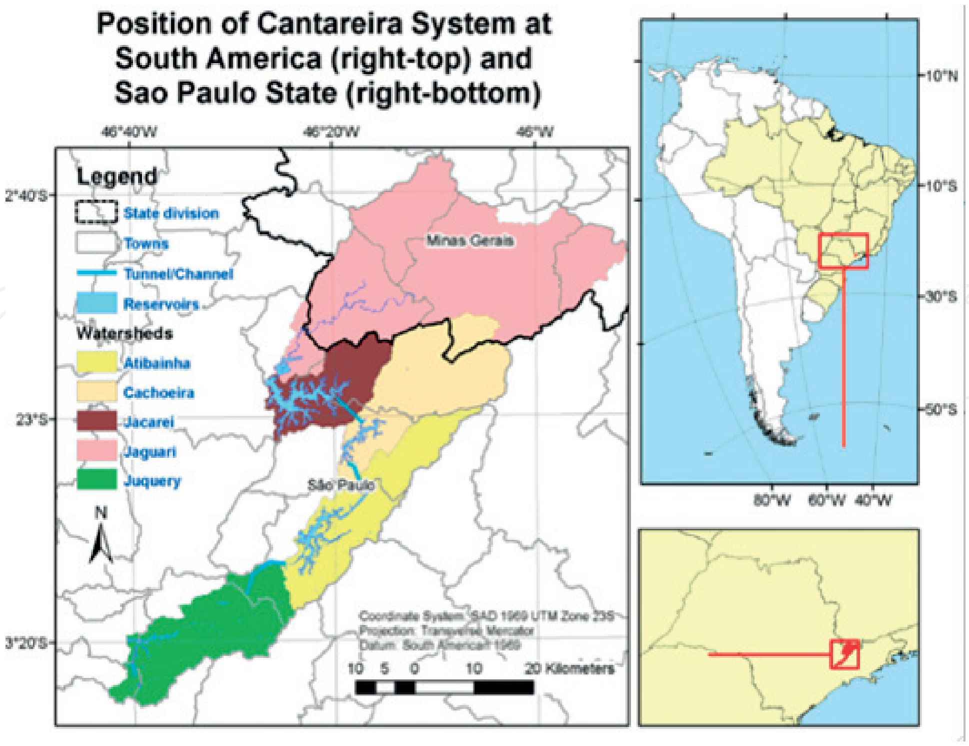


Figure 4. Watersheds of the Cantareira water supply system (left) and its position in South America (top right) and in Sao Paulo state (bottom right).

Figure 5. A general view of the Cantareira system region, a 2300-km^2 drainage area connected to the 1000 hm^3 of reservoirs in the anthropized Atlantic Forest biome. Photo by Denise Taffarello, December 2012.

was caused by the exploration of forest resources, advancements of agricultural borders and by coastal urbanization, as well as a zone going between 40 and 50 km into the inland [53].

The large area of Brazil encompasses six biomes. They consist of the following Brazilian names: *Amazônia*, *Caatinga*, *Cerrado*, *Mata Atlântica*, *Pampa*, and *Pantanal*.

First, the Amazon rainforest is the largest forest in the world, conditioned by the humid equatorial climate (**Figure 3**). It represents around 35% of the forest areas globally. However, recent predatory agricultural practices, new acts, and decrees have (1) reduced environmental licensing requirements, (2) suspended the ratification of indigenous lands, (3) reduced the size of protected areas, and (4) allowed land grabbers to obtain the charters of deforested areas [54]. This has led Amazon deforestation to 17%, which makes it difficult for Brazil to fulfill the Paris Agreement.

Second, Caatinga occurs in the Brazilian Northeast. Its vegetation is formed by palm trees which usually grow in dry and poor (in terms of nutrients) soils. Rossato et al. [55] used weather data from the CPTEC/INPE platform to estimate the Palmer Drought Severity Index (PDSI) in Brazil in the 2000–2015 period and found that the PDSI achieved severe to extreme dry scales over time in the Northeast, where the dry conditions are a socioeconomic and environmental problem. They concluded that the PDSI is useful to assess different soil moisture water conditions and design risk maps.

Third, the Cerrado, which presents diverse regions, ranging from clean fields devoid of woody vegetation to *cerradão*, a dense tree formation, is also in danger [54].

Fourth, the Atlantic rainforest encompasses 35% of Brazilian's biodiversity and boasts high levels of species richness but also has critical rates of deforestation. Only 11–16% of the Brazilian Atlantic Forest still remains on the coastline [51], and the hydrometeorological patterns of the region are very different. However, the presence of humid winds from the ocean is remarkable, and it favors vegetation development.

Fifth, the Pampa is composed of different herbaceous species, and in some areas, their environment is integrated with several *Araucaria* trees, in the South region of Brazil.

Last but not least, the Pantanal is an alluvial plain influenced by rivers that drain the Upper Paraguay basin, where it develops a fauna and flora of rare beauty and abundance. The flood regimes are seasonal, and during the increased flows of the Paraguay river, the water chemistry changes depending on the mineral composition of parent material, soil use, and vegetation cover. Consequently, not only flow direction and magnitude fluxes change but also transparency, temperature, and the macro-ionic composition of the water. These environmental variabilities induce a habitat pattern that influences the composition of aquatic communities. It favors those that have adopted strategies to exist within a specified range of environmental conditions. Karr and Chu [56] described five dynamic environmental factors that regulate the structure and functioning of any aquatic ecosystems shown in **Figure 6**. These factors can be applied to explaining, for example, the beauty and high abundance of organisms found in the Pantanal biome.

3.3. Some Latin America projects for watershed restoration

Research has shown that degraded watersheds are related to higher poverty levels [57]. Thus, restoration and creation of wetlands have been recommended for the development of human populations in an integrated way [58]. Most restoration projects have multiple purposes regarding the quality of the biological community and the hydrological functioning of the system.

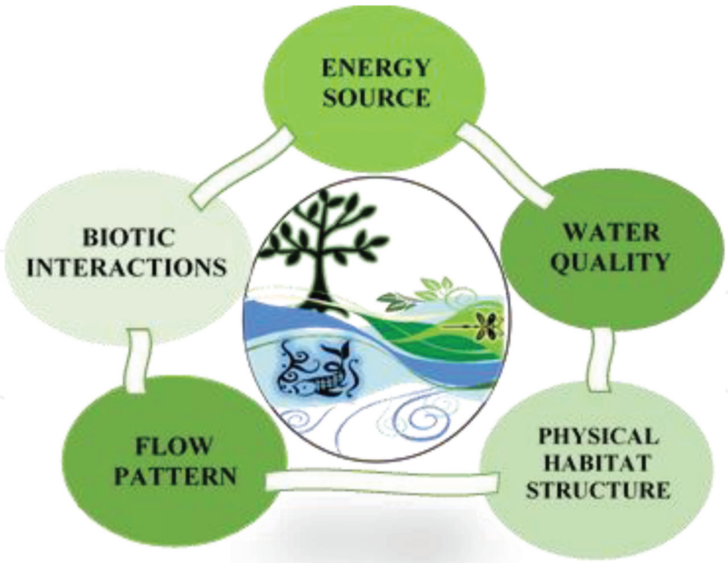
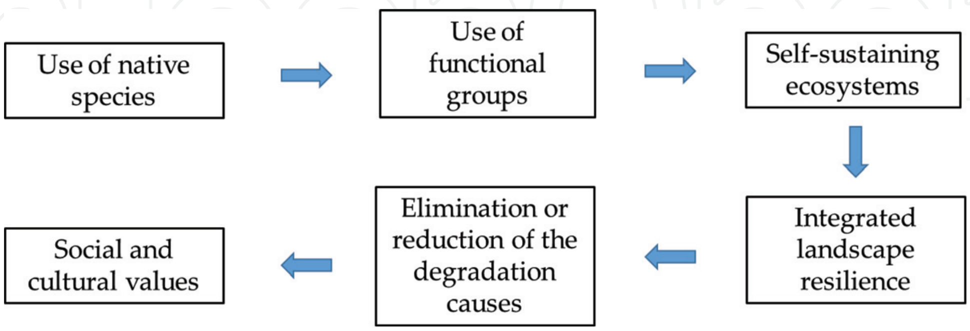


Figure 6. The dynamic environmental components structuring ecosystem functioning. Source: Adapted from Karr and Chu [56].

However, the nature of ownership in forested areas (e.g., whether private or government property) greatly affects forest management and, consequently, affects the water yield, water quality, and their services. In Latin America, forest plantation, that is, *Eucalyptus* and *Pinus*, mostly occurs on private land, whereas native forests prevail in public areas. Moreover, the Brazilian government has recently signed decrees, which potentially threat native forests, due to political bargaining [54]. This fact is very worrisome to the risks associated with hydrological extremes, climate/environmental changes, and losses of ecosystem services.

The most common actions to enhance hydrological services and resilience front disturbances, which can be conducted in both private and public lands, are hydrological control, wetland construction, denitrification barriers, biogeochemical barriers, and food web manipulation. A successful restoration strategy, according to the Society for Ecological Restoration (2011), consists of the steps highlighted below.



Thus, there are some initiatives in Latin America which can achieve this goal (the watershed restoration), mainly through EbA methods.

Latin American countries were pioneers in development and implementation of PES projects as a kind of EbA method. There is a wide range of initiatives, which apply PES on various scales, in different contexts and with diverse specific objectives [59], serving as a general mechanism to align economic investments in human and ecosystem welfare [60].

Previous formal PES programs began in Cauca Valley, Colombia, in the mid-1990s, where silvopastoral practices were used in a pilot project to protect upper watersheds [61, 62]. PES research reflects the watershed's particularities, different topographic, soil, and climate conditions, that hold a major part of the world's unique biodiversity [63].

Costa Rica was the first country to establish a formal PES, called *Programa de Pagos por Servicios Ambientales*, in 1997. There are governmental subsidies to help water users (such as hydropower companies) to pay land owners for benefits generated by their conservation actions in the watersheds. In Quito (Ecuador), the water and hydropower companies pay for the protected area's upstream withdrawal, which is a source of a significant amount of clean water [64]. Currently, there are EbA projects under ongoing implementation in all the 20 countries of Latin America [63, 65]; however the freshwater PES experiences that have been developed still act on a very small scale, contributing to the conservation and restoration of a small area related to the total area in each country).

The first publication about ecosystem services in Latin America is from 1997: a researcher from the National Institute for Research in the Amazon (INPA) proposed a strategy for achieving sustainable development in rural Brazilian Amazonia, which required both short-term and long-term measures [66]. Later, the improved strategy was proposed for the Cocibolca Lake watershed, Nicaragua, showing four scenarios built on the *Soil and Water Assessment Tool* (SWAT) model to reduce the potential of sediments and nutrient loads. Currently, various initiatives have spread throughout Latin America, especially the platform called "Water Funds" [60, 65], but the majority are still small scale and present failures in the forest growth and hydrological monitoring.

3.3.1. Some Brazilian examples

The Brazilian Atlantic Forest is a biodiversity hotspot in the world and constitutes a carbon sink. For these reasons, it offers an economical opportunity for establishing restoration or conservation practice [67, 68]. One of these initiatives is the Atlantic Forest Restoration Pact [69, 70], a public-private partnership with the aim to restore 150,000 km^2 of forest by 2050 using native species. Another initiative was the "Produtor de Água/PCJ Project" [71]. This project aims to stimulate actions of forest restoration, conservation of fragments, and soil conservation practices on private properties to provide remuneration to the farmers to create and/or maintain ecosystem services [72].

The following EbA projects are or were implemented in the five regions of Brazil:

- "Bolsa Floresta Program" (North)
- "Monte Pascoal-Pau Brasil Project" (Northeast)

- "Manancial Vivo Program" (Central West)
- "Mina d'Água Project" (Southeast)
- "Corredores Ecológicos Chapecó-Timbó Project" (South), to quote only a few examples

There are public-private partnerships working with EbA for the restoration of watersheds and carbon sink, as well as private companies and nongovernmental organization initiatives. In some of these, there is support from Brazilian universities in the ecohydrological monitoring of the projects [46, 47]. See the EbA initiatives in the Brazilian Atlantic Forest developed until 2015. You can find more details on these and more initiatives in the paper by Taffarello et al. [29] (**Table 2**).

Starting year	Number of cases	Project's total area (km^2)	Investment value (million US $)	Average payment value per project (US$/ha/year)	Adaptive measures considered for long-term changes
1997	1	0.5	1.4	77–254	No
2005	1	28.5 (by 2011)	2.986	77.5 UFEX (March/2010)	Yes. Monitoring partnership with Esalq-USP, EESC-USP, IAG-USP, and Viçosa Federal University Fiscal Unit of Extrema municipality (UFEX in Portuguese) (1 UFEX = USD 0.70 in 2018)
2006	3	20.9; 1640; 14.8	1.112	33–242	Partially. Vegetation, hydrographic, and property management monitoring occur in the Oasis Project
2008	1	32.3	2.846	88	No. The *Bolsa Verde* operations manual (IEF, 2010) does not mention monitoring
2009	8	12.48; 36.77; 1.12; 22.22; 19.62; 10.00; 0.41; 31.99	14.828	4.4–968	Yes. The Camboriu Project and Water Producer/PCJ (EESC-USP), through water quantity (rainfall and runoff measures); water quality (turbidity, total suspended solids, pH, dissolved oxygen, electrical conductivity, organic matter, and nutrients such as ammonia, nitrogen, nitrates, and total phosphates); hydrologic health (geomorphologic analyses of the water bodies' structure)
2010	4	0.39; 11.6; 11,000; 8.8	3768	17.79–633.43	Partially. Mina d'Água: monitoring plan and impact assessment developed with the support of specialists from the World Bank
2012	1	Priority areas of the town for public supply		25 UFM 1 UFM = US$ 46,62	No

Source: Adapted from [29].

Table 2. Case studies of EbA projects for watershed restoration at the Brazilian Atlantic Forest.

Current research has been developed to improve existing methodologies and market-based policy tools to identify the generation and maintenance of the ecosystem services by the watershed restoration [73, 74].

The potential provision of the ecosystem hydrological services depends on the equilibrium of the hydric balance, namely, the relation between the hydric availability and demand (variable given natural oscillations or induced by impacts from anthropic activities), besides the state and functional distribution of the ecosystems on the watersheds. From this interaction, the composition "water+climate" is the principal element of sustainability [75, 76], directly influencing the biodiversity. Therefore, the ecosystemic approach is a strategy for the integrated management of soil, water, and biodiversity, promoting a balanced conservation and sustainable use of natural resources.

3.3.2. Some Colombian examples

The Paramo biome is a set of neotropical alpine grassland ecosystems covering the upper region of the northern Andes. It plays a key role in the hydrology [77–79]. It is characterized by elevations between 3000 and 5000 miles above sea level (MASL) and a constant mean monthly temperature with large diurnal temperature fluctuations. The precipitation patterns in the Paramo are exceedingly complex in terms of amount and seasonality; the precipitation varies from approximately 600 to 4400 mm from a bimodal pattern to a unimodal one depending on the location [80]. Over the last years, these ecosystems have been strongly impacted by human interventions and climate change [77, 81–85]. This has shown its

Water fund name	Phase, stage	Year founded	Ecosystem description	Conservation target area (ha)
Bogotá, Water We are	Operation	2009	Paramo system and high Andean forests	60,000
Valle del Cauca, Water for Life and Sustainability Foundation	Operation	2009	Some Paramo areas, high Andean forests, and inter-Andean valleys	65,000
Medellín, Green Basin	Operation	2013	High Andean forests and Paramo	22,300
Cali, Madre Agua	Creation	2015	Humid forest, tropical forest, cloud forest, and Paramo	4550
Cúcuta, Biocuenca Alliance	Creation	2015	Paramo system and high Andean forests	15,900
Cartagena Water Fund	Creation	2016	Riparian wetland	138
Sierra Nevada de Santa Marta	Idea and prefeasibility	TBD	Mountainous coastal system isolated from the Andes and Paramo	TBD
Santa Marta y Ciénaga	Idea and prefeasibility	TBD		TBD
Santander, Bucaramanga	Idea and prefeasibility	TBD	Paramo system and high Andean forests	TBD

Table 3. Colombian water funds description projects (modified from [86]).

vulnerability and importance as a water supply source of some of the main cities in South America. Therefore, initiatives, such as PES, are tools that in recent years have been implemented in Colombia, but they are not yet common practice. Recently the Colombian government, through law 870 of May 2017, established the payment for environmental services and other incentives for conservation. Among the most recognized PSE implementation projects in Colombia are the Water Funds (see **Table 3**), an initiative led by The Natural Conservancy (TNC), which is currently benefiting nearly 12,295,247 million people [86]. These Water Funds projects, which are in the operational phase, were established to benefit populations from the Valle del Cauca (Water for Life and Sustainability Water Fund Cauca Valley, Southwestern Colombia) and the cities of Medellin (*Cuenca Verde*) and Bogotá (*Agua Somos*), all these with the particularity of being developed for a complex and fragile Paramo Andean ecosystem [80]. While in the creation and feasibility phase, there are funds such as Cucuta (Biocuenca Alliance), the Cartagena Water Fund aiming to conserve the riparian wetland areas and the Sierra Nevada de Santa Marta Fund, a mountainous coastal system isolated from the Andes, and Santander, designed for water conservation in the metropolitan area of Bucaramanga with major conflicts over mining exploitation in the Paramo area [87, 88].

4. Conclusions

Relationships between water and forests depend on the soil characteristics, including moisture dynamics, which in turn impacts the water security and overall sustainability of water resource management. As a result of the interaction among soil, water cycles, forest, and climate, we address further parameters and guidance for the conservation of the hydrologic and forest resources in the watersheds. In this chapter, we discussed ecohydrological processes and the associated ecosystem services provided by the catchments and promising opportunities for watershed restoration. In this context, we argue that EbA strategies can help to develop the economy of Latin American countries, where the population is expected to increase more and more over the next few years. Such strategies would require the creation or expansion of markets for ecosystem services, hydrologic and forest participative monitoring (e.g., through hydrosociology and citizen science), human resource development, and training. Thus, linking water and vegetation is essential to secure diverse hydrometeorological services and the resilience of the biodiversity hotspots. In South America's biomes, these services can be used to optimize annual costs and benefits of conservation and provide financial support for restoration projects in most affected communities. Not only South American society's demands, but also environmental needs in Latin America in general, can be achieved through holistic and transdisciplinary PES projects, some of them briefly summarized in this chapter. The PES initiatives can also increase income and, to a certain extent, boost employment rates and community development. For example, the Water Funds can help comprehend the relationships between water yield and forests through "research-for-action" initiatives. This integrated management can reduce people's and ecosystems´ vulnerability, as well as increase their resilience to cope with global change impacts.

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Conflict of interest

The authors declare that they have no conflict of interest.

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