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BALANCING CONSERVATION NEEDS WITH USES OF RIVER ECOSYSTEMS

Compatibilizando las necesidades con los usos en la conservación de los ecosistemas fluviales

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ABSTRACT

Rivers are among the most diverse and threatened ecosystems on the Earth, but their conservation is a requisite for sustainable development. Conservation must consider both the structure and the functioning of the elements (usually species), as well as of their ecosystem. Therefore, successful river conservation must go beyond protecting species to protecting entire ecosystems and the processes that give each ecosystem its special characteristics. River conservation has to meet the legitimate aspirations of human populations for clean, readily available supply of water, without compromising the water needs of ecosystems and nature. Therefore, it is essential to take a landscape perspective that incorporates processes occurring in the riverine riparian areas as well as on connectivity with the land and across the river network.

Keywords: Andean, biodiversity, conservation, ecosystem functioning river.

RESUMEN

Los ríos son uno de los ecosistemas más diversos y amenazados de la Tierra, pero su conservación es esencial para un desarrollo sostenible. La conservación debe tener en cuenta tanto la estructura y el funcionamiento de los elementos (por lo general las especies), así como de su ecosistema. Por tanto, la conservación debe ir más allá de la protección de especies, para contemplar la protección de ecosistemas enteros y de los procesos que en ellos acontecen y les proporcionan sus especiales características. La conservación fluvial tiene que responder a las legítimas aspiraciones de las poblaciones humanas de un suministro limpio de agua fácilmente disponible, sin comprometer las necesidades de agua de los ecosistemas y la naturaleza. Por tanto, es fundamental adoptar una perspectiva del paisaje que incorpore procesos que ocurren en las áreas ribereñas fluviales, así como la conectividad con el ecosistema terrestre y toda la red fluvial.

Palabras claves: Andes, biodiversidad, conservación, funcionamiento del ecosistema río.

INTRODUCTION

Importance of River Ecosystems for Humans

River ecosystems cover only a tiny portion of the Earth surface. At any moment, they contain about 0.0002 % of all water. Still, their relevance is much larger than their size. Rivers have been key elements in the history of humanity, since people drank water from the rivers, foraged in their fertile floodplains, fished and hunted in their channels, or used them as waterways for transportation. With the development of agriculture, most civilizations occupied the river banks and cultivated the floodplains taking profit of the fertilizing effect of floods. With time, rivers were used for irrigation, as a source of energy, and as a source of raw materials, from fish to minerals. Changes accelerated since the Industrial Revolution (Steffen *et al.*, 2007), and development occurred at the expenses of river ecosystems, which have been overharvested and degraded in multiple ways. Today river ecosystems provide essential benefits and services to society, including water purification, transport and transformation of organic matter and other materials, nutrient cycling, flood control, and others (Costanza *et al.*, 1997). Some of these services, such as water purification or fish production, have clear monetary value, whereas for some others such as biodiversity this is less obvious. The services provided by ecosystems are based on the biophysical processes occurring in the river, and these depend on the elements (species, guilds) and functioning of the ecosystem. The value of these services is increasingly recognized and is leading to restoration projects tailored to improve ecosystem functioning (Palmer and McDonought, 2013). The economic benefits of river restoration can indeed be larger than its costs. For instance, Acuña *et al.*, (2013) assessed the economic benefits of restoring channel complexity in forested streams draining into a drinking water reservoir, and reported that channel restoration increased the value of streams 10- to 100-fold in terms of sediment retention, self-purification capacity, fish provision, and opportunities for recreation. Even this limited list of services in that stream accounted for recovery times of a few decades of the money invested in restoration.

Biodiversity is an essential part of ecosystem health, together with ecosystem functioning (Karr, 1999). Rivers maintain an extremely rich biodiversity, as 40 % of the total fish diversity and one third of global vertebrate diversity (i.e. including amphibians, reptiles and mammals) inhabit freshwater ecosystems (Dudgeon *et al.*, 2005), even more if we include riparian areas (Naiman and Décamps, 1997). The role of species in the climate regulation and the cycle of elements amongst other functions make essential their preservation.

Characteristics of River Ecosystems Important for Their Conservation

Rivers are transport-driven ecosystems: they transport and process water and other materials, dissolved and particulate, organic and inorganic. These materials ultimately come from their drainage basins, what makes rivers intimately dependent on the characteristics of these basins and sensitive to all human impacts occurring there.

Additionally, rivers are hierarchically organized. River networks are dendritic, small tributaries merging to form larger rivers. This spatial organization has strong implications for river conservation, as impacts such as pollution tend to travel fast downstream, and the communities of nearby headwater reaches can only contact each other through long-distance travel, first downstream to the main river stem, and again upstream. Because of their hierarchical arrangement, biological communities exhibit longitudinal transitions along the river; these are predictable in general terms, but their details depend on specific features of individual rivers. This longitudinal transition on species is one reason why rivers sustain so much biodiversity.

Rivers are dynamic systems, and this dynamism depends on the periodic occurrence of floods and droughts. Floods are important disturbances for species, since they dislodge the sediments, scour organisms downstream, and dramatically change the characteristics of the environment. Therefore, riverine species have adapted through natural selection to the specific hydrologic regime of their habitats, to the frequency, magnitude, duration and seasonality of flood and droughts in a given river (Poff *et al.*, 1997). In small streams floods are ephemeral, and hardly predictable, but in large rivers the flood pulse may last for months and is highly predictable, governing many of features of the biological communities (Junk *et al.*, 1989). Also important is the fact that floods are the main factors shaping the river channels, creating habitats such as bars, meanders or backwaters. All this makes floods and river dynamism an essential part of the habitat templet for organisms (Townsend and Hildrew, 1994).

According to Ward (1989), four dimensions need to be considered when studying and managing rivers. In the longitudinal dimension, rivers change from source to mouth, both in physical characteristics of the channel and in the associated biological communities. In the vertical dimension, rivers are tightly linked to underground water, including hyporheic habitats. In the lateral dimension, rivers are not limited to the channel, but also include their margins and floodplains. In the temporal dimension, rivers are in constant change, including short-lived flood pulses, seasonal variations in habitat characteristics, long term migration of channels, and so on. Maintenance of this multi-scale temporal variability is essential for river health. Meyer (1997) adds a further relevant dimension: the social or human context. Rivers are affected directly or indirectly by multiple human activities, and effective river conservation cannot be based solely on the needs of wildlife. Indeed, river conservation must take account of the needs and interests of people living along their banks and within the drainage basin.

The main threats to river conservation

Among the main threats to river conservation are alterations of the water flow. Rivers are dynamic ecosystems, and change is an essential characteristic of healthy riverine ecosystems (Karr, 1999). This dynamism is again based on the hydrological regime, and its interaction with the physical setting of the river. This often collides with the human will to avoid changes, leading to bank reinforcement, floodplain simplification, or damming.

Human activities deeply affect the global water cycle, modifying the amount of water and the seasonality of flood and drought periods, both essential components of river health. Today, about 15 % of the world's total runoff (40 000 $km^3 y^{-1}$) is retained in 45 000 large dams, greater than 15 m in height (Nilsson *et al.*, 2005), and a further 10% is abstracted (Vörösmarty and Sahagian, 2000). As a result of these manipulations and subsequent irrigation, up to 6 % of the water is evaporated (Dynesius and Nilsson, 1994). A total of 52 % of the surface area connected by large river systems (discharge over 350 $m^3 s^{-1}$) is heavily modified. The decline in freshwater biodiversity is associated with this heavy impact on the global water cycle (Sabater, 2008). The alterations of the hydrologic regime directly affect the availability of water, which is the essential environment for many riverine species and an important force shaping habitats both in the channel and on the floodplain (Elosegi and Sabater, 2013). Direct or indirect effects on the hydrologic regime will become all the more critical as population increase (upto 8.9 billion people in the world by 2050; Cohen, 2003), together with the associated rising demand for water (Gleick, 2003). In most cases the frequency, timing and magnitude of floods and droughts in impaired rivers are altered, what has detrimental consequences for organisms adapted through natural selection to the natural water regime. In the most extreme cases, abusive water abstraction dries out entire river sections wiping out the services they provide and the biodiversity they harbor. Such 'silenced' rivers are the paradigm of an impaired ecosystem. The number of these rivers is expected to increase with the pressure on water resources, though the distribution of these pressures among various areas of the globe will remain uneven, and so will be the effects on river ecosystems and their biodiversity.

Humans have also wrought profound changes upon the physical structure of river channels, impairing their life-supporting architecture (Elosegi and Sabater, 2013). Natural river channels are complex and dynamic, and river species are adapted to and depend upon these characteristics for survival. The technological capacity of humans has often conflicted with the natural flooding and wandering of rivers, and has paved the way to huge investments of damming, building levees, channelizing, of otherwise controlling channel form and mobility. Many rivers are today an extremely simple versions of the complex and dynamic ecosystems they once were, and biodiversity and ecosystem functioning are consequently profoundly compromised.

Pollution is an epidemic threat to rivers. Sometimes pollution can be caused by natural substances when they appear in too high concentrations. This is the case of nutrients, essential elements for primary producers such as algae and other plants, but that in too high concentrations produce fouling of water, lack of oxygen, and declines in biodiversity (Stevenson, 2011). Human activities have caused an enormous increase in the amount of nutrients circulating worldwide, either through diffuse sources such as agricultural fertilizers, or through point or end-of-pipe sources such as urban wastewater (Heathwaite, 2010). Other pollutants are more insidious, as they are novel substances, synthesised by humans for various purposes, but which nevertheless end up in rivers. This is the case of pharmaceutical drugs, pesticides, and other substances with potentially powerful biological effects, which are frequently detected together with their degradation products. These so-called emerging pollutants pose a large challenge to science and environmental management, as very little is known on their action mechanisms in the biota, on their mobility and accumulation in food-webs, nor on their interactions in complex mixtures (Petrovic *et al.*, 2002). Depending on their chemical characteristics, many pollutants remain dissolved or are stored in the sediments. Others are more volatile, and cross entire watersheds to areas far from where they were originally released (Nizzetto *et al.*, 2010). The pollutants volatilize in warm areas and are deposited in cooler localities. The high concentrations of pollutants detected in apparently pristine regions like the Arctic or high-mountain areas show the pervasive effect of human actions, and the need for global responses to the current threats (Ross *et al.*, 2000). Costs of river pollution in the USA have been estimated to range between 2.2 and 4.6 billion US dollars per year in the United States alone (Dodds *et al.*, 2009), even without taking in account the costs of environmental degradation.

The impacts stressors may produce on organisms and ecosystems depend on their intensity, timing and duration (Stevenson and Sabater, 2010). There is a hierarchy of stressors according to their intensity, frequency and scale, and their effects range from transient to irreversible. Some stressors operate at small spatial scales, such as excess nutrients, or pollutants. The temporal scales at which stressors affect organisms and ecosystems are also different. Short stresses such as toxic pulses can produce effects on organism physiology or in community composition, but most of these will likely be transient. Large-scale stressors will instead produce more persistent effects on organisms, whose responses will progressively transmit from individuals to populations, communities and ecosystems. However, most ecosystems are exposed simultaneously to several stressors, in the so-called multiple-stress situations. Rivers offer prime examples of ecosystems threatened by multiple stressors (Fig. 1). The hierarchical arrangement and complexity that characterize river systems make the interactions between stressors especially complex. The effects may be synergistic, and are certain to be further amplified by changes in the global water system driven by climate change, with likely detrimental consequences for river ecosystem structure and functioning (Milly *et al.*, 2008; Ferguson and Maxwell, 2012).

Even though the above list of threats is by no means fully comprehensive, it should be stressed that they affect both biodiversity and human water security. The exhaustive analysis made by Vörösmarty *et al.*, (2010) on human access to water

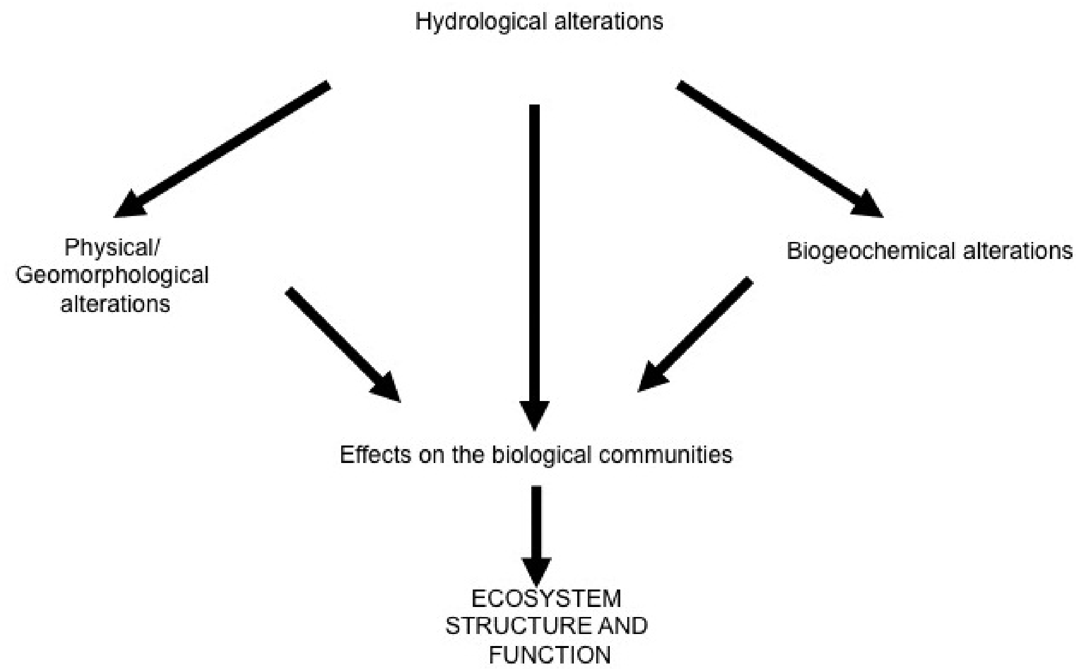

Figure 1. Physical and biological alterations interact through complex feed-backs and affect the biodiversity and functioning of river ecosystems.

and on risks for biodiversity worldwide, produces amazing coincidences. Those areas having the higher risks for humans are also those where the biodiversity is at its stake.

Status of rivers across the world

Rivers are perhaps the most endangered ecosystems on the Earth, and their biodiversity is declining faster than its terrestrial or marine counterparts (Dudgeon, 2013). As species are being lost, serious concerns are raised on their effects on ecosystem functioning — an important field of current scientific research. A fundamental question for scientists is how much biodiversity can be lost without seriously compromising natural processes? Although some general principles have emerged (Hooper *et al.*, 2005), there is still much debate on the relationship between biodiversity and ecosystem functioning. The 'conventional' view, also called the diversity-stability hypothesis, states that as we lose species ecosystem function is affected proportionally. A second possibility (the redundancy or rivet hypothesis) is that loss of species has no effect on function until some critical threshold below which ecosystem functioning fails. A third possibility, called the idiosyncratic hypothesis, holds that there are no general rules, that functioning may be unaffected by the loss of certain species, but greatly impacted by the loss of others. According to this hypothesis some species would be more important than others. Amongst these may be top predators, which, by predating disproportionately on some prey species affect food webs, and ultimately ecosystem functioning, or species that actively modify habitats, like the beaver, whose dams create ponds and reduce the downstream transport of material. Whatever the case, it is becoming clear than the biodiversity necessary to maintain ecosystem processes increases with the number of processes considered (Hector and Bagchi, 2007). A related point is that the magnitude of variability in ecosystem processes increases when species are lost and this tends to reduce the likelihood that multiple ecosystem functions can be sustained (Peter *et al.*, 2011).

In most parts of the world's watercourses, particularly dramatic modifications have occurred as a consequence of their intensive use by human societies (Sala *et al.*, 2000). Typical examples of these changes include the elimination of meanders, lagoons and oxbows, while water is increasingly transferred between catchments. The simplification of the channel network and the alteration of water fluxes have an impact upon the capacity of fluvial systems to recover from disturbances, because of their irreversible character. Hydrological connectivity is at the base of river conservation (Fig. 2). Even though connectivity is not a unique characteristic (and its potential loss a unique problem) of river ecosystems, it is especially complex in relation to other ecosystems. In rivers, connectivity is linked to hydrological paths, and is therefore conceived at multiple dimensions (lateral, vertical, longitudinal; Ward, 1994) that should be considered in management and conservation efforts. A corollary for this multiple-dimensioned connectivity of rivers is that protection of a given species, habitat, or river segment cannot be focused on a single location, but needs to include upstream and downstream reaches, the riparian zone or the floodplain.

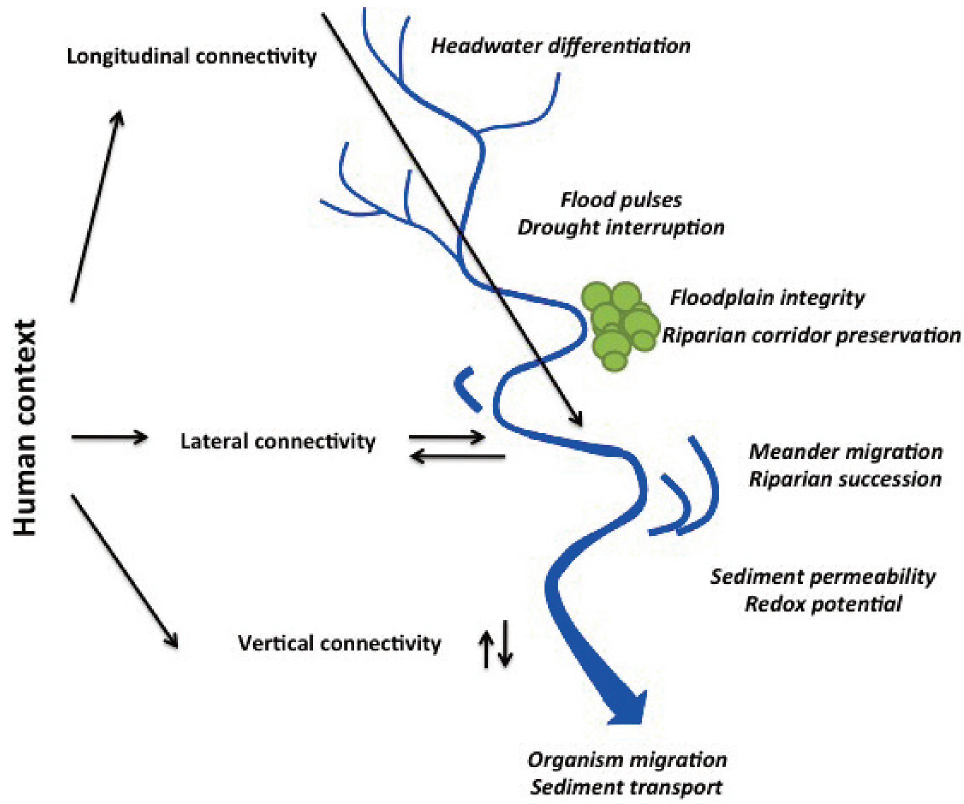

Figure 2. The different scales of river connectivity (left) and the main processes associated to each scale, in the context of a whole river network. The human context defines effects on every scale of the river.

There are large differences between regions regarding the rate, intensity and the nature of change affecting rivers and their biodiversity. The tropics, which harbour some of the most diverse and least-known ecosystems in the world, suffer high rates of habitat destruction, often associated with rapid increase in human population (Sala *et al.*, 2000). Also there are large differences in regulation and policy between countries. In North America and Europe large investments in environmental policies and implementation of relevant legislation have been made. Other regions of the world are in different stages of policy implementation, and therefore local impacts may be much higher. At the global scale, local improvements are often based on the relocation of highly-impacting activities to countries where environmental standards are less strict, providing a low net balance. On the other hand, water policies are often brought about by economic investment in water treatment rather than by prevention of impacts on freshwater ecosystems (Barceló and Sabater, 2010; Vörösmarty *et al.*, 2010), and the result is a gradual depletion of biodiversity and homogenization of river ecosystems.

What needs to be done?

Because water is a multi-user resource, societal and political interests often become entangled with river management and conservation. Very often, the water issue becomes a conflict between human uses and nature conservation, with the usual outcome that consideration about which human uses to satisfy take precedence, whatever the cost for nature. The most significant challenge for river conservation is to meet the legitimate aspirations of growing human populations for a clean, readily available supply of water, without compromising the water needs of ecosystems and nature (Dahm *et al.*, 2013).

As previously argued, effective river conservation needs to take a landscape perspective since rivers depend crucially on processes occurring in their riparian areas and on connectivity with the land and across the river network. This is not a new perspective. Almost 40 years ago, the seminal paper of Noel Hynes (1975) stressed the influence of the valley on the river. This reminds us that it is necessary to cast the spotlight away from the water alone and shifting to the surrounding landscape to make an effective conservation.

Although species that have become extinct are gone forever, part of the damage done to freshwater ecosystems is potentially reversible (Röckstrom *et al.*, 2009). Visible signs of this include the dramatic improvement of water quality in many European rivers (Tockner *et al.*, 2009), and the rise of citizen stewardship related to river conservation in several countries (Boulton *et al.*, 2013). Rivers are especially resilient ecosystems: pollutants tend to be diluted and washed downstream much faster than they disappear from soils, and river biota, shaped by natural selection in a highly variable environment, shows remarkable resilience and, so long as connectivity within rivers is maintained, rapid re-colonisation ability. Recovery of degraded rivers also requires alleviation of human stressors or pressures upon them, which demands both scientific understanding and, perhaps more importantly, political will (Boulton *et al.*, 2013).

One possible avenue for effective conservation is to increase efforts in river restoration. Ecosystem restoration is an activity devoted to recovering lost structure and functions, and thus, should not be confounded with 'gardening' river margins in urban areas, as it often is. Instead, river restoration should focus on recovering the dynamic characteristics of rivers, characteristics that include the lateral mobility of the channel and the capacity to flood the floodplains, upon which many important ecological features and ecosystem functions depend (Palmer *et al.*, 2005). But to what state should a river be restored? As we go further back in time, we have less precise information on the state of the river, and must face the possibility that land-use transformation, the establishment of non-native or invasive species, and climate shifts may make it impossible to restore the river to its original state. In such circumstances, it may be more appropriate to aim at river rehabilitation: i.e. changing the condition of the river to an extent that some ecological functionality can be maintained and some enhancement of biodiversity brought about (Elosegi and Sabater, 2013).

Irrespective of whether the goal is river restoration or rehabilitation, conservation and management practices must be integrated within a landscape framework. As mentioned above, river conditions are product of activities within their drainage basins, and the solution to problems at one locality within the river network often lies some distance away within the catchment or upstream. The landscape framework is necessary not only when addressing pollutants originating in the drainage basin. River architecture imposes special constraints upon the movement of aquatic animals, which has important implications for the long-term viability of populations. For instance, when any factor causes the loss of a given species in a particular reach, the population of this species can sometimes recover if there are upstream sources of colonists. Therefore, the presence of barriers can produce far-reaching impacts by blocking animal migration.

The present environmental crisis cannot be attributed to a lack of knowledge. Indeed, it could be argued that it is rather a product of a failure to apply the knowledge that already exists. Nevertheless, many scientific questions remain to be addressed. There is an urgent need to gain knowledge of the effects and fate of the many toxic compounds (pharmaceuticals, cosmetics, and a host of pesticides and other chemicals) that are being added to inland waters globally, so as to better understand their effects on humans and ecosystems. We need better knowledge on the transport and fate of pollutants in the biosphere, of their bioaccumulation and of their interactions. We also need deeper understanding of biodiversity and its relationship to ecosystem functioning and the benefits enjoyed by humans since, at present, the function and ecological role of the vast majority of species remains unknown. This is particularly so for the microorganisms (Peter *et al.*, 2011). An entirely different challenge is posed by the need to enhance river restoration and rehabilitation efforts: we must define ways to restore the dynamism of fluvial channels, so as to provide the appropriate conditions to maintain biodiversity and ecosystem functioning, and to do so in a highly modified human-dominated landscape. Maintaining the spatiotemporal variability of river ecosystems (e.g. the annual flood cycle), to which the native biota are adapted, provides one of the best defences against the invasion by exotic or non-native species. It is also necessary to find ways of connecting populations of animals that have been fragmented by dams or by highly altered river reaches. Environmental water allocations (e-flows) for rivers must also be defined so as to meet the needs of intact ecosystems while, at the same time, satisfying human needs for water. This will be a major challenge in more arid regions.

Above all, it is essential to demonstrate and convey the importance of freshwater biodiversity to ecosystem functioning, as well as the need to protect both that diversity and the benefits accruing to humans. Arguably, awareness of citizen and decision makers is a key issue. To date, however, public perception of the importance of freshwater biodiversity, and the need to protect it, falls far short of what conservation biologists wish for, and fuller engagement of the scientific community will be needed to translate our good intentions into the necessary action by public stakeholder groups. Success in that regard will require an innovative combination of scientific knowledge, political conscience and economic perspicacity with societal willingness and environmental ethics (Elosegi *et al.*, 2013).

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REFERENCES

Acuña V, Diez JR, Flores L, Meleason M, Elosegi A. Does it make economic sense to restore rivers for their economic services? J Appl Ecol. 2013;50(4):988-997.

Barceló D, Sabater S. Water Quality and assessment under Scarcity. Prospects and challenges in Mediterranean watersheds. J Hydrol. 2010;383(1-2):1-4.

Boulton A, Dahm C, Correa L, Kingsford R, Jenkins K, Negishi J, *et al.* Good News: Progress in Successful River Conservation and Restoration. In: Sabater S, Elosegi A (eds.).River conservation: challenges and opportunities. Fundación BBVA, Bilbao, Spain. 2013. p. 399.

Cohen JE. Human population: the next half century. Science. 2003;302(5648):1172-1175.

Costanza R, Darge R, Degroot R, Farber S, Grasso M, Hannon B, *et al.* The value of the world's ecosystem services and natural capital. Nature. 1997;387:253-260.

Dahm C, Boulton A, Correa L, Kingsford R, Jenkins K, Sheldon F. The role of science in planning, policy and conservation of river ecosystems. In: Sabater S, Elosegi A (eds.).River conservation: challenges and opportunities. Fundación BBVA, Bilbao, Spain. 2013. p. 399.

Dodds WK, Bouska WW, Eitzmann JL, Pilger TJ, Pitts KL, Riley AJ, *et al.* Eutrophication of U.S. freshwaters: analysis of potential economic damages. Environ Sci Technol. 2009;43(1):12-19.

Dudgeon D. Anthropocene Extinctions: Global Threats to Riverine Biodiversity and the Tragedy of the Freshwater Commons. In: Sabater S, Elosegi A. (eds.). River conservation: challenges and opportunities. Fundación BBVA, Bilbao, Spain. 2013. p. 399.

Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Leveque C, *et al.* Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev. 2005;81(2):163-182.

Dynesius M, Nilsson C. Fragmentation and flow regulation of river systems in the northern third of the world. Science. 1994;266(5186):753-762.

Elosegi A, Sabater S. Effects of hydromorphological impacts on river ecosystem functioning: a review and suggestions for assessing ecological impacts. Hydrobiologia. 2013; 712(1):129-143.

Elosegi A, Sabater S, Boulton A. Concluding remarks on river conservation. in: Sabater S, Elosegi A (eds.).River conservation: challenges and opportunities. Fundación BBVA, Bilbao, Spain. 2013. p. 399.

Ferguson IM, Maxwell RM. Human impacts on terrestrial hydrology: climate change versus pumping and irrigation. Environ Res Lett. 2012;7(4):044022. DOI: 10.1088/174 89326/7/4/044022

Gleick P H. Global freshwater resources: soft-path solutions for the 21st Century. Science. 2003;302(5650):1524-1528.

Heathwaite AL. Multiple stressors on water availability at global to catchment scales: understanding human impact on nutrient cycles to protect water quality and water availability in the long term. Freshw Biol. 2010;55:241-257.

Hector A, Bagchi R. Biodiversity and ecosystem multifunctionality. Nature 2007;448:188-190.

Hooper DU, Chapin FS, Ewel JJ, Hector A, Inchausti P, Lavorel S, *et al.* Effects of biodiversity on ecosystem functioning: aconsensus of current knowledge. Ecol Mon. 2005;75(1): 3-35. Doi. http://dx.doi.org/10.1890/04-0922.

Hynes HBN. The stream and its valley.Ver InternatVerein Limnol. 1975;19:1-15.

Junk WJ, Bayley PB, Sparks RE. The flood-pulse concept in river-floodplain systems. In: Dodge D P. (ed.), Canadian Special Publication in Fisheries and Aquatic Sciences 106: 1989. p. 110-127.

Karr JR. Defining and measuring river health. Freshw Biol. 1999;41(2):221-234.

Meyer JL. Stream health: incorporating the human dimension to advance stream ecology. J N Am Benthol Soc. 1997; 16(2):439-447.

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, *et al.* Climate change. Stationarity is dead: whither water management?. Science. 2008;319:573-574.

Naiman RJ, Decamps H. The ecology of interfaces: riparian zones. Annu Rev Ecol Syst. 1997;28:621-658. DOI: 10. 1146/annurev.ecolsys.28.1.621.

Nilsson C, Reidi CA, Dynesius M, Revenga C. Fragmentation and flow regulation of the world's large river systems. Science. 2005;308(5720):405-408.

Nizzetto L, Macleod M, Borgå K, Dachs J, Ghirardello D, Hansen KM ,*et al.* Past, Present, and Future Controls on Levels of Persistent Organic Pollutants in the Global Environment. Environ Sc Technol. 2010;44(17):6526-6531.

Palmer MA, McDonough OT. Ecological restoration to conserve river ecosystem services. in: Sabater S. and Elosegi A., River conservation. Challenges and opportunities. Fundación BBVA, Madrid. 2013. p. 399.

Palmer MA, Bernhardt ES, Allan JD, Lake S, Alexander G, Brooks S *et al.* Standards for ecologically successful river restoration. J Appl Ecol. 2005; 42(2):208-217.

Peter H, Ylla I, Gudasz C, Romaní AM, Sabater S, Tranvik LJ. Multifunctionality in microbialbiofilms is constrained by diversity. PLoS ONE. 2011;6(8): e23225. DOI: 10.1371/journal.pone.0023225

Petrovic M, Solé M, López de Alda MJ, Barceló D. Endocrine disruptors in sewage treatment plants, receiving river waters, and sediments: integration of chemical analysis and biological effects on feral carp. Env Toxicol Chem. 2002;21(10):2146-2156.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, RICHTER BR, *et al.* The natural flow regime: A paradigm for river conservation and restoration. BioScience. 1997; 47(11):769-784.

Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin EF, *et al.*A safe operating space for humanity. Nature. 2009;461:472-475.

Ross PS, Ellis GM, Ikonomou MG, Barret-Lennard LG, Addison RF. High PCB concentrations in free-ranging pacific killer whales, Orcinus orca: effects of age, sex and dietary preference. Mar Poll Bull. 2000;40(6):504-515.

Sabater S. Alterations of the global water cycle and their effects on river structure, function and services. Freshw Rev. 2008;1:75-88.

Sala OE, Chapin FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, *et al.* Biodiversity - Global biodiversity scenarios for the year 2100. Science. 2000;287(5459):1770-1774.

Steffen W, Crutzen PJ, McNeill JR. The Anthropocene: are humans now overwhelming the great forces of nature?. Ambio. 2007;36(8):614-621.

Stevenson RJ. A revised framework for coupled human and natural systems, propagating thresholds, and managing environmental problems. Physics Chem Earth. 2011; 36(9):342-351.

Stevenson RJ, Sabater S. Understanding global change in River Ecosystems: Science to support Policy in a Changing World.Hydrobiologia. 2010;657(1):3-18. DOI:10.1007/s10750-010-0392-7.

Tockner K, Uehlinger U, Robsinson CT. Rivers of Europe. Academic Press. 2009. p. 728.

Townsend CR, Hildrew AG. Species traits in relation to a habitat templet for river systems.Freshw Biol. 1994; 31(3):265-276.

Vörösmarty CJ, Sahagian D. Anthropogenic disturbance of the terrestrial water cycle. Bioscience. 2000;50(9):753-765.

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, *et al.* Global threats to human water security and river biodiversity. Nature. 2010;467:555-561. DOI:10.1038/nature09440.

Ward JV. The four-dimensional nature of lotic ecosystems. J N Am Benthol Soc. 1989;8(1):2-8.