Sabater, S., Elosegi, A. i Ludwig, R. (2021). Framing biophysical and societal implications of multiple stressor effects on river networks. *Science of The Total Environment*, vol. 753, art. num. 141973

https://doi.org/10.1016/j.scitotenv.2020.141973

Framing biophysical and societal implications of multiple stressor effects on river networks

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Abstract

Urbanization, agriculture, and the manipulation of the hydrological cycle are the main drivers of multiple stressors affecting river ecosystems across the world. Physical, chemical, and biological stressors follow characteristic patterns of occurrence, intensity, and frequency, linked to human pressure and socio-economic settings. The societal perception of stressor effects changes when moving from broad geographic regions to narrower basin or waterbody scales, as political and ecologically based perspectives change across scales. Current approaches relating the stressor effects on river networks and human societies fail to incorporate complexities associated to their co-occurrence, such as: i) the evidence that drivers can be associated to different stressors; ii) their intensity and frequency may differ across spatial and temporal scales; iii) their differential effects on biophysical receptors may be related to their order of occurrence; iv) current and legacy stressors may produce unexpected outcomes; v) the potentially different response of different biological variables to stressor combinations; vi) the conflicting effects of multiple stressors on ecosystem services; and, vii) management of stressor effects should consider multiple occurrence scales. We discuss how to incorporate these aspects to present frameworks considering biophysical and societal consequences of multiple stressors, to better understand and manage the effects being caused on river networks.

Key words: biodiversity, ecosystem functioning, human well-being, global change, water security, socio-economy.

Highlights:

- Multiple stressors impact both biophysical and societal domains
- To address multiple stressor effects mismatches in their occurrences in space and time must be considered
- Effects of multiple stressors may depend on present and past events
- Multiple stressors may produce conflicting effects on ecosystem services

Multiple stressors in river networks

Rivers, as suppliers and waterways of drinking water, energy, timber and food, have since long been exposed to multiple stressors. Today, very few river networks remain in pristine condition, as most are affected by land use transformation (Donchyts et al., 2016), water resources management (Loucks and van Beek, 2017, Sadat et al. 2020), pollution (Malaj et al. 2014, Palmer and Ruhí 2019), fragmentation (Grill et al., 2019, Rolls and Bond, 2017) and climate change (Milly et al., 2005, Pletterbauer et al., 2018). Rivers within regions with intense human pressure are subject to “cocktails of stressors” (Feld et al., 2016), whose effects span a large range of scales in time and space. River biodiversity (Dudgeon, 2006; Reid et al., 2018), ecosystem functions (Palmer et al., 2014), and the services derived from these ecosystems to humans (Kundzevicz et al., 2008), are consequently impaired.

Disturbance is defined as “any natural or human-driven discrete event in time that is characterized by a frequency, intensity, and severity outside a predictable range, and that disrupts ecosystem, community, or population structure and changes resources or the physical environment” (Pickett and White, 1985; Resh et al., 1988). The term “stressor” describes disturbances caused by humans, including hydrological alterations, pollution, or spread of invasive species (Segner et al., 2014; Crain et al., 2008; Piggott et al., 2016). Human-driven disturbances typically differ from natural others in their characteristics and mode of action (Sabater et al., 2019). So forth, stressors have their origin on abiotic or biotic factors associated to human activities (drivers), and cause receptors (i.e. populations, communities, or ecosystems) to move out of their normal operating range. River networks are affected by a multiplicity of drivers, which produce co-occurring stressors that interact in complex ways at the local, regional, and global scales (Stevenson and Sabater 2010, Jackson et al. 2016).

Drivers such as agriculture, mining or urbanization differ across the world and, accordingly, stressors will show heterogeneous regional distributions. Agricultural intensification and farming affect most tropical and temperate regions of the world, driven by an expanding population and rising meat consumption (Vranken et al., 2014). Approximately 40% of the Earth’s surface is currently occupied by croplands and pastures (Foley et al., 2005, FAOSTAT, 2019). Agriculture, and its associated deforestation, contributes nutrients, pesticides, and sediments to freshwaters (Tilman et al. 2001; Piggot et al., 2015). Mining affects river networks with large inputs of toxicants and fine sediments (Best 2019). The ever-growing urban areas (Jones and O'Neill, 2016) and their ramping water demand (Flörke et al. 2018) cause drastic changes in hydrology and channel forms (Walsh et al. 2005), as well as in water quality, caused by complex cocktails of contaminants (Kuzmanovic et al., 2015). Yet, the impacts of urbanization differ widely depending on population density, state of sanitation and water treatment infrastructures (Booth et al., 2016). Water and hydropower demands promote damming and flow regulation, a trend likely to increase in the future (Zarfl et al., 2015, Best 2019), and which will further reduce river connectivity (Grill et al., 2019) and alter seasonal flow dynamics (Pfister et al., 2020). Superimposed to all these drivers, climate change is an additional source of stressors. It directly affects river networks through changes in temperature and hydrology, but also indirectly, as a consequence of effects on agricultural production and water security (Kang et al. 2009), which force adaptation measures such as the building of dams and flood defenses, extensive water transfers, or canalization (Nilsson et al., 2005; Eekhout et al., 2018).

The stressors listed above are amongst the most common in river networks, and their effects range from local to regional, and global (Table 1), whereas their impacts are also modulated by societal factors including technological development (reliance on water resources, ability for water treatment; Vörösmarty et al., 2010), governance and legislative approaches (presence and implementation; Carvalho et al. 2019), and environmental awareness (Cabello et al., 2015). Therefore, the occurrence and intensity of stressors, as well as their effects, differ widely around the world (Vörösmarty et al., 2010, Elosegi et al., 2019).

Scales in multiple stressor occurrence

The occurrence of multiple stressors, as well as their effects on both river ecosystems and human societies, may be considered at contrasting ecological and socio-political scales. One of these is the *region*, which usually has a political definition as an area with relatively homogenous socio-economic characteristics, governance, and management (Omernik 2004). Another scale is the *ecoregion*, defined as an area with specific climate, landforms, vegetation cover and soil settings, which host distinctive biological communities (Omernik 2004), as a consequence of environmental filtering of the available species pool (Mittelbach and Schemske 2015, González-Trujillo et al.

2020). Ecoregions often do not coincide with regions, what causes a mismatch between ecologically-based and politically-based approaches.

An especially relevant scale for river networks is the *river basin*. Whereas large basins may enclose several ecoregions, many small basins can fit in a single ecoregion. The basin is the scale onto which physiographic factors (vegetation, climate, geological setting), water flow patterns, water chemical characteristics, and social and economic factors, coincide (Heathcote, 2009). The basin generally is the unit most directly associated to human activities, and it is therefore the one at which stressor occurrence is considered (Pistocchi, 2019). The basin is also the managerial scale in many legislative frameworks, such as the EU Water Framework Directive, with its River Basin Management Plans (Hering et al. 2015, Carvalho et al. 2019).

Finally, within each basin, the *river segment* (i.e., a part between tributaries, Frissell 1986) and their *waterbodies* (parts of the segment with clear physical boundaries), are the scales at which physical habitats operate, as well as the biological communities therein. Within a river network, analogous sets of stressors do not necessarily produce coincidental responses in different segments (Timoner et al. 2019). Responses can differ between headwaters, middle, and lowland segments, given their contrasting geomorphological, hydrological, and biological characteristics (Lemm et al. 2019, Schinegger et al., 2016; Table 2). Also, the position of each waterbody within the river network (i.e. main reach, or confluence between tributaries; Benda et al. 2004, Swan and Brown 2014), may affect the composition and structure of biological assemblages (Heino et al., 2015) as a result of the heterogeneity associated to network drainage architecture.

Overall, the occurrence and effects of stressors must be considered according to their scale. However, forecasting their effects is difficult because of complex ecological and human interactions (Table 2, Table 3). At some scales, integrating causes and effects is simpler. For instance, directly measurable elements (biophysical or social) are best characterized at the waterbody scale, thus reliably relating stressors to effects (Voulvoulis et al. 2017, Carvalho et al. 2018). However, these relationships become fuzzier at larger scales, such as the basin or the ecoregion, often constrained by the availability of detailed data. Climatic, hydrological, biological, and social data must then be obtained by means of adequate transfer functions, modeling, or "expert-criteria". For instance, Vörösmarty et al. (2010) estimated river water security at the basin scale from urbanization and agriculture as main drivers, and then related them to biodiversity and to human water security through several indicator variables. Such approaches enclose high uncertainties but can also predict the effects of multiple stressors at large scales, by assuming straightforward, simplified, relationships between stressors and effects.

The dendritic structure of river networks further complicates stressor analyses. For instance, modelling the transmission of contaminants through river networks and their effects, requires the consideration of physical phenomena such as advection or dispersion, but also on how they affect the transformation of these substances by the system itself, as well as social aspects involved (i.e. inflow type, treatment, management). Most models consider dilution and first-order degradation processes, complemented with various approximations to estimate water quality in poorly monitored areas (Font at al. 2019). Some of these models consider the linkages between engineered (e.g. WWTPs) and natural systems (e.g. rivers) (e.g. Oldenkamp et al., 2018, Font et al. 2019), and simulate the fate of single chemical compounds. Nevertheless, accounting for the huge complexity of urban or industrial effluents, which contain both subsidizers and stressors of biological activity is exceedingly complex, and so are the feed-backs that these mixtures can produce on biological receptors (Sabater-Liesa et al. 2019, Pereda et al. 2019). Further, many models only partially consider the societal patterns which drive the occurrence of multiple stressors in the basin, and usually do not consider a dynamic adaptation of river management (i.e. by assuming steady state conditions over longer periods, or by neglecting variations in e.g. water abstraction, changes in irrigation patterns, or contaminant inputs).

Another layer of complexity is added when aiming to understand the temporal evolution of human activities and the associated stressors. In these cases, modelling against storylines is an option to describe integrated scenarios at the basin scale (Moss et al., 2010). Examples are the so-called Shared Socio-Economic Pathways (SSP) (O'Neill et al., 2014), where several narratives describe alternative pathways of global future development in societal, economic and governance terms. Regional scenarios are essential elements for societal inference but also introduce large uncertainties on adaptive and forward-looking management decisions (Veenman and Leroy, 2016; Webster et al., 2003). The uncertainty of these predictions is high, both when moving towards global scales or when downscaling to river networks (Bateman et al., 2016; Van Vuuren et al., 2014). In the case of downscaling, it often requires the concourse of local expert knowledge and the participation of stakeholders (Koundouri et al., 2019), e.g. to include the perception of expected alterations of water demand in the narratives of global change (Ker Rault et al., 2019). So forth, the downscaling of the SSPs proves to be a valuable tool to better understand the interactions and implications of global change on regional scales. In a recent exercise, Huber-Garcia et al. (2019) showed that a technology-driven world is more likely to exacerbate the water demand for irrigation and will thus add stress to areas with previously existing water scarcity.

A conceptual path to integrate the biophysical and societal effects of multiple stressors

Researchers often analyze separately the biophysical and the societal effects of stressors, i.e., the effects on the biodiversity and function of river ecosystems on one side, and on human societies (including aspects associated to ecosystem services) on the other. This separation is conceptual but also disciplinary, likely departing from the different backgrounds and methods followed in the biophysical and societal research domains. Nevertheless, there are obvious interactions and feedbacks between the ecosystem and the social perspectives (Fagan, 2011), which include common scrutiny over stressors, common perception of primary effects, and commonly implemented management scenarios (Fig. 1).

Several frameworks have connected stressors to their effects. Some emphasized the biophysical mechanisms, others the societal consequences, and a few have already considered the two. The MAES approach (Maes et al. 2016) considers delivery of ecosystem services as the link connecting the ecosystemic and socio-economic components of socio-ecological systems. The IPBES (Diaz et al. 2015) connects biodiversity and ecosystem functions with the intrinsic values of nature for people, and with good quality of life. It considers stressors and governance (respectively qualified as direct and indirect drivers) on those links, but the mechanisms associated to multiple stressor effects are not “the main focus of the platform” (Diaz et al. 2015).

The Driver-Pressure-State-Impact-Response (DPSIR) concept (Smeets and Weterings, 1999) is the most widely used of the biophysically based frameworks, and it can incorporate a wide range of societal aspects. Originally designed to assess the relevance of indicators for policymakers, it has been central in the application of the WFD (Hering et al. 2015). The DPSIR indeed recognizes the chain of effects departing from drivers to societal responses and impacts on freshwater ecosystems, and therefore considers the physical and societal components of the sources and effects associated to stressors (Birk, 2019). The DPSIR has been applied to multiple freshwater ecosystems through the EU-funded project MARS, where it was used in connection to risk assessment and ecosystem services workflows (Hering et al. 2015, Segurado et al. 2018, Birk 2019).

These frameworks depart from the occurrence of stressors to their effects on ecosystems and society, by means of stepwise, iterative, processes (Fig. 1). Human activities in a region drive land use changes, resulting in specific types, number, and intensity of stressors (Fig. 1, main upper connection). Every stressor will affect the environmental conditions and impact biological communities and ecosystem functioning (biophysical process). Consequently, the societal interface (Fig. 1, upper part of the loop) associated to the river ecosystem services (e.g. water purification, food production, erosion control), is also impacted. The relationship between ecological status (as defined by the EU Water Framework Directive), or river health (Rapport et al., 1998; Karr, 1999), and the ecosystem capacity to fulfill the demands for drinking water, food, energy and recreation under optimal conditions is at the core of the Ecosystem Services delivery (Adams, 2014). Nonetheless, this relationship not necessarily matches with ecosystem conservation goals, since ecosystem service provisioning does not necessarily support a good ecological status (Duncan et al., 2015).

At the societal interface (Fig. 1, lower part of the loop), the society can disregard or even accept environmental degradation, then reinforcing effects through further pressures affecting river networks. Otherwise, the impairment caused by stressors can be mitigated (e.g. restoration) through governance or stewardship (Pahl-Wostl et al. 2012, Pistocchi et al. 2017, Huber-Garcia et al. 2019, Koundouri et al. 2019). For example, large investments in water treatment and infrastructure may reduce the negative effects of pollution to humans (Pistocchi 2019), but not necessarily improve the ecological status of the river ecosystems unless accompanied by specific restoration actions (Pander and Geist 2013). These ecosystem-societal interactions may become complicated by legacies of ancient or long-lasting disturbances (Lake et al., 2007), which reduce the success of corrective measures (Pander and Geist 2013).

Overall, the outcome of the ecosystem-societal decisions is uncertain and difficult to generalize. Uncertainties, associated to the poor understanding of causality (Downes, 2010), affect both the biophysical and societal realms. An example can be found in the case of drinking water management, where a multi-barrier approach conventionally involves pollution control, source water protection, water treatment technology and managed distribution networks. Delpla and Rodriguez (2019) showed that integrated management of drinking water must consider the chain from source to tap, to leave river (basin) managers with more acting options in the future.

All in all, unwanted returns of stressor effects may affect the well-being of the society, which can respond by either strengthening or weakening the associated driver (Fig. 1, bottom lower part). The extent and directions of these feedbacks largely depend on how much society relies on the goods (water, food, etc.) and services provided by the river (Liquete et al., 2011), on their ability to implement appropriate managerial constructs, and on the degree of impairment of the system (regarding water quality and conservation), which affect its ability to provide services.

An integrated concept of multiple stressors

The approach described so far, although adequate to frame the impact of dominant stressors on ecosystems and human societies, remains insufficient to account for the complexity of stressors at multiple co-occurring scales. In this section, we discuss a workflow incorporating some key aspects for the biophysical and societal implications of multiple stressors on river networks. We therefore analyze several aspects potentially affecting the causal relationship between stressor occurrence and their effects on biological receptors, which later will propagate to ecosystem function, ecosystem services provision, and societal impacts. Overall, these aspects come to modify the relationships summarized in Fig. 1:

i) *Drivers may be at the origin of more than one stressor*, pointing out that the often-perceived connection of one driver – one stressor is overly simplistic. As an example, river regulation (driver) is at the basis of several stressors (hydrological pressure, lower water temperature, light regime alteration, siltation; Abbott et al. 2019, Grill et al. 2019), which affect the river downstream the infrastructure. This evidence should be contemplated in conceptual schemes (Fig. 2), and calls for a wider perspective on causal relationships

ii) *Consider the spatial and temporal scale at which stressors co-occur*. From the range of geographical and temporal scales at which stressors can occur (Table 3), it is important to understand where and when exactly co-occurrence exists. For instance, sometimes there are permanently occurring stressors, to which others are intermittently superposed. As an example, climate change and associated rainfall anomalies may exert continuing influence on river networks over large spatial and temporal scales; basins under these anomalies may additionally receive locally acute or chronic stressors (such as nutrients in excess, or pollutants) within selected river segments, which may overlap with climate change stressors and produce conjoint effects. Ponsatí et al. (2016) analyzed the relative effects of water flow alterations, nutrient inputs, and organic micro-pollutants on the structure and function of river biofilms, and observed that basin-specific climate influences, water use, and human activities, were superposed to contaminant effects. This is the case of many basins dominated by agricultural uses, submitted to periodical overpressures on water resources because of abstraction and/or irrigation, onto which chemical stressors from diffuse sources co-occur continuously (Sabater et al. 2018). The most common scenario is that co-occurring stressors may not always overlap, showing a suite of varying intensities when they co-occur (Fig. 2). Allan et al. (2013) merged high-resolution spatial analyses of occurring stressors with mapping of ecosystem services to inform on the Great Lakes Restoration Initiative; they determined that cumulative effect of stressors was higher in areas with high spatial concordance of several stressors, and so there were the effects to associated ecosystem services. However, we still have a poor knowledge on the responses of ecosystems being subject to a suite of stressors of varying intensity.

iii) *Stressor order of occurrence is probably determining different effects*. It is yet unknown how much the response of receptors to the cumulative impact of stressors may be influenced by the order onto which the successive stressors impact (Figure 2). It is likely that the cumulative effect differs according to the intensity of the successive stressors, the most intense ones weakening more strongly the biological structure (Segner et al. 2014). Ascending or descending sequences of intensity might thus produce different outcomes, although there is so far no experimental support for this statement. Similarly, the outcome of locally co-occurring multiple stressors can be complicated by the hierarchical structure of river networks (Frissell 1986). Even though stressors impacts perform locally, extending or not to other parts of the river basin may be favored, or not, according to the stressor's mobility (e.g. microorganisms *vs.* fish), but also related to the original position of the impact (e.g. the presence of a dam at the medium or lower part of the river network may have specific effects to mobile or less mobile species). The spatial and temporal ordering of stressors occurrence likely shows relevant socio-ecological implications.

iv) *Consider current and legacy stressors*. The effects of current stressors can be mediated by legacy effects of past stressors, as when past events have affected the available species pool, then modifying the response of existing species to current stressors. This is the case in a study of invertebrate communities exposed to nutrient amendment and habitat heterogeneity (Baumgartner and Robinson 2015), where responses were related to historical physical impairment, then reflected in depauperate macroinvertebrate assemblages. The response to stressors, even when the current impact of stressors is negligible (Combination 3, Fig. 2), cannot be properly understood without considering legacy effects. This is particularly relevant when effects are searched on organisms with longer life cycles, such as fish.

v) *The cumulative impact of stressors depends both on their combination and on the response variable*. Stressor effects can be additive (i.e., the sum of the caused effects by each of the stressors), or non-additive. These include synergistic (stronger than the sum of the separate effects) or antagonistic (weaker effects than those resulting from the expected combination; Piggot et al., 2016, Crain 2008; Schäffer and Piggott 2018). Jackson et al. (2016) showed that a large fraction of occurring interactions was non-additive and could then generate ecological surprises (Ormerod et al. 2010, Filbee-Dexter et al. 2017), i.e. an unexpected or idiosyncratic response of an ecosystem to multiple stressors. Still, these models are hard to translate to real situations since most have been limited to pairs of stressors (Noges et al. 2016). In the few cases on which more than two stressors have been tested, results have been imprecise or unexpected. Romero et al. (2019) combined the effects of warming, hydrological stress, and pesticide exposure on river biofilms in artificial streams and observed that most stressor combinations (71%) resulted in additive effects, and that 3-way interactions had smaller effect sizes than other combinations. Further, it is increasingly clear that the outcome may differ according to the biological group considered (Galic et al. 2018), and even that it may change depending on the variable measured (Romero et al. 2019).

vi) *Multiple stressors can produce conflicting effects on ecosystem services*. Impacts of multiple stressors on biological receptors ultimately affect ecosystem functions and services, but the response of all concerned services is not necessarily coherent. Dams are simultaneously a source of stressors (e.g., altered hydrological and thermal regimes, Ward and Stanford 1995) and providers of ecosystem services, such as hydropower or water supply (von Schiller et al., 2015; Grizzetti et al., 2016). The effects of dams on the river network varies with their operational age, affecting from their sedimentary dynamics (Batalla and Vericat 2011) to their biogeochemical processes, or biological communities (Sabater and Muñoz 1990, Sabater et al. 2008). As an example, regulation in the lower Ebro River has reduced turbidity and changed the hydraulics of the river below, favoring macrophytes spread (Ibáñez et al. 2012), and associated masses of blackfly larvae, whose adults produce extensive nuisances to riverine towns (Carvalho et al., 2019). Declining water levels and flow velocities in response to changing climate conditions and increasing water abstraction in the lower Ebro have favored tolerant alien species, such as the apple snail (*Pomacea maculata*), putting the survival of endemic species at risk (López-van Oosterom et al., 2019). Stagnation associated to dams and irrigation channels have been also related to the spread of hosts (snails) mediating the transmission of schistosomiasis to humans mostly in Africa (Steinmann et al. 2006). Ecosystem services become blurred in these examples after the impact of associated stressors.

vii) *Management of stressor effects should consider multiple scales of stressor occurrences*. Current management of river networks is mostly restricted to main occurring stressors. Most monitoring plans are directed to survey the impact of specific stressor classes (e.g. contaminants, invasive species), and as such neglect overlapping scales (Elements and Factors, Table 3) and complexities associated to multiple stressor occurrence and effects. Current management practices rarely consider the coincidence of short-term or long-term stressors (e.g. contaminant vs. climate change stressors), their varying intensity, the complex responses of biological stressors, or the impacts these combinations may produce on ecosystem services. As such, most management strategies do not fully integrate the biophysical implications that multiple stressors may cause to ecosystems together with their unwanted returns to society. Environmental monitoring and management programs may have to be adapted to better incorporate the novel findings of multiple stressor studies; the iterative approach proposed by Pistocchi et al. (2018) already heads in this direction.

Overall, adopting the modifications outlined above require expanding the former conceptual scheme of Fig. 1, and incorporate the complexity of scales associated to the presence of multiple stressors. In such a renewed workflow scheme (Fig. 2), the specific occurrences in space and time of multiple stressors (stressor hub), as well as their respective intensities and frequencies, should be considered at the scale of basin, at least. The different outputs associated to stressor combinations need to be associated to the assembly of receptors (receptor lounge; Fig. 2), from which it will derive the biological implications on species assemblages, the likely alteration in their functions, and the associated impairment on ecosystem services. As much as in the former scheme of Fig.1, management and governance would converge on the use of the produced ecosystem services as well as on the proper regulation of the drivers, as a first and necessary step to reduce the extent and impact of multiple co-occurring stressors.

Concluding remarks

The above seven items remain intertwined and incorporate managerial and research implications. Incorporating the recorded occurrence of stressors in a basin-wide perspective, their present and past spatial and temporal occurrence, and relating them to the drivers originating them (items *i* and *ii*), may help to define causal relationships and the potential distribution of multiple stressor effects (item *vii*). Although some regularities associated to the simultaneous occurrence of stressors are already known, moving from simultaneous to non-simultaneous occurrences, or to the transmission of effects in space and time, is yet a gate to the unknown. Ongoing research has clarified some issues regarding the transmission of effects from small to larger scales, or the additive *vs* non-additive nature of co-occurring stressors (item *v*). However, there is a lively debate on whether ones or the others may prevail in river networks, and on whether those outcomes depend on the organisms or variables considered. Not only potential regularities occurring in the ecosystem, but the mechanisms supporting these responses are still poorly understood. Precisely, a clear gap in such understanding is how much the order of occurrence of stressors (either in time or space, or in their intensity; items *ii*, *iii*, and *iv*) may modify the output of multiple stressors as well as its effect on foreseen ecosystem services (item *vi*). Research is to be implemented to determine the response patterns in populations, communities, and ecosystems, and how much it differs according to the different timing, and transmission of effects through space, or the delayed effects of past stressors.

These research needs, when fulfilled, may be used to improve the planning and management of river basins. As the human population steadily increases, and despite all efforts for an increasing environmental awareness, multiple stressor situations will likely become more frequent and complex, and their consequences could have serious, region-specific effects (Diaz et al. 2019). Some World's regions are able to respond technologically and probably will cope better with the associated impairments; however, societies with lower technological capabilities, which often harbor higher biodiversity and the most fragile ecosystems, will face higher difficulties in mitigating unwanted responses to multiple stress situations. The economic and social globalization makes the single-local perspective unrealistic to approach the real impact of multiple stressors to ecosystems and people. As an example, salmon-farming booming in Chilean Patagonia, a recognized driver of impairment in rivers and lakes in the region (Soto et al. 2006, Quiñones et al. 2019), cannot be separated from the escalating trade of cultured salmons to developed countries.

Finally, recognizing multiple stressors in any conceptual framework should lead to several academic and managerial consequences. There should be a change of paradigm in which the river carrying capacity is carefully considered across scales, both for the resources and services river networks may contribute (water, timber, food), and for their ability to cope with natural perturbations and anthropogenic stressors. Regarding these, minimization of local stressors (e.g. pollution, damming, biological invasions), while keeping a basin-wide perspective, is essential. Further, perspectives should embrace wider scales, and considering effects on distant, well-preserved areas (including headwaters, as well as tropical and boreal systems) is of maximum urgency. These areas can be essential to maintain the species pools and biological structures from which we still require to learn. This urgency cannot be separated from the paradigm of a joint fate of nature and human societies, i.e. that keeping a healthy environment is key for a healthy society.

Acknowledgements

This research was supported by the EC 7th Framework Programme (GLOBAQUA; 603629-ENV-2013–6.2.1). Additional support was provided by the projects CLIMALERT (PCIN-2017- 068) and SPACESTREAM (CGL2017-88640-C2-1-R) of the Spanish Ministry of Science and Innovation. SSA acknowledges the support from the Economy and Knowledge Department of the Catalan Government through the Consolidated Research Group (ICRA-ENV 2017 SGR 1124) – Catalan Institute for Water Research. ICRA is part of the CERCA program.

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Table 1. *Main drivers and stressors affecting river networks, potential intensity, and extent, of impacts associated to the occurrence of stressors.*

Driver		**Stressors**	**Potential Intensity**	**Geographic extent**
Climate change		Rainfall anomalies	Moderate	Regional to local
		Exceptional flood or drought events	High	Regional to local
		Temperature anomalies	Moderate	Regional
Land use and changes	Mining	Heavy metal contamination	High	Regional to local
	Agriculture	Nutrient excess, pesticides	Moderate to high	Regional to local
	Farming	Nutrient excess, pesticides	Moderate to high	Regional to local
	Urbanization	Imperviousness, damming	High	Regional to local
	Forestry	Siltation	Moderate to high	Regional to local
Hydrological cycle alterations		Damming	High	Local
		Water abstraction	High	Regional to local
		Groundwater exploitation	High	Regional to local
Geomorphological alterations		Siltation	Moderate to high	Regional to local
		Temperature alteration	Moderate to high	Local
Physico-chemical alterations		Nutrient increase	Moderate to high	Local
		pH alteration	Moderate to high	Local
		Heavy metal pollution	High	Local
		Organic microcontaminants	High	Local
		Salinization	High	Local
		Thermal pollution	Moderate to high	Local
Biological alterations		Overharvesting	Moderate to high	Regional to local
		Exotic invasive species	High	Local

Table 2. *Environmental and biological elements modulating the effects of multiple stressors on river ecosystems, arranged in a spatial of increasing complexity.*

Characteristics of biological assemblages	Composition of the species pool in each biological group Life-cycle duration of each biological group; combination of all of them Dispersal capacity of the assemblage Resistance and resilience of each biological assemblage to stressors Food web complexity
Ecosystem configuration	Size Longitudinal connectivity within the river network; lateral and vertical connectivity Geomorphological complexity and availability of refugia (spatial / temporal)
Environmental characteristics (physical and chemical)	Present environmental characteristics of the ecoregion or biome Past environmental conditions (legacy effects)

Table 3. *Socio-economic elements and factors to be considered to determine the relevance of multiple stressor effects to river networks.*

Elements	**Factors**
Basin	Population density Economic sector(s) prevailing Land uses
Region/Country	Governance and institutional involvement on sustainable development Implemented legislative framework Societal stewardship on environmental issues Financial capacities and technological development

Figure 1. *Stressors affect the biophysical condition of the river networks and have consequences for ecosystem functioning. Societal interactions can either mitigate or reinforce the drivers promoting the stressors. Effects transmit from the biological receptors to the ecosystem functions and ecosystem services. Societal responses differ in governance and socio-economic conditions. Colours reflect biophysical (blue) or societal (brown) implications on the loop*

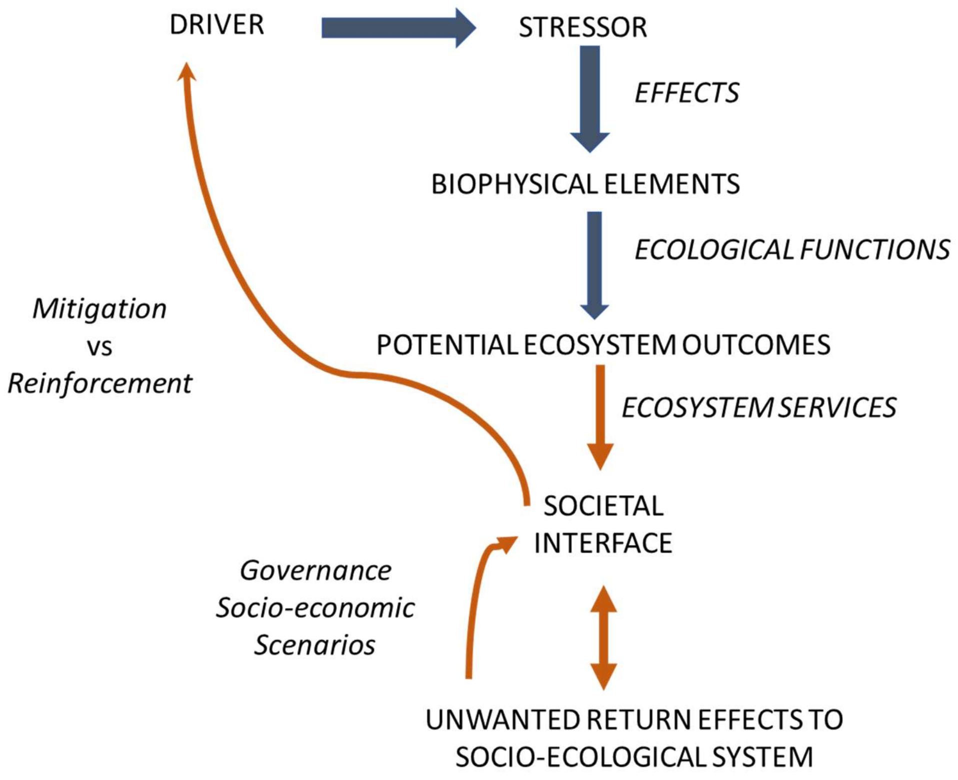

Figure 2. *Co-occurring multiple stressors may show variations in space and time regarding their occurrence, intensity, and frequency. The figure exemplifies several combinations of stressors occurring within the stressor hub, and their likely different impacts on the receptors (receptor lounge). Changes in ecosystem services can be expected in each of the cases, which therefore will require changes in management and governance, and if appropriate will likely modify the drivers at the source of stressors.*