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Multiple stressors and social-ecological traps in Pampean streams (Argentina): a conceptual model

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ABSTRACT

Fluvial systems are particularly sensitive to changes in the terrestrial ecosystems where they are embedded, receiving simultaneously the impact of multiple stressors. The design of adequate management policies requires analyzing fluvial systems as social-ecological systems, because the decoupling of natural and social systems can lead to a severe mismatch between maintaining ecological integrity and the pursuit of human well-being. Pampean streams are especially prone to the impact of human activities because they are located in a region that provides almost half of the agricultural production of Argentina and concentrates 66% of the whole population of the country. In the present work, we conceived a general social-ecological framework that links the occurrence of multiple stressors and their impacts on ecosystem services, with changes in environmental perception of streams, which in turn feedback over institutional actions at the watershed's governance. We identified four current key drivers of the dynamics in Pampean streams: a dominant agro-industrial model for the region, a command-and-control governance regime mainly based on an engineering hydraulic perspective, the real estate market speculation of surrounding lands, and the persistence of structural poverty in urban areas. The resulting dynamics resembles the occurrence of different kinds of social-ecological traps, i.e., a highly stable but undesirable state of the system that is difficult to escape. Based on this analysis, we provide a leverage point perspective to avoid this trap. Together, this approach could be applied to other fluvial systems of the world to link the ecological and social domains to multiple stressors analysis, and to improve institutional fit for the sustainability of fluvial social-ecological systems.

Key words: social-ecological systems, water governance, Pampean lowland streams, environmental perception, ecosystem services, leverage points.

1. INTRODUCTION

As humanity has a greater impact on nature, producing undesirable feedbacks on their benefits to society, the need to integrate the social and ecological aspects of the systems become more evident than ever (Carpenter et al., 2009; Díaz et al., 2015). Fluvial systems are particularly sensitive to changes in the terrestrial ecosystems where they are embedded, receiving simultaneously the impact of multiple kind of stressors derived from stakeholder's activities and management actions through the governance system (Carpenter et al., 2011; Green et al., 2015; Vörösmarty et al., 2010). The design of adequate management policies requires analyzing fluvial systems as social-ecological systems, because the decoupling of natural and social systems can lead to a severe mismatch between maintaining ecological integrity and the pursuit of human well-being (Folke, 2003; Navarro-Ortega et al., 2015; Palmer, 2010). Particularly, a relegated aspect regarding the dynamics of fluvial systems refers to the potential interplay between the quality of the ecosystem services provided by the aquatic environment, the environmental perceptions/attitudes of the local communities and stakeholders, and the current management actions taken by them. How do these human-nature feedbacks act and which are the main drivers? Can we associate the persistence of undesirable ecological conditions in fluvial systems to specific feedback loops?

The dynamics of any social-ecological system is governed by the interaction among its components and the frequency and intensity of its perturbations (Stuart Chapin et al., 2009). In this sense, patterns of fluvial degradation due to the interplay of multiple stressors vary markedly within continents and countries (Booth et al., 2016; Vörösmarty et al., 2010). Stressors can have different effects on the ecological integrity and the ecosystem services derived from fluvial ecosystems, depending on the regional ecological context, stream or river size (Artigas et al., 2013; Hale et al., 2016), and the economic and social context (e.g., low-income versus high-income countries, cultural differences regarding human-nature relationships, tendency to corrupt behavior) (Capps et al., 2016; Enqvist et al., 2019; Green et al., 2015; Knieper & Pahl-Wostl, 2016). Moreover, different watershed governance regimes adopted - e.g., hierarchical or polycentric, public or private governance systems- may influence the occurrence, frequency and magnitude of multiple stressors affecting rivers and streams, such as channelization, dam construction, pollution or climate change (Pahl-Wostl & Knieper, 2014). This remarks the importance of characterizing the social-ecological context to understand the impact of multiple stressors on the aquatic environment.

Furthermore, the stability and dynamics of a social-ecological system depends on the kind of feedbacks they have (Stuart Chapin et al., 2009). Feedbacks can be categorized in stabilizing (A causes B which in turn causes less of A), or amplifying feedbacks (A causes B, which in turn causes more of A). In particular, social-ecological traps are characterized by the occurrence of amplifying feedbacks generating the persistence of an undesirable social-ecological state derived from human actions, which is very difficult to reverse (Carpenter and Brock, 2008; Cinner, 2011; Tidball et al., 2016). Human-induced alternations of the social-ecological dynamics lead to regime shifts, altering the ecosystem capacity to generate services for human well-being, and triggering societal responses that reinforce this negative pathway (Haider et al., 2018; Stockholm Resilience Centre, 2012). Social-ecological traps may be driven by economic opportunities, persistent poverty, or belief systems, among others (Boonstra and De Boer, 2014; Cinner, 2011; Haider et al., 2018; Scheffer and Westley, 2007; Steneck et al., 2011; Tidball et al., 2016; Tidball, 2016).

Recently, Masterson et al. (2019b) have revisited the connection between the integrity of ecosystems with human well-being, particularly highlighting the feedback loop between people’s attitudes and behavior and conservation of local ecosystems (ecosystem integrity generates benefits to people, which in turn causes a positive perception of the environment and the conservation of the ecosystem structure through sustainable management practices). Environmental psychology has also shown that environmental perception is an important factor influencing human intentions and behavior (Klöckner, 2013), although in a complex relationship with other social, psychological and institutional factors (Bai et al., 2020; Bamberg Sebastian, 2003; Gifford and Nilsson, 2014; Paraskevopoulos et al., 2003). Therefore, the interplay between people’s perceptions, attitudes and values and social structures (such as institutions) is a key element, which can generate positive reinforcing dynamics of sustainable outcomes, or reinforce negative dynamics such as social-ecological traps (Gottwald and Clark, 2020; Masterson et al., 2019b).

In this article, we elaborate a conceptual model of fluvial landscapes as social-ecological systems that emphasize the interplay between the impact of multiple stressors, human environmental perceptions and attitudes, and their feedback to management actions. We hypothesize that the impairment of fluvial ecosystems is the result of the emergence of different kind of social-ecological traps operating on them. We conducted a literature review to: 1) analyze the empirical support for our conceptual model, 2) characterize the co-occurrence of multiple stressors in a specific regional context, i.e., Pampean lowland streams of Buenos Aires province (Argentina), including their ecological, social and institutional features, and 3) analyze the emergence of regional feedbacks loops within a local case study (the Lujan River basin). Furthermore, we identify several leverage points -or places to intervene- to break the existing regional social-ecological traps from an inclusive and participatory social management perspective. We finally analyze the current limitations of our framework and outline new approaches for further analysis.

2. THE CONCEPTUAL FEEDBACK MODEL: HOW STRESSORS CAN REINFORCE THEIR IMPACT ON FLUVIAL ECOSYSTEMS THROUGH SOCIO-ECOLOGICAL INTERACTIONS

We present a conceptual model (Figure 1) that applied recent advances in the theoretical understanding of social-ecological systems to fluvial systems, to explain the persistence, and even the reinforcement, of multiple stressors impacting on them. It has similarities with previous efforts that linked the social and natural domains for ecosystem researchers and watershed policy makers (Collins et al., 2011; Navarro-Ortega et al., 2015; Wantzen et al., 2019). The main difference with former approaches is the particular emphasis given to the potential feedbacks between four key features of any social-ecological fluvial system: stressors, ecosystems services, human environmental attitudes, and management actions. In our model, the occurrence of multiple stressors impacts on the fluvial ecosystem through a positive feedback mechanism, maintaining the *status-quo* on institutional management actions, and lock-in the system in an emergent social-ecological trap. Furthermore, key external drivers influence the maintenance of the system dynamics (Schlüter and Herrfahrdt-Pähle, 2011). In the following sections, we focus on the most novel features of our model, given that the effects of multiple stressors and disturbances on ecosystem structure, function and services are well known in the fluvial ecosystem literature (Mazzorana et al., 2019; Sabater, 2008; Stevenson and Sabater, 2010).

2.1 – Institutions mediate the frequency and magnitude of fluvial stressors on ecosystem structure and function

In Figure 1, stressors are derived from the current institutional policy and market behavior, impacting on specific features of the ecosystem structure-function relationship. This, in turn, may affect the maintenance of particular ecosystem services, impairing human well-being. Evidence has been accumulated regarding the influence of governance systems and their derived management actions on the frequency and magnitude of fluvial stressors (Knieper and Pahl-Wostl, 2016; Pahl-Wostl and Knieper, 2014). In what follows, we define the governance system as ‘the interconnected ensemble of political, social, economic and administrative elements that performs the function of water governance’, and the governance regime as ‘the interdependent set of institutions (formal laws, societal norms or professional practices) that is the main structural component feature of a governance system’ (Pahl-Wostl, 2015:26).

Typically, governance systems are based on a command-and-control scheme, i.e., a highly hierarchical and bureaucratic regime where control and rigidity are the main features of the management scheme (Cox, 2016). These systems have historically adopted a hydraulic perspective based on river regulation, channelization, diversion and water abstraction to control flooding and water provision, and they turn out to be inadequate for establishing effective regulatory policies (Lebel et al., 2013; Pahl-Wostl et al., 2013). As an example, Lebel et al. (2011) showed that flooding response in Thailand was undermined by several institutional features of water governance structures, such as institutional fragmentation, rigid planning and a focus on reacting in the face of emergencies and crisis, without strategic, long-term planning.

In contrast, adaptive governance based on social-ecological resilience, nature-based solutions or ecosystem-based approaches proposes alternative management options that directly impact on the frequency and magnitude of fluvial stressors (Keesstra et al., 2018; Nesshöver et al., 2017; Richter et al., 2015). An adequate integration between ecosystems and institutions is also needed to minimize the impact of stressors (Qiu et al., 2017), along with the implementation of a broader network of social actors (Wang et al., 2019). In general, these alternatives are resisted from a command-and-control perspective because they introduce complexity and uncertainty to the socio-ecological system (Folke, 2003; Richter et al., 2015; Roy et al., 2008), and require new legal and institutional norms to deal with them (DeCaro et al., 2017; Green et al., 2015; Olsson & Head, 2015). For example, an analysis of pollution control and the adoption of polycentric governance regimes (i.e., multi-level, coordinated and flexible network of actors) showed that only an effective implementation of these features can successfully promote an adaptive governance system (da Silveira and Richards, 2013).

In summary, governance systems and their derived management actions have the potential of profoundly shaping the occurrence and impact of several stressors on fluvial ecosystems, affecting their structure and function, and consequently their contribution to societies. Of course, overall human pressure is another element that strongly affects the frequency and magnitude of aquatic stressors irrespective of the kind of governance structure (Knieper and Pahl-Wostl, 2016), and thus should be also addressed in an integrative water governance framework.

To complete the analysis of the conceptual model, the next section delves into the impact of society and ecosystem alteration on management practices. This feedback is mediated by people attitudes and environmental perceptions, which close the social-ecological feedback loop by adopting a subjective or agency perspective.

2.2 – Environmental perception and people attitudes constrain the institutional responses to

multiple stressors

In our model, the loss of ecosystem services triggers changes on attitudes and perceptions of individuals or collective actors about the environment, which influence the norms and behaviors that regulates ecosystem management, closing the feedback loop and maintaining the *status-quo.* Several lines of research provide empirical support to this feedback mechanism in different geographical contexts and socio-ecosystems (Fatti and Patel, 2013; Fernández-Llamazares et al., 2016; Masterson et al., 2019b; Oldekop et al., 2012). For instance, Fernández-Llamazares et al. (2016) show that local perceptions are part of the mechanism used by a Bolivian Amazonian community to track the availability and change of the stock of thatch palm, and thus regulate management actions taken by the community. Oldekop et al. (2012) found a similar feedback loop between the perception of environmental impact and resource scarcity in an indigenous Amazonian community. In a different context, Fatti and Patel (2013) show how risk perception influences local management associated to urban flood risk in a locality of South Africa. Next, we complement these evidences with a detailed discussion on the mechanisms that may contribute to link ecosystem's state and services with social perception and attitudes, and their consequences on the resulting management actions.

There is evidence that the (bio)physical state of the environment influences different psychological aspects of behavior, including environmental perception, people attitudes and place attachment (Gottwald and Clark, 2020; Masterson et al., 2019b). For example, the loss of ecosystem structure and services in fluvial landscapes has a measurable impact on the perception of the environment, which can reflect positive or negative changes depending on social preferences and use of each particular ecosystem benefit (Asah et al., 2014; McNally et al., 2016; Narducci et al., 2019; Rojas et al., 2017; Tuvendal and Elmqvist, 2011). Furthermore, Ingalls & Stedman (2017) argue that the physical environment constrains the psychological meanings that can be attributed to a landscape by individuals, thus impacting on the social constructions and the institutional management outcomes.

On the other hand, institutional analysts have not clearly outlined how human attitudes and perception influence institutional outcomes (DeCaro and Stokes, 2013), which is one of the keys to understand the persistence of multiple stressors acting on ecosystems (cf. Oldekop et al., 2012). One of the main obstacles is the lack of a linear relationship between human intentions and behavior in the psychological literature (Bai et al., 2020; Gottwald and Clark, 2020; Webb and Sheeran, 2006), which is reflected in the fact the even pro-environmental attitudes do not translate automatically to a positive outcome for the environment (Gifford and Nilsson, 2014; Masterson et al., 2019a). Despite of these facts, several research lines provide theoretical and empirical evidence on the different mechanisms that could account for an interaction between people environmental perceptions and the lack of positive institutional outcomes. In this sense, we propose three non-exclusive mechanisms that could explain this phenomenon: 1) a cost/benefit rationale, 2) physical disconnection and alienation from nature; 3) social exclusion associated with a lack of public participation. We consider these mechanisms as plausible psychological processes that different groups (governmental stakeholders, local residents, dominant societal groups, etc.) can internally develop, and which may explain the lack of corrective actions to unsustainable management practices and the reinforcement of the *status-quo*. We predict that, depending on the particular context, one or several of these mechanisms may be acting in different social groups to explain their behavior.

First, cost/benefit relationships have been shown as a driver of management outcomes in theoretical and empirical contexts (Janssen and Anderies, 2007; Shortle and Horan, 2017). In a recent study on common-pool resources management in the Ecuadorian Amazon (Oldekop et al., 2012), resource scarcity, or the perception thereof, was the main driver of management practices based on cost/benefit relationships. If perception of resource scarcity is low, incentives for the implementation of management measures are also low because the costs of an institutional reform will outweigh perceived benefits from regulating abundant resources. But the same outcome will be obtained if resources are much degraded, because costs of creating new regulations will be high compared to the perceived little benefit from regulating irrecoverable resources. Only conditions where benefits surpass costs produce desirable management outcomes (Oldekop et al., 2012).

Second, some authors argue that physical disconnection from ecosystems promotes alienating behaviors and increases destructive tendencies (Kasper, 2009; Worthy, 2008). Social structures, which can dissociate people from natural systems, could be an explanation of the resistance of stakeholders towards pro-environmental management practices (Worthy, 2008). In this sense, several studies show how distinct discourses, experiences, or institutions help to produce such kind of dissociations (Harclerode et al., 2016; Lebel and Lebel, 2017; Norgaard, 2006; Onkila, 2011; Ruzol et al., 2017; Santoro et al., 2019). Mental models for example, in the form of stakeholder’s narratives, can block the rise of pro-environmental management practices (Lebel and Lebel, 2017). Other studies showed that denial is a primary cause of the lack of response despite full knowledge of environmental issues (Norgaard, 2006; Preston et al., 1983).

Finally, researchers also have argued that models that link attitudes to behavior should explicitly consider the context in which people act (Guagnano et al., 1995). Unplanned settlements characterized by substandard living conditions are common in many watersheds, particularly in low and medium income countries (Capps et al., 2016). Social exclusion, considering its multiple dimensions (economic, social, and political), can act over people’s environmental perception, increasing their negative behavior on fluvial ecosystems and favoring the occurrence of multiple stressors (Paraskevopoulos et al., 2003).

In the following sections, we explore the use of this model to the regional case of Pampean lowland streams in Argentina, starting with a socio-ecological characterization of the system. Then, we identified the main key drivers and the particular components of the model which favor the emergence of positive feedback loops, and identify the occurrence of different kinds of social-ecological traps.

3. SOCIOECOLOGICAL CHARACTERIZATION OF LOWLAND STREAMS FROM BUENOS AIRES PROVINCE, ARGENTINA

3.1 – Lowland streams from Buenos Aires Province

Buenos Aires province is included in the Pampean region, a vast grassy plain located in central Argentina. The original landscape has been modified since the XVII century due to the introduction of plants and animals by the first European settlers in the region. This process was intensified by the expansion of agriculture at the end of the XIX century, which replaced the original grassland in most parts of the region (Brailovsky and Foguelman, 1992; Cabrera, 1976). Moreover, Buenos Aires has experienced sustained population growth since XVII century (Pereyra and Rimoldi, 2003). Actually, the region provides almost half of the agricultural production of Argentina (INDEC, 2018) and concentrates 66% (15.6 million of inhabitants) of the whole population of the country (INDEC, 2010).

Due to the quite uniform relief of the region (slope between 0.1-1 m/km), most Pampean streams originate in small wetlands and are mainly fed by groundwater. Typically, the streams lack riparian forests and have slow water flow (0-0.25 cm/s), high irradiances, and dense assemblages of biofilms and macrophytes (Feijoó & Lombardo, 2007; Giorgi et al., 2005). Streambeds are formed by hard and homogeneous substrata with fine sediments (primarily silt and clay), high content of calcium carbonate, and a total absence of stones or pebbles (Feijoó and Lombardo, 2007). Stream waters are generally alkaline, with high conductivity (1082-6012 µS/cm) and elevated dissolved oxygen and nutrient concentrations (Feijoó & Lombardo, 2007). Pampean streams are eutrophic under USEPA (2000) guidelines because mean annual concentration of phosphate and nitrate are >0.15 mg/L and >1.5 mg/L, respectively (Amuchástegui et al., 2016; Feijoó & Lombardo, 2007). It must be noted that paleo-limnological records suggest that eutrophic conditions were common in Pampean water bodies even before the rise of agriculture in the XIX century (Prieto, 1996; Zárate et al., 2000).

3.2 – Main stressors and loss of ecosystem services

Pampean streams receive the impact of multiple stressors derived from human activities, which are increasingly affecting their ecological integrity (Table 1). One of the most important stressors is the pollution by pesticides (Aparicio et al., 2013; Hunt et al., 2016; Iturburu et al., 2019; Lupi et al., 2015; Peruzzo et al., 2008), wastewaters (Efron et al., 2014; López et al., 2013; Marucci et al., 2011; Piccinini et al., 2015), and industrial effluents (Ceballos et al., 2018; Giorgi and Malacalza, 2002; Rimoldi et al., 2018), due to diffuse and point sources that affect both stream water and sediments. Agricultural production is based on the cultivation of transgenic crops (generally soybean and maize) combined with no-till practices and a massive intensive use of plaguicides (mainly glyphosate and AMPA, chlropyrifos, cypermethrin, and endosulfan; Arias et al., 2020; Hunt et al., 2016; Primost et al., 2017). However, fertilizer use is relatively low in the Pampean region (especially in the case of phosphorus), which is reflected in negative balances in soil phosphorus and nitrogen in the Pampas (Díaz de Astarloa and Pengue, 2018; Viglizzo et al., 2001). This model of agricultural intensification implanted in the last decades has increased the presence of pesticides in freshwaters and altered the abundance and diversity of aquatic communities (Pérez et al., 2007; Solis et al., 2018; Vera et al., 2010). Agrochemicals such as fertilizers and pesticides are the main possible sources of nitrates and phosphorus to rural streams: however, agricultural cover was directly associated to nitrate but not to phosphorus concentration in 23 Pampean streams (Amuchástegui et al., 2016). In urbanized areas, many industries lack adequate wastewater treatment systems and effluents are released to streams and rivers without a complete treatment (Casares and de Cabo, 2018; Magdaleno et al., 2001; Salibian, 2006). In addition, the Metropolitan Area of Buenos Aires has 9% of its population with unsatisfied basic needs (INDEC, 2010), and almost 45% of its population without adequate sewage infrastructure (Tobias and Fernández, 2019). Therefore, a significant amount of domestic effluents are delivered to informal septic systems, where they can leak into the groundwater and, ultimately, to streams and rivers (Cirelli & Ojeda, 2008; Öberg et al., 2014), carrying a complex mixture of contaminants to the aquatic environment (Elorriaga et al., 2013a, 2013b). Sediments also reflect the input of this organic pollutant load associated with increased levels of nitrates, phosphorus and several metals (Rimoldi et al., 2018).

Modification of the morphology of Pampean watercourses altered the variability of flow, producing abrupt changes in the hydrograph curve (Scarpati and Capriolo, 2013). Hydraulic modifications such as dredging, channelization, rectification, and macrophyte harvesting are very common in Pampean streams (Bazzuri et al., 2018; Graziano et al., 2019; Licursi and Gómez, 2009; Maidana et al., 2005; Paz et al., 2018). Channelization alters fluvial structure and function, such as nutrient retention (Booman & Laterra, 2019; Pozzobon et al., 2018).

Streambed sediments are also affected, in particular by increasing the sand fraction (Rimoldi et al., 2018). The replacement of the riparian herbaceous vegetation by invasive woody species or implanted trees, including some woody invaders such as *Gleditsia triacanthos* L. (Fernandez et al., 2017), is another relevant stressor impacting on Pampean streams (Guida-Johnson and Zuleta, 2019). For instance, it has been shown that the presence of *G. triacanthos* in the margins of Pampean streams affects some ecological functions, decreasing ecosystem productivity and decomposition, and fluvial processes such as streambank erosion (Gantes et al., 2011; Giorgi et al., 2014; Vilches et al., 2019).

Adjacent land-use changes of Pampean streams is another important stressor predominant in the region. In the last decades, floodplain area and wetland cover have been reduce due to advance of crop fields to the margins of streams and rivers, the expansion of urban areas without adequate planning, and uncontrolled real estate market speculation of surrounding lands (Amuchástegui et al., 2016; Borzi et al., 2020; Pintos, 2018). The development of large urbanization projects on lowlands has changed the topographic relief and indeed the superficial runoff in certain suburban areas, increasing the risk of flooding in nearby low-income districts (Pintos, 2012; Potocko, 2018). In fact, flooding events have exacerbate in the last decades, in particular at the Metropolitan Area of Buenos Aires. More than 1,075 flood events have been recorded from 1970 to 2012 in this area, with over 300,000 people being evacuated (Flores et al., 2020). Transport of fluvial sediments to coastal areas is also increased, associated to the increase in superficial runoff and increased peak flow (De Marco et al., 2020).

Recreational activities in Pampean streams are restricted to occasional fishing, mostly in suburban or rural areas, and the use of riparian zones as places for leisure or educative activities (Courtalón et al., 2019; Graziano et al., 2019; Guida Johnson et al., 2014). Recreational bathing is limited to few streams, mainly in urban areas out of the metropolitan area (Peluso et al., 2014, 2012). However, bathing is frequently discouraged due to low water quality and associated health risks (Kuczynski, 2016; Magdaleno et al., 2001; Peluso et al., 2016). Therefore, the impact of recreational activities on Pampean streams can be considered generally low compared to other anthropic activities, although it should be recognized that this issue was poorly addressed in the literature.

The co-occurrence of various stressors causes the decline of the ecosystem services provided by Pampean streams. Especially affected ecosystem services are those of support of biodiversity, habitat heterogeneity and nutrient retention (Capítulo et al., 2010; Cochero et al., 2016; Gantes et al., 2017, 2011; Giorgi et al., 2005; Granitto et al., 2016; Túnez et al., 2005; Vilches and Giorgi, 2010), and those of provisioning of water, fishes and freshwater mammals (Escosteguy, 2014; Bértora et al., 2018). Other authors have also reported the impairment of regulation services such as pollution and flood control (Booman and Laterra, 2019; Borzi et al., 2020; Cunha et al., 2020; Efron et al., 2014; Piccinini et al., 2015; Pozzobon et al., 2018; Re et al., 2019; Suárez and Lombardo, 2004), as well as cultural services (loss of aesthetic value, tourism and recreational activities) in some streams of the province (Guida Johnson et al., 2014; Peluso et al., 2011; Rotger, 2016; Ursino, 2012). Urbanization of natural places can lead to the destruction or impairment of their aesthetic value because the presence of protected areas stimulates the advance of urbanization near these areas, as in the case of "*naturbanization"* near Chascomús Lake (Giusti and Prados Velasco, 2013). In addition, agriculture is increasingly occupying the margins of the streams and this may affect the ecosystem services provided by the riparian zones, such as nutrient and pesticide removal and refuge for biodiversity (Capítulo et al., 2010; Álvarez et al., 2015; Stutter et al., 2019).

3.3. Environmental perception and watershed's governance system

Paintings and historical chronicles are a vehicle to study past environmental perceptions (Saarinen, 1974). Chronicles of the first Spaniards that arrived to the Pampean region described a hostile landscape, with fantastic animals and savage Indians (Brailovsky and Foguelman, 1992). Later, during the colonial period (XVI-XIX centuries), naturalists remarked the need of modifying natural ecosystems to improve them. These ideas were not only based on productive purpose but also on the ignorance of local flora and fauna (Brailovsky and Foguelman, 1992). Up to the XIX century, the Pampas were described as a desert and a dangerous territory due to the presence of Indians and thieves (Haigh, 1831; Head, 1827). The Campaign to the Desert (1878-1885), a massive military offensive against native people to control the region, was presented as the contrast between civilization and barbarity. The result of this campaign was the extermination of the original people of the Pampas.

The same beliefs are reflected in Argentine painting of the XIX century. Paintings that depicted Pampean waterbodies represent the plain as a homogenous landscape with short grasses, which do not agree with the descriptions of early chronicles. For instance, an English trader that traveled across the Pampas in 1817 said: "The appearance the country presented was that of a dreary flat, not a habitation to be seen, nor a tree, nor a shrub: it was covered with high grass, and full of marshes" (Haigh, 1831). Perhaps the best representation of the original Pampean landscape is an iconic painting titled "La vuelta del malón" ("The return of the Indian ride"; Figure 2). Painted by Ángel Della Valle in 1892, it represents a group of Indians returning to their tents and carrying their loot after attacking a village. In this desolate landscape, the stream was so realistically represented that it is possible to identify the macrophyte species on the margins (*Pontederia cordata* L.). The message of the painting is clear: nature is a threatening place where barbarians hide out after destroying civilization (again, civilization against barbarity).

When analyzing current environmental perceptions of Pampean streams by local communities, we found that perceptions of flood risk and water pollution was reported by groups associated to both urbanized and agricultural streams and rivers (Feijoó and Momo, 1991; Johnson et al., 2014; Prada and Penna, 2008; Sardi et al., 2012; Suárez and Lombardo, 2004). However, water pollution was considered a less important problem in rural environments, especially among farmers (Prada and Penna, 2008; Sardi et al., 2012). In addition, Guida-Johnson et al. (2014) observed that residents in urbanized areas perceived streams as somewhat dangerous and insecure due to crime. In accordance with previous research, these authors suggest that people relate environmental degradation with danger linked to social vulnerability. Denial is another response to environmental degradation of residents in the metropolitan region (Ursino, 2012). Therefore, it is not surprising that one third of people living close to the streams think that tubing (the hydraulic paradigm) is the most appropriate solution to these problems (Guida Johnson et al., 2014), which in fact only reinforces them (Graziano et al., 2019; Suárez and Lombardo, 2004). In addition, ecosystem services perceived by local communities were generally related to agricultural production, transport and water provision in rural streams (Sardi et al., 2012), and to recreation in urbanized streams. However, health risks associated to urban streams are not perceived by local communities in many cases (Peluso et al., 2016).

To summarize, it seems that natural Pampean streams are unconsciously perceived as “dangerous” systems that must be “domesticated” (or controlled), and that this perception is rooted in past beliefs. Therefore, local communities may disregard the intrinsic value of the streams and the ecosystem services provide by them, reinforcing human decisions and practices that impaired their ecological integrity.

On the other hand, watershed governance is structured at the Provincial and Municipal level, organized in 39 basin committees (ADA, 2020), with unequal implementation and social participation (Fernández Bouzo, 2014; Gutiérrez, 2008; Merlinsky, 2017). The main government structure that regulates watershed management practices is the Water Authority of the Buenos Aires Province, along with the provincial Ministry of Infrastructure and local municipalities. Inside basin committees, the main actors are the provincial and municipal authorities. In basin from rural areas, committees are more open to the participation of social actors (agricultural producers, local civil society organizations, researchers from scientific institutions), but without formal power sharing (Fernández Bouzo, 2014; Gutiérrez, 2008). Regarding decentralization, only two basin committees have autonomy, corresponding to the most visible polluted basins in the metropolitan area (Matanza-Riachuelo and Reconquista basins). The other committees depend on the Provincial Water Authority, and display a more uncertain, centralized and infrequent operation (Gutiérrez, 2008).

In general, the centralization of decision-making at the Provincial level, the lack of effective coordination between institutions (i.e., fragmentation), the predominance of a hydraulic management perspective, and the lack of an ecosystem-based view are the main features of the governance system (Graziano et al., 2019; Gutiérrez, 2008; Maidana et al., 2005; Palmer et al., 2002; Suárez and Lombardo, 2004). Basin committees operate discontinuously, and generally when they receive financial support from National or Provincial authorities, or when there are emergency situations such as flooding events (Pochat, 2005). Government structures have fragmented responsibilities, e.g., water quality, flooding and flow regulation, control of industrial effluents (Pace and Barsky, 2012). Moreover, a regulatory context for environmental protection laws abounds, since there are regulations at the national, provincial, and local level, which partially overlap among them (Gutiérrez, 2008; Rotger, 2016). However, in many cases environmental laws lack specific regulations or they are not designed with a conservationist criterion, as it is the case of the protection of riparian areas where a hydraulically perspective prevails (Giorgi et al., 2020).

4. KEY DRIVERS AND FEEDBACK REGIONAL LOOPS: EMERGENCE OF GILDED AND RIGIDITY TRAPS

Based on the previous characterization of the social-ecological system, we propose four regional feedback loops that can potentially explain the persistent degraded state of most of the Pampean streams (Figure 3). We also identified the key external drivers that foster their dynamics: a) the intensification of an agro-industrial model for the region; b) a command-and-control governance regime focused on a hydraulic perspective; c) the expansion of urbanization in lands adjacent to streams and rivers driven by real-estate market speculation.; and d) a persistent structural poverty at the metropolitan area that lead to the occupancy of surrounding areas.

Each one of these drivers promotes a reinforcing feedback loop modulating the occurrence of the multiple stressors outlined previously, and a cascade of effects over the ecosystems affecting their contributions to people and, as a consequence, to human well-being. They also influence environmental perceptions of stakeholders and local communities, and people attitudes and behavior. We distinguish two prevailing perceptions driven by these pervasive loops: 1) a denial perception of fluvial systems, contributing to their landscape invisibility (streams as unnecessary elements of the landscape); 2) a deep rooted negative perception, adopting a hydraulic perspective of them (streams as drainage pipes). Both kind of perceptions, as stated in section 2, reinforces current management practices, producing a persistent negative social-ecological state of urban and rural Pampean streams. On the other hand, some positive perceptions about Pampean aquatic environments may, in fact, impair their ecological integrity. For instance, people of high-income level move from urban settlements to gated communities due to the aesthetic value of natural environments. But these new urbanizations may alter the topography of the terrain and eliminate wetlands, impacting the fluvial environment and some associated ecosystem services, such as flood attenuation. This, in turn, may affect other social groups, increasing their negative perception of fluvial systems (Pintos and Sgroi, 2012). In the last section we will return to this idea when analyzing some features and limitations of our conceptual model.

The dynamics reflected in Figure 3, which is supported by empirical and conceptual evidence, highlights the existence of reinforcing feedback loops that lock-in the system in an undesirable ecosystem state. Based on this, we postulate the emergence of social-ecological traps as the mechanism that explain the persistence of stream ecological degradation. Different kind of social-ecological traps has been identified. “Rigidity traps” occur in social–ecological systems when institutions/actors become highly connected, self-reinforcing, and inflexible (Gunderson and Holling, 2002). A typical example of a rigidity trap are overly bureaucratic administrations that fail to acknowledge new information (Carpenter and Brock, 2008). Rigidity traps are also associated with lock-in situations, referring to technical systems in which a society becomes stuck in a particular technology that once established is very difficult to change (Haider et al., 2018; Laborde et al., 2016). Meanwhile, “gilded traps” describe situations in which social drivers (e.g., population growth, globalization, market demand) increase the value of natural resources as the ecological state moves closer to a tipping point of change without warning about the risk (Haider et al., 2018; Steneck et al., 2011). In turn, “social poverty traps” describe a situation in which people are unable to mobilize the resources to overcome chronic low-income situations, and thus they engage in a behavior that may reinforce their own poverty, becoming trapped in a stable or increasing poverty state (Cinner, 2009). Poverty traps are not considered a social-ecological trap because of their social character, but they can become part of the drivers of social-ecological traps (Brown, 2016). According to this, we suggest that feedback loops driven by a command-and-control regime and the persistent structural poverty in metropolitan areas of Buenos Aires are linked to rigidity and social poverty traps (Figure 3a and 3b), meanwhile the agro-industrial model and the presence of a real-estate market speculation of lands surrounding fluvial systems can be characterized as gilded traps (Figure 3c and 3d). Several studies analyzing the complementary dynamics of land use change, poverty and urbanization in Latin America provide support to this idea, including the analysis of causal loop diagrams as evidence of feedback loops (Graziano et al., 2019; Mirza et al., 2019; Rocha et al., 2019; Romero-Lankao & Gnatz, 2013; Zuberman, 2019). According to Haider et al. (2018), the persistence of social-ecological traps in the dynamics of the system may be identified by: 1) the duration spent in the undesirable state, and 2) the persistence of the state despite positive interventions. Next section provides further evidence of the presence of key drivers and feedback loop dynamics in a local case study. But see the Supplementary Material for a review of the proposed key drivers in several basin of the Pampean region.

5. LOCAL CASE STUDY: LUJAN RIVER BASIN

Together with Matanza-Riachuelo and Reconquista basins, the Luján River basin is one of the most important watersheds of Buenos Aires Province, covering an area of 2,690 km^2 with a total population of approximately 1,500,000 inhabitants. The main channel runs throughout eight municipalities and finally flows into the Río de La Plata Estuary. The river's feeding regime is pluvial and the average flow is 5.4 m^3 s^{-1}. It can be divided in three sub-basins with different slope and drainage. The upper course is 40 km-long and flows from the headwaters to Jauregui town, receiving the most important tributaries in terms of discharge (Moyano, Grande, Balta, and Ranchos streams). Historically, cattle raising prevailed in this area, but in the last 50 years cropland cover has increased by a factor of 10, covering currently about 60% of the upper section with transgenic soybean as predominant crop (Ruggerio et al., 2018). The middle course is 30 km-long and ends at Pilar city. This section is characterized by the presence of small and medium cities and horticultural production areas. The increase of transport pathways with Buenos Aires city during the 90's promoted the expansion of private country clubs and gated communities in this section. Finally, the lower course flows into the Tigre area of the Paraná Delta. Streams of the lower courses drain larger areas, albeit incompletely, covered by marshes and frequently floodable zones (Andrade, 1986; Sala, 1972). This area, which is closer to Buenos Aires city, had not been greatly inhabited until recently due to its floodable characteristics. However, urbanization is rapidly expanding following a real-estate market development because it is perceived as a natural area close to the city ("naturbanization"). The conjunction of considerable extensions of rural and urban areas along the basin, in addition to the presence of areas with high population density and marked inequalities related to land access and habitat conditions (Michelini and Pintos, 2016), makes this basin an interesting case to analyze the key drivers identified in the previous section.

In the Lujan river basin, we can identified the four feedback loops proposed for Pampean fluvial systems (Figure 3), as well as their specific drivers and stressors and the concomitant loss of ecosystem services. We identified several sections of the river network where the current operation of the four main drivers can be observed: intensification of the agro-industrial model, real-estate market speculation, structural poverty in urban areas, and command-and-control governance regime (Figure 4). It is important to highlight that the different types of feedback dynamics are not present concurrently throughout the entire basin. However, most of the impact of local stressors on streams located in the upper course will be transferred downstream to the whole fluvial network. Historical data allow us to analyze the persistence of these dynamics over time.

The first recurring dynamic in the basin is the intensification of agriculture in rural areas (Figure 4a). The basin has been progressively changing its agricultural matrix, replacing traditional livestock practices and fruit production by soybean crops. In 1970, only 2000 ha of soybeans were cultivated in the basin, but this value increased to 80,000 ha in 2002 and to 120,000 ha. in 2010 (Pengue, 2009; Ruggerio et al., 2018). The expansion of the agricultural cover has promoted the raising of livestock in feedlots where up to 500 animals are grouped in small spaces, each one producing 40 kg of manure per day (Pengue, 2009). Supporting evidence shows that feedlots located close to streams and rivers of the basin increase pollution levels of nutrients, pathogens and sediments (Sánchez Caro et al., 2012; Troitiño et al., 2010; Viglizzo et al., 2010). Furthermore, agricultural activities in the Luján River basin reduce the extent of natural riparian and wetland zones, and promote the modification of channel morphology and the input of nutrients and pesticides (Arreghistegui et al., 2016; Feijoó et al., 2012; Gantes et al., 2014; Peluso et al., 2013; Ronco et al., 2016).

In addition, market speculation has transformed low-cost land areas near rivers and streams into habitable areas, especially in zones close to cities (Figure 4b). This modality has expanded significantly in the last 30 years, being responsible for many transformations, especially in the lower course (Michelini and Pintos, 2016; Pintos, 2013; Pintos and Norodowski, 2012; Pintos and Sgroi, 2012). The process begins with the acquisition of floodplain lands situated close to urban centers and highways at low prices. Lands are then elevated to avoid the risk of floods, and parceled (Pintos and Norodowski, 2012). Finally, public utilities are provided, creating private residential areas for sectors of high socio-economic level (Ríos, 2005). Ninety gated communities were registered in the floodplain of the lower Luján River, occupying 7,700 ha and 22.5 km of the river margins (Fabricante et al., 2015; Pintos, 2017). In addition, 25 % of the surface occupied by private residential areas corresponds to artificial lagoons and channels (Pintos and Sgroi, 2012). Fabricante et al. (2015) estimated an increment of 13 gated communities per year in the lower basin that will cover 1,650 ha/year, if the same trend continues. The elevation of terrains and reduction of the river floodplain by private housing favor the damming during flood events, increasing flood level and residence time of water (Pintos, 2017). This situation may change the living conditions of inhabitants of nearby localities, who originally resided in the region, altering their way of life (Michelini and Pintos, 2016). In addition, gated communities promotes the densification of nearby localities because of the arrival of new inhabitants that provide services (as maids, gardeners, etc.) to the private residential areas (Pintos and Norodowski, 2012).

The third feedback loop is related to the structural poverty in urban areas faced by many residents of the Luján River basin, especially in the lower course where population density is higher (Figure 4c). The limited access to housing for low-income families leads to the development of unplanned and informal settlements on riparian areas, which generally lack basic utilities (Giorgi, 2007; Michelini & Pintos, 2016). The estimated population in the Luján River basin was 982,288 inhabitants in 2010, with an average density of 9.50 inhab/ha and a poverty rate of 54% (INDEC, 2010). Water supply and sewage systems are lacking in 80% of the basin area, but this is critical in the lower basin where there is the highest population density. There, only 22% and 9% of the population has access to drinking water and sanitary services, respectively (AySA, 2010). Moreover, in 70% of the basin area, less than 50% of the houses have septic tanks, increasing the risk of a direct discharge to groundwater or even surface waters (Baxendale and Buzai, 2017). As a result, the input of raw sewage and industrial effluents into urban areas of the lower basin greatly impairs the quality of river water (Peluso et al., 2013; Sánchez Caro, 2010; Sánchez Caro et al., 2012), affecting its fluvial structure and function, and consequently the ecosystem services provided by the Lujan river (Giorgi et al., 2020).

Finally, the historical management practices in the Lujan river basin were based on a hydraulic perspective following a command-and-control governance system, centralized in the Provincial Authority and dominated by the Public Works or Infrastructure Ministry (Charriére, 2017). Although in the last years a basin committee has been formed through the Provincial Water Authority, in practice it has the same failures as the other basin committees of Buenos Aires Province (section 3.3). The current administration of the watershed is characterized by the superposition and fragmentation of competencies between public institutions (Ferro & Minaverry, 2019). In addition, local water regulations and management actions do not consider the conservation of natural environments or their ecosystem services (Potocko, 2018): e.g., due to the advance of planned residential areas on the floodplains, there has been a drastic transformation of the natural terrain through embankments, landfills, excavations, barriers and refining, mainly in lowland and wetland areas (Figure 4d). Moreover, typical management actions taken in the basin to control river overflow were hydraulic interventions like ditches and small dams (Malagnino, 2015). Agricultural producers also generates a network of artificial channels that end in streams and the Luján river, increasing their flow and contaminant load and reducing their nutrient retention capacity, among others effects (Amuchástegui et al., 2016;

Ronco et al., 2016). The increase of flood risk is another consequence of this paradigm, in particular in the metropolitan area of the basin (Flores et al., 2020). For instance, at least 15 floods were registered in the city of Luján, on the middle course of the Luján River basin, with an increase of water level between 4 and 6.7 m (Grosso Cepparo and Valverde, 2018).

From a social-ecological perspective, the transformations undergone in the Luján River basin have led to a change of attraction domain, where the ecosystem is progressively moving away from situations of sustainable stability to undesirable ecological states, in close accordance with the emergence of social-ecological traps. The persistence of an undesirable ecological state of the Luján River basin can be traced out in the literature, showing a deterioration with time (Ruggerio et al., 2018; Sánchez Caro, 2010; Sánchez Caro et al., 2012). In addition, socio-environmental perception and attitudes of local residents evidence the exacerbation of the impact of flooding events in the imaginary of people living in the watershed, but also show a denial to recognize other environmental problems such as urban or agricultural pollution in the basin (Feijoó & Momo, 1991; Luchetti, 2008). Although there are some civil society organizations that demand for ecological management alternatives for the basin (Luchetti, 2008), in general the main credible interventions for residents and policymakers are hydraulic modifications such as channelization and piping, supporting evidence of feedback loops to maintain the status quo in management actions (Ferro and Minaverry, 2019). The lack of social recognition of ecosystem benefits, and the prevailing perception of ecosystem disservices, are the main factors explaining social behavior (Carballo, 2014; Luchetti, 2008).

6. BREAKING THE TRAPS TO IMPROVE MULTIPLE STRESSORS MANAGEMENT IN FLUVIAL ECOSYSTEMS

The application of our conceptual model to Pampean streams of Buenos Aires Province has shown the emergence of different social-ecological traps, suggesting new ways of analyzing the impact of multiple stressors on river ecosystems. Two kinds of traps were identified: rigidity traps that generates a lock-in technocratic system based on a hydraulic paradigm and a command-and-control governance style, and gilded traps related to the predominance of economic and financial market forces controlling current land use change. In addition, a negative environmental perception of streams, which emerges from denial attitudes towards environmental problems and a poor comprehension of the benefits of rivers and streams for societies, is strengthened by their continuous degradation, reinforcing decisions that deepen their impairment.

In the last years, several authors analyzed different pathways to break these dynamics in different social-ecological systems (Baker et al. , 2018; Cinner, 2011; Enqvist et al., 2016; Graziano et al., 2019). We take here the proposal of Meadows (1999) about the perspective of “leverage points” to deal with transformative change, i.e., the identification of different levels of intervention to influence the behavior of a system. Meadows (1999) characterized them as ‘places’ or points in complex systems where a small shift may lead to fundamental changes in the system as a whole, distinguishing different levels of effectiveness and feasibility around them. Shallow leverage points are desirable modifications that do not produce a lasting change in the entire basin, such as conserving some stretches of the streams or reducing the use of agrochemicals. On the contrary, deep leverage points are those modifications that produce changes on the general perspective, as an adequate urban planning or a change in the management paradigm. According to Fischer & Riechers (2019) the leverage point perspective has several advantages to influence transformations; in particular, the identification of shallow and deep system changes and, maybe more important, the potential bridges between them. Shallow leverage points may improve the ecological quality of the basin, and doing this they can offer better conditions to achieve deep leverage points. But the achievement of shallow leverage points do not prevent the action of external drivers or the maintenance of undesirable feedback loops, whereas deep leverage points do so. According to these considerations, we suggest places to intervene in the social-ecological Pampean fluvial dynamics, categorized in four realms of influence (Table 2; Abson et al., 2017). These realms are: stream ecosystem features or parameters (e.g., mitigate or reduce point pollution sources); disruption/improvements of system processes or feedbacks (e.g., improve stream cleaning and sanitation practices); modification of social structures or institutions (e.g., strengthening of local actors, foster alternative governance systems); and the promotion of changes in underlying values (or worldviews) affecting stream management (e.g., shift to an ecosystem-based management paradigm).

Some reflections should be made on this analysis. First, while shallow leverage points can be thought of as very surficial elements of the system, we suggest that levels of intervention and derived pathways of action should be planned in an integrative fashion, recognizing that the interaction of shallow and deep processes can synergize transformative changes (Fischer and Riechers, 2019; Tourangeau and Sherren, 2020). For example, knowledge co-production with local actors can promote specific innovative interventions to increase stream biodiversity and, at the same time, strengthen the political influence of local environmental actors on watershed governance (Graziano et al., 2019).

On the other hand, human responses to traps are very diverse, ranging from conformity and resignation, to innovation and rebellion (Boonstra et al., 2016). The leverage point perspective gives a systemic framework indicating places and levels to intervene, but does not tell the particular actions to be undertaken. Innovative experiences should be empowered, combining individual pro-environmental responses, imitative behavior and leadership with collective actions, thus influencing social conditions and opening windows of opportunity for transformative changes (Bai et al., 2020; Olsson et al., 2006; Pereira et al., 2018). Bottom-up pressures originating from civil society organizations can be thought as a general mechanism to promote transformative changes and should be fully addressed as a potential mechanism for scaling-up interventions (Elmqvist et al., 2019; Lam et al., 2019). Moreover, in addition to favoring polycentric governance frameworks, unequal power distribution among civil society organizations, academics, and governmental policy-makers should be prevented, if a transparent resolution to potential conflict among stakeholders' vision in a participatory framework is to be established (Ayala-Orozco et al., 2018; Crona and Bodin, 2010; Fortnam, 2019; Mancilla García and Bodin, 2019).

7. LIMITATIONS OF THE MODEL

The model deserves some considerations about its validity, both in general and when it is applied to a particular case. One of the main simplifications of the model is the lack of recognition of confronting perceptions about the fluvial landscape, and their relationships with the management outcomes. In addition, the model do not consider that social access to ecosystem services can be unequal due to power relationships in the social structure (Berbés-Blázquez et al., 2017, 2016; Ernstson, 2013). We mentioned that the loss of ecosystem services can trigger positive or negative changes in people perceptions and attitudes about the environment. However, the model do not included mechanisms to explain management outcomes that can emerge from confronting perceptions, which may emerge from unequal use or access to ecosystem services (Asah et al., 2014). In the regional case, this was exemplified with the identification of positive perceptions associated with the urbanization of natural lands ("naturbanization"). In this sense, further analysis should address the heterogeneity of the social structure, the unequal access to ecosystem costs and benefits (and its impact on environmental perceptions), and the effect of power asymmetries among social groups. This may help to understand the resulting feedbacks on management actions. Other crucial issue is to consider the challenges and limitations of alternative governance regimes (Fortnam, 2019; Morrison et al., 2019). Finally, the introduction of the concept of ecosystem disservices in the conceptual model can enhance the interplay between perceptions and management outcomes. Some authors have noted that, under certain situations, ecosystem disservices can be potentially more relevant in influencing people's behavior than ecosystem benefits (Blanco et al., 2019).

In addition, further analysis can be done to give additional support to the underlying hypotheses.

One challenge is the inherent difficulty to identify causal mechanisms in complex social-ecological systems (Biesbroek et al., 2017; Villamayor-Tomas et al., 2020). The use of quantitative and qualitative process-tracing tools can add additional evidence of causal relationships between the components of the feedback loops (Boonstra and de Boer, 2014; Meyfroidt, 2016; Schlüter et al., 2019; Uden et al., 2018; Villamayor-Tomas et al., 2020). Studies on specific environmental conflicts related with the identified feedback dynamics can also provide complementary evidence of the persistence of undesirable states (Scheidel et al., 2017). Finally, it may be necessary to identify proxies of the main key drivers, such as price of parcels adjacent to fluvial natural environments in the case of real-estate market speculation, or soybean export levels for the agro-industrial driven feedback loop. Proxies can be then related to indicators of watershed ecological integrity (e.g., water quality or riparian indexes) to test the underlying hypotheses. However, it must emphasized that current data accessibility and availability can constraint this type of analyses, particularly in the Global South, highlighting the relevance of our work to open new opportunities of research.

8. CONCLUSIONS

Our conceptual study incorporates the well-known impact of fluvial stressors into an integrative systemic model, including the social, political and natural components of the system. Considering the possibility that fluvial ecosystems can be part of a social-ecological trap dynamics can offer new perspectives for their sustainable management. We believe that the present framework can be extended to other aquatic systems and geographies. In particular, it can be applied in other countries of the Global South, which can face similar situations and are generally underrepresented in the global literature (Wantzen et al., 2019). Finally, we consider that our study opens some questions for further explorations, such as the feedback connections between environmental perception and decision-making attitudes in specific governance configurations, the interaction between shallow and deep leverage points as a driving force for systematic change, and the application of these principles into concrete political actions, which may emerge from the science-policy-society interface (van Kerkhoff and Lebel, 2015). We believe that engagement on these topics will have important consequences for the sustainability of the world's river ecosystems.

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FIGURE LEGENDS

Figure 1. General framework of the self-reinforcing feedback between social and natural domains of a fluvial system.

Figure 2. Historical roots of the negative socio-environmental perception of Pampean streams. (A) “La vuelta del malón” by Ángel Della Valle (1892), (B) detail: the stream with the macrophyte *Pontederia cordata*, which is shown in the insert. The painting is exhibited at the National Museum of Fine Arts of Buenos Aires (Image from Google Arts Project).

Figure 3. Regional reinforcing feedbacks at Pampean streams and the dynamics derived from four key external drivers: A) intensification of a regional agro-industrial model, B) expansion of urbanization in lands adjacent to streams and rivers drive by real estate market speculation, C) command-and-control governance regime with a hydraulic perspective, D) persistence of structural poverty in metropolitan areas.

Figure 4. Examples of regional drivers impacting on the Luján River Basin, as case study. A) Agricultural intensification in the middle course, with the decrease of natural riparian areas, greater drainage network to tributary streams, and increase of croplands. B) Emergence of private urbanizations and gated communities (San Sebastian estate). C) Dense informal settlements in the lower course. D) Predominance of hydraulic works to attenuate floods (Gobernador Arias channel in the lower course).

Table 1. Identification of main stressors impacting Pampean streams at the Buenos Aires Province, and affected ecosystem services (according to Collins et al., 2011)

STRESSORS

Pollution loads (pesticides, domestic, sewage and industrial effluents, solid waste)	Aparicio et al, 2013; Ceballos et al, 2018; Casares & de Cabo, 2018; Cirelli & Ojeda, 2008; Efron et al, 2014; Giorgi & Malacalza, 2002; Hunt et al., 2016; Iturburu et al., 2019; Luppi et al., 2015; Peruzzo et al., 2008; Rimoldi et al., 2018; Salibian, 2005
In-stream channel and riparian modifications (channelization, dredging, impoudments, reduction of aquatic macrophyte cover, introduction of invasive species)	Bazzuri et al., 2018; Cochero et al., 2016; Fernández et al., 2017; Graziano et al. 2019; Licursi & Gómez, 2009; Maidana et al., 2005; Paz et al., 2018; Potocko, 2018; Pozzobon et al, 2018; Scarpati & Capriolo, 2013;

Adjacent land-use changes (reduction of wetland and natural cover, loss of lateral connectivity)	Amuchástegui et al., 2016; Borzi et al., 2020; Guida Johnson & Zuleta, 2019; Michelini & Pintos, 2016; Pintos, 2018
IMPAIRMENT OF ECOSYSTEM SERVICES QUALITY	
Provisioning (fishing, hunting and trapping)	Bértora et al., 2018; Escosteguy, 2014; Túnez et al., 2005
Regulation (pollution control, disease control, flood control, storm protection)	Booman & Laterra, 2019; Cunha et al., 2019; Borzi et al, 2020; Efron et al, 2014; Piccinini et al., 2015; Pozzobon et al., 2018; Re et al., 2017; Suárez & Lombardo, 2004; Troitiño et al., 2010
Cultural (aesthetic, recreational)	Giusti & Prados Velasco, 2013; Guida Johnson et al., 2014; Peluso et al., 2011; Rotger, 2016; Ursino 2012
Support (water, oxygen, biodiversity, habitat heterogeneity)	Capitulo et al., 2010; Cochero et al., 2016; Gantes et al. 2011; Gantes et al. 2017; Giorgi et al., 2005; Granitto et al., 2016; Túnez, et al. 2005; Vilches & Giorgi, 2010

Table 2. Breaking socio-ecological traps: suggested leverage points to transform the fluvial social-ecological system and to foster sustainability.

SHALLOW LEVERAGE POINTS	**Parameters** (variables or features of the system)	Reduce nutrient and contaminant loads Reduce hydraulic changes on streams Increase biodiversity Increase habitat heterogeneity
	Processes/Feedbacks (interaction between elements of the SES system)	Increase self-purifying capacity of streams Improve stream cleaning and sanitation practices Improve socio-economic and infrastructure conditions of local community

DEEP LEVERAGE POINTS	**Design** (social structure and institutions)	Strengthing of local environmental actors (e.g., co-producing transformative spaces) Improve access to information about the benefits of rivers and streams to the local community Promote polycentric participatory governance systems with effective power distribution
	Intent (underpinning values, goals, and world views of actors)	Foster changes to an ecosystem based management paradigm of rural and urban streams within stakeholders Increase the knowledge about alternative ecocentric productive systems

Declaration of competing interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Credit author statements

MG, CF y AG conceive the study. MG developed the conceptual model with significant contributions of CF and AG. AG and CF collected and review background information on Pampean streams and rivers. The three authors integrate the gathered information in the model. MG wrote the manuscript, with the participation of CF. AG commented on and contributed to revising draft versions.

Graphical abstract

HIGHLIGHTS

- Integrating social and natural domains of stream management is still challenging
- We offer a general framework to understand their social-ecological dynamics
- Pampean streams are subject to self-reinforcing feedbacks
- Emergence of social-ecological traps constrains their ecological integrity
- Key regional governance drivers force their self-reinforcing dynamics

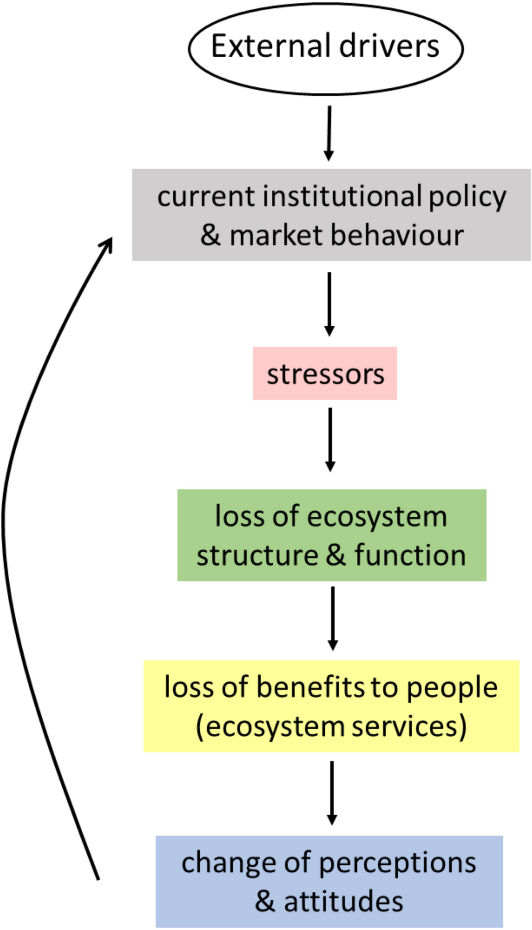
External drivers
current institutional policy & market behaviour
stressors
loss of ecosystem structure & function
loss of benefits to people (ecosystem services)
change of perceptions & attitudes

Figure 1

Figure 2

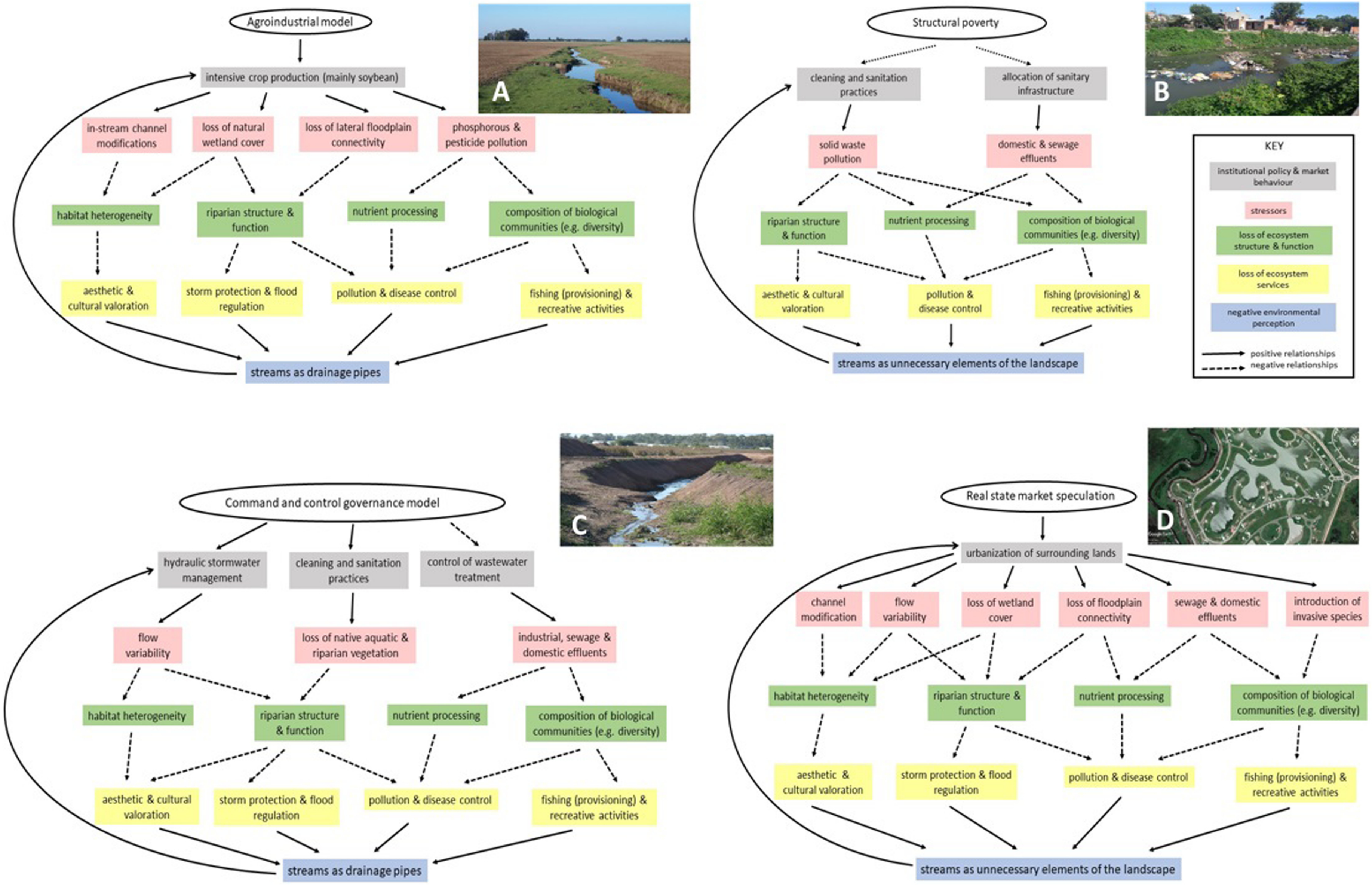
Agroindustrial model
intensive crop production (mainly soybean)
in-stream channel modifications
loss of natural wetland cover
loss of lateral floodplain connectivity
phosphorous & pesticide pollution
habitat heterogeneity
riparian structure & function
nutrient processing
composition of biological communities (e.g. diversity)
aesthetic & cultural valoration
storm protection & flood regulation
pollution & disease control
fishing (provisioning) & recreative activities
streams as drainage pipes
A
Structural poverty
cleaning and sanitation practices
allocation of sanitary infrastructure
solid waste pollution
domestic & sewage effluents
riparian structure & function
nutrient processing
composition of biological communities (e.g. diversity)
aesthetic & cultural valoration
pollution & disease control
fishing (provisioning) & recreative activities
streams as unnecessary elements of the landscape
B
KEY
institutional policy & market behaviour
stressors
loss of ecosystem structure & function
loss of ecosystem services
negative environmental perception
positive relationships
negative relationships
Command and control governance model
hydraulic stormwater management
cleaning and sanitation practices
control of wastewater treatment
flow variability
loss of native aquatic & riparian vegetation
industrial, sewage & domestic effluents
habitat heterogeneity
riparian structure & function
nutrient processing
composition of biological communities (e.g. diversity)
aesthetic & cultural valoration
storm protection & flood regulation
pollution & disease control
fishing (provisioning) & recreative activities
streams as drainage pipes
C
Real state market speculation
urbanization of surrounding lands
channel modification
flow variability
loss of wetland cover
loss of floodplain connectivity
sewage & domestic effluents
introduction of invasive species
habitat heterogeneity
riparian structure & function
nutrient processing
composition of biological communities (e.g. diversity)
aesthetic & cultural valoration
storm protection & flood regulation
pollution & disease control
fishing (provisioning) & recreative activities
streams as unnecessary elements of the landscape
D

Figure 3


A
Luján River
Google Earth
©2020 Google
Image © 2020 Maxar Technologies
1 km
N
B
Luján River
Google Earth
Image © 2020 Maxar Technologies
1 km
N
C
Luján River
Google Earth
Image © 2020 Maxar Technologies
100
D
Paraná River
Gob. Arias Channel
Luján River
Google Earth
Image © 2020 Maxar Technologies
4 km
N

Figure 4