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ADVANCES IN RECEIVING WATER QUALITY MODELS

Application of Systems Thinking to the assessment of an institutional development project of river restoration at a campus university in Southern Brazil

Fabiane Andressa Tasca[1] · Roberto Fabris Goerl[2] · Gean Paulo Michel[3] · Nei Kavaguichi Leite[4] · Djesser Zechner Sérgio[5] · Saman Belizário[1] · Jakcemara Caprario[1] · Alexandra Rodrigues Finotti[1]

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Abstract

Rapid urban growth and high population density have become a problem for urban water resources, especially in developing countries. In general, the pollution of rivers and degradation of ecosystems are the result of both management failures and lack of sewage treatment. River restoration appears as a solution to improve this scenario, but it is common for there to be an absence of a systemic vision in these projects. Thus, this work analysed one of these projects as an initial approach to create coherent (qualitative) shared perspectives on the same problem. This project was developed in a Brazilian university territory in response to a Public Civil Action. Rivers within the university surroundings are degraded due to sewage disposal and wastewater pollution from external and internal sources within the university, but the programme actions contemplate only interventions within the perimeter of the university while excluding the other parts of its watershed. We analyse this problem under a Systems Thinking approach by using causal loop diagrams, being clear that ecosystems cannot be reduced to territorial limits only. The systemic map shows many actions that contribute to the water quality degradation, with emphasis on illegal dumping of wastewater (sewage) and land use change in the upstream areas prior to the university. Point measures are palliative and do not guarantee the quality of river water. Regulation of impervious surfaces and correct disposal of wastewater can improve the current panorama, but greater integration between stakeholders and other key actors is required.

Keywords Causal loop diagrams · Mental models · Receiving waters · Socio-ecological system · Urban water management · Water governance · Water resources

Introduction

Urban water problems in developing countries require immediate attention due to their nature and severity. Rapid growth and high population density have become a problem for urban water resources (Stephenson 2001). This is due to the usual practice of urban drainage control, which is treated from a hygienist perspective. It is based on the assumption that "drainage is necessary" to drain stormwater, often mixed with sewage, as quickly as possible. Most of the effluents discharged along the watershed have urban rivers as their final destination. This is seen in most developing countries, where sanitation is still precarious and there are deficits in sewage collection and treatment (Tasca et al. 2017). This leads to degradation of the receiving waterways and their ecosystems, contributing to an increase in water challenges, instead of considering wastewater as an economic and socially precious resource (Wichelns et al. 2015). So, the transport of these

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Responsible editor: Philippe Garrigues

✉ Fabiane Andressa Tasca
fabitasca@gmail.com

[1] Department of Sanitary and Environmental Engineering, Federal University of Santa Catarina, Trindade, Florianópolis, Santa Catarina, Brazil

[2] Department of Geosciences, Federal University of Santa Catarina, Trindade, Florianópolis, Santa Catarina, Brazil

[3] Department of Hydraulic Works, Institute of Hydraulic Research, Federal University of Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil

[4] Department of Ecology and Zoology, Federal University of Santa Catarina, Trindade, Florianópolis, Santa Catarina, Brazil

[5] Federal University of Santa Catarina, Trindade, Florianópolis, Santa Catarina, Brazil

pollutants by urban stormwater into receiving waters is now widely recognized as a significant environmental threat to sustainable development (Vlotman et al. 2007) and is one of the major challenges for environmental policy in the twenty-first century (Pahl-Wostl et al. 2008).

In order to reduce such impacts, several solutions for stormwater management (SWM) have been adopted and applied worldwide (e.g. best management practices, stormwater control measures, sustainable drainage systems, and river restoration techniques, amongst others). They are measures that aim to preserve, restore, and create green spaces (Fletcher et al. 2014), being used to store or treat urban stormwater runoff, reduce flooding, remove pollution, and provide other amenities (Ellis et al. 2004). Amongst these solutions, river restoration is an increasingly popular management strategy for improving the physical and ecological conditions of degraded urban streams (Whol et al. 2005, Bernhardt and Palmer 2007). In addition, rivers have been reintroduced as living elements in the urban landscape, improving both the health of streams and the quality of life of the inhabitants (Araújo et al. 2017). However, the traditional restoration techniques have not achieved the desired results. Johnson et al. (2019) pointed out that river management approaches based only on physical science have proven to be unsustainable and unsuccessful. This statement is grounded in the fact that river problems like flood hazards, water scarcity, and channel instability have not been solved and the deterioration in river environments has reduced the capacity of rivers to continue meeting the needs of society.

The task of analysing and proposing solutions for river restoration in urban areas is complex. It has multiple variables that are not always manageable and requires interaction between the different agents, such as those responsible for land use, landscape, protection of the aquatic environment, and flood control (Loucks and Jia 2012). In many cities, there is poor interaction amongst these stakeholders, which act predominantly in a disjointed manner. Consequently, these problems and possible solutions are performed in a limited way. This type of fragmented conception is reproduced in the most varied organizational models: politics is separate from administration and planning is separate from execution, besides the separation between those who think and those who actually act. Many problems in water management are associated more with governance failures than with the resource base (Bakker et al. 2008) or technological limitations, since human actors typically tend to reduce the complexity and dimensions if they are confronted with a problem to be tackled (Sterman 2000).

Critical voices have pointed out the need for a radical paradigm shift in order to avoid the causes of failure of prevailing environmental resource management approaches: mechanistic and technocratic strategies that neglect complexity and the human dimension (Pahl-Wostl et al. 2010). Typical water-resource planning and management approaches are based on methodologies that ignore feedback and adaptations amongst the natural, social, and infrastructure systems (Giacomoni et al. 2013). In this way, few publications are available that explicitly connect these spheres of governance (van den Brandeler et al. 2018). When analysing environmental resources, it is impossible to think of them as isolated disciplines, since a considerable range of collective benefits arise from the use of water resources. Rivers are goods that belong to the whole community (Kondolf and Pinto 2017), so a broader and more inclusive approach is needed.

Therefore, scientists, environmentalists, and concerned citizens have called for holistic and adaptive approaches to address environmental issues. One of these holistic approaches is given by Systems Thinking, where “everything and everyone is interconnected, interdependent and interrelated” (Capra, 1997). It offers not only a set of tools but also a framework as a systematic whole (Anderson and Johnson 1997) instead of analysing its parts, ensuring that they are functioning and are related properly together to serve the purposes of the whole (Jackson 2003). Applying Systems Thinking is an effective approach that encourages an understanding of the full context and wider environment and this approach can be applied in almost any domain (Mingers and White 2010). It provides a basis for sustainable and multiple resource use by facilitating multidisciplinary planning and by creating an effective communication interface between scientists, citizens, and policy makers (Grant 1998).

In order to verify how systemic thinking has been approached in urban water management in a representative developing country (Brazil), an institutional development project (IDP) that was proposed to restore a degraded river was analysed. This project has been developed by the Water Study Nucleus of the Federal University of Santa Catarina (NEA/UFSC) and was imposed as a result of a Public Civil Action in order to limit and potentially reverse damage to receiving waters and associated ecosystems (Pompeo 2017). These streams are degraded due to the input of untreated sewage, polluted wastewater, and erosion from both external and internal sources. However, the programme has been implemented only within the campus area, which represents only a small area (18%) of the entire watershed. Thus, different experts sought to answer whether this approach could be effective in resolving all the previously mentioned problems. For this purpose, a long literature review was necessary to enable the team, in which the roots of systemic thinking and the characteristics of systems were addressed, with the core approach being to understand the current dynamics of this degraded river. To answer this, a conceptual model (systemic map) that can express the collective understanding obtained by different insights about the processes governing the analysed system is generated and discussed. In this context, the present work is an answer to the concerns of Pinter et al. (2019) that most river research still operates within home-grown local paradigms and that the main focuses are the USA, Canada, Europe, and China. Thus, besides presenting a new approach to river management, the present paper shows a research developed in the context of South America reality. It is hoped that this study can provide practical guidance to decision makers and professionals on the importance of systemic thinking in river restoration projects.

Systems Thinking

This section describes our Systems Thinking approach as well as the project context in which it was applied.

Background—a brief overview

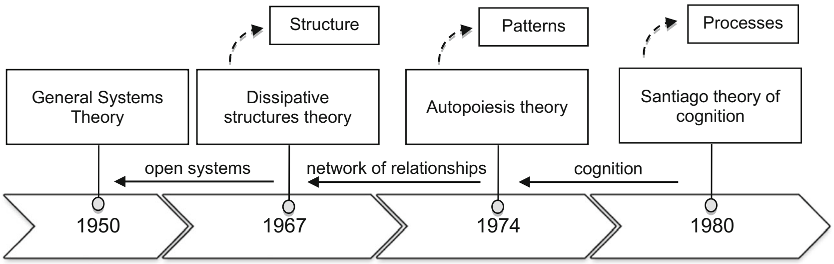
Systems Thinking consists in the ability to understand systems according to the General Systems Theory (GST) approach and is formed from the knowledge and characteristics of systems (Fig. 1). The fundamental concepts of Systems Thinking were developed during the 1920s in three different fields: organismic biology, Gestalt psychology, and ecology. In all of these fields, scientists explored living systems, that is, integrated wholes whose properties cannot be reduced to those of smaller parts, where "everything and everyone is interconnected, interdependent and interrelated" (Capra 1997). So, a system is a regularly interacting or interdependent group of units forming an integrated whole (Von Bertalanffy 1969), making sense of the interrelationships between system components to understand what drives the dynamic behaviour of the system, that is, the changes in stock and flow variables or even of the structure or purpose of the system over time (Sedlacko et al. 2014). The application of this concept across many other disciplines was recognized by Von Bertalanffy, in "An Outline of General Systems Theory" in 1950, in which he proposed principles he considered valid for all systems.

In the following decades, GST has been enhanced to handle the enormous complexity of living systems, which were recognized as open systems by Prigogine (1967) in his theory of dissipative structures. He was intrigued by the fact that living organisms were able to maintain their life processes under conditions far from equilibrium. This state was stable and might even evolve when the flow of energy and matter through them increased, going through processes of instability and transforming structures into new ones of increased complexity (hence dissipative structures). The study of emergent properties suggested that they offer analogues for living systems due to internal self-reorganization, but the connection between it and life was not known.

As Systems Thinking is considered in terms of relationships, a shift from the parts to the whole is needed and requires a shift of focus from objects to relationships. Understanding relationships is not easy, because operative pathways are hidden and virtual (Patten 2014). Relationships cannot be measured and weighed; relationships need to be mapped. Relationship mapping makes it possible to find certain configurations that occur repeatedly, that is, based on patterns. So, the study of relationships leads to the study of patterns. There are some contributions in this area. One of them was brought by Varela et al. (1974), who understood that the key to understanding these processes lay in understanding the organization of life. They described the pattern of organization of a living system as a network of relationships in which the function of each component is to transform and replace other components of the network. They called this pattern "autopoiesis", which represented further developments in the field of GST. The network is produced by its components and in turn produces those components. The authors suggest that autopoiesis is a general pattern of organization common to all living beings, regardless of the nature of its components, and is fundamental to the understanding of the living form. However, autopoiesis concerns the organization of living systems (a visual pattern) but does not provide information about the physical characteristics of its components. For this, the study of systems structure is also necessary and involves describing their actual physical components; that is, the pattern of organization can only be recognized if it is embodied in a physical structure.

At the same time, an understanding of the living structure is also necessary to comprehend the ongoing processes that occur in a system. So, the process criterion of life is the link between patterns and structure. This process was described by Maturana and Varela (1980) through the Santiago theory of cognition, a direct consequence of the theory of autopoiesis. Its central insight is the identification of cognition, the process of knowing, with the process of life. In other words, cognition is considered as the ability to adapt in a certain environment

Fig. 1 Timeline of Systems Thinking formulation and some contributions to this theory



and involves perception, emotion, and behaviour processes. The continuous interaction between the system and its environment can trigger perturbations, and the system uses these processes (ontogeny) to adapt to them (structural coupling). Structural coupling is always mutual; both organism and environment undergo transformations in and through their ongoing interactions (Introna 2007). The system only stops adapting when it experiences destructive interactions. An understanding of life processes is perhaps the most revolutionary aspect of the emerging theory of living systems, incorporating a systemic conception of life, mind (or cognition), and consciousness in GST. For the first time, a scientific theory unified mind, matter, and life (Capra, 1997).

These contributions form the main axiom of systemic thinking, in which the behaviour of the system is latent in its structure; that is, it is through the structure of interconnections between their elements that systems produce their own behaviours over time and that the actual function or purpose of the system comes into being (Meadows 2008). In short, living systems constitute autopoietic networks with dissipative structures and cognitive systems. In this way, for a comprehensive understanding of living systems, studies of pattern (or relationships, order, quality), structure (or constituents, matter, quantity), and process criteria are needed. There is a need to bring back Systems Thinking more generally to water resources planning and management because of the increasing complexity, scope, and urgency of environmental issues. However, GST is more than just a collection of theories; it is also an underlying philosophy, serving as a bridge for interdisciplinary dialogue between autonomous areas of study. This philosophy brings the role of structure in the construction of adverse conditions encountered, recognizing the existence of powerful but unknown laws that operate in sensitizing human actions to the circularity of nature in the world.

System delineation

Several authors seek to understand what are the requirements or basic structures of a system. Every system is delineated by its spatial and temporal boundaries, surrounded and influenced by its environment, described by its structure and purpose, and expressed in its functioning (feedback). All these analyses are performed by one or more observers, who impose their world view (ontogeny) on this system (Fig. 2). For this reason, there are some key concepts in the GST: the system, boundaries, environment (and its input and output in a given system), feedback, and observers (Alves 2012), which are briefly explained below.

System Systems are generalizations of reality. Systems theory views the world as a complex system of interconnected parts, where its delineation is arbitrary since one universe is always part of a larger one. A system must be defined considering the entity whose interactions we want to know. A system can be represented by its upper (super-system) and lower (sub-system) levels (such as a sub-basin that is part of another, larger basin), characterizing the hierarchy of the system (Alves 2012). There are many types of systems such as bioenergetic, biological, control, cultural, ecological, economic, engineering, psychological, thermodynamic, social, and so on, giving rise to other theories (e.g. chaos theory, dynamical systems theory, and complex systems).

Boundaries These are barriers that define a system and distinguish it from other systems in the environment. They make it possible to choose which entities are inside and/or outside the system, as part of the environment. Within the boundary of a system, three kinds of properties can be found: elements (parts that make up the system), attributes (characteristics of the elements that may be perceived and measured), and relationships (associations that occur between elements and attributes—i.e. input and output). The state of the system can be defined by determining the values of these properties (Pidwirny 2006).

Environment Also known as the surroundings, neighbourhood, or environ, the environment is the remainder of the universe that lies outside the boundaries of the system. The interactions between systems and their environments are categorized as relatively closed (where there are exchanges of energy but not matter) and open systems (where there are exchanges of matter and energy). Most systems are open systems (Von Bertalanffy 1950). All living forms must adjust to conditions imposed on them by their environments, but life in

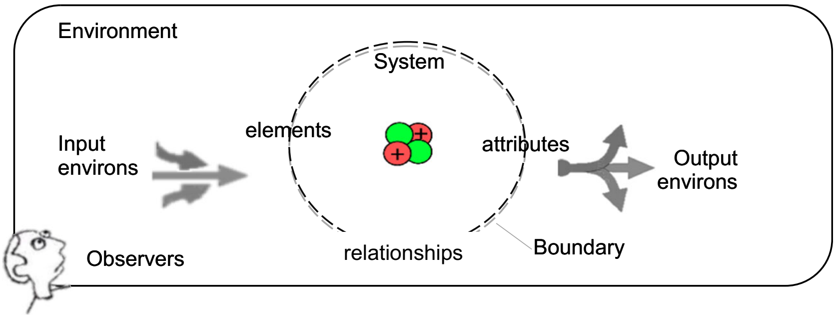


Fig. 2 Representation of a system delineation

turn modifies, in various ways, these conditions. Presently, five areas of environ analysis have been developed: pathways, throughflows, storage (standing stocks), utility, and distributed control (Patten 2014).

Feedback This is a control process to keep the system in balance, where loops back to influence the system component emitting the signal or initiating the mechanism or process. Many ecological systems can exist in different self-organizing configurations or regimes, and each of these different configurations provides a state of the system (Biggs et al. 2015). The state of a system is typically some kind of equilibrium state and if the current system configuration produces a desired set of ecosystem services (taking into account diverse stakeholder needs), this typically involves maintaining the current system configuration. In response to changes in an environment, the system state may change and acquire an undesirable configuration. In this situation, it may be necessary to weaken the feedback and controlling variables that keep it there in order to restore a previous regime or transform it into a new configuration that produces a more desired set of ecosystem services (Walker et al. 2004). This involves identifying and managing the key controlling variables and feedback that underpin and control the configuration of the system (Biggs et al. 2015).

Observers A system comprises multiple views and a model is required to describe and represent all these views. These views are interpreted by one or more observers in the light of their individual experiences.

The identification of these requirements represents a model of the system, an abstraction to facilitate the design and/or the analysis of systems. A model is fundamental for understanding the structure and dynamics of a given system, being a useful simplification of a more complex reality that makes it possible to predict how nature works. Each model is designed with a specific purpose in mind. In this sense, systems transcend the subject/object boundary by connecting relevant elements of individuals, social systems and the natural environment through pathways and feedback loops (Sedlacko et al. 2014). Types of system mapping include the following: graphs of behaviour over time (also called reference modes), iceberg models, causal loop diagrams (CLDs), connected circles, stock-and-flow diagrams, system archetypes, computer simulation software packages, and microworlds (Anderson and Johnson 1997; Jackson 2003). CLDs, also known as feedback loops, are based on principles of system dynamics and cybernetics and are probably the most frequently used systems visualization and communication tool (Sedlacko et al. 2014).

Socio-ecological systems

Ecological systems (ecosystems) refer to self-regulating communities of organisms interacting with one another and with their environment (Berkes et al. 2008). So, the ecology of the river refers to the relationships that living organisms have with each other and with their environment (the ecosystem), including non-living physical and chemical components (Wetzel 2001). But after all, what is a river and a river system? What relations must be present for a river to be recognized as such? What are its components? How does it work? Rivers are natural streams of water flowing in channels and emptying into larger bodies of water (as sea, oceans, lakes, marshes, or even larger rivers). A river system is an open system (Fig. 3); that is, it has inputs (as water, sediments, dissolved minerals, solar energy, organic matter), processes (storage, transfers, and flows), and outputs. It operates inside a drainage basin (or river basin) that is composed of an area of land drained by a main river and its tributaries, including superficial and underground waters. Its boundary is called the ridgeline (an imaginary line joining the highest parts of upland, being a conceptual model), which is defined by its topographical and hydrological entities.

The organization of watersheds shows some reproducible phenomena, as exemplified by self-similar fractal river network structures and typical scaling laws (Rodriguez-Iturbe and Rinaldo 2001, Kleidon et al. 2013). Basically, all rivers

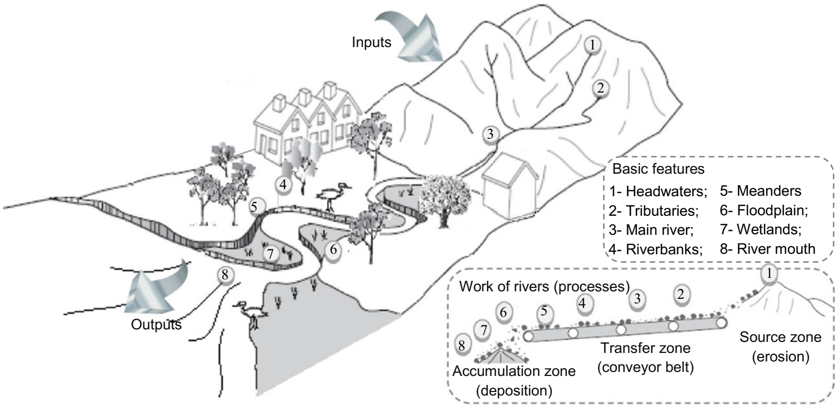


Fig. 3 Representation of a river system. Source: Modified from Brierley and Fryirs (2013)

around the world share some basic features: headwaters, tributaries, a main channel, riverbanks (and their riparian zones), and a mouth (delta). Besides these features, floodplains and wetlands can also be found along stretches of rivers, acting as natural sponges by absorbing floodwaters. Because of this, wetlands also help to provide clean water by naturally filtering out pollution, besides being an excellent habitat for many forms of wildlife. In a more complex way, a river system can be represented as a hierarchically organized system incorporating, at successively lower levels, stream segments, reaches, pool riffle sequences, and microhabitat subsystems (Frissell et al. 1986). Each subsystem plays a particular structural and functional role (physically and biologically) in the stream system. Scientists or managers must select the level of resolution most appropriate to their objectives.

Some rivers get enough water from their headwaters, tributaries, rainwater, and groundwater to flow all year round (inputs). The processes that occur (precipitation, interception, evaporation, transpiration, infiltration, and percolation) in the watershed are responsible for groundwater/surface runoff storage and flow supplying the rivers. Because of that, watersheds have been described as the fundamental spatial unit of landscapes (Chorley 1969) within which rivers operate, constraining the range of river behaviours (which are controlled by the balance of sediment supply and the relative energy to transport or deposit it) and associated morphological attributes (Brierley and Fryirs 2013). In this way, what happens upstream affects everything downstream and therefore the health of the whole river. The characteristics of stream hydrology, water quality, and limnology all vary in somewhat predictable ways along the river continuum gradient, which has been described as the River Continuum Concept (Vannote et al. 1980).

Jørgensen et al. (2016) believe that systems ecology is sufficiently developed to offer a consistent theory about ecosystem function, that is, how ecosystems work as systems. However, Patten (2014) states that scientific ecology is confused about many fundamentals of how systems work and that there is a need to better understand some topics of both systems and empirical ecology (to “get the science right”). These topics include an understanding of ecology and environmentalism (Table 1) and allow assessment of the interaction between the system boundaries and internal compartments (Kazanci and Ma 2012).

Aquatic ecosystems are increasingly impacted by anthropogenic perturbations, which may affect these natural processes, and multiple use of water can be compromised (Vörösmarty et al. 2010). Usually a river’s behaviour adjusts to any factor that changes the boundary conditions under which it operates. On the other hand, even small perturbations may result in big changes if a system is close to a threshold condition. Human disturbance has introduced a source of change that is foreign to the natural condition of the river systems. Flow regulation probably represents the greatest single human impact on river ecosystems (Postel and Richter 2003), causing adjustments to the substrate and the imposition of barriers to fish migration, alterations to processes that affect nutrient cycles, alterations to channel–floodplain interactions and food webs, reductions in riparian vegetation, increases in sediment loads, and adjustments to channel geomorphology (Brierley and Fryirs 2013). In addition to quantity, water quality can also be altered by pollution from several sources (pesticides, sewage, solid waste, and so on). Rivers may be unable to respond to disturbing events, and this may reflect on the resilience of these systems.

Therefore, another type of system needs to be analysed along with ecological systems: social systems. Social systems include those dealing with governance, consisting of institutions, networks, bureaucracies, and policies. Ecosystem sustainability implies maintaining the capacity of ecological systems to support social and economic systems (Berkes et al. 2008), and this requires analysis and understanding of the feedbacks and dynamics of the interrelations between these systems. This has given rise to the Socio-Ecological Systems (SES) approach, which consists of interacting ecological components and social actors. SES is characterized by multiple equilibria, and the core question is how to understand their dynamics. This requires modelling highly complex interactions between linked human and ecological systems (Duit et al. 2010).

In most SESs, there are a limited set of key variables and internal feedback processes that interact to control the configuration of the system (Holling 2001). These feedbacks are critical in determining how the SES responds to shocks (abrupt changes), such as droughts and floods, and ongoing changes. Diversity in SES components increases the reliability of ecosystem services, providing a variety of options to respond to change and disturbance. Amongst these components, species, landscape types, knowledge systems, actors, cultural groups, or even institutions stand out (Kotschy et al. 2015). Often, the response by human actors stands out from the others: it has been to increase control over resources through domestication and simplification of landscapes to increase production, avoid fluctuations, and reduce uncertainty (Folke et al. 2005). This can cause vulnerable ecosystems to shift into undesired states in the sense of providing ecosystem services to society. The existence of such alternate regimes poses new fundamental challenges to environment and resource management (Scheffer et al. 2001).

The problems of the environment are particularly difficult because their complexity, interrelatedness, and dynamic behaviour are beyond the cognitive capacity of most humans to fully understand and manage. This makes the decision-making often compartmentalized and fragmented, where the bigger, integrated picture gets lost (Van den Belt 2004). A lot of knowledge is necessary to study an SES. There is growing

Table 1 Topics required to understand systems ecology

Topics	Key findings
Ecology	Ecological energetics (The first and second laws of thermodynamics): The understanding of the use of, need for, and transfer of energy by ecosystems, understood as a breakdown of an imposed gradient by an irreversible, dissipative process can be used as indicators of functional state or be subjected to optimization by adaptive and selective processes. This is environmental degradation, a necessary correlate of the performance of any work. Living systems build themselves up (+) by tearing down the environments (−) that sustain them in a life–environment (+,−) win–lose relationship.
	Dynamical systems: Systems whose behaviour is determined by a combination of internal and external variables. Steady-state seeking and near-linearity were judged to be consistent pairings that fit most natural dynamics fairly well most of the time.
	Epistemic mediation (genetics and cognition): Environ theory holds that one of the defining properties of life is making models (representations), which means converting physical signals that drive nonliving dynamics to phenomenal ones (physical + epistemic) that drive living dynamics. However, each species is a cognitive island isolated from the others – and this is a challenge to scientific understanding.
	Indirect effects (which are dominant compared to direct effects, making dominant indirectness the source of dominant holism in ecological systems): Network nonlocality is the single most important result of environ theory because it means that system-wide properties contribute more to local determination than the direct interactions themselves.
Environmentalism	Overpopulation (which over-consumes resources and over-degrades environments): Humanity is not overpopulated and carrying capacity of Earth is not presently exceeded on a global scale.
	Biodiversity (as a dynamical process with both input and output sides – speciation and extinction, respectively): Network theory establishes that node diversity contributes to dominant indirect effects, and these underlie salubrious network properties that mould global goods from local bads.
	Invasive species: System boundaries are breached in this process because the invaded systems must have unfilled niches or be malleable to invaders' shaping of new niches, thus manifesting gradient breakdown.
	Sustainability: This is effectively a near-steady-state concept in an ever-changing reality.
	Global change: The globe, like all things ecological, is an open dynamical system. It can be expected to continue changing perpetually; this is a constant. The speciation–extinction mechanism of biodiversity generation will continue providing biospheric stability and adaptability. Directing change to human advantage rather than preventing it altogether might become the better direction.

Source: Compiled from Patten (2014)

interest in the potential of deliberately increasing the diversity of knowledge available by combining diverse types of knowledge, such as local ecological knowledge and scientific knowledge (Bohensky and Maru 2011). SESs and the complex properties of such systems make modelling an indispensable tool for their description and analysis, in which scientists, managers, and others cooperate in framing conceptual models from which further steps in modelling can proceed.

Materials and methods

The methodology was divided into two stages (Fig. 4): (i) problem structuring and (ii) formulation of a conceptual model using the Systems Thinking method. These stages were conducted with professionals from different areas of expertise (related authors of this paper) linked to the academic field. Therefore, the researchers involved are knowledgeable about the study area and can be considered as observers of this environment.

Problem structuring

As part of the problem structuring, a review of the scope of the institutional development project (IDP) was performed to understand the context of the study and its underlying problem issues. At the end of this step, the researchers carried out an IDP critical analysis. The Degraded Area Recovery Plan (DARP) has not yet been drawn up.

Study area

UFSC has its main campus located in Florianópolis city, capital of the state of Santa Catarina in Southern Brazil, and is ranked amongst the best universities in Brazil and in Latin America. UFSC has a large academic community consisting

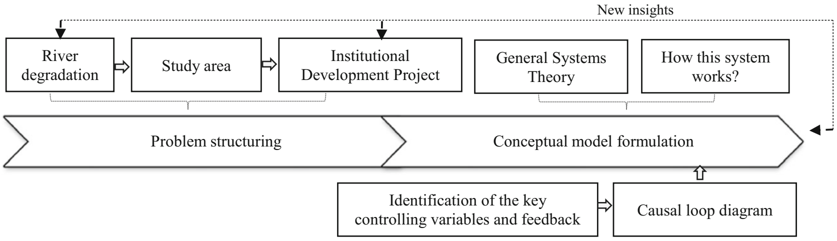


Fig. 4 Representation of the methodology of this research

of 50,000 people, including about 6000 faculty and staff members (UFSC 2017). Therefore, UFSC can be compared to a small city, producing socioeconomic and environmental impacts. Its surroundings are characterized by intense urbanization, motivated also by the installation of federal and state companies since the 1960s, which exerts a strong pressure on the existing water resources even today. Figure 5 shows the boundaries of UFSC as well as the rivers that cross its boundary, which integrate the Itacorubi River watershed.

Itacorubi River watershed has an area of 25 km^2, and its population is about 61,000 inhabitants according to the last Brazilian national census (IBGE 2011). However, there is a large floating population due to the location of important administrative, educational, and commercial activities in this area. It is estimated that there are 45 000 people circulating daily across the region, meaning that more than 100 000 people per day can be found in the Itacorubi River watershed. It is the second most urbanized watershed with its 41% of its basin being urban area. The median monthly income of the households is about USD 1692.48, which is classified as high class according to Brazilian standards. These aspects attest to the socioeconomic relevance of the Itacorubi watershed to Florianópolis city. Another concern about UFSC and Florianopolis itself is that both are located on an island, which makes the surrounding ecosystem very sensitive to environmental change. All rivers of Itacorubi watershed flow into the Itacorubi mangrove, an environmental protection area which is the second largest urban mangrove in Brazil. This mangrove has characteristics that classify it as highly sensitive due to degradation processes suffered during the last decades.

The major contributors of fresh water to the Itacorubi mangrove are the Três Córregos and Itacorubi River, which merge inside the mangrove before draining towards the North Bay. Três Córregos River and other secondary streams cross UFSC, where they have been channelled and straightened in order to solve the problems of both areas considered unhealthy and floods in adjacent districts. Três Córregos River receives all tributaries of UFSC in its watershed. It has artificial straightening and channel adjustments, and because of this there is doubt about whether it is really a river or a drainage channel. The changes in its bed were made so many years ago that there is no consensus amongst experts on this subject. In a natural river, each habitat type may have a characteristic pattern of flow velocities, depths, and sediment dynamics, which is of

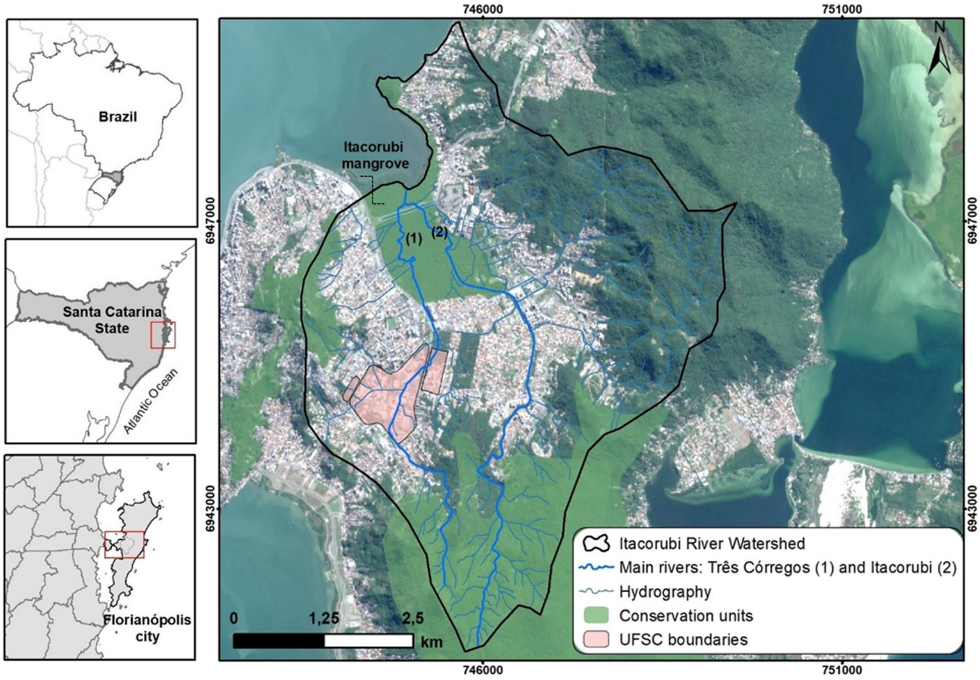


Fig. 5 UFSC location and its insertion in the context of the Itacorubi River watershed

prime importance in determining its suitability as habitat for different organisms. Três Córregos River (within UFSC) has a homogeneous substrate type, and both average water depth and velocity are relatively low due to the enlargement and canalization of streams. It is quite clear that the management of water resources has concentrated on the “command and control” of water (Fig. 6) instead of on “living with the river”.

After entering the UFSC Campus, Três Córregos River loses some characteristic features of fluvial systems (see Fig. 3). Basically, there are no natural riverbanks, riparian vegetation, meanders, floodplains, or wetlands. This has several predictable and negative effects (e.g. loss of river channels habitats such as wetlands and floodplains, disturbance of the stream equilibrium, increased downstream flooding, the absence of riffles and pool habitats, changes in stream velocities, increases of erosion and sediment load, and declines of fish populations). The final disposal of solid waste, inadequate drainage works that have affected its hydrodynamics, and vegetation suppression are other types of pollution sources that have reached the Itacorubi mangrove.

The ecological implications of this environmental neglect for the rivers are unknown since there are no up-to-date specific studies of UFSC watershed or Itacorubi mangrove. There are no studies on this scale to understand the changes that the river has undergone over the last few decades. The distributions and trophic and life history adaptations of stream organisms and the structure and dynamics of communities are unknown. Usually, no fish are seen in the rivers that cross the university, but there are clues to the presence of aquatic invertebrates due to some species of birds seen in this region. The bare-faced ibis (*Phimosus infuscatus*), whose diet consists of insects, worms, clams, and other small invertebrates, has been seen frequently in Três Córregos River and its tributaries. Other species of birds and animals, such as lizards and alligators, can be found inside UFSC (Fig. 7). Low levels of either diversity or redundancy can compromise the resilience of a system and a detailed study is needed. However, some dynamics are observed in this environment, which still retains some fluvial characteristics. It is possible to observe that these rivers connect the existing conservation units of Itacorubi watershed, having great potential to form an ecological corridor and connect these fragmented habitats.

Analysis of institutional development project

Despite all the problems observed, there are no policies currently in place to address water quality or river restoration in Itacorubi River watershed. In 2013, UFSC was sentenced through a Public Civil Action to implement a Degraded Area Recovery Plan (DARP) because it is one of the main sources of pollution. The Public Ministry applied the polluter-pays principle (PPP) to UFSC, which stipulates that those who produce pollution should bear the costs of managing it to prevent damage to human health or the environment. PPP is a principle for internalizing external costs and assigning liability when conflicts emerge and must be resolved between people holding different value systems and competing interests and also between different representations of future states and different visions of the world (O’Connor 1997).

In this way, UFSC was obligated to improve the water quality of rivers (natural or artificial, channelled or not) within the university campus in order to maintain their ecological function and collaborate with the improvement of environmental quality of both Itacorubi mangrove and Itacorubi watershed. Therefore, the project should carry out the following

Fig. 6 **a** Public works outside the UFSC and construction waste on the Eletrosul riverbank. **b** Construction waste (sediments) arriving at UFSC. **c** The confluence of Três Córregos and Serrinha rivers. **d** Três Córregos River flood (inside UFSC). **e** Usual flow of rivers, where it is observed various concrete blocks that have fallen from bank protection along the reach. **f** Sediment bank in the outlet of UFSC watershed, with a magnified view of an alligator (inset)

Fig. 7 Some species found in UFSC: Bare-faced ibis, lizard, and alligator

activities inside its area: (a) analyse the water quality of the watercourses that cross the campus; (b) indicate the pollution sources, when found, and forward this information to the agencies responsible for the necessary appropriate measures; (c) perform the measures necessary for water recovery (where the source of pollution is from UFSC) within its territory based on the DARP.

In order to meet this legal obligation, in 2015 an IDP was proposed, which was designed as a “research action in innovative and exemplary solutions”. The IDP actions are described in Table 2. The project was finalized in 2018 and it was restricted to the identification and monitoring of some actions (1–3), which were called environmental compensation activities. The most urgent activities (DARP and other pollution control implementations) have not yet been performed.

PPP should be a collective internalization; that is, we are all polluters and we all pay in more or less unequal actions. However, only the UFSC was sentenced, whereas responsibility for the degradation of both the rivers and the mangrove was not attributed to the other polluters in the watershed. To contribute to this discussion, the group analysed urban land use in the Itacorubi watershed. Sentinel 2A images (red/green/blue composite imagery and an image resolution of 10 m) from July 2017. ArcMap 10.4.1 was used to process these images and collect the information of interest. The unsupervised classification of images was used to automatically compute the impervious and pervious areas based on Iso Cluster and Maximum Likelihood Classification. As input parameters, different values of Maximum Class Size were tested until a satisfactory classification was performed. Since only urban and non-urban classes were used, the number of class parameters was two. In each attempt, the results of the classification were imported into Google Earth Pro and a qualitative assessment was performed. The result of the image classification was used to support the group discussion about the processes of urbanization and river degradation in the watershed.

Besides that, the group compared current land use for the Itacorubi watershed and the water quality index (WQI) produced in the IDP by Pompeo (2017), which is composed of the parameters pH, dissolved oxygen, temperature, turbidity, total solids, biochemical oxygen demand, thermotolerant coliforms, total phosphates, and total nitrates (CETESB 2013).

Table 2 Action lines described in the institutional development project

Description	Progress and results
1- Quality and quantity monitoring of river and streams	A hydrosedimentometric monitoring system (rainfall, water flow and water turbidity parameters) was implemented at seven points and the Water Quality Index was analysed. These analyses were carried out in the period 2015–2016 and the results ranged from bad to very bad.
2- Mapping of all effluents discharged into rivers and streams within UFSC and notification of the responsible authorities when the contamination source is external to the university.	Thirty-nine effluent points were identified, of which four are polluted and 20 may be polluted because they present runoff even without rain. The main internal source of stream pollution is car washing at 32 locations inside the campus, which discharges a large amount of detergent effluent and other chemicals into rivers. This activity is authorized by the university, but there is no pollution control for it. The regulation of this activity is in progress.
3- Pollution control	Monitoring of the water consumption of the university hospital to identify possible leaks flowing into streams.
4- Implementation of stream restoration projects through a Degraded Area Recovery Plan (DARP)	Not started

Source: Data extracted from Pompeo (2017)

After this, the group pointed out the main positive and negative points observed.

Conceptual model formulation

After the problem structuring, all discussion was organized by means of the qualitative model, which led to the development of a shared view of the problems, pressures, and impacts characterizing the river basin (which lead to the degradation of rivers crossing the UFSC). Thus, the goal of the second phase is to develop a conceptual (qualitative) model of the system of interest through the Systems Thinking approach. Attempts were made to understand how this river system works and the following strategy was used (Fig. 8). Each step served as input to the subsequent step.

Based on IDP objectives, goals were set in river restoration and key controlling variables were identified. Based on these, the system (target, boundaries, and components) was outlined and it was decided which components of the real system should be included in the system of interest and how they should be related to one another. To identify them, we searched for those variables that contributed to a result linked to the change. The most relevant variables in the system, including potential actions, were identified considering the mental models that are behind the thought structure. This brings the discussion back to the fundamental question of knowing what nature is made of and how it is organized (Fig. 3 and Table 1). To figure out how these components interact to realize the system, that is, to identify the processes of life, a CLD was used.

CLDs are powerful, simple, and commonly used tools of the Systems Thinking method for the qualitative analysis of systems (Halbe et al. 2013), being used at the beginning of the modelling exercise in order to develop a preliminary dynamic hypothesis. They are valuable tools for eliciting and mapping mental models (Elsawah et al. 2017). They depict causal relations between selected variables, focusing on positive and negative feedback loops that are often responsible for difficulties in controlling the inherent dynamics of the management system. In these diagrams, elements of the system are connected by positive and negative arrows. They are either positive (directly proportional relationship, where changes reinforce the direction of an initial change) or negative (inversely proportional relationship, whereby one change tends to offset another, creating a natural counteracting effect that is generally beneficial because it tends to help the system maintain equilibrium).

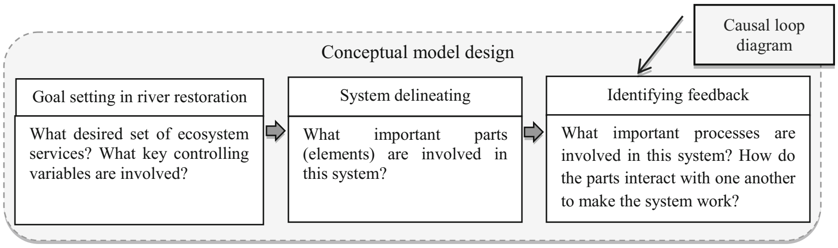
The feedback loops signs were also identified. Loops are a further central concept in Systems Thinking, which shows what type of behaviour the system will produce: reinforcing, R (leading to exponential growth or exponential decay), or balancing, B (leading towards an equilibrium or goal value, it promotes stability, resistance, or limits marked). Reinforcing loops have an even number of negative links, including zero, while balancing loops have an odd number of negative links. The variables, the links between them (feedback), the signs on the links (which show how the variables are interconnected), and the sign of the loop (R or B) constitute the basic elements of a causal loop diagram (Sedlacko et al. 2014). The way in which the links are distributed within a system determines its structure and they may be one-way interactions or mutual (reciprocal) interactions.

In this way, preliminary problem definition and the identification of the causes of the defined problem as well as the polarity of causal links were discussed. After this, feedback loops were found. By understanding the structure of a system, it becomes possible to determine its behaviour over a certain time period, analysing it qualitatively. It may be particularly useful for scoping complex issues and reaching a better understanding of their underlying feedback loops (Coyle, 2000). These actions provide a co-production of knowledge and group learning. As a result, a CLD was developed and analysed to provide insights into the scope of the DARP through a systemic vision, synthesizing knowledge and perspectives from many distinct disciplines within a single problem-solving philosophy.

Validity of the results

In order to minimize the subjectivity involved in this qualitative research as well decrease the process distortions, the transactional approach was used to validate of the conceptual model. It is based on active interaction between the enquiry and the research participants in order to achieve a higher level of accuracy and consensus by means of revisiting the facts, feelings, experiences, and values or beliefs collected and interpreted

Fig. 8 Guiding questions for a conceptual model design



(Cho and Trent 2006). Amongst the transactional techniques, member checking based on the triangulation method was used. Member checking consisted in reproducing the data collected by one observer (author) for another to check for perceived accuracy and reactions. In this case, the main author elaborated the first version of the CLD based on the list of components that act on the reality of the system, which was built by all the authors in the previous step. Subsequently, the CLD was sent to each author, an expert in a particular area (ecology, hydrology, public sector, social, SWM, and urban planning), who modified or agreed to the original CLD, making a "within-method" triangulation (Fig. 9).

When the modifications or agreements were listed by most authors, they were incorporated. On the other hand, when only one author presented a modification, it was sent to all the other authors to verify their agreement or not. When the CLD modification complied with the first criterion (by agreement of most authors), it was incorporated into the conceptual model. In sum, the CLD was checked by each expert (member checking), which involved cross-checking for internal consistency or reliability (triangulation method). The final CLD was created after five rounds. These procedures follow the principle that multiple viewpoints result in greater accuracy (Jick 1979).

Results and discussion

Analysis of institutional development project

The main criticism of the group is about the geographic scope of the Public Civil Action. This Action indicated that the plan should only contemplate the rivers that cross the campus, disregarding all water bodies upstream of the university, that is, the input environs (see Fig. 2). Given the biophysical feedback inherent in healthy aquatic ecosystems, river rehabilitation programmes must understand and cover the biophysical processes within a watershed context. This is well illustrated by the comparison of land use and WQI of the UFSC sub-basin (Fig. 10). Pantanal and Carvoeira rivers, as well as the junction between Cesar Seara and Eletrosul rivers, have bad water quality. Serrinha River has very bad water quality, which is maintained after its confluence with Carvoeira River. Três Córregos River shows bad water quality after it receives waters from Cesar Seara, Eletrosul, and Pantanal rivers; however, the quality showed a great deterioration with the reception of waters from Serrinha River, passing into the very bad quality range. Três Córregos River flows with very bad water quality until the outflow point of UFSC sub-basin, reaching another receiving water—Três Córregos River—and Itacorubi mangrove. This analysis refers to a part of the Itacorubi River watershed, where UFSC is located. Other studies (SOS 2017) have indicated that the other part, more specifically in the Itacorubi River (indicated in Fig. 5), is also polluted. This bad and very bad WQI is mainly related to the absence of sanitary sewage collection in the Itacorubi watershed, which is non-existent in 38% of the households.

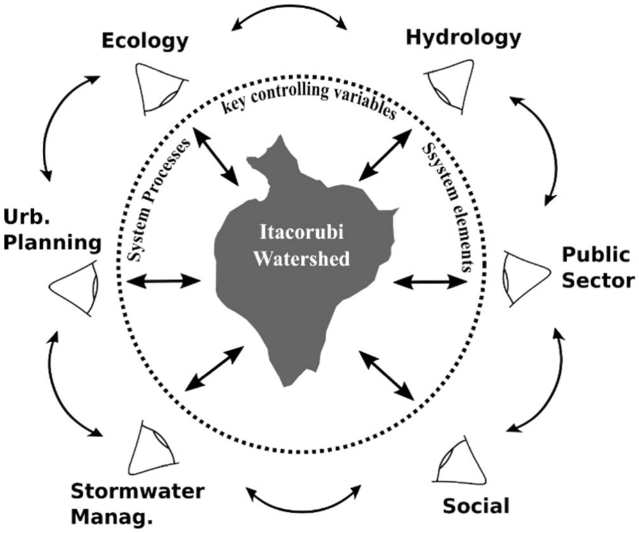


Fig. 9 Process to design the causal loop diagram by different experts (system observers)

In this way, the two main rivers of Itacorubi watershed carry pollution into the mangrove. In the case of Três Córregos River, the bad water quality occurs even before entering the UFSC campus as a result of clandestine sewage and wastewater connections to the stormwater system. The collection of wastewater is a solution to avoid pollution of groundwater and of surface water resources (Bertrand-Krajewski et al. 2006). In separate sewer systems, as occurs in Brazil, it is very important to detect illicit and faulty connections, which result in transport and infiltration of unwanted water into the pipeline network from different sources (Beheshti et al., 2015). It has been noticed that, in most Brazilian cities, such control is inefficient or does not exist. Furthermore, there is little or no control of soil conservation practices in the upstream urban areas, which are characterized by steep slopes with high propensity for erosion and sediment transport. After entering UFSC, rivers receive additional pollutants as wastewater from laboratories and car wash ventures. There is no pollution control of the latter, but the regulation of this activity is in progress. In practice, these rivers work as receiving streams for wastewaters, and deterioration in water quality (owing to reduced effluent dilution) is observed. How ecosystems undergo such environmental changes on different scales of space and time is one of the main frontiers in ecology (Rietkerk et al. 2004).

It is clear from the IDP analysis that the main positive points refer to the beginning of monitoring of the rivers, making it possible to know their dynamics and sediment budgets and to identify the effluents discharged into them. In addition, the implementation of an environmental management team

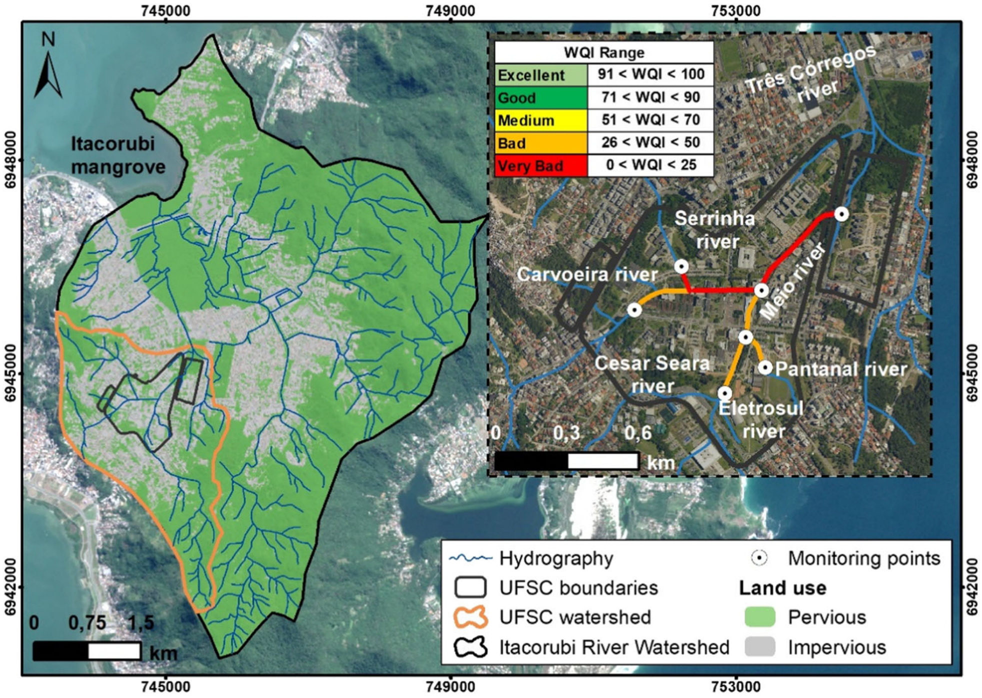


Fig. 10 Land use map and WQI in the rivers that cross the university

signals an initial commitment to environmental policies. However, there are some negative aspects related mainly to the absence of shared responsibility amongst all stakeholders who should have been included in the sentence. The relationship of the strengths and weaknesses of the IDP are shown in the Table 3. After analysis of the IDP, it was observed that this is not a project but a simplified diagnosis of the current campus situation. From it, a DARP to achieve established targets will be prepared and delivered to the competent authorities (Institute of the Environment of Santa Catarina).

In many countries, improving freshwater management in the urban environment is currently seen with a sense of urgency (Walsh et al. 2005). However, this issue is not a priority in Florianópolis city, even though it has been affected by water scarcity in recent years. Water scarcity is both a natural and a human-made phenomenon, and the latter has intensified in this city since too much freshwater is wasted, polluted, and unsustainably managed. There is some concern for river health, but this is not reflected by effective actions. Maintaining or restoring environmental water flows is not a priority issue. The main implication of the insights presented here is that efforts to reduce the risk of unwanted state shifts are not enough. The IDP should address the gradual changes that affect the system resilience rather than merely control disturbance. Management should include the interlinkages between the resource system (rivers), water management system (infrastructure), and water governance system (regulatory structures and processes). This leads us to discuss the frontiers in urban water management and how effective the IDP can be in reducing environmental degradation, maintaining the ecological function of rivers, and collaborating in the improvement of the environmental quality of the Itacorubi mangrove and Itacorubi watershed (civil action objectives). River ecosystems cannot be reduced to territorial limits, since significant pollution comes from external sources (inputs) to the university territory and a broader approach is needed to address this problem.

Conceptual model

Goals in river restoration and identification of key controlling variables

Based on the previous scenario, goals in river restoration were set (Table 4). Scientific understanding of how river ecosystems work provides a strong foundation for general restoration strategies. Each amenity of interest is limited by a few key conditions. In an urban system like this, the potential for ecological improvement is limited, and some actions, such as stream restoration, are very complex and costly.

Delineation of the system

- **Target system and boundaries**

Through the introduction of a systems view in IDP analysis, it has been clearly demonstrated that when attempting to understand rivers as (eco)systems, we are dealing with structures organized in a hierarchy and with a very high complexity. A water resources system integrates by components and

Table 3 The main positive and negative aspects in the institutional development project

Activity	Positive aspects	Negative aspects
Implementation of hydrosedimentological monitoring	It allowed the dynamics of streams to be known.	Geographic scope (UFSC territory), Ecological flow and streamflow deficits are unknown, Reliable information will only be available after many years.
Mapping of effluents discharged into rivers and streams	Survey of pollution sources, which may allow the reduction of internal pollution; The regulation of car washing activities is in progress; Repairs of overflow pipes; Deactivation of septic tanks.	Lack of shared responsibility between different agencies responsible for socio-environmental issues; Disregards water degradation agents that do not come from effluents (i.e. diffuse sources); Some septic tanks have not been disabled because their location is unknown (their location is not visually obvious and there is no sanitary sewer network).
Implementation of an environmental management team	Increased environmental awareness amongst policymakers and academic field; Social and environmental commitment, covering various themes.	Reduced staffing; staff members do not have exclusive dedication
Implementation of a Degraded Area Recovery Plan (river restoration)	Academic involvement through scientific studies (especially in completion of course work).	It was not started; Financial resources for its preparation are not available; Ecological disturbance remains sub-known; No clear conception in river recovery can be drawn from the IDP.

Table 4 List of amenities that can motivate the Degraded Area Recovery Plan

Amenity of interest	Key conditions	Key direct drivers	Potential restorative actions
Water quality	Water/sediments; Pathogen density, bioindicators	(1)–(6)	Clean up point-sources of pollution; Alter land use in catchment; ecotoxicological essays; Implement best practices for soil conservation; Erosion control.
Water availability	Flow regime; Water uses; Riparian/aquatic vegetation	(4)–(6)	Alter land/water use in catchment; Re-establish natural flow regime; Manipulate vegetation composition; Riparian restoration; Implement best practices for soil conservation; Erosion control.
Aesthetic appeal/ human recreation potential	Water clarity, odours; Bank stability; Channel shape; Riparian/aquatic vegetation	(1)–(5)	Alter land/water use in catchment; Reinstate natural channel shape; Reinstate natural flow regime; Manipulate sediment composition; Manipulate vegetation composition; Stabilization of river banks.
Valued biota	Water/sediments; Habitat structure; Flow regime; Production dynamics; Other non-human biota	(1)–(6)	Clean up contaminant sources; Alter land/water use in catchment; Reinstate natural habitat structure; Reinstate natural flow regime; Reinstate natural productivity; Stock target biota; Reduce biota with adverse effects; Implement best practices for soil conservation; Erosion control.

(1) Vegetation conversion and habitat fragmentation; (2) external inputs (wastewater and sewage); (3) species introduction or removal; (4) infrastructure development; (5) environmental shocks (e.g. floods); (6) soil erosion and land degradation

Source: Adapted from Wohl et al. (2005) and Rocha et al. (2018)

processes much more broadly than an analysis focused exclusively on the water component, being described as the "whole made from connected hydrologic, infrastructure, ecological, and human processes that involve water" (Brown et al. 2015). For this reason, the UFSC watershed was chosen as the target system, including all surface waters, with multidirectional energy flows.

Thereby, this system has hydrology-based boundaries, whose limit is its own catchment area, in which matter and energy in the form of soil particles, rock fragments, large woody debris, solar energy, and precipitation enter the stream while heat energy dissipates into the atmosphere and the stream bed. Water and sediments leave the system through the river flow (outlet), where they empty into the mangrove and ocean, and precipitation provides an input of water to the system. In short, the natural dynamics are determined by climate inputs and hydrological processes.

- **System components**

The target system was divided into three main components (parts) to identify important elements that have functional roles in both the organization and the structure of the system: natural, socio-economic, and management. At the UFSC watershed level, the status of rivers is the result of natural processes and human activities. However, human elements have a crucial role in fluvial systems, which are often modified to meet their needs. Because of this, diverse groups of actors with different roles were identified (Table 5) in order to give them a specific degree of participation, thereby accounting for their heterogeneity. Brainstorming was used to identify these stakeholders.

Identifying feedback

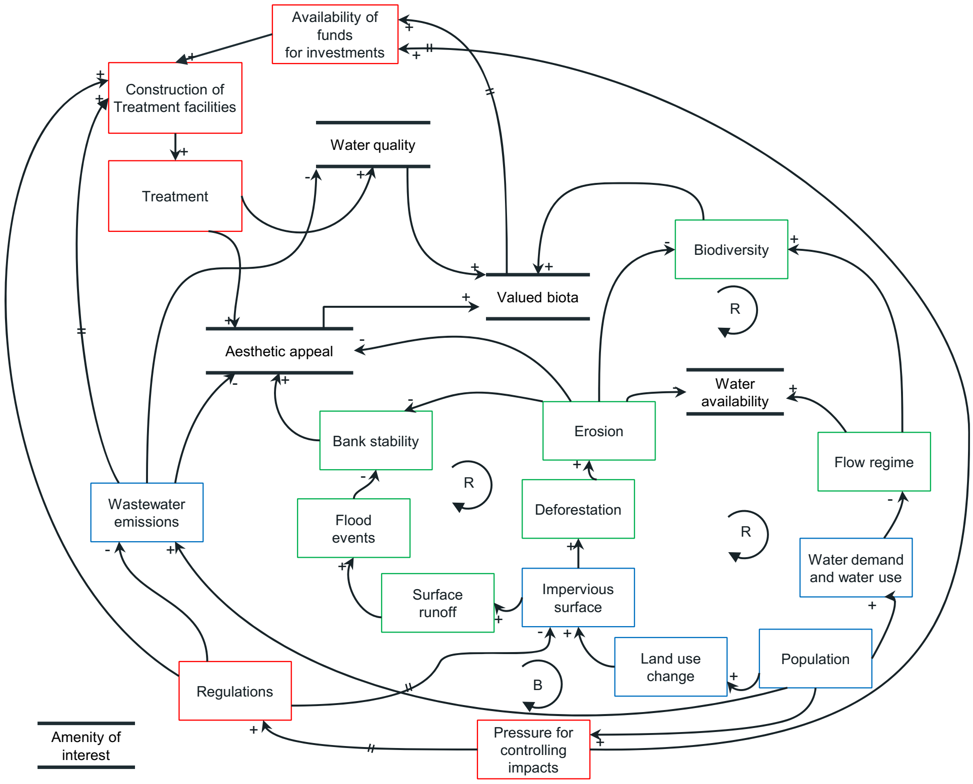
The CLDs built by individuals or groups represent individual or collective cognitive maps regarding a problem. The configuration of the system and the shifts between its different configurations arise from the interplay between the internal feedback processes and the levels of key controlling variables. Once the feedback structure of a system is understood and captured in a model, it can be managed to achieve a desirable state. In this case, degradation of water quality (lack of clean water due to pollution), unpleasant aesthetics, devalued biota, and insufficient availability of water (mainly within rivers) were analysed under a systemic view. The amenities of interest of these concerns are the model variables. The CLD is shown in Fig. 11. Compared to the IDP, the CLD shows several aspects that were not incorporated in the project. First, the CLD shows how natural, socio-economic, and management systems could interact or are connected with each other. In this sense, it is possible to indicate the actor responsible for each problem that affects the whole system. At the second level, the CLD reveals which subsystem needs to be analysed and monitored, for how long, and considering which parameters. Thus, a team of experts could be involved, as well the governmental

Table 5 List of components that act on the reality of the system

System	Subsystem	Main elements
Natural	Biological	Fauna
		Flora[1] (riparian vegetation, conservation areas)
	Physical	Climate, soil, relief, streams, groundwater
Socio-economic	Companies	Eletrosul power station
	UFSC	Educational centres, university hospital, laboratories, car wash ventures, restaurant
	Population	Students, community organizations, inhabitants, tourists
Management	UFSC	Environmental management staff (CGA); rectory; Office of Budget and Planning (SEPLAN); Office of Works, Maintenance and Environment (SEOMA),
	Service providers	Sanitation company
		Town hall
		Eletrosul power station
	Governance	Government department, town hall, Sanitation Regulatory Agency
	Environmental protection	Institute of the Environment of Santa Catarina
		Municipal Environment Foundation
		River Basin Committee
		Mangue Vivo Institute (Live Mangrove Institute)
	Disasters	Civil defence

[1] Itacorubi mangrove is outside the target system but is impacted by activities within UFSC watershed

Fig. 11 Causal loop diagram of target system. Green, blue, and red variables belong to the natural, socio-economic, and management systems, respectively



Notation	Description	Notation	Description
A;B	Variables	+ →	Positive feedback (reinforcing)
→	Cause and effect relationship (Immediate)	- →	Negative feedback (balancing)
‖→	Cause and effect relationship (with delay)	R	Self-reinforcing (positive feedback) loop
═	Amenity of Interest	B	Self-regulating (negative feedback) loop

or non-governmental institutions that play an important role in watershed management. Thus, positive or negative feedbacks and a reinforcing or balancing relationship could be identified and a solution or improvement pointed out. In this sense, the CLD shows the big picture at different levels of positive and negative relations of the processes that impact the quality of the ecosystem (Itacorubi basin). The efforts and energy of each actor that plays an important role could be oriented and better performance can be achieved. The CLD could provide valuable insights into how the system works and what are the actions that need be taken. Otherwise, the scale problem in river restoration (applied only in a reach) will persist.

Wastewater emissions are the main stressor of the environment. After generation, there are two paths which wastewater can follow: to a treatment facility, due to environmental regulations, or directly to the rivers as a result of irregular connections. In the latter, the pollutant load is higher and impairs water quality. The negative feedback (untreated wastewater) that has fuelled the amenities of interest (water quality) needs to be weakened. In this regard, a balancing loop was identified, where human decision-making (pressure to control impacts and regulations) has an important role in SES systems. In other words, if there is greater regulation, untreated wastewater emissions will be lowered.

Stakeholders acting on target systems have been identified (Table 5) and play important roles in feeding systems. On the other hand, it was observed that there are some overlapping domains of authority (e.g. regulation belonging to the management system, which is managed by different stakeholders). In this way, different organizations play a similar role. Thus, the actions can become either redundant or ineffective.

Another potential stressor for the environment is the land use change of the upstream areas. In the last decades, there was intensifying pressure on the environment mainly due to urban sprawl. During the construction of buildings, soil erosion can be greater than on land used for agriculture (USDA 2004). The problem is aggravated by the absence of soil conservation practices in the basin. After the construction, there is an increase in the impervious surface and in the runoff, causing erosion and enhancing sediment transport. In some cases, the time necessary for the high sediment loads to be flushed away from the system varies from years to decades (Chin 2006). Since the UFSC watershed has been constantly modified, the impacts in the system could take decades to resolve, even with measures being taken urgently. Downstream, in the alluvial fan, represented by the UFSC campus in this case, there are sediment deposits that could be harmful to biota and could increase floods and water availability problems. To control the erosion and sediment yield in the basin, there is a need for regulations on land use and soil conservation besides the establishment of guides to best practice for construction. In some cases, it would be useful to build erosion control structures, such as filter strips and sediment traps.

Therefore, an important item in this diagram is the regulation of impervious surfaces, which is necessary because of urban growth. Growth mobilizes energy and material resources to do work and passes degraded residues back to the environment for decomposition and regeneration. Linked to this, an increase in wastewater disposal is also observed, and the construction of a treatment facility is required. Its absence is largely responsible for river pollution, as previously highlighted. It is observed that the system supports its existence and is behaviour through the circular relations of cause and effect (an idea that was brought by cybernetics). However, closed loops are critical features of CLDs because the system is caught in a vicious cycle of circular chain reactions. These cycles need to be broken, with emphasis on the reduction of impervious surfaces, water demand, and water use variables. In these cases, sustainable urban SWM (e.g. wastewater reuse and recycling) associated with regulations can be useful.

The developed CLD provides a holistic understanding of the key factors and processes and the role that systemic feedback plays in determining the basin's behaviour. Holism itself requires more than a varied group of people sitting at the same table and talking with one another (Gattie et al. 2007). However, this initial approach is aimed at creating coherent shared perspectives (qualitative) from initially divergent viewpoints and opinions.

River management and restoration, in a general way, focuses on a single, isolated reach of river (Whol et al. 2005), probably because restoration projects are discussed in the academic fields of geomorphology and hydrology and also because restoration projects are expensive and require, in most cases, engineering interventions (Johnson et al. 2019). Typical water resource planning and management approaches are based on methodologies that ignore feedback and adaptations amongst the natural, social, and infrastructural systems. Traditional reach restoration does not bring discussion between the different actors that are causing the disturbance in the ecosystem. For example, this traditional approach could lead to disregarding the mangrove located downstream of the degraded reach, in the case of Itacorubi watershed. In the same way, the sources of pollutants carried by urban stormwater located in different places of the watershed need to be fixed to the success of the restoration plan, even at reach scale.

When analysing environmental resources, it is impossible to think of them as isolated area, since there are a considerable range of collective benefits of water resource use. The use of the Systems Thinking theory allows us to observe the river degradation and restoration in terms of different aspects and in the whole watershed, not only in the reach to be restored. In this sense, the exercise of observing the whole system also brings the benefit of identifying the actors that could propose solutions to the river degradation, even without an engineering project. Starting a restoration project based on the Systems Thinking approach could be a key to enhancing the success of the project and identifying the stakeholders who need to be brought to the discussion table.

Final considerations

This paper analysed, from the viewpoint of systemic thinking, an IDP (design) applied to a small urban watershed located in Brazil, which shows that several rivers that cross a university campus have compromised water quality. The solutions implemented or suggested were restricted to a small part of the watershed (UFSC campus) and did not fully cover the complexity of the processes that occur in the basin and the interconnectivity between them. The search for solutions to environmental degradation did not take into account what occurs upstream and downstream of the university. A water resources system integrates by components and processes much more broadly than an analysis focused exclusively on the water component. This was demonstrated by a qualitative model, which was elaborated based on Systems Thinking. It indicated both the connections between the causes of degradation and the system components that must be observed in environmental recovery.

The amenities of interest (water quality, aesthetic appeal, valued biota, water availability) are fed from diverse sources and the interconnectivity between them must be analysed. Wastewater emissions are the main environmental stressor due to unregulated untreated wastewater connections, and regulation plays a crucial role in weakening this feedback. Other potential environment stressors were identified: land use change of the upstream areas and impervious surfaces, and there is a need for regulations on land use and soil conservation besides the establishment of guides to best practices for construction. The design should address the gradual changes that affect the system resilience rather than merely controlling disturbance. Management should include the interlinkages between the resource system (rivers), water management system (infrastructure), and water governance system (regulatory structures and processes). University managers can only execute actions and act in their territory, and because of that it is clear that the project is not effective in achieving the objectives required by Public Civil Action (reduction of environmental degradation and maintenance of the ecological function of the rivers, contributing to improvement of the environmental quality of both the Itacorubi mangrove and the Itacorubi watershed). The target system is fed from several sources external to the university territory, and therefore these plans should be part of a larger project. The river ecosystem cannot be reduced to territorial limits.

Fluvial systems are too complex to permit a single model to explain all of their environmental components and how they affect one another. In this case, this paper shows some initial insights to improve the scope of the IDP and DARP (which will be further elaborated). The applying Systems Thinking has proved to be an effective approach that encourages consideration of the full context, considering feedback and adaptations amongst the natural, social, and infrastructural systems in the whole watershed and identifying all stakeholders that deal with the governance of the system. This is of great importance given the current context of intense environmental degradation in many river basins around the world and can help improve both the health of streams and the quality of life of the inhabitants as well as contributing to environmental sustainability.

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