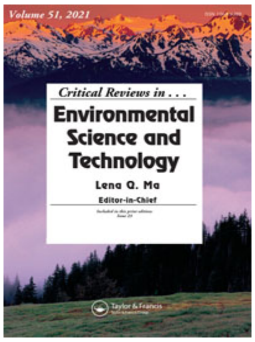

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Articulating the new urban water paradigm

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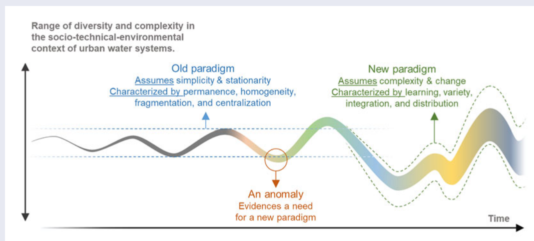
ABSTRACT



Urban water systems in industrialized countries have underpinned unprecedented improvements in urban living standards through effective drinking water supply, sanitation and drainage. However, conventional urban water systems are increasingly regarded as too rigid and not sufficiently resilient to confront growing social, technological and environmental complexity and uncertainty, manifested, for example, in the maladaptation to climate change, depletion of nonrenewable resources, and degrading urban livability. In response, a new urban water paradigm has emerged in the last two decades within the context of a broader societal change that promotes a more organic worldview over the classical mechanistic and technocratic understanding of reality. This article develops and applies an analytical framework to coherently describe the new paradigm and contrast it with the old urban water paradigm. The framework includes a philosophical foundation and set of methodological principles that shape the new paradigm's approach to governance, management, and infrastructure.

KEYWORDS Paradigm shift; new water paradigm; integrated urban water management; sustainable urban water management; water sensitive urban design; complexity

1. Introduction

The provision of water supply, sanitation and urban drainage services to households, businesses and communities has led to unprecedented improvements in life expectancy, economic growth, and quality of life in industrialized countries during the last 150 years. These services have relied on a system of social structures and material infrastructures—referred to in

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Supplemental data for this article can be accessed at publisher's website.

this paper as urban water systems (UWSs)—that have remained strikingly unchanged over the last century. In general terms society abstracts, cleans, transports, consumes and disposes water in the same ways it did at the end of the 19th century. However, the context in which these conventional UWSs operate has profoundly changed during recent decades. Western societies have grown increasingly complex due to accelerated technological development and faster exchange of information, where social, technical and biophysical elements have become more and more diversified and interdependent (Beck et al., 2003; Castells, 2010). This complexity has resulted in emerging problems—particularly climate change, rapid urbanization, and environmental degradation—and new societal needs, values and expectations—like social equity and urban livability—which conventional UWSs are poorly equipped to approach (Andoh et al., 2008; Bell, 2015; Daigger, 2009; Hering et al., 2013; Ludwig, 2001; Marlow et al., 2013; Pahl-Wostl et al., 2009). In other words, the ideas and assumptions that underpin our current UWSs are no longer fit for purpose.

A growing number of scholars have reported the gradual emergence of a new set of ideas and assumptions, a new mental framing or water paradigm (Gonzales & Ajami, 2017; Pahl-Wostl et al., 2011; Schoeman et al., 2014) that shapes new types of social structures and infrastructures capable of properly addressing current and anticipated needs and challenges. This new paradigm for UWSs can be seen as the local expression of a broader societal transformation that moves from a mechanistic to an organic worldview (Capra & Luisi, 2014; du Plessis & Brandon, 2015) which arguably started during the 1960s-70s (Franco-Torres, 2020) as an attempt to adapt to a more complex and dynamic reality. This broad paradigmatic transition had emerged in other sectors earlier (like urban planning (Jacobs, 1961), energy management (Lovins, 1976), or economic management (Schumacher, 1973)) and it is now increasingly recognizable in popular concepts like planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) sustainability, resilience and green economy (UNEP, 2011), or the United Nations Sustainable Development Goals (UN, 2015).

While there is wide consensus about the existence of a new paradigm in the water sector, many authors have characterized the incumbent urban water paradigm as rigid and resistant to change, prone to continued operation under old beliefs and values despite evident problems of sustainability and increasingly complex societal needs (Brown & Farrelly, 2009; de Haan et al., 2015; Kiparsky et al., 2013; Roy et al., 2008). The incumbent paradigm has a distinct inertia as old ideas are entrenched within widespread technologies and infrastructures, management practices, rules, or organizational structures. This inertia is useful in providing stability and certainty, but also creates an impediment for adaptation to a changing reality. New ideas risk being discarded in favor of solutions that are firmly ingrained in the incumbent paradigm; they do not fit with established framings. See, for example, Sofoulis' (2015) description of the difficulty of introducing rainwater tanks—despite their obvious advantages—in the Australian water sector, Binz et al.'s (2016) report of problems to legitimize potable water reuse in California, or Coombes et al.'s (2016) analysis of engineering and economic assumptions belonging to the old paradigm impeding the adoption of governance policies toward water cycle management.

Despite this so-called *lock-in*, a growing number of scholars, policymakers and practitioners recognize the need for innovative approaches that derive from the new paradigm. Salient examples include Singapore's integration of the whole water cycle (Jensen & Nair, 2019; Lee & Tan, 2016), urban design responses that are sensitive to water environments in Melbourne (Australia) (Brown et al., 2013; Ferguson, Brown, Frantzeskaki, et al., 2013), the use of stormwater to enhance urban livability in Copenhagen (Denmark) (Franco-Torres et al., 2020; Ziersen et al., 2017), and collaborative planning processes in Rotterdam (The Netherlands) (de Graaf & van der Brugge, 2010; Dunn et al., 2017).

Thorough analysis of these successful case studies often point to key factors that supported the local adoption of new solutions, like the work of champions, the creation of communities of practice, the diffusion of narratives, or the creation of pilot projects. We argue, however, that a broader enactment of the new urban water paradigm could be accelerated with a better understanding of the paradigm itself, and an integrated definition of its constituent elements, which so far remain dispersed and fragmented in the literature. A plethora of normative water management frameworks that implicitly reflect the new paradigm (Table 1) has emerged (Esmail & Suleiman, 2020; Furlong et al., 2015; Schoeman et al., 2014), typically focusing on particular aspects of management, theories, and methods incorporated from other disciplines. These frameworks tend to be ambiguous (Biswas, 2004; Furlong et al., 2015; Molle, 2008) and "remain open to a multitude of interpretations which pose insurmountable obstacles in finding practical ways for their implementation" (Saurí & del Moral, 2001, p. 352). We argue that this coexistence of similar and ill-defined frameworks and terms means they tend to compete, hindering understanding and the development of the discipline and associated practices. The rampant diversity of partially overlapping terms used in the subfield of urban drainage management serves as a prime example of the reigning confusion (Chocat et al., 2001; Fletcher et al., 2015).

We therefore suggest that a transition to more sustainable and adaptive urban water management could be accelerated if scholars, policymakers and practitioners become conscious of their cognitive framings that may limit the consideration of alternative solutions, and of the existence of an

Table 1. Selection of management frameworks.

Framework	Focus	Framework
Integrated (Urban) Water (Resource) Management (IWM, IUWM or IWRM)	IWM seeks to combine multiple natural processes, scales, perspectives and needs in order to define holistic solutions.	(Biswas, 2004; GWP, 2000; GWP, 2012; Mitchell, 2006; Mukhtarov, 2008; Rahaman & Varis, 2005)
Adaptive Water (Resource) Management (AWM or AWRM)	UWSs are explicitly considered complex and dynamic systems that present a high degree of uncertainty. AWM proposes to understand and collaborate with the "natural" self-organizing processes of the social and natural systems through continuous experimentation, broad participation and learning, instead of forcing them toward certain predefined and narrowly defined outcomes.	(Georgakakos et al., 2012; Pahl-Wostl et al., 2007)
Sustainable (Urban) Water Management (SWM, SUWM)	SUWM builds on principles like adaptation, holistic decision making, broad stakeholder participation, decentralization, resource use efficiency, and community and environmental values, although these principles are not well linked in the framework.	(Hellström et al., 2000; Larsen & Gujer, 1997; Loucks, 2000; Marlow et al., 2013)
Water Sensitive Urban Design (WSUD)	WSUD is a multidisciplinary approach that highlights the link between urban design, land use, the efficient use of water, and the improvement of urban livability.	(Ashley et al., 2013; Mouritz, 1996; Wong, 2006; Wong & Brown, 2009)

alternative and coherent paradigm that can more effectively respond to present and future water-related needs (Abson et al., 2017; Meadows, 1999).

Certainly, there have been several insightful attempts to describe this new water paradigm (Capodaglio et al., 2016; Gleick, 2000; Grigg, 1998; Keath & Brown, 2009; Marlow et al., 2013; Ma et al., 2015; Mitchell, 2006; Novotny et al., 2010; Pahl-Wostl et al., 2011; Pinkham, 1999; Schoeman et al., 2014; Zandaryaa & Tejada-Guibert, 2009). However, these have not engaged with an in-depth explanation of what a paradigm is, tending to list characteristics that lack connection or a clear structure. They also tend to emphasize a particular water service—either drinking water provision, stormwater management, wastewater treatment, or water ecology—and have scarce reference to their common philosophical foundations.

This article therefore aims to describe a coherent framework that holistically connects the multiple ideas that underpin the new urban water paradigm and its derived social and technological structures in the water sector, across the different water services, and with particular attention to their shared philosophical foundations—the same foundations that underpin the broader social paradigm now emerging.

2. An analytical framework to describe urban water paradigms

Our paradigm framework encompasses three main categories: philosophical foundations, methodology, and operational articulations (Figure 1).

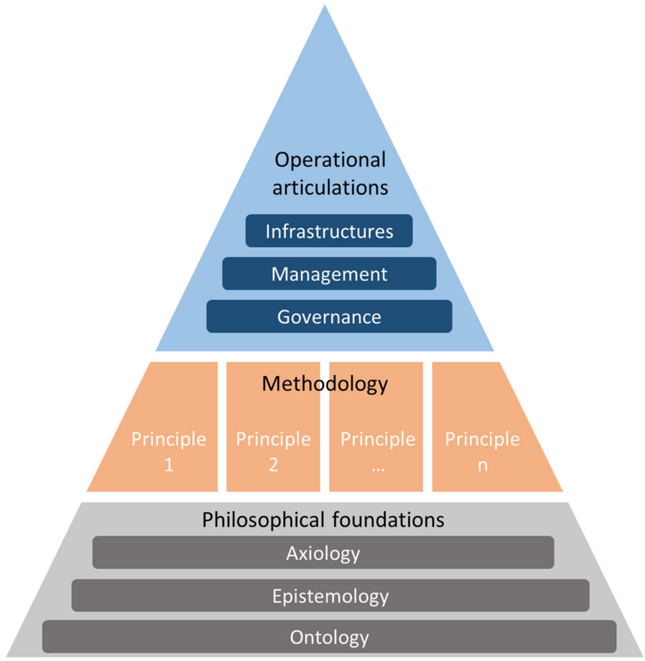


Figure 1. Urban water paradigm framework, encompassing three main categories and seven themes. Philosophical foundations (grey) provide the basis for methodological principles (orange), which further supports the operational articulations of UWSs (blue).

The first category, *philosophical foundations*, encompasses three themes that correspond with three nested branches of philosophy, which underpin both the broader social transformation and the sectorial transformation of the new urban water paradigm. These themes are rarely discussed explicitly in literature on UWSs. The first branch of philosophy, *ontology*, describes how the paradigm conceives the structure and nature of reality. The second, *epistemology*, expresses how knowledge about that reality is obtained. The third, *axiology*, describes the needs and values that guide actions. The description of these philosophical foundations builds on a theoretical argument that borrows elements from a wide range of disciplines, including science studies, philosophy, complexity studies, cybernetics or systems thinking.

The second category, *methodology*, encompasses a series of *methodological principles* that both reflect the paradigm's foundational philosophies and shape or orient the design of water governance, management, and infrastructures. These three elements are therefore referred to as *operational articulations* of an UWS.

The first operational articulation, *governance*, includes the social structures and practices that allow actors to work together in order to achieve common goals. The second, *management*, defines how interventions on the available resources are understood, planned, implemented, monitored and evaluated —within the rules and policies demarked by governance—in order to fulfill societal needs. And third, the design, construction, and operation of *infrastructure* mediates society with its natural environment and makes the management of resources possible. Infrastructure, at the top of the framework, represents the most tangible signature of an urban water paradigm, the tip of the iceberg, and serves as the mechanism for delivering urban water services.

In the following, we elaborate these different aspects of our framework, gradually moving from the abstract theory of ontology to the most practical examples of infrastructure of urban water systems. The sources that support the framework have been identified through a nonsystematic literature screening that included 148 key books and articles. The methodology of this search and the selected sources can be found in the supplemental material that accompanies this article.

In addition, the analysis and examples presented below juxtapose the old and the new urban water paradigm, making clear that both are holistic understandings of the world with their corresponding governance, management and infrastructure.

3. Philosophical foundations

3.1. Ontology

The understanding of reality that lies behind the old urban water paradigm—its ontology—is deeply influence by classical Newtonian physics (Dunn et al., 2016) and more concretely by its ontological reductionism (Biswas, 2004). This perspective describes the world as an orderly place where the similarities among elements are highlighted—and their dissimilarities neglected—in order to create a limited number of discrete and homogeneous categories. These elements are assumed to be poorly interconnected. Their relationships are linear—i.e. propagate change proportionally—and governed by few, simple, well-defined, deterministic, and immutable laws that provide simplicity and regularity, creating subsystems that are independent of their context and eternally oscillate within well-defined boundaries (Guba, 1990; Mazzocchi, 2016). All these characteristics suggest the metaphor of the world as a deterministic clockwork machine (Capra & Luisi, 2014; Heylighen et al., 2007; Human & Cilliers, 2013; Morin, 2007).

In contrast, the ontology of the new urban water paradigm is as a complex system (Coombes & Kuczera, 2002; Voulvoulis et al., 2017). This emphasizes the heterogeneity of elements and their strong interdependence, recognizing a holistic system behavior rather than focusing on the study of the individual elements in isolation (Ackoff, 1991). There is not a universally accepted definition of complex system (Mikulecky, 2001; M. Mitchell, 2009), but most agree they are profusely interconnected systems that can generate emergent behaviors. Individual component elements typically have multiple, short-ranged, and dynamic connections with neighboring elements (von Foerster, 2002). As a result, while the number of elements grows linearly, the number of links among elements grows exponentially (Cilliers, 1998; Heylighen, 1999). High interconnectivity also means complex systems are typically open, exhibiting rich interactions with its environment and making it difficult to delimit a boundary between the system and its context (M. Mitchell, 2009). This high interconnectivity renders in practice a dense and continuous reality that is constantly modulated, a space that is experienced as a continuous heterogeneity—what in physics is known as a *field*—with unique local properties. All these characteristics of complex systems facilitates the metaphor of the world as a *living organism* (Waldrop, 1993), rather than as a machine.

Despite the short range of interactions between neighboring elements, their rich connectivity allows the propagation, modulation and amplification of signals through long ranges, producing multiple circular causations and positive (reinforcing) feedback loops (von Bertalanffy, 1968). This provokes non-linear behaviors; very small signals can get amplified, resulting in unpredictable system-wide change (Kofman & Senge, 1993; Waldrop, 1993). Feedback signals can also be negative, providing temporal order and stability to the system by counteracting perturbations. However, this stability is superficial because complex systems are in a permanent dynamic state, which guarantees its survival: "Equilibrium is another word for death" (Cilliers, 1998, p. 4). Complex systems have a history and continuously evolve.

Interestingly then, complex systems are self-organizing; they lack a central controller (Prigogine & Stengers, 1997; Waldrop, 1993). They create new structures and behaviors at the macro level that could not be inferred from the local rules that govern the relationships of the entities and their individual properties. This phenomenon, characteristic of complex systems, is called emergence (Heylighen et al., 2007; Kauffman, 1995; Prigogine & Stengers, 1997) and can be easily recognized in systems like ant colonies, DNA, or markets. The human brain is also a good example: the study of individual neurons does not provide much information about the emergence of human consciousness.

This transformation of ontology permeates the water sector, which is today being widely understood as complex, non-stationary and susceptible to emergent behaviors at physical and social levels (Larson et al., 2015; Milly et al., 2008; OECD, 2015).

3.2. Epistemology

As for ontology, the quest for knowledge about the world in the old urban water paradigm is heavily influenced by the classical Newtonian physics, from which it inherits an *epistemological reductionism* (Morin, 2007). In the same way that one can disassemble a clockwork to understand its mechanisms, (epistemological) reductionism attempts to explain the functioning of a well-defined system by analyzing its constituent elements and their relationships. It involves the isolation of a subsystem from its context, its fragmentation in smaller parts, and their classification in homogenous categories. Then, it defines the relationship among parts to finally infer the "regular" behavior of the whole system, and predict its future state (Kofman & Senge, 1993; Mazzocchi, 2016). Relying on reductionism, the "apparent" complexity is never a hindrance for the acquisition of knowledge, as it is assumed that all systems can be reduced to simpler ones in order to be easily understood.

However, this reduction to simplicity does not eliminate complexity, it just makes it invisible by neglecting the particularities of the constituent parts, their rich and dynamic relationships, and their dependence on the context (Morin, 2007). Whereas reductionism may be an acceptable explanatory approach to well-defined and isolated problems (like basic water services), its utility to understand and predict complex, open, and dynamic systems (such as the urban water services demanded by industrialized societies today) is limited (Cilliers, 1998; Kofman & Senge, 1993).

Unfortunately, the distinction between simple and complex is not always straightforward (Andersson et al., 2014; Kurtz & Snowden, 2003). From the point of view of an observer embedded in a complex system, everything may appear simple: its own properties, the short-range relationships with its neighboring elements, and the extension of the system are known. However, this same observer is usually unaware about the dependence on its context, the feedback effects of its own actions, and the emergent phenomena at the system level. A complex system is, therefore, incompressible (Richardson & Cilliers, 2001); any model that perfectly mimics its behavior must be at least as complex as the systems themselves, easily surpassing the human capacity of understanding. Then uncertainty is not about external randomness, but rather about the observer's lack of knowledge (epistemic uncertainty) (di Baldassarre et al., 2016). This realization has influenced the epistemology of the new urban water paradigm, which has shifted from reductionism to holism, highlighting the contextual, dynamic, and always uncertain nature of knowledge.

In particular, the embracing of uncertainty is a key epistemological transformation. Relying on the power of reductionism and the deterministic nature of reality, the old paradigm is self-confident and predictive. It assumes that by carefully observing the past and accumulating knowledge about the mechanics of the system, it is possible to make accurate predictions and design optimal solutions, fostering the dream of a future without uncertainty. Contrarily, the new paradigm rejects simplicity, regularity, and the power attributed to reductionism. It focuses instead on open and dynamic systems, non-linear processes, emergent phenomena that are unpredictable, and the inability of the observer of acquiring the necessary knowledge (Allen et al., 2011; di Baldassarre et al., 2016; Heylighen et al., 2007; Morcol, 2001; Prigogine & Stengers, 1984).

Based on the perceived deterministic nature of reality and the power of reductionism, scientists and practitioners embedded in the old paradigm firmly believe they see the world "as it is"; that an objective reality exists "out there", to which they have direct access through careful observation, quantification, and reason. In this view, humans are external and objective observers that search for the unique truth awaiting to be unpacked (Morin, 1977; Zwarteveen & Boelens, 2014). As there is just one possible (rational) interpretation of reality, this has to be revealed by experts that apply supposedly rigorous and value-free scientific methods, yielding a context-independent knowledge that will unambiguously settle all disputes and orient policy design (Sarewitz, 2004).

Contrarily, the new paradigm recognizes that knowledge in a complex system is always imperfect and subjective because there are no fixed points of reference or external points of view. The observer is inexorably embedded in the observed system and any of her interpretations are inevitably situated and contextual (Cilliers, 1998; Prigogine & Stengers, 1984). For example, a complex system like the Internet cannot possibly be objectively and comprehensibly described by one user, who can only aim at providing a description of his use of the network and contextualized experience. Narratives, then, are effective ways to describe a certain aspect of a complex system, to provide structure and meaning under particular circumstances from a partial view, while still being coherent with the underlying objective reality (Lyotard, 1984).

Cilliers (1998) gives perhaps a better illustration of narrative knowledge by picturing a complex system as a dynamic network (Figure 2). A narrative forms one of multiple possible paths through the network that rest on the objective truth. These paths are just temporal framings, subjective interpretations of a connection between an input and an output, defined in terms of particular and temporal points of view, needs, and constraints.

The new paradigm recognizes the impossibility of finding the absolute truth and that strictly scientific knowledge built from the point of view of a single discipline has limited value. It focuses instead on "pragmatic" or "useful" truths (Pierce, 2011) that "work" in a certain context or situation.

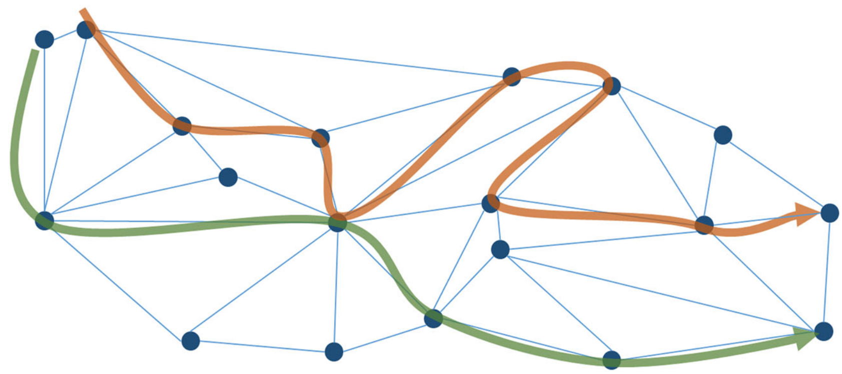


Figure 2. Alternative narratives (green and brown lines) provide situated explanations of a complex system (blue network) that do not necessarily contradict the underlying reality (the dots represent scientific "hard" facts). This figure is inspired by Cilliers (1998, p. 130).

They are *bricolage narratives* (Levi-Strauss, 1968) that integrate heterogeneous sources of information (Barbosa et al., 2012; Blanco-Gutiérrez et al., 2013; Croke et al., 2007) and have a practical relevance for concrete problems and needs. This "useful" truth is the only truth that will affect us, and the only truth that we may know (Bach et al., 2014; Gerlak, 2008; Harremoës, 2002).

The water management literature offers us multiple examples about the adoption of this new epistemology, advocating for participatory water management, multidisciplinary solutions, incorporation of uncertainty in planning, or continuous experimentation (Farrelly & Brown, 2011; Pan & Guo, 2019; Varady et al., 2016).

3.3. Axiology

In our review of ontology and epistemology we saw that the old urban water paradigm is essentially anthropocentric; the "external reality" is reduced to only those things that humans can observe or understand. Complexity and an ecological perspective are largely disregarded, largely due to the lack of the cognitive capacity (Simon, 1997) and analytical tools (Kellert, 1994) necessary to understand them. Unsurprisingly then, the fundamental values that steer behavior in the old paradigm (axiology) are also fundamentally anthropocentric; subsistence and (economic) growth. These are translated into a few universal, independent, and easily identifiable needs that typically include the provision of sufficient and safe drinking water, sanitation, and drainage (de Graaf et al., 2007; Gleick, 2000; Pahl-Wostl et al., 2011; Sofoulis, 2005), eclipsing any other "superfluous" needs.

This approach derives from an instrumental view of nature (Beck et al., 2003), which is regarded as a neutral context that lacks any intrinsic value. Nature is simultaneously seen as an unlimited source of resources, which generates a feeling of dominance for people, and as a constraining frame to fulfill human needs, which generates a feeling of fear related to the possibility of losing control of it (Wolfe & Brooks, 2017). The relationship with nature is, therefore, competitive. It is about nature's benefit or humans' benefit; a zero-sum game (Bernhardt et al., 2006). For example, there is a conflict between maintaining ecological flows of rivers and increasing abstractions of water to meet growing water demands.

The complex systems approach of the new urban water paradigm reveals that humans are not independent of their environmental context, but rather a part of it (Brooks & Brandes, 2011; Mebratu, 1998; Schmidt, 2013). Instead of competing with nature, humans must collaborate with it and design synergistic solutions that contribute to support human wellbeing (Bernhardt et al., 2006; Costanza & Daly, 1992; van Zeijl-Rozema et al., 2008; Zandaryaa & Tejada-Guibert, 2009). For example, during the last decade most industrialized countries have approved legislation that protect ecological flows in rivers in order to improve social welfare (EC, 2015; ICCATF, 2011). Therefore, the most salient values of the new paradigm are ecological sustainability and associated social welfare (sometimes referred as livability) (Garrote, 2017; Partzsch, 2009). This does not negate the importance of the values of the old paradigm, but expands them to include many others like physical and mental health, recreation, beauty, sense of community and social integration, equality, justice, or even cultural and spiritual values (de Haan et al., 2014; Ferguson, Brown, & Deletic, 2013; Marlow et al., 2013; Zwarteveen & Boelens, 2014).

The values considered in the new urban water paradigm are varied, ill-defined, subjective, interdependent (often conflicting) (Wong & Brown, 2009) and incommensurable. Therefore, it has become common praxis to lump them in the ambiguous concept of *sustainability*. This concept is not exclusive to the new paradigm; it has also been utilized in the old paradigm with a slightly different meaning. In line with the linear thinking of the old paradigm, sustainability has traditionally been understood as a static and objective goal or end-state, a point of optimal and static equilibrium in a perfect future where all needs are fulfilled in harmonic balance (Brown et al., 1987; Hardi, 1997). This is the so-called substantive sustainability (Truffer et al., 2010) and it is often reflected in sustainability indicators (UN, 2007; van der Steen & Howe, 2009; van Leeuwen, 2013) that provide a "deterministic single-criterion optimality" (Reed & Kasprzyk, 2009, p. 411).

In contrast, *procedural sustainability* (Truffer et al., 2010), which is more in line with the philosophical underpinnings of the new paradigm, acknowledges the dynamic nature of needs and values, and the complex system in general (e.g. Slocombe, 1990). In this interpretation, sustainability is an open-ended process—not a goal—that focuses on the available pathways to reach a moving target—a dynamic, socially constructed, unachievable ideal (Bagheri & Hjorth, 2007; Newman, 2005; Nonaka & Toyama, 2005; Voß & Kemp, 2006)—that must be constantly renegotiated within an evolving context (Robinson & Cole, 2015). Contrasting with the ambivalent feelings of dominance and fear that characterized the old paradigm, the new paradigm is associated with feelings of humbleness, hope and enthusiasm, guided by a utopic image of human welfare in perfect harmony with nature (Franco-Torres, 2020).

4. Methodology

Within a paradigm, a *problem* can be conceptualized as the factor that opens a gap between the present state and desired (optimal or sustainable) state where certain needs are effectively fulfilled. Building on the Merriam-Webster dictionary definition, this conceptualization leads to an understanding of *methodology* as "a body of methods, rules, and postulates employed by a discipline" to acquire knowledge or solve problems. Similarly, in the case of a paradigm, we interpret a methodology as a set of *(methodological) principles*, designed to modify or *regulate* the present state of things, solve concrete problems, and approximate to a desired state. These principles are shaped by the paradigm's philosophical foundations and used as a guide to define a *regulator*. From the point of view of cybernetics, regulators are sub-systems that locally constrain the variation of a wider system in which it is embedded (its sociotechnical-environmental context) within certain bounds in order to fulfill a certain set of needs (Ackoff, 1991; Ashby, 1956).

4.1. UWS as regulators of their context

An UWS can be conceptualized as a *regulator*. Urban water services like drinking water provision, sanitation or drainage require an UWS that regulates certain natural processes (basically to retain, convey, or treat water) with physical infrastructures (like dams, pipes, pumps and water treatment plants) and regulates certain social behaviors with social rules (like policies, guidelines, contracts, prices, technical standards and roles). To do so, the UWS, and more concretely its operational articulations (governance, management, and infrastructures), follow a set of characteristic methodological principles associated with each paradigm.

A core theorem of cybernetics, states that "*every good regulator of a system must be a model* [a replica] *of that system*" (Conant & Ashby, 1970, p. 89). Accordingly, the old urban water paradigm's methodology proposes an UWS that projects the stationarity and simplicity of its context and problems, while the new paradigm's methodology promotes an UWS that mimics the complexity and dynamism of its context and problems.

4.2. Tame problems vs wicked problems

In order to explain the methodological principles of each paradigm, it is convenient to describe first what problems they aim to solve, which clearly align with their respective ontologies.

For the old urban water paradigm, the simplicity of the world and the well-defined needs and values yield what Rittel and Webber (1973) call *tame problems*; simple, clearly structured, and static problems that are independent from other problems (Bagheri & Hjorth, 2007; Pahl-Wostl et al., 2011). Among several possible solutions there is always a unique optimal alternative—the "right solution"—an UWS configuration that has the capacity to solve the problem once and for all, which can be rationally inferred and that must be imposed as standard (R. R. Brown et al., 2006; Kreuter et al., 2004; Sarewitz, 2004).

The new paradigm focuses instead on *wicked problems*, which are complex, interdependent, unstructured, and pervasive (Rittel & Webber, 1973). There are infinite solutions to wicked problems but none of them are optimal or definitive—there are no silver bullets (Capodaglio et al., 2016; Ludwig et al., 1993). Whereas different solutions fulfill interlinked needs in variable degrees, being more or less attractive from different points of view (Kreuter et al., 2004), they also alter the system in a way that creates new problems elsewhere. Typical wicked problems in UWSs are the pervasive challenges that give rise to the need for a new paradigm, such as climate change, urbanization and non-point source pollution.

4.3. Methodological principles. From control to resilience

By focusing on a perceived existence of optimal and definitive solutions to tame problems, the old paradigm aims to build UWSs that function as rigid regulators based on prediction and control. These are able to withstand natural disruptions and change, keep homeostasis, and permanently fulfill a limited set of basic and independent needs in a de-contextualized environment (Capodaglio et al., 2016; de Bruijn et al., 2017; Pahl-Wostl, 2007).

From the perspective of the new paradigm this prediction and control approach is seen as a naïve delusion; it is considered not only ineffective, but also may result in unexpected and undesirable consequences (Holling & Meffe, 1996; Ludwig et al., 1993). For example, the straightening of rivers and construction of canals to facilitate urban development often results in greater flood risk (Castonguay, 2007; Wolsink, 2010). Instead, the new paradigm is inclined toward the development of *resilience* (Folke, 2006; Holling, 1973) as a regulative function to fulfill human and environmental needs.

Certainly, resilience has become a buzzword in academia and policy over the last decade, receiving varied—and sometimes contraposed—interpretations (Béné et al., 2014; Davoudi, 2012; Folke, 2006). For example, *engineering resilience* refers to the capacity of a system to quickly recover from a range of disturbances and maintain its ability to deliver its single intended function (de Bruijn et al., 2017; Holling & Meffe, 1996). This interpretation is more aligned with the old urban water paradigm, which aims to resist change by building up a threshold capacity to buffer contextual variations (Gleick, 2000), rigidly controlling the system and keeping it in homeostasis.

In contrast, the definition of resilience we attribute to the new paradigm, aligned with the concept of procedural sustainability, is the so-called *evolutionary resilience* (Davoudi, 2012). This resilience can be defined as the capacity of a regulatory system to continuously adapt to changes, identify synergies, and avoid conflicts with its environment in order to deliver a timely and convenient set of variable functions (Berkes et al., 2008; Simmie & Martin, 2010; Walker et al., 2004). This approach is radically opposed to the *control methodology* of the old paradigm and its engineering resilience, which seeks to force and dominate the environment to permanently yield a concrete output. Evolutionary resilience requires then relentless efforts of adjustment to ever changing values, knowledge and physical variables (Darnhofer et al., 2016; Takala, 2017), without losing fundamental structures that give continuity to the system (Herrfahrdt-Pahle & Pahl-Wostl, 2012). The design of flood-prone neighborhoods serves as a good illustrative example (Hale, 2016; Rode & Gralepois, 2017), where resilience is achieved through a range of measures (e.g. elevated buildings, flow-through neighborhoods, water storage, reduction of imperviousness) that reduce risks and simultaneous support new functions that improve urban livability.

We have identified four pairs of opposite principles that contrast the control methodology of the old paradigm and the resilience methodology of the new paradigm: stationarity vs learning, homogenization vs variety, fragmentation vs integration, and centralization vs distribution. Later we will explore how these four principles, shaped by the philosophical foundations of each paradigm, become reified as the operational articulations of the UWS.

4.3.1. Stationarity vs learning

To permanently dominate the environment and deliver a consistent service, the old urban water paradigm constrains the natural variability within

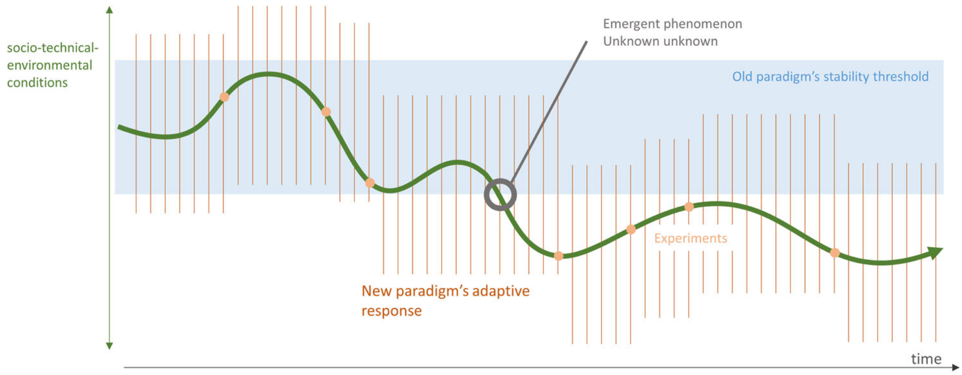


Figure 3. UWSs operate under non-stationary conditions (green line) (Milly et al., 2008). The old paradigm assumes stationarity; based on past behavior predicts that the conditions will remain within a certain range (blue stripe). Due to emergent phenomena (unknown unknowns (di Baldassarre et al., 2016)) the conditions unexpectedly move out of the predefined stability threshold. Contrarily, the new paradigm does not assume a fixed stability threshold, but continuously experiments (brown dots) to temporarily adjust to new conditions (brown vertical bars).

predetermined bounds, forcing it to be stationary (Gleick, 2000; Schoeman et al., 2014). This is done in practice by, for example, constructing large hydraulic infrastructures like reservoirs for water storage, desalination plants, or dikes for flood retention. In this conservative approach, the reliability of infrastructures stands out as the main issue since a loss of control is potentially catastrophic. There is an aversion to uncertainty and risk, relying on only well-known, standard, and fail-safe methods that stifle innovation and experimentation (Brown & Farrelly, 2009; Farrelly & Brown, 2011; Harremoës, 2002).

Contrarily, the new paradigm sees stationarity in UWSs as a problem rather than a solution, since it promotes a non-responsive regulation, neglecting the emergence of new needs and the evolving nature of context (Figure 3). Constant learning by doing—i.e. relentless experimentation (Allen et al., 2011; Farrelly & Brown, 2011; Kato & Ahern, 2008; Moberg & Galaz, 2005; Vreugdenhil et al., 2010)—is a preferred methodological principle that pragmatically reveals convenient ways to adapt to a dynamic and uncertain context. Small experiments purposefully create controlled instabilities and low-regret alternatives where it is safe to fail (Hashimoto et al., 1982; Holling, 1973), fostering innovation and anticipating emergent events, allowing the timely adaptation of an UWS to its environment (Conant & Ashby, 1970). However, learning not only requires proactive and persistent experimentation, but also the acceptance of uncertainty, tolerance of failure, constant monitoring, sensitivity to recognize change, trends and opportunities, reflexivity to continuously reconsider frames and goals, and the flexibility associated with the capacity to abandon old practices and structures and incorporate new ones (Burnham et al., 2016; Gunderson & Holling, 2002; Jiggins et al., 2007; Schelfaut et al., 2011; Wolsink, 2010).

In contrast to the predictive approach of the old paradigm, the new paradigm turns to other type of learning that could be called *abstract experimentation* (also referred as *possibilistic thinking* (Clarke, 2008), *what-if analysis* (Brown et al., 2015), or *counterfactual thought experiments* (Klotz & Horman, 2010)). This type of experimentation consists of creating a range of hypothetical future scenarios (Ingram & Lejano, 2007; Novotny et al., 2010; Schoonenboom, 1995), typically narratives of success (dream scenarios) or narratives of failure (nightmare scenarios) that project backwards to the present, providing guidance for action.

4.3.2. Homogeneity vs variety

In cybernetics, the term *variety* refers to the total number of states in which a system can exist (Ashby, 1956). The *law of requisite variety* (Ashby, 1956, 1958) postulates that the greater variety of responses a regulator can perform (like policies, rules, management solutions, or infrastructures), the greater variety of disturbances the system is able to successfully adapt to.

The old urban water paradigm assumes the context to be simple and regular, making a large variety of regulatory responses a burden rather than a solution. Conversely, the new paradigm confronts a complex context and therefore fosters a larger variety in its constituent elements (Aerts et al., 2008; Wong & Brown, 2008) in order to enhance its capacity for local adaptation and innovation, efficiency or redundancy (R. Biggs et al., 2012; Keath & Brown, 2009).

The new paradigm promotes a many-to-many relationship between needs and solutions. A combination of interdependent interventions of different nature and scale (Marsalek & Schreier, 2009; Pahl-Wostl, 2007) provide a suboptimal and temporary accommodation of multiple, diffuse, ever-changing, and interdependent needs (Capodaglio et al., 2016; Gonzales & Ajami, 2015; Werbeloff & Brown, 2011), which also are deeply embedded in their unique local context (Coombes & Kuczera, 2002; Dunn et al., 2016; Liu et al., 2007).

4.3.3. Fragmentation vs integration

The old paradigm rests on the underlying assumption that both the regulatory system (the UWS) and its regulated context can be divided in isolated subsystems that perform easily identifiable functions. These individual elements can be locally optimized and reassembled to produce universal optimal solutions (Schoeman et al., 2014; Wong & Brown, 2009). Accordingly, the *fragmentation principle* (*methodological reductionism*) becomes a prerequisite for prediction and control (Capra & Luisi, 2014; Turton & Meissner, 2002).

However, during the last two decades it has become widely accepted in the water sector that fragmentation in governance, management and infrastructures is a serious barrier to sustainability (Mukhtarov, 2008). Fragmentation represents the negation of the systemic nature of reality and implies an artificial rupture of connections, generating confrontations, interferences, inefficiencies, and risks (Brown & Farrelly, 2009; GWP, 2000; Ioris, 2008; OECD, 2016)

Integration, on the other hand, reinforces the systems ontology of the new urban water paradigm. Focusing attention on the dynamic relationships among parts and with their context (being context-sensitive), it produces a holistic view that is more likely to produce (evolutionary) resilient outcomes than a fragmented one (Gonzales & Ajami, 2015; Hardy et al., 2005; Varady et al., 2016; Wong & Brown, 2009). It can, for example, facilitate the development of coordination and synergies (R. Biggs et al., 2012), reduce tradeoffs and conflicts (Pahl-Wostl et al., 2008; Wolsink, 2006), suppress vulnerabilities (Gober, 2010; Pahl-Wostl et al., 2007), allow autoregulation, and foster serendipity (Darnhofer et al., 2016; Merton & Barber, 2011).

4.3.4. Centralization vs distribution

Despite its tendency toward fragmentation, the structures of the old paradigm are not completely disconnected. They exhibit centralized designs of control that excel at top-down integration where a central node concentrates resources. Still, centralized systems rely on fragmentation and homogenization. This is the typical scheme of networks of water distribution dependent on a single water treatment plant, or organizational schemes in hierarchical organizations dependent on a single leader.

Opposing centralization, many scholars argue that the new urban water paradigm supports *decentralization* (Daigger, 2009; Larsen et al., 2013; Leigh & Lee, 2019; Zhang et al., 2009), which implies that the whole system is not dependent on a central node, with the elements of the UWS geographically dispersed and often working in isolation. This claim is in line with the principle of variety, however, it opposes integration. Strictly speaking, decentralized sets of elements do not constitute a system because they may be disconnected—for example, a single household that exclusively relies on a private water well.

Instead, we argue that the varied and integrated regulatory systems of the new paradigm are actually *distributed* (Baran, 1964) (Figure 4). Distribution, as decentralization, implies that the elements of the system

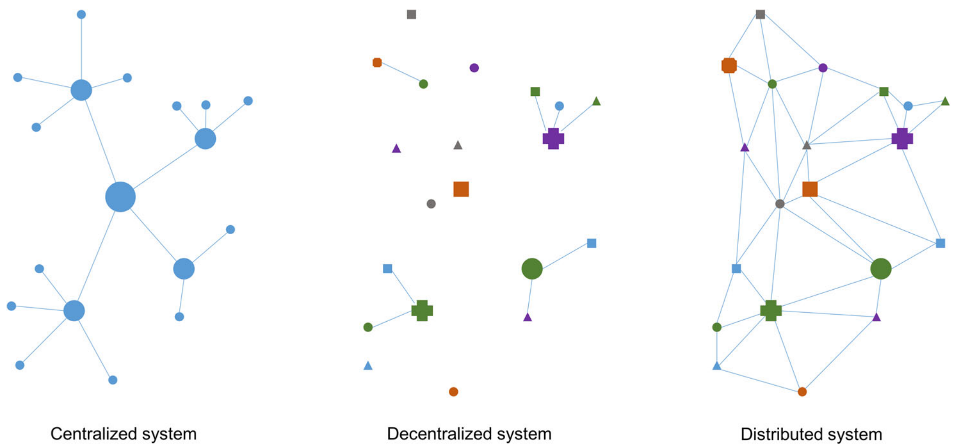


Figure 4. Types of system configurations. Adapted from (Baran, 1964). The points indicate units of production or consumption (differences in shape, size and color indicate their homogeneity), while the lines indicate their links to exchange resources and information.

are not exclusively dependent on a central node and that the nodes are geographically dispersed, but in addition it requires that the elements are connected to exchange resources and information to (ideally) all adjacent elements (Baran, 1964; Ryan, 2009). These "nodes" are semi-autonomous agents, meaning that they "work" at a range of scales; they both function autonomously, and they function as a part of a larger system generating emergent behaviors. Distributed systems are in general terms more resilient than both centralized and decentralized systems (C. Biggs et al., 2009; Chanan et al., 2009). They reduce risks, increase efficiency, and are more flexible and adaptable (Baran, 1964).

5. Operational articulations

Earlier, we conceptualized UWSs as regulators of their context that aim to solve water-related problems and fulfill water-related needs. They include aspects of governance, management, and infrastructures that reify some methodological principles, which in turn are shaped by the philosophical foundations of their corresponding paradigm.

In the old urban water paradigm, UWSs are meant to fulfill few, well-defined, immutable and non-contested needs (like drinking water provision, sanitation, and drainage) (Pahl-Wostl et al., 2011). This means that in order to achieve those well-defined goals, old management focuses on how to physically control nature and keep it within optimal bounds. The UWS of the old paradigm is therefore largely a material or technical issue (Saurí & del Moral, 2001; Swyngedouw, 1999).

In contrast, the new urban water paradigm sees water not only as a material issue, but also as a social issue (Zwarteveen & Boelens, 2014). It considers a variety of ill-defined and often conflicting needs in an ever-changing context that must be navigated and accommodated with help of good governance (Mguni et al., 2015). Indeed, recent literature widely acknowledges that water problems are mostly problems of governance (Bucknall et al., 2006; OECD, 2016; Pahl-Wostl, 2015; van Dijk, 2012).

5.1. Governance

The old paradigm assumes that it is possible to rationally design a simple and rigid institutional framework that provides guidance toward the optimal fulfillment of a few universal and undisputed water needs, including a small set of formal rules that keep human behavior in check—largely ignoring social or cultural variability (Bakker, 2010; Ioris, 2008; Pahl-Wostl, 2008).

The design of this rational system of rules and policies is the duty of a select group of actors with well-defined roles (the government) that are organized in rigid, centralized, hierarchical structures. The final decision-makers—usually politicians—are at the top, far from the resources that are being managed (Castonguay, 2007; Chandler, 2014), and carry the ultimate responsibility for water services (Turton & Meissner, 2002). They concentrate the authority, power, legitimacy, and information to rationally control the system by imposing formal coercive rules (Bakker, 2010). These decision-makers are supported by experts (Brown, 2005)—often engineers (Ingram & Schneider, 1998)—who have access to the "unique" truth. At the bottom of the hierarchy are the operators and consumers, whose participation in the policy design and rule-making is deemed as unnecessary or even detrimental (Bagheri & Hjorth, 2007; Schoeman et al., 2014; van Dijk, 2012), as the "right" technical decisions are already defined by experts: the beneficiaries of urban water services are mere rule-followers (Turton & Meissner, 2002).

However, when the old style of governance tries to engage with growing institutional complexity, where stakeholders have conflicting values, interests, agendas and horizons, sector-specific policies and rules become contradictory (Zandaryaa & Tejada-Guibert, 2009); governance becomes fragmented and multiple contestations and interferences emerge (Brown & Farrelly, 2009; Segrave et al., 2014). Governance problems become wicked.

The new paradigm fully recognizes that these problems transcend science and technology (Funtowicz & Ravetz, 1993; Weinberg, 1972) and cannot be optimally and permanently solved, fostering instead the coherence of local governance with its social context (Gonzales & Ajami, 2017; Neto, 2016; Wade, 2011) and the internal integration of policies and rules that affect the UWS. This integration requires wide participation of all actors

(Brandes & Kriwoken, 2006; Carr et al., 2012; Zandaryaa & Tejada-Guibert, 2009), with active engagement on the definition of problems and the design of coherent and synergistic policies and rules across sectors (Ananda & Proctor, 2013; Everard & McInnes, 2013; Mitchell, 2006). More concretely, participation is deemed essential to: gather diverse resources, skills, knowledge, values, interests and needs (Allon & Sofoulis, 2006; Arnold, 2013; Jameson & Baud, 2016; Rijke et al., 2013; van der Brugge, 2009; van Dijk, 2012); harness enthusiasm and commitment (Patterson et al., 2013; Sofoulis, 2015); provide transparency, trust, and equity (Dietz et al., 2003; Domènech et al., 2013; Hahn et al., 2006; Wolsink, 2010); and confer legitimacy on the selected alternatives (Hering et al., 2013; Sofoulis, 2015).

This *new governance* (Osborne, 2010) is distributed in clusters (also referred to as *network* or *polycentric governance*). These clusters create partnerships between diverse actors through interactions to find synergies and negotiate conflicting interests (Bos et al., 2015; Pahl-Wostl et al., 2008; Torfing et al., 2012). For example, between public agencies specializing in different sectors (not only for water provision, sanitation, or flood prevention, but also other sectors like transport, energy, urbanism and recreation), private actors (like technology providers, consultants or land developers), research actors (like universities and research centers) and civil society organizations (like NGOs and neighborhood associations). These interactions are conducted not only through formal relationships, but also through informal (shadow) networks (Bos et al., 2015).

At the same time, there is a shift from the few rigid roles in the old paradigm to a wide variety of overlapping and flexible roles. For example, government agencies like water utilities are not only *supply developers,* but also *resource custodians* and *information providers* (Brown et al., 2009; Pires, 2004; Prasad Pandey & Kazama, 2014). For distributed infrastructures, consumers also become producers (*prosumers*) (Novotny et al., 2010; Sofoulis, 2015) of their own water supply or wastewater, and private competitors also become collaborators to achieve synergistic solutions. All those actors are dependent on each other to fulfill their duties and goals. For example, public water utilities are often dependent on private contractors or consultants to deliver the desired water service.

Hence, governance in the new paradigm is not the exclusive function of the government (Gleick, 2000; van de Meene et al., 2011; van Dijk, 2012); it is the collaborative effort of a group of actors with access to power, legitimacy, information, and knowledge in varying degrees, which aim to carry out enterprises that often involve conflicting interests (Costa et al., 2012)—water services become everybody's responsibility (Turton & Meissner, 2002). The outcomes of this distributed governance are collaboratively created and emergent, instead of rationally planned by an elite (Bos & Brown, 2012). Therefore, pragmatic solutions arise from a learning approach that involves participation, continuous experimentation, monitoring, and revision of strategies, policies and rules (Bos & Brown, 2012; Hukka & Katko, 2015; Jameson & Baud, 2016; OECD, 2011). Policies are not fixed solutions, but instead "questions masquerading as answers" (Gunderson, 1999).

5.2. Management

The regulative function of management in the old urban water paradigm has a clear bias toward simplification and homogenization. For example, water is classified in binary: it is either fit or unfit for consumption, it is a resource or a waste (Bindra et al., 2003; Partzsch, 2009; Pinkham, 1999). Potable water, the highest water quality, is employed for all purposes (*one-size-fits-all*), including drinking, irrigation and toilet flushing. After its use, it is considered a waste and conveyed to the sewer, regardless of its quality or new characteristics. Compare this with the new urban water paradigm, which considers that all water is valuable, even when it is of low quality (Listowski et al., 2009; Wilcox et al., 2016). Here, water of the highest quality is used for human consumption, while lower quality water can be used for different non-consumptive purposes by matching it with their intended use (*fit-for-purpose*) (Gikas & Tchobanoglous, 2007; Lee & Tan, 2016; Makropoulos et al., 2018).

Another example is stormwater, which, in the old paradigm, is always considered a nuisance that must invariably be drained away by underground pipes—the only and standard structural solution. Conversely, in the new paradigm stormwater is seen as a valuable resource that contributes to improving urban amenity (Martin et al., 2007). Stormwater management tools are also manifold (Chocat et al., 2001; Hale, 2016; Marsalek & Schreier, 2009; Meinzen-Dick, 2007), including structural and technical solutions (like various green infrastructures or more traditional infrastructures), economic incentives and disincentives (like markets, insurances, innovative rate structures, taxes, rebates, or subsidies), or sociopolitical instruments (like benchmarking systems, educational and behavioral programs, water rights, changes in routines, or even organizational reforms).

The few, simple problems and solutions considered by the old paradigm are managed as if they were independent from other subsystems, while the new paradigm pays attention to the linkages between multiple problems and multiple solutions. For instance, while drinking water provision, sanitation, and urban drainage have traditionally been managed as independent subsystems in the water sector (Anderson & Iyaduri, 2003; Mukheibir et al., 2014), the new paradigm focuses on the coordinated management of these water services (Mitchell, 2006; Ross, 2018; Vairavamoorthy et al., 2015). Stormwater can be a source of drinking water (Campisano et al., 2017; Sharma et al., 2013; Sofoulis, 2015), leaky sewers can pose a pollution risk for water supply, and wastewater can be used to refill groundwater aquifers (Binz et al., 2016; Evans & Evans, 2012).

The fragmentation (methodological) principle of the old paradigm is also reflected operationally in other ways. For example, water management is usually approached through the individual lens offered by a particular discipline or functional silo (like hydraulics, hydrology, biology or economics) (Brown, 2005; Brown & Farrelly, 2009; Garrote, 2017; Saraswat et al., 2017). These predict the behavior of a few environmental variables and describe clear, linear paths of action to accomplish their objectives independently of other goals or constraints (Deng et al., 2013; Loorbach, 2014). Another example of fragmentation in management is the separation of UWSs from natural processes (its context), which must be understood, predicted, and tightly controlled. In practice, this means that natural processes not directly benefitting human interest must be disrupted or constrained, and substituted by rationally designed linear processes that permanently fulfill a fixed set of human needs (Bagheri & Hjorth, 2007; Brandes et al., 2005). For example, the natural water cycle is disrupted and converted to an artificial one-path-flow process (Daigger, 2009): raw water (the input) is abstracted from far locations where it is easily accessible (the "external" context), transported through long distances (often by interbasin transfers) (Domènech et al., 2013; Gleick, 2000; Saurí & del Moral, 2001), treated and distributed, consumed and polluted (the output), and discarded as waste back to nature (the "external" context) (Bindra et al., 2003; Everard & McInnes, 2013; Rojas et al., 2015; Takala, 2017). This linear flow creates an illusion of resource abundance (Stuart, 2007), in which higher demand urges increased raw water abstraction from the environment (Gleick, 2003; Saurí & del Moral, 2001).

In contrast, the integration (methodological) principle of the new paradigm invites a style of management that is context-sensitive and mimics or allies synergistically with natural processes of cyclical character (Byrnes, 2013; Zandaryaa & Tejada-Guibert, 2009), rather than a parallel linear process of environmental control (Hering et al., 2013; Niemczynowicz, 1999). For instance, it mimics circular natural processes where water—together with its associated energy and nutrients—is recovered or recycled to remain part of the system, as there is not an "outside" where it can be infinitely extracted or disposed (Anderson, 2003; Gondhalekar & Ramsauer, 2017; Haase, 2015; Hoff, 2011; Pennisi, 2012; WWAP, 2017). Following this logic, the concepts of *waste* (for wastewater) or *nuisance* (for stormwater) become obsolete because any element is eventually recycled and should be rather seen as a potential resource

(Arden et al., 2019; Chocat et al., 2001; Grant et al., 2012; Ma et al., 2015; Novotny et al., 2010), use of which saves costs, prevents pollution and avoids the depletion of their sources (Chanan et al., 2013; Hemmes et al., 2011; van der Hoek et al., 2016; Wallace et al., 2017).

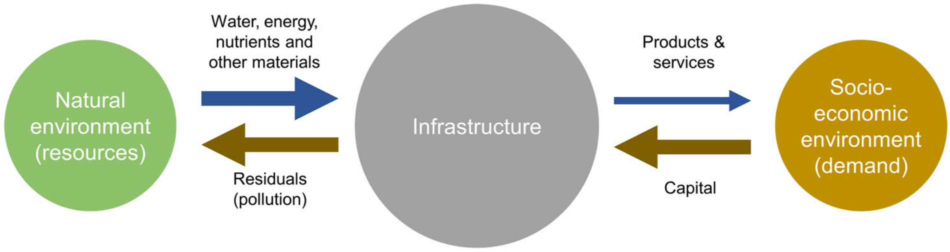
This type of management approaches also aligns with so-called nature-based ("green") solutions for water (WWAP, 2018), which utilize ecosystems that can potentially deliver any water-related service that humans might require (MEA, 2005; Schuch et al., 2017)—for example, flood risk management and natural drainage (Pappalardo et al., 2017), water purification (Everard & McInnes, 2013), urban cooling (Norton et al., 2015; Schmidt, 2010), support of biodiversity (Filazzola et al., 2019), or even enhancement of physical and psychological health (Tzoulas et al., 2007)—often with lower costs and higher efficiencies than those of the "grey" solutions. Context-sensitive management requires then a local management style that benefits from intimate knowledge of local characteristics (like ecology, geomorphology, infrastructures, urban form, demographics, rules, standards and cultural characteristics) seen from an integrated perspective (Ferguson, Brown, & Deletic, 2013; Marlow et al., 2013; Mitchell, 2006; Rygaard et al., 2014).

Finally, management planning clearly reflects an epistemological transformation in shifting from the old to the new urban water paradigm. The old paradigm relies on isolated mathematical models that are regarded as prediction machines to find optimal solutions that unambiguously point toward the "right" course of action. Contrast this with the management planning of the new paradigm, which aims at producing pragmatic illustrations of reality (Bach et al., 2014; Deletic et al., 2018; Schmitt & Huber, 2006) and does not dismiss predictive models but combines them in a process of iterative and situated bricolage. It integrates their results (Brouwer & van Ek, 2004; Croke et al., 2007; Zhou, 2014) to produce hypothetical scenarios and narratives that improve the understanding of complex UWSs and support—but never settle—the decision making process (Bagheri & Hjorth, 2007; Rygaard et al., 2014; Westley et al., 2011).

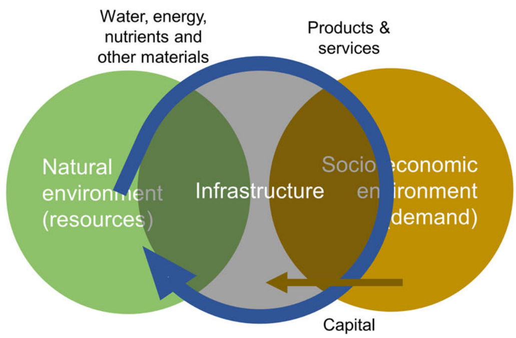
5.3. Infrastructures

Infrastructures are the physical manifestation of urban water paradigms, reflecting their understanding of reality, relationship with nature and most important needs and values.

Considering that the old paradigm aims at physically forcing natural processes into certain linear processes to fulfill human needs, it is not surprising that in this frame, UWSs becomes a mechanical and technocratic issue (Capodaglio et al., 2016; de Bruijn, 2004; Wolsink, 2010), with focus



a) Infrastructure systems in the old urban water paradigm



b) Infrastructure systems in the new urban water paradigm

Figure 5. (a) In the old paradigm, hard infrastructures are the dominant factor, the socioeconomic environment is perceived as simple, and the natural environment is reduced to a container for the resources that need controlling and as a sink for residuals. Linear production (one-way flow) results in the depletion of resources and the proportional creation of pollution. The products and services produced are few and the capital costs high. Adapted from Sahely et al. (2005). (b) In the new paradigm, infrastructures merge with the complex socioeconomic and natural environment, supporting circular flows of resources without residuals, and generating multiple products and services. The capital compromised is low as the system is more efficient and self-sustaining.

on the construction of robust infrastructures (normally built from concrete, plastic or metal materials) (Pinkham, 1999).

Conversely, in the new paradigm, the concept of infrastructure acquires a wider meaning, merging technical and environmental elements that build synergies with its social and environmental context (Fletcher et al., 2015; Goonetilleke et al., 2005; Masi et al., 2017; Novotny, 2009). For example, infrastructures benefit from ecosystem services (Carlson et al., 2015; Fletcher et al., 2015) and strengthen popular values in our contemporary society like livability and sustainability, shaping and supporting certain social identities and social behaviors (A. Amin, 2014; Bell, 2015) (Figure 5).

The old paradigm's infrastructures are large and robust constructions with definite and long lifespans (Sharma et al., 2010). They respond to the need to withstand and dominate nature, create optimal economies of scale, and support professional management by technical experts. They exhibit a limited repertoire of standard, independent, and discrete elements that perform only one function—generally of hydraulic character—and are linearly connected in centralized schemes (Ashley et al., 2015; Everard & McInnes, 2013; Partzsch, 2009; Pinkham, 1999). Typical examples are large water treatment plants, urban channels, or dams.

On the other hand, infrastructures of the new urban water paradigm are distributed (Fane, 2005): varied, decentralized, and integrated (Chanan et al., 2009; Chocat et al., 2007; Makropoulos & Butler, 2010; Mitchell, 2006; Sharma et al., 2010). They form richly connected networks that continuously exchange resources and information (Yuan et al., 2019). These networks encompass locally adapted and semi-autonomous elements (Novotny, 2009; Rygaard et al., 2011) that have multiple forms and sizes (Fryd et al., 2010; Novotny et al., 2010; Saurí & Palau-Rof, 2017), are made with natural and artificial materials, perform and contribute to circular processes, and continuously fulfill multiple functions at multiple scales (Fletcher et al., 2015; Gill et al., 2007; Novotny et al., 2010; Pappalardo et al., 2017; Semadeni-Davies et al., 2008; Sharma et al., 2013). They conform organic systems in constant adaptation that can be regarded as ephemeral infrastructures with indefinite lifespans (Capodaglio et al., 2016; Chanan et al., 2010; Vieira et al., 2014).

While the infrastructure of the old paradigm is comprised of independent elements, invisible to the public (often buried, like pipes, or in distant locations, like treatment plants), and detached from its context, the new paradigm exhibits ubiquitous networks firmly embedded in the city fabric and environment, intentionally visible and representing a vital part of the public life (Bernhardt et al., 2006; Brandes & Brooks, 2007; Gleick, 2003; Pahl-Wostl et al., 2011; Saurí & del Moral, 2001). For example, stormwater managed at a catchment scale with a distributed network of green roofs, swales, or urban creeks that support biodiversity, provide an esthetic value, trap pollutants, act as temperature regulators for the city, or diminish the peak runoff under a storm (Andoh et al., 2008; Berardi et al., 2014; Schuch et al., 2017; Wong & Brown, 2009).

Advocates of distributed infrastructures argue that they are more resilient than centralized systems for several reasons. First, because they make possible a locally tailored management approach with solutions that efficiently adapt to multiple contexts, purposes or types of resources (Chanan et al., 2013; Díaz et al., 2016; Keath & Brown, 2009; Leigh & Lee, 2019; Wolsink, 2006). Second, because their modular nature gives them a sensitivity and scalability that efficiently allow the system to adapt to changing circumstances (Amin & Han, 2007; Gikas & Tchobanoglous, 2007; Marlow et al., 2013). Third, because they work on the basis of redundancy and complementarity of other solutions at multiple scales, minimizing risk and providing alternative functions (Andoh et al., 2008; Gonzales & Ajami, 2017; Marlow et al., 2013; Werbeloff & Brown, 2011; Wong & Brown, 2009).

A disadvantage of distributed systems is that they develop slowly (Baran, 1964). Therefore, in practice, distributed water infrastructures are most often implemented as a supplement to existing centralized systems, which serve as the backbone that connects all nodes (Ferguson, Brown, Frantzeskaki, et al., 2013; Lee et al., 2013; Porse, 2013). However, it is expected that, with time, the local stations turn to be the main centers of production and consumption. This is the case of urban drainage systems, for example, where local infrastructures for stormwater management are built today to support the traditional centralized system, but eventually will manage most of the stormwater locally in a distributed fashion (Saurí & Palau-Rof, 2017).

6. Discussion and conclusion

In this paper, we articulate a coherent and holistic set of ideas, values and assumptions that are shaping urban water innovations that aim to respond adaptively to the non-stationary nature, uncertainty and emergent needs of our current society. This description is intended to equip water scholars, policymakers, and practitioners with a frame of reference to understand and embrace the benefits of novel styles of governance (like participative approaches), management (like circular use of resources) and infrastructures (like solutions based on ecosystem services). The articulation of the new paradigm that we provide may also offer concrete guidance for action and decision making to these actors when defining the types of governance arrangements, management systems, and infrastructures needed to improve the sustainability of UWSs in complex contexts; namely, promoting variety, integration, distribution and constant learning. For instance, scholars could be encouraged to consider problems from the lens of different disciplines; policymakers could open decision processes for participation by multiple stakeholders and the creation of intersectoral policies; and practitioners could continuously experiment with distributed infrastructures that simultaneously deliver multiple functions, complement each other, and build synergies with nature.

In developing the urban water paradigm framework, we have aimed to be coherent but not necessarily comprehensive, as the depth of the paradigm cannot be fully encapsulated in a single article. The characterization of the new paradigm that we present in this article should be regarded then as a heuristic tool or an ideal type (Doty & Glick, 1994); an idealized model that does not exist exactly as described anywere in the world, but that serves as a benchmark to recognize and create innovative approaches that help to address emerging challenges in the water sector. Therefore, future studies that analyze the degree of implementation of these new styles of governance, management, and infrastructure could provide valuable insight into the key enablers and strategies that have helped enact the key methodological principles in practice.

Finally, we reflect on the parallel shifts being experienced in other parts of society as part of a broader paradigm change. According to recent literature, most sectors—like energy (Geels et al., 2017; Verbong & Geels, 2010), health (Johansen & van den Bosch, 2017), and education (Yarime et al., 2012)—are experiencing similar transitions toward more sustainable modes of production and consumption (Loorbach et al., 2017). These transitions reflect the same underlying changes in society that drive the transformation of the water sector, and share multiple aspects with the new urban water paradigm—like promotion of diversity, learning approaches, distributed structures, or greater citizen participation. The construction of a more solid definition of the new urban water paradigm would benefit from a deeper analysis of the roots of this broader societal change through further research.

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