Science-design loop for the design of resilient urban landscapes

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Abstract

Urban landscapes face significant challenges, as they must transform towards sustainability while remaining resilient. Urban landscape transformation is a complex task for landscape designers. They must not only create new solutions for landscapes but also ensure that their proposals are capable to deliver and maintain key ecosystems services over time and especially after shocks. In practice, designers must increase their dialogue with scientists and engineers to include expertise on ecosystems functions and services. Through science-design feedback loops, designers can be challenged by scientists' models and simulations and thus create informed designs. Lastly, stakeholders also catalyse key steps of such a process, in particular by providing local expertise as well as co-constructing and validating the informed designs. In this paper, we introduce a roadmap, centred on an intensive interdisciplinary dialogue – a science-design loop. We illustrate the relevance of this roadmap with the analysis of five case studies about flood management and blue-green infrastructures. We analyse them according to the main steps of our roadmap and with the support of key interviews with experienced practitioners. First, this analysis provides an overview of best practices and challenges in the current urban landscape design world. But above all, we show the relevance of the proposed roadmap to muster science and design in a balanced manner in urban transformations.

Keywords

urban landscape transformation; science-design loop; interdisciplinary dialogue; blue-green infrastructures; flood management

1. Introduction

We live in the urban century. Humans have become an urban species (Elmqvist et al., 2019; Folke et al., 2021). Cities account for 60% to 80% of worldwide energy consumption, generating as much as 70% of human-induced greenhouse gas emissions, and being the site of more than 80% of global economic activities (OECD, 2010). While cities offer tremendous opportunities to thrive, the pressures of rapid urban growth on the global environment are challenging the design, planning, and management of cities for meeting human needs for health and well-being. Environmental changes interact in complex ways with human-driven processes within and across scales creating new forms of Anthropocene risks (Keys et al., 2019). Management of such risks is further complicated by complexity, non-stationarity and inertias in urban social-ecological-technological

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systems with self-reinforcing feedbacks that can create both desirable and undesirable outcomes (Olsson et al., 2017; McPhearson et al., 2021). The urgency of developing innovative interdisciplinary approaches to provide societally valued and needed qualities has become central on the agenda of recent UN-led initiatives such as the Sustainable Development Goals, the Inter-Governmental Panel on Climate Change, and the New Urban Agenda.

Design is increasingly being recognised as common ground among practitioners to help shape cohesive and socially acceptable urban development projects, and accelerate their implementation. Design is a course of action that formally expresses culture and socioeconomic factors (Herrington, 2016, pp. 12–33), envisions existing situations into preferred ones (Steinitz, 2008), and integrates creative and aesthetic meaning with functional purpose (Stokman & Haaren, 2011). Yet, pressing needs for functioning solutions and restrained budgets have often left little room for creating place-specific responses and negotiation between ecological or economic goals with other design factors such as cultural context, public amenities, and safety. The concept of "experimental design", promoting the use of design projects in ecological experiments, has already been advocated at the start of the millennium (Palmer et al., 2004; Felson & Pickett, 2005; Nassauer, 2005; Steenbergen, 2008). Also Cook et al., (2004) showed how an urban landscape design can be treated as an experimental substrate to help test the ecological effects of different strategies using adaptive experimentation. Nassauer & Corry (2004) employed it to simulate the effects of alternative landscape design and management strategies on water quality and biodiversity. Nassauer then developed with Opdam a new framework linking process and design for landscape change (Nassauer & Opdam, 2008). The growing field of Geodesign also builds on using science in decision making and vice-versa (Steinitz, 2012; Batty, 2013) to enable dialogue between holders of local and technical knowledge and fostering creative thinking between local stakeholders and scientists (Oteros-Rozas et al., 2015). In recent years, the approach entered the urban ecological community showing the effectiveness of a transformative model that iteratively links urban design and ecology to foster an inclusive, creative, knowledge-to-action process (Vollmer, Costa, et al., 2015; Urech et al., 2020); particularly if the iterative design-science process is embedded in a civic discourse.

Among the designer options to build greener cities are nature-based solutions like blue-green infrastructures that have tremendous potential to help achieve urban sustainability (Brears, 2018; Gottwald et al., 2021). These infrastructures can support water quantity and quality management, provide recreational opportunities and reduce heat load (Žuvela-Aloise et al., 2016; Carter et al., 2018; Chan, Griffiths, et al., 2018). In lower-income communities, they are essential to cover basic needs such as food, water, and sanitation services (Vollmer & Grêt-Regamey, 2013). Yet, consumption of these services often comes along with exposure to higher flood risk and other water-related health hazards. While many growing cities are slowly beginning to rehabilitate degraded waterways, budgets are mostly spent on engineering and construction efforts aiming to enhance the physical capacity of the river, discounting the opportunities to enhance the provision of the other life-sustaining ecosystem services (de Oliveira Rolo et al., 2021).

Interestingly, while the workflows followed by engineers, scientists and designers involved in such processes have many similar steps, they often are conducted independently, rarely exchanging their products in the phase of conception. Designers, who aim at creating place-specific responses to express particular values, miss an opportunity to test the performance of their designs, whereas engineers and scientists successfully produce knowledge about the functioning of blue-green infrastructures (Dar et al., 2021), but often fail to engage in a public process to co-create value-driven nature-based solutions. We hypothesise that a deliberately planned iterative loop between scientists/engineers and designers could help frame science and engineering to become more salient and legitimate, and consequently have a greater and longer lasting effect on the urban transformation. A continuous, inter- and transdisciplinary dialogue along the workflow will ensure a resilient transformation pathway, securing the delivery of essential services demanded by next generations.

In this contribution, we present a roadmap for such a dialogue, highlighting important interactions in the main steps towards co-creating blue-green infrastructures, legitimate for the local community, able to deliver on key ecosystem services and contributing to the city's resilience to global change. To illustrate the relevance of our proposal, we reflect on it with five projects of innovative designs in blue-green infrastructures for flood management around the world, including (1) sponge cities in China, (2) the ABC Waters program in Singapore, (3) urban stormwater bioretention gardens in post-industrial Detroit, USA, (4) the 3rd correction of the Rhône in Switzerland, and (5) the rehabilitation of the Ciliwung River in Jakarta, Indonesia. These studies benefited from semi-structured interviews with senior practitioners involved in these projects: Prof. Joan Nassauer, Prof. Yu Kongjiang, Ing. Diego Salmeron, Ing. Tony Arborino, Dr. Martin Fritsch and Dr. Derek Vollmer. We close by formulating main principles to improve the outcome of landscape design projects, especially in their capacity to deliver resilient projects. By taking such an approach, scientific knowledge may become part of societal discussion on a planning level.

2. Informed design through the science-design loop

In this section, we introduce our ideal roadmap for the science-design loop process and detail our understanding of the main elements of this process: (1) Context analysis and problem framing, (2) the science-design loop, and (3) validation and implementation of the informed design. The informed design roadmap is described in the following Figure 1. It builds on the main steps of classical modelling processes (Grimm et al., 2005; Jakeman et al., 2006).

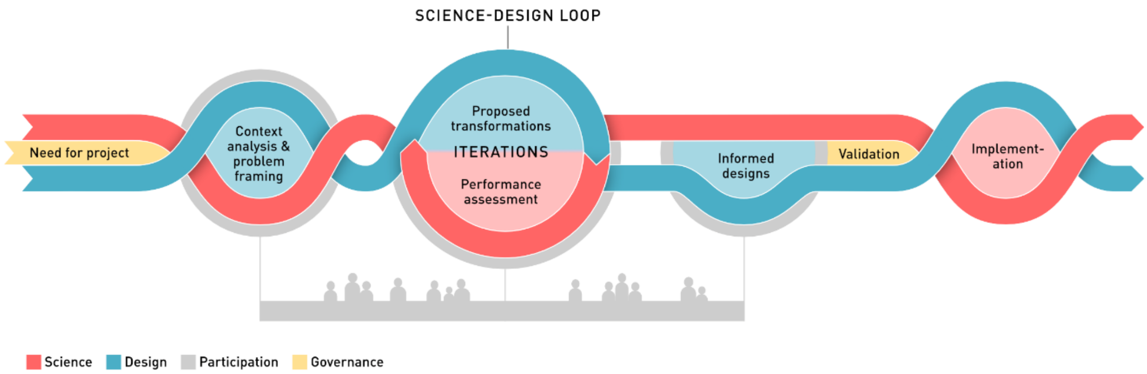

Figure 1: The roadmap to informed design through science-design iterative loops.

Context analysis and problem framing: Lang et al. (2012) state that proper "problem framing" is essential at the start of a transdisciplinary project. Problem framing should include identifying necessary disciplines to evaluate the design (Nassauer & Opdam, 2008). Designers may tend to look for societal needs while scientists may tend to look for analytical problems (Rittel & Webber, 1973; Buchanan, 1992; Funtowicz & Ravetz, 1994). Complex or wicked problems require more than just experts, demanding an adaptive, participatory, and transdisciplinary approach (Xiang, 2013). The formulation of guiding questions is a key step to state clear objectives for all participants. The scientific and design processes must align their goals and make them transparent to each other to meet stakeholder needs. The guiding questions should be salient and transparent in the process (Nassauer & Opdam, 2008). For example, Steingröver et al. (2010) made explicit the boundary object (green-blue infrastructures) that they mobilised in their collaborative design process. Guiding questions from different stakeholders and disciplines may not overlap, and efforts to rationalise and blend them are well known (Callon, 1986).

As problem framing progresses, context analysis starts to formulate hypotheses and gather data. The boundaries and scale(s) of the system at stake should be set (Ostrom, 2009). Acquiring knowledge about end-users and beneficiaries of designs is key, for example through stakeholder analysis and actor typology (Reed et al., 2009). Designers may prefer a participatory design approach that favours conversation with users (Luck, 2003; Bannon & Ehn, 2012). Local ecological knowledge from experts can be extremely helpful to scientists gathering information about a system (Murray et al., 2005; Chalmers & Fabricius, 2007; Ballard et al., 2008), especially in data-poor environments like cities in developing countries. Social and environmental functions to be maintained throughout design implementation must be identified, especially for ecosystem services, which might be complicated to assess because of their relative invisibility or timespan (Lavorel et al., 2019). For instance, the key function, resilience, is defined through the speed of recovery in relation to a given shock intensity. Defining key variables and performance criteria early is essential in the science-design loop. Without such knowledge, further assessment of design relevance is impossible. For complex problems involving different stakeholder perspectives, participatory visioning (Robinson, 2003) can help to establish a common vision (i.e., a common set of key variables, functions and performance criteria set in time). Several sets of variables, performance criteria, and functions can be established in case of incompatible perspectives (Campo et al., 2010; Allain & Salliou, 2022).

The dialogue between scientists and designers at this stage should aim for a shared understanding of the system. Regular exchange of views and knowledge between them leads to congruent representations (Mathevet et al., 2011). Such dialogue and convergence of context analysis must lead to a shared list of key variables related to environmental and social performance criteria for the future testing of the models. Ensuring a good integration of user needs can rely on participatory design methods (Sanoff, 1999). It has been shown that the level of participation – the exchange with stakeholders – correlates with satisfaction of end-users (Ammar et al., 2013). Participatory design depends on reflexive practitioners in design (Schön, 1983) which requires a specific education for such designers (Luck, 2018).

The science-design loop: With good knowledge of the context as well as key variables and performance criteria defined, designers have a strong basis for prototyping. At this stage, designers start to produce artefacts (physical and/or digital mockups) transforming the site under scrutiny in the problem-space (Simon, 2019). Prototypes are refined in iterative loops between science, society, and designers (Cantrell & Holzman, 2015). In the science-design loop, scientists run simulations, test designs against key social and environmental variables and provide feedback about the performance of the design. Designers adapt their prototypes accordingly, trying to optimise the fitness of its proposal in function of the received feedbacks.

The role of boundary objects in the iterations between design and science has been recognised as fundamental (Star & Griesemer, 1989; Nassauer, 2012). Boundary objects are concepts or objects allowing individuals with heterogeneous mental models to share perspectives on a topic. They do so by allowing a shared understanding while remaining specific to the needs and worldview of each community. Multi-dimensional concepts like blue-green infrastructures (Steingröver et al., 2010), landscape (Sayer et al., 2013) or artefacts produced during the design proposal (Simon, 2019) make excellent candidates for boundary objects to enhance the efficiency of the iterative loops. Landscape-based visions, by constructing a shared future among different stakeholders creates a boundary object to ensure coherent design (van Rooij et al., 2021). In design, physical models have been going along digital models with the use of geographic information systems (GIS) (Collins et al., 2001) as well as parametricism, or the use of computer and algorithm for design (Schumacher, 2009). Building models in urban design as a digital process is the "new normal" (Raxworthy, 2017). Digitalization and recent 3D technologies open new forms and new processes for designers. For example, the use of 3D point cloud models opens a dialogue between landscape designers and planners (Urech et al., 2020). The potential of such digital models to assess the performance of urban design in relation with bundles of ecosystem services that contribute to resilience and sustainability is state of the art research (Alavipanah et al., 2017; Urech et al., 2022). While visual simulation of flowing ecosystem services (like water for example) using point cloud models is achievable (Vollmer, Costa, et al., 2015), visualizing other services like carbon storage remain a challenge. Achieving this will require interdisciplinary research and feedback loops between designers and scientists to connect different understandings of models and concepts underlying ecosystem services.

Iterations among scientists, designers and the rest of society increase the fitness of the design to the context in the solution-space. As Lawson (2006) noticed for design, there are many "return loops" between steps; these represent mistakes, re-assessment of previous steps, etc. Other authors stress that feedbacks producing continual evaluation, are essential to responsive designs (Cantrell & Holzman, 2015). Feedback loops may trigger the acquisition of essential learning in reflective practice (Schön, 1983; Sitkin, 1992). Some authors defend an agile and fast approach to prototyping and testing in order to maximise learning in an intense back and forth between these two steps (Tripp & Bichelmeyer, 1990; Fowler & Highsmith, 2001). In a paradoxical manner, while feedback loops may be seen as a negative delay, they actually are a means to get closer to a solution for designers and closer to truth for scientists (Firestein, 2015).

In data-poor environments or when stakeholder behaviour is not well known, participatory modelling can be employed to test designs (Voinov & Bousquet, 2010). Participatory design processes bring high legitimacy and modulate conflict and trade-offs between stakeholders (Sanoff, 1999; Voinov et al., 2018). It is usually recognised that engaging stakeholders as early as possible enhances this potential (Voinov & Bousquet, 2010). Many participatory methods to co-design pathways towards sustainability can be considered (Voinov et al., 2018; Moallemi et al., 2021). Stakeholder participation is key to ensuring design fitness and avoiding the problem of retro-fitting the design, which is a costly process (Devadiga, 2017).

Validation and implementation: Typically, when a design is commissioned, the institutions initiating the design process are the ones validating the design. Once the design is validated, it can be implemented. Most of the time, designers lead implementation. Designers, often with engineers, ensure that the implementation is consistent with the approved design.

At this stage, stakeholders' perspectives should already be integrated into designs informed by previous dialogue. Careful attention to stakeholders' perspectives in the concrete implementation itself promotes a sense of care from participants in participatory design (Nassauer, 1997; Sanoff, 1999). Concerns that participatory design limits the creativity of designers or leads to a lower quality design have not been supported by evidence (Lawrence, 1982). Ideally, the implemented informed design should be monitored to measure its effect on the key variables and evaluate the capacity of the design to deliver an expected level of ecosystem services.

Integrating resilience: Compared to traditional views on resilience in ecology (Holling, 1973; Scheffer, 2009), the transformation process proposed in this paper does not rely on the concept of equilibrium. Despite being undeniably powerful heuristics, resilience concepts from physics and ecology about regime shifts, attractors, thresholds, etc., may not find relevance in the transformation of urban landscapes. Resilience here is both an outcome and a property of a system (Lade et al., 2017), meaning the dynamic capacity of a system to maintain a given function despite a shock or a collapse (Elmqvist et al., 2019). A resilient outcome can be estimated through simulation models prior to a shock as well as the observation of a successful implementation leading to fast recovery in the real world. Key indicators of resilience in this regard are the time to recovery and the magnitude of the shock that the system can cope with. According to this view it is thus fundamental to define the identity of the system (Cumming & Peterson, 2017) in order to define what function should be kept resilient and where resilience might have to be repaired or constructed. More, cities are heterogeneous and resilience might depend on scales and the focus on physical objects or communities (Vale, 2014). The definition of the identity of a system and key functions might lead to difficult co-design processes, especially when undesirable properties are resilient. In many cities for example, air pollution and poverty are extremely persistent (Lade et al., 2017).

3. Illustrating the science-design loop with case studies

Our framework in Figure 1 is an idealised roadmap for a science-design loop that we think has the potential to improve science-design iterations and quality of outcome. In this section, we studied five major urban design projects to cope with urban floods. We introduce each case study and describe it with our roadmap formalism for comparison. Table 1 at the end of this section 3 summarises all case studies according to main steps of the roadmap.

3.1 The case of Chinese sponge cities

Chinese sponge city program has been initiated in 2013 by Xi Jinping and the Ministry of Housing and Urban-Rural Development (MHURD) (Li et al., 2017). Rapid urbanization in China is leading to significant flood issues, fatalities and property loss, due to the reduction of retention capacity of artificialised areas (Chen et al., 2015). The sponge city concept relies on the idea of re-designing the urban environment with green and blue infrastructures and Low-Impact Development (LID) (terraces, water gardens, green roofs, etc.) to increase the natural water absorption, relying on natural processes to be resilient to floods (see Figure 2). The objective set by the Chinese government is to increase water absorption by 20% and urban storm water reuse by 70%. In 2015-2016, 30 cities were selected as pilots to test the sponge city approach (Li et al., 2017). Other benefits mentioned are the access to leisure areas for inhabitants, carbon storage, cooler temperatures and increases in nearby properties value (Oates et al., 2020).

Figure 2: Sponge city in Nanchang, capital city of Jiangxi Province. Local engineers make final height elevation control measurement for a built pond fed by natural infiltration and draining into nearby Jiulong Lake. Credits: Diego Salmeron

The guiding question leading to the idea of the sponge city comes from flood risks raised by rapid urbanization. Context analysis is at the national scale in a top-down manner from central government to provincial government to cities (Dai et al., 2018). The transformation phase could be improved – as many authors stress – by avoiding use of a single set of guidelines for sponge city programs in very diverse cities all around China (Oates et al., 2020). We did not find science-based simulation models in the literature that were used to assess the performance of sponge city designs before implementation. The population was informed about the project plans and could give their opinion but not actively participate and co-design. The pilot projects of sponge city have been described as fast tracked from concept to implementation due to time and budget constraints (Dai et al., 2018). Yin et al. (2021) mention in that regard that assessment is mostly after implementation; they call for monitoring and models to assess the effects of the sponge city, which they consider "poor" so far. Chan et al. (2018) also stress the need to implement assessment tools for sponge cities.

Moreover, some authors consider ex-post assessment criteria to assess design oversimplified or lacking integration of systemic thinking and interactions between different services provided by ecosystems (Ma et al., 2020; Oates et al., 2020). Additionally, ex-post evaluation has shown many project designs to be "economically feasible from a government perspective but not financially viable", leading to "irrational" and "unsustainable" design (Liang, 2018). Many authors stress the lack of local adaptation (Yin et al., 2021) and call for a participatory plan and co-design (Oates et al., 2020). Fast implementation that bypasses a systemic, co-design approach may lead to designs requiring ex-post adaptations and potential failures from lack of maintenance. The summary of the design process for sponge cities according to our roadmap is proposed in Figure 3.

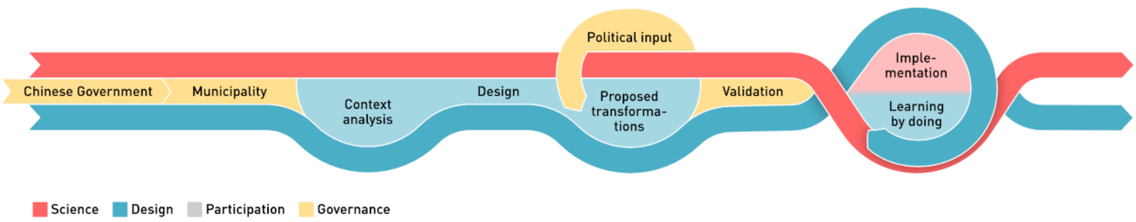

Figure 3: Summary of the design process for Chinese sponge cities.

3.2 Singapore ABC Waters program

In many regards, the process of flood alleviation in Singapore is a success story. The city-state reduced its area exposed to flooding from 6900 hectares in the 1960's to 50 hectares in 2012 (Chan et al., 2018). Singapore is able to cope with 1 in 100 year flood events while many other Asian cities cope with 1 in 10 year events (Chan et al., 2018). Most of this success comes from more than 8000 km of concretised rivers, canals and drains as well as dams creating 17 reservoirs (Chan et al., 2018; Liao, 2019). In 2006, Singapore's water agency (PUB; Public Utilities Board) launched its ABC Waters program (Active Beautiful Clean). The approach builds on the development of widespread Low-Impact Development techniques like swales, rain gardens, constructed wetlands that emulates pre-development water flow in order to manage storm waters (Lim & Lu, 2016). Influences of Australia's Water Sensitive Urban Design (WSUD) approach are fundamental. This approach recognises that stormwater runoff, despite being charged with many pollutants, is also a resource that can increase the supply of water, enhance thermal comfort, improve the aesthetics of the city and provide recreational opportunities (Lim & Lu, 2016).

The ABC Waters approach builds on the "Garden city" project of 1963 to the "city in a garden" generally aiming at improving aesthetics and city attractiveness with the establishment of green spaces in the urban landscape (Ng, 2019). The ABC Waters program aims at establishing a set of LID design features throughout the city. The "clean" component is significant in the establishment of greeneries (e.g. cleansing biotopes) aiming to "transform the city into post-card pretty community spaces" (Liao, 2019).

The guiding question is unambiguous as the city tries to build an urban landscape that can deal with stormwater for both quantity and quality by using LID features. Doing so, the city also wishes to engage with the population and create a beautiful environment. The context analysis is also a strong side of ABC Waters as the city carefully selected which sites are the most adapted to implement LID and which particular design features are most adapted to each site (PUB, 2018; Liao, 2019).

The proposed designs, however, lack integration of inhabitants' perspectives at the outset. Further, ecological as well as hydrological modelling could have improved nutrient management. The most extended evaluation of this program by Lim & Lu (2016) concludes that while the "Active" and "Beautiful" aspect of the program is a success and brought many rewards to the program, the "Clean" dimension remains shallow. While the ABC Waters program did establish some clear performance criteria and success thresholds for runoff nutrient removal, their assessment reveals poor efficiency overall (Lim & Lu, 2016). While there is success on the restoration of some ecological functions (like the reestablishment of an otter community), the integration of ecological functions and ecosystem services is lacking. As a consequence, Lim and Lu question the capacity of the system to cope with climate change by using the resilience based on ecological functions (Lim & Lu, 2016). In accordance with the roadmap we present in this paper, Lim and Lu identify a need for more ecological and hydrological modelling to improve flood management. In that sense, resiliency gains from ABC Waters designs are unknown, with probable continued reliance on grey infrastructure.

Implementation is strong aspect of the ABC waters program. As of 2016, 30 ABC Waters sites were implemented and 100 more potential sites are expected by 2030. Despite the lack of feedback loops between design and science during the transformation phase, which may function more like conventional landscaping, the program showed outstanding integration of lessons learned over the years of LID implementation through a learning by doing approach coupled with updating its design guidelines (2009, 2011, 2014, 2018).

The program is not very participatory because inhabitants can only provide ex-post feedbacks after the implementation of LID. Complaints are channelled towards the garden city committee council through direct communication, community leaders and park staff (Tan, 2006). It is also participatory because these sites are meant to be strongly connected with educational programs for students of all ages to learn about water and its sustainable management. Compared with participatory design principles (Sanoff, 1999) and scales of participation in design (Wulz, 1986) there is still room for much more integration of stakeholders earlier in the design process. The summary of the design process for ABC Waters designs is proposed in Figure 4 below.

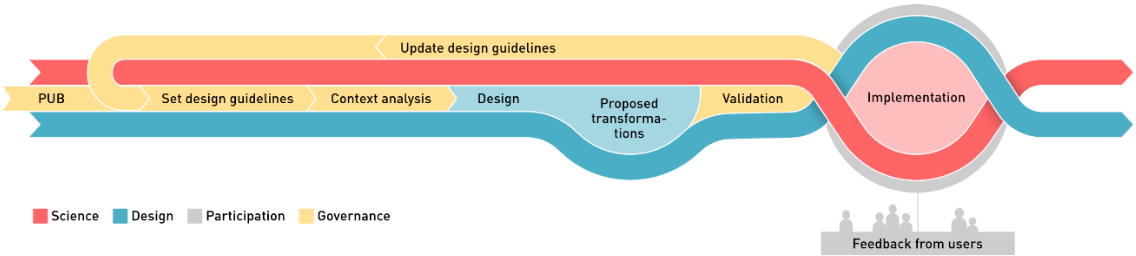

Figure 4: Summary of the design process in the ABC Waters program in Singapore. (PUB is Singapore's National Water Agency.)

3.3 River rehabilitation of the Ciliwung River in Jakarta

The Ciliwung River crosses the Indonesian capital of Jakarta on its way to the Java Sea. This urban river exposes nearby local communities (Kampung) to flood risks. A research project, financed by the Singapore National Research Foundation and the Singapore-ETH Centre's Future Cities Laboratory, was conducted to propose a nature-based blue-green design for the Ciliwung River's rehabilitation.

The context analysis and guiding question was led by an inter-disciplinary team of scientists who identified the need for the ecological rehabilitation of the Ciliwung River (Vollmer et al., 2016). The need for intervention was shared by Indonesian authorities but with a different vision of coping with floods, by using grey infrastructure. The context analysis conducted by researchers involved extensive investigation at the Kampung level, in particular to assess the value of riparian cultural ecosystem services at the heart of local inhabitants' livelihoods (Vollmer, Prescott, et al., 2015) (see Figure 5).

Figure 5: Research team conducting a field investigation of riverside neighbourhoods (Kampung) along the Ciliwung River in Jakarta in 2012.

For the transformation of the site, proposals were designed by landscape architects to rehabilitate a section of the river (Girot & Melsom, 2015). Researchers were able to test design proposals by using water simulation models and 3d visualization (Lin et al., 2016). The design was confronted with other simulations estimating ecosystem services at the river and regional scales, exploring in particular the long-term possibility to increase flood resilience by upstream afforestation financed by Kampung inhabitants (Vollmer et al., 2016). This science-design loop led to informed designs able to demonstrate their effect on floods, water quality and improvement of the livelihood of nearby communities. The summary of the design process for the rehabilitation of the Ciliwung river is proposed in Figure 6 below.

The main pitfall of this project is in the validation and implementation phase. Despite strong participation at the grass-root level and the production of informed designs following a science-design loop (Vollmer, Costa, et al., 2015), the low connection with decision makers prevented implementation. The project did not influence decision makers, who used a classical top-down grey infrastructure approach, which did not solve flooding issues for the city and Kampung. This case study shows the critical significance of including decision makers early in any science-design loop process.

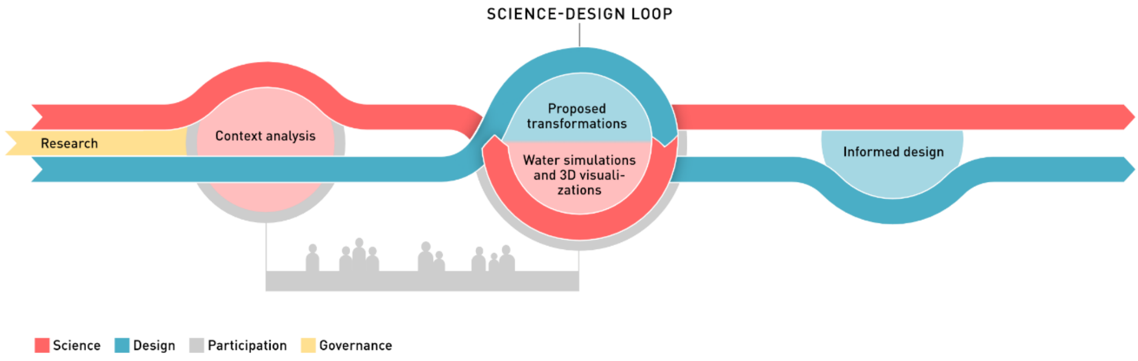

Figure 6: Summary of the design process for the Ciliwung River rehabilitation project.

3.4 The 3rd correction of the Rhône River

Flood events in the late 20th century challenged the idea that dikes built along the Rhône River in Switzerland could be resilient enough to accommodate 100 year floods. Different from traditional and ageing grey infrastructure, the new correction is based on the widening of the river (with occasional deepening). This widening is a re-naturalization of the river, creating more space for recreation activities and conservation purposes. This option is more resilient than the previous infrastructure because the overflow has more room to be buffered. However, this widening of the river is at the expense of the area previously gained by protecting dikes that farmers and many inhabitants want to retain.

The guiding question was based on observed failures of the current and ageing infrastructures during two major floods in seven years. Consequently, there is a wide agreement among stakeholders that a new project was necessary to achieve resilience to major floods. The context analysis is a long story starting from first technical studies conducted in late 1980's by the Swiss Federal Institute of Technology in Lausanne. The official decision to act was taken in 2000 by involved Cantonal authorities (Valais and Vaud) following the publication of the synthesis of the diagnostic for the correction of the Rhône.

For the transformation, the choice of design for each section of the river is based on multi-criteria analysis (MCA) (security, socio-economic, environment and general characteristics like minimizing costs, consistency and flexibility) that filtered a limited number of variants for each section. Since 2005, the project has had a strong participatory structure with main stakeholders integrated into the technical development via regional and thematic steering committees (Utz et al., 2017). This wide participation integrating local development goals in the choice of variants had more influence on the local level rather than on the overall river design due to its highly technical-legal constraints. The debate and iterations came also during the public consultation phase (2008-2012). Initially, the public consultation communicated the best design from the MCA and was open to amendments for six months. Natural protection associations like WWF asked for more widening of the river and more space for nature, basing their requests on legal requirements. On the other side, ADSA (Association de Défense du Sol Agricole - Association for the Protection of Agricultural Land) and some communes proposed an alternative based on deepening of the river rather than widening. The Canton asked for expertise (Zwahlen, 2009; Minor, 2009; Zimmerli et al., 2011) which concluded that this variant deepening the river was neither safe nor legal. The Canton decided however to integrate the remarks of the consultation phase to adapt the project, in particular on the localization of the widenings (Canton du Valais/Kanton Wallis, 2015), to decrease the loss of agricultural surfaces (310 ha instead of 380 ha). Overall, despite active use of participatory principles, the amount of co-design remained limited by technical, scientific and overall legislative constraints (Utz, 2018). The process can be seen as a technical-legal-stakeholder loop with limited co-design input. Feedback from key stakeholders changed the project to mostly increase its social acceptability. The fundamental difficulty was that some stakeholders disagreed with the federal law requiring more space for the rivers and used the participatory process to ask for modifications of the project not compatible with the federal law rather than to affect other functions.

As for validation and implementation, the scale of the project requires implementation in several steps. Sites with high risk of property damage, like the city of Visp, started as soon as 2009. Cantonal authorities approved the final budget for the whole project in 2014. The opposition subsequently organised and lost in 2015 a referendum against the funding of the project. This referendum demonstrates the social polarization and the divergent views on the laws that set the requirements for rivers. The participatory process could not completely compensate for this. However, the referendum ultimately demonstrated support by the majority of voters and thus increased the legitimacy of the overall design process (Utz et al., 2017). The section-by-section implementation is estimated to last over several decades. This case study shows the incredible challenge for a large-scale river rehabilitation project with both democratic institutions and a participatory process. The summary of the design process for the 3rd correction of the Rhône river is proposed in Figure 3.

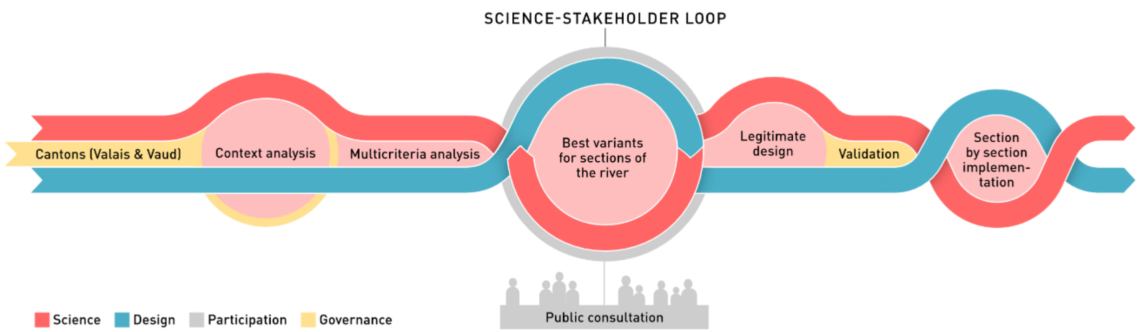

Figure 7: Summary of the design process for the 3rd correction of the Rhône River

3.5 Stormwater management in Detroit

Detroit has become a symbol of post-industrial decline mirroring the economic and social decline propelled by disinvestment, deindustrialisation, and racism. While the city's population reached almost 2 million people in the 1950's, it fell below 700,000 in 2020 (www.census.gov). This decline left the city with tens of thousands of vacant properties in 2013 (Detroit, 2013), many owned by a public agency, the Detroit Land Bank Authority (DLBA). That year the state of Michigan, enforcing the federal Water Pollution Control Act, approved the Detroit Water and Sewerage Department (DWSD) plan to develop and implement green infrastructure (GI) to manage storm events.

In a novel proposal, the University of Michigan's problem framing offered synergies between DWSD's commitment to implement GI and, at the same time, address DLBA's need to manage pervasive vacant property (Nassauer et al., 2019). This proposal suggested that GI investments could be leveraged to enhance design and maintenance of vacant lots for neighbourhood social benefits. Further, it suggested that, given the flat, clay soils of Detroit, the costs of vacant property demolition could be leveraged for more effective GI stormwater management - if basement excavations were filled with constructed soils in bioretention cells (see Figure 8). This novel problem framing led designers to guiding questions about how to optimise neighbourhood social benefits of improved vacant lots while also effectively managing stormwater to manage pollutants in a 2-year storm. Working among design and science disciplines and with several government and local community partners, Michigan researchers used a "design in science" approach (Nassauer & Opdam, 2008) to design, implement, and assess the transformations.

For the context analysis, the transdisciplinary team identified operationalised research questions about water quality and quantity, and neighbourhood residents' well-being. To select pilot sites, they worked within parameters defined by the distribution of DLBA vacant property as it was spatially coincident with points where stormwater could be retained before entering the existing grey infrastructure system.

For the transformation, researchers engaged in participatory research with an advisory committee (including the DWSD, the Land Bank, other public agencies, and neighbourhood stakeholders) in order to implement four pilot projects. Researchers being knowledgeable in science and design turned out to be an important feature of the success of this program. Designers' objectives aimed at residents' well-being, with designs perceived as attractive and safe, as well as limiting public agencies' maintenance costs (Nassauer et al., 2019). They conducted a pre-construction survey with 164 neighbourhood households to understand resident's perceptions of different designs, post-construction focus groups, a post-construction survey of 171 neighbourhood households, monitoring of water quality and flows on pilot sites, as well as a study of the GI governance in US legacy cites like Detroit (Nassauer et al., 2019).

Figure 8: Bioretention garden in Detroit designed on vacant property according to local authorities' and inhabitants' preferences for flowers, lawn and bollards as cues of care. Credits: Joan Nassauer

The validation and implementation was a highly iterative process over 5 years. After forging an agreement with the DLBA, the DWSD financed implementation, including design features that were included specifically for the purpose of data gathering for assessment. The implementation followed the agreed upon design discussed in the frame of the advisory committee. Based on advisory committee feedback, the post-construction surveys explored nuances of the pilot site GI designs to address public agencies' concerns for maintenance costs, assessed against relative effects on the well-being of inhabitants (Nassauer et al., 2021). Ex-post assessment also revealed satisfying levels of resilience with set objectives about coping with one in two year storms. This assessment also revealed important lessons for future projects, in particular around the trade-off between maintenance, efficiency and preferences from localised inhabitants (Nassauer et al., 2019). The maintenance of pilot projects was transferred to the DWSD rather than relying on local communities. The summary of the design process for bioretention garden in Detroit is indicated below in Figure 9.

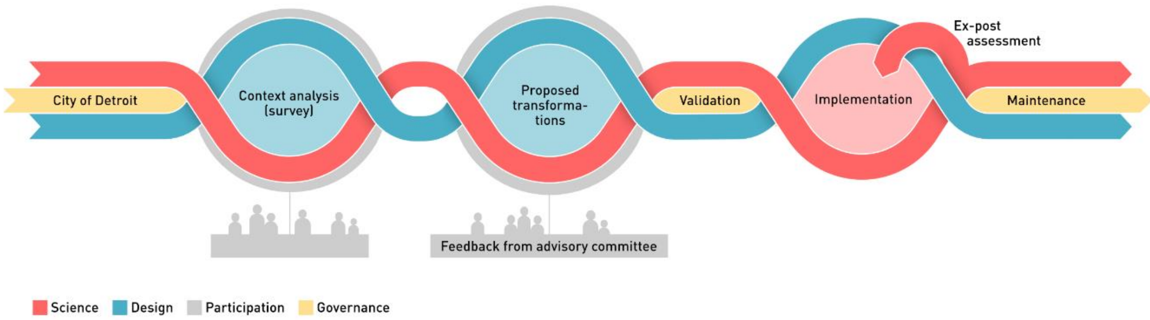

Figure 9: Summary of the design process for the Detroit bioretention garden project.

Table 1: Summary of case studies on the main steps of the science-design roadmap.

Case	Scale	Guiding question & context analysis	Transformation towards resilience	Validation & implementation	Co-design
Sponge city (China)	City district	How to cope with floods increased by rapid urbanization? Analysis conducted by the Ministry of Housing and Urban-Rural Development. Identification of 30 pilot cities in China.	Proposal from designers. No science-design loop documented.	Validation by authorities.	No co-design. Top-down approach from central government to municipalities.
ABC Waters (Singapore)	City	How to increase the attractiveness of the city and display a clean and orderly image of the city with green infrastructures? Evaluation of relevant sites for future designs.	Based on latest ABC Waters guidelines. No science-loop documented.	Dozens of projects implemented, 100 overall planned in 2030.	No co-design but lessons learned from realised projects are integrated in future design guidelines.
Ciliwung River restoration (Jakarta)	Urban river	How to rehabilitate an urban river while maintaining key ecosystem services? Interviews for river ecosystem services assessment. Survey on willingness to pay.	Design tested with hydrological models.	No implementation.	Active participation of stakeholders in defining key ecosystem services. Validation of final design (consultation level of participation).
3rd Correction of the Rhône	River	How to cope with floods by naturalizing part of the river? Studies from EPFL (Swiss polytechnic Engineering school). 1:52 3d geo-hydrological models for specific sections of the river.	Technical studies to explore design strategies. Proposed variants on sections. Multi-criteria analysis of variants.	Validation by cantonal governments (Vaud & Valais). Referendum triggered by opposing parties. Section by section implementation.	Participatory process framework along the project. Expertise battle with opposing parties. Public consultation amending the design of each section.
Stormwater management in post-Industrial Detroit	Neighbourhood & vacant plot scale	How to manage storm waters with vacant urban property using green infrastructures? Pre-construction neighbourhood survey (164 households) on acceptability. Study of governance.	4 pilot bioretention gardens	Ex-post well-being assessment. Ex-post evaluation of peak flow reduction.	Residents and local authorities in Advisory Committee.

4. Comparison of case studies with our science-design roadmap

Each summary of case studies (Figures 3, 4, 6, 7 and 9) suggests a process with a focus on design (more blue steps and arrows) or on the science (more red steps and arrows). With this information, we positioned the case studies on a science design spectrum (Figure 10). Cases in the middle of this spectrum show a balance between science and design and are particularly in line with the roadmap proposed in this paper. In the following sections, we compare the different case studies with each step of the roadmap.

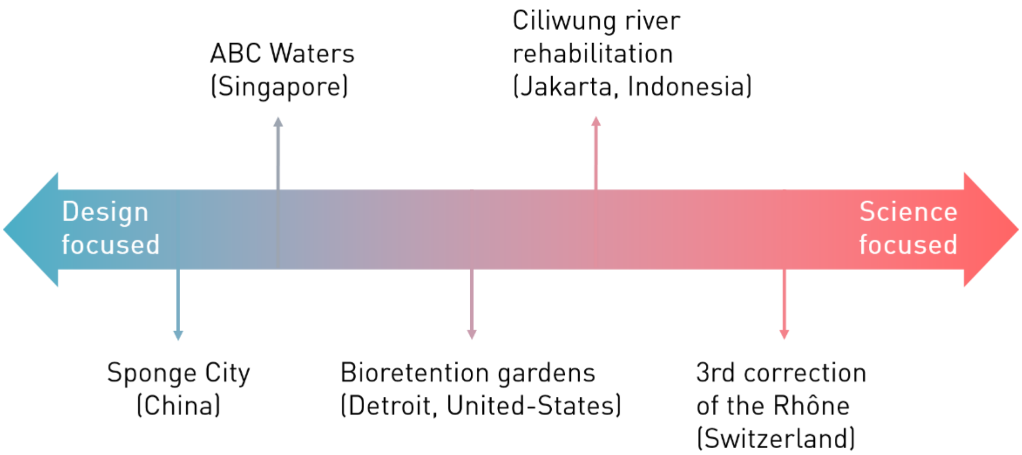

Figure 10: Case studies positioned along the science-design spectrum.

4.1 Guiding question and context analysis

The context analysis step proved to be very important in all case studies for two reasons: (1) setting variables and performance criteria to evaluate the design and (2) ensuring the participation of key stakeholders from the start.

First, design-focused projects (see Figure 10) tend to overlook the setting of variables and performance criteria while science-focused projects tend to define them adequately. For example, the 3rd correction of the Rhône had a clear process to set objectives and weight variables used in their multi-criteria analysis. Sometimes, legal frameworks impose some performance threshold as in the Detroit or sponge city cases. But the latter proved that designers are not always bound to demonstrate this efficiency.

Second, the case from Ciliwung River showed that, despite a good balance between science and design, the lack of decision makers on board during the design process probably seriously reduced the chance of some level of implementation. On the contrary, in Detroit, intense communication and integration of key decision makers from the start played a part in the financing, implementation and maintenance of pilot projects. Including decision makers seems as important as integrating impacted end users.

4.2 Transformation and Science design loop

Some of the case studies showed some limitations in neglecting the feedback from science in the transformation step of the design. Both sponge city in China and ABC Waters in Singapore have low level of science integration during the transformation part of the design process. Unsurprisingly, studies available showed mixed results regarding the impact expected on water quality and flood reduction (Lim & Lu, 2016; Yin et al., 2021). A stronger integration of science would probably enhance the impact from implemented design.

On the opposite side of the science-design spectrum, the 3rd correction of the Rhône relies heavily on science and engineering for its transformation process (see Figure 7). This project displays outstanding science and engineering with precise elaboration of performance criteria and modelling for evaluation of variants and integration of technical, scientific and legislative constraints. In this project, design is mainly understood as the transformative process from humans and nature. This view partially neglected the dimension of design concerned about the subjectivities of end users' preferences and needs. A complete assessment of users' needs might have been needed like the one conducted for the bioretention gardens in Detroit. This shortcoming in the 3rd correction of the Rhône project led to a polarization of the public consultation with some communes and farmers proposing a radically different design to fit their needs. A similar process of polarization happened in the Ciliwung rehabilitation process where grey infrastructure proposals, led by authorities, was originally perceived by researchers as opposed to bottom-up green-blue infrastructures.

Overall, the main factor enabling/hindering transformation is the role of governing bodies as they hold the final say in what is implemented or not. Consequently, any science-design loop that does not have the support of governing bodies is probably bound to see no implementation. However, while their role is critical to see any implementation, top-down governance is also likely to be at the expense of the quality of the final design because it tends to disregard other stakeholders' needs. It is particularly visible in the Singaporean and Chinese case studies. As such, including political science expertise along the process to involve decision makers and integrate them in the whole process could enhance the likelihood of a successful implementation of an informed design.

4.3 Validation and implementation

With bottom-up study of users in Detroit and Jakarta, researchers guaranteed a high level of legitimacy of their designs in relation to these end-users as they could ensure a good level of delivery of essential ecosystem services (flood control but also increasing inhabitant's well-being). Projects that do not include such steps, like sponge cities in China, showed uncertain impacts for local inhabitants. Some projects rely on a learning by doing approach to improve design principles over time. ABC Waters in this regard shows the best capitalization of such a learning-by-doing process by updating its guidelines for designs. However, no evaluation is available to measure the efficiency of such learning approach. These projects seem to put as a secondary objective the real delivery of ecosystem services or the building of resilience below the display of beautiful greenery, the improvement of real estate values nearby and/or the harvest of political prestige for those in charge.

Mostly, projects presented here conducted ex-post assessment of the designs. The science-design loop process suggests it should also be done before, in the evaluation of the prototypes, in order to avoid the learning-by-doing approach that can be unnecessarily expensive when long-term sustainability and resilience is at stake. For these reasons, we assert that some level of participation in the science-design loop process during context analysis and in the definition of the performance criteria to test the design prototypes is critical for the success of such process once implemented.

4.4 Participation

Participation in most of the case studies remained at a low level, mostly on degrees of tokenism (Arnstein, 1969). Sponge city projects involved no participation. Only in the case of Detroit, designed solutions were in direct dialogue with stakeholders in an advisory committee and iteratively assessed in pre- and post-construction neighbourhood surveys. Other case studies remained consultative using surveys (Ciliwung River, the 3rd correction of the Rhône) and post-design assessments (ABC Waters). Simulation models designed by scientists (Detroit, the 3rd correction of the Rhône and Ciliwung River) did not follow a participatory modelling approach. Models in these three cases focused on acquiring facts about the case study or performing quality assessment. In complex multi-stakeholder environments like the Ciliwung River and 3rd correction of the Rhône, a participatory modelling approach would have increased the chance of more legitimate designs and limit conflicts (Voinov & Bousquet, 2010). Participatory modelling can be notably efficient for water management (Gaddis et al., 2010). Therefore, it is clear that there is room in real-life processes to engage in participatory simulations to enhance the quality of final designs and ensure a higher level of legitimacy.

5. Aligning science and design to foster resilience

Our science-design roadmap, centered on an iterative loop between scientists and designers, is built on the idea that this dialogue will enhance resilience in urban projects. We have seen that despite policy makers in China setting clear resilience objectives of 20% more absorption of stormwater, there is little scientific evidence of pilot projects delivering such a result. This disconnection between implementation and resilience objectives in policy has been stressed by some authors (Cai, 2017; Ma et al., 2020). Without scientists testing the design in a dialogue with designers, water resilience indicators among different sponge cities projects indicate quite diverse outcomes (Wang et al., 2021). On the contrary, bioretention gardens built in Detroit, which voluntarily integrated science and design within clear objectives set by policy-makers, were able to demonstrate their capacity to deliver good resilience outcomes. The Ciliwung River project, while having a similar science and design dialogue was not able to be implemented due to the lack of integration within the Indonesian policy-making environment. In this regard, Restemeyer et al. (2015), in a case study about floods in Hamburg, have shown how political support is fundamental in successful implementation of projects to build resilience. Finally, for projects having more superficial resilience objectives in policy connected with green infrastructures, like in the ABC Waters program, it is not surprising if they don't show particular results in that domain, as they mostly rely on significant investment in grey infrastructures.

McClymont et al. (2020) showed that many scientists working on flood risk management do not consider resilience as an iterative adaptive process. As we studied the five case studies in this paper, it appeared clear that it was also the case in practice. No studied projects seemed to fully integrate in practice the idea that resilience is a never-ending adaptation pathway (Elmqvist et al., 2019). The 3rd correction of the Rhône suggests some form of iteration (as previous corrections happened in 1863-1894 and the second in 1936-1861), but it was never based on a conscious strategy over centuries. Rather, the need for new designs came after catastrophic floods, showing the flaws of the system in place. In that sense, our roadmap presented in this paper is a pragmatic proposal fitting the current project-by-project linear approach in urban flood management. However, ideally, the iterations between science and design should be a constant dialogue that does not end with the implementation of a design but continues over time as an integral part of spatial planning instruments at all administrative levels. As designs are exposed to flood events, scientists and designers should be able to learn together from them, adapt previous designs and implement new tested transformations (Nguyen & James, 2013). A constant dialogue between science, design and policy makers could potentially cope with other challenging dimensions of resilience related to stresses. Stresses refer to persistent problematic states, like air pollution or poverty, rather than occasional shocks like floods (Lade et al., 2017). While most case studies in this article do not relate to stresses but shocks, integrating stresses in this dialogue could be explored in the future. Because stresses are continuous, a long-term dialogue would be particularly adapted to cope with them. In practice, as the implementation usually ends a project, building up resilience is still mostly a discontinued process. As resilience objectives are increasingly delivered through more integrated dialogue between science and design in individual projects, we think that policy makers should also aim at making resilience a continuous process by making such dialogue permanent.

6. Conclusion

This article proposes a roadmap for resilient urban landscape design integrating a science design loop to produce informed and legitimate design. It builds on a fundamental assumption that the quality of the product is significantly improved by maximizing the dialogue and feedback between design and science. This intense dialogue is also catalyzed by the integration of decision makers and other stakeholders, in a participatory design fashion.

To illustrate our roadmap, we introduced and compared five case studies conducted around the world showing that a balance between science and design can bring the best of the two worlds: the production of creative and aesthetical solutions on one side and the reality check of effective resilience on the other side. The formalization of steps in our roadmap force such dialogue between these two spheres with scientific inputs challenging the prototypes from designers and triggering improvement through iterations. The bet of this approach is that the extra cost of such dialogue will be compensated by the higher quality of the product - with more lasting public acceptance and resilience performance resulting from a legitimate informed design. While this approach is pragmatically proposed for individual projects building resilience, the long-term prospect is to make this dialogue between science and design a continuous, never-ending one.

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