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*Article*

# A Systematic Assessment for the Co-Design of Green Infrastructure Prototypes—A Case Study in Urban Costa Rica

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**Abstract:** The management of urban water has evolved from single-function systems to more sustainable designs promoting society and nature as inputs to engineer novel infrastructure. In transdisciplinary research, co-design refers to a design thinking strategy in which people jointly frame a problem-solution. This article presents a conceptual framework to assess a case study focusing on the process of co-design and implementation of green infrastructure as a prototype for stormwater management. The evaluation is carried out from a self-reflective post-implementation perspective. Research activities are translated into the framework to evaluate conditions shaping the trajectory of the prototype. As a result, key aspects driving the research regarding levels of stakeholder participation and dimensions of power are identified. Planning resilient co-design strategies to retrofit urban spaces is necessary to avoid unintended consequences, especially at the initial experimental stages. This study aims to contribute to the continuous improvement of pilot strategies in urban spaces by providing a framework for a structured evaluation of research experiences.

**Keywords:** green infrastructure; transdisciplinary; water systems; Costa Rica; co-design; prototype

## 1. Introduction

Scientists and politicians have declared that overcoming social inequalities ensures water and sanitation for all. This planetary goal, included in the UN's 2030 Agenda [1], calls for the co-creation of more resilient and sustainable human habitats, which implicates the involvement of local actors to solve their most pressing problems. It includes inter- and trans-disciplinary dimensions of knowledge found in the field of sustainability or in transdisciplinary research (TdR) that question the traditional roles of science to solve real-world problems [2] and advocate for more participation and action, thereby placing scientists in real-life situations, confronting them with aspects commonly out of their professional academic domain.

"Nature-based Solutions" (NbS) can be defined as the management and use of nature as a means to mitigate human impacts on ecosystems and to achieve sustainability [3], [4]. Green Infrastructure (GI) is an approach related to NbS in which natural counterparts complement, augment, or replace conventional infrastructure [5]. GI combines natural and semi-natural elements as an important strategy for sustainable development, especially for urban systems [6]. Multifunctionality is commonly associated with GI [7] to provide numerous benefits, for example, to enhance biodiversity, support water management, or mitigate environmental degradation [8]–[10]. Moreover, there is an increasing interest for GI in Latin America [11], [12]. In Costa Rica, for instance, the concept has been adopted at the national scale to refer to the resilience required for developing transportation infrastructure [13]. Since participation in its design is advocated to achieve multifunctional GI [14], different understandings might be expected to define those novel elements.

In contrast, dealing with nature is highly contested [15], [16]. GI is a popular term [17]–[19] that might lead to ambiguous or selective interpretations [20]–[22], especially

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regarding the management of water [23]. Moreover, GI interventions might produce or exacerbate social–spatial inequalities because of different perceptions about nature [24]. Promoting transformational interventions using ideas about nature in urban areas requires identifying institutional structures and rethinking the knowledge production process [25]. Therefore, designing GI involves a social–ecological dimension. Although design methods have different rational or reflective ways of framing a problem-solution [26], the co-design method is acknowledged to foster change toward sustainability [27], especially when iterative participation creates operational knowledge for the desired result [28].

Since the popularity of GI expands to different contexts, integration of the cultural and social aspects of nature might be necessary for its design to achieve effective implementation, requiring a shift in the conventional engineering thinking that dominates the design process of infrastructure. Kees Dorst [29] presented deduction, induction, and abduction as modes of logical thinking. The first two modes are commonly used in science and analysis to predict results based on knowing an object and its working principle, or to explain a hypothesis made from observations of a specific phenomenon. In design, the abduction mode conceives results as the desired value obtained when both the working principle and the desired outcome or only the desired outcome are known at the beginning of a problem-solving iteration.

In this context, [28] highlighted co-design as an imaginative process in which communication and cooperation are ways to bring about positive change, which differs from mainstream science based on a "spectator conception of knowledge". The notion of “framing” [29], which is the creation of a standpoint from which a problematic situation can be tackled, supports designing the resulting value..

In this study, we develop a conceptual framework to evaluate and assist the co-design processes of GI. We employ the framework in the post-implementation experience of a GI prototype in the metropolitan area of Costa Rica. This evaluation is presented in a Nautilus geometry to summarize key insights and interactions during the co-design process. The framework first defines conceptual phases for an iterative co-design. Then, it assesses levels of participation and relations of power, which guides the self-reflection on the experience of promoting GI through a co-designed prototype. The objective of this evaluation is to systematize the researchers’ experience with the co-design process and synthesize the lessons learned. The goal of the article is twofold: to present a framework as a guidance tool for assessing the co-design process of a GI prototype and, based on this, to identify drivers governing research action in real-world scenarios through an analysis of power relations and participation.

Such an approach is necessary for transdisciplinary research to improve co-design strategies based on previous experiences. A systematic evaluation of co-design experiences can contribute to comparing general patterns of systemic behavior identified from specific and context-dependent studies. Reflexivity and applicability are TdR principles for sustainability [30]. In this context, a self-reflection on co-design experiences can support the transference of empirical knowledge at both specific site contexts and the more general research–practice interface. Moreover, a systematic evaluation can reveal how participants embark on the design journey [31], thereby increasing the transformative potential of active citizen participation in green space governance [32]. In addition, evaluating lessons from the co-design of GI might prevent future management strategies from moving a social–ecological system into undesirable configurations [33]. This can be achieved by revealing the dominant dynamics of those systems [34] and documenting TdR processes to cope with criticism about the level of reflexivity required in similar experiences [35]. In this context, this study aims to propose a general guide to systematically assess abductive co-design strategies of innovative infrastructure in urban systems, especially in those highly governed by normative procedures in relation to water management and retrofitting of urban landscapes.

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The following section presents the case study of this analysis, which was based on a learning-by-doing approach to involve stakeholders in the co-design of a GI prototype and the co-production of operational knowledge during the mapping, planning, and implementation phases. Next, the methodology describing the framework and its conceptual background is introduced. It emphasizes translating empirical research activities into conceptual phases for evaluation. Then, the relations of power and stakeholder participation in each phase are assessed as a self-reflection exercise to identify patterns that steer the results of the co-design process. The Results section presents the outcomes from the application of the proposed framework. Finally, the Discussion section focuses on the identification of those patterns and the implications for an output-oriented approach. Recommendations for future studies and guidelines are presented in the Conclusions section.

## 2. Materials and Methods

### *2.1. Case study: origin, background, and key insights*

The research platform for sustainability, FONA, funded by the German Federal Ministry of Education and Research (BMBF), funds the research group SEE-URBAN-WATER in the field of socio-ecological TdR. The research focus of the group is on the socio-ecological improvement of already developed urban areas through retrofitting measures by employing NbS, especially for the management of urban drainage and wastewater systems. The co-design of prototypes has been developed in the group as an empirical experiment to identify how GI can be effectively implemented [36]–[38].

The research group selected an urban context in Costa Rica as a case study for exploring social–ecological dynamics concerning GI. As none of the researchers had a previous relationship with the area, the first contact with local universities and municipalities resulted in a cooperation agreement to jointly explore the research topic in a 28 km² watershed located within the main metropolitan area of the country, where the local parties had previously worked together in the context of urban flooding. Primarily over the last few decades, about 63% of this area has been urbanized [39]. As a result, periodical flooding events define a major social concern, especially in two of the five municipalities located within the hydrological boundaries. Major activities in the past to counteract urbanization effects are related to enlarging the hydraulic capacity of the main river and public infrastructure or regulating construction permits at the municipal scale.

Funding for the prototype was provided by the research group. Moreover, ensuring local participation during the planning, design, implementation, and operational stages was a key principle encapsulated in the co-design idea. The prototype considered in this study resulted in retrofitting a sewer collector into a detention tank [37]. The outflow reduction in the collector was compensated for by a hydraulic bypass. The misplacement of a mesh by the constructor led to clogging and subsequently to the temporary collapse of an upstream manhole. Complaints from the residents about unexpected flooding areas, noise, dust, and the presence of outsiders reached the municipality during the implementation and operation phases. Simultaneously, the dependence on a specific municipal partner for the co-design had practical consequences when this person left the municipality.

As new partners were skeptical about the experimental nature philosophy intended by the researchers, the prototype stopped its operation and the system returned to its initial configurations during the COVID-19 pandemic. This also impeded monitoring the performance of the resulting system in a quantitative way, as initially intended. Despite progressing through the co-design stages until its implementation, the prototype failed to become a permanent element managed by the local actor constellation. Nevertheless, the transdisciplinary and collaborative planning, design, implementation, and experimental operation of the prototype resulted in important insights for future replication, promotion, and implementation of GI [38], [40], [41]. An appropriate and effective post-implementation evaluation of this transdisciplinary GI prototyping experience enabled a systematic analysis of the co-design process to synthesize the lessons learned, thereby providing assessment guidance and identifying the drivers governing research action in real-world scenarios.

### 2.2. *Evaluation of the case study*

The evaluation was a post-implementation analysis carried out by the researchers involved in all experimental phases up to the operation of the prototype. It was based on a systematic assessment framework, adapting concepts proposed previously by different authors who dealt with co-design as a collaborative design–thinking process in TdR, as described in the following subsections. First, the principal research activities of the co-design process were categorized into conceptual phases and subphases (Section 2.2.1). Sources of information included project reports, previous academic publications, research diaries, interview notes, and local regulations and ordinances that served as a basis for project-related choices that determined the subsequent activities. The categorization of research activities supported the definition of factors that influenced the development of the project. In a subsequent process, those factors supported the identification of the relational dynamics of power and participation (Section 2.2.2). This analysis was first conducted by each of the involved researchers. They then summarized the drivers influencing each phase. Finally, the results from the previous steps were integrated into a Nautilus geometry as a graphical representation to summarize the project trajectories, thereby identifying the drivers governing the research activities related to power and participation dynamics (Section 2.2.3).

#### 2.2.1. Conceptual phases and related activities of the co-design process

The authors of [42] and [28] argued that co-design is a collaborative design–thinking process in which problems and solutions are iteratively re-framed. Both suggested similar strategies for co-design. Pearce [42] approached co-design as a design–thinking tool for TdR based on steps related to empathizing, defining, ideating, prototyping, and testing potential solutions. Similarly, Steen [28] proposed five stages for an abductive co-design based on an indeterminate situation in which the real problem is still unknown; the institution of the problem-solution as a common agreement for a specific situation; an iterative determination of the solutions expected for such a problem; a reasoning stage in which those solutions are evaluated; and an operational stage where they are tested. Both perspectives were integrated into the framework by merging the steps proposed from the design–thinking with the abductive stages for co-design. An explorative phase governed by the creation of empathic relations was connected to an indeterminate situation in which insights and contradictions were discovered by the researchers. Then, the viewpoint of different actors about a specific issue was "institutionalized" as a problem. The next phase, related to the emergence of specific ideas for the prototype, gave way to the determination of an expected solution for the pre-defined problem. It led to the next phase, in which the reasoning of potential solutions was iteratively contrasted with real limitations for the implementation. The final phase was related to testing activities in the field.

However, those two perspectives omitted aspects related to the initial phase of a TdR project. To address initial research conditions, the framework proposed in this study also included an additional phase based on the concept of "Phase 0" [35]. Because of the strong context dependency of TdR, this notion stressed the importance of understanding the background aspects of the research foundations. It consisted of three sub-phases: selection of the case study, initial understanding of the context from a TdR perspective, and the fostering of premises. In addition, the "research purpose" was included as another sub-phase to target how it influenced further trajectories.

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A summary of the six phases considered for the conceptualization of co-design is presented in Table 1. The activities carried out by the research team over time were associated with each phase and the corresponding sub-phases. For each sub-phase, decision-influencing factors were defined that steered subsequent activities.

**Table 1.** Conceptual framework for evaluation of a co-design process, adapted from [28], [35], [42].

| | Phase | Sub-phase | Description |
|---|---|---|---|
| 1 | "Phase 0" | Research Purpose<br>Selection study case<br>Fostering premises<br>Context understanding (TdR) | Setting up initiation of the mutual learning process in a science-driven approach before co-design begins. |
| 2 | Indeterminate situation | Problem situation<br>Insight into a theme<br>Pinpoint contradiction | The situation experienced is problematic, yet the problem is not known. Subjective experiences are critical to making a situation questionable. |
| 3 | Institution of a problem | A provisional definition of a problem<br>Agreement meaningful insight<br>Point-view problem statements | A common view of a problem is iteratively refined later. The way the problem-setting is conceived decides the direction of solution-finding. |
| 4 | Determination of problem-solution | Brainstorm potential solution<br>Criteria for a type of solution<br>Framing design procedure | An iterative process to restate and refine the problem. Problem-solution is best explored using perception-conception (what is-what could be). |
| 5 | Reasoning | Iterative co-design idea<br>Materialize | Critical discussion of relationships-interactions between means and ends. |
| 6 | Operational character | Input<br>Construction<br>Operation | Test and experiment. Discuss roles and recognize conflict to develop a shared understanding of how to cooperate. |

2.2.2. Analysis of stakeholders' participation and the relations of power

An analysis of the relations of power and participation was systematically conducted to identify the aspects controlling the co-design procedure. A typology of degrees of citizen participation proposed by [43] served as the main reference to evaluate how researchers involved the different stakeholders in the project (Table 2), while a structural analysis of the dimensions of power and elements of participation proposed by [44] was adopted to determine instrumental, structural, and discursive conditions (Table 3). We merged those two conceptual frameworks to identify the factors influencing the project at each phase, thereby defining which decision factors influenced the future trajectories of the project.

**Table 2.** Degrees of citizen participation adapted from [43].

| Category | Description |
|---|---|
| Citizen control | Full managerial power |
| Delegated power | Majority of decision-making seats |
| Partnership | Negotiation and engagement in trade-offs |
| Placation | Allowance to advise |
| Consultation<br>Informing | Allowance to hear and be heard |
| Therapy<br>Manipulation | Educative and healing attitudes |

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A relational understanding of participation through the lens of power was proposed by [44]. “Power over” was defined as “the realization of researcher’s own will in asymmetrical relations”, which acts from instrumental, structural, and discursive dimensions over three elements: subjects, objects, and procedures. In instrumental power, researchers influence other actors to do something the latter might otherwise not do. Institutional conditions influence a decision to shape the structural dimension. Discursive power refers to the influence over the desires and beliefs of other actors. Regarding the elements: subjects are the actors taking part; objects are the issues and concerns being debated (i.e., agenda); procedures refer to the rules and formats that are employed. Moreover, sources of power can be material aspects (e.g., financial means, accessibility to equipment) or ideational aspects such as social constructs (e.g., ideas, values, norms, perceptions). Table 3 summarizes the dimensions of power concerning those elements, including key questions to consider on the sources of power. These questions supported the identification of prominent elements influencing decisions made during the different phases of the study.

**Table 3.** Dimensions of power concerning elements of participation, proposed by [44].

| **Element / Dimension** | **Who (subjects) Actors interacting** | **What (objects) Agenda** | **How (procedures) Rules** |
|---|---|---|---|
| Instrumental | Who decides who participates and who directly influences this decision? | Who sets the agenda of the process? | Who sets the rules of the process and controls its enactment? |
| Structural | In what ways do structural conditions predetermine the selection and participation of actors? | In what ways do structural conditions circumscribe the issues which enter the agenda? | In what ways do structural conditions predetermine the formats of participation? |
| Discursive | Which norms and ideas are actors selected and positioned in the process? | How do ideas and norms shape the framing of issues and agendas? | To what norms, ideas, or standards do the formats of participation allude? |

Ref. [14] proposed a Chambered Nautilus model as a heuristic tool to visualize the trajectory of co-designing GI. It illustrates the idea of the co-design process for resilient urban systems at multiple scales. However, it fails to address how this process is influenced by researcher choices or by initial research conditions. Although the study focuses mostly on describing stakeholders’ participation, it proposes the use of the Nautilus geometry to show the key insights of an iterative procedure related to the planning of GI. The successive turns of the Nautilus toward its center represent an abductive design that depends on the results of previous phases. A top-down approach is represented by an inward movement, while a bottom-up process is depicted by an outward flow. Each spiral chamber is linked to previous stages that depend on the working principle ("how") and the material object ("what") toward the end value (i.e., project purpose). Both the "how" and the "what" are unknown during the experiment, revealed only during practice because of the site context of TdR. The motion to approximate the origin of the spiral is conditioned to a research-driven approach, associated with the boundaries of the geometry. **Error! Reference source not found.** presents the integration of the conceptual framework from Table 1 into the components of the Nautilus.

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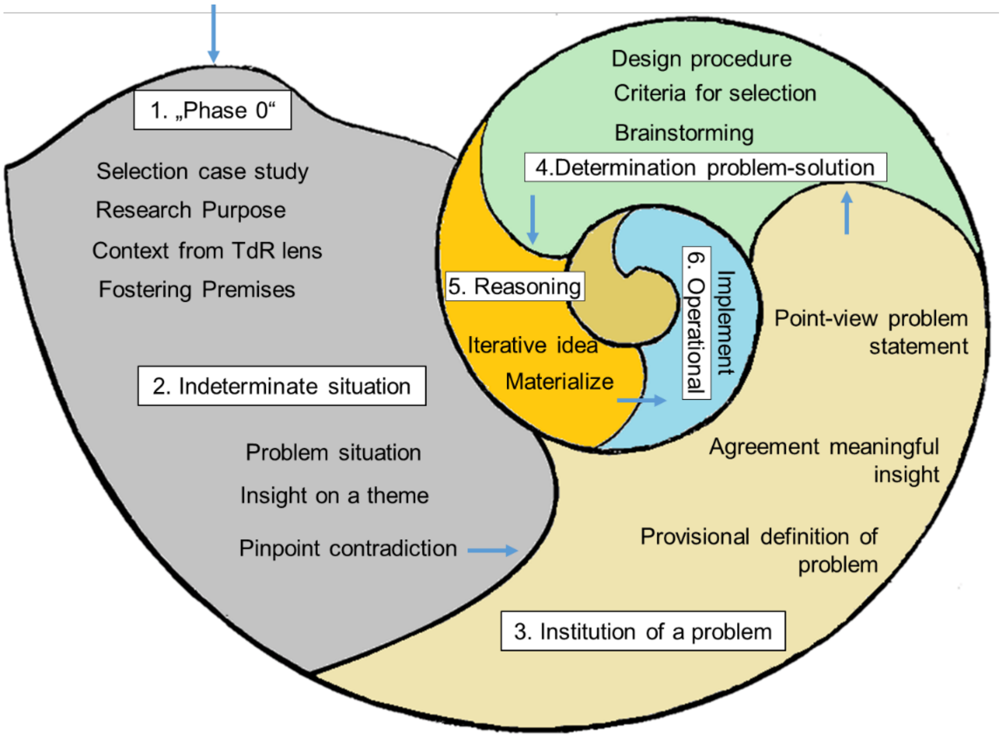


**Figure 1.** Graphical representation of the conceptual framework based on the Nautilus shell geometry for the assessment of the co-design of Green Infrastructure.

## 3. Results

*3.1. Conceptual phases and research activities*

Table 4 presents the major research activities, how they related to each conceptual sub-phase, and the factors that influenced the decisions, which were formulated during the post-implementation assessment of the co-design process. These decision-influencing factors reflected the temporal understandings associated with the development of problem-solution framing.

The principal research purpose was predetermined during the conception of the project when it was presented to the funding agency. In the first phase (“Phase 0”), the selection of a study area departed from a shared perspective with an academic actor aiming to foster a mutual learning process between scientists and societal representatives. This partnership agreed on the contrasting ideas between conventional single-function reactive water systems and the views of nature within social–ecological systems to support sustainable urban water management.

The identification of the site led to the exploration of local views of the present environmental situation, especially along the river. Key terms employed in the research communication, such as the increase in stormwater runoff from impervious areas or the lack of green spaces as recreational areas, were locally associated with the context of flooding in the watershed, mainly by municipal representatives. Field activities at different locations in the watershed were carried out (i.e., site visits, hydrological monitoring, and meetings with different stakeholders) to avoid considering only specific perspectives. This diversified the researchers’ insights and allowed formulating an understanding of the local situation especially associated with the effects of urbanization. The authors also came to know a legal sentence from the constitutional court referring to river degradation and flooding. In the second phase, referring to this sentence during dialogues with involved actors allowed researchers to pinpoint contradictory accusations concerning environmental responsibilities, thereby considering different ideas about the existing situation.

**Table 2.** Research activities of the case study associated with the conceptual phases.

| Phase | Assigned activities | Sub-phase | Decision influencing factors |
|---|---|---|---|
| 1 | Research team meetings, first contact local research partner, literature review | Research Purpose | Real-world lab to experiment with green infrastructure as a multifunctional prototype |
| | | Fostering premises | Social-ecological system and sustainable urban water management |
| | | Selection study case | Local researcher with previous experiences and empathy for the project |
| | | Context (TdR lenses) | Conventional hydrological-driven practice |
| 2 | Site exploration and bilateral interviews | Problem situation | Flooding events endanger citizens and result from rapid/informal urbanization |
| | | Insight into a theme | A legal sentence from a citizen demand |
| | | Pinpoint contradiction | Mutual accusations about environmental responsibilities |
| 3 | Workshop with authorities | Provisional definition of problem | Reactive, short-term conventional practices are not sufficient to counteract the impacts of urbanization |
| | | Agreement meaningful insight | Potential social benefits of integrating GI |
| | | Point-view problem statements | Researcher/citizen/authority: Hydro-spatial-social knowledge / Nature for water sustainability/ Adapted regulations, cooperation |
| 4 | Site downscaling | Brainstorm potential solution | Researchers select a proposal and collaborate on defining the function and location of the prototype |
| | | Criteria for a type of solution | Match with research purpose, empathy for collaboration, feasibility |
| | | Framing design procedure | Hydro-social-spatial knowledge to iteratively co-design prototype designs and locations with residents |
| 5 | Second workshop and drafting ideas. | Iterative co-design idea | Compromise between researchers' ideas and authority consensus |
| | | Materialize | Design principle agreement: location, function, construction mode, funding |
| 6 | Formalities | Input | Call for tenders: locally certified engineer, budget |
| | | Construction | Fulfilling legal regulations |
| | Experimental observation | Operation | Emergent conditions unrevealed during design led to failure of the prototype |

A shared viewpoint defining the problem was achieved in the third phase during a workshop attended by local authorities or their representatives. The event consisted of an informative overview of the research and discussions about the meaning of the project in the study area. This event formalized the institution of the problem phase, highlighting traditional practices for water management and the social benefit of GI. Moreover, it addressed the role of each actor, including the needs of researchers, citizens, and authorities to effectively participate. In detail, the main problems for the researchers were the lack of local knowledge and access to information; citizens were seen as lacking access to nature because of the high degree of urbanization, while political institutions appeared to need more collaboration to develop regulations that included nature-based solutions in conventional infrastructures at regional scales.

The fourth phase included establishing a procedure to determine pilot solutions regarding the management of stormwater runoff. Selection criteria for its location and function were initially based on brainstorming with the workshop participants. Researchers asked participants to propose areas for potential implementation of GI within their jurisdictions and to characterize them by filling out a survey. After field visits to the suggested sites and additional bilateral interviews with the proponents, they decided on a proposal that aligned with the research purpose and the researchers' perceptions of potential collaboration, discursive empathy, and feasibility. Downscaling the study focus to a smaller area, the neighborhood scale, created a new partnership with the local public administration, hereafter referred to as the political partnership. It led to organizing new activities based on the perception of this partnership regarding adapted infrastructure, such as dialogues, design workshops, and public events with residents, and intensive monitoring activities within the boundaries of the selected area. Thus, the perspectives of the problem at the larger scale (i.e., the watershed) were restated from a site-specific viewpoint.

During the reasoning phase, boundaries between research ideals and restrictions were confronted. This phase shaped the prototype as a pragmatic implementation under site limitations. Researchers acted as designers during the drafting and planning phases of the prototype, based on their site insights and the purpose of implementing an experimental element for further research in a real-world lab context. The drafts were iteratively contrasted with the views of the local representatives, especially concerning the legal regulations and potential benefits they perceived for the residents.

The final phase initially contained a formal dimension related to the procedures needed to intervene in public spaces. It included calling tenders for the construction, and the maintenance required post-implementation as a responsibility of the public administration. As a result, the construction fulfilled the norms established for retrofitting urban spaces. During the implementation, researchers provided general insights into the construction activities and observed the development of conditions arising from predefined circumstances. These observations were related to the dynamics residents perceived regarding the construction. For instance, high vegetation was discarded because neighbors were against it because of their feelings of insecurity resulting from more shadows.

### *3.2. Participation and relations of power*

A summary of the forms of power and participation at each phase is presented in Table 5. The instrumental dimension of power was combined with the degrees of participation because both complemented the goal of identifying interactions among actors. Although participatory dynamics were promoted by the researchers, the dynamics were also influenced by the pre-existing relations among local actors, such as mutual empathy or previous experiences beyond the scope of this analysis. In addition, the elements of the three dimensions of power (i.e., subjects, objects, procedures) were summarized in the table to present, after the researchers' reflection process, the major factors driving the trajectory of the study. In general, the conceptual approach to the forms of power and participation served as a tool for an overall analysis at each phase rather than an exhaustive guide for specific research activities. In the following, the key elements of the instrumental, structural, and discursive dimensions are presented.

Regarding the instrumental role of actors, the dynamics between researchers and local authorities aimed to build partnerships supporting a feasible intervention. This contrasted with the role of residents who were consulted initially about flooding issues and their dynamics with the river, which were later involved using different formats (social events, ad-hoc interviews, workshops) to determine potential types, functions, and placements of GI preferred for the prototype. The communication means of including local actors departed from their views over NbS and GI and how those concepts were related to water management issues or the urbanization process. In detail, this communication strategy allowed the creation of the initial partnership by sharing a robust message about the importance of considering nature functions in novel infrastructures. However, the participatory formats subjectively assumed for each actor potentially limited the identification and inclusion of alternative perspectives in the co-design. For instance, participation rose to placation levels during the institution of the problem phase, in which a pre-established agenda positioned researchers as organizers and advisers.

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**Table 5.** Identification of relations of power and dynamics of participation between subjects, objects, and procedures at each phase.

| Phase | Instrumental | Structural | Discursive |
|---|---|---|---|
| 1 | A informs and partners B | Research-driven output-oriented approach, disciplinary background | Water management, watershed scale, GI-NbS, TdR, social-ecological urban systems |
| 2 | A consults B, D, E, F about the situation; A partners B, D | Learning-by-doing and snowball methods, institutional organization | Flooding, informal settlement, legal sentence, previous experiences along the river, the hydraulic capacity of infrastructure |
| 3 | A, B inform-placation C, D about research | Partners' understanding, institutional organization, municipal spatial boundaries | Only one proposal was selected, urban development |
| 4 | A partners D; A placates E about the research; A informs, consult E, F knowledge | Administrative complexity, existing regulations, actors' role to opine | Co-production knowledge, representability, retrofitting |
| 5 | A partners D | Co-design and safe-to-fail | Green-to-gray infrastructure, preferences, and perceptions |
| 6 | A partners D, G during procedures; A informs E, D during construction | Legal formalities for intervention in public spaces, funds availability | Local complaints, willingness to continue experimentation from key partners |

A: researcher–practitioner; B: local research partners; C: local authority; D: authority representative; E: concerned citizen and civil representatives; F: random citizen, G: constructor.

The structural dimensions of power were related to the rules followed to frame the prototype around the existing institutional formats. The learning-by-doing method, for instance, was strongly associated with a snowball effect, a process in which first insights guided the involvement of new actors and ideas. As stakeholders came mostly from environmental or planning departments, they referred particularly to their domains and provided few insights outside their formal position. This information guided the prototype purpose in a specific direction up to the fulfillment of regulations for the construction and operation of the experiment. To proceed with the implementation, this dimension moved to a safe-to-fail view, which refers to the idea of avoiding disturbing social conditions as a result of the experiment. This shift was governed by the perception of the partnership with the municipality as a political actor iteratively defining characteristics of the prototype, choosing riparian zones as a preferential space to develop this type of prototype. This choice was linked to both the ideas about nature contained in the GI concept and the administrative capacity to grant intervention permissions in public zones categorized as degraded or with low social value.

Other components of the structural dimension referred to socially organized entities bounding the learning-by-doing. Since the administrative limits diverged from hydrological boundaries, the complexity of participation increased because of the number of existing representatives. Moreover, participation was influenced by an institutional specialization, which led to establishing first contacts at the departments matching research keywords, such as environmental or planning instances. Procedures, norms, and regulations were also included in this structural dimension. In addition, memories of previous local efforts dealing with flooding issues influenced the researchers' immersion into an actor–network constellation. These situations constrained the creative capacity to develop nonconventional systems, limiting the transformational desire for urban spaces in which natural components were included.

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Regarding the discursive dimension, an initial research message about the benefits of natural functions for urban infrastructure evolved, as ideas were translated into contextualized issues. The dominant use of water-related concepts was associated with the downstream–upstream position of existing stakeholders and their perspectives about (non)-conventional solutions. This condition was reinforced by similar disciplinary backgrounds found not only within the partnerships but also the actors from environmental urban planning departments or social committees. A keystone was the legal sentence from the constitutional court referring to the responsibility of local institutions to act regarding the flooding issue, as it was referred to by most of the stakeholders. It enabled the use of the sentence as a concrete context to refer to the potential adaptation of NbS and explore further local views. Connecting conceptual ideas to the stakeholders' narrative attempted to increase empathy for the project, especially at the initial research stages.

### *3.3 Graphical representation of the co-design process*

**Error! Reference source not found.** presents a graphical summary of the key interactions identified during the study. In the figure, red arrows at the borders represent inputs controlled by the researchers, while internal green arrows represent inputs influenced by site conditions. From this approach, two types of systemic drivers were deduced: the external conditions guiding the project and the processes guiding the site adaptation toward the research goal. In addition, blue arrows summarize the decision-influencing factors steering those drivers.

External drivers were prominent during "Phase 0" and at the determination of the problem-solution. An overarching factor influencing the research was related to the funding conditions. The research purpose formulated during this funding stage defined the keywords shaping the communication strategy for the local actors. This discursive dimension led to partnerships with those sharing common grounds and narratives for the framing of the problem-solution. This first external driver in the form of a research-driven approach guided the message about including natural functions in the prototype until the downscaling activities (i.e., selection of a specific area for implementation). Once the partnership for the site implementation was established, a new driver emerged related to the selection criteria employed to design the prototype. In our case, the multifunctional perspective for GI departed from a stormwater management function because of the main research focus on urban watersheds with flooding problems, the disciplinary background of most of the involved actors, and the matching of their site views with environmental problems. This driver for the design criteria established the activities performed for the final design. For instance, mapping activities dealing with the identification of available public spaces or the dimensioning of existing infrastructures became relevant to determining the function and location, which might have created a bias in the data available for initial design drafts.

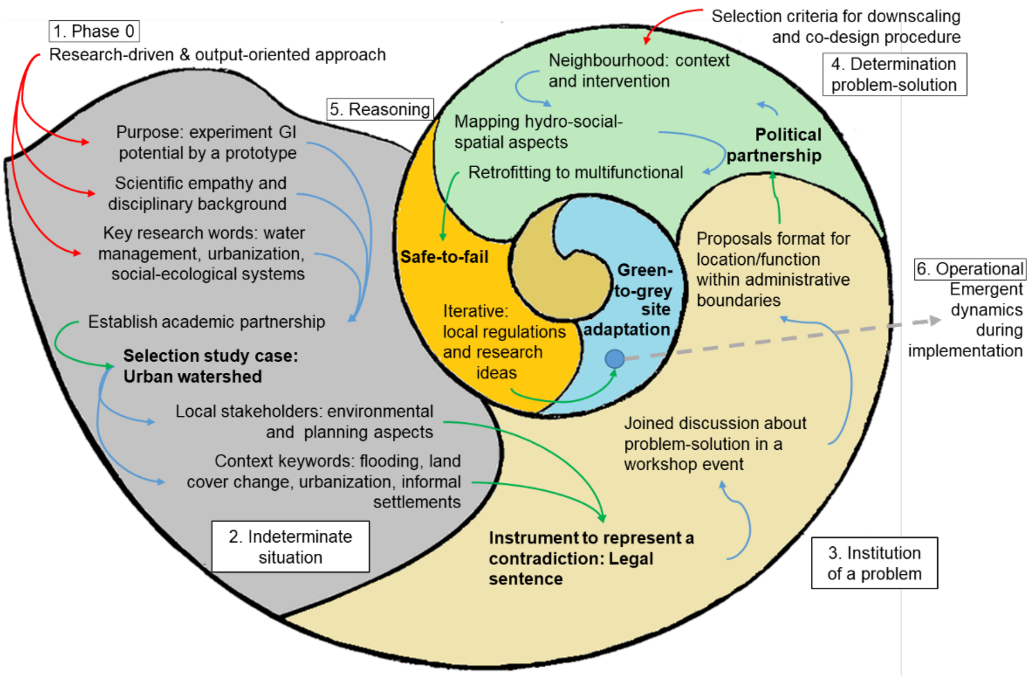


**Figure 2.** Summary of key drivers for the evolution of the research experiment.

On the other hand, internal drivers represented the progress of the project crossing conceptual phases. First, actors involved in the initial phase shaped the research trajectory (i.e., snowball effect) by virtue of their previous experiences and existing relationships with other actors. Another driver was the use of a central object evoking different opinions. Referring to a legal sentence was a potential way to discover contradictory arguments, thereby further exploring the problem dimensions. In addition, shifting to a partnership at the municipal scale after the downscaling became the third driver of the implementation purpose. It provided context to the research, revealing realistic constraints such as the willingness of local actors to participate or regulations for the intervention. As a result, the determination of site limitations led to the safe-to-fail approach, which was identified as a fourth driver. Avoiding the disturbance of dominant urban dynamics by focusing on areas with low social value ensured the implementation goal. The last driver referred to adaptation of the GI concept to a reality mandating conventional engineering standards to allow the intervention. Contrary to the initial expectations of considering nature as a fundamental element of the prototype, this context led to integrating traditional gray components to simulate functions of nature, such as storage or infiltration.

## 4. Discussion

In this study, a framework was proposed to evaluate the co-design process in a TdR project related to a GI prototype. To exemplify the use of the framework, it was applied to a case study of urban retrofitting of public infrastructure in Costa Rica. It contributed to identifying drivers of the decision-making process during an abductive co-design format. For instance, different understandings of a nature-based approach led to asymmetric levels of participation when specific stakeholders were selected as major contributors, thereby creating path dependencies that influenced outcomes or the resulting position of the researchers within the stakeholder's constellation. As stakeholders act according to their roles, systematic drivers can potentially be forecasted during such cooperation efforts. Therefore, revealing when such drivers become dominant requires a reflective position toward initial experiences in a structured manner. The framework presented in this study supported such reflection by conceptualizing typical co-design phases and the dynamics emerging between stakeholders, procedures, and ideas at each phase.

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Forecasting such drivers can not only contribute to creating more resilient site-adapted strategies for future interventions in the transition of urban water systems but also support engineering and natural scientists to raise self-awareness of their interaction within the social system during the socio-ecological engineering of urban water infrastructure. The different and often contested views of nature [15], [16] can influence how natural processes are adopted in non-conventional designs. Therefore, making an explicit choice about the desired paradigm shift that includes natural components requires effective communication of the expected conflicts in the current reality, which can result from pilot experiences. The graphical representation in a Nautilus geometry as a summary of the assessment results might also assist those communication efforts from a TdR perspective, especially to connect the dots of how initial assumptions, research backgrounds, or epistemological positions influence the interactions between actors and procedures.

On the other hand, the application of the framework is restricted to researchers involved in the entire process of the design, who simultaneously reflect on participatory and power dimensions. It can lead to subjective views during the evaluation. As they become part of the system under study, mutual accusations are prone to emerge, especially in water management practices where technical domains might be subject to practices of purification (i.e., politicizing engineering practices by way of dominant views) [45]. However, a self-critical reflection on their actions is not only suggested in TdR studies [30] but also necessary when researchers become practitioners trying to solve real-world problems [2], especially when the rationalization process of knowledge production occurs [19], [26].

Some assessment results from the application of the framework were related to the particularities of the TdR project considered in this study. The project departed from the external vision to test and promote GI, with funding available for the prototype but lacking a specific area and partners with a previous interest in the target. As we have seen, these factors influenced the trajectory of the final results, potentially differing from other TdR projects with existing initiatives or strong partnerships established at their initial phases. Although the application of the framework to the initial phases of such cases might reveal different insights, the identification of systematic drivers or the visual representation of the co-design in the Nautilus geometry is equally possible by adapting the framework phases to such contexts. In addition, the framework is not necessarily limited to post-implementation evaluations; it can support the discussion of intermediate results among inter- and transdisciplinary groups to project expected outcomes.

In detail for the case study, a compromise resulted between research ideals, contradictory beliefs, and the preferences of different actors. These trade-offs directed the conceptual goal toward realistic conditions constrained not only by social–political factors, but also by the researchers' capacity to immerse themselves in the existing reality. For instance, social contracts regulating interventions in public spaces reflected the external researchers' limitations when experimenting with the prototyping of GI from a top-down approach, modifying the initial expected scenario as a retrofitting of urbanized areas to riparian spaces perceived socially as conflictive. Moreover, conceptual views considered in the NbS-GI thinking were confronted with the action boundaries of the municipal representatives willing to participate, who must act in accord with their hierarchies of power. It led to re-framing the green character of the prototype to a hybrid mode that included gray components as a way to progress to the intervention target, fulfill legal regulations, and avoid predicted conflicts.

As a whole, the participatory approach empirically adopted for the co-design appeared to be a selective process guided by an output-oriented goal. The research project's goal of co-designing, constructing, and operating a retrofitted GI prototype led to a partly pragmatic output orientation to achieve the goal within the project's duration of five years. Starting without a predefined implementation site for the prototype and an initial group of stakeholders already engaged in the overall goal turned out to be highly ambitious, given the available time. In general, it can be said that such a TdR setting requires more time and flexibility in final goals or outcomes. In addition, the co-design of GI prototypes was not limited to the one dealt with in this paper, the research project included other GI prototypes and upscaling and mainstreaming GI objectives.

Although TdR is highly context-dependent, the patterns we identified from our experience can be a reference for researchers of potential archetypes existing in similar projects. The external drivers, the initial research purpose, and the final determination of design criteria relied on the choice of the researcher; while internal drivers (i.e., selection of specific actors, use of referential objects, shifting partnerships, safe-to-fail principle) were site- and context-specific adaptations. From the researcher's viewpoint, the flexibility required for achieving an output-oriented approach resulted in the deviation from the conceptual view for the prototype, from a non-conventional organic element to a green-gray element fulfilling conventional conditions. This contradictory result exemplified the balance required in TdR between an explicit pivotal intervention for sustainability, the social legitimacy of researchers' choices, the institutionalized boundaries, and the willingness of local actors to participate.

### *4.1. Transdisciplinarity underlying the research project*

For this research project, the transdisciplinary co-design was established as a cornerstone to proposing the sustainability of tailor-made realistic GI infrastructures. We carried out this post-implementation self-reflection process to share our experiences as researchers working in a real-world context. In the following, we discuss the main challenges to this approach that underpinned our case study. Other researchers have also shared their self-reflection as an evaluation process; identifying challenges, constraints, and obstacles to an ideal TdR application [46]–[50]. They have remarked on the importance of iterative self-reflection during the process. Though standardized evaluation procedures have not been established in the TdR field, each contribution, regardless of its methods and context, improves the overall understanding of the complexity of research on sustainability within social–ecological boundaries.

Although the desired, active, and constant participation of all stakeholders was not attainable, municipal practitioners were active mostly during the initial phases, whereas residents were approached from a consultative scale. [46] advised we must recognize and accept that not every step has to be performed together with all stakeholders. However, time constraints and agenda limitations on interacting with municipal representatives, as well as the lack of modes and spaces for coming together with residents, limited the social impact of the project. Because of the temporary condition of TdR projects, the risk exists of losing the momentum and curiosity of stakeholders by the end of the project [47]. This situation was experienced in our project, isolating the researchers during the construction of the prototype. Moreover, researchers are usually external actors who must interact with local actors to achieve meaningful impacts. In our case, the establishment of bilateral relations created close partnerships that eased the way through networking, which is necessary to increase the legitimacy of external actors [48]. A side effect of this trust-building practice was the emergence of a **"**hierarchy of knowledge**",** which influenced the inclusion and exclusion of actors. This dynamic has been highlighted in other contexts as a common practice deeply rooted in colonial relationships between locals and foreigners in Latin American studies [48]. Beyond the dependence created between specific partners in our case study, this traditional thinking to legitimize action reduced the chances for exploring alternative transformative processes or knowledge systems by favoring those actors holding more power.

In addition, the effective transference of information and communication between local actors and researchers during the different phases of the project appeared to be a major weakness of our experience. Communication is a difficult and main challenge of TdR [46], [48], [49]. In our case, the use of nature-related concepts such as GI or NbS based on academic terminologies combined with the unfamiliarity with local terms referring to

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environmental practices could have hindered the proper involvement of non-scientific actors. Although adequate target-group-oriented communication is required to counter such limitations [49], time constraints also influence the focus on specific participants, thereby raising several different expectations among these actors. The fluctuation of participants during the co-design process also reduced their chances to understand the core intentions of the prototype, leading to different views of the same context. Retrospectively, stakeholders proved to be mostly procedural objects rather than real partners, with a few exceptions. In consequence, an assumed consensus governed the progress of the experiment rather than an effective co-production of knowledge from different views of the conflict. A systematic self-reflection on the communication strategies and the produced knowledge can be achieved by considering the conceptual phases of the framework presented in this study, thereby enabling a common understanding of actions and objectives [49].

Reflecting on the relations of power, the degree of commitment to a project has been related to the self-interest of participants [49]. In our case, the foundations of a research-driven output-oriented experience resulted in a strong but subjective sense of ownership for the prototype as a priority to fulfill the research goal. Moreover, the desire to avoid a political instrumentalization of the project by local political actors [47], [49] and the bureaucratic means to guarantee authorization for the project led to trade-offs with decision makers in order to establish consensual views. Politicians, for instance, seemed motivated to participate when tangible results were produced in the short term and matched their agendas. However, this consensus at the academic–political interface weakened during the construction and testing of the prototype, as some still unknown residents expressed to the local authorities their disagreement with an unknown experiment in their surroundings. In consequence, this assumed consensus combined with a dependence on single actors to downscale the research, increased the uncertainty about the representability of the prototype experience. Therefore, making explicit the interests of the stakeholders and merging them into a common view is not only a challenging task, but also represents a strategy that ensures the resilience of piloting projects involving politicians, residents, and researchers.

### *4.2. Impact of the transdisciplinary research*

Ref. [46] categorized transdisciplinary results as “tangible product-related outputs” such as reports or publications and as “process-related outputs” that are intangible and largely experiential. Originating from a TdR funding platform, the experience evaluated in this article represented a research output aiming to increase the awareness of researchers during the co-production of knowledge for sustainable urban water management. After our reflection process, we argue that the research outcomes were predominantly intangible-related because the lessons from the application of the framework (i.e., external and internal drivers presented previously) supported a deeper understanding of the expected dynamics of future similar projects. Although the delivery of “real-world outputs” is regarded as a main objective of TdR [49], [50], this approach can also hamper the production of scientific outputs [46]. This study focused on the latter by providing a conceptual framework as the basis for evaluating transformative efforts in the form of co-design processes in urban spaces. We claim that the prototype experience, rather than being a physical object implemented by way of an empirical mode, supports the explicit understanding of governing dynamics from both the researchers’ choices and social structures.

Expectations are inevitably created when approaching local actors, which represents a constant struggle for TdR projects [51]. Being realistic about the transformative impact of site research has been already advised in TdR [49]. Lessons from our experience indicated the vulnerability to excessively adapting to well-established institutional conditions when aiming for the promotion of non-conventional views. This antagonism between theory and practice might have potential side effects that require consideration during the

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manipulation of social–ecological systems in real-world labs. For instance, the implications of failed experiments might limit future efforts on similar topics, reinforcing existing fragmentations that remain in the local memory. Little attention is paid to this dimension of experience [49], which is reflected in the lack of long-term observations about the TdR outputs of similar projects [44]. Therefore, considering the potential effects in the long run of piloting co-design prototypes should also be considered in the initial phases of TdR.

On the other hand, the "cognitive impacts" [46] of the research can be related to the individual learning competence development by those involved in the project. Empowerment during the development of site activities is seen as a positive side effect observed during data collection campaigns. The development of hydrological monitoring networks, for instance, supported increasing the discussion on water topics with different actors. It also led to identifying and contrasting the dominant conditions for our case study. Being aware of the systematic drivers previously presented might improve future planning strategies for approaching real-world scenarios more holistically. In contrast to our initial desire to avoid conflict during practice, a pivotal intervention should rather acknowledge the participatory frontiers expected for the actors involved from joint development of capacities [51] and the adoption of TdR as a cognitive-emotional-relational process of social learning [48] to increase the resilience of experiments challenging conventional practices in sustainable development.

## 5. Conclusions

In this article we shared the evaluation of a co-designed pilot experience related to the retrofitting of water systems in urban spaces. Transitioning from observers to nature-promoting participants provided lessons about the archetypes existing within the practice of such experiments. The shortcomings of the prototype called the researchers' attention to the procedure employed. This resulted in identifying the need to develop a systemic framework as a tool to guide a self-reflection process to improve future well-targeted small-scale co-designed interventions in the long term. The framework proposed in this study makes explicit the subjective aspects empirically adopted during a real-world scenario. Intermediate evaluations of participation and relations of power, as well as the influence of pre-established conditions, are necessary to rethink co-design trajectories. In this case study, those trajectories appeared linked to the relations between the actors and concepts that create a common narrative to define a function and location for the prototype. However, the differential inclusion of actors throughout the process and the development of unanticipated situations isolated the researchers at the final stages. While transdisciplinary research is commonly committed to timelines and explicit goals just as is any other research type, providing reflection spaces at the different co-design phases is necessary and contributes to contextualizing planning strategies that aim to stimulate social–ecological transformations. Conceptualizing the driving mechanisms and synthesizing them graphically, as presented in this study, can also support the transference of knowledge between academic and non-academic actors as it does between science and practice. Even with the failure of prototypes, revealing the hidden mechanisms at the research–practice interface contributes to producing common knowledge that improves communication and collaboration efforts. Therefore, understanding the real value behind prototype experiences helps to improve the resilience of transitional academic efforts attempting to support the sustainability of urban water systems.

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