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DIGITAL VERSION

IMPLEMENTING NATURE-BASED SOLUTIONS AND GREEN INFRASTRUCTURE FOR CITIES, CITIZENS AND RIVERS

The SEE-URBAN-WATER Project

SEE-URBAN-WATER


Aereal view of the district of Llorente, Flores and the Quebrada Seca-Rio Burío River, in the Greater Metropolitan Area of Costa Rica.

PREFACE

Global urbanization has increased substantially since the mid-20th century. In 1950, 30% of the world's population resided in cities; by 2018, this figure had risen to 55%. In the face of today's climate and environmental crises, cities find themselves confronted by a variety of challenges often exacerbating the impact of urbanization. In the past, the presence of rivers was often a prerequisite for establishing larger settlements, as they supplied drinking water, increased agricultural production, and provided a waterway for trading. Over the centuries, in line with the development of cities, streams and rivers have been continuously transformed by humans, for instance to increase their functions as drainage and waste receivers or to produce energy.

As a result of these significant transformations, cities and their rivers have experienced several undesirable ecological, economic and social impacts, such as increased flood risks, groundwater depletion and pollution, accelerated soil erosion, drinking water shortages, a decline in fisheries and biodiversity, and a loss of natural and semi-natural green space diminishing landscape aesthetics and recreational functions. Being one of the ecosystems most affected by urbanization, rivers are additionally challenged to adapt to changes in the flow regime caused by climate and ecological crises. The Urban Stream Syndrome, characterized by flashier hydrographs (higher flow volumes & peak flow rates, faster times-to-peak), increased concentrations of nutrients and pollutants, modified channel morphologies and diminished biotic richness (Walsh 2005), illustrates this severe environmental challenge. Yet even so, rivers are the only remaining ecosystems providing habitat and ecosystem services within cities.

In light of this, global interest has turned to research into measures able to mimic pre-development conditions, such as nature-based solutions (NbS). According to the European Commission, NbS are "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits, and help build resilience". This multifunctional potential implies the integration of multiple fields of knowledge, in turn requiring holistic research approaches capable of addressing the complex social-ecological challenges and achieving successful long-term operational results.

The purpose of this book is to summarize and disseminate the inter- and transdisciplinary work of our research group **SEE-URBAN-WATER** (**S**ocial-**E**cological-System **E**ngineering of **Urban-Water**-Systems; short: SUW) whose work was funded within the framework of the Research for Sustainability programme (known by its German acronym FONA) run by the German Federal Ministry of Education and Research (abbreviated to BMBF in German). Our aim is to provide robust knowledge and a methodological basis for achieving a social-ecological transformation through implementing NbS in highly urbanized areas prone to environmental and climate risks. These NbS are intended to contribute to the development of a resilient and multifunctional Urban Green Infrastructure (UGI).

Between 2018 and 2023, the SUW research group produced numerous master's and doctoral theses, methodological frameworks, research & technical guidelines, and scientific publications. More than just a compendium of these outputs, this book provides a comprehensive view with a clear narrative illustrating the systematic inter- and transdisciplinary evolution of ideas over the course of the research project — from the study areas' characterization to the co-production of knowledge with local stakeholders, the implementation of NbS prototypes, and the development of upscaling strategies. Since this book summarizes a large amount of research work, references to our full Open Access publications and other freely available products are included throughout the book.

The book starts with an introduction to our research group and approach, the project's objectives and expected results, as well as the geographical contexts and spatial scales considered. As will be discussed later, the project originally started in Nicaragua, but had to be relocated to Costa Rica owing to evolving social-political conflicts in Nicaragua that impeded the further course of our transdisciplinary, multi-stakeholder work there. Nevertheless, a description of the Nicaraguan case study and important results of further relevance for our subsequent work in Costa Rica are presented in the second chapter. Chapter 3 showcases the general characterization of the case study in Costa Rica, with a focus on the impact of urbanization on flood generation and an analysis of current flood-generating climatic conditions. Based on this, Chapters 4, 5 and 6 present the project's primary results in three main domains of the Costa Rican research context:

- co-design and implementation of NbS using a Real-World Lab approach (Chapter 4),
- modeling and multifunctional scenario analyses (Chapter 5), and
- governance for NbS development (Chapter 6).

Chapter 7 presents a summary of the project's outputs and products, while Chapter 8 provides an outlook for further research on the promotion of NbS and green infrastructure in urban areas.

The primary target readership is the scientific community and research-driven practitioners working on sustainable water resource management and urban planning. The outcomes of our research have practical implications for improving urban drainage, wastewater treatment, water protection, river basin management, and disaster control. Therefore, we believe that this book will also appeal to decision- and policymakers, as well as to the general educated public interested in fostering the development of resilient cities.

We hope that this book will inspire and encourage many other research groups in these and other fields of knowledge to bridge the gap between theory and practice as the best way to translate the sustainable development paradigm into concrete actions that deliver for our society and the environment.

Special features

Throughout this book, reader will find several special features. Explained on this page, these not only enhance overall understanding of each chapter, but also offer an interactive experience allowing the further exploration of SEE-URBAN-WATER's (SUW) research topics and delving into additional bibliographic and practical tools.

INTER- AND TRANSDISCIPLINARY CONNECTIONS BETWEEN RESEARCH DOMAINS IN DIFFERENT BOOK SECTIONS

The SUW research objectives are of inter- and transdisciplinary nature, facilitating the complementary and intertwined use of methodologies, resources and outcomes. Readers can easily identify and gain a deeper understanding of these interconnections through distinctive, blue-bordered boxes pointing to related material in other chapters or sections of the book.

Insights from NbS prototyping as basis for policy readiness assessment

Some of the proposed prototypes were used to analyze the readiness of Costa Rican policy for taking up and implementing Nature-based Solutions at different scales and dimensions (Section 6.2).

GUÍAS VERDES

'Guías Verdes' is a compendium of guidelines developed by the SUW team, aiming to promote and support the implementation of Nature-based Solutions and Green Infrastructure in urban areas. These guidelines stem from the SUW's transdisciplinary work in a Real-World Lab in Costa Rica, involving extensive collaboration with local stakeholders. By scanning the QR code, readers can access this material (currently available only in Spanish) which includes not only the objectives and description of each guideline but also its step-by-step application, expected results, rules, scope and challenges, as well as references and additional information.

Guías Verdes

For more information on how to install, maintain and use a hydrological monitoring station, while involving local stakeholders in its set up and operation, please refer to the following guidelines (only available in Spanish):

- Instalar, mantener y usar una red de monitoreo hidrológica.
- Involucramiento de actores locales durante la instalación y operación de una red de monitoreo hidrológica.

REFERENCES TO OPEN ACCESS SCIENTIFIC PUBLICATIONS

This book summarizes numerous scientific publications produced within the SUW project in a coherent, complete and comprehensible form for a broad readership. To allow full access to these open-access scientific publications, gray boxes list the relevant bibliographic information and QR codes linking to them.

For more information about the change in the watershed's hydrological response due to the increase of urban coverage, please refer to:

Bonilla Brenes, R., Morales, M., Oreamuno, R., and Hack, J. (2023). Variation in the hydrological response within the Quebrada Seca watershed in Costa Rica resulting from an increase of urban land cover. Urban Water Journal, 20(5), 575–591. https://doi.org/10.1080/1573062X.2023.2204877

ADDITIONAL INFORMATION

Relevant additional information can be found in blue boxes supplementing the book's content and encouraging readers to explore other freely available resources or tools for planning, modeling, and implementing Nature-based Solutions and Urban Green Infrastructure.

INFO

The population of the Quebrada Seca-Burio River watershed is about 115,800 corresponding to nearly 2.5% of the country's population and 25% of the population of the province of Heredia.

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SEE-URBAN-WATER – A JUNIOR RESEARCH GROUP IN SOCIAL- ECOLOGICAL RESEARCH

SEE-URBAN-WATER (SUW) is a Junior Research Group in the field of socio-ecological research funded within the framework of the Research for Sustainability programme (known by its German acronym FONA) run by the German Federal Ministry of Education and Research (abbreviated to BMBF in German). Junior Research Groups are a BMBF structural funding format aimed at enhancing the skills of young researchers to work in an interdisciplinary and transdisciplinary manner and thereby contribute to solutions for complex societal problems such as climate change or energy transformation. The funding format's objective is to further develop both institutional and individual capacities, as these are direly needed in interdisciplinary and transdisciplinary sustainability research. Young researchers receive the opportunity to enhance their qualifications in the interlinked fields of natural sciences, engineering, and social sciences, thus improving their academic qualifications and career opportunities in interdisciplinary and transdisciplinary research.

Working on self-chosen topics, the Junior Research Groups are encouraged to focus – beyond the research results themselves – on developing and cultivating an interdisciplinary research culture. A further aim of the funding is to encourage universities in particular to boost interdisciplinary and transdisciplinary research approaches. Projects are scheduled to run for five years. This fairly long project duration is intentional in order to cope with the specific challenges of interdisciplinary and transdisciplinary research, while at the same time ensuring that junior researchers attain higher academic qualifications.

Federal Ministry of Education and Research

FONA Research for Sustainability

SEE-URBAN-WATER

Encouraged by the need to develop and cultivate an inter- and transdisciplinary research culture, SUW explores innovative approaches, tools, and technologies to address waterborne challenges through the design and implementation of Nature-based Solutions (NbS) in urban watersheds, with a primary geographic focus on Latin America.

The group started its work in January 2018 at the Institute of Applied Geosciences (IAG) of the Technical University of Darmstadt, Germany. At that time, the leader of the Junior Research Group, Prof. Dr.-Ing. Jochen Hack, held a Professorship for Ecological Engineering at the IAG. In March 2022, following his appointment as Professor for Digital Environmental Planning, the project moved to the Institute of Environmental Planning at Leibniz University Hannover, Germany, where the research project was finalized after six years in December 2023.

Our interdisciplinary team is composed of researchers with a broad variety of academic backgrounds in Civil and Environmental Engineering, Biology, Political Sciences, and Economics. It is also an international team with members from different Latin American countries (Nicaragua, Ecuador, Colombia, Costa Rica) and Germany – all with Spanish as their mother tongue or advanced Spanish language proficiency as well as experience in living and working in Latin American countries. This familiarity with the Spanish language and the Latin American culture enabled the researchers to conduct efficient fieldwork and exchange with different local stakeholders in the study areas in Latin America.

TEAM LEADER

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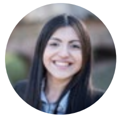

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COOPERATION PARTNERS

During the project, the research group worked closely with local partners in the city of León, Nicaragua, as well as in the Greater Metropolitan Area of San José, Costa Rica, all of whom contributed their local knowledge and experience to the research project's development.

Municipalidad de Flores

1.1. Research context and questions

Functioning ecosystems (e.g., river corridors, urban woodlands, and coastal wetlands) and the services they provide form the basis for sustainable societal development. However, ecosystem performance and persistence are affected by numerous anthropogenic factors, such as climate change, biodiversity loss, land-use changes, and especially accelerated urbanization. As a complex societal process, urbanization has a particularly pronounced impact on a landscape's natural water and energy balance, both in the urban space itself as well as in the surrounding city and natural environments. Urban societies are heavily dependent on functioning ecosystems, themselves intertwined with their technical infrastructures. Water bodies (natural and artificial) play a crucial role in maintaining this complex relationship as they represent a vital resource and pollution sink for societies, provide habitat to sustain biodiversity, and help reduce the environmental impacts of anthropogenic activities. Without clean and sufficient water, the functionality of important ecosystems is at risk, as are the communities depending on them.

In the face of these global concerns, Nature-based Solutions (NbS) – an umbrella term for similar concepts such as ecological engineering, green and blue infrastructure, ecosystem-based adaptation, and building with nature – stand out for their multifunctional operation and their ability to deal with the complex socio-environmental challenges of urban environments.

NbS are defined "as solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions" (European Commission, 2015).

We refer to the terms NbS and Urban Green Infrastructure (UGI) throughout this book, understanding NbS as elements of a multifunctional UGI network. UGI includes both green and blue infrastructure, whereby its network character and strategic planning are key elements. Furthermore, we differentiate between in-stream and off-stream NbS measures. While in-stream NbS river restoration measures initiate or accelerate the recovery of damaged or degraded river ecosystems (examples include wetland restoration, reconnection of seasonal streams, and the revitalization of seasonal floodplains), off-stream NbS measures aim to re-establish a more natural water balance and flow regime (examples include bioswales, green roofs, and infiltration trenches).

Bearing these novel approaches in mind and recognizing the importance of addressing the interaction between urban ecosystems and technical infrastructure systems, the SUW research group posed the following general and overarching research question:

How can urban areas, green spaces and water bodies in cities be sustainably designed and managed with the aim of improving the quality of life while protecting biodiversity and ecosystem services?

This central research question reflects the integral consideration of the built and natural elements of cities within a multifunctional vision. The following, more specific research questions were addressed in an inter- and transdisciplinary manner and applied to the case studies in Nicaragua and Costa Rica:

- How do urban drainage systems interact with the natural water cycle and ecosystems connected by river systems?
- Is urban drainage and wastewater management technically possible through the targeted use of ecosystem functions (Nature-based Solutions in the form of Urban Green Infrastructure)?
- In what ways can a co-design of urban space with the inclusion of Urban Green Infrastructures be achieved?
- What political-institutional changes does a transition from traditional urban drainage concepts to Nature-based Solutions imply?

For more information about Nature-based Solutions for river restoration, please refer to:

Hack, J. and Schröter, B. (2022). Nature-Based Solutions for River Restoration in Metropolitan Areas BT - The Palgrave Encyclopedia of Urban and Regional Futures. In R. C. Brears (ed.), Cham, Springer International Publishing, 1104–1113. https://doi.org/10.1007/978-3-030-87745-3_166.

1.2. Overall objective and research approach

The overall project objective was to establish the foundations for a sustainable socio-ecological transformation by developing and testing nature-based urban drainage and wastewater treatment infrastructures. In particular, the integration of applied knowledge across technological, ecological, and socio-economic domains was identified as the key axis of such a transformation with and for society.

To accomplish this, and considering our research questions, SUW developed a **Real-World Lab (RWL)** where the co-design of NbS prototypes, alternative uses of public space to include Urban Green Infrastructure (UGI), and holistic socio-economic approaches were tested in a representative neighborhood. The insights from this empirical experimentation were used to analyze the reproducibility of these measures at intermunicipal sub-watershed and watershed levels. This in turn enabled the formulation of concrete recommendations with practical implications for improved urban drainage and sustainable wastewater management, thereby promoting the multi-scale development of **multifunctional UGIs**.

In the SUW's project context, UGI multifunctionality is achieved by integrating three main functional dimensions:

1. **A hydrological dimension** targeting the reestablishment of a more natural urban water balance in quantitative (reduction and retention/detention of surface runoff, increased infiltration and evapotranspiration) and qualitative (treatment of both greywater and contaminated surface runoff, and sediment control) terms.
2. **A socio-economic dimension** targeting the delivery of ecosystem services provided by UGIs and increasing the local population's accessibility to green and blue spaces in an equitable, safe, recreational, educational, and affordable way.
3. **An ecological dimension** increasing the connectivity of natural and semi-natural green spaces and waters for the benefit of biodiversity, i.e., building a green urban network of higher ecological value.

1.3. Geographic contexts and spatial scales of the project

SUW's work started in the city of León, Nicaragua, focusing on studying the Pochote River and the impact of urbanization on ecosystem service provision. However, the evolving socio-political tension in the country in April 2018 necessitated relocating the project to Costa Rica, where the Quebrada Seca-Río Burío (QSRB) watershed was selected as the final case study.

Using a transdisciplinary problem-oriented approach, SUW addressed the major socio-ecological challenge of urban river degradation and pollution with well-defined study sites in both the Pochote River and the QSRB watershed. Real-World Labs were used to develop, test and study the impacts of nature-based drainage and graywater treatment at regional (watershed) and local (city and neighborhood) scales.

Investigations were performed in representative locations with the aim of providing transferable and scalable knowledge for other geographical and/or hydrological contexts.

Our work focused on the urban river, Pochote, in León Nicaragua and "the Quebrada Seca-Río Burío watershed" in the Great Metropolitan Area of Costa Rica. Together with different stakeholders from academia, public institutions and societal actors, we discussed, experimented and attempted to gain new knowledge from a socio-ecological perspective for the development of alternative infrastructures.

In both cases, SUW designed and organized transdisciplinary research involving science and society in a continuous and reciprocal learning process. Stakeholders from academia, the public sector and civil society were encouraged to engage in the multiple stages of the project, whereby their perceptions, practical experience, knowledge and feedback were incorporated from problem definition to solution co-production. This approach enabled us to gain new insights from a socio-ecological perspective in a way transcending the boundaries between scientific knowledge and practical expertise, thus enabling successful UGI development.

2

RESEARCH IN NICARAGUA

RESEARCH IN NICARAGUA

In Nicaragua, the project's work focused on the city of León. Located about 93 km northwest of the country's capital Managua, the city is known for its colonial heritage. León is the country's second-largest city with 180,000 inhabitants. One of the country's longstanding intellectual centers, León is also known to be a lively student city. The city structure is typically Latin American: a main square (Parque Central) together with a cathedral, a town hall, and several administration buildings make up the city core and the tourist center. León is fortunate to possess two rivers – the Chiquito and Pochote Rivers – that have the potential to become major recreational areas for its inhabitants.

However, these water bodies are currently characterized by their poor environmental quality. Water-related issues stem from the inefficient operation of the sewerage system and wastewater treatment plants, with untreated household wastewater, as well as industrial effluents from tanneries and slaughterhouses, directly discharged into the rivers. Other problems are related to hydraulic stress and scouring due to high amounts of surface runoff from sealed surfaces, solid waste dumping and riverside burning sites.

While the Chiquito River traverses the city from east to west through the most densely populated and old-established southern area, the Pochote River originates at the northern city boundary and has only recently become part of the urbanized area due to the rapid urban expansion over the last decades. These two rivers converge at the western city limits.

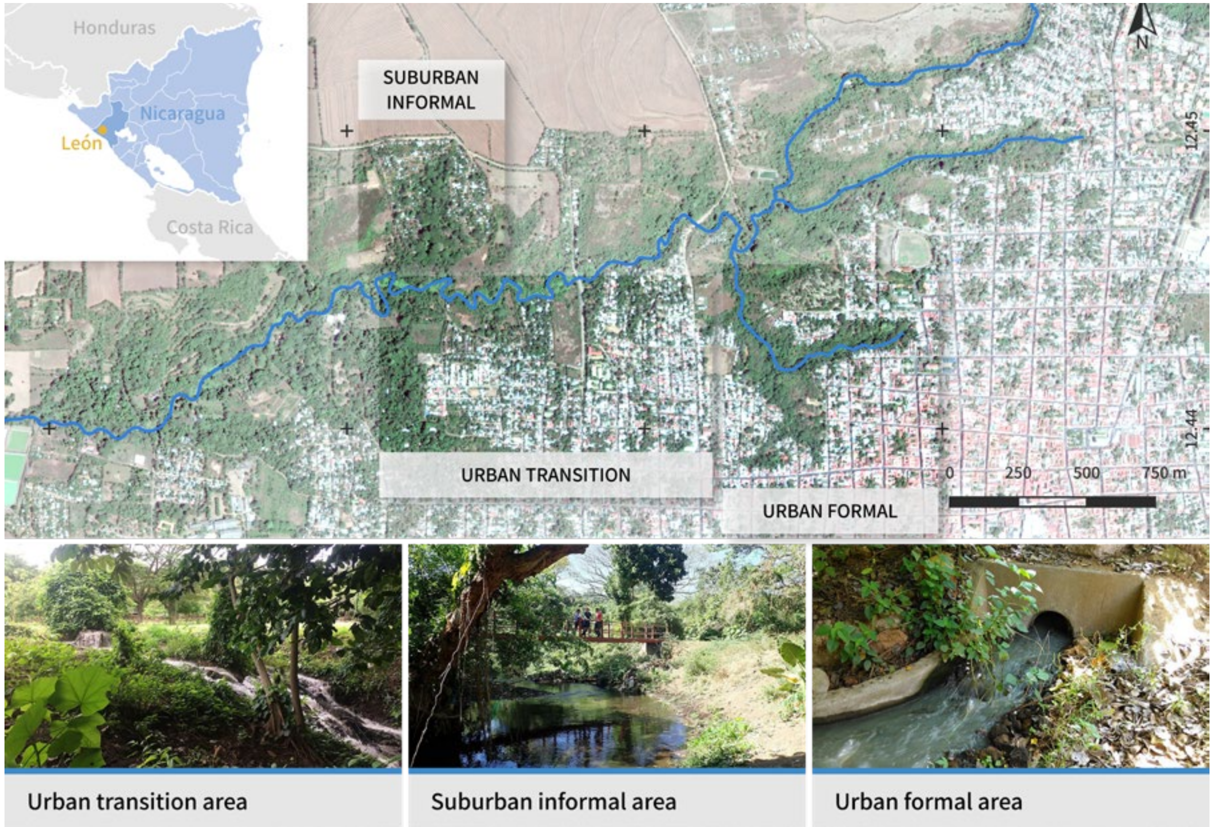

Figure 2.1. Study area in the surroundings of the Pochote River in León, Nicaragua, featuring the three urban area categories established for site characterization.

Our work focused on the Pochote River since it offered more opportunities to test a variety of Nature-Based Solutions because of the different degrees of urbanization along the river. In addition, diverse socio-economic characteristics and social practices can be found in these areas (Figure 2.1). Sourced by three tributaries, each approximately 1 km long, the river flows 6 km along the city's northern border before converging with the Chiquito River. Despite being located in a highly urbanized area, the river's topography limits its accessibility. In its middle course, the river presents meanders and floodplains shaping its hydro-morphological characteristics. These not only create diverse ecological conditions around the river, but also influence settlement patterns.

Our research in León focused on the one hand on developing a convenient and efficient methodology to classify land use and land cover with high spatial resolution to detect and quantify detailed structures of urban green and built-up infrastructure. On the other hand, a combined field and remote-sensing-based methodology to assess the ecosystem service potential of urban rivers and a conceptual approach to modeling the geospatial impact of typical urban threats on the habitat quality of river corridors were developed and tested for the Pochote River as a case study.

Unfortunately, due to rising socio-political tension and violent conflicts in April 2018 in Nicaragua and particularly in León, no further transdisciplinary research was possible. It was instead undertaken in a new study area – the Quebrada Seca-Río Burío watershed – in Costa Rica. Nevertheless, an important methodological development and groundwork for the analysis and improved understanding of urban socio-ecological systems, including river corridors and the ecosystem services they provide, were accomplished. The results of our research in Nicaragua are presented in the following sections.

2.1. Development of a high-resolution urban land use classification method

The initial aim of the project was to gain an overview of the study area, including a Land Use/Land Cover (LULC) classification to identify, quantify and characterize even very small-scale blue and green infrastructures in densely urbanized areas. Due to the unavailability of low-cost high-resolution satellite imagery, a LULC classification method was developed using satellite imagery provided by Google Earth. As the images obtained from this source are only available as true color, classification possibilities are limited. Moreover, the project region is highly urbanized and therefore features very high structural diversity on a small scale, an important factor when planning when planning Nature-based Solutions (NbS). However, freely available satellite imagery with bands of different wavelengths, as often used for LULC classification, do not offer sufficient spatial resolution of the project region's urban context, even if these images have the advantage of being both freely available and having a high spatial resolution.

The cost-free and high-resolution satellite imagery provided by Google Earth seems to be the best base for LULC classification of highly structurally diverse areas, e.g., urban areas.

For the development of the method, three areas along the Pochote River, in and around León, all featuring different degrees of surface sealing (built-up areas) and vegetation, were selected. They correspond to the above-mentioned categorization (urban, transitional, suburban, Figure 2.1). The "urban" area is a typical urban neighborhood comprising a mixture of single-story houses and small commercial units, as well as facilities for socio-cultural exchange (sports stadium, church, etc.). The streets are mainly paved. The "transitional" area, by contrast, presents a combination of houses, forested patches and agricultural land. The structuring of built-up areas in rectangular building blocks – dating back to colonial times and common in the centers of many Latin American cities – is only partially present in the transitional area. "Suburban" is defined as a recently urbanized area connected to the central part of the city by an unpaved road. The area still lacks basic services and there is a prevalence of green patches in-between built-up residential parcels.

For the classification of each of these three project areas, three satellite images taken during the wet season (Oct - Dec) were chosen based on their quality (brightness, contrast, sharpness) and the amount of cloud coverage (< 20%) to minimize the seasonal influence of the flora. The classification was carried out by a semi-automatic tool in which characteristic training areas are assigned to their respective land use for each category (buildings, wasteland, shadows, clouds, etc.). Once a satisfactory result had been obtained, post-processing began, i.e., editing shadows, clouds, cars, pedestrians and other temporary or misclassified pixels and reassigning them to their correct land use classes. Involving relatively little effort and low costs through the use of a combination of freely available satellite imagery and the road and river network from OpenStreetMap, this method yielded a sufficiently detailed and accurate

LULC classification for urban planning. Table 2.1 shows the measured accuracy of the classification, whereby 100% represents the highest possible accuracy.

It was evident that the more recent images from 2015 and 2018 exhibit greater accuracy, suggesting that higher resolution is associated with improved LULC accuracy when compared to the less detailed imagery from 2009. It is also noticeable that, for two images of the suburban region, post-processing resulted in only a slight classification improvement (less than 2% accuracy increase). The general advantages and disadvantages of the methodology are summarized in Table 2.2.

A higher spatial resolution of land use characteristics in urban areas is of particular importance for analyzing complex water balance processes (surface runoff, infiltration and evapotranspiration) since urban micro-watersheds feature small-scale man-made drainage systems. Small green patches are also relevant for biodiversity and social benefits: street trees provide shade and a better microclimate for pedestrians, while small green patches improve habitat connectivity, an important facilitator of biodiversity.

Study Area	Year	Accuracy without post-processing (%)	Accuracy with post-processing (%)
Urban	2009	44.2	69.9
	2015	71.7	81.7
	2018	72.2	85.2
Transitional	2009	54.6	60.1
	2015	56.5	77.1
	2018	72.0	78.4
Suburban	2009	56.1	57.7
	2015	80.6	82.6
	2018	68.3	76.3

Table 2.1. Measured accuracy of the LULC, 100% represents the highest possible accuracy.

	Advantages	Disadvantages
Urban scale applications	Suitable resolution for identifying complex and heterogeneous inter-urban structures.	Better accuracy between boundaries of different LULC classes require a higher pixel resolution.
True color image utilization	Simple, user-friendly, reliable and quick.	Relative computer-resource intensive for large scales; no multi-band (multi-spectral) assessment possible (for better distinction of vegetation).
Data and software availability	Open access, free of cost, low time consumption.	Access to high resolution images could still be limited to commercial products only; QGIS Plug-in can be unstable in some QGIS Versions.
Post-processing	Extraction of urban objects, LULC categories or deliniation of specific zones of interest is possible; quick and reliable; analysis at different scales.	Results depend on image quality and availability, as well as initial criteria to define ROIs and LULC categories; user effort is unavoidably required to reduce errors due to mobile or temporal objects.

Table 2.2. Advantages and disadvantages of the proposed LULC methodology.

Figure 2.2 illustrates how important this high resolution can be in specific research areas for detecting socio-ecological changes. From left to right, it shows how urbanization has progressed over the years 2009, 2015 and 2018 in the study area. Green pixels represent vegetation (light green = low vegetation, dark green = high vegetation) while the different shades of brown represent buildings (darkest), bareland and unpaved roads (lightest).

The high-resolution LULC method developed in the context of our research in Nicaragua was used in the subsequent research in Costa Rica in different contexts. For example, it was used to generate the LULC input for hydrological and hydraulic models at different spatial scales (neighborhood, micro-, sub-watershed and watershed levels) as well as for the microclimate modeling of the status quo. It was also employed for evaluating the existing Urban Green Infrastructure in the Quebrada Seca-Rio Burío watershed and the effect of NbS in the Real-World Lab through developing scenarios for improvements.

Application in modeling contexts

The high-resolution land use classification method developed for the case study in Nicaragua was used to provide landscape information for hydrological, hydraulic and micro climate models for Costa Rica. The classification information was also the basis for analysis of Urban Green Infrastructure and landscape metrics calculations about habitat and green space connectivity (Chapter 5).

For more information about this Land Use Classification method please refer to:

Chapa, F., Hariharan, S., and Hack, J. (2019). A New Approach to High-Resolution Urban Land Use Classification Using Open Access Software and True Color Satellite Images. Sustainability, 11(19), 5266. https://doi.org/10.3390/su11195266.

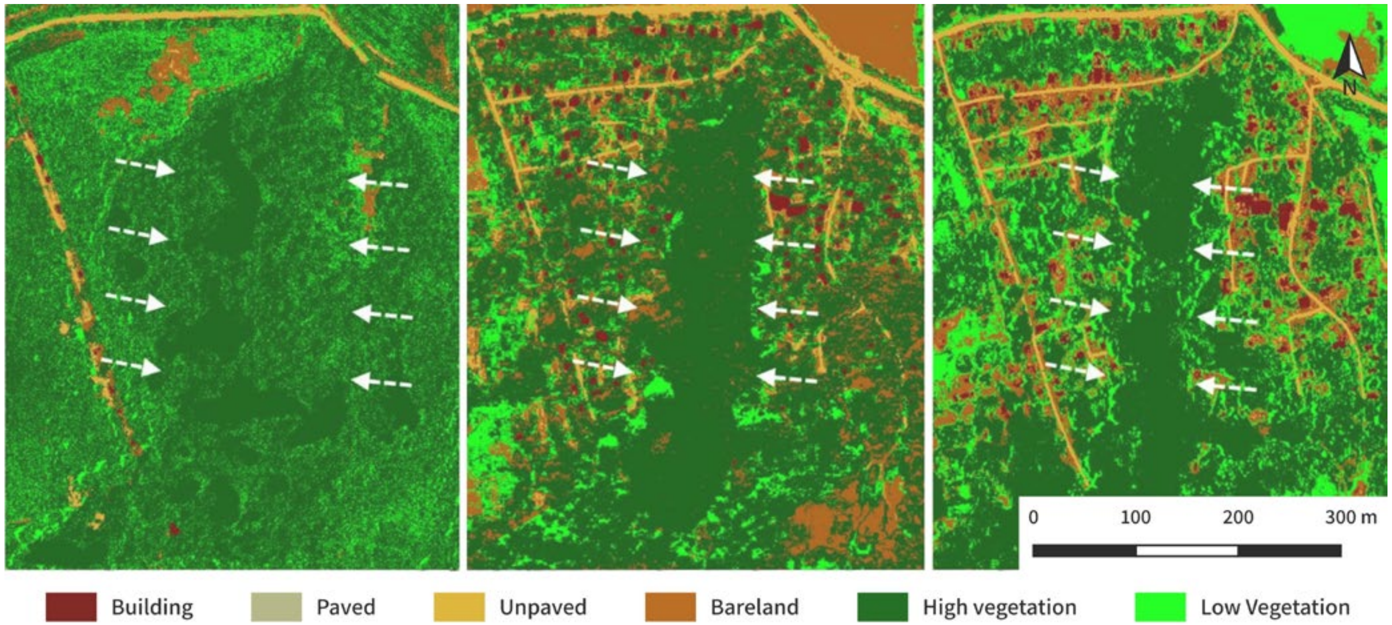

Figure 2.2. From left to right: Urbanization over the years 2009, 2015, 2018 in the study area; green pixels represent vegetation (light green = low vegetation, dark = green high vegetation) while the different shades of brown represent buildings (darkest), bareland and unpaved roads.

2.2. Assessment of Urban River Ecosystem Services

Natural or near-natural rivers in urban areas have significant potential to provide ecosystem services for people living in their surroundings. However, surface sealing caused by housing developments, street networks, urban drainage infrastructure, and waste and wastewater disposal have deteriorated urban rivers and riparian areas, ultimately impairing their ability to provide ecosystem services. In the context of the SEE-URBAN-WATER project an innovative methodology was developed for a rapid and low-cost assessment of the ecological status of urban rivers and riparian areas in developing countries under data scarcity conditions. The methodology – called MAPURES (Methodology to Assess the Potential of Urban River Ecosystem Services) – uses a combination of field data and freely available high-resolution satellite images to assess three ecological status categories: river hydromorphology, water quality, and riparian land cover. The focus was assessing proxies for biophysical structures and processes representing ecological functioning that enable urban rivers and riparian areas to provide ecosystem services. These proxies represent a combination of remote-sensed land cover and field collection-based indicators. The three ecological status categories are then combined to quantify the potential of different river sections to provide regulating ecosystem services. The components and workflow of MAPURES are illustrated in Figure 2.3.

Generally speaking, MAPURES can be applied by untrained professionals. All required indicators (LULC, water quality, hydromorphological quality) can be collected using simple remote sensing as well as field-based methods. These features are then linked to specific ecosystem services to show the potential benefits of urban rivers and whether or not their provision is in danger. This tool can be used by local communities and practitioners to raise awareness about the importance of preserving urban river ecosystems and advocating for their protection. Although we worked with low-cost assessments, the methodology can also be used in association with other techniques or data, for example to map different ecosystem services.

For more information about the MAPURES methodology please refer to:

Beißler, M. R. and Hack, J. (2019). A Combined Field and Remote-Sensing based Methodology to Assess the Ecosystem Service Potential of Urban Rivers in Developing Countries. Remote Sensing, 11(14), 1697. https://doi.org/10.3390/rs11141697.

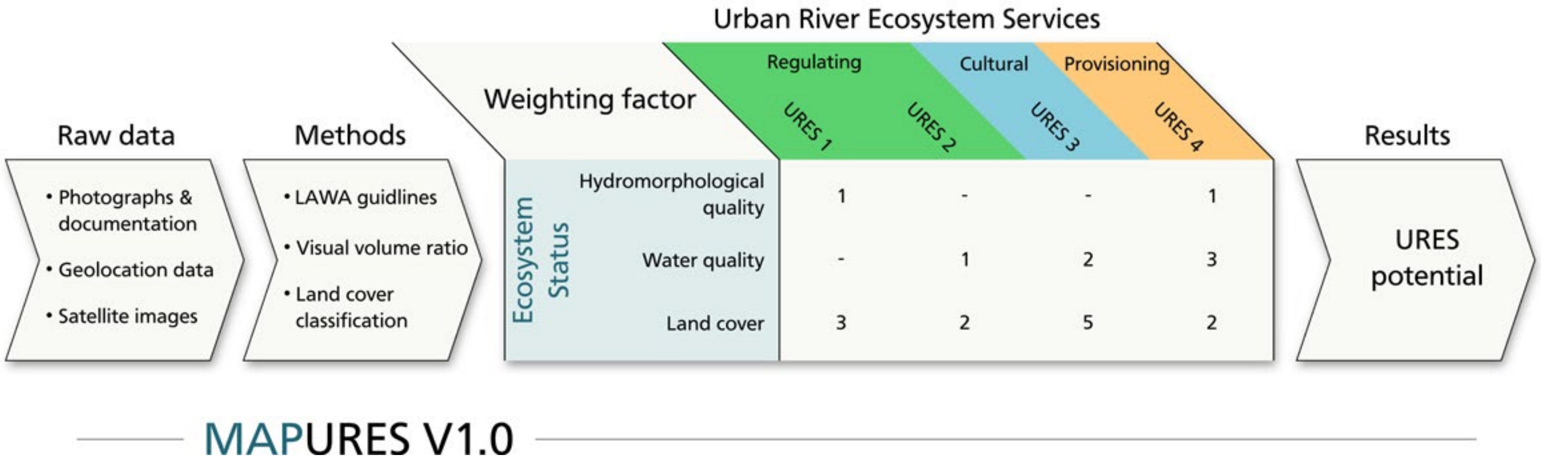

Figure 2.3. Illustration of the components and workflow of the developed MAPURES methodology.

MAPURES was applied to the complete urban riparian corridor of the Pochote River in León, with the river divided into 100-meter sections. Figure 2.4 shows the ecosystem status for the three categories: hydromorphological quality, water quality and land cover, for each of the 100-meter sections.

The resulting spatially distributed information on the ecosystem service potential of individual sections of the urban river and riparian areas serves as an important source for decisions on the protection, future use and urban development of these areas, as well as on the targeted and tailor-made development of nature-based solutions such as green infrastructure.

Figure 2.5 shows the potential for providing urban river ecosystem services for each 100-meter section, ranging from 0% (no potential) to 100% (very high potential) for i) Hydrological cycle and water flow regulation, and ii) Regulation of chemical conditions by living processes.

The greatest negative impact in this case seems to be associated with water pollution, which should be far easier to tackle than surface sealing and changes in river morphology. Besides these findings, decision-makers can also deduce where and how to act. For example, areas worthy of protection can be identified. These results can be interpreted relatively easily, making it quite simple to communicate the information to decision-makers. Furthermore, the application of the methodology does not require specialist tools, so the effort needed to collect and produce the results is reasonably straightforward. However, the quality of the results can only be as good as the quality of the input data, which is why the methodology is more suitable as guidance for identifying hotspots or for creating general awareness for the topic.

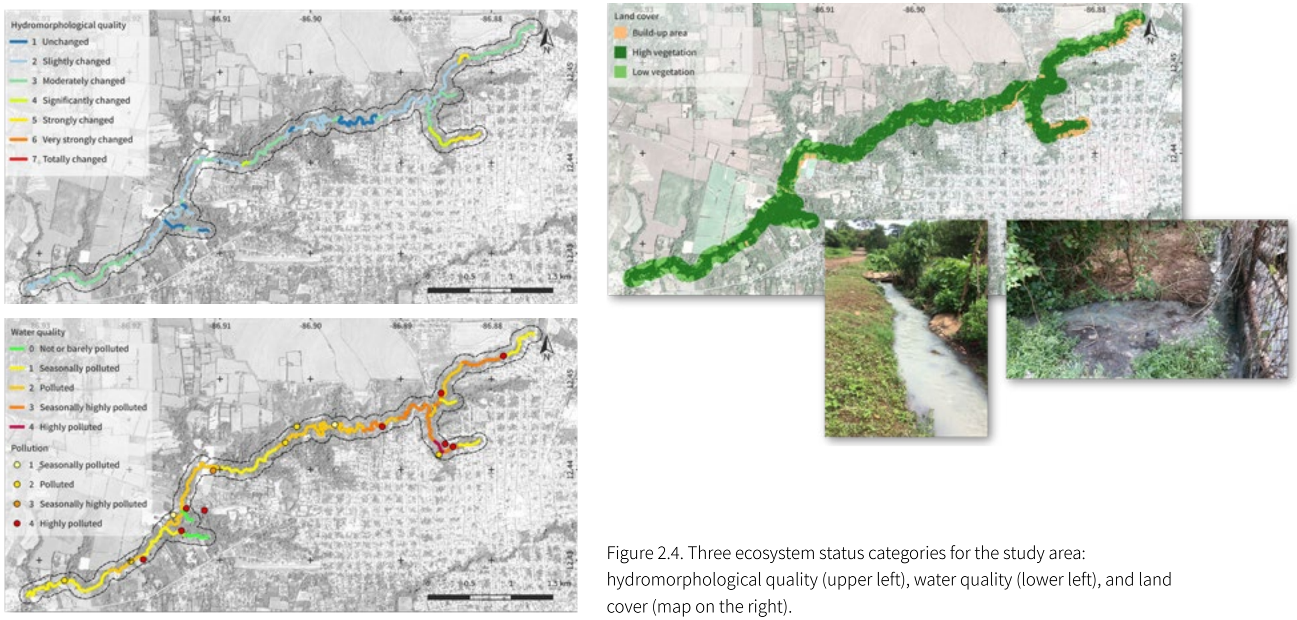

Figure 2.4. Three ecosystem status categories for the study area: hydromorphological quality (upper left), water quality (lower left), and land cover (map on the right).

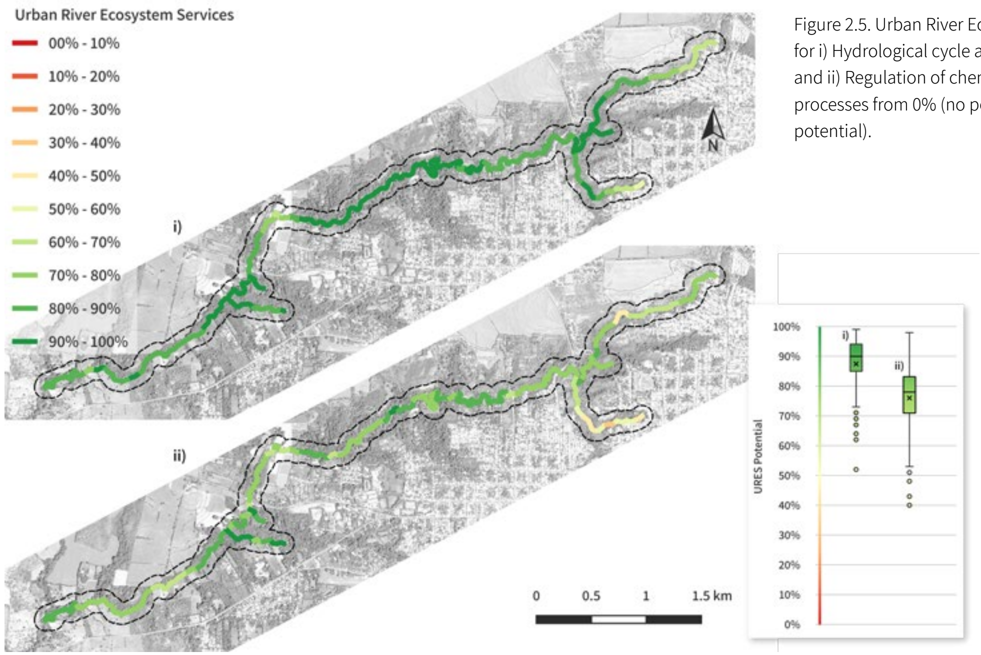

Figure 2.5. Urban River Ecosystem Services Potential for i) Hydrological cycle and water flow regulation, and ii) Regulation of chemical conditions by living processes from 0% (no potential) and 100% (very high potential).

2.3. Modeling geospatial impacts of urban threats on the habitat quality of river corridors

The water quality and Land Use / Land Cover (LULC) data resulting from the previous study can also be used to determine their impact on habitat quality. For this analysis the habitat quality model of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) was used. InVEST is a suite of free, open-source software models used to map and value the goods and services from nature that sustain and fulfil human life. In the past, the InVEST habitat quality model was mainly used for large-scale applications but not for small urban areas (<10 km^2). Moreover, it has not yet been used to model threats such as water contamination. Applying the model to the urban trajectory of the Pochote River was therefore a novelty.

INFO

InVEST is a suite of free, open-source software models used to map and value the goods and services from nature that sustain and fulfill human life. InVEST models are spatially-explicit, using maps as information sources and producing maps as outputs. InVEST returns results in either biophysical terms (e.g., tons of carbon sequestered) or economic terms (e.g., net present value of that sequestered carbon).

Rivers are often the most important biophysical and ecological link between cities and their surrounding ecosystems, despite usually being greatly modified through man-made infrastructure. To conserve urban rivers as ecological corridors, it is important to assess the impact of typical urban threats on habitat quality. In this study, we assessed the individual and combined impacts of built-up areas, first- and second-order roads, water pollution from urban drainage and wastewater discharge on habitat quality within a 200 m wide corridor along the Pochote River. In addition to assessing the corridor's current habitat quality, the goal was to derive spatially-explicit recommendations for habitat protection.

In the model, habitat quality is described as the ability of an ecosystem to provide conditions appropriate for individual and population persistence. Thus, habitat quality is considered a continuous variable, ranging from low to high, based on the resources available for survival, reproduction, and population persistence. High-quality habitats are defined as those that are intact, featuring ecological structures and functions able to effectively support persistence.

InVEST models the habitat quality as a proxy for biodiversity by estimating the extent of habitat and vegetation types and their state of degradation across a landscape. The model assumes that high-quality habitats have a better chance to maintain their biodiversity. It similarly assumes that habitat quality decreases with the proximity and intensity of anthropogenic land use or impact and that the decrease varies according to the type of land use or impact.

As a general rule, habitat quality becomes degraded when the intensity of nearby land use increases or when specific anthropogenic threats are present. Furthermore, habitat quality is considered to be a function of habitat suitability and four threat parameters (Table 2.3). In this study, InVEST was used to estimate the habitat quality of the Pochote River for the current LULC and threat situation based on field data and remotely sensed LULC information. Model inputs were assumed not to be specific to any particular species, but rather applied to biodiversity in general.

Upstream section of the Pochote River in León, Nicaragua.

Downstream section of Pochote River after confluence with Chiquito River, outskirts of the city of León, Nicaragua.

Threats [-]	Max. effective distance [km]	Weight [-]	Decay over space [-]	LULC classes [-]		
				High vegetation	Low vegetation	Built-up
				Habitat suitability score [-]		
				1	0.6	0
				Sensitivity score of habitats to threats [-]		
Built-up	0.2	1	exp	0.8	0.7	0
First order road	0.2	0.8	exp	0.8	0.7	0
Second order road	0.2	0.7	exp	0.6	0.5	0
Water pollution – seasonally polluted	0.01	0.1	exp	0.6	0.4	0
Water pollution - polluted	0.01	0.3	exp	0.6	0.4	0
Water pollution – seasonally highly polluted	0.01	0.7	exp	0.6	0.4	0
Water pollution – highly polluted	0.01	0.9	exp	0.6	0.4	0

Table 2.3. Threat parameters, habitat suitability scores, and sensitivity scores for the threats and land cover classes used in this study.

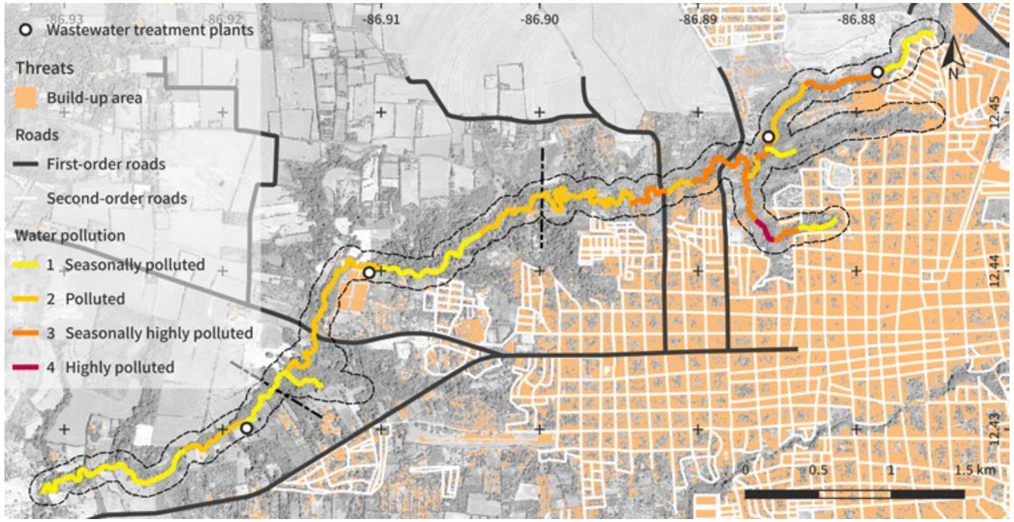

Figure 2.6. Spatial extent and threat quality of all considered urban threats on the river habitat.

Habitat quality is determined by an original LULC-specific habitat suitability score and the specific anthropogenic threats affecting the previously defined LULC classes LULC classes. On the basis of raster cells – the data format used for land cover and threats – threats affecting the habitat quality of different LULC classes are assigned a relative weight. Threats are effective up to a maximum distance to a specific land cover raster cell and poses a distance-related threat-specific spatial decay function for the threat impact. These threat-specific characteristics are called threat parameters. Moreover, the habitat suitability of different LULC classes (habitat suitability score) reflects different sensitivities to different threats (sensitivity score), meaning that the impact of different threats to the same LULC class can differ. The threat parameters, habitat suitability scores, and sensitivity scores for the threats and land cover classes used in this study are displayed in Table 2.3.

Simulations were performed for each threat individually and for all threats combined to determine the main source for the respective impact. Figure 2.6 shows the spatial extent and threat quality of all considered urban threats. As can be seen in Table 2.3, each of them has a different weight assigned, while they also vary in their maximum effective distance.

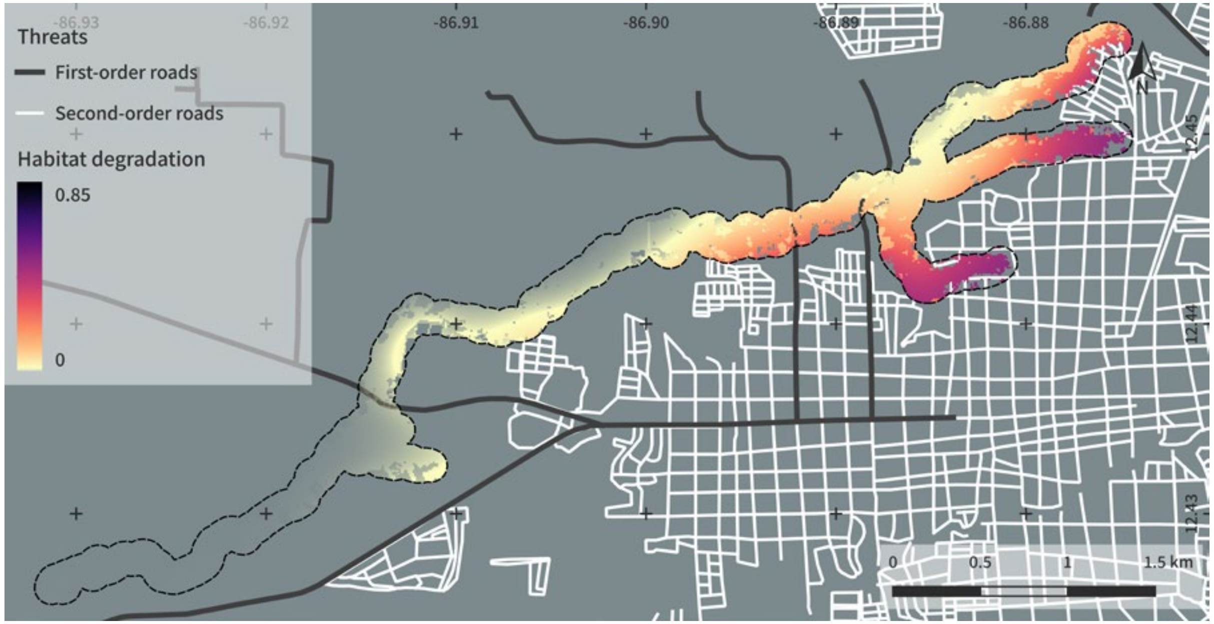

Figure 2.7. Habitat degradation impact resulting from the current road infrastructure.

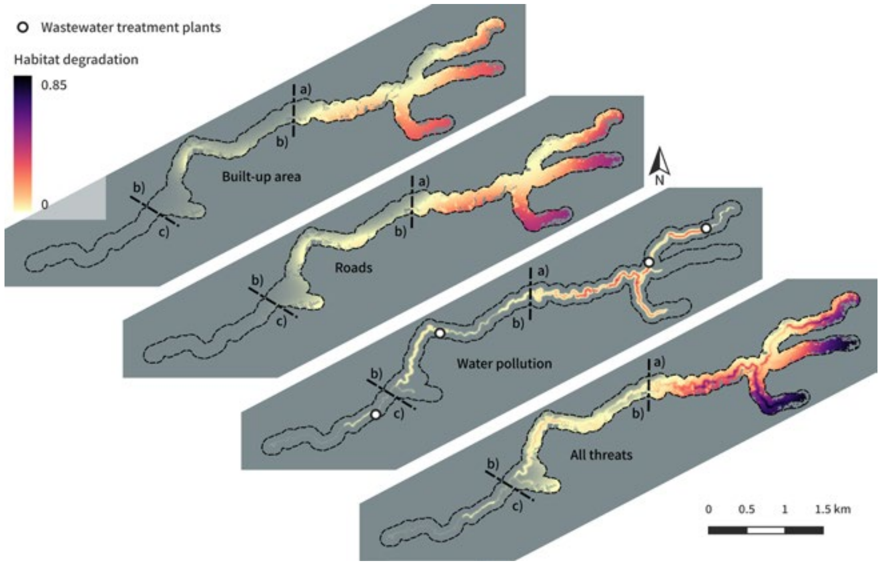

Figure 2.8. Habitat degradation impact resulting from each of the threats (built-up, roads, water pollution) individually (upper three illustrations) and in combination (lowest illustration).

To show how a threat translates into a habitat degradation via the model for the case at hand, the results relating solely to the road network are shown in Figure 2.7, together with the locations of the threats. The impact of first-order roads crossing the river corridor and of an increased presence of second-order roads near the three river tributaries in the northeast are evident, whereas in the southwest, a section with a less-developed road network, there is no or hardly any impact on habitat quality.

The habitat degradation resulting from each of the threats (built-up, roads, water pollution), individually and in combination, is shown in Figure 2.8. As can be seen in the figure's three upper diagrams, the individual impacts of the threats on the general habitat quality differ in spatial extent and intensity. For example, roads cause greater habitat degradation than built-up areas in most of the studied area. Along the river corridor's core zone (the actual watercourse), the influence of water pollution is clearly apparent, but compounded by the other threats. In addition, we see that degradation is not homogeneous: the river corridor can be divided into three sections: a) highly degraded, b) moderately degraded, and c) slightly degraded, as indicated in Figure 2.8. This differentiation applies to each individual threat as well as to their combination. The combination of threats shows that the highest degradation occurs where the strongest impact of all three threats coincides spatially (in Section a).

Figure 2.9 shows the general habitat suitability derived from the three LULC classes (top) and the resulting habitat quality due to habitat degradation (bottom). This figure reveals options for action. For example, ongoing urbanization could be limited in Section b) to stop degradation or protective measures could be implemented to restore degraded habitats. Water quality discharged by wastewater treatment plants can also be improved, thereby reducing habitat degradation. Areas in red and yellow generally indicate where habitat restoration is needed, while green areas still feature good habitat quality and should be preserved and/or protected. In particular, the few remaining light green areas in the strongly degraded Section a) should be protected from further threats caused by urbanization.

For future applications, a LULC classification with more LULC classes could lead to better and more specific results for different habitats. For example, by considering the LULC class "farmland", threats such as fertilizer input (which contribute to eutrophication) and pesticides could be taken into account. Within this methodology, the InVEST habitat quality model can be used to assess the impact of typical urban threats on habitat quality in river corridors with a high spatial resolution. The results can help guide urban planning and development with a view to improving habitat conservation and protection along urban rivers.

For more information about this approach of geospatial modeling please refer to:

Hack, J., Molewijk, D., and Beißler, M. R. (2020). A Conceptual Approach to Modeling the Geospatial Impact of Typical Urban Threats on the Habitat Quality of River Corridors. Remote Sensing, 12(8), 1345. https://doi.org/10.3390/rs12081345.

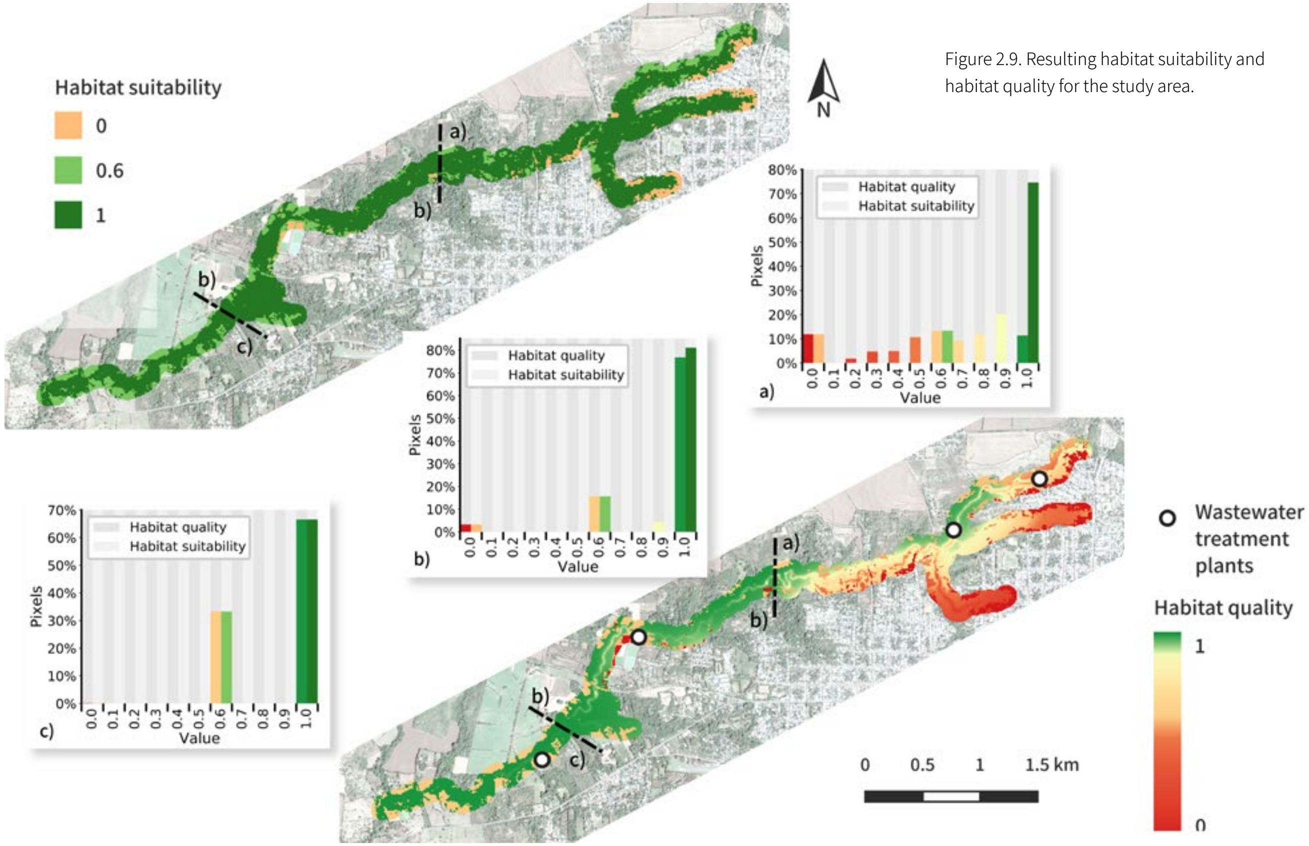

Figure 2.9. Resulting habitat suitability and habitat quality for the study area.

3

THE QUEBRADA SECA-RIO BURÍO WATERSHED IN THE GREATER METROPOLITAN AREA OF SAN JOSÉ, COSTA RICA

THE QUEBRADA SECA-RIO BURÍO WATERSHED IN THE GREATER METROPOLITAN AREA OF SAN JOSÉ, COSTA RICA

SEE-URBAN-WATER's (SUW) research in Costa Rica was developed in the context of the Quebrada Seca-Río Burío (QSRB) watershed. This study area (Figure 3.1) was chosen to investigate the potential of Nature-based Solutions (NbS) as part of a complex, multifunctional Urban Green Infrastructure (UGI) network envisaged for comprehensive urban water management. The QSRB watershed is characterized by a high degree of urbanization as it is located in the Greater Metropolitan Area (GAM for its Spanish acronym) of San José, home to about 50% of Costa Rica's total population (Castro, 2016). We consider the watershed as representative of other highly urbanized watersheds, both in the GAM and in comparable developed environments in other countries. This qualifies it for an inter- and transdisciplinary investigation of NbS and UGI implementation, allowing the study's findings to be used not only for regional applications but also in other watersheds sharing similar characteristics.

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The population of the Quebrada Seca-Burio River watershed is about 115,800 corresponding to nearly 2.5% of the country's population and 25% of the population of the province of Heredia.

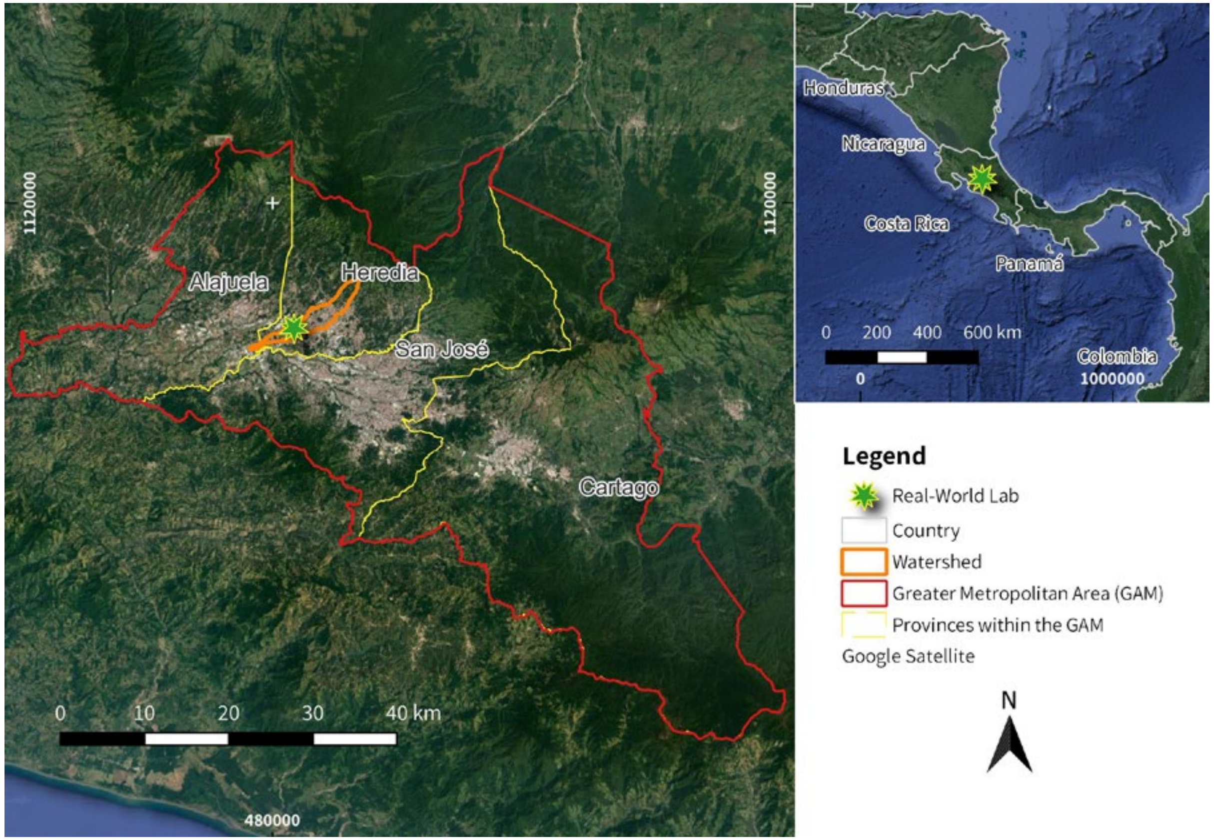

Figure 3.1. Geographical location of the study area.

The QSRB watershed is located in the province of Heredia, northwest of San José, the capital of Costa Rica. Its drainage area is approximately 23 km^2 and comprises three main watercourses: Quebrada Seca, Burío River and Quebrada Aries. Furthermore, the watershed spans six municipalities: San Rafael, Barva, Heredia, Flores, Belén and Alajuela. Its average slope is 20%, descending from its highest point at an altitude of 1626 m in the San Rafael municipality to its control point at 869 m in the Alajuela municipality (Figure 3.2). Further geomorphological information can be found in Table 3.1.

Influenced by the Inter-Tropical Convergence Zone and its location along Costa Rica's Pacific coast, the QSRB watershed is characterized by the presence of two well-defined seasons, a dry period from November to April and a rainy season from May to October. Its average annual temperature is 24.8°C (Chaves Herrera et al., 2014), while average annual precipitation is approximately 2000 mm (Solano and Villalobos 2012; Masís-Campos and Vargas-Picado 2014). Due to its proximity to the Barva Volcano, the watershed has a primarily volcanic origin featuring highly permeable soils optimal for aquifer recharge and surface runoff control under natural conditions (Masís-Campos and Vargas-Picado 2014).

Since the 1980s, the QSRB watershed has undergone dense and disorganized urbanization, resulting in 66% of its total area becoming impervious, and in recurrent flooding and water quality deterioration.

Parameter		Value
Drainage area	A (km^2)	22.85
Watershed perimeter	P (km)	36.82
Length of all streams	∑L (km)	24.10
Main course length		18.36
Watershed shape	L (km)	
• Compactness index	I_G	2.16
• Shape factor	K_f	0.07
Equivalent rectangle		
• Major side	L_{re} (km)	17.07
• Minor side	l_{re} (km)	1.34
Average watershed elevation	(m.a.s.l.)	1119.34
Maximum watershed elevation	(m.a.s.l.)	1626
Minimum watershed elevation	(m.a.s.l.)	869
Slope index	I_p	0.20
Slope of main course	S_1	3.68%
Drainage system		
• Order number		2.00
• Drainage density	D_d (km/km^2)	1.05

Table 3.1. Physical characteristics of the Quebrada Seca-Río Burío watershed.

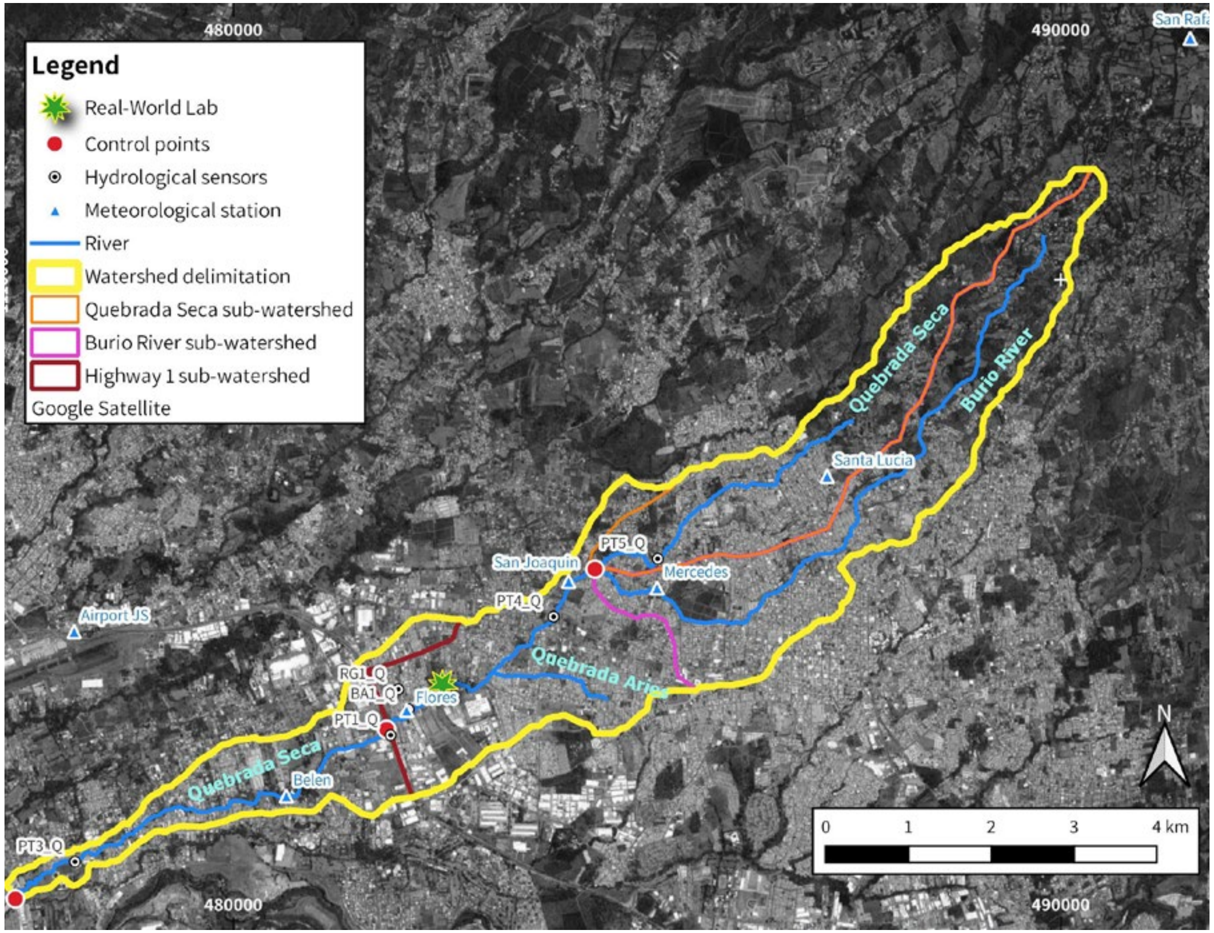

Figure 3.2. SEE-URBAN-WATER study area in Costa Rica: The Quebrada Seca-Río Burío watershed, its sub-watersheds and the location of the Real-World Lab.

The QSRB watershed has undergone dense and disorganized urbanization due to the accelerated urban growth, mostly in the 1980s. Currently, about 66% of its surface area is impervious, with 97% of the developed land used for residential purposes (predominantly single-family houses). These anthropogenic transformations have induced recurrent flooding in various parts of the watershed, water quality deterioration, riverbank instability and scouring. Furthermore, the watershed is part of the Tarcoles River basin, the most polluted river in Central America through receiving about 67% of Costa Rica's total untreated organic material and industrial waste from a large part of the GAM (Bower, 2013). Urbanization-related water problems increased to the point that, in 2005, the Constitutional Chamber of Costa Rica issued a regulatory instrument, Vote 4050, preventing municipalities from granting permits for activities not contributing to the watershed's natural recovery.

Aerial view of the Quebrada Seca-Río Burío River in Hereda, within the Greater Metropolitan Area of Costa Rica.

The SUW studies at various spatial scales provided model-based evidence of the cumulative effects of a multifunctional Urban Green Infrastructure of Nature-based Solutions including their potential to contribute to climate change adaptation.

These challenges, faced not only in the study area but also in many developing cities, highlight the urgent need to explore alternative methods able to counteract the adverse effects of accelerated urbanization and promote both the hydraulic and socio-ecological recovery of the QSRB watershed. However, assessments solely at watershed level omit the multifunctional potential of NbS and UGI at sub-watershed and neighborhood level. SUW therefore developed its inter- and transdisciplinary research on three additional spatial scales – sub-watershed, river corridor and Real-World Lab (RWL) –, focusing on the QSRB watershed. These assessments are covered in depth in Chapters 4 and 5.

The following section contains a historical characterization of urbanization in the QSRB watershed, providing valuable insights into the relationship between changes in land cover and hydrologic response. This laid the groundwork for evaluating the potential of NbS as flood and urban water management measures in highly urbanized watersheds.

The work in the Real-World Lab provided important information and insights for the calibration and validation of hydrological, hydraulic and micro-climate models, in turn enabling us to develop multiple implementation scenarios to assess the NbS upscaling potential, suitable private- and public-land policies, and the socio-institutional contexts needed to encourage wider adoption.

3.1. Analysis of the historical urbanization and the watershed's hydrological response thereto

As previously stated, abrupt changes in land use as a result of accelerated population growth result in major hydrological and socio-ecological stress within cities. Latin America has experienced rapid and unplanned urbanization (Barros 2004), with populations concentrated in metropolitan areas subject to frequent urban flooding (Vaux et al. 2020). SEE-URBAN-WATER analyzed the spatial-temporal urbanization of the Quebrada Seca-Río Burío (QSRB) watershed in detail, conducting a land cover classification between 1945 and 2019 for a total of 11 uniformly distributed years using remotely sensed imagery.

Aerial images with panchromatic bands obtained from the National Geographic Institute of Costa Rica were used for the years 1945 and 1960, while satellite images from Landsat sensors (2, 5, 7 and 8) obtained from the United States Geological Survey (USGS) Earth Explorer were used for the period between 1975 and 2019. The satellite images were selected at intervals of approximately 5 years to avoid information on changes in land use coverage being lost. To avoid the cloud cover, images taken between the months of December and April, corresponding to the dry season, were selected. A supervised classification based on the maximum likelihood methodology was then used to determine the land cover distribution, considering four main land cover types: high vegetation, low vegetation, urban and pastures. This classification was based on field visits and previous work in the watershed.

The results of this land use classification served as the basis for developing hydrological models to calculate a flood hydrograph for each analyzed period. These models were used to assess the watershed's hydrological response to increased urban cover for a particular precipitation event, keeping the remaining model parameters unchanged.

Land Use/Land Cover (LULC) classification for NbS and UGI modeling and planning

The LULC classification was crucial for the strategic planning of NbS and UGI. The method was applied to develop realistic scenarios for UGI implementation and determine optimal locations for NbS to reduce flood risks (section 5.1), with a focus on maximizing benefits across several dimensions. Additionally, LULC classification was applied to assess the existing UGI (section 5.3) regarding its fragmentation and connectivity as well as its potential to provide hydrological, social, and ecological benefits.

The study site's changing urban hydrology over time was modeled using PCSWMM, a software combining the open-source Stormwater Management Model (SWMM) with a geographic information system (GIS) interface. In this model, we discretized the watershed into 17 drainage areas (Figure 3.3), following the local topography and hydraulic runoff routing. This enabled a detailed spatial analysis of flood- and runoff-generating processes over time. These drainage areas were aggregated at three spatial scales to evaluate the hydrological response at watershed, sub-watershed and individual drainage area levels. The representative precipitation event used for all model runs corresponds to a design storm event with a ten-year return period and a precipitation volume of 130.9 mm.

INFO

US EPA's Storm Water Management Model (SWMM)

The United States Environmental Protection Agency (US EPA) Storm Water Management Model is a free, open source, public software; used to perform hydrologic, hydraulic, and water quality simulations and visualize the results in a variety of formats. It is used for planning, analysis, and design related to stormwater runoff management. It can be used to evaluate stormwater control strategies for gray infrastructure, such as pipes and storm drains, and is a useful tool for creating cost-effective hybrid green/gray stormwater control solutions. The SWMM was developed to support stormwater management goals to reduce runoff through infiltration and retention, and help reduce discharges that cause deterioration of water bodies.

The watershed's hydrological response to long-term land cover changes was analyzed with high spatial and temporal detail using a hydrological model.

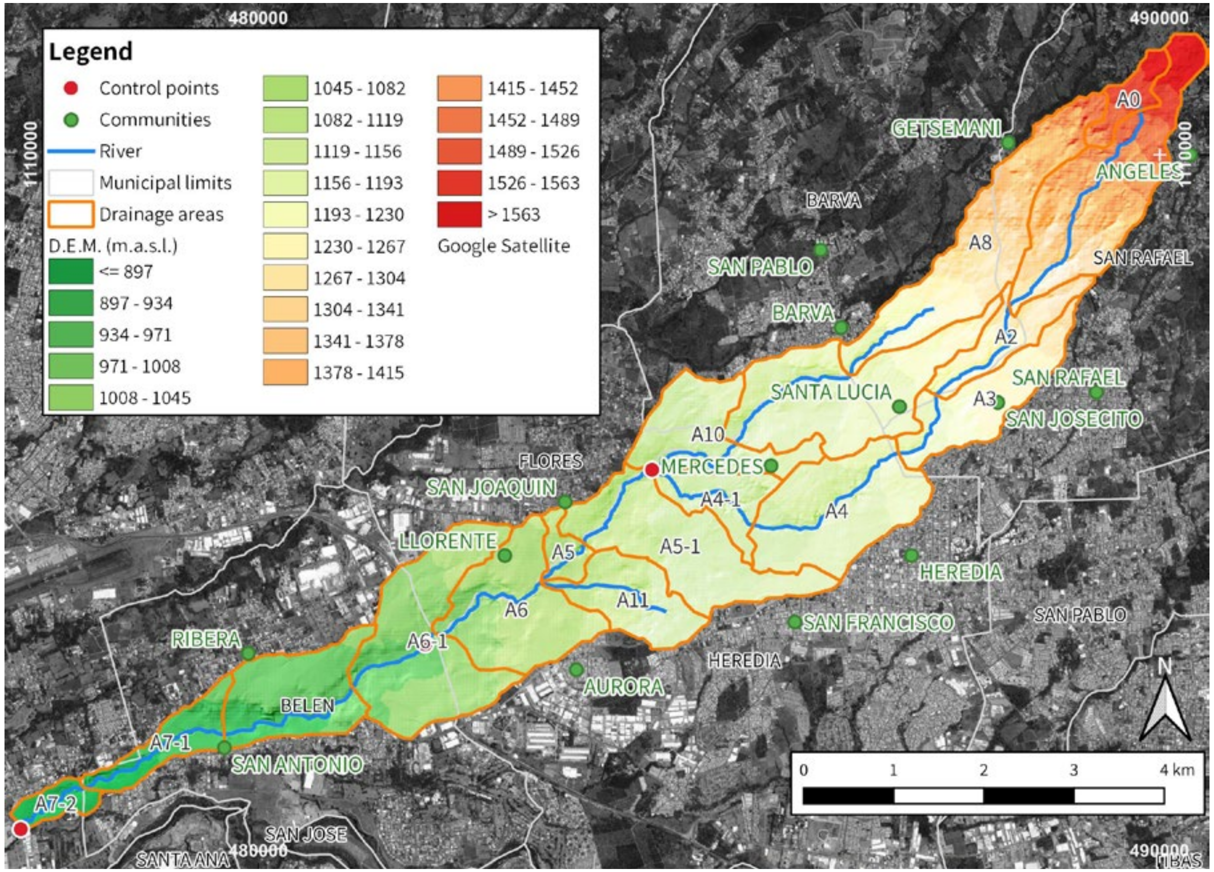

Figure 3.3. Municipal delimitations, communities, control points, and drainage areas of the Quebrada Seca-Río Burío watershed.

A detailed spatial analysis of runoff generation and evolution over time, coupled with a historic flood event assessment, provided a meaningful basis for identifying critical flood prone areas requiring immediate attention. This supports decision-making in flood risk management in terms of an appropriate spatial distribution of effective flood prevention measures.

The three sub-watersheds, i.e., Quebrada Seca, Burío River, and Highway 1, were defined based on three control points. The first was located at the confluence of the Quebrada Seca and the Burío River, resulting in the formation of two sub-watersheds, one for each watercourse. The second was located at the intersection of the Quebrada Seca-Burío River with Highway 1, as a representative flood-prone site having experienced several issues in the past. The third corresponded to the watershed's outlet, located in the Municipality of Belén.

The main objectives of this study were 1) to analyze long-term land cover changes as a result of urbanization; and 2) to analyze flood generation due to these changes using a hydrological model. This enabled the identification of the flood-producing effect of different degrees of urbanization in relation to previous land cover conditions and to put them in the context of historically reported flood events (Figure 3.4). Both the land cover change analysis and the hydrological modeling are characterized by high spatial and temporal resolution.

In 1945, coffee plantations accounted for 58% of the watershed area, urban land cover for only 1.6%, while the remaining area was pasture for cattle breeding. Urbanization began in the Municipality of Heredia, today the capital of the Heredia province, and spread north- and westward towards the municipalities of Barva, Flores and Belén. The sealed urban area increased from 4.7% in 1960 to 10.4% in 1975, mainly in the four previously mentioned municipalities, which were connected by a basic road system. By 1985, the sealed urban area occupied 29% of the total area.

The highest urban land cover growth in the QSRB watershed occurred between 1979 and 1985, when sealed surfaces increased from 14.4% to 29% (an average annual increase of 2.43%). After 1985, urban coverage increased at a lower mean rate of 1.08% per year, reaching 65.6% of urban coverage in 2019. The most recent urban expansion occurred between 1997 and 2007, when it reached 53.9% of the watershed area. Figures 3.5 and 3.6 show the land cover classification for each analyzed period.

In 1945, only 1.6% of the watershed was urbanized, mainly the city of Heredia, which began to grow gradually to connect the cities of Barva, Flores and Belén. By 1975, urban coverage was 10.4% and, following accelerated growth in the 1980s, reached 29% in 1985. After 1985, annual urban growth continued at an average rate of 1.08% reaching 65.6% impervious coverage in 2019.

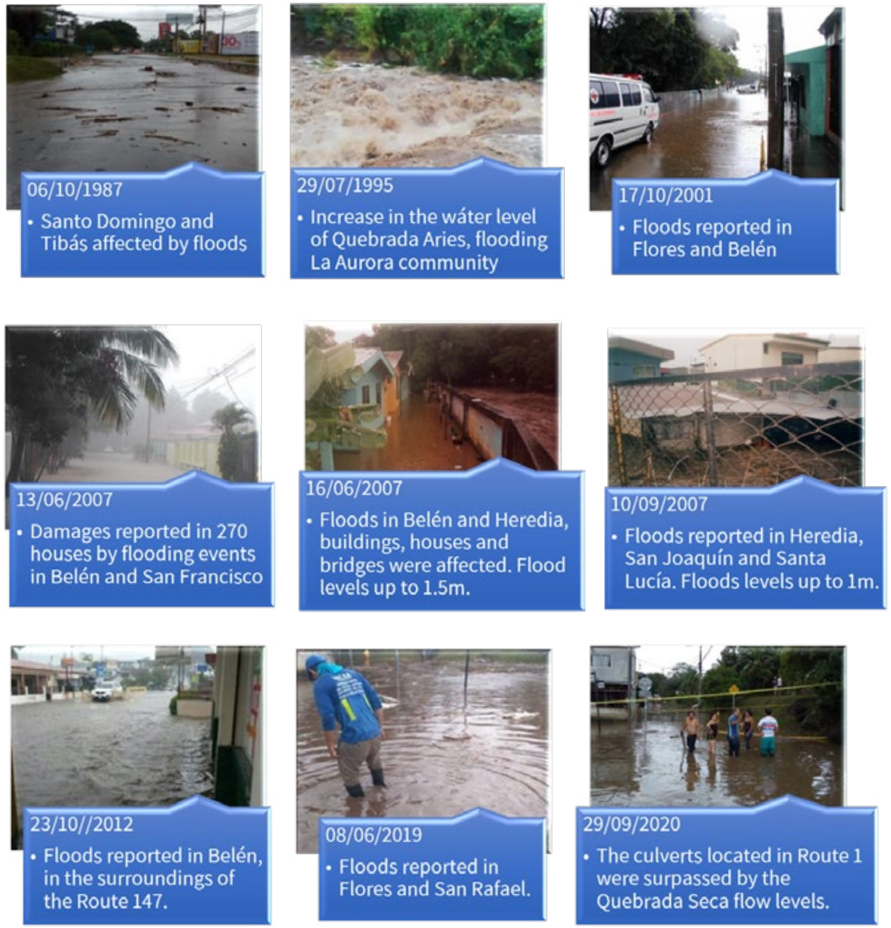

Figure 3.4. Flood events in the Quebrada Seca-Río Burío watershed reported in Costa Rican newspapers in chronological order.

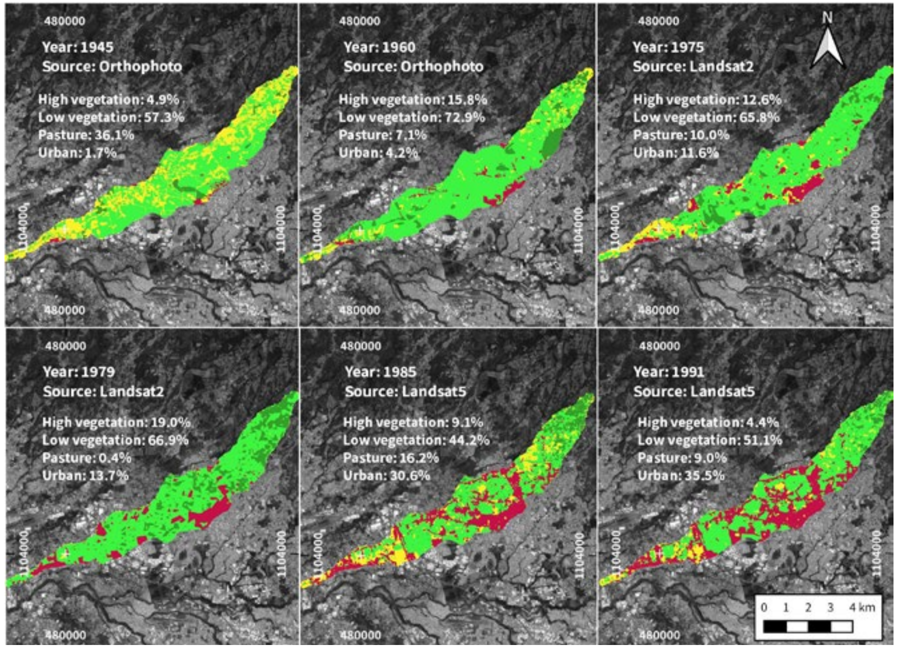

Figure 3.5. Land cover distribution between 1945 and 1991.

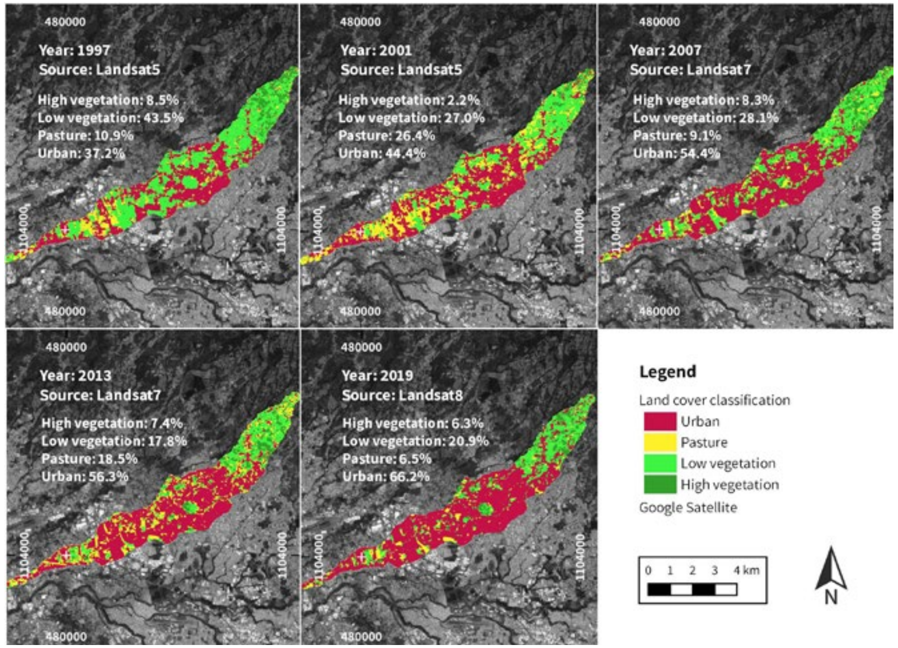

Figure 3.6. Land cover distribution between 1997 and 2019.

Hydrological response at watershed and sub-watershed levels due to changes in land cover

As previously stated, the highest urban growth at watershed level occurred in the 1980s. In turn, runoff volume and peak flow increased by 17% and 26% respectively, mainly between 1979 and 1985. Conversely, significant changes in time-to-peak and maximum specific discharge occurred over a longer period (1945-2019), the former decreasing from 125 to 100 minutes, the latter tripling from 2.9 $(m^3/s)/km^2$ to 9.1 $(m^3/s)/km^2$.

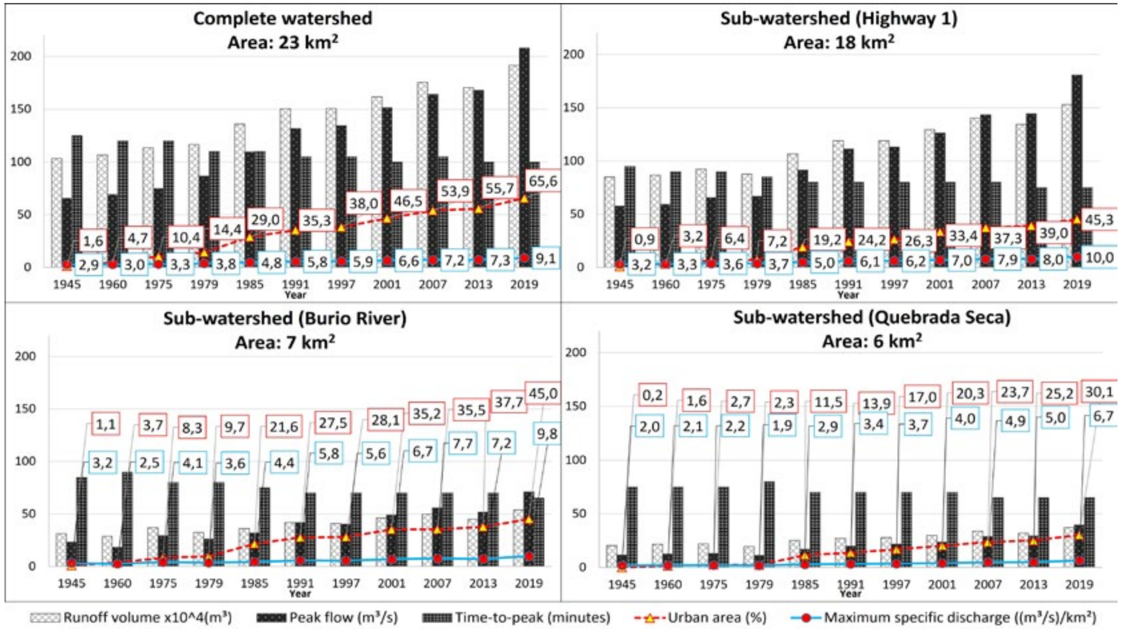

Figure 3.7. Changes in the degree of urban area and modeled hydraulic indicators for the three sub-watersheds and the entire watershed for all analyzed years.

From 1945 to 2019, the urbanized area in the watershed increased by 64%, resulting in an 80% rise in runoff volume generation. This tripled the peak flow and maximum specific discharge while decreasing the time-to-peak by 25 minutes for the lower part of the watershed for a 10-year rainfall event.

The Quebrada Seca and Burío River sub-watersheds were individually analyzed to examine the hydrologic response in the upper part of the watershed. In the Quebrada Seca sub-watershed, the change in urban cover occurred primarily between 1979 and 1985, rising from 2.3% to 11.5% and resulting in 28% higher runoff volumes and 51% higher peak flows. In the case of the Burío River sub-watershed, while the biggest increase in urban coverage occurred between 1979 and 1985 (from 9.7% to 21.6%), the most significant rise in runoff volumes (29%) and peak flows (60%) occurred between 1960 and 1975.

Urban land coverage changes also impacted the hydrological response in terms of time-to-peak and maximum specific discharge. For instance, by 1945, peak times were 75 minutes and 85 minutes in the Quebrada Seca and Burío River sub-watersheds respectively. These values decreased to 65 minutes by 2019 in both cases. Furthermore, in 1945, maximum specific discharge was 2.0 $(m^3/s)/km^2$ for the Quebrada Seca sub-watershed and 3.2 $(m^3/s)/km^2$ in the Burío River sub-watershed. By 2019, these values had increased to 6.7 $(m^3/s)/km^2$ and 9.8 $(m^3/s)/km^2$ respectively. Figure 3.7 shows the results for each analyzed period in terms of runoff volume, urban area percentage, time-to-peak, peak flow and maximum specific discharge for the entire watershed as well as for each sub-watershed.

The hydrological response of the Highway 1 sub-watershed showed similar behavior to that of the upper part of the watershed (Quebrada Seca and Burío River sub-watersheds). Following slow urban growth until 1979, urban coverage accelerated between 1979 and 1985, rising from 7.2% to 19.2%. This resulted in a 22% rise in runoff volume and a 37% increase in peak flow for that period. Conversely, changes in time-to-peak and specific maximum discharge were less pronounced, occurring over a longer time period from 1945 to 2019. For instance, time-to-peak decreased from 95 minutes to 75 minutes, while specific maximum discharge increased from 3.2 $(m^3/s)/km^2$ to 10.0 $(m^3/s)/km^2$.

Hydrological response of the basin due to the change in land cover at drainage area level

A discretized analysis of the watershed at drainage area level was performed to determine the hydrological response in more detail. This analysis enabled the identification of critical areas, irregularities, and hydrological dynamics resulting from urbanization. The assessment focused on four specific parameters that play a key role in understanding the hydrological response in built environments: urban area, runoff volume, peak flow and maximum specific discharge.

The analysis of the drainage areas allowed the identification of areas of highest percentage of urban area and highest runoff volume generation. In 2019, 7 drainage areas generated more than 160 million liters of runoff volume and exceed 80% urban coverage. All areas are located in the middle-upper part of the watershed.

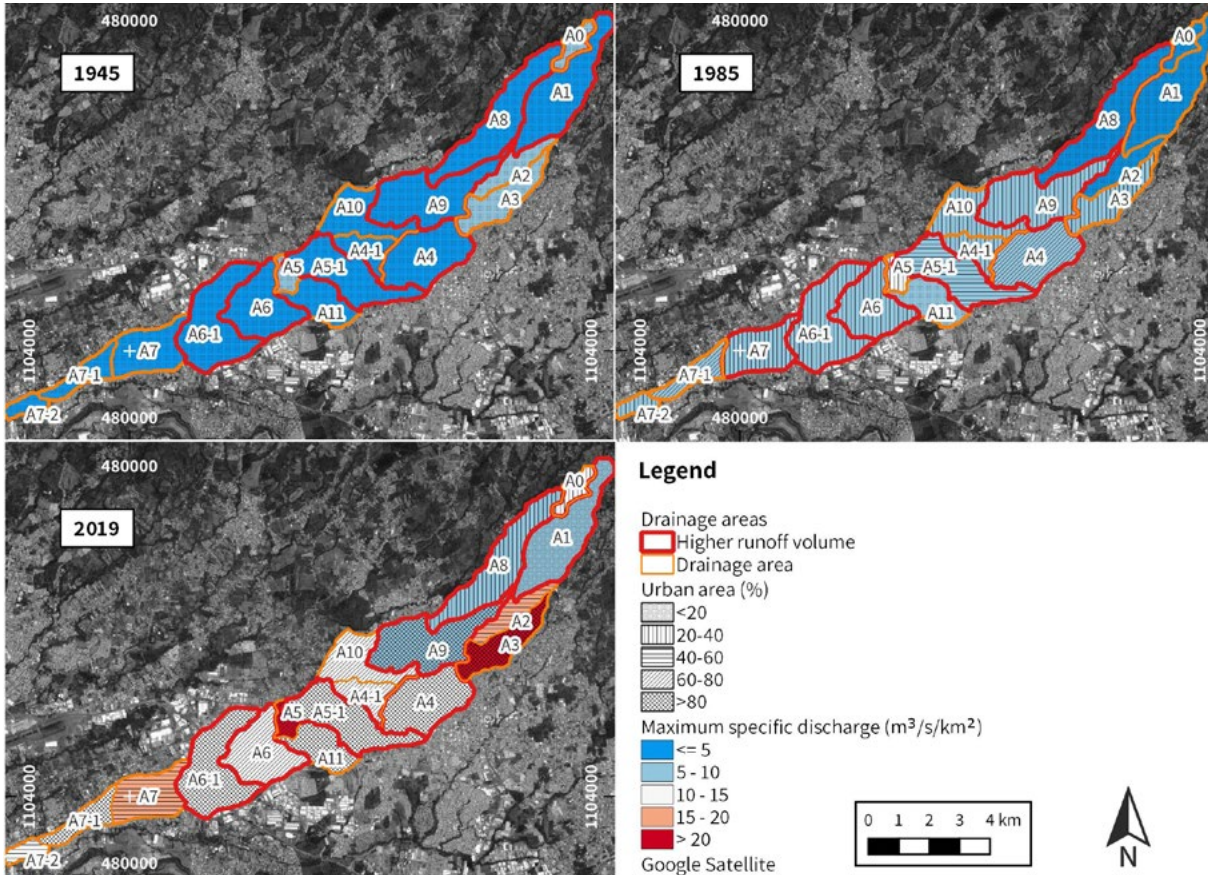

Figure 3.8. Map showing the percentage of urban area, maximum specific discharge, and areas with highest runoff volumes of all drainage areas of the watershed, for the years 1945, 1985 and 2019.

Figure 3.8 shows the drainage areas categorized by their percentage of urban area and their maximum specific discharge. The figure also depicts the drainage areas with the highest runoff volume production in 1945, 1985 and 2019, which, as can be seen, varies from year to year. For instance, in 1945, area A1 produced the highest runoff volume, totaling 115.6 million liters (ML), while in1985, area A4 surpassed all others, producing 160.2 ML of runoff. In turn, area A6-1 had the highest volume in 2019, a staggering 194.7 ML. All areas are located in the upper middle part of the watershed.

In terms of the maximum specific discharge, areas A3 and A5 showed the highest values, 20.4 $(m^3/s)/km^2$ and 24.9 $(m^3/s)/km^2$ respectively, reflecting their significant urban coverage increases. Area A1, despite being the only one with less than 20% urban coverage, is one of the drainage areas generating the largest runoff volume due to its large size.

It is worth highlighting that the areas with the highest runoff volumes may not be the most flood-affected ones. This is because sewage systems are designed to swiftly transport runoff to water bodies, making downstream sectors more susceptible to flooding. For instance, the Municipality of Belén, located in the lower part of the QSRB watershed, has been the most flood-affected area in the last 30 years. The first reports of flooding occurred in the 1980s, coinciding with the high increase in urban land cover between 1979 and 1985.

Changes in hydrological response due to rapid urbanization have been observed in other GAM watersheds, including the María Aguilar River watershed which tripled its peak flow and doubled its runoff volume between 1945 and 2013 (Ramírez-Sandí 2016).

Conclusions

Through this study, the SEE-URBAN-WATER research team were able to confirm the impact of urbanization on hydrologic responses at watershed, sub-watershed and individual drainage area levels. A parallel analysis of land cover changes and variations in runoff volume, peak discharge, time-to-peak and maximum specific discharge provides robust model-based information to support decision-making in urban planning, stormwater management and sustainable development.

For instance, the Quebrada Seca-Río Burío watershed assessment can serve as a foundation for future research in watersheds sharing similar geo-spatial and precipitation features, either within the GAM or in other regions of Central and South America. The methodology developed in this study is heavily reliant on readily accessible information, tools and software, thereby greatly enhancing the reproducibility of both historical land cover analysis and hydrological modeling. Importantly, its scope extends beyond the assessment of historical urbanization trends, demonstrating its versatility.

Moreover, assessing changes in hydrological responses resulting from abrupt changes in land cover and use is critical for flood-resilient city planning. Such assessments facilitate the identification of tipping points with respect to changes in land cover, in turn allowing solutions and regulatory instruments to be found that adapt to these evolving dynamics. Watersheds with high urbanization levels often face significant challenges in implementing sustainable flood mitigation measures due to space constraints, the magnitude of required construction, and the high cost of replacing existing infrastructure. In such cases, Nature-based Solutions offer a feasible alternative to restoring the lost hydrological processes through mechanisms such as infiltration and evapotranspiration, as they can be designed to fit into the available space and complement conventional infrastructure.

Finally, the spatial discretization performed in this study enables us to identify the most historically urbanized areas as well as the gradual change in natural soil permeability. This demonstrated that urban growth occurred at a pace out of step with the construction of the necessary infrastructure to address the increase in runoff volumes, thereby making areas vulnerable to flooding. For this reason, this study is also significant in determining the most effective locations for site control measures such as Nature-based Solutions, which can be extended to sub-watershed and watershed levels within a multifunctional Urban Green Infrastructure network.

For more information about the change in the watershed's hydrological response due to the increase of urban coverage, please refer to:

Bonilla Brenes, R., Morales, M., Oreamuno, R., and Hack, J. (2023). Variation in the hydrological response within the Quebrada Seca watershed in Costa Rica resulting from an increase of urban land cover. Urban Water Journal, 20(5), 575–591. https://doi.org/10.1080/1573062X.2023.2204877.

Urbanization in the District of Llorente in Flores, Costa Rica.

3.2. Analysis of flood-generating rainfall events

As described in the previous section, the Quebrada Seca-Río Burío (QSRB) watershed has experienced accelerated and unorganized urbanization over the last 25 years, resulting in a significant increase in sealed surfaces and subsequently surface runoff, as well as the loss of green areas. These dynamics have led to regular flooding, usually coinciding with the start of the hydrological year in April and May. However, the highest flood volumes and impacts occur during the main wet season between August and October.

Figure 3.9. Previous inundations documented in Belén between 2001 and 2014 (Barrantes Mayorga, 2022).

Flooding effects include disruption of local infrastructure, loss of belongings, riverbank instability and road erosion. Moreover, flood events can increase pollution loads in water bodies due to the transport of trees, debris and waste accumulated in the dry season. Belén is one of the municipalities most affected by regular fluvial flooding (Figure 3.9). In recent years (2020-2022), there have been a total of 22 flood events observed in this municipality, causing river overflow and high economic impacts. The "La Amistad" neighborhood in particular has had to grapple with recurrent flooding, impacting 15 houses and over 80 individuals.

Early Warning System for Flood Control in the Municipality of Belén

In response to the pressing flood risk situation, the municipality of Belén has installed an Early Warning System (EWS) to monitor rainfall and water levels at different points within the watershed (Figure 3.10). In addition to providing valuable information for urban runoff management, this system is designed to warn the population of any risk of flooding during a rainfall event. Operating semi-automatically, the EWS consists of four hydrometeorological stations (Figure 3.11), complemented by real-time surveillance cameras located along the river channel and in affected residential areas. The hydrometeorological stations transmit rainfall and water level data every 5 minutes, except for the upstream station in San Rafael (SR) ("Monte de la Cruz"), which only measures rainfall. Downstream, stations are located in San Joaquín de Heredia (SJ), Mercedes (M) and Belén (B) (Figure 3.10).

INFO

Early Warning Systems

Early Warning Systems are used to monitor precipitation and water levels. They send out warnings to potentially affected people or areas, reducing associated risks and hazards. Rainfall-runoff models can be incorporated to predict weather conditions and thus better anticipate potential flood situations.

Rainfall data is collected using a tipping-bucket rain gauge with a resolution of 0.254 mm. As for the river level measurement, a sensor is used to measure the hydrostatic pressure caused by the height of the water above the sensor, which is then converted into a digital signal. Sensor readings are taken every 60 seconds, while the system records the average water level at 5-minute intervals. The hydrometeorological stations also measure temperature, humidity and solar radiation.

Surveillance involves the continuous and combined observation and analysis of sensor data and real-time camera images in the event of rainfall. Sensor data is monitored and regularly updated on a website and mobile app, providing users with the most recent information every 5 to 15 minutes. In addition, real-time camera images help assess the current river situation in the event of critical rainfall. This allows timely decision-making based on changing conditions.

Alerts are issued when the river water depth or rainfall reaches critical levels based on past experience, ensuring timely communication to stakeholders. A critical river level is defined as exceeding 2.4 meters, while significant precipitation is indicated by the Mercedes and San Joaquín stations measuring more than 10 mm of accumulated rainfall simultaneously.

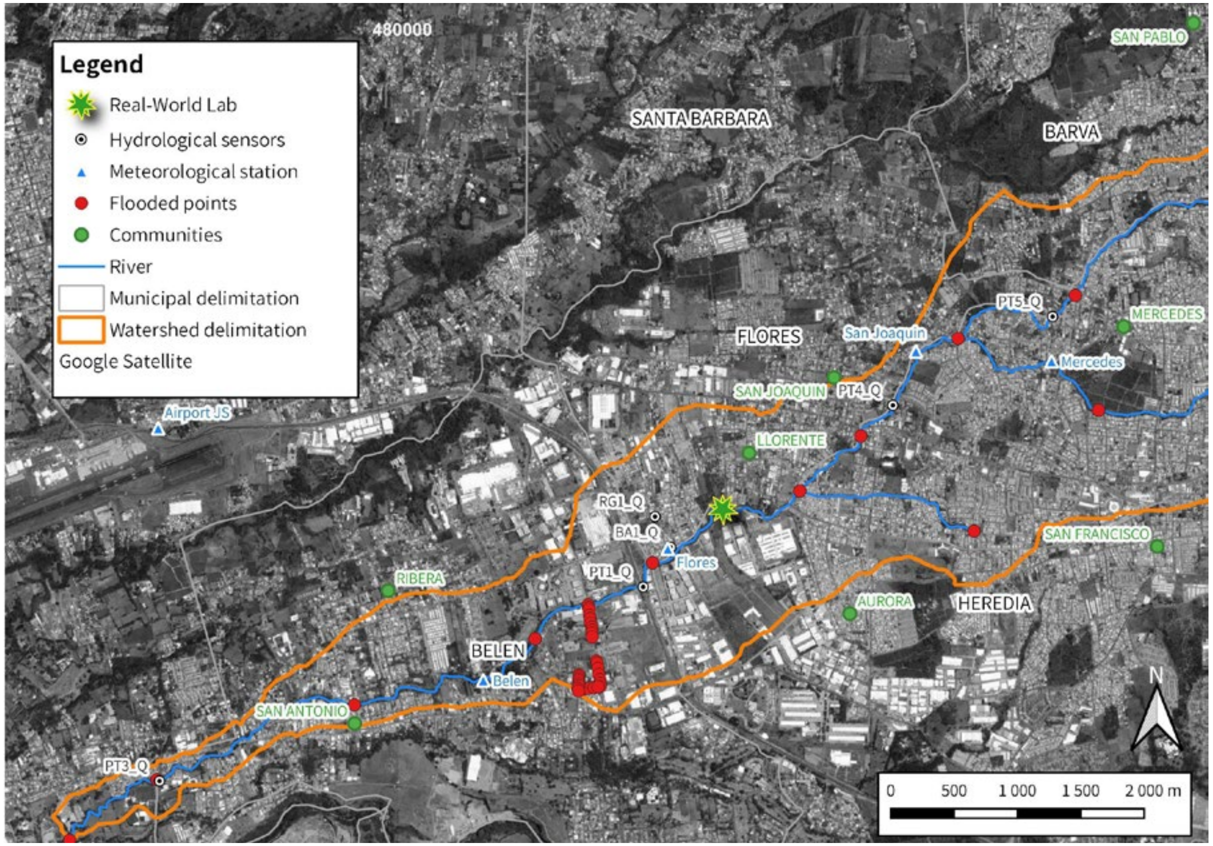

Figure 3.10. Reported flood-affected areas within the Municipality of Belén.

Three alert levels are used: yellow, orange and red. A yellow alert is issued when rainfall increases at one station, with expected rainfall exceeding 10 mm. An orange alert is triggered when precipitation surpasses 10 mm at one station and concurrently increases at another. In turn, a red alert is delivered when both the Mercedes and San Joaquín stations measure more than 10 mm of rainfall, and the river level is rising. In addition, the alert level can be adjusted if the river water depth decreases while precipitation persists, resulting in an orange alert. Similarly, if the river level drops below a specific threshold, a yellow alert is issued to ensure continued awareness (Figure 3.12).

During an alert situation, it is important to act quickly and efficiently to ensure the safety of the affected population. When faced with an orange alert, a patrol is sent out to monitor the water level on site. Furthermore, the frequently affected bridge in the La Amistad neighborhood is closed at the beginning of a critical water level rise. A red alert is triggered when the river level in Belén reaches 2.4 m, with patrols deployed to warn and evacuate affected households.

Three loudspeakers located in the La Amistad neighborhood broadcast messages to alert the population within 15 to 17.50 minutes. Moreover, a message is phoned through to the Belén emergency group to provide information to the responsible institutions. Communication is also established with the Municipal Police and the Belén Emergency


Figure 3.11. Hydrometeorological station of Belén's Early Warning System.

SAT BELEN 29 DE SETIEMBRE DE 2020

HORA	MERCEDES LLUVIA	MERCEDES NIVEL	SAN JOAQUIN LLUVIA	SAN JOAQUIN NIVEL	BELEN LLUVIA	BELEN NIVEL	CONDICION	INDICACION	ACCION
13:05:00							NORMAL EN TODAS LAS ESTACIONES		MONITOREO
13:20:00	5,0			0,03			LLUVIA EN MERCEDES Y SAN JOAQUIN		ATENCION ESPECIAL AL MONITOREO
13:30:00	6,8			1,92			LLUVIA EN MERCEDES SAN JOAQUIN CON NIVEL ALTO		ALERTA AMARILLA POSIBLE CRECIENTE
13:40:00	17,0	1,06	4,3	2,50			LLUVIA EN MERCEDES CON NIVEL ALTO SAN JOAQUIN NIVEL ALTO		ALERTA NARANJA PARA BELEN
13:50:00	29,2	1,50	10,4	2,36			LLUVIA EN MERCEDES CON NIVEL ALTO SAN JOAQUIN NIVEL ALTO		ALERTA ROJA PARA BELEN
14:00:00	43,4	1,45	20,3	1,39			LLUVIA FUERTE MERCEDES NIVEL ALTO -- SAN JOAQUIN LLUVIA NIVEL BAJANDO		ALERTA ROJA PARA BELEN
14:10:00	54,1	1,16	37,5	0,90	5,5		LLUVIA FUERTE MERCEDES NIVEL BAJANDO ---SAN JOAQUIN LLUVIA FUERTE NIVEL BAJANDO ---LLUVIA EN BELEN		ALERTA NARANJA PARA BELEN
14:20:00	55,3	0,49	45,9		12,5	2,61	LLUVIA FUERTE MERCEDES NIVEL BAJANDO ---SAN JOAQUIN LLUVIA FUERTE NIVEL NORMAL--- LLUVIA EN BELEN NIVEL SUBIENDO FUERTE		ALERTA NARANJA PARA BELEN
14:30:00	57,9		49,2		19,0	2,82	LLUVIA BAJA MERCEDES NIVEL NORMAL--- LLUVIA MEDIA SAN JOAQUIN NIVEL NORMAL--- LLUVIA BAJA BELEN NIVEL ALTO		ALERTA AMARILLA SITUACION A LA BAJA
14:40:00					21,6	2,70	TODO NORMAL SAN JOAQUIN TODO NORMAL LLUVIA BAJA EN BELEN NIVEL BAJANDO		ALERTA AMARILLA SITUACION A LA BAJA
14:50:00						1,95	MERCEDES Y SAN JOAQUIN NORMALES BELEN SIN LLUVIA NIVEL BAJANDO		SITUACION NORMAL
15:00:00							TODAS LAS ESTACIONES EN CONDICION NORMAL		SITUACION NORMAL
15:10:00							TODAS LAS ESTACIONES EN CONDICION NORMAL		SITUACION NORMAL
15:20:00							TODAS LAS ESTACIONES EN CONDICION NORMAL		SITUACION NORMAL
15:30:00							TODAS LAS ESTACIONES EN CONDICION NORMAL		SITUACION NORMAL

Figure 3.12. Illustration of alert stages in the Belén Early Warning System with their prospective criteria (Barrantes Mayorga, 2022).

Group. Previous experiences have revealed divergent response times between stations: 11.54 minutes from the Mercedes to the San Joaquín station, 26.57 minutes from the San Joaquín to the Belén station, and 17.50 minutes from the Belén station to the flooded bridge, resulting in a total response time of 56.40 minutes. This implies that in the case of a critical event, there is less than one hour to assess the hazard and risk of the ongoing event as well as take all necessary measures.

The hydrological response time between the most upstream measuring station and the bridge "La Amistad" in Belén, where flooding may occur, is less than 1 hour.

Spatial-temporal analysis of flood occurrence

The Belén EWS's precipitation and water level records for the years 2020-2022 were used to determine the precipitation events resulting in floods in this municipality. Furthermore, an event analysis was conducted to investigate flood event characteristics, enhance the assessment of the potential hazard of a critical event, and thereby improve the effectiveness of the measures taken during an alert situation. With this information, a file was created, containing event characteristics, photos and documentation of past flood events. This can now be used in hydrological simulations as well as for calibrating and verifying models.

The flood-affected areas are in the administrative districts of San Joaquín de Flores and San Antonio de Belén. Specifically, three sites with insufficient hydraulic capacity were previously identified by Oreamuno Vega & Villalobos Herrera (2015): two culverts on Route 1 and Route 147 (incl. the La Amistad bridge and neighborhood) and the Avenue 2 bridge in Belén. Three additional river overflow-prone sites were identified during the revision of previously documented flood events.

The spatial-temporal characteristics of precipitation in the QSRB watershed were evaluated with regard to flood occurrences at the La Amistad bridge. It was observed that when the water level exceeds 2.4 meters at the measuring station in Belén, riverbank overflow begins downstream of the La Amistad bridge. For instance, between 2020 and 2022, 22 flooding events were recorded at this site. In 18 of them, the Belén station recorded water levels exceeding 2.4 m.

In addition, 37 events with a water level exceeding 2 m were identified (Figure 3.13).. There were thus 55 events triggering a high flood risk alert over the past 3 years. Observed patterns showed that floods occur during the main rainy season from August to October, but also in the low rainy season between April and June. Furthermore, out of 55 events, a pattern involving two floods on consecutive days or a combination of one flood and one water level rise was observed in 15 instances.

Between 2020 and 2022, 55 events with high flood alert potential were recorded. 22 were categorized as flooding events causing river overflow at the "La Amistad" bridge in Belén.

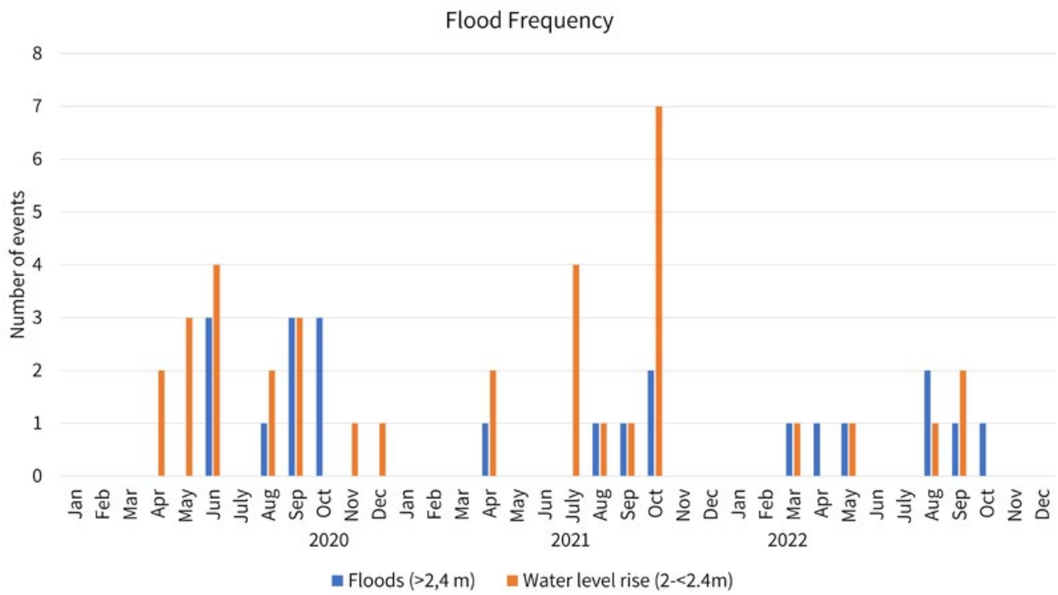

Figure 3.13. Recorded water levels with high flood alert potential (2.0 - 2.4 m) and categorized as flood (> 2.4 m) at Belén station between 2020 and 2022.

For the analysis of the spatial distribution of precipitation, parameters like daily precipitation [mm], event precipitation [mm], event duration [Δt] and precipitation intensity [mm/h] were examined. As simplified methods (e.g., calculating the arithmetic mean for area precipitation) were chosen, it should be noted that this assessment only provides average values for the entire watershed. In reality, all of these rainfall-related parameters display spatial differentiation across their aerial extent. The arithmetic mean was employed as it provides a sufficient level of detail, allowing us to compare events and their respective magnitudes. The spatial distribution of precipitation for all events was performed using the inverse distance weighting interpolation in ArcGIS Pro 2.8 to visualize precipitation distributions.

In general, a concentration of precipitation was observed in the central part of the watershed (SJ and M), with precipitation events averaging 41.4 mm and ranging from 15.3 mm to 181 mm. In most cases, rainfall intensity reached a heavy to very heavy level (30 mm/h on average), with one event having a torrential intensity of 141 mm/h on August 14, 2022. The highest intensities are concentrated in the middle part of the watershed, reaching peaks 20 minutes after the onset of rainfall. This contrasts with the findings of Oreamuno Vega & Villalobos Herrera (2015), who observed a concentration of intensity in the southern part of the watershed.

In addition to event intensity, precipitation intensity over 10 minutes was investigated. The maximum observed 10-minute intensity reached 157.73 mm/h on March 31, 2022 in Mercedes, 20 minutes after the onset of precipitation. Ten minutes earlier, intensity had only reached one-fifth of its maximum value, indicating a rapid development within the watershed and a short reaction time. Moreover, the duration of precipitation events was relatively short, averaging 83 minutes.

Precipitation leading to flooding in Belén usually occurs in the afternoon, from 3 pm onwards. Lasting on average 80 minutes, intensity can be heavy to very heavy, i.e., exceeding 30 mm/h.

Based on observed patterns and regional similarities in precipitation characteristics, spatial distributions could be categorized into three precipitation patterns:

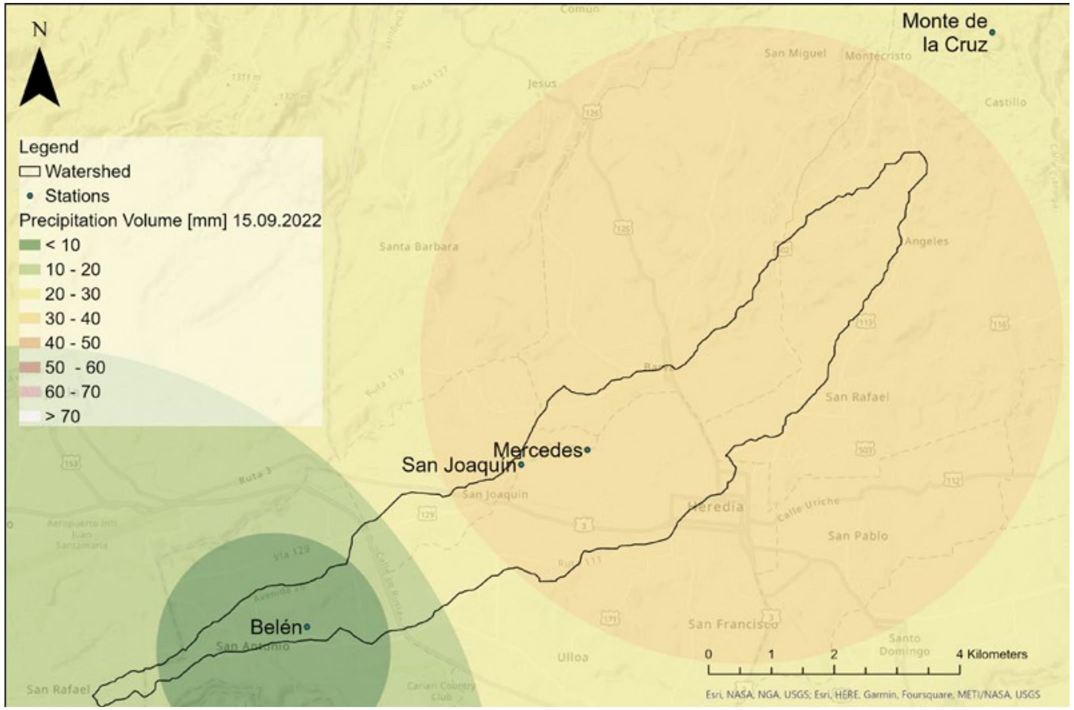

Figure 3.14. Spatial distribution of Type 1 precipitation events (interpolation results of measurements on 15.09.2022).

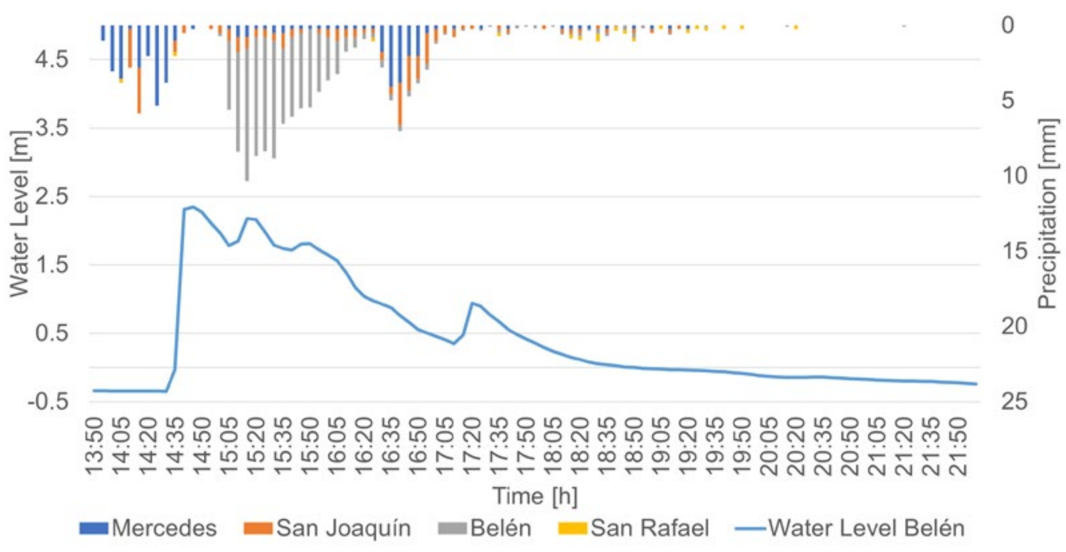

Figure 3.15. Mean temporal distribution of Type 1 precipitation events.

TYPE 1: Precipitation in the middle part of the watershed (SJ and/or M), but low or no precipitation in Belén (<10 mm) (Figure 3.14). 6 of the investigated 22 flood events could be assigned to this pattern. Average rainfall was 43 mm (M) and 38 mm (SJ), with an average of 27 mm for the whole area. Type 1 events usually last 1.5 hours, with the maximum water level at the Belén station reached within the first 30 minutes of rainfall (Figure 3.15).

TYPE 2: Simultaneous precipitation in Belén and in the central (SJ, M) or entire watershed (+SR) with precipitation concentrated in Belén and the mid-watershed (Figure 3.16). Five observed events were attributed to this precipitation pattern. The mid-watershed stations of SJ and M recorded rainfall averages of 35 mm and 34 mm respectively, while the Belén station averaged 39 mm. Precipitation events in areas with a Type 2 rainfall pattern average 31 mm and usually last 2.5 hours, with the maximum water level at the Belén station reached within the first 40 minutes (Figure 3.17).

TYPE 3: Simultaneous precipitation in Belén and in the central part of the watershed, with concentrated precipitation in SJ and/or M. For the Type 3 rainfall pattern, eight events were observed (Figures 3.20-3.22). This pattern can be further divided into two subtypes: Type 3A, with precipitation concentrated in SJ (four observed events) and Type 3B, with precipitation concentrated in M (four events) (Figure 3.18). Rainfall for stations in the mid-watershed averaged 46 mm (M), 52 mm (SJ) and 27 mm at the Belén station. Average precipitation for the area with a Type 3 rainfall pattern was 32.6 mm. Events of this type usually last 2.5 hours; with the maximum water level at Belén station reached within the first 30 minutes of rainfall (Figure 3.19).

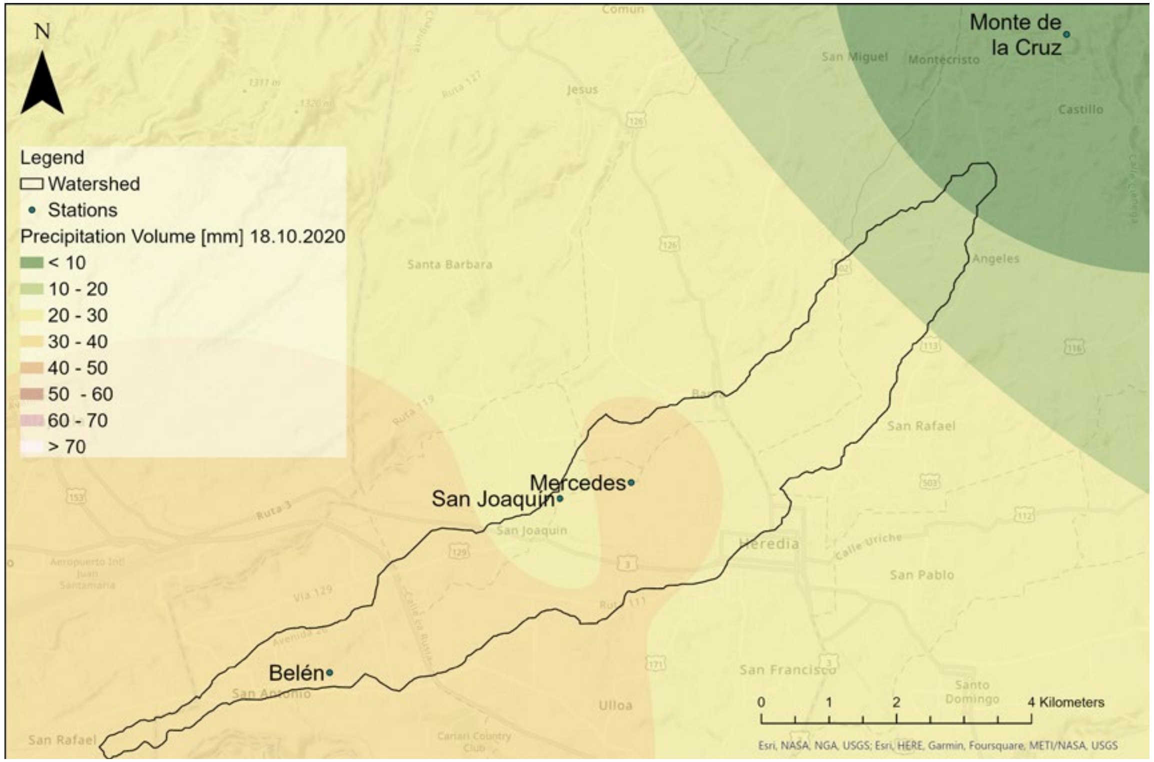

Figure 3.16. Spatial distribution of Type 2 precipitation events (interpolation results of measurements on 18.10.2020).

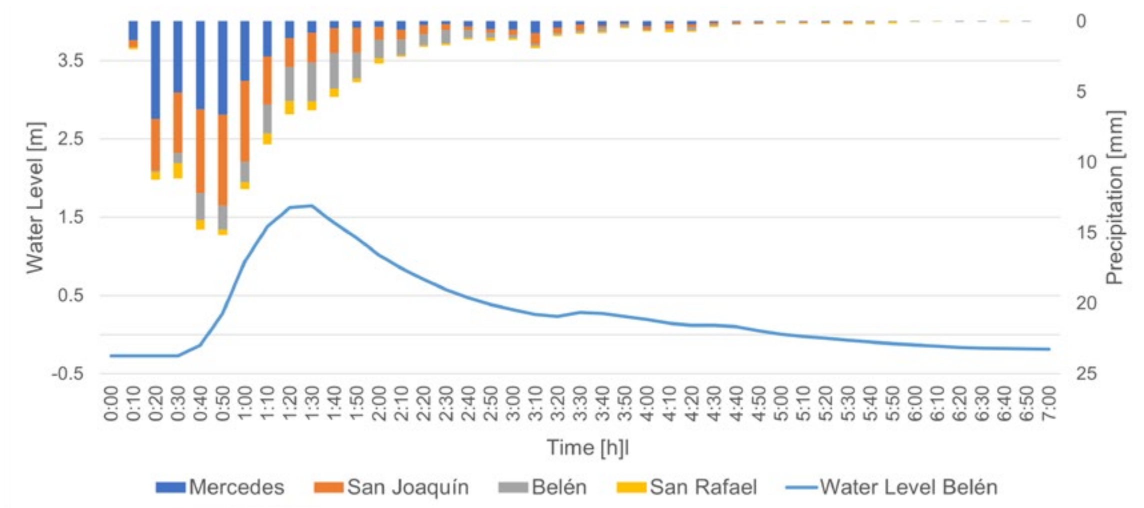

Figure 3.17. Mean temporal distribution of Type 2 precipitation events.

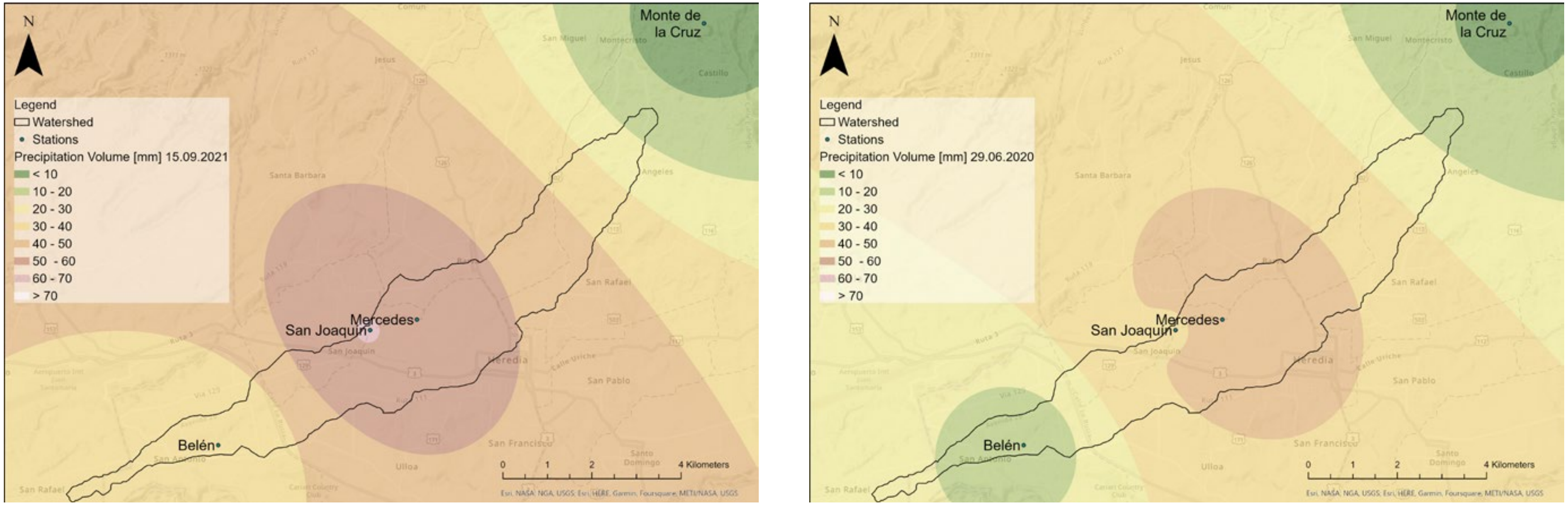

Figure 3.18. Spatial distributions of Type 3 precipitation events: Type 3A (left) and Type 3B (right) (interpolation results of measurements on 15.09.2021 and 29.06.2020).

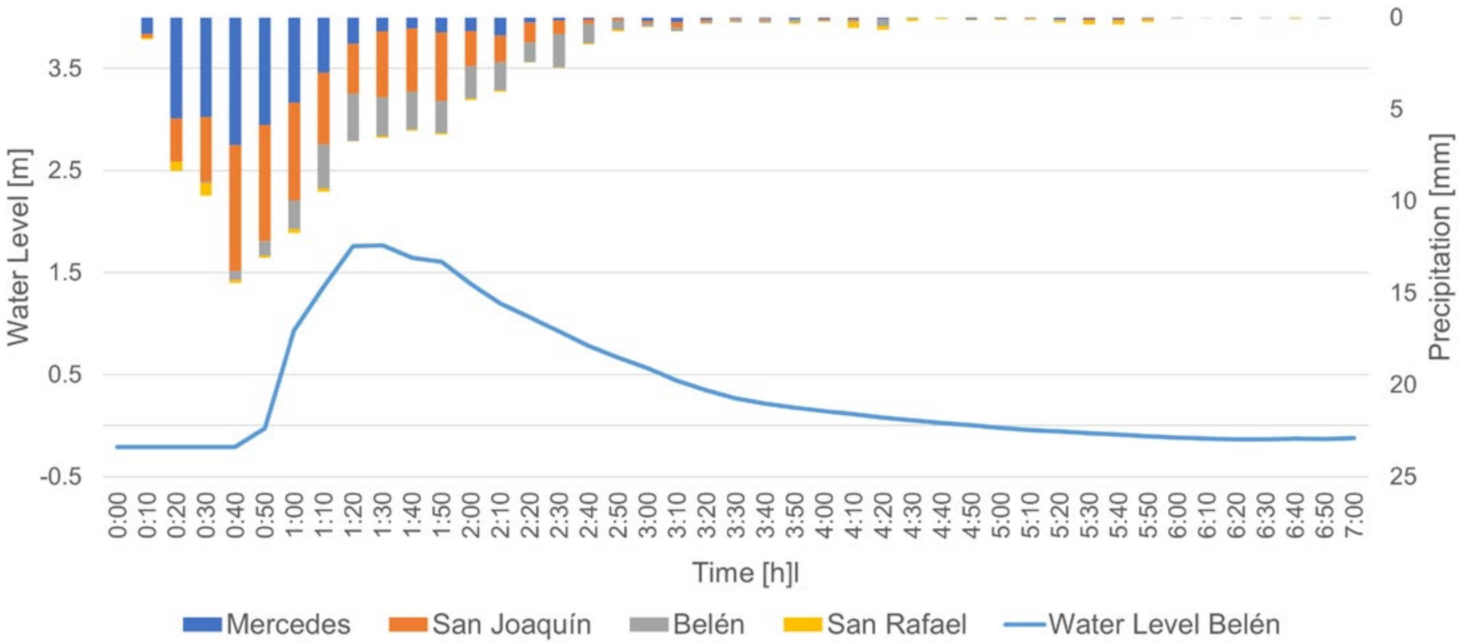

Figure 3.19. Mean temporal distribution of Type 3 precipitation events.

Rainfall events in Belén can be classified into 3 spatial patterns; Type 3 generates the highest impacts. Rainfall events occurring at the Mercedes and San Joaquin stations have the greatest influence in the occurrence of flooding. An accumulated rainfall of 10mm in one of these stations is sufficient to cause flooding.

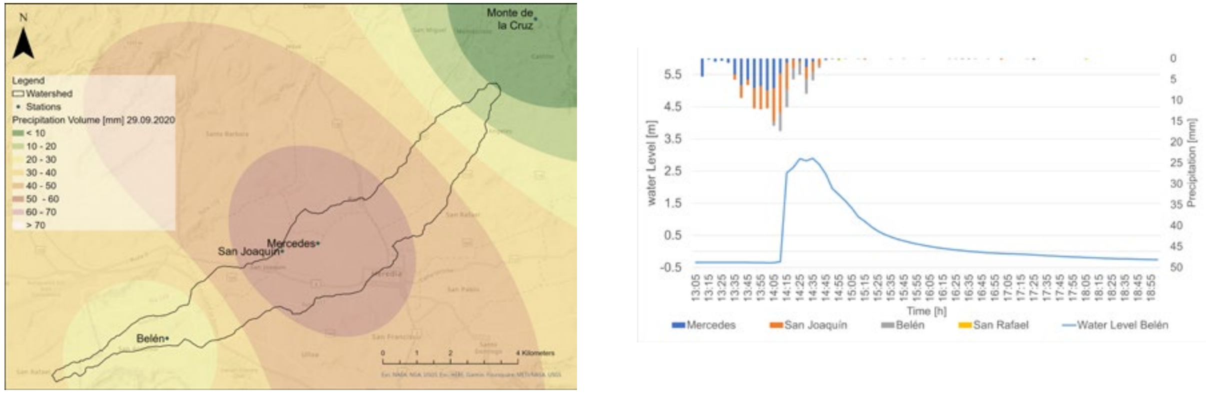

Figure 3.20. Flood event of 29.09.2020 - Characteristics, spatial and temporal distribution.

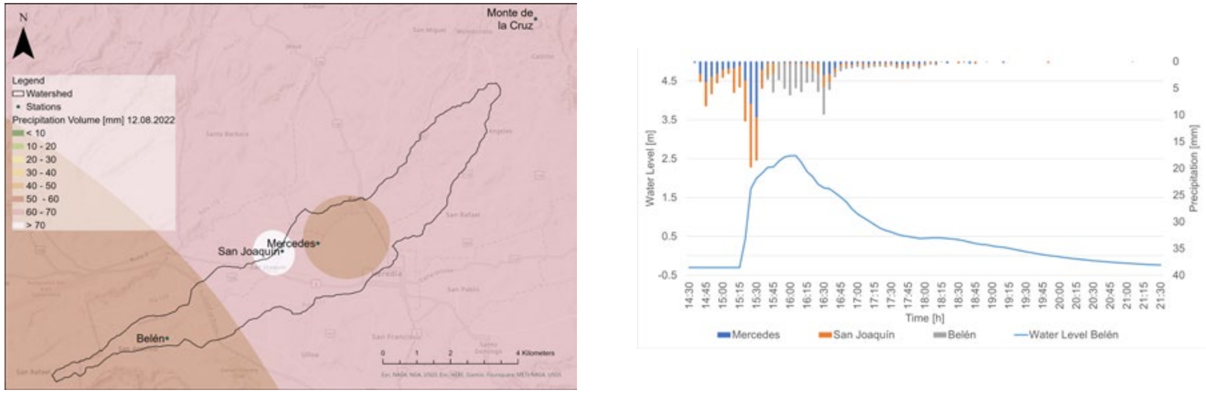

Figure 3.21. Flood event of 12.08.2022 - Characteristics, spatial and temporal distribution.

In accordance with this spatial event typology, a comprehensive examination of events causing the most significant impact was undertaken. The aim was to determine rainfall characteristics able to trigger instances of extreme flooding and consequent high-level impacts. This assessment showed that three of the four extreme flooding events belonged to Type 3, with rainfall concentrated in Mercedes. For instance, on September 29, 2020, an aerial precipitation of 34.5 mm and an intensity of 33 mm/h were sufficient to generate severe flooding, affecting seven houses and 52 people in the La Amistad neighborhood (Figure 3.20). For all events, water levels rose remarkably fast, with just 5 minutes in Belén between the pre-event water level and the critical level of 2.4 m. Also, the response time (time-to-peak between stations) was fast: just 20 minutes between Mercedes and Belén.

The three event types and their temporal distributions show that water level rises in Belén typically occur during the afternoon, with a duration of only 2 hours. The peak water level is reached within the first 20 to 25 minutes of the event, resulting in a sudden rise in water levels at all stations. In cases of extreme flood events, the shortest time observed between the

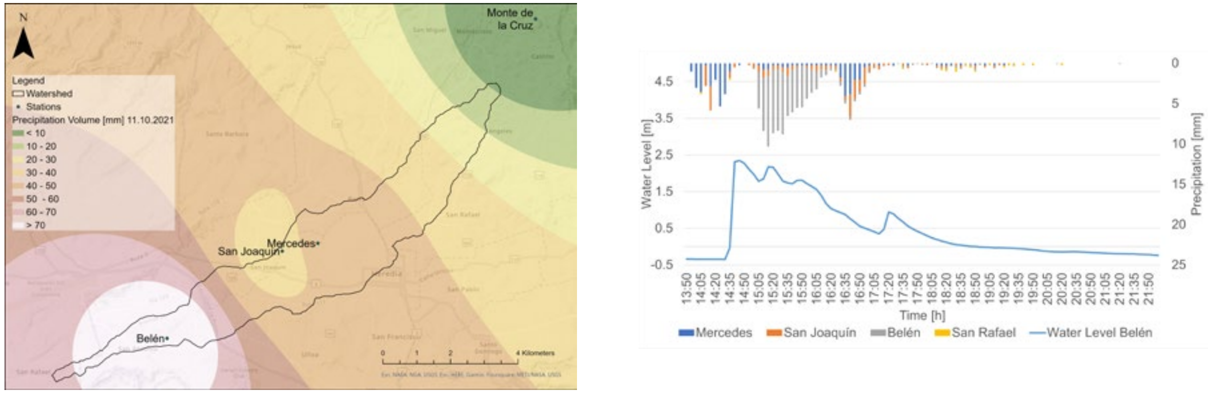

Figure 3.22. Flood event on 11.10.2021 - Characteristics, spatial and temporal distribution.

pre-event rest level in Belén and the critical level of 2.4 m was 5 minutes. However, there are no discernible correlations in the timing of water level increases across the stations, suggesting that the rate at which water levels rise at the upstream stations does not correspond to a similar pattern observed in Belén.

The response time (peak times between stations) showed similar results. Previous observations made by EWS staff are consistent with the event analysis results, with mean response times from Mercedes to San Joaquin of 13 minutes, from San Joaquin to Belén of 15 minutes, and a total of 28 minutes between Mercedes and Belén. In cases of extreme flood events, minimum values are just 20 minutes between the most upstream station, Mercedes, and Belén. As the times of water level rises and response times show no correlations between stations for the same event, no conclusions can be drawn from the upstream stations. This complicates any hazard assessment for Belén during a critical event.

These results can be used to guide the further development of Belén's Early Warning System and future decision-making on flood mitigation measures.

Stormwater quickly concentrates in the Quebrada Seca-Burío River, leading to a maximum water level within the first 20-30 minutes and resulting in a high flash flood frequency.

Conclusions

The present study demonstrates that detailed spatial-temporal assessments of rainfall and flood-generating events, complemented with information from an Early Warning System (EWS), are a great tool for improving flood risk management decision-making. High rainfall intensities, steep slopes, and a high proportion of sealed surfaces cause effective rainfall to concentrate quickly, increasing the frequency of flash floods. This phenomenon is exacerbated by water levels rising in short periods of time, in some cases leaving only 20 minutes response time (e.g., between Mercedes and Belén).

Moreover, it was evident that an accumulated rainfall of 16 mm for the central stations (San Joaquín de Heredia and Mercedes), with one station having more than 10 mm, or a water level in Belén above 2.3 m, is sufficient to cause water level rises and flooding at La Amistad Bridge. Therefore, the current threshold defining an orange and red alert (2.4 m) could be lowered (2.3 m), as the water level resulting in an orange alert is sufficient to cause flooding.

Overall, this study is highly relevant for any improvement of Belén's current EWS, allowing the design of more effective pre- and post-event management plans and strengthening the resilience capacity of both the local community and the authorities in charge. In other regions with similar spatial and rainfall characteristics, this study highlights the importance of a robust EWS and local cooperation for reducing fatalities and mitigating economic losses, while at the same time speeding up recovery.

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Flash Flood Formation

Within an urban watershed, there are two common types of floods: flash floods and pluvial floods. They vary in the amount and intensity of rainfall and, consequently, in the development of the flood wave. The formation and progression of a flood wave is a complex (non-stationary) process. Alongside precipitation, other watershed-specific factors play an important role, such as the presence of built-up areas, the shape of the watershed and the density of the drainage network. In general, a flood occurs when the water level in a watercourse or drainage channel exceeds its capacity.

Unlike pluvial floods that occur due to heavy rainfall over a wide area, following a specific spatial pattern influenced by topography and large-scale weather conditions, flash floods follow intense, short-lived rainfall or storms within a smaller area, usually less than 5 km in diameter. Such precipitation does not follow a specific spatial pattern and may occur suddenly, with alert times ranging from a few minutes to a few hours. Flash floods are often very intense, especially in areas with high rainfall or low vegetation cover, as well as in rugged terrain. Water "precipitates" from the surface, resulting in the sudden formation of the flood wave. This type of flood poses significant risks due to the potential high flow rates transporting heavy debris, trees and large objects and destroying infrastructure (Seibert & Auerswald, 2020).

3.3. Inter- and transdisciplinary research for the promotion of Nature-based Solutions

The data- and model-driven evidence presented in Sections 3.1 and 3.2 highlights the limited capacity of traditional, gray infrastructure-based runoff management approaches to cope with the challenges posed by intensive urbanization and extreme climatic conditions. As previously mentioned in Section 1.1, Nature-based Solutions (NbS) are promising alternatives for building resilient cities in social, environmental and economic dimensions. There is ample evidence of their potential for hydrological control, ecosystem protection, well-being provision, and the delivery of a wide range of ecosystem services for the benefit of society and environment (Cohen-Shacham, 2019). Nonetheless, NbS implementation remains weak, hindered by a range of technical, financial, institutional, social and political hurdles (Sarabi, 2020).

Given the significance of a paradigm shift towards sustainable solutions, SUW conducted an inter- and transdisciplinary investigation into the factors required for the successful promotion and implementation of NbS in the context of the Greater Metropolitan Area of San José, Costa Rica. This served as a relevant case study to evaluate the potential of NbS in highly urbanized and flood-prone watersheds.

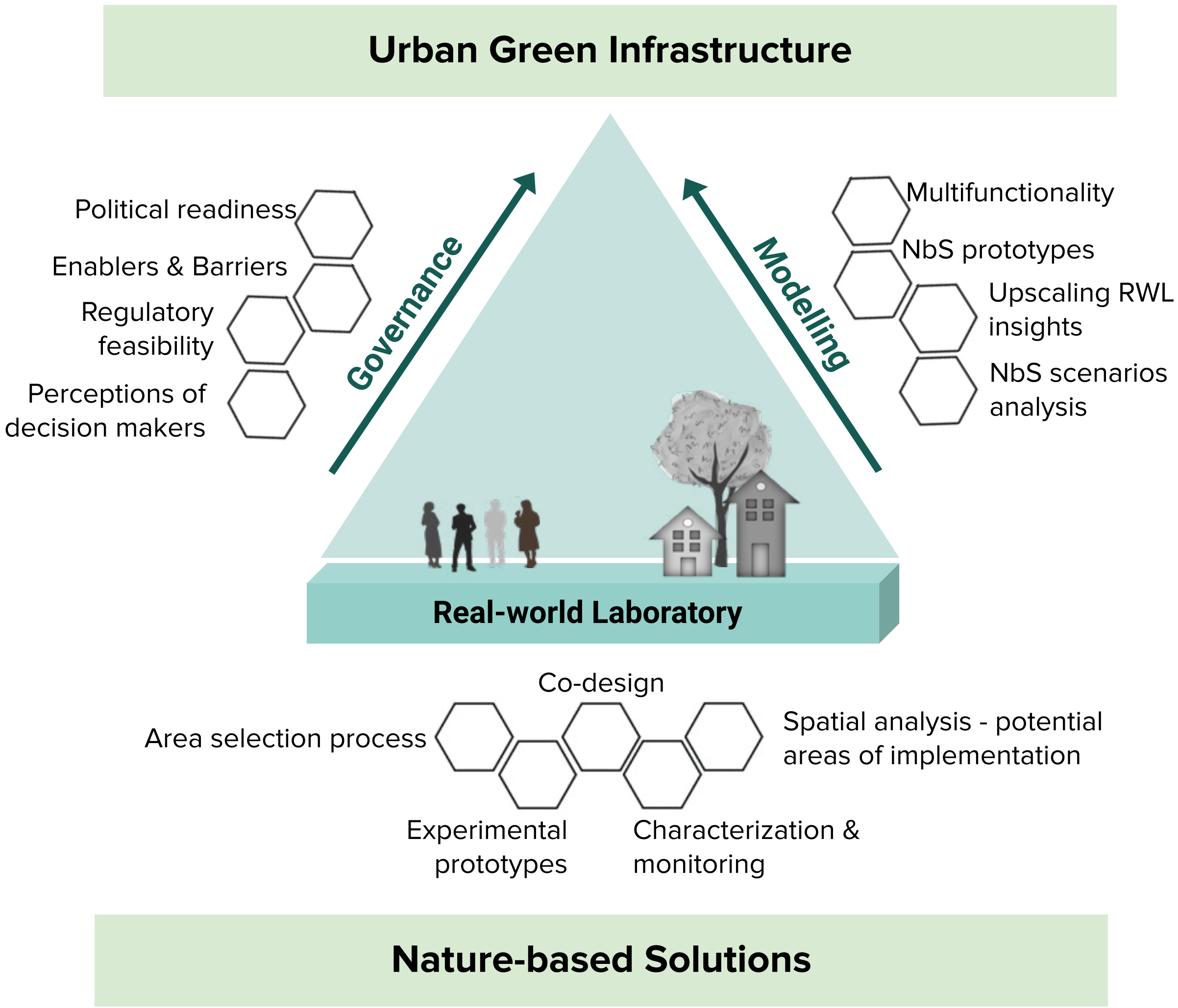

Figure 3.23. Interlinkage of SUW's three main research domains - Real-World Lab, Modeling and Governance - bridging the experimental implementation of Nature-based Solutions with the planning of a multifunctional and multi-scale Urban Green Infrastructure.

Research activities focused on three main domains:

- Transdisciplinary research in the Real-World Lab (Chapter 4)
- Modeling of Nature-based Solutions and planning of multifunctional Urban Green Infrastructure (Chapter 5)
- Governance of Nature-based Solutions (Chapter 6)

The transdisciplinary methodological interlinkage of the three domains enabled a holistic analysis of opportunities and challenges facing the effective promotion and implementation of multifunctional NbS in complex urban settings (Figure 3.23). It considers a multi-spatial scale approach (from building level to a larger metropolitan area) and multi-level stakeholder involvement in the promotion, design, implementation and upscaling processes.

The Real-World Lab (Chapter 4) played a key role in providing a physical space and socio-economic context representative of the functional preferences of NbS among different stakeholders and in the testing of co-designed NbS prototypes. Results from this domain include preferred NbS functions, designs, and the effective placement potential (suitable sites and legal complexity) for NbS at building and street level, as well as on a neighborhood scale. Through a detailed and comprehensive field assessment, the implementation potential for NbS to create a multifunctional Urban Green Infrastructure (UGI) were described and quantified, forming the basis for developing NbS scenarios on other spatial scales (neighborhood, sub-watershed and watershed). The experimental testing of NbS prototypes provided important feasibility insights through comprehensive reflections on their co-design, construction, operation and maintenance.

In combination with field measurements and ground observations, the prototyping and monitoring data provided by the RWL enabled NbS performance assessment and supported the calibration and validation of hydrological and hydraulic models (Chapter 5). In the modeling and multifunctional planning domain, the realistic NbS placement potential and hydrological performance to reduce flooding at different spatial scales (neighborhood – (sub)watershed) were evaluated thoroughly based on the insights from the Real-World Lab exploring different implementation strategies. Besides hydrological criteria, we also assessed the social and ecological functions of different NbS types as well as economic trade-offs by applying different scenarios. Furthermore, NbS multi-functionality was investigated comprehensively with regard to its potential to regulate the micro-climate and integrate ecological and social functions when planning regional UGI.

To ensure the effective integration of NbS into the built environment, it is crucial to consider not only biophysical and social factors but also institutional and political aspects. For this reason, SUW also investigated the governance of NbS implementation (Chapter 6), mainly from an upscaling point of view. In this domain, we assessed factors such as regulatory feasibility, political readiness, and the perceptions of critical administrative and political decision-makers. Understanding governance as a cross-cutting factor for a wider adoption of NbS, this domain not only yields significant insights for regulating and operationalizing its implementation but also provides a regional perspective by assessing notable progress in this field within a Latin American context.

Aerial view of the SEE-URBAN-WATER Real-World Lab and the Quebrada Seca- Río Burío River in Llorente, Flores, Costa Rica.

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4

TRANSDISCIPLINARY RESEARCH IN A REAL-WORLD LAB

TRANSDISCIPLINARY RESEARCH IN A REAL-WORLD LAB

Real-World Labs or Laboratories (terms used in German research communities), sometimes also called Living Labs, represent a recent approach in sustainability and transdisciplinary transformative research, emerging in the first years of the 21st century in Europe. Their application in Latin American countries is very recent. Real-World Labs (RWLs) are predominantly established in urban contexts and are understood as research, innovation and learning infrastructures or spaces in which scientific and civil society stakeholders collaborate in the co-production of knowledge to support a more sustainable development of society. An RWL is a place in time in which specific players mutually invent and conduct real-world experiments in order to gain systems knowledge, target knowledge and transformation knowledge (Schneidewind et al. 2018; Wanner et al. 2018). Furthermore, RWLs have also been conceptualized as "places of learning" in which the societal context plays a fundamental role in the co-production of knowledge and the development of new skills, thus enhancing individual and collective coping capacity.

INFO

Core characteristics of Real-World Laboratories are that ...

- ... they contribute to transformation by experimenting with potential solutions, and support transitions by providing evidence of the robustness of solutions;
- ... they deploy transdisciplinarity as the core research mode in order to "(...) integrate scientific and societal knowledge, related to a real-world problem" (Schäpke 2018 p.87). They "(...) can build on previous transdisciplinary processes of, for instance, co-designing a shared problem understanding and related vision (...) or they can include these steps." (Schäpke 2018, p.87);
- ... they establish a culture of sustainability around the laboratory, stabilize the cooperation between stakeholders and empower the practitioners involved;
- ... they therefore have a strong normative and ethical component and aim to contribute to the common good;
- ... they include experiments as a core research method, providing concrete settings and actively involving stakeholders in their co-design and co-production;
- ... they attempt to create solution options that "(...) have a long-term horizon, potentially going beyond the existence of the lab" (Schäpke 2018, p.87);
- .... they have a strong educational aspect and support three levels of reflexive learning: individual competency, social learning and learning with regard to transdisciplinary collaboration;
- ... learning outcomes are used to evaluate and possibly improve the research procedure, and are transferred to other transformation processes;
- ... they create knowledge on and for transformative processes, consisting of system knowledge, target knowledge and process knowledge.

Read more about Real-World Laboratories in
https://sustainabilitymethods.org/index.php/Living_Labs_%26_Real_World_Laboratories

4.1. Selection process of the SEE-URBAN-WATER Real-World Lab

The SEE-URBAN-WATER (SUW) research focused on the socio-ecological improvement of developed urban areas through retrofitting Nature-based Solutions (NbS), with a focus on the management of urban drainage and wastewater systems. NbS prototypes are Urban Green Infrastructure elements implemented in an individual or combined way. Their application in the Real-World Lab (RWL) context enables the assessment of hydrologic/hydraulic performance as well as their socio-ecological capabilities. Therefore, our co-design approach for the NbS prototypes was developed as an empirical method to investigate how NbS can be effectively planned, designed and implemented in practice. In this context, we used an RWL to provide a physical space as well as a socio-economic context for co-designing and monitoring these experimental measures.

Nevertheless, RWLs are more than just physical spaces for innovations and experimentation with novel techniques. The RWL approach also enables the creation of a robust evidence base for successful upscaling, i.e., the broader regional application of NbS. Herein lies the importance of selecting a representative case study area, which in the SUW project is the Quebrada Seca-Río Burío (QSRB) watershed (see Chapter 3), owing to its highly urbanized context and its connection to river ecosystems under tropical conditions. For this reason, the RWL was envisaged as a representative urban area with relevant socio-ecological dynamics, infrastructure and land-use characteristics, socio-political settings, and geomorphological and climatic features, all of which are key to assessing other urban settlements in the region and enabling more effective NbS upscaling.

Real-World Labs are spaces in which scientific and civil society players co-produce knowledge enabling a broader socio-technological transformation.

Aerial view of the district of Llorente in Flores, Costa Rica.

In 2018, SUW, in collaboration with the Center for Research in Sustainable Development (CIEDES) of the University of Costa Rica (UCR), selected the QSRB watershed for implementing an RWL and testing NbS prototypes. Recognizing the involvement of five municipalities in the management of the QSRB watershed, namely Belén, Flores, Heredia, Barva, and San Rafael, the SUW team proposed a participatory approach for selecting a suitable RWL location and identifying the preferred NbS types. This participatory process included several bilateral meetings with staff members of the five municipalities and interviews with local residents, thus strengthening the decision-making process. Field visits, a review of policy instruments, and the use of GIS data complemented the suitability assessment. Furthermore, SUW employed a standardized form to receive the necessary feedback from the municipalities justifying their proposals. An overview of the locations and main characteristics of the suggested RWL sites

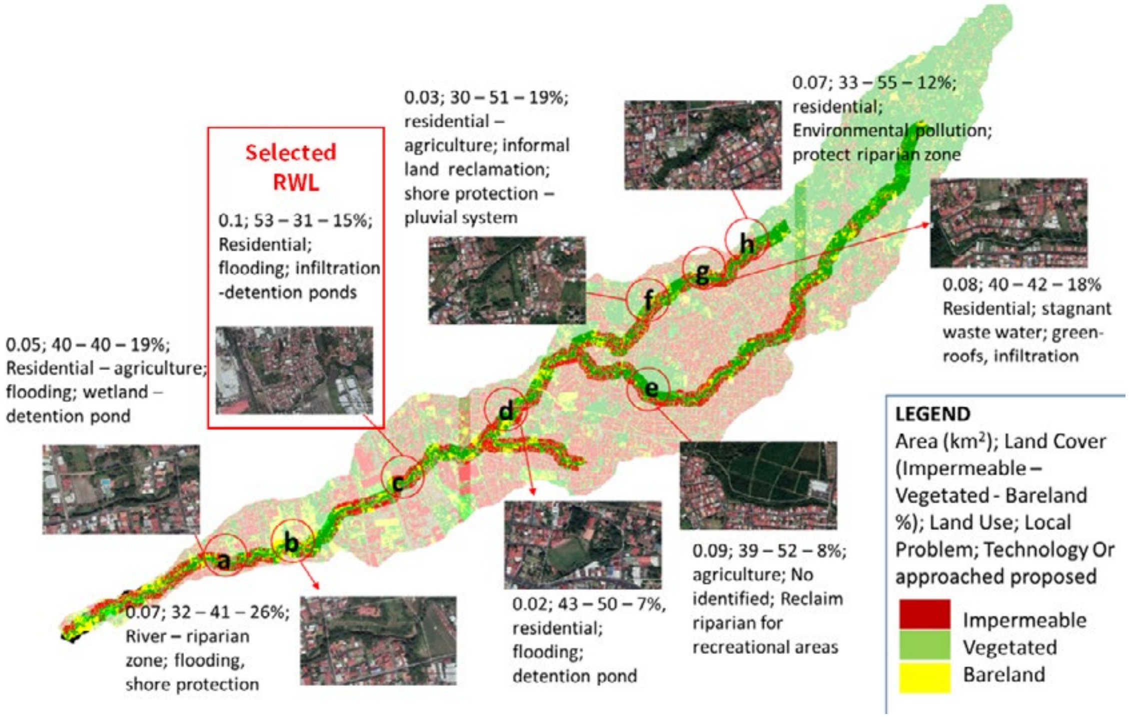


Figure 4.1. Summary and location of proposals presented by the municipalities during the Real-World Lab (RWL) selection process.

(area, land cover distribution, land use, problem to be addressed, and NbS type), as well as the preferred NbS types, is presented in Figure 4.1.

SEE-URBAN-WATER used a Real-World Lab in Costa Rica to plan, design and implement Nature-based Solution prototypes in a transdisciplinary manner.

Four municipalities submitted proposals (two from each one, for a total of eight), all of which proposed deploying the RWLs along the river. Land cover distributions for the suggested RWL locations ranged between 30-50%, 31-55%, and 7-26% for impermeable, vegetated and bare-land cover, respectively. Furthermore, seven proposals indicated public spaces as potential sites, arguing suitability and feasibility reasons. In general, proposals were based on a combination of NbS measures to be developed during interventions along riparian corridors or when vacant areas became subject to urbanization.

In assessing the proposals, the SUW team perceived notable differences in the objectives that upstream and downstream options were supposed to fulfil. For instance, three downstream proposals (a-c in Figure 4.1) highlighted the need for flood control measures, whereas the upstream ones (e-h, Figure 4.1) targeted recreational use and protection of the riparian zone. Furthermore, the NbS types proposed by the four municipalities considered only their implementation on vegetated or vacant land, except in one case where a stormwater control measure was proposed along the streets. While there was not a preferred NbS type, suggestions included constructed wetlands, detention ponds or infiltration trenches. Proposed riverside NbS alternatives constituted measures aimed at mitigating negative effects along the river by making the most of the available space while avoiding impacting existing urban development. Nevertheless, end-of-pipe solutions continued to shape the preferences of local decision-makers in the study area as flood control measures.

The participatory approach culminated in one of the RWL proposals from Flores, a municipality situated in the Llorente District, being selected. This result was particularly appealing to the SUW team due to the municipality's level of engagement and keen interest in retrofitting NbS in public space.

Furthermore, the Flores municipality was eager to work together with local associations, such as the Integral Development Association (ADI, Spanish acronym), local community groups, the Ministry of Environment and Energy (MINAE, Spanish acronym), the Public Service Company of Heredia (ESPH, Spanish acronym), the Costa Rican Institute of Aqueducts and Sewers (AyA, Spanish acronym), and the Ministry of Housing and Human Settlements (MIVAH, Spanish acronym). This was key to a successful long-term implementation and a better distribution of monitoring and maintenance responsibilities.

The urban regulatory plan of the Flores municipality contained criteria for resilient territorial planning and the sustainable management of resources, and thus in line with alternative urban water management strategies such as NbS.

Guías Verdes

For more information on the process of selecting a representative area for exploring green infrastructure implementation, please refer to the 'Selección de un área experimental para la implementación y promoción de prototipos de infraestructura verde' guideline (only available in Spanish).

The participatory approach with its transparent and standardized methodology based on proposal forms proved to be very effective for the selection and establishment of a Real-World Lab in a study area without previous collaboration with a partner. The proposals for RWL sites in different parts of the watershed provided important insights into the problems related to sustainable water management as perceived by the participating stakeholder groups (decision-makers). For the ensuing work in the selected RWL, the proposal generated a sense of ownership among the stakeholders and promoted a mutual understanding and commitment for a common cause.

For more information about the selection process of the Real-world Lab of SUW please refer to:

Chapa, F., Pérez, M., and Hack, J. (2020). Experimenting Transition to Sustainable Urban Drainage Systems—Identifying Constraints and Unintended Processes in a Tropical Highly Urbanized Watershed. Water, 12(12), 3554. https://doi.org/10.3390/w12123554.

Pérez Rubi, M. and Hack, J. (2021). Co-design of experimental nature-based solutions for decentralized dry-weather runoff treatment retrofitted in a densely urbanized area in Central America. Ambio, 50(8), 1498–1513. https://doi.org/10.1007/s13280-020-01457-y.

Neumann, V. A. and Hack, J. (2022). Revealing and assessing the costs and benefits of nature-based solutions within a real-world laboratory in Costa Rica. Environmental Impact Assessment Review, 93(106737). https://doi.org/10.1016/j.eiar.2022.106737.

4.2. SEE-URBAN-WATER Real-World Lab in Llorente, Flores, Costa Rica

The selected Real-World Lab (RWL) represents a densely urbanized residential area (Figure 4.2) composed of four neighborhoods, Los Ángeles, Año 2000, Siglo XXI and El Rosario, located within the Quebrada Seca-Río Burío (QSRB) watershed in the Llorente District, itself part of the Flores municipality. This RWL presents largely identical challenges to those found throughout the QSRB watershed: flood vulnerability, riverbank instability and scouring, water quality degradation, insufficient solid waste disposal, and loss of green areas due to urban intensification. These problems are also common to most of the watersheds in the Greater Metropolitan Area of San José (Oreamuno Vega & Villalobos Herrera 2015). Moreover, continuous greywater runoff flowing through the stormwater drainage infrastructure is discharged untreated into the Quebrada Seca River.

The Real-World Lab as a key methodological approach was the starting point for all subsequent SUW activities.

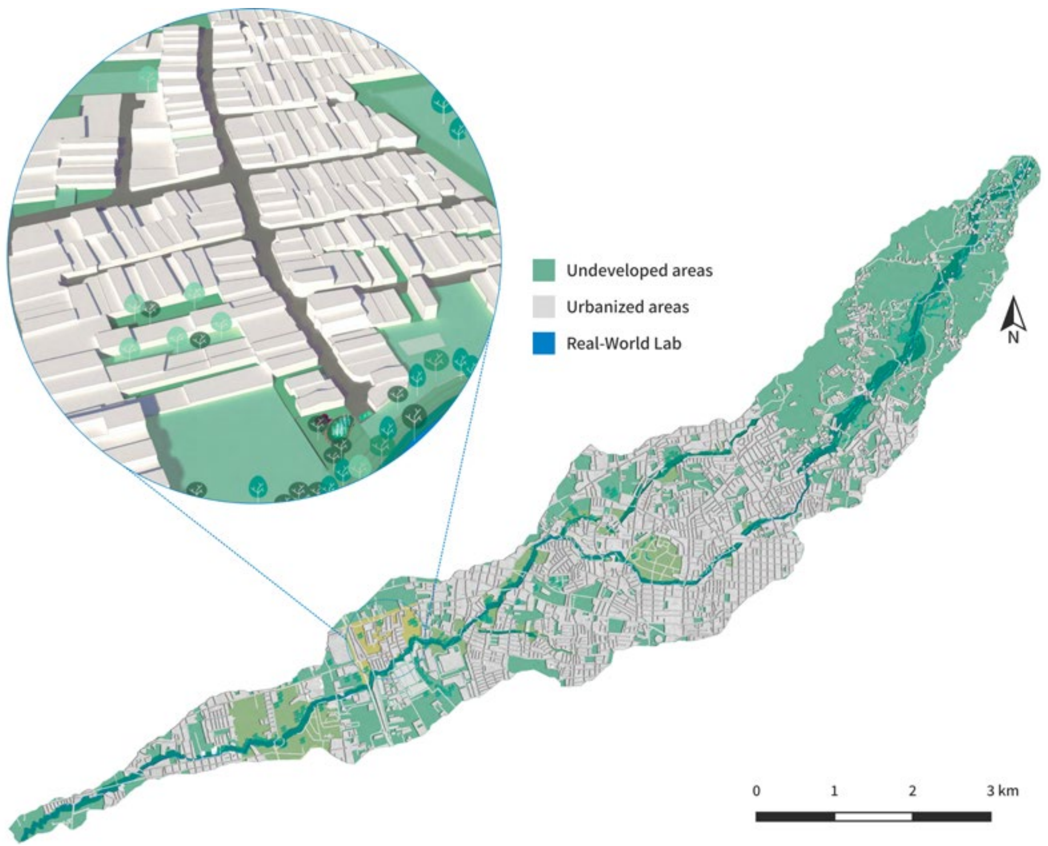


Figure 4.2. Location of the SEE-URBAN-WATER Real-World Lab in the Quebrada Seca-Río Burío watershed, Greater Metropolitan Area of San José, Costa Rica.

INFO

Real-world Laboratory in Llorente, Flores

- Name of the Neighborhoods: Los Angeles, Año 2000, Siglo XXI, El Rosario
- Total area: 0.33 km^2
- Residential areas: 59%
- Houses: 697
- Population: 2500 Approx.

Geospatial characterization and hydrological-hydraulic monitoring in the Real-World Lab

Geospatial assessments, fieldwork, and rainfall and flow rate monitoring were conducted to better understand the specific biophysical, hydrological and hydraulic features of the selected RWL. For instance, the RWL spatial distribution was defined employing a Land Use/Land Cover (LULC) classification, following a high-resolution imagery classification methodology (See Section 2.1). We retrieved satellite imagery from Google Earth Pro 7.3.3 © for the year 2020. Impermeable areas (i.e., buildings and streets), vegetation (i.e., trees, shrubs, and open grass spaces), and bare land (i.e., vacant land) were selected as LULC classes. Furthermore, fieldwork was used to survey the local topography and existing infrastructure, i.e., household-level greywater discharge systems, stormwater drainage systems, open spaces and the road network. The local municipality provided a digitalized georeferenced database of lots, used to distinguish between private and public spaces.

To characterize the local hydrology, a tipping-bucket rainfall collector (Hobo® RG3, Onset, U.S.) with a resolution of 0.2 mm was installed in the study area. Rainfall was monitored for one year, including the 2019 wet season. In addition, precipitation data for the three previous years was obtained from two nearby meteorological stations (part of Belén's municipal Early Flood Warning System, see Section 3.2), positioned 1 km upstream and 1 km downstream of the RWL's tipping-bucket rain gauge. These stations were also equipped with tipping-bucket rain gauges, providing precipitation data at 5-minute intervals and 0.2 mm resolution. Furthermore, five residents participated in collecting rainfall data using simple rain gauges. They were trained in their correct use before the gauges were installed in open space in their backyards. Whenever it subsequently rained, they diligently took a photo of the accumulated volume within the rain gauge and sent it via instant messaging to the SUW team. This data was used to validate the automatic rain gauge.

Finally, greywater and stormwater flows were monitored using an ultrasonic flow sensor (PCM PRO®, Nivus, Germany) providing water depth records

Guías Verdes

For more information on how to install, maintain and use a hydrological monitoring station, while involving local stakeholders in its set up and operation, please refer to the following guidelines (only available in Spanish):

- Instalar, mantener y usar una red de monitoreo hidrológica.
- Involucramiento de actores locales durante la instalación y operación de una red de monitoreo hidrológica.

at 2-min intervals. This sensor was installed (Figure 4.3) in the upstream sewer of the Quebrada Seca River's outfall (2 m after the last manhole junction). The flowmeter uses both hydrostatic pressure and ultrasonic sensing techniques to obtain flow level measurements. To capture flow velocity, it uses an ultrasonic cross-correlation method and digital pattern detection. Since this method is based on ultrasound reflection, it is critical for the system to operate properly, taking account of particles in the water capable of reflecting the ultrasonic signal sent by the sensor (dirt particles, gas bubbles, or similar substances). It calculates the flow rate (l/s) based on the flow velocity distribution, flow level, and sewer pipe shape and dimensions.

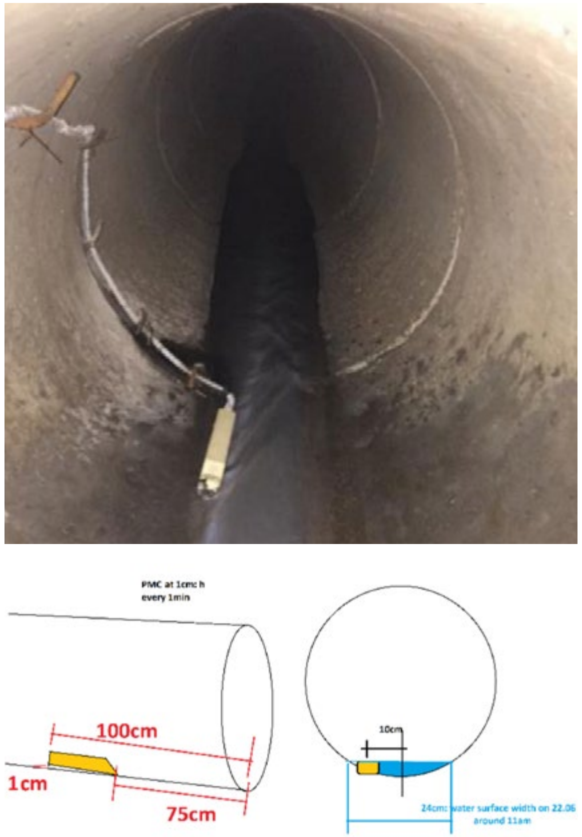


Figure 4.3. Ultrasonic flow sensor installation in a pipe of the drainage system in the Real-World Lab.

Monitoring data from Real-World Lab used in watershed modeling

The geospatial characterization and hydrological-hydraulic monitoring in the Real-World Lab served as baseline data for calibrating and validating several models and analyses at the watershed scale (Chapter 5).

For more information about LULC, monitoring and results please refer to:

Chapa, F., Pérez, M., and Hack, J. (2020). Experimenting Transition to Sustainable Urban Drainage Systems—Identifying Constraints and Unintended Processes in a Tropical Highly Urbanized Watershed. Water, 12(12), 3554. https://doi.org/10.3390/w12123554.

Bonilla Brenes, R., Morales, M., Oreamuno, R., and Hack, J. (2023). Variation in the hydrological response within the Quebrada Seca watershed in Costa Rica resulting from an increase of urban land cover. Urban Water Journal, 20(5), 575–591. https://doi.org/10.1080/1573062X.2023.2204877.

Towsif Khan, S., Chapa, F., and Hack, J. (2020). Highly Resolved Rainfall-Runoff Simulation of Retrofitted Green Stormwater Infrastructure at the Micro-Watershed Scale. Land, 9(9), 339. https://doi.org/10.3390/land9090339.

4.3. Assessment of the potential for implementing Nature-based Solutions

As a fundamental principle for implementing an efficient Urban Green Infrastructure (UGI), multifunctionality addresses a wide range of social and environmental concerns, as well as providing economic benefits encouraging the sustainable development of the place in question. Therefore, to assess the Real-World Lab (RWL) potential for implementing a multifunctional UGI, consisting of a broad variety of individual Nature-based Solutions (NbS), a four-step methodology (Figure 4.4) was developed and applied in the Real-World Laboratory.

The methodology enables a comprehensive planning and design process for Urban Green Infrastructure, taking into account its potential multifunctionality.

Evaluation of the spatial properties and distribution of the study area reveals specific context-related opportunities for multifunctional UGIs as well as the potential constraints hindering their successful implementation. Envisaged as the basis for multifunctional UGI implementation, Step 1 therefore includes a land-use distribution assessment, i.e., areas occupied by buildings, sidewalks, the road network and green spaces (both public and private), as well as the local topography and drainage system delineation.

In Step 2, the design criteria and placement strategies to achieve different dimensions of multifunctionality are defined (Figure 4.5). In this step, hypotheses, priorities and suggestions for the design process are formulated, supported by the findings of Step 1. Due to the multifunctional character of UGIs, many different design criteria or priorities can be established, such as stormwater management, biodiversity enhancement, urban heat island reduction, air quality improvement, social cohesion strengthening, or recreational or educational uses.

Design criteria and placement strategies as integrated in the SUW suitability methodology for UGIs facilitate a truly multifunctional planning and performance assessment.

In Step 3, spatial typologies for different UGIs are formulated, considering a portfolio of suitable locations based on the site analysis in Step 1. Various scenarios can be proposed by considering the

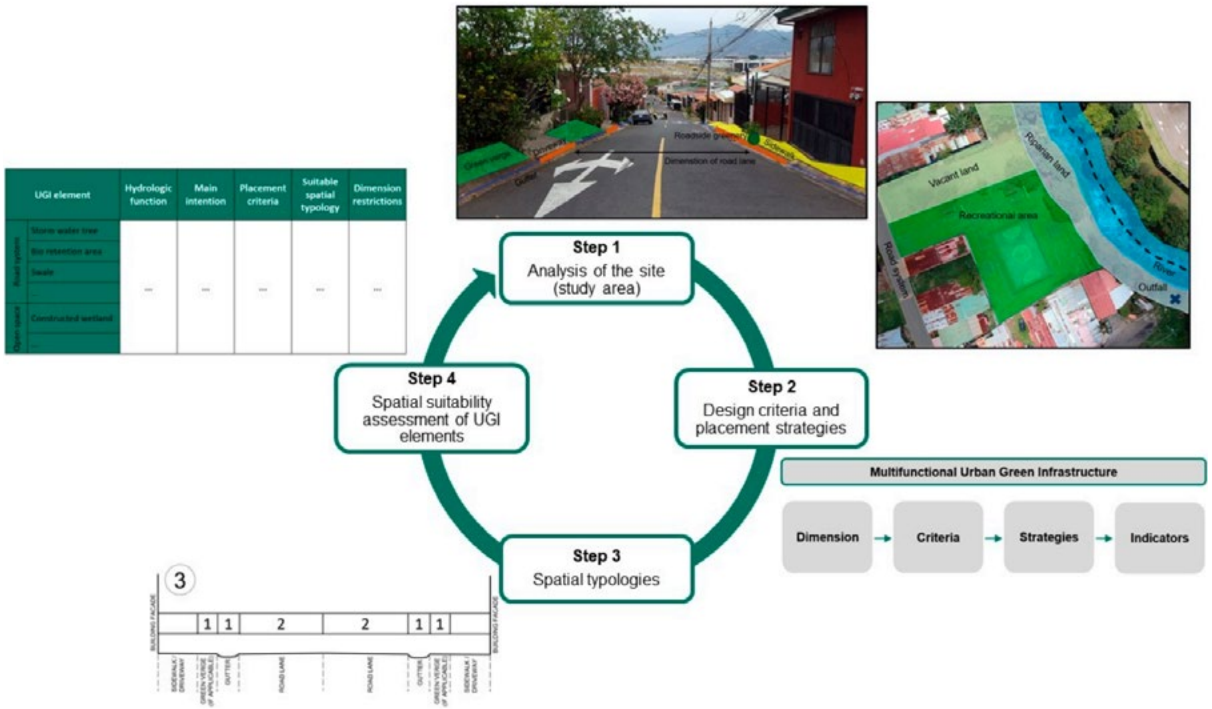


Figure 4.4. Methodological steps to assess the placement potential of multifunctional Urban Green Infrastructures (UGIs.)

characteristics of open green spaces or the dominant road network, such as street dimensions and traffic volume. Depending on the available information, further criteria can be added. This step includes a review of possible UGI elements to understand their functions and select those most suitable for the particular area. Furthermore, dimensioning and placement constraints are determined by the site characteristics assessed in Step 1 and the design parameters recommended for individual UGI elements (e.g., the maximum area to be drained). For instance, the minimum space requirements of specific UGI elements needed to improve the local hydrological performance can be determined based on the targeted storm event.

As a result, design proposals are developed, including specific suggestions for placement, dimensions and technical configurations, as part of Step 4. Figure 4.6 illustrates the result of Step 4 for potential stormwater tree placements, while Figure 4.7 shows the potential locations for different UGI types. In turn, Figure 4.8 displays the proposed roadway redesign for the integration of green infrastructure with the built environment.

Real-World Lab spatial typologies used in watershed modeling

Steps 3 and 4 of the methodology were the basis for assessing the UGI implementation potential in other parts of the watershed, leading to corresponding UGI implementation scenarios that could be modeled and compared to the Status quo (Section 5.1).

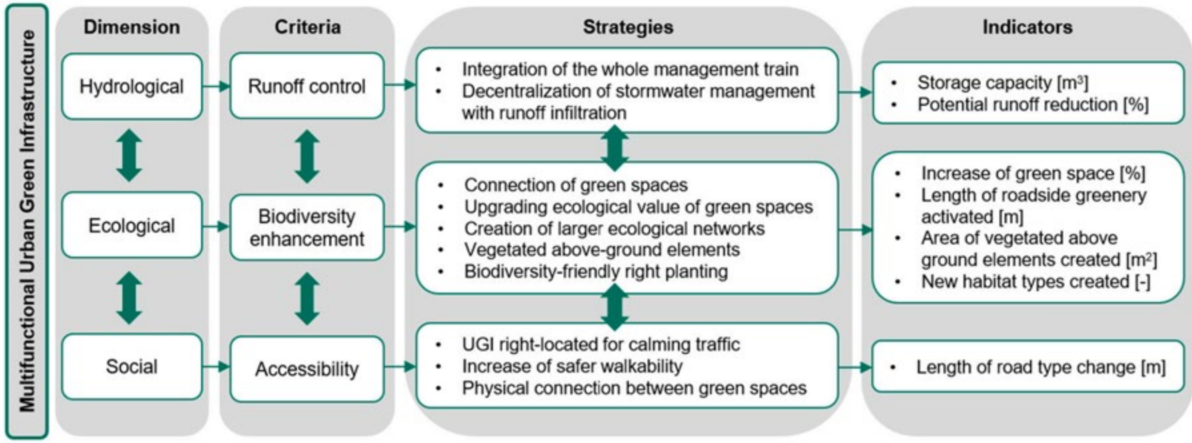


Figure 4.5. Dimensions, design criteria and placement strategies for assessing the implementation of multifunctional Urban Green Infrastructures.

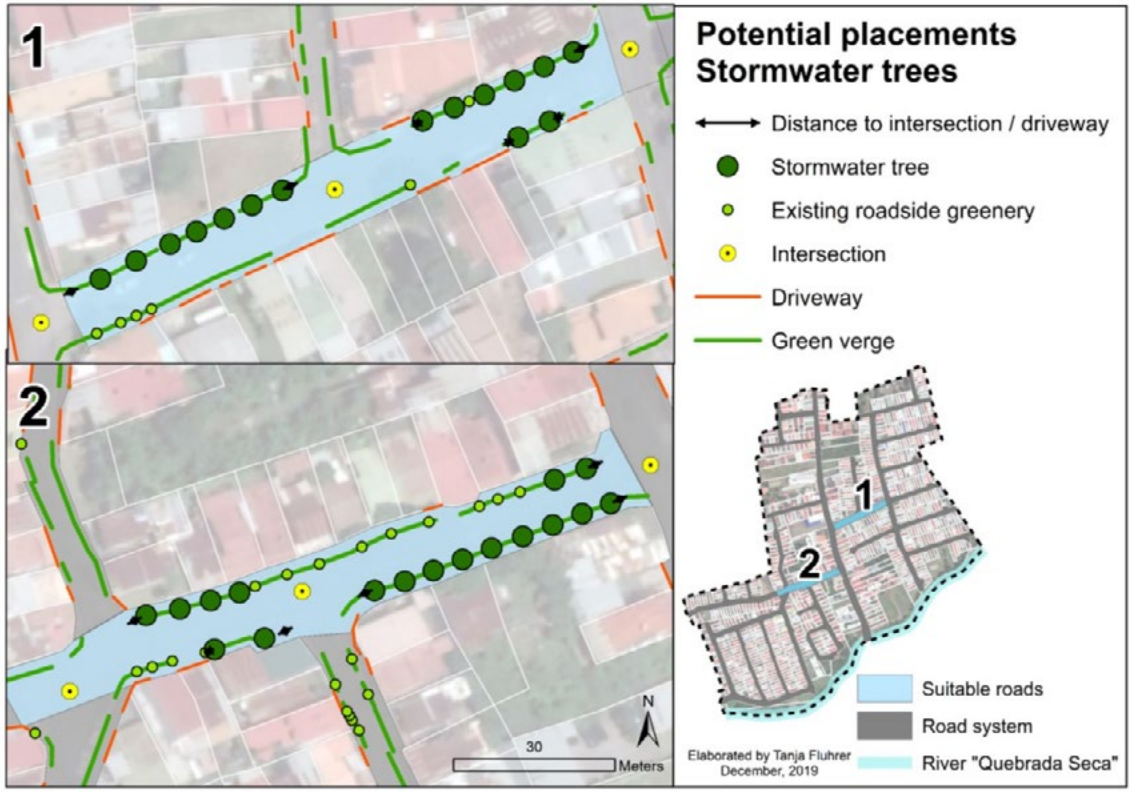


Figure 4.6. Potential locations of stormwater trees along two main roads in the Real-World Lab.

For more information about this methodology please refer to:

Fluhrer, T., Chapa, F., and Hack, J. (2021). A methodology for assessing the implementation potential for retrofitted and multifunctional urban green infrastructure in public areas of the Global South. Sustainability (Switzerland), 13(1), 1–25. https://doi.org/10.3390/su13010384.

As previously mentioned, the described methodology was applied to the four RWL neighborhoods in the Llorente District. The results showed the great potential for enhancing local conditions across multiple aspects by implementing UGI. At the hydrological level, for instance, a reduction potential of up to 34% in surface stormwater runoff was calculated. Ecological aspects could be improved through increasing green space by 2.2% and creating 1500 m of roadside greenery, along with two new habitat types. Moreover, 2200 m of road could potentially be upgraded, providing more pleasant spaces to the community and thereby enhancing socio-cultural dynamics. The proposed methodology can guide local planners and decision-makers in UGI implementation at the neighborhood scale. An analysis of local conditions and site-specific design criteria can help amplify the multifunctional benefits of UGIs. If UGI elements are to be successfully implemented in a densely urbanized area, careful account must be taken of the interdependence of the different aspects of multifunctionality and other urban functions in the design process. Considering all dimensions of multifunctionality requires a structured and strategic approach.

Potential UGI sites in Real-World Lab analyzed in micro-climate modeling

The results of this assessment served as the basis and input for modeling and analyzing ways of mitigating the heat island effect through implementing different UGIs scenarios (Section 5.2).

Many ecological and social challenges in urban areas of tropical countries in the Global South could be addressed with engineered UGI elements. These

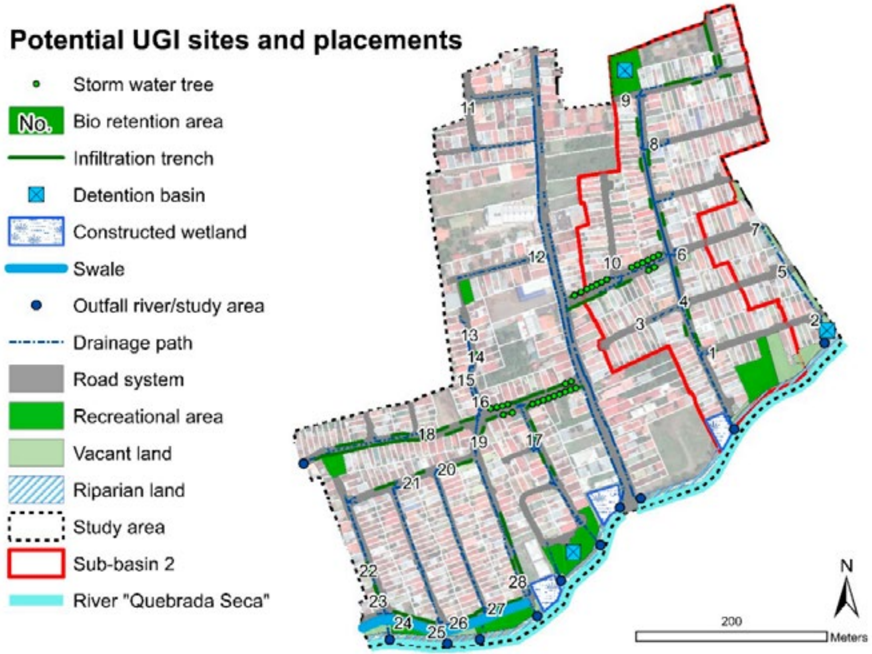


Figure 4.7. Potential placement of UGIs in the RWL, numbers 1-28 show suitable locations for bio-retention areas.

Figure 4.8. Proposal for a redesign of the road system in the RWL to integrate green areas and improve the social dimension of UGI multifunctionality.

strategies may help alleviate the constraints of existing drainage systems, combat flooding, reduce urban sealing, establish new public green recreation areas, mitigate the heat island effect, support other traffic participants such as pedestrians, and reduce the pollution load of untreated greywater. Thus, the UGI concept offers many possibilities beyond the hydrological aspect. UGI elements may become an integral part of spatial planning and territorial development as they offer a better alternative to standard gray solutions by providing multiple functions.

UGI offers many benefits beyond hydrological, as an integral part of spatial planning a variety of urban challenges can be addressed, offering multifunctional green alternatives to conventional gray solutions

Nonetheless, greater clarity in administrative/institutional responsibilities and increased public participation constitute fields for improvement. Furthermore, social acceptance, the creation of local knowledge and sufficient budget are basic requirements for successful UGI implementation.

4.4. Co-design and implementation of Nature-based Solution prototypes

In the context of SEE-URBAN-WATER (SUW), the involvement of local stakeholders was a cornerstone of the transdisciplinary research approach and for designing and implementing Nature-based Solutions (NbS) prototypes. We intended to co-produce solutions adapted to the local context and able to contribute to solving existing problems. Though there are several ways to involve citizens in the design of these infrastructures, co-design is a special form of engagement we found suitable to develop in our project.

SUW co-produced Nature-based Solutions adapted to the local context and needs through a transdisciplinary co-design approach.

Definition of co-design

Co-design is a transdisciplinary process that involves a range of stakeholders in the creation, redesign or evaluation of a service or product (Polk 2015; Webb et al. 2018; Wilk et al. 2020). Experts and end-users are encouraged to participate in this process, thereby combining professional expertise with practical experience in problem-solving. There are no fixed step-by-step procedures for co-design applications. Instead, Pearce (2020) and Steen (2013) have argued that co-design is a collaborative design-thinking process in which problems and solutions are iteratively reframed.

INFO

A co-design process, as a collaborative and participatory approach, helps to:

- better understand local (problem) perceptions and transformation preferences, forms of social organization, and power relations;
- effectively engage and enter into exchanges with residents;
- co-produce knowledge on NbS planning and design;
- identify suitable types and placements of NbS prototypes and UGI potential in the neighborhood;
- inform about and promote sustainable transformations; and
- gain acceptance for prototype planning, design and construction.

The term co-design itself is a compound term of “co” and “design”, which can be understood as a collective shaping. When transferred to the implementation of NbS and Urban Green Infrastructure (UGI), the co-design process allows academics and practitioners to work in a transdisciplinary manner. In most cases, the experts seek the support of stakeholders from the economic sector and civil society. Through the integration of knowledge, it is believed that co-design results in significantly better outcomes, ensuring

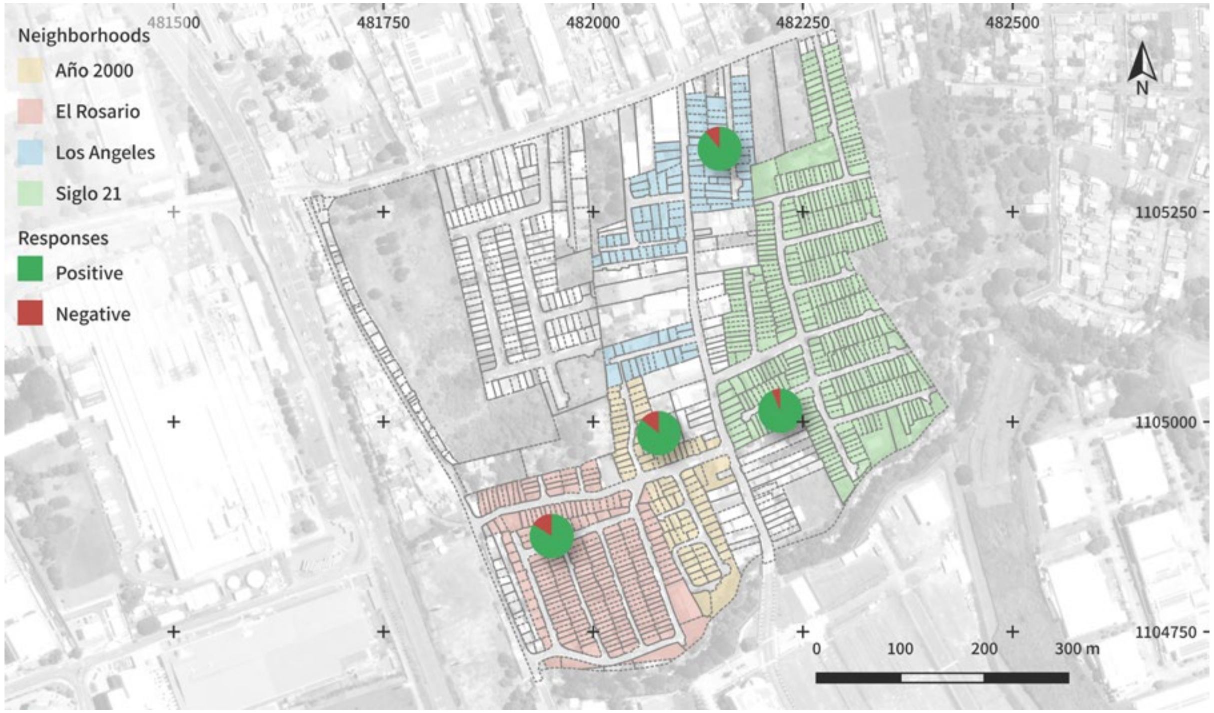


Figure 4.9. Results of 154 interviews carried out in the four Real-World Lab neighborhoods on the question: "Would you like to increase green areas in your neighborhood?". The Siglo XXI neighborhood had the highest percentage of positive responses.

a project's sustainability. In addition, if residents themselves formulate their demands for a sustainable city, they become more sensitive to this topic and to possible solutions.

When co-designing a NbS, local residents should ideally be consulted since they can contribute their preferences, experiences, and knowledge of socio-environmental elements potentially affecting the co-design process and implementation.

Co-design of NbS prototypes in the Siglo XXI neighborhood

For the SUW project, the co-design process focused on developing NbS prototypes able to be realistically implemented. One of the four pre-selected Real-World Lab (RWL) neighborhoods had to be chosen as the area for implementing the prototype. To assess social acceptability and public perceptions thereof, we conducted 154 interviews with citizens of the RWL, exploring their receptiveness and willingness to include urban greenery in their surroundings (other factors – such as location and design preferences – also gleaned in these interviews are addressed in the next section: "Co-design factor 3"). The results of this participatory approach (Figure 4.9) were evaluated in conjunction with the previously identified potential for NbS implementation and their spatial suitability in the RWL, described in Section 4.3. Consequently, the SUW team narrowed down the choice of a neighborhood for co-designing NbS prototypes to Siglo XXI.

SUW kicked off the stakeholder engagement process with governmental stakeholders, NGOs and interested citizens at watershed level, aiming to understand the problem context and framing. Governmental stakeholders were identified as the main decision-makers for NbS in public spaces.

The selected implementation area (area marked green in Figure 4.9) is delimited in such a way that the drainage system does not drain into other tributary areas, i.e., it is a closed drainage area with a single outfall to the Quebrada Seca River. This allowed us to analyze the hydrology of the densely urbanized residential area using high-resolution precipitation data and detailed flow discharge measurements, in turn facilitating the calibration and validation of hydrological and hydraulic models. These models were used to gain a better understanding of runoff generation within the area and the discharge dynamics into the river under the status quo scenario. They were also used to estimate the effects of different prototype designs. This setting also enabled an evaluation of the post-construction impacts of the prototypes.

The co-design of the NbS prototypes was achieved by engaging potential users and/or those potentially impacted by the outcomes of the NbS to be implemented (Figure 4.10). In this case, local residents played a key role as they were likely to be the end-users or beneficiaries of any NbS prototype. They were considered as experts owing to their experience and perceptions shaped by the local environment. Practitioners were also involved in the co-design, including representatives from local government, the water supply company, central government institutions and universities.

As daily users of NbS, residents can provide valuable insights into how they perceive and desire their surroundings. This information helps adapt NbS functionality and design to the local context. In SUW's research, local communities were considered important collaboration partners and resource providers for the subsequent project phases.

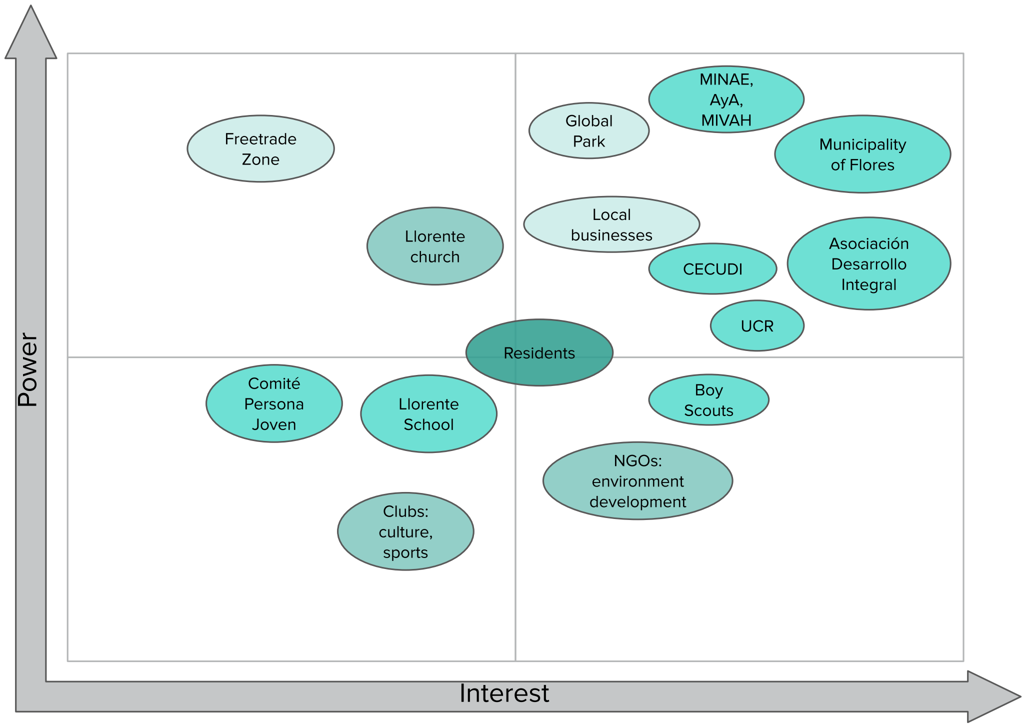


Figure 4.10. Stakeholder analysis for the Real-World Lab in Llorente, Flores.

Under the transdisciplinary framework, the contributions of academics from different disciplines and non-academic actors, i.e., local stakeholders, were systematically integrated throughout the co-design process. Moreover, field visits and an intensive exchange with them were the initial steps for identifying and understanding the particular challenges. This multi-stakeholder approach was employed to collect, analyze and synthesize information on local concerns and gain insights into key aspects to be taken into account when developing potential solutions.

Guías Verdes

For more information on how to identify and assess the level of interest of relevant stakeholders in the NbS planning and implementation process, please refer to the 'Mapeo de actores revelantes' guideline (only available in Spanish).

Co-design factors

Since SUW studied the applicability of NbS for sustainable water management in urban areas, the co-design process implemented in the RWL was based on the analysis of three co-design factors (Figure 4.11): the urban landscape configuration, the existing drainage configuration and social acceptance. The evaluation of these factors provided key information, i.e., design inputs, for determining the final functionality, dimensions and placement of the site-adapted Nbs prototypes.

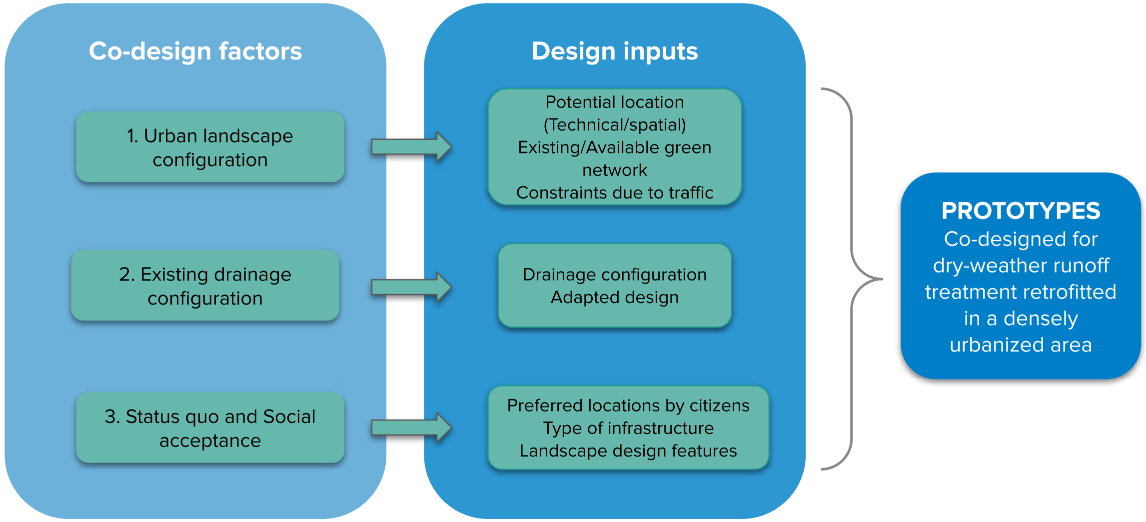


Figure 4.11. The three co-design factors analyzed during the SUW co-design process.

For more information about the co-design process of SUW please refer to:

Pérez Rubi, M. and Hack, J. (2021). Co-design of experimental nature-based solutions for decentralized dry-weather runoff treatment retrofitted in a densely urbanized area in Central America. Ambio, 50(8), 1498–1513. https://doi.org/10.1007/s13280-020-01457-y.

Co-design factor 1: Urban landscape configuration

Potential sites for implementing NbS for urban water management were undeveloped areas with various types of unsealed/green surfaces such as open spaces, green areas or road components. These were identified and classified using cadastral information provided by the municipality and field data measurements and observations. Figure 4.12 shows the spatial classification and identification of potential implementation sites in the Siglo XXI neighborhood. Recreational areas such as playgrounds and sports facilities, vacant land, riparian areas and unsealed surfaces of the road system were considered green areas. Along almost all streets, there is an existing green network of vegetated verges and roadside greenery, with widths varying from 0.3 to 0.5 meters. There are also two playgrounds designated as recreational areas to the north and south of the neighborhood and two vacant areas belonging to the municipality designated as public parks, near the

Figure 4.12. Existing land-use and road configuration in the selected Real-World Lab implementation site.

riverbank. Moreover, a green corridor runs along the river's riparian area. The analysis of this co-design factor allowed us to define and restrict the retrofitting of any NbS infrastructure to public areas. Therefore, two main constraints should be considered as input for the NbS design:

1. The current use and functionality of the public space should be preserved. For instance, green verges along the streets are potential locations for treatment NbS prototypes. However, these spaces are interrupted by house driveways.
2. The design of public areas must comply with national regulations, i.e., dimensions and functions cannot be altered.

Guías Verdes

For more information on how to characterize and identify the potential opportunities for green infrastructure prototype development, please refer to the 'Identificar el potencial para implementar infraestructuras verdes en un área urbana' guideline (only available in Spanish).

Co-design factor 2: The existing drainage system (greywater discharge and stormwater runoff)

The configuration of the existing drainage system, designed only for stormwater conveyance, was determined by field measurements and observations. Figure 4.13 shows the two stormwater drainage sub-basins in the Siglo XXI neighborhood and their outlets to the Quebrada Seca River. Furthermore, the location of every household's greywater outlet (i.e.,

Guías Verdes

For more information on how to identify the distribution and management of the existing stormwater and greywater control systems, please refer to the 'Identificar el sistema de escorrentía y sus características en el área de estudio' guideline (only available in Spanish).

Figure 4.13. Configuration of the existing drainage system in the Siglo XXI neighborhood.

effluents from kitchens, showers and washbasins) are indicated by gray dots.

The analysis of this co-design factor allowed the SUW team to map the existing drainage infrastructure and identify design possibilities for the NbS prototypes as runoff treatment systems, since gutters and pipes could be used to collect and convey greywater and stormwater as well as to temporarily store runoff.

INFO

Household greywater production: Theoretical calculation vs. Monitoring

Estimating greywater production is crucial for designing efficient NbS prototypes aimed at improving the quality of both household effluent and the receiving water body. To achieve this, the SUW team calculated the greywater production of the Siglo XXI neighborhood based on the total water consumption per day:

- Total water consumption per residential unit (survey data): 0.7 m^3/day
- Theoretical fraction of greywater production (66%): 0.5 m^3/day
- Greywater production in Siglo XXI neighborhood (322 residential units): 161 m^3/day

This result was then compared with greywater monitoring data obtained from an ultrasonic sensor installed at the outlet of the Siglo XXI neighborhood sewerage system sub-watershed. The monitored value was **173 m^3/day**, indicating a high level of reliability in the theoretical calculations of greywater production. This approach proves to be a significant advantage, especially in the absence of high-precision equipment.

Co-design factor 3: Status quo of water management in the RWL and social preferences for the implementation of NbS

Since the SUW's transdisciplinary research focus was on urban water management, we needed to identify both the formal and informal practices associated with this topic in the local context. This involved studying the prescribed methods for urban water management as defined by existing laws and regulations, as well as understanding the practical aspects of how they were actually implemented, not only in the framework of the RWL but also on the broader political-administrative scale of the municipality of Flores.

Referring to the current urban water management practice in the municipality as the "status quo", we used the Hydro-Social Contract method to analyze and understand it. We undertook a comprehensive evaluation of relevant documentation (including academic studies, research papers and policy frameworks) and conducted interviews with local experts and representatives from municipal authorities, NGOs and practitioners. This was complemented with semi-structured interviews with citizens and community/neighborhood associations belonging to the RWL. This participatory approach resulted in a better understanding of the local dynamics and the underlying causes of local water-related problems. With this as our basis, we identified the objectives to be achieved as well as the constraints to be overcome. This information was then used as input for the design of prototypes.

Formal urban water management (institutional roles and responsibilities)

In Costa Rica, there is no single body of regulation comprehensively governing the protection, extraction, use, management and efficient administration of water resources and wastewater. Instead, responsibilities for stormwater and wastewater management are fragmented across various entities at two territorial administration levels: national and municipal (local).

INFO

Wastewater management in Costa Rica

Over 70% of Costa Rican households dispose wastewater in septic tanks. It is estimated that only 14% of wastewaters receive proper treatment.

*Source: Costa Rican water utility AyA, Informe el AyA "Agua para consumo humano y saneamiento en Costa Rica al 2020: Brechas en tiempos de pandemia"

The cost of emptying a septic tank ranges between 140 USD and 270 USD.

For instance, stormwater management is a public task with well-defined responsibilities. Under the Organic Law of the Environment of Costa Rica, the mandate for stormwater management is exclusively assigned to local government, i.e., the municipalities. This responsibility includes the operation and administration of stormwater drainage systems, infrastructure maintenance, and developing investment projects to collect and convey rainwater to discharge points such as streams and rivers. The vision behind the existing stormwater network design was to quickly evacuate stormwater runoff without considering an integral approach with environmental variables. Furthermore, stormwater control is to a certain extent governed by national water or risk management policies.

As for wastewater management, the national water utility, the Costa Rican Institute of Aqueducts and Sewers (AyA, Spanish acronym), assumes competence for wastewater within its area of coverage, which is not the entire country. However, there is considerable ambiguity in the allocation of competences for municipal wastewater management.

"Status quo" of informal water management in the Real-World Lab

Interviews revealed that the way wastewater is managed is not clear-cut, with stakeholders preferring non-regulated operation. While in the long run the water supplier is required to connect households to a centralized wastewater treatment system (e.g., sewage treatment plant), since such infrastructure does not currently exist, it is a homeowner responsibility to properly dispose of wastewater. Septic tanks are the decentralized solution most commonly used by local residents. Wastewater is discharged into an underground septic tank on the property, which has to be emptied regularly by a licensed company that then transports the wastewater to a treatment facility.

When it comes to monitoring and controlling the correct treatment of wastewater, responsibilities are similarly not clearly defined. For example, there is substantial overlap between the scope of the Ministry of Energy and Environment (MINAE) and the Ministry of Health. On the one hand, the MINAE is the competent body "for regulating, monitoring and controlling the use of water bodies, including the disposal of wastewater"; on the other hand, the Ministry of Health is responsible for regulating, monitoring and controlling the wastewater discharge of industrial, commercial and service activities. This lack of clearly defined roles opens up potential gaps in management and governance, affecting the enforcement of the limited regulatory instruments.

Aside from the aforementioned factors, wastewater management is also affected by major financial constraints. For municipalities, community financing schemes do not allow for significant investments or higher water prices, as performance-based revenues cover only the supply of drinking water and stormwater management. In summary, the provision of extensive centralized wastewater infrastructure appears economically unmanageable and, under present conditions, is unlikely to happen in the RWL.

This circumstance is even more worrying because most RWL residents (low-income families) lack the financial resources and space to ensure adequate septic tank construction and maintenance. As a result, alternative wastewater management measures are required. The lack of employment opportunities has caused many families to add extra floors to their homes as an extra source of income, but without obtaining the corresponding building permits. The resulting increased wastewater production encourages people to circumvent the formal treatment regulations with a view to reducing the septic tank's emptying frequency. The most common practice is to concentrate blackwater in the septic tank and discharge the larger volume of greywater (i.e., from showers, kitchens and washing machines) into the stormwater drainage system's gutters. While this practice is illegal and may entail administrative sanctions up to the seizure of a property seizure (by law), enforcement is rare. Such discharge is the "normalized common practice", i.e., practiced by 100% of RWL households as shown in Figure 4.13.

The status quo in the Real-World Lab is that greywater is discharged into the stormwater drainage system. Though this is illegal, it is the common "normalized" practice.

The underlying causes of the practice of discharging greywater into road gutters include a lack of regulations and enforcement mechanisms, a lack of resources, and a preference for informal management. Our hydro-social contract analysis revealed a "blocked" status quo, with those involved either benefiting from the current situation, expecting disadvantages from any intervention, or not having the necessary resources to change the problem independently. As a result, no action is to be expected, despite the fact that the present situation pollutes the environment.

Our analysis of the status quo led to the definition of three primary needs and four constraints to be considered in the co-design of the NbS prototypes.

NEEDS

1. Effective solution for the problem: the solution ought to effectively reduce river pollution by filtering domestic greywater from kitchens and bathrooms (mainly involving soap residues, fats and food leftovers).
2. Reproducibility: The solution should have a positive impact on both the whole study area and the QSRB watershed. This represents a great opportunity to test the NbS prototypes at river basin level. The predominant urban design and housing scheme need to be considered in the design.
3. Clear responsibilities: The solution should contribute to resolving the current blocked status quo. Therefore, its implementation and maintenance should be managed by one single authority.

CONSTRAINTS

1. Lack of centralized treatment: due to the current status there is only a low probability of a centralized wastewater treatment solution being implemented in the near future. A decentralized solution would be suitable due to the clear responsibility for its management, i.e., by private citizens.
2. Lack of space: The current neighborhood's urban configuration considerably restricts the potential building area. The residents' properties are in most cases fully developed, leaving little room for implementing a solution without significant reconstruction.
3. Lack of resources for investment/ construction: This limits the scope/variety of technologies that could be implemented.

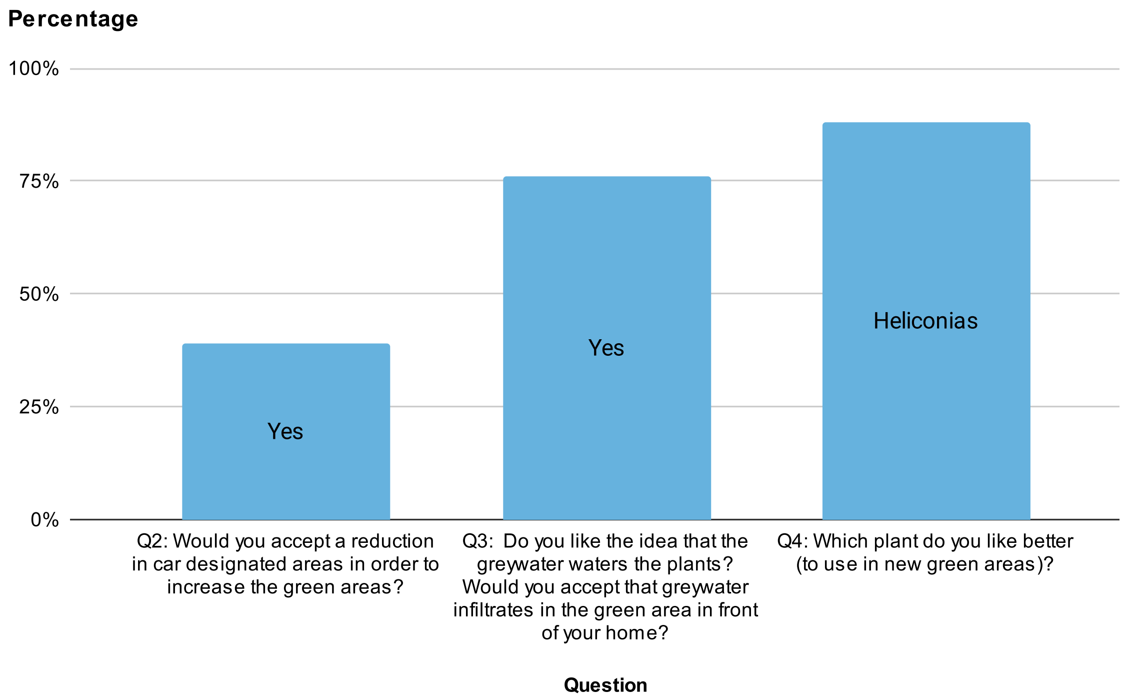


Figure 4.14. Results of 154 interviews exploring residents' perceptions and preferences for Nature-based Solutions prototyping in the Real-World Lab.

4. Lack of resources for maintenance: This limits the scope/variety of technologies that could be realistically sustained over time.

Once the general status quo was understood and the needs and constraints in the Real-World Lab were identified, 154 interviews (also mentioned in the previous section "Co-design of NbS prototypes in the area of implementation") revealed the social perception of RWL residents (Figure 4.14) in relation to:

- The level of approval for changing the street design to increase green areas in their neighborhood.
- Their willingness to implement a greywater treatment system in front of their homes.
- Preferred plant species in the NbS treatment system, either decorative (flowers) or reeds.
- Their willingness to allocate funds for wastewater treatment. The results showed that an average of 7 US$ per month could be invested by residents, with a medium-term payment period of 2 to 5 years.

Based on the findings of this survey, we concluded that most RWL residents were against changing both the current design and use of public space. However, there was general interest in increasing the amount of green areas in their neighborhood. They also perceive greywater as a resource to improve greenery. Hence, it was considered an approvable design opportunity to enhance green spaces by adding other functions such as the treatment of greywater.

TRANSDISCIPLINARY RESEARCH IN A REAL-WORLD LAB

As one of the activities concluding the SUW Research Project, we carried out a self-reflection of the project's main activities, focusing mainly on the co-design as a cornerstone of the project's transdisciplinary approach. We divided the co-design process into six phases (Figure 4.15), in line with the strategies for co-designing proposed by Pearce's (2020) "design-thinking" and the abductive stages for co-design by Steen (2013). In addition, to cover aspects related to the initial phase of the transdisciplinary project, we included a first phase based on the concept of "Phase 0" by Horcea-Milcu et al. (2022). This resulted in six consecutive phases, each related to the main activities carried out by the SUW team.

As a result of the self-reflection process, a Nautilus shape (Figure 4.16) was used as a graphical representation of the key interactions identified during the co-design process. Red arrows on the borders represent inputs ('drivers') controlled by the researchers. Considering these as external conditions guiding the project, they were

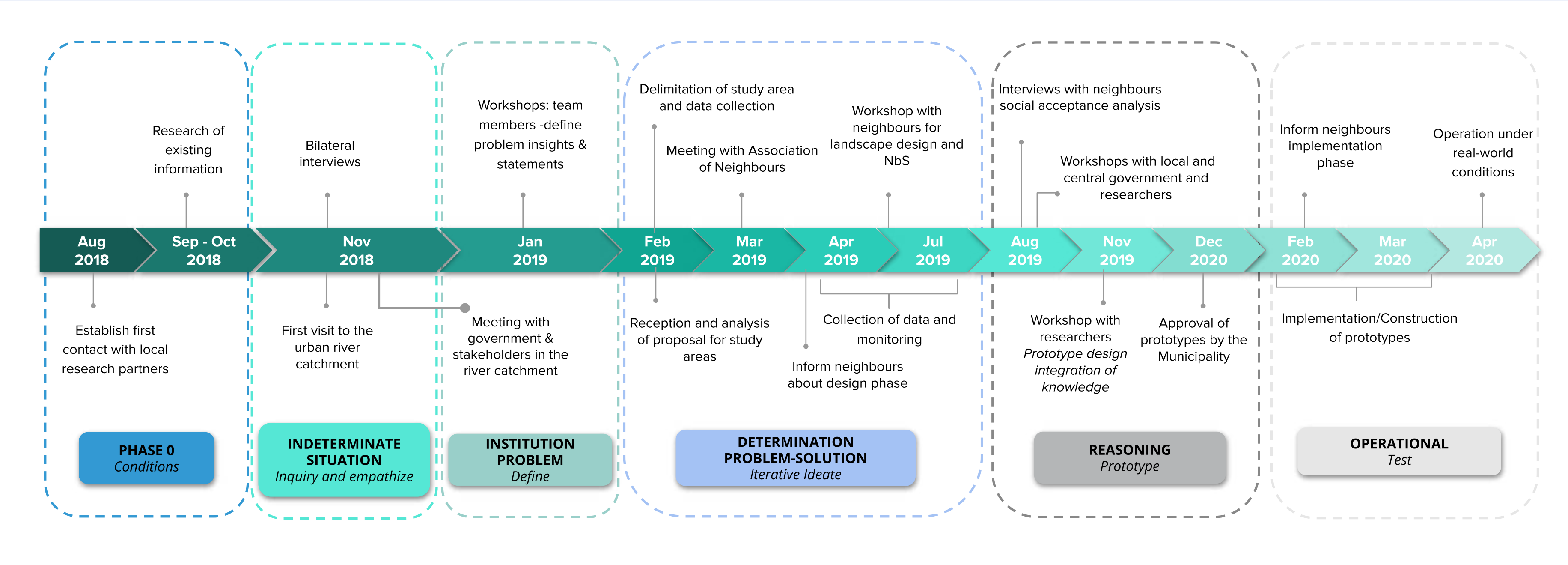
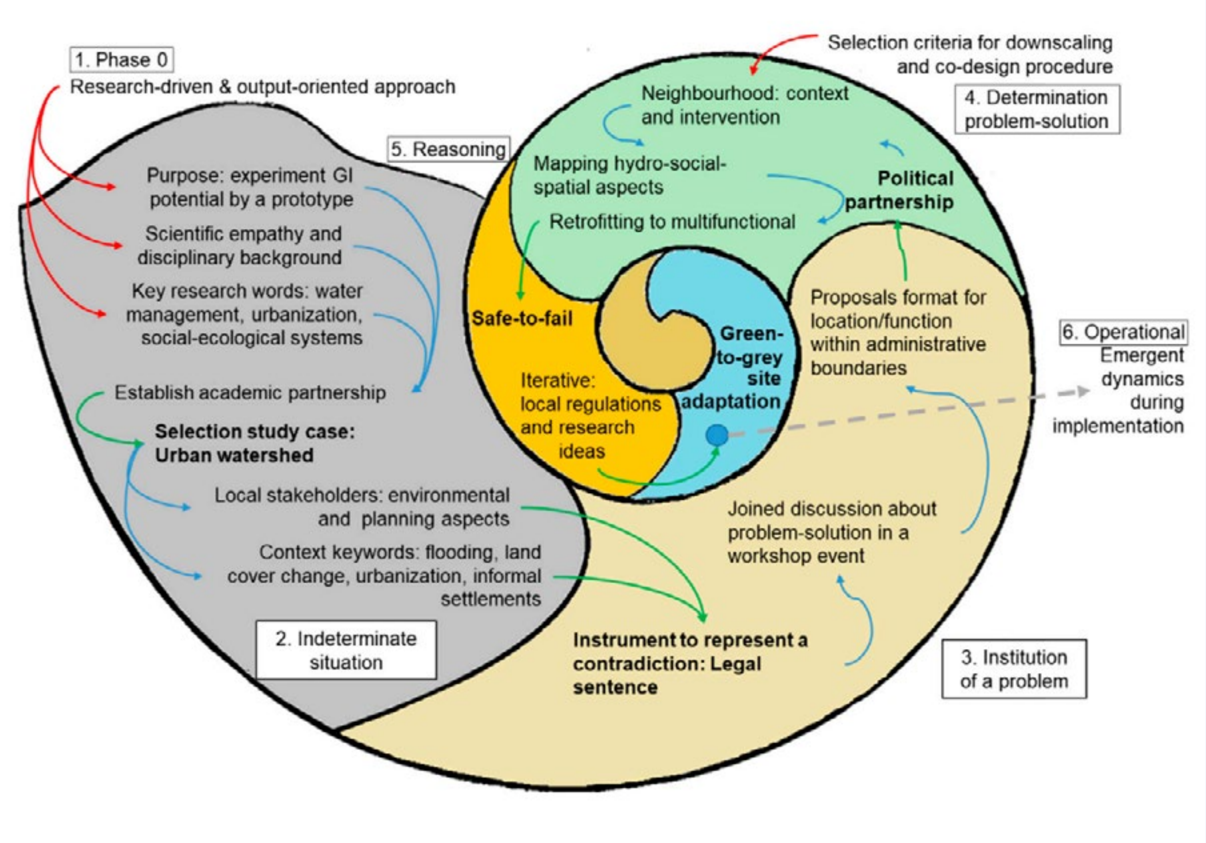


Figure 4.15. Main SEE-URBAN-WATER research activities associated with the conceptual co-design phases.

prominent during Phase 0 and in determining the problem–solution context. The first external driver is the research-driven approach which guided the messaging about including natural functions in the prototypes up to the downscaling activities, i.e., selection of a specific area for implementation. Once the partnership for implementing the prototype was established, a new driver emerged related to the selection criteria and co-design factors employed by the research team.

Internal green arrows represent inputs influenced by site-specific conditions. We concluded that these conditions steered the adaptation of the prototypes to achieve the research goal, i.e., to implement the prototypes. Each of those drivers determined the activities carried out during the co-design process and the final design of prototypes.



For further information on this self-reflection process please refer to:

Chapa, F., Perez Rubi, M., and Hack, J. (2023) A Systematic Assessment for the Co-Design of Green Infrastructure Prototypes—A Case Study in Urban Costa Rica. Sustainability, 15(3). https://doi.org/10.3390/su15032478.

Proposals for experimental prototypes – output of the co-design process

The co-design process culminated in the identification of suitable sites for implementing a set of NbS, presented in a catalogue of six site-adapted NbS prototypes (Figure 4.17). They were identified in an interdisciplinary workshop with local stakeholders and researchers, synthesizing all the information gathered in the year-long co-design process.

The six proposed prototypes were:

- Infiltration area in a public park.
- Bioretention areas in sidewalks.
- Hybrid system for stormwater retention and greywater infiltration at a micro-watershed scale.
- Rainwater harvesting system in a kindergarten.
- Urban farming in a public green area.
- Constructed wetland for greywater treatment integrated in the sidewalk – household scale.

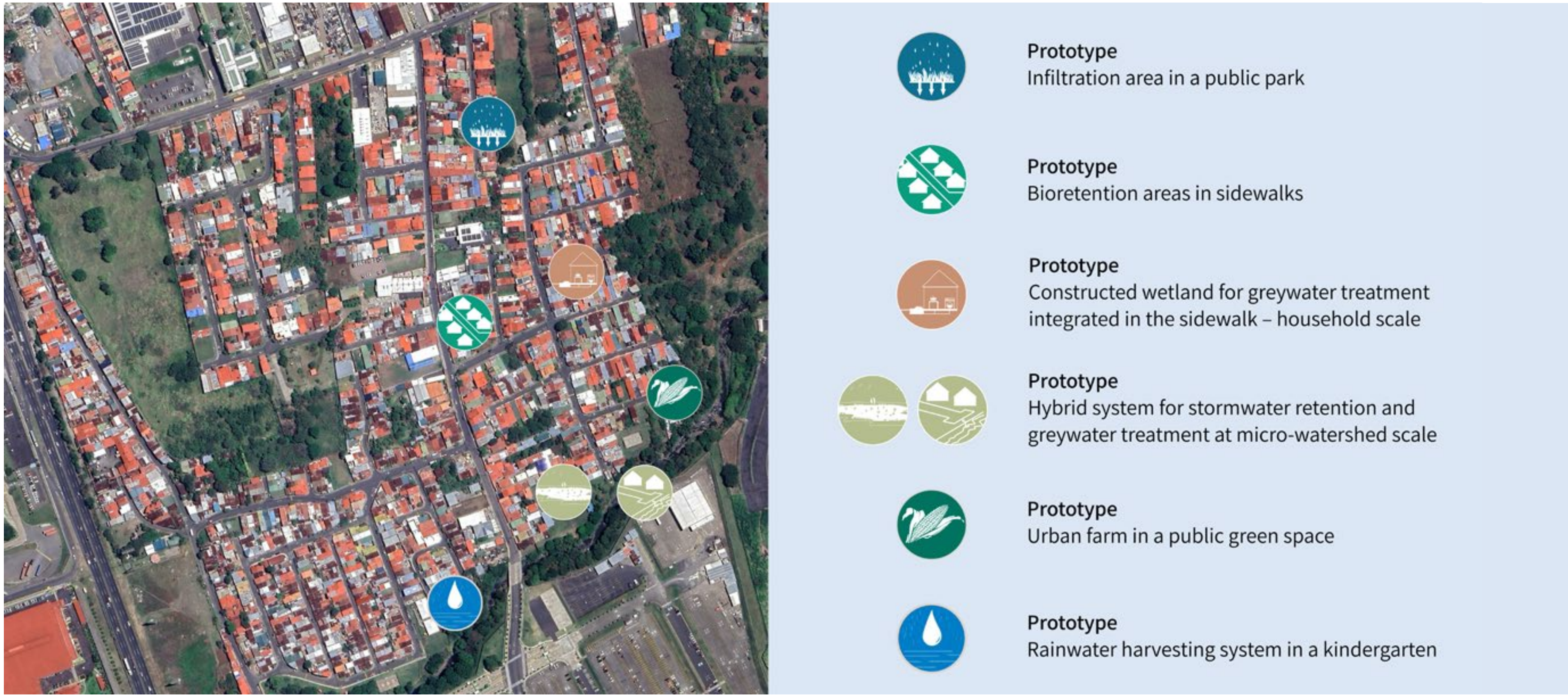


Figure 4.17. Location of the six Nature-based Solutions prototypes proposed at the culmination of the SEE-URBAN-WATER co-design process.


Aerial view of the area of implementation of prototypes in the neighborhood “Siglo XXI” in Llorente, Flores, Costa Rica.

INFILTRATION AREA IN A PUBLIC PARK

LOCATION

This prototype was designed as a runoff (stormwater and greywater) management scheme between the Siglo XXI micro-watershed and Parque Norte (Figure 4.18). The tributary area of the infiltration prototype accounts for 12% of the total micro-watershed area.

Figure 4.18. Tributary area (in yellow) and location (outlined in white) of the infiltration area prototype.

DESCRIPTION

This prototype has a shallow infiltration zone with a walkable surface (Figure 4.19), taking advantage of both a dead-end adjacent to a public park and its

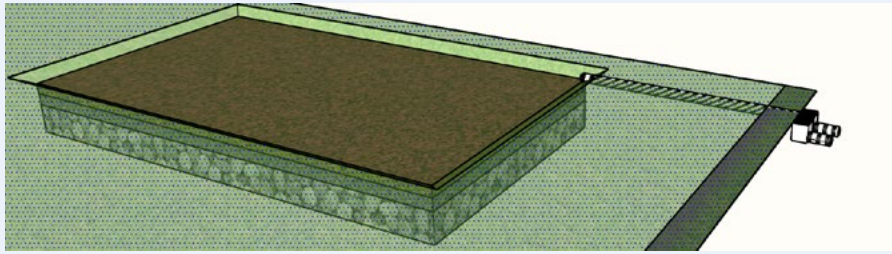


Figure 4.19. Schematic representation of the shallow infiltration zone, featuring a walkable surface as part of the prototype design.

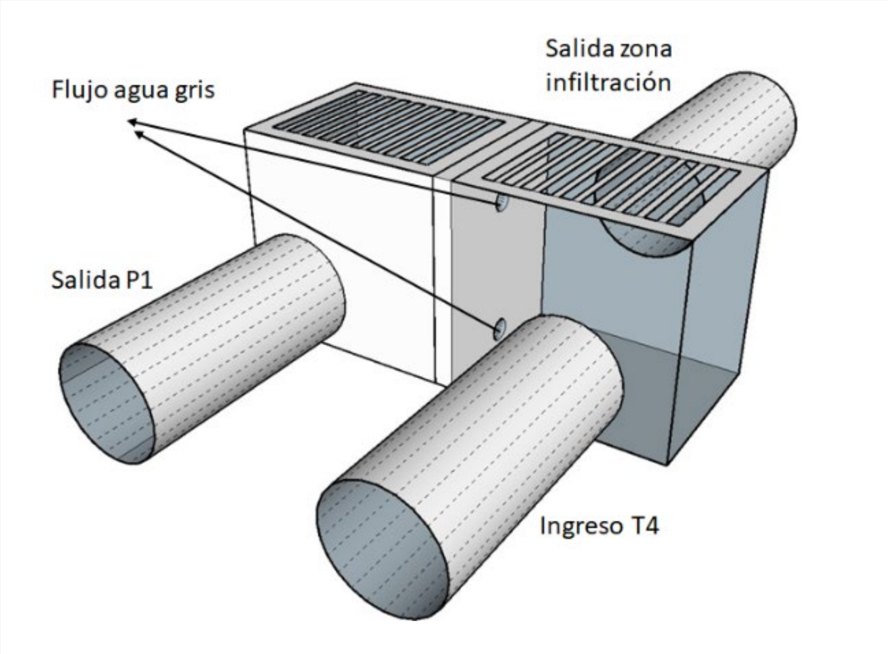


Figure 4.20. Proposed system for stormwater and greywater flows separation.

corresponding sidewalk. These are expected to be colonized by vegetation and transformed into public green spaces. The infiltration area is envisaged as a source control measure since large runoff volumes are not expected in this upper part of the micro-watershed.

TECHNICAL DETAILS

To ensure exclusive stormwater drainage in the planned infiltration area, catch basins 3 and 4 (in blue, Figure 4.18), which currently discharge both rainwater and greywater into manhole 1 (in red, Figure 4.18), are to be upgraded to separate these flows using two different-sized outlets (Figure 4.20).

Stormwater from catch basin 3 will subsequently be conveyed to the infiltration area through an excavated channel (depth (d)= 20 cm; width (w)= 15 cm; maximum length (max. l)= 10 m). We recommend filling the channel with pebbles (5-7 cm in diameter). In addition to conveying stormwater, this channel will also serve as a filter to prevent solids and sediments entering the infiltration zone.

Water in the proposed infiltration area (w= 4 m; l=20 m; max. d= 1.5 m, Figure 4.21) will slowly drain into the native soil. The top layer of concrete blocks provides a walkable surface (not appropriate for vehicles), as well as being ideal for a light coating of fertile soil.

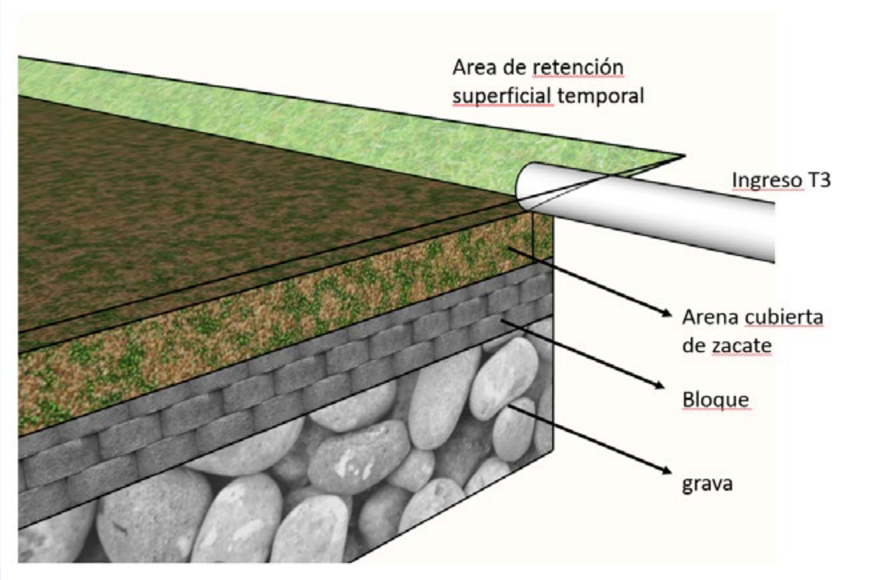


Figure 4.21. Layer distribution of the shallow infiltration zone.

STAKEHOLDERS INVOLVED

Municipality, community members.

EXPECTED BENEFITS

- Decentralized (source control) storm- and greywater management and treatment.
- Promotion of grass/opportunistic vegetation growth, therefore contributing to greening the urban landscape.

BIORETENTION AREAS IN SIDEWALKS

LOCATION

This prototype has a tributary area of approximately 23% of the Siglo XXI micro-watershed (Figure 4.22). The area is intersected by the “Urbanización Siglo XXI”, a major transit artery in the neighborhood. The area’s topography enables the efficient hydraulic transport of combined flows (greywater and stormwater).

DESCRIPTION

The aim of this prototype is to modify the course of the combined surface runoff currently flowing through the Siglo XXI drainage ditches. Including slight changes to these infrastructures, it capitalizes on the existing green spaces in the streets without impacting any of the current functionalities (e.g., pedestrian mobility, vehicle access). The prototype includes:

1. An experimental slow-paced conveyance system.
2. Stormwater infiltration areas.
3. Infrastructure for greywater retention and treatment.

TECHNICAL DETAILS

Conveyance channels: In this case, the current drainage ditch layout is preserved, but with separate grey- and stormwater channels (d= 15 cm; w= 20 cm, i.e., half the width of the current ditch). These must be lined and filled with pebbles (5-7 cm diameter), with grass expected to cover the surface naturally (Figure 4.23). Flow separation occurs as follows: the channel’s base flow (greywater) is diverted to green areas designed for greywater treatment, while stormwater flows are routed to infiltration areas.

Figure 4.22. Tributary area of the bioretention area prototype.

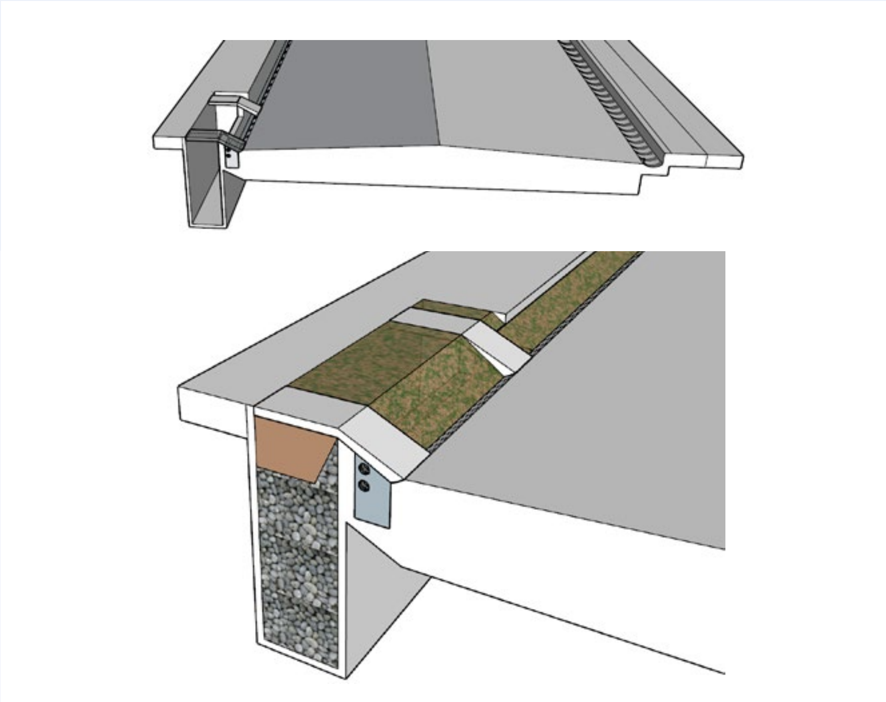


Figure 4.23. Schematic representation of the proposed conveyance channel for separating stormwater and greywater runoff.

Stormwater infiltration chambers: these chambers are designed to capture overflow from channels during rainfall events. They are to be built in available green areas on sidewalks (w = 60 cm; l= 10 m; d= 1.20 m) and filled with pebbles. The top 20 cm should be filled with soil native to the area, and later be covered by grass or flowers.

Greywater bio-filtration/treatment chambers: Construction of these chambers is planned in available green spaces on the sidewalks (d= 1.2 m; w= 60 cm; max. l= 4 m) (Figure 4.24). These treatment chambers must be filled with pebbles, volcanic stone and fine aggregate; planting decorative species with a high resistance to humidity is recommended.

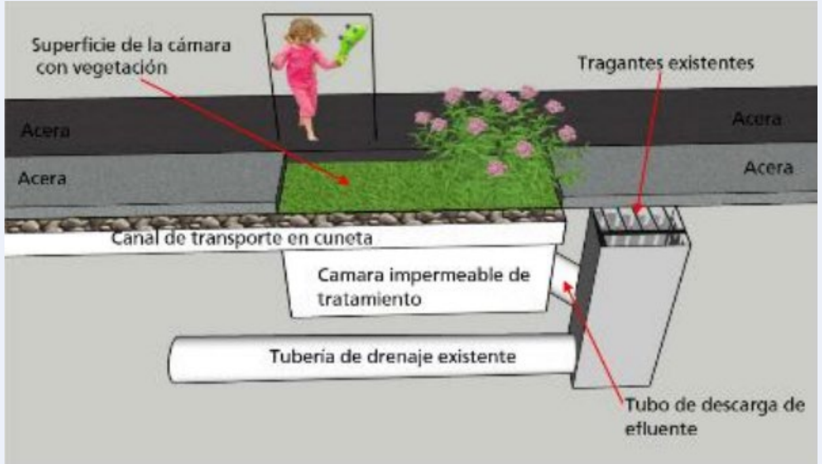


Figure 4.24. Schematic representation of the proposed greywater bio-filtration and treatment chambers.

In addition, the chambers should be lined to prevent greywater infiltrating into the subsoil. Treated greywater will be diverted to the adjacent downstream catch basin, whereas excess flow during extreme rainfall events will be directed to the catch basin by gravity.

STAKEHOLDERS INVOLVED

Municipality, neighbors with properties in direct contact with the area of intervention.

EXPECTED BENEFITS

- Channels reduce the amount of water conveyed to the stormwater system since they intensify surface moisture and baseflow evaporation. In this way, surface flows will be evident only in cases of heavy precipitation.
- The bio-filtration/treatment chambers are designed to remove contaminants from greywater flows through a multi-layered filtration process, resulting in the discharge of higher quality water into the drainage system and the river.

HYBRID SYSTEM FOR STORMWATER RETENTION AND GREYWATER TREATMENT AT MICRO-WATERSHED SCALE

LOCATION

This prototype specifically targets the outlet of the local sewage system from the Siglo XXI neighborhood to the Quebrada Seca River. Its tributary area accounts for 100% of the total micro-watershed area (Figure 4.25).

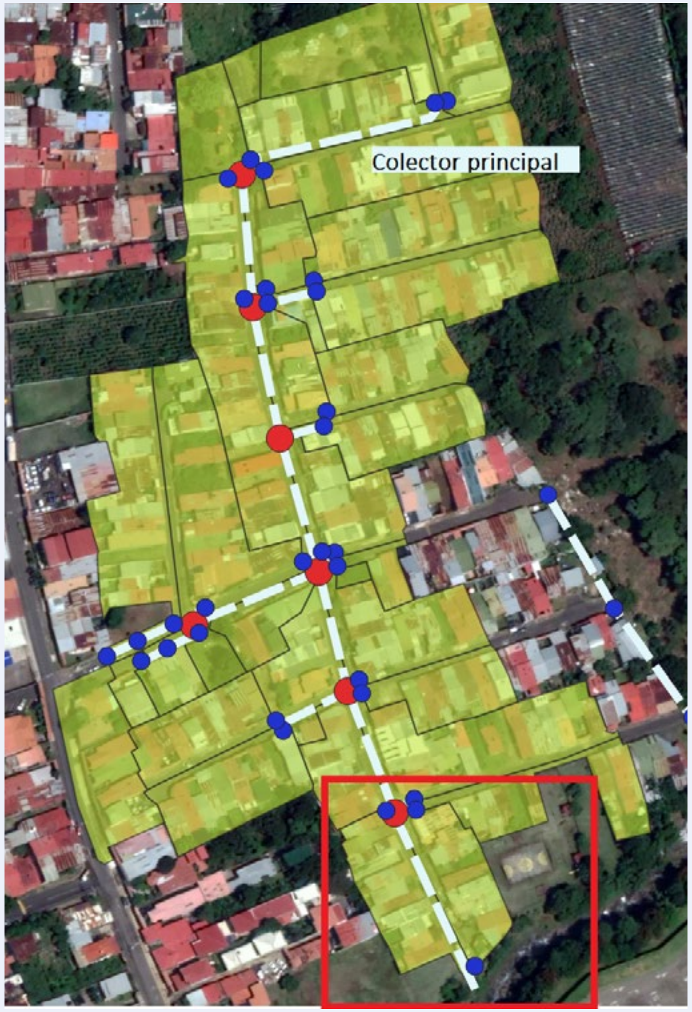


Figure 4.25. Tributary area of the hybrid prototype for stormwater retention and greywater treatment.

DESCRIPTION

Making the most of the local topography, this prototype was proposed as a complete transformation of the final section of the drainage system by implementing four different systems, shown in Figure 4.26:

1. SW1 (stormwater storage)
2. GW1 (greywater conveyance)
3. Sr-Street (greywater collection)
4. AW1 (greywater treatment)

TECHNICAL DETAILS

SW1 system (Figure 4.27): The aim of this infrastructure prototype is to store and attenuate peak flows and runoff volumes. It comprises a storage tank (l=2 m; w=1.5 m; d=4 m) with an emptying time of 16 hours (after reaching its maximum capacity) through a bottom orifice (Ø=5 cm) that allows a slow discharge to the river. A top orifice was also suggested to discharge excess volume, thus preventing the system from collapsing upstream.

Figure 4.26. Distribution of the proposed storage, conveyance, collection, and treatment systems for the hybrid prototype.

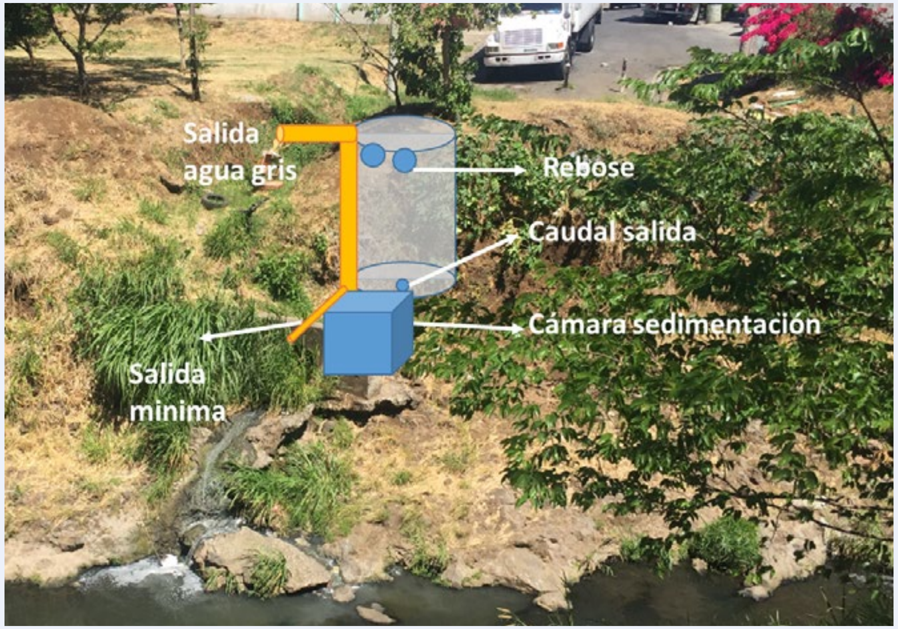


Figure 4.27. Schematic representation of the stormwater storage system.

GW1 system: This includes a) a network of pipes to convey greywater to the treatment (AW1) system and b) a sedimentation tank (l= 2 m; w= 1.5 m; d= 1 m). Hydraulic pressure and continuous greywater flow are ensured to avoid stagnation, making the most of the location's favorable topography. The sedimentation tank is intended to remain completely filled, only being emptied during maintenance and inspection. After sedimentation, the water is routed to the AW1 system.

Sr-Street system: This system was designed to collect surface greywater runoff from the immediate upstream residential area. Drainage ditches along the street will be transformed into temporary retention channels filled with porous material. If runoff volumes exceed AW1's discharge capacity, they will be released directly into the river.

AW1 system: This system features a constructed wetland (300 m^2) in a vacant public area adjacent to the river. Flows from the GW1 and Sr-Street systems pass through a greywater sedimentation tank, before being routed to the wetland. There, discharged flows can either infiltrate into the soil or be released into the river.

STAKEHOLDERS INVOLVED

Municipality, neighbors with properties in direct contact with the intervention area.

EXPECTED BENEFITS

- Decentralized storm- and greywater treatment and management.
- The constructed wetland has significant potential for reducing pollutant loads from greywater inflows by using locally adapted vegetation, positively impacting the quality of urban runoff currently discharged untreated into the river.
- The suggested location of the wetland enables the creation of ecological niches and aids in controlling erosion and degradation of land slopes and river banks.

RAINWATER HARVESTING SYSTEM IN A KINDERGARTEN

LOCATION

This prototype was proposed as part of the current facilities of CECUDI, a childcare and development center located in the El Rosario neighborhood, Flores (Figure 4.28).

Figure 4.28. Aerial view of the selected site (childcare facility) for developing the rainwater harvesting system prototype.

DESCRIPTION

The rainwater harvesting system (RWHS) prototype effectively captures and utilizes stormwater runoff currently wasted by being discharged into the stormwater drainage system. It achieves this by collecting rainwater through a rooftop area of approximately 450 m^2. The primary intended uses include toilet flushing, cleaning tasks and landscape irrigation.

TECHNICAL DETAILS

The roof drainage system should be adapted to a collection-distribution system based on the current building's drainage set-up (Figure 4.29). The internal water supply system will need to be modified, particularly regarding the pipe network for toilet flushing. Since the drinking water storage tank will not be affected, this system will remain autonomous. Storage tanks for non-potable uses were suggested at the rear of the building where sufficient space was identified.

The non-drinking-water storage tanks were designed for a max. daily demand of 500 l/d, i.e., a 5 m^3-tank allowing an overall 80% system efficiency. Two or more tanks can be interconnected to increase the system's capacity. Each tank should have an overflow device connected to the local drainage system. Furthermore, we recommend covering all pipes, valves and access points with steel mesh to prevent mosquitoes or other unwanted elements entering the system.

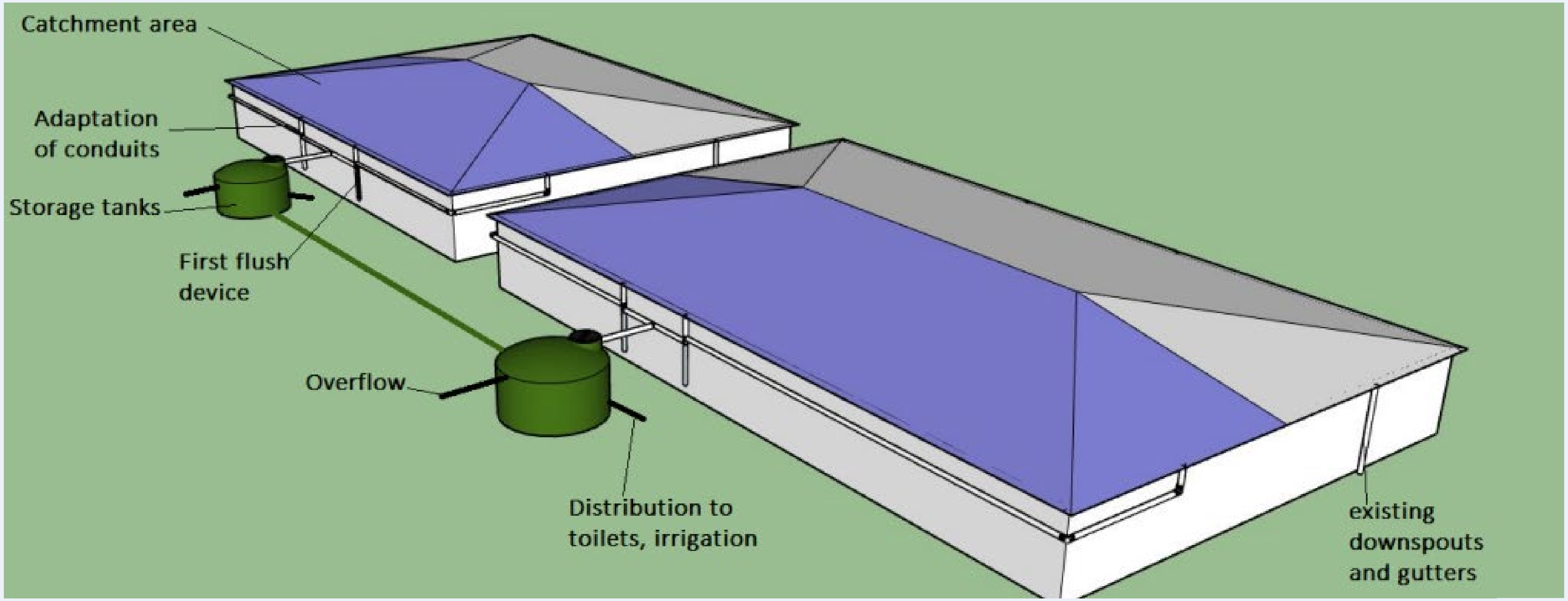


Figure 4.29. Schematic representation of the collection-distribution system for the proposed rainwater harvesting system prototype.

STAKEHOLDERS INVOLVED

CECUDI administration.

EXPECTED BENEFITS

- Greater promotion and awareness of these systems.
- Economic benefits due to the high potential of RWHS for non-potable uses owing to the amount and distribution of rainfall in the area.
- Catering to environmental concerns related to:
  - High environmental pressure on local aquifers owing to the high demand for water in the region.
  - Degradation of urban rivers by direct runoff discharge.
  - Increased drinking water demands due to high urbanization levels.

URBAN FARM IN A PUBLIC GREEN SPACE

LOCATION

The urban farm prototype was proposed for a vacant public space adjacent to the Parque Sur and the Quebrada Seca River (approximate available area = 510 m^2), shown in Figure 4.30.

DESCRIPTION

The urban farm project was designed with a mini-plot structure, offering residents individual parcels to grow their own food and flowers. Developing this prototype involves the definition of three key aspects:

1. Required space: Before developing this prototype, authorization from the municipal administration was mandatory. In addition to identifying the number of interested community members, it was necessary to define the minimum size of these mini-plots, suitable species, rules of use, maintenance activities, etc.
2. Irrigation infrastructure: Any irrigation system should directly supply each mini-plot. This led to SUW proposing an RWHS-based watering plan that would also support general cleaning tasks. Nonetheless, it is recommended that the required storage tank be connected to the local supply network in order to keep the system operational throughout the dry season.
3. Organization, assistance, and monitoring schemes: Assuming its responsibility for the prototype's execution and monitoring, SUW can coordinate these tasks in the initial three years in direct collaboration with members of the municipality. The aim is to provide significant information to assess the social and spatial potential of this prototype in the overall Metropolitan area. If the initiative is successful, tasks related to organization, assistance, and monitoring should be shared between the municipality and the local community.

STAKEHOLDERS INVOLVED

Municipality, interested residents.

EXPECTED BENEFITS

- Community engagement.
- Enhanced food security and resilience.
- More green space and biodiversity.
- Social impact and empowerment.

Figure 4.30. Aerial view of the proposed site (outlined in red) for developing the urban farm prototype.

CONSTRUCTED WETLAND FOR GREYWATER TREATMENT INTEGRATED IN THE SIDEWALK – HOUSEHOLD SCALE

LOCATION

This prototype was proposed to be implemented on at household scale, integrated in the sidewalk in one of the streets of the Siglo XXI neighborhood. Location and dimensions are shown in Figure 4.31.

Figure 4.31. Selected plot (left), bird's-eye view (center), and dimensions (right) of the proposed constructed wetland prototype.

DESCRIPTION

The greywater treatment system was designed as a horizontal subsurface flow (HSSF) constructed wetland prototype, targeting discharges from a property's kitchen, shower and washing machine. The system (Figure 4.32) employs multiple processes such as bacterial degradation, sedimentation, precipitation, adsorption and filtration to improve the physicochemical quality of greywater discharges in terms of:

- biological oxygen demand (BOD),
- chemical oxygen demand (COD),
- total suspended solids (TSS),
- fats and oils,
- settable solids,
- methylene blue active substances, and
- fecal coliforms.

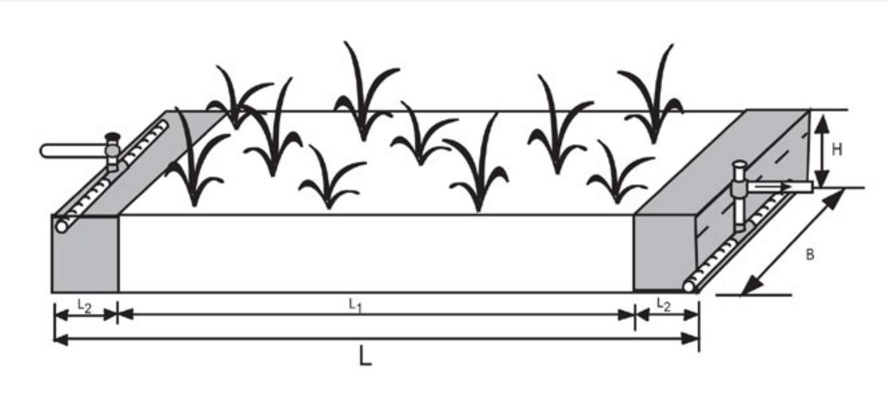


Figure 4.32. Schematic representation of the horizontal subsurface flow constructed wetland prototype.

TECHNICAL DETAILS

Upstream of the treatment stage, we highly recommend installing a pre-treatment device (grease trap) to retain grease and sediments. The HSSF wetland prototype itself is comprised of a filter media (pebbles with integrated vegetation), a distribution layer (coarse media), and a main filter bed. Water is kept beneath the surface of the substrate, flowing through and around the plant roots. Plants provide oxygen, thus enhancing microbial growth and the quality of the greywater discharge.

STAKEHOLDERS INVOLVED

Owner of the property.

EXPECTED BENEFITS

Reduction of pollutant loads discharged into water bodies

The previously displayed catalog was submitted to the Flores municipality for internal evaluation. Following this, three of the six proposed prototypes were approved for construction:

- Bioretention areas in sidewalks.
- Hybrid system for stormwater retention and greywater infiltration at a micro-watershed scale.
- Constructed wetland for greywater treatment integrated in the sidewalk – household scale.

The most important selection factor considered by the municipality was the technical feasibility of the prototypes, with a view to maintaining the current configuration of both the road network and the urban landscape. In fact, building permits were obtained specifically for those prototypes not interfering with traffic flows or pedestrian accessibility. The proposal for an "infiltration area in a public park" was discarded due to the latent risk of groundwater contamination by greywater infiltration around water supply wells (the Costa Rican Water Code specifies a protection radius of 100 m for wells).

Construction of the Nature-based Solution prototypes

Construction of the prototypes (Figure 4.33) began in early 2020, funded by the SUW project. Ensuring local participation was a key principle not only throughout the prototype's co-design (planning, placement, designing), but also during the implementation and operational stages. The transdisciplinary and collaborative planning, design, implementation and experimental operation of the prototypes resulted in important insights for the future replication, promotion and implementation of NbS, especially in urban areas.

The planning and construction processes revealed several challenges in terms of NbS implementation and maintenance in densely urbanized areas to achieve a greater socio-ecological transformation from the neighborhood to the watershed level. The SUW's NbS prototyping initiated an important learning process in this regard.

These challenges, if not effectively addressed, could hamper the extensive adoption of NbS. Therefore, we argue that efforts are needed to better understand and consider context-specific aspects in the design and long-term operation of NbS.

KEY CHALLENGES

Planning phase

- The lack of knowledge and experience in NbS implementation seems to endorse conventional technology in the socio-political sphere.
- The lack of information or records regarding the existing public infrastructure made it challenging to retrofit fully developed areas.
- Low public investment: Investments are allocated for the construction of conventional technology following standards from developed countries; this results in low opportunities for innovation due to rigid construction regulations based on conventional methods.
- Poor data availability and quality can affect the progress of any NbS retrofit project. For instance, the mismatch between the official drawings of the drainage system and what was observed during the construction phase prompted last-minute changes to the prototypes, delaying the overall project's development.
- Silo mentality and resistance to change on behalf of some local stakeholders impeded the use of innovative systems within the built environment.
- Lack of interest in and application of co-design processes that encourage the participation of multiple stakeholders to help frame the problem and prioritize local needs.

Construction and operation phase

- Local professionals are unfamiliar with NbS construction, therefore lacking awareness of the expected goals and functionality of the infrastructure to be built.
- Mismanagement of solid waste represents an additional burden on the existing drainage infrastructure. This results in an increase in maintenance requirements or negative effects on the operation and long-term integrity of NbS infrastructures; e.g., excessive solid waste in the inlet of prototypes can negatively impact normal operation.
- Tropical climates may favor faster decomposition of stagnant water; for that reason, green/blue infrastructures are associated with mosquitos breeding, increasing the occurrence of waterborne diseases. This causes negative social perceptions and even rejection of these systems in favor of

conventional gray infrastructures able to quickly convey water away.

- Intrinsic cultural perceptions and social prejudices can hinder the successful implementation of NbS retrofits. For instance, residential areas with trees/ bushes are perceived as dark and dangerous places, leading to rejection by local residents.

INFO

Challenges and implications of the COVID pandemic in Real-world Labs

During the COVID-19 pandemic between 2020 and 2022, the work of place-based social-ecological researchers faced significant challenges. For instance, strict social distancing protocols affected the collection of biophysical data and participatory research with local actors or communities. Despite these setbacks, the use of video conferencing platforms emerged as an alternative approach for real-time qualitative data collection, enabling the participation of multiple stakeholders from different locations. For further details about research opportunities, methodologies, and recommendations in challenging research contexts, please refer to:

Hermans, K., Berger, E., Biber-Freudenberger, L., Bossenbroek, L., Ebeler, L., Groth, J., Hack, J.… Wiederkehr, C. (2021). Crisis-induced disruptions in place-based socialecological research - an opportunity for redirection. GAIA - Ecological Perspectives for Science and Society, 30(2), 72–76. https://doi.org/10.14512/gaia.30.2.3

Figure 4.33. Locations of the three constructed Nature-based Solutions prototypes in the SEE-URBAN-WATER's Real-World Lab.

Co-design approaches are useful to identify all these relevant factors, thereby enhancing the overall planning process. Though stakeholders' involvement may be a time- and resource-consuming task, the integration of different fields of knowledge contributes to the development of more tailored solutions to satisfy the prioritized needs.

Prototyping is a valuable way to co-produce knowledge regarding construction, operation, maintenance, costs, benefits and services, and the long-term effectiveness of NbS. This could help reduce existing uncertainties around these aspects.

HOUSEHOLD-LEVEL TREATMENT: CONSTRUCTED WETLAND FOR GREYWATER TREATMENT INTEGRATED IN THE SIDEWALK

From the factors analyzed during the co-design process, we identified a great potential for NbS-based household greywater treatment before it is discharged into street drainage gutters. This can be achieved by first intercepting the main discharge pipe and then using the sidewalk area in front of the property to install the treatment system. Therefore, the constructed wetland prototype was proposed as a source control or household-level treatment strategy.

During the interviews with local residents that took place during the co-design process, one particular family was willing to accept having this prototype installed in front of its property. The treatment system was designed based on guidelines for horizontal subsurface flow constructed wetlands, adapted to fit in the available area and operate within the existing configuration of sewer and rainwater networks and the present urban layout.

The prototype consists of a small-scale horizontal subsurface flow constructed wetland extending into the sidewalk and adjacent green verge in front of the property. Pictures after construction and the respective design sketch are displayed in Figures 4.34 and 4.35. The treatment area is 5.2 m^2 (w= 1.5 m; l= 3.5 m) and h= 0.6 m, and impacts neither the street design nor the underground infrastructure (e.g., energy, sewerage, or water supply networks). This system is equipped with a pre-treatment grease trap installed in the outlet pipe of the property's kitchen. The complete system is simple to operate; the owner can ensure functionality by performing regular inspections and cleaning. The constructed wetland design considered the use of decorative plant species, i.e., *Heliconea spp.*, in line with the identified RWL residents' preferences (see section "co-design factor 3).

Figure 4.34. Top view of the constructed wetland prototype, depicting its condition soon after implementation (above) and one year later (below).

Figure 4.35. Design sketch of the constructed wetland prototype for greywater treatment, integrated into the sidewalk.

STREET-LEVEL TREATMENT: BIORETENTION AREAS IN SIDEWALKS

In addition to the possibility of installing household-level treatment systems, the co-design process also revealed the potential for green verges and sidewalks to treat greywater freely flowing through the streets. The conceptual design of this solution is based on guidelines for bioretention areas or rain gardens, commonly used along streets or parking lots to detain stormwater by infiltration and, at the same time, improve its quality.

In consultation with local residents, the co-design process revealed that they would accept the use of treated greywater for irrigating flower beds and bushes, thus enhancing greenery in public areas. Therefore, this prototype was proposed as a collective treatment strategy able to manage greywater discharges from multiple residential units in one block of the neighborhood.

This prototype consists of a bioretention area with an underdrain pipe that discharges the treated effluent into the existing stormwater drainage network. The installed prototype covers both the sidewalk and green verge of a residential street. Its effective area of treatment is 20 m^2 (w= 2 m; l= 10 m) and h= 0.6 m, without affecting the current street design. The bioretention area design considered the use of decorative plant species, i.e., *Heliconea spp.* Pictures after construction and the respective design sketch are displayed in Figures 4.36 and 4.37.

Figure 4.36. Top view of the bioretention area prototype, displaying its condition soon after construction (left) and one year later (right).

Figure 4.37. Design sketch of the bioretention area prototype.

MIXED-USE TREATMENT: HYBRID SYSTEM FOR STORMWATER RETENTION AND GREYWATER TREATMENT AT MICRO-WATERSHED SCALE

After analyzing the existing drainage configuration and available green spaces in the neighborhood, it was found that the riparian area behind the drainage system's outfall into the river could serve as a valuable site for greywater treatment and stormwater retention. The main challenge when designing this prototype was to separate greywater runoff from stormwater runoff in order to implement an efficient greywater treatment system. A further key criterion was that the current use and function of the riparian area should not be changed. Therefore, only underground treatment systems allowing their top surface to be used for recreational purposes could be considered.

Two subsystems were designed as part of this hybrid prototype: a greywater treatment facility and a stormwater retention unit (Figure 4.39). Greywater runoff is collected at the outlet of the largest micro-watershed in the Siglo XXI neighborhood.

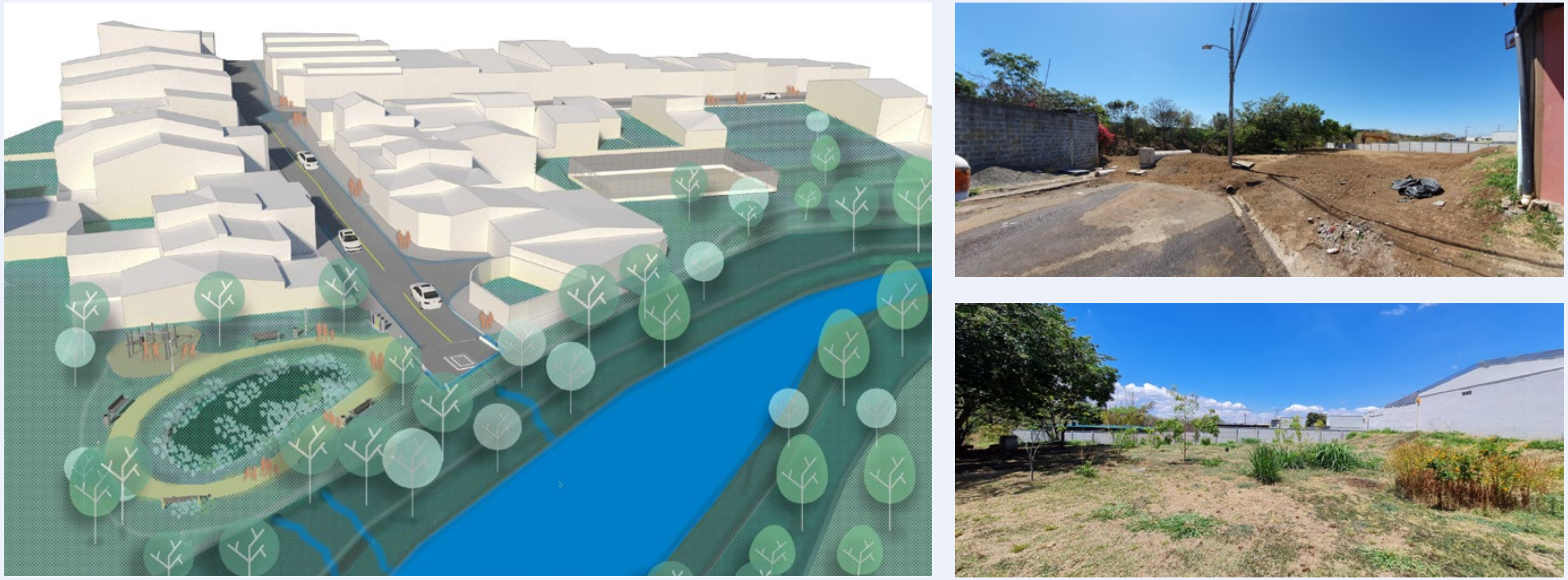


Figure 4.38. Design sketch of the hybrid system prototype for stormwater retention and greywater treatment at the micro-watershed scale (left) and panoramic views soon after construction (top-right) and one year later (bottom-right).

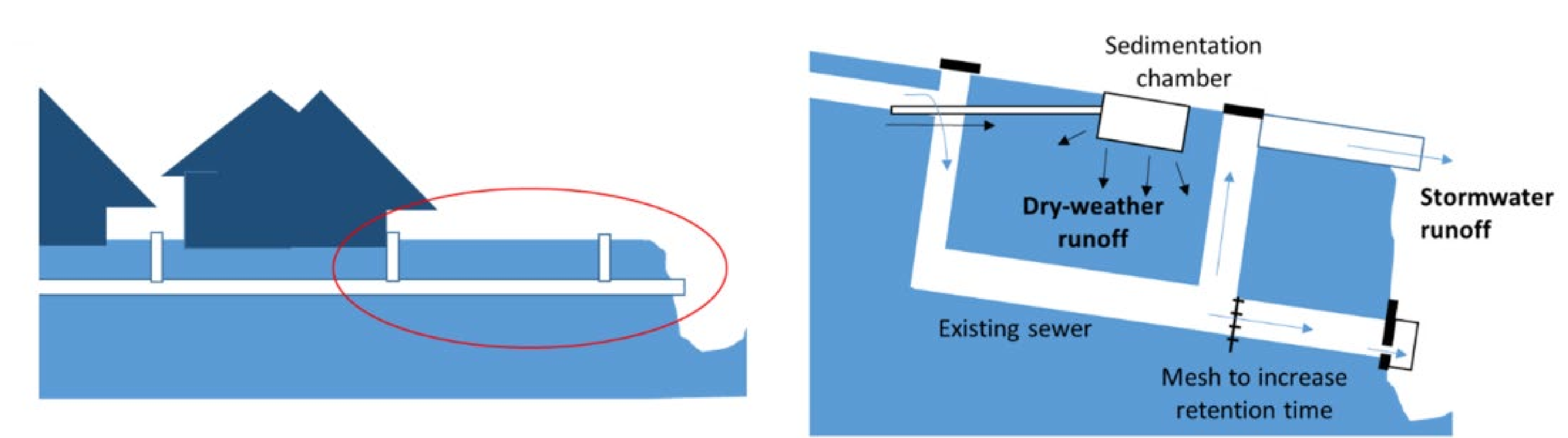


Figure 4.39. Schematic representation of some elements that are part of the hybrid system prototype, including a cross-sectional view of the existing drainage system and the location of the stormwater retention unit (right) and a pretreatment facility that enables the separation of stormwater and greywater runoff (left).

The greywater facility is designed to function as an infiltration area (with an underdrain distribution pipeline) that reduces the pollutant load of greywater discharges from the entire micro-watershed during dry weather. This subsystem consists of an infiltration area of 160 m^2 and h= 1 m, designed as a multifunctional element of a public park owned by the municipality. Its design considered the use of two bamboo species, i.e., *Gigantochloa atroviolacea* and *Bambusa oldhamii*. Furthermore, pretreatment is performed in a two-chamber sedimentation tank of 3 m^3 capacity. There, greywater runoff is collected and then distributed to the infiltration area through a 5 m underdrain pipe, placed across a gravel infiltration layer. A design sketch and pictures after construction are displayed in Figure 4.38.

The prototype's other subsystem, the stormwater retention unit, was envisaged as a gray-green component. Figure 4.37 shows the subsystem schematically, including the structural modifications made to the existing sewer system. The final section of this network was converted into a temporary runoff storage tank. The diameter of the outfall pipe was reduced from 75 to 7 cm, thereby increasing the concentration time in the system to reduce peak flow. To keep sediments from clogging the orifice, a mesh with a 5 cm open diameter was proposed in the adapted manhole. When the storage capacity is surpassed, runoff is discharged into the river using a bypass fitted in the manhole located prior to the original outfall. Maintenance work includes periodic cleaning of both the manhole and mesh, to be performed by the municipality. The hydrological performance of the system was tested by a hydrological model developed using the software PCSWMM.

Modeling the hydrological performance of the NbS prototypes

Fieldwork in the RWL enabled a detailed representation of small-scale stormwater management infrastructure. This was crucial for effectively modeling flow patterns and the hydrological performance of the existing drainage system, considering the scattered distribution of small-scale NbS measures (Section 5.1).

Comparison of the prototypes

Table 4.1 presents a comparative summary of the prototypes, including the scale of treatment, investment costs, operational and maintenance requirements, and stakeholder involvement (at municipal and community levels). This assessment allowed us to establish the prototypes' efficiency as well as their potential for replication or scaling up at watershed level.

For more information about the prototypes please refer to:

Chapa, F., Pérez, M., and Hack, J. (2020). Experimenting Transition to Sustainable Urban Drainage Systems—Identifying Constraints and Unintended Processes in a Tropical Highly Urbanized Watershed. Water, 12(12), 3554. https://doi.org/10.3390/w12123554.

Pérez Rubi, M. and Hack, J. (2021). Co-design of experimental nature-based solutions for decentralized dry-weather runoff treatment retrofitted in a densely urbanized area in Central America. Ambio, 50(8), 1498–1513. https://doi.org/10.1007/s13280-020-01457-y.

The implemented NbS prototypes reflect different scales of treatment and retrofitting opportunities to capitalize on existing green spaces and the drainage configuration. This also fosters empowerment and ownership among beneficiaries, e.g., house owners and municipalities in the case of household-level and micro-watershed treatment facilities, respectively.

The insights gained from the RWL and the prototypes' co-design and implementation fostered further investigation to analyze other aspects of NbS adoption in the Costa Rican context. SUW conducted a post-implementation cost-benefit analysis for one of the prototypes. The hybrid system for stormwater retention and greywater treatment at micro-watershed scale prototype was selected for a socio-economic analysis using the Triple Bottom Line Cost-Benefit Analysis (TBL-CBA) which considers social, environmental and financial impacts to reveal most of the representative costs and benefits of NbS perceived by local stakeholders (Table 4.2).

The SUW RWL provided the necessary input to perform the TBL-CBA. Furthermore, integration of the prototype outcomes in this analysis contributed to a more socially comprehensive and meaningful economic assessment of NbS. The results provide insights into the economic performance of NbS in real-world conditions, taking account of the local and legal context. The TBL-CBA weights the inputs generated in the RWL across all three bottom lines, i.e., social, environmental and financial. As a result, applying the TBL-CBA to the SUW RWL offered an opportunity to identify the potential costs and co-benefits of NbS, to leverage synergies, and to

Prototype	Scale of treatment (beneficiaries)	Investment costs in US$	Operational & maintenance requirements	Stakeholder involvement: Municipality	Stakeholder involvement: Residents
Horizontal subsurface flow constructed wetland	Household level (1 house)	2 500	System works by gravity and natural processes. Cleaning tasks (vegetated surface) could be undertaken by the house owner.	Consult: Municipality approved the modification of public space	Empowered: The owner of the property * Neighbors were only informed
Bioretention area	Street level (15 houses)	11 000	System works by gravity and natural processes. Additional tasks to be distributed: cleaning and pruning the vegetated surface and removing solid waste from the system's components.	Partner: Municipality has undertaken to maintain the prototype	Consult
Infiltration area	Sub-watershed level (approx. 260 houses)	35 000			Involved: Closest residents *Other residents were only informed

Table 4.1. Summary of three prototypes that resulted from the co-design process implemented in the study area.

Perceived benefits by local stakeholders (simplified table):	First year	Second year
Total economic costs	US$ – 81.277,80	US$ -8.400,00
Total social benefit:		
• Potential cost savings in inclusive recreation	US$ 26.800,00	US$ 26.800,00
• Potential energy consumption costs savings due to recreation in public spaces	US$ 14.668,10	US$ 14.668,10
• Potential increase of property value	US$ 38.812,00	US$ 38.812,00 0
Total environmental benefit: Water sanitation – pollution reduction	US$ 2.640	US$ 2.640
Total net present value (TNPV)	US$ 1.642,30	US$ 76.520,10

Table 4.2. Results of the Triple Bottom Line Cost-Benefit Analysis (TBL-CBA) for the hybrid system prototype.

integrate and assess local knowledge, i.e., to capture and integrate the value of NbS as perceived by local stakeholders, into a valuation method. This not only enables the resolution of practical barriers to NbS implementation but also highlights the need for NbS interventions that are socially comprehensible and acceptable.

The SUW project incurred a series of costs related to the identification of the nature-society interaction, the promotion of the NbS and its benefits, as well as the stakeholder engagement for knowledge production and exchange between scientific and non-scientific players. Most of these costs are usually not included in the NbS cost-benefit analysis, as many estimates solely address implementation and maintenance costs. In our assessment, several activities and qualitative research methods, such as interviews and meetings with local stakeholders to understand the local, legal and economic context, were included. This ultimately helped in identifying other synergies and benefits for cross-sectoral integration of NbS within the context of other institutional and governmental goals.

In total, 200 families are expected to benefit from the implementation of the NbS prototypes in the RWL area. These benefits are related to recreational opportunities along the riparian areas. This recreational potential was also seen as an opportunity to reduce energy consumption costs (by reducing television, computer and video game usage), enhance property values, and increase a sense of safety. Other benefits acknowledged by scientists include pollination enhancement, biodiversity augmentation, enhanced wildlife habitat, improved air quality, and greater aesthetic value of the area.

While implementing the NbS prototypes, we experienced several issues relating to the planning, design and approval, as well as the construction, operation and maintenance of the prototypes. Major practical hurdles to NbS implementation can only be revealed through prototyping, especially in urban contexts where these solutions still represent novel and unconventional approaches. Identifying these hurdles was a principal objective of the prototyping.

The insights from the Real-World Lab and Lab-scale modeling were used to develop scenarios for the regional modeling of NbS, taking into account the most suitable NbS types and geospatial distributions. The regional modeling enabled a better understanding of the differences in NbS implementation potential across residential and industrial neighborhoods as well as an estimation of the larger-scale impact of a more widespread implementation of NbS.

Insights from NbS prototyping as basis for policy readiness assessment

Some of the proposed prototypes were used to analyze the readiness of Costa Rican policy for taking up and implementing Nature-based Solutions at different scales and dimensions (Section 6.2).

For more information about the cost benefit analysis, please refer to:

Neumann, V. A. and Hack, J. (2022). Revealing and assessing the costs and benefits of nature-based solutions within a real-world laboratory in Costa Rica. Environmental Impact Assessment Review, 93(106737). https://doi.org/10.1016/j.eiar.2022.106737.

NbS prototypes used for legal barrier analysis

To understand the legal barriers hindering NbS in urban areas of Costa Rica, the SUW NbS prototypes were used as input for expert focus groups in the fields of urban water management, urban development and planning to analyze their legal and regulatory feasibility. This analysis revealed that the legal feasibility for implementing NbS in urban areas depends on their location and functionality (Section 6.1).

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Aerial view of the urban green corridor of Quebrada Seca-Río Burío, Heredia, Costa Rica.

5

MODELING OF NATURE-BASED SOLUTIONS AND PLANNING OF URBAN GREEN INFRASTRUCTURE

MODELING OF NATURE-BASED SOLUTIONS AND PLANNING OF URBAN GREEN INFRASTRUCTURE

As described in Chapter 4, the Real-World Lab (RWL) approach proved to be highly effective for the robust co-production of knowledge by combining the insights and experience of academics and various practitioners. It ultimately helped in the identification of suitable sites for different types of Nature-based Solutions (NbS) and the strategic planning of multifunctional Urban Green Infrastructures (UGIs). However, the project's RWL was not just the starting point for the co-design of NbS prototypes.

INFO

Numerical modeling is a widely applied technique to tackle complex problems through the computational simulation of scenarios. It uses mathematical models to describe the physical conditions of these scenarios, applying numbers and equations. The use of models can help to explain a system, to study the effects of different components, and to make predictions about its behavior.

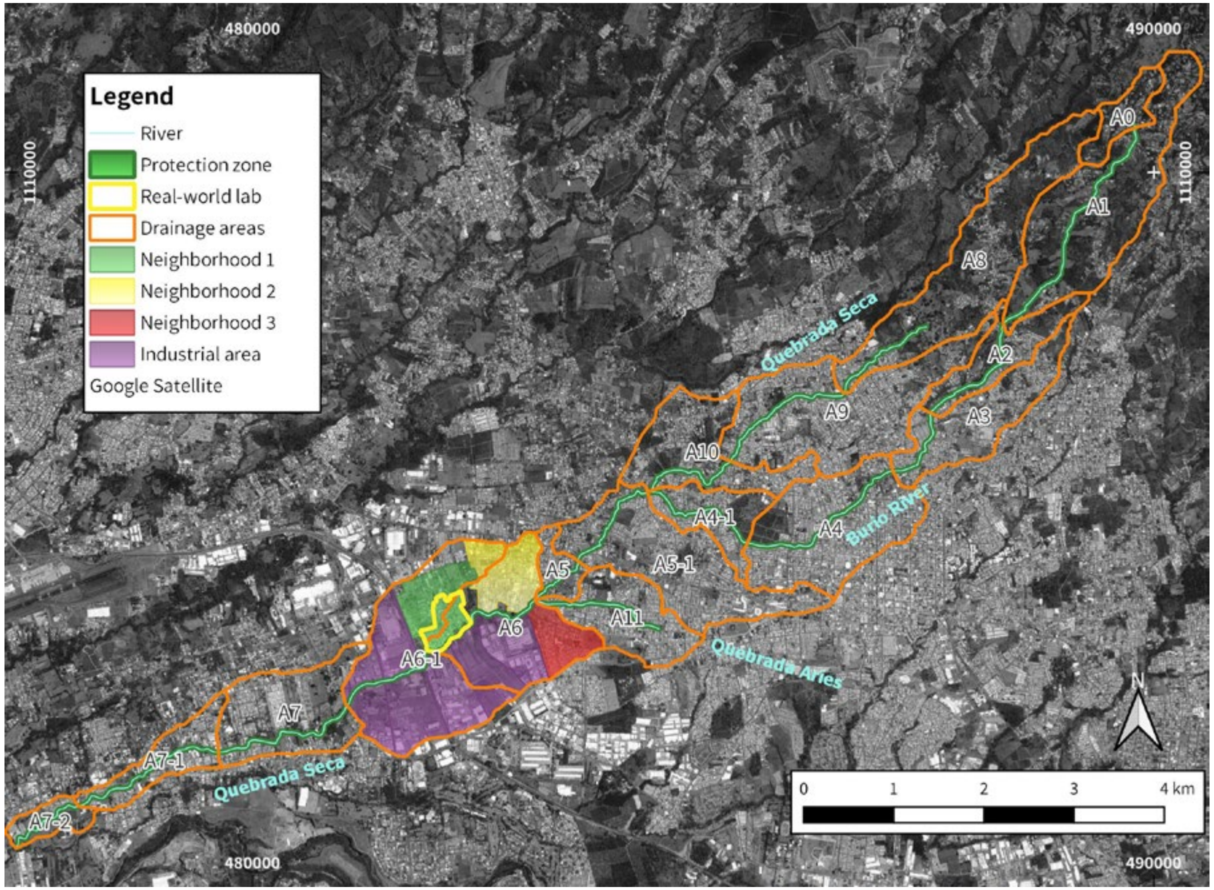

Figure 5.1. Spatial scales applied for hydrological and hydraulic modeling including the project's Real-World Lab, different residential neighborhoods, industrial areas, and socio-ecological sub-areas.

Throughout this chapter, the main results of hydrological (rainfall-runoff relationship), hydraulic (surface-stormwater drainage and river-floodplain hydraulics), and climate regulation (water and energy balance) assessments will be presented – factors that are increasingly addressed in the

NbS and UGI literature, albeit mainly in developed country contexts. However, while hydrological and hydraulic performances are of specific importance in the RWL's study area due to the severe flooding problems caused by a high degree of urbanization, NbS were also evaluated in terms of other social and ecological functions when integrated into a larger multifunctional UGI network.

Furthermore, the transdisciplinary knowledge gained in the RWL allowed the development of several realistic scenarios featuring differing scales of implementation, taking into account specific geo-spatial conditions, local preferences, and both formal and informal regulatory land use constraints. Figure 5.1 illustrates the various spatial scales tested, starting from a high-resolution NbS prototype model at the Real-World Lab to upscaling scenarios on a neighborhood, sub-watershed and watershed scale.

Real-World Lab as the basis for NbS suitability modeling

The RWLs monitoring data, design criteria and placement strategies - to achieve a broad multifunctionality of UGIs - served as the foundation for numeric simulations to assess the performance of this novel infrastructure in several dimensions (Section 4.3).

The purposes of the different spatial scales is explained in the following:

1. **Real-World Lab scale:**
   - High resolution model for prototype performance prediction, calibration and validation with in-situ measurements, basis for upscaling (parametrization and scenario-building at larger spatial scales; Towsif Khan et al., 2020).
   - Micro-climate regulation of NbS (Wiegels et al. 2021).
   - Multifunctionality of different NbS scenarios (Milagres, 2020).
2. **Sub-watershed scale**
   - Residential neighborhoods and industrial areas: Consideration of urban fabric heterogeneity and use (residential and industrial) in assessing the space available and suitable for UGI as a basis for modeling scenarios, i.e., rainfall and runoff retention potential (contribution to downstream flood reduction) of different residential and industrial areas and different NbS (Aparicio Uribe et al., 2022).
3. **Watershed scale:**
   - NbS implementation scenarios at watershed scale based on insights of space availability and suitability from the Real-World Lab and sub-watershed scales to model rainfall and runoff retention potential (contribution to downstream flood reduction), i.e., feasibility of different NbS and combinations (Chen et al., 2020).
   - Multifunctional UGI planning for the entire watershed and the region (Arthur and Hack, 2022).
4. **River corridor scale:**
   - Complementary in-stream NbS along the river corridor to reduce downstream fluvial flooding while providing social and ecological functions as elements of a multifunctional UGI (Lopes Monteiro et al., 2023).

The hydrological and hydraulic flood-reducing performance of a NbS was simulated by applying different open-source models. On the one hand, we used the Storm Water Management Model (SWMM) developed and distributed by the United States Environmental Protection Agency (EPA) for hydrological rainfall-runoff modeling of the urban drainage system, the QSRB watershed, and various sub-watersheds. In these cases, we compared different NbS and UGI scenarios to the study area's status quo (current land use and drainage conditions) by evaluating four main parameters: runoff volume, peak flow, time-to-peak, and runoff coefficients. Moreover, when evaluating the performance of in-stream NbS measures, UGI scenarios were employed to determine their performance at the most critical sites in the watershed.

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The Storm Water Management Model (SWMM) **was developed by the United States of America Environmental Protection Agency (EPA) and is used throughout the world for planning, analysis, and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems. It can be used without costs to evaluate gray infrastructure stormwater control strategies, such as pipes and storm drains, and is a useful tool for creating cost-effective green/gray hybrid stormwater control solutions, including Urban Green Infrastructure.**

On the other hand, we used the numerical model HEC-RAS developed by the Hydrologic Engineering Center (HEC) of the United States Army Corps of Engineers (USACE) for the hydraulic modeling of river flow. The River Analysis System (RAS) is used for the development of hydraulic models simulating the flow of water through channels with different geometries, allowing the modeling of natural water bodies as well as artificial channels. HEC-RAS allows the implementation of hydraulic structures over the analyzed channel, such as bridges, culverts, spillways, gates, pumping stations, and retention areas.

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The United States of America Army Corps Hydrologic Engineering Center's (CEIWR-HEC) River Analysis System (HEC-RAS) is a free software that allows the user to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling.

5.1. Hydrological modeling of Nature-based Solution prototypes and implementation scenarios at different spatial scales

Assessing the hydrological performance of novel stormwater management strategies such as Nature-based Solutions is of key importance not just for their large-scale implementation in new and built environments but also for strengthening urban water-related decision-making. This is especially important given the loss of permeable surfaces caused by rising urbanization leading to reduced natural soil infiltration capacity and increased runoff volume in cities (Figure 5.2).

Modeling of the hydrological conditions of the Real-World Lab and Nature-based Solution prototype performance

SEE-URBAN-WATER (SUW) developed a high-resolution model representing the drainage system and Nature-based Solutions (NbS) prototype implementation within the Real-World Lab (RWL), specifically in the Siglo XXI neighborhood (Figure 5.3). The model was used to evaluate the rainfall-runoff processes in the study area, as well as the expected performance of the NbS prototypes, thus obtaining relevant information for the final design of the infrastructures envisaged for stormwater management. The model was based on detailed data collected in several RWL field surveys, considering the above- and below-ground stormwater drainage systems (infrastructure and dimensions), street design, sealed surfaces, traffic intensity, parking spaces, street greenery and green spaces, and suitable sites for NbS prototypes.

Modeling of NbS co-designed in the Real-World-Lab

NbS prototypes resulting from the project's co-design process in the RWL were modeled as small-scale bioretention cells and infiltration trenches in street curb gutters to valuate their hydrological performance (Section 4.4).

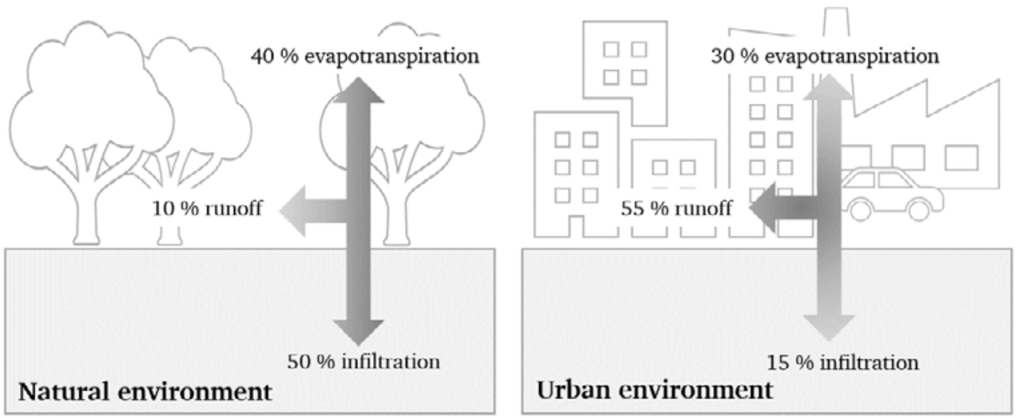

Figure 5.2. Changes in the water balance due to urban development.

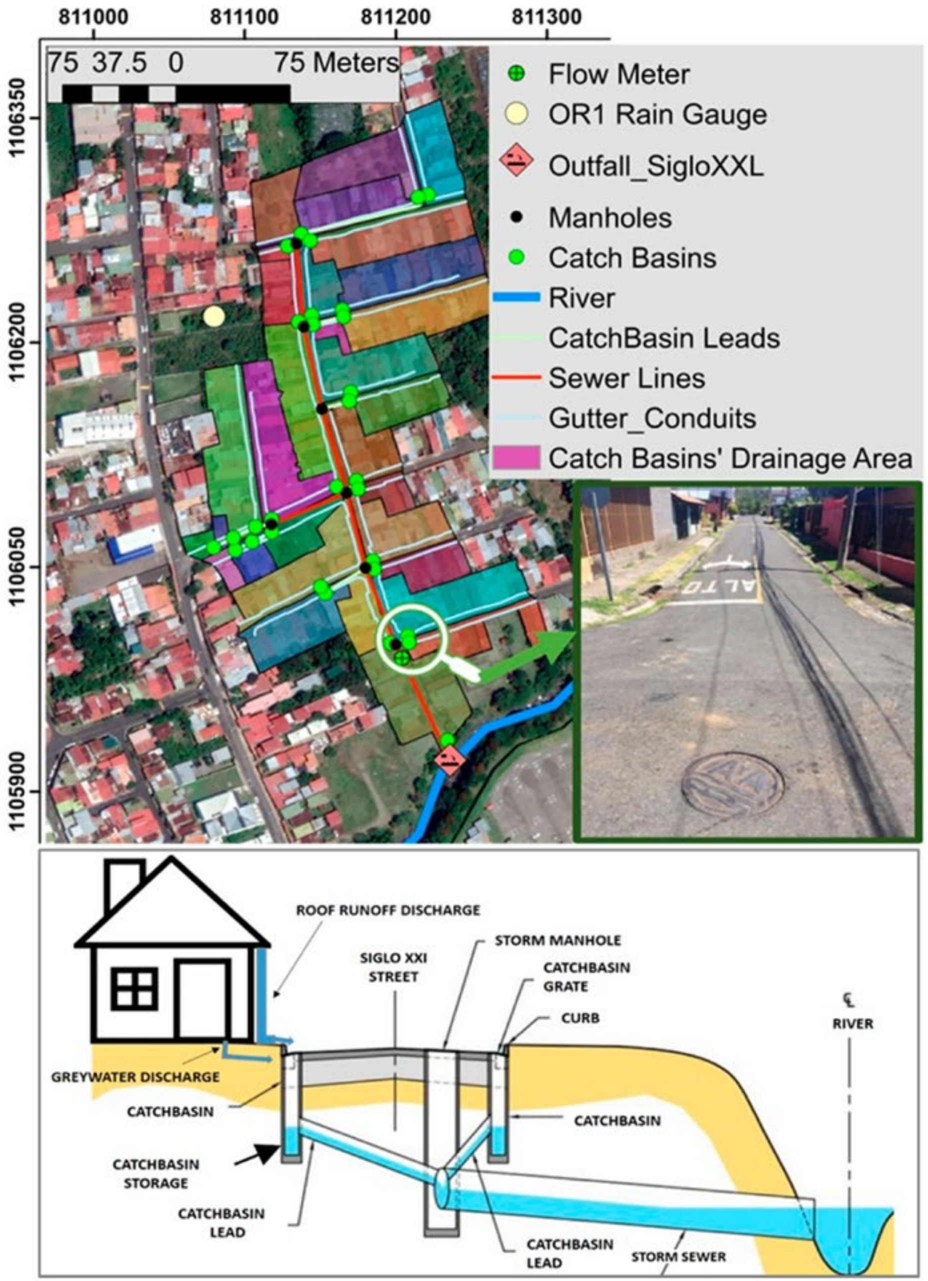

Figure 5.3. Drainage area (top) and schematic representation of hydraulic features (bottom) of the Siglo XXI neighborhood used for rainfall-runoff modeling of the status quo and Nature-based Solutions prototype implementation in the Real-World Lab.

SUW employed the Low Impact Development (LID) module of SWMM to assess the potential for reducing peak runoff and time-to-peak through small-scale NbS elements, as part of a scattered Urban Green Infrastructure (UGI) network.

The stormwater-control NbS types resulting from the project's co-design process in the RWL were represented in the model as small-scale bioretention cells and infiltration trenches in street curb gutters (Figure 5.4). Model simulations yielded satisfactory results considering specific event-based calibration and validation (Table 5.1), underlining the reliability of both the RWL's data collection and the hydrological model. For instance, SUW was able to prove that dispersed, retrofitted, small-scale measures could significantly reduce surface runoff (peak runoff reduction up to 40%) during frequent, less intense storm events, as well as delay peak surface runoff by 5–10 min at the implementation area's outlet in the RWL (Figure 5.5). With this study, we confirmed the relevance of understanding the rainfall-runoff response in a heavily urbanized micro-watershed, while also demonstrating the efficiency of site-control NbS measures for sustainable stormwater management.

Our modeling approach can benefit stormwater practitioners and modelers in developing and transition countries in conducting small-scale hydrological simulations of NbS under considerable spatial data constraints. This can help to improve the general understanding and promotion of these measures. Modeling urban drainage systems at the micro-watershed scale requires specific data that, in some cases, is missing, access-limited, or whose resolution is not accurate enough for such an objective. Since data constraints might be a limiting factor, relying on publicly available data from platforms such as Google Earth, as well as field

Event Code	Date (Month/Day/Year)	Type of Event	Duration (h)	Mean Rainfall (mm/h)	Total Rainfall (mm)
S1	7/8/2019	Used for Calibration	6	4.5	27
S2	7/14/2019	Used for Validation	5.37	4.547	24.4
S3	4/24/2017	Extreme Events	4.25	22.5	95.5
S4	8/29/2016		4.08	15.0	61.22
S5	5/24/2018	95 percentile	5.08	8.2	41.91
S6	11/11/2017	90 percentile	2.08	16.7	34.8
S7	11/9/2018	75 percentile	2.25	11.7	26.42
S8	5/31/2017	50 percentile	1.1	13.6	15

Table 5.1. Storm events modeled at Real-World Lab scale.

surveys of land use and land cover, topography, and stormwater network data, has proven to be an effective alternative. In some cases, this might be the only feasible option, as evidenced by the SUW team, owing to the high costs associated with field work and the hydrological sensors required for a model's proper calibration and validation.

Building on the successful hydrological performance assessment of NbS prototypes at the RWL scale, the SUW team decided to evaluate the potential of UGI at a sub-watershed level, considering the areas surrounding the RWL. However, in order to perform such upscaling, an evaluation of the spatial heterogeneity of the urban built environment is critical. The following section describes the SUW team's work to assess the potential of NbS retrofitting for sustainable urban flood management, taking into account a mixed-land use, i.e., residential and industrial.

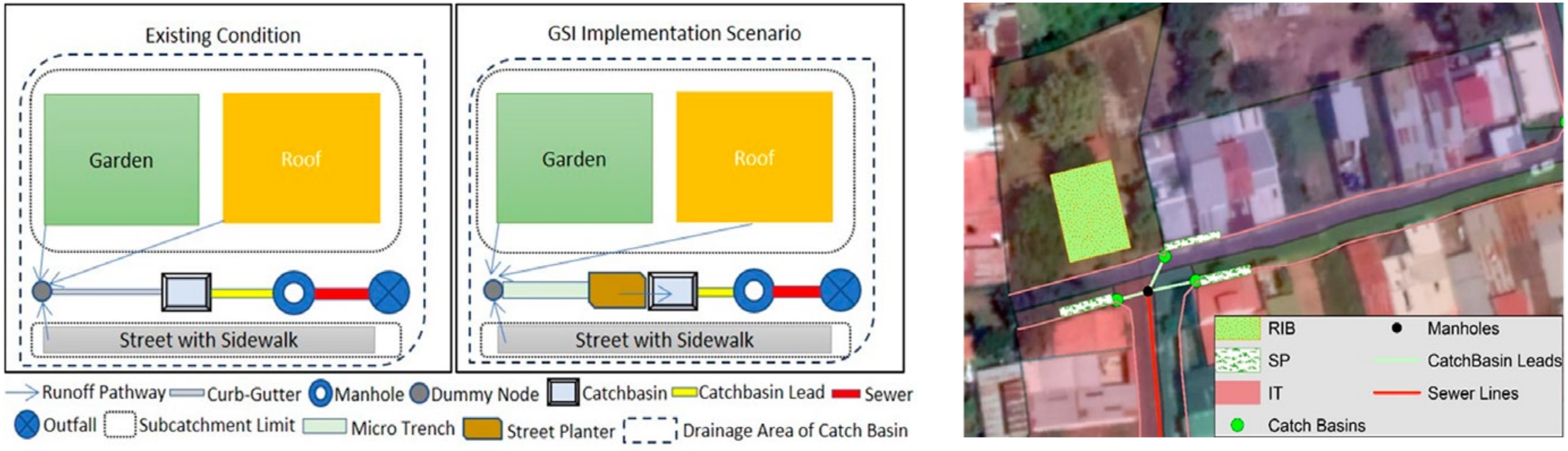

Figure 5.4. Detailed view of the site within the drainage area in the Real-World Lab where Nature-based Solutions were modeled as part of an Urban Green Infrastructure.

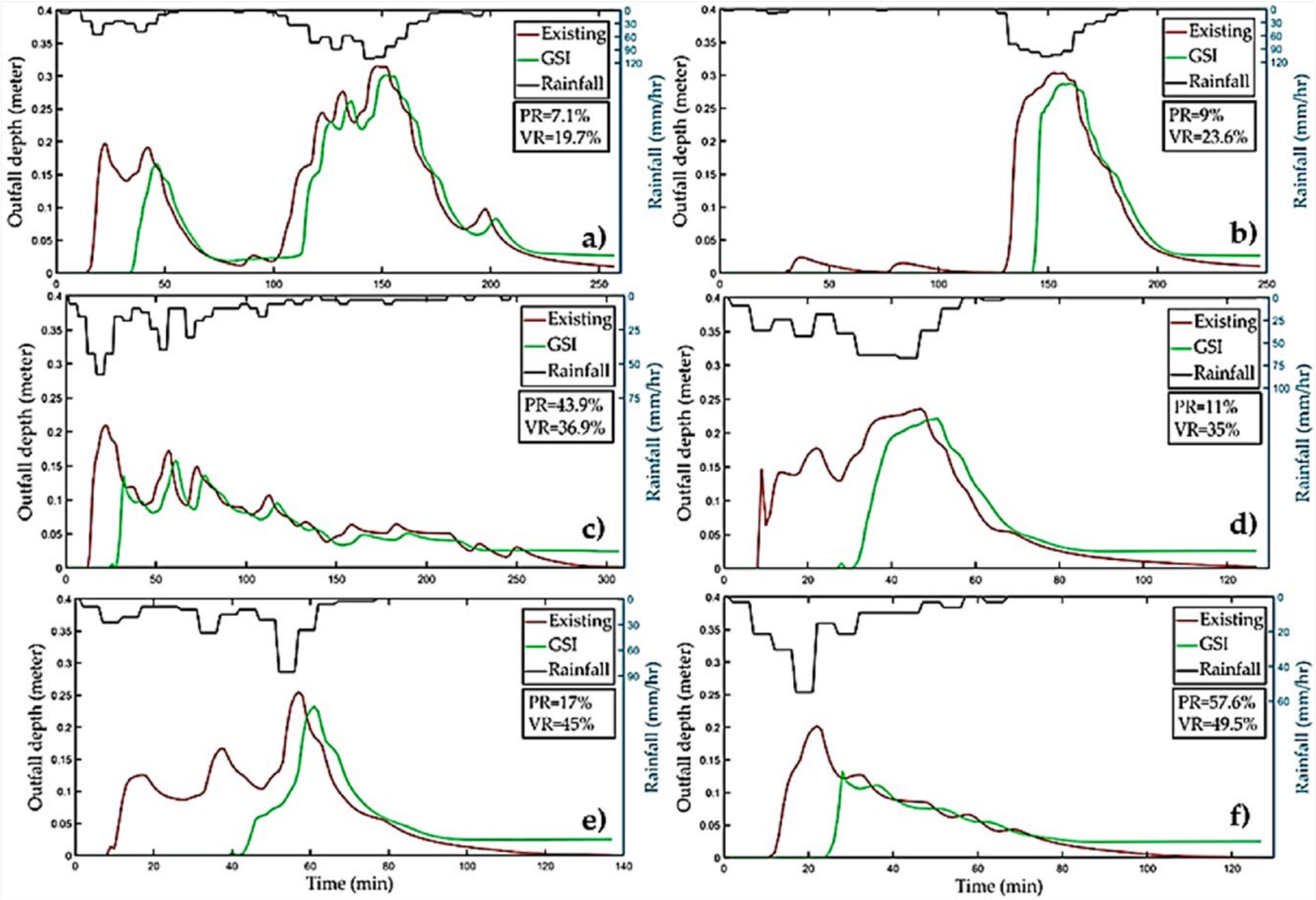

Figure 5.5. Hydrological modeling results (water level at the drainage area's outfall) for the existing drainage system (red line) and with NbS (green line, here named GSI) for different rainfall events (a – f). Peak Reduction (PR) and Volume Reduction (VR) as a result of NbS are indicated.

In the model applications presented, the level of detailing in the representations was reduced, though spatially explicit placements and design criteria remained the basis for developing upscaling scenarios based on the insights from the RWL.

For more information about the hydrological modeling of Nature-based Solutions in a Real-World Lab please refer to:

Towsif Khan, S., Chapa, F., Hack, J. (2020). Highly Resolved Rainfall-Runoff Simulation of Retrofitted Green Stormwater Infrastructure at the Micro-Watershed Scale. Land 9(9), 339. https://doi.org/10.3390/land9090339

Accounting for spatial heterogeneity and actual availability of space for particular Urban Green Infrastructure elements

Several studies have investigated the capacity of Nature-based Solutions (NbS) as sustainable urban flood management strategies, highlighting three main mechanisms of stormwater runoff control: infiltration, retention, and storage. While NbS can operate through one or more of these principles, their capacity is intrinsically related to the configuration of the built environment. Therefore, Urban Green Infrastructure (UGI) design and planning must take account of the site-specific spatial heterogeneity of a place, especially if implementation is intended within a highly urbanized watershed. To accomplish this, a detailed study of the land use distribution permits a tailored UGI network design, in turn increasing the potential for reducing runoff volume and thus contributing to effective urban flood management.

To implement an Urban Green Infrastructure (UGI), it is important to consider site-specific constraints such as the availability of space for particular UGI elements across different parts of an urbanized watershed, as there can be significant spatial heterogeneity.

In a follow-up study, insights from Towsif Khan et al. (2020) and the Real-World Lab were used to compare the residential area containing the Real World Lab with other residential and industrial zones in the surroundings (Figure 5.1), looking at land use characteristics, space availability and UGI suitability.

We developed a methodology to assess the potential for implementing suitable UGI in residential areas based on the characteristics of the road network and open spaces, i.e., traffic density and geometry. Using it, we evaluated the potential for street planters (SP), infiltration trenches (IT), and bioretention cells (BC) for this urban setting. Moreover, UGI retrofitting in parks and riparian zones was estimated considering raingardens (RG) and swales (SW), whereas for industrial zones this assessment included the potential implementation of rain barrels (RB), green roofs (GR), and permeable pavements (PP). The potential of different road types (Figures 5.6 and 5.7.) and open spaces for retrofitting permeable pavements, infiltration trenches, bioretention cells, street planters, swales, and raingardens was quantified and spatially determined for the three residential neighborhoods. In a similar manner, the potential of large parking lots and rooftops for retrofitting permeable pavements, rain barrels and green roofs was quantified and spatially determined for 7 industrial zones.

Aerial view of the drainage area outfall of Siglo XXI neighborhood in the Real-world Lab, Flores, Costa Rica.

Based on the UGI implementation potential, retrofitting scenarios were developed and modeled using the Storm Water Management Model (SWMM) to assess runoff and peak flow reductions in both residential and industrial neighborhoods. This work clearly showed how site-specific constraints determine the potential degree and type of Urban Green Infrastructure. Hence, the ability to reduce runoff through Urban Green Infrastructure depends on urban built-up characteristics, meaning that a context-adapted Urban Green Infrastructure development for different areas is needed (Figure 5.8).

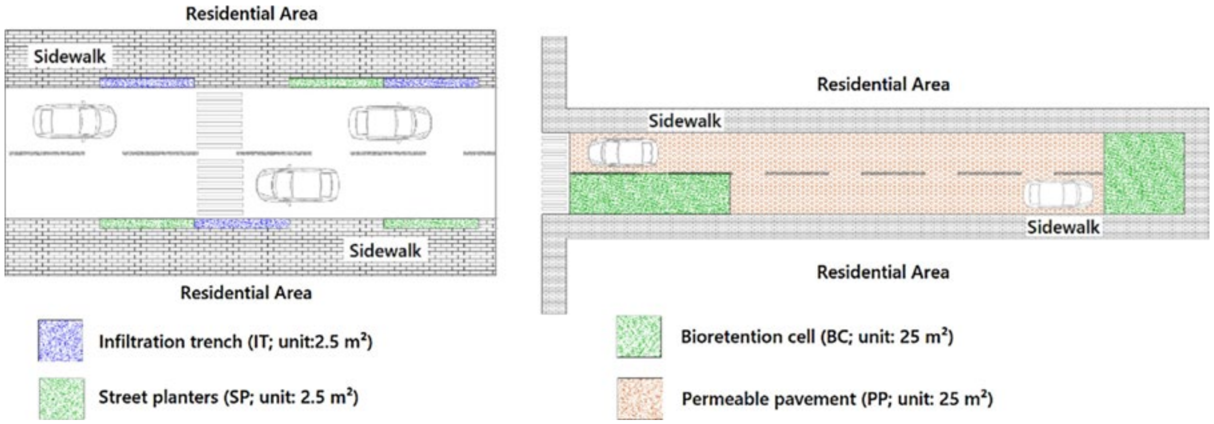

Figure 5.6. Schematic implementation of selected UGI in secondary roads (IT & SP; left) and in residential roads (BC & PP; right).

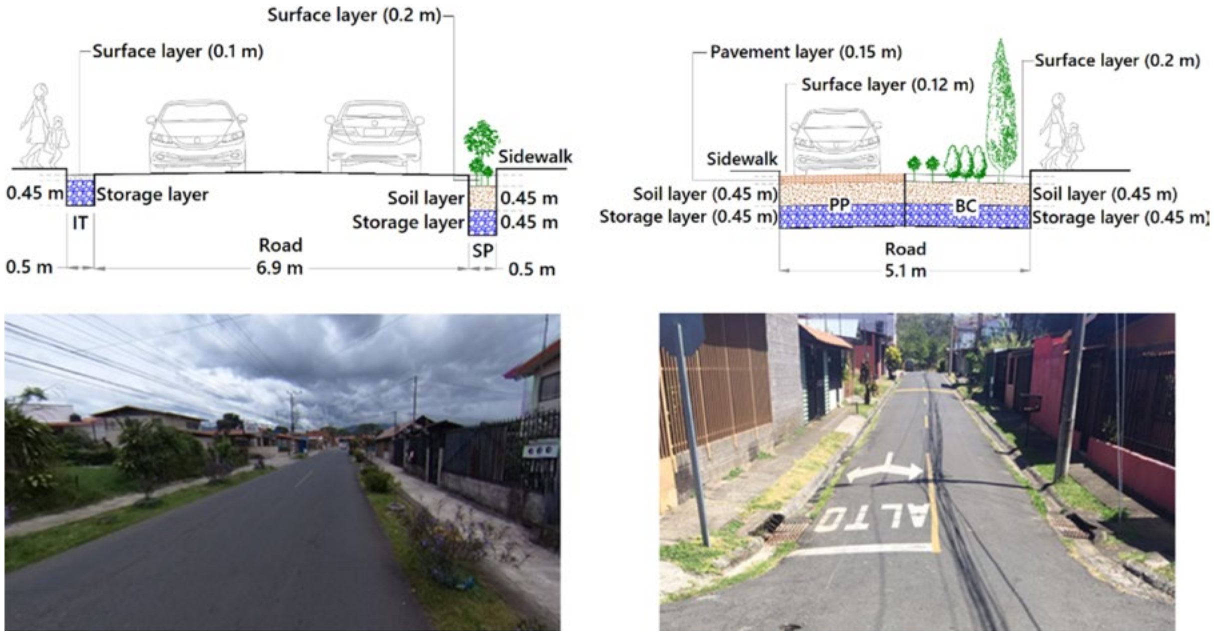

Figure 5.7. Cross-section representation (tops) and street view (bottoms) of selected Urban Green Infrastructure in secondary roads (infiltration trenches and street planters; left) and in residential roads (bioretention cell and permeable pavement; right).

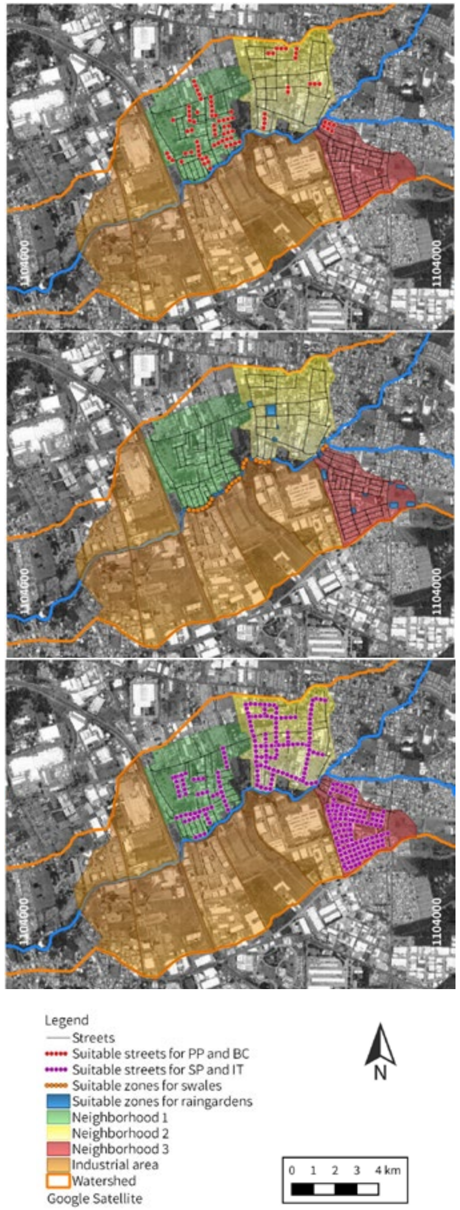

Figure 5.8. Roads and open spaces in the three residential neighborhoods identified as suitable for Urban Green Infrastructure implementation. Top: permeable pavement (PP) and bioretention cell (BC); middle: swales (SW) and rain gardens (RG); bottom: street planter (SP) and infiltration trench (IT).

Study area	Total Area (km²)	Total length of road network (km)	Total road area (km²)	Density of road network (km/km²)	Permeable pavement (m²)	Bio-retention cells (m²)	Street planters (m²)	Swales & Rain gardens (m²)	Swales & Rain gardens (m²)	Rain barrels (%)	Green roofs (%)	Total (%)
Residential neighborhoods N1 – N3												
N1	0,55	7,75	0,053	14,1	1,90%	0,21 %	0,18%	0,18 %	0,14%	–	–	**2,61%**
					(10385)	(1200)	(1013)	(1013)	(350 & 450)	–	–	
N2	0,55	6,76	0,049	12,3	0,50%	0,06%	0,23%	0,23%	0,32%	–	–	**1,34%**
					(2970)	(350)	(1267)	(1267)	(300 & 1050)	–	–	
N3	0,36	7,14	0,052	19,8	0,27%	0,03%	0,41%	0,41%	0,71%	–	–	**1,83%**
					(1000)	(100)	(1485)	(1485)	(150 & 2500)	–	–	
Industrial Areas (IA) 1 - 7												
IA 1	0,402	–	–	–	2,49%	–	–	–	–	0,05%	1,24%	**3,78%**
IA 2	0,371	–	–	–	2,70%	–	–	–	–	0,01%	0,27%	**2,98%**
IA 3	0,391	–	–	–	2,56%	–	–	–	–	0,05%	1,02%	**3,63%**
IA 4	0,435	–	–	–	2,30%	–	–	–	–	0,02%	0,46%	**2,78%**
IA 5	0,241	–	–	–	4,15%	–	–	–	–	0,04%	0,83%	**5,02%**
IA 6	0,137	–	–	–	7,30%	–	–	–	–	0,07%	1,46%	**8,83%**
IA 7	0,345	–	–	–	2,90%	–	–	–	–	0,03%	1,16%	**4,09%**

Table 5.2. Residential neighborhoods and industrial areas assessed in the SEE-URBAN-WATER Real-World Lab and surrounding areas, with respective placement potential for different Urban Green Infrastructures.

The hydrological modeling results of three residential areas (N1 – N3; Figure 5.8) and one industrial zone (IA 1) for the status quo and with full implementation of the identified UGI potential are shown in Figure 5.9. As the graphs show, the discharge reduction potential through UGIs is greatest for residential area N1, the SUW's RWL, and the industrial area. The residential areas feature varying discharge volumes, peaks and response to UGI implementation.

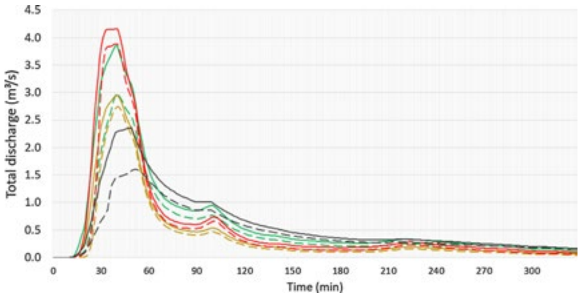

Figure 5.9 Total discharge hydrographs in the three residential neighborhoods and the Industrial Area 1 for the 10-year rainfall event (green N1, yellow N2, red N3, gray IA 1). Before (solid line) and after Urban Green Infrastructure implementation (dotted line).

Aerial view of an open space in the Quebrada Seca-Río Burío river corridor, Llorente, Flores.

Conclusions

Our results revealed that UGI implementation potential (available placement sites and possible parameterizations) is greatly dependent on urban fabric characteristics. Furthermore, the study demonstrated the significance of hydrologically modeling various UGI implementation scenarios since efficiency is affected by land use distribution. For instance, permeable pavements, infiltration trenches, and street planters performed best in terms of reducing runoff when implemented in residential areas. Conversely, in industrial areas, only permeable pavements proved to be efficient for achieving this goal. Overall, industrial areas offer greater potential for UGI implementation and runoff volume reduction.

The placement potential of Urban Green Infrastructure (UGI) is greatly dependent on urban fabric characteristics and thus varies across urban landscapes. Hydrological modeling of possible UGI implementation scenarios is helpful to estimate the performance of different UGI elements and combinations. The most available areas – roofs and street space – are often suitable for green roofs, permeable pavements and/or bioretention cells.

Such an explicit modeling approach enables the development and better assessment of tailored UGI scenarios providing robust model-based evidence that can inform and guide both decision- and policy-making. Furthermore, hydrologic modeling is important to assess the impact of UGI on reducing flood risk, whether as retrofitted measures in the built environment or as in-stream NbS implementation. Such modeling can help evaluate whether retrofitted measures are sufficient to counteract flooding issues or whether additional measures (e.g., flood retention along the river corridor) are necessary to control downstream flooding.

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Cost-Effective Optimization of Nature-Based Solutions

In our study "Cost-Effective Optimization of Nature-Based Solutions for reducing urban floods considering limited space availability", different NbS implementation scenarios for the sub-watershed "Quebrada Aries" of the Quebrada Seca Burío River watershed were modeled and economically evaluated. It could be shown that an optimal combination of NbS can drastically reduce the requirement of large capacity drainage channels and result in cost-effective solutions. This information can help policy-makers to analyze trade-offs between urban development and flood control measures.

Read more in: Singh, A., Sarma, A.K., Hack, J., (2020). Cost-Effective Optimization of Nature-Based Solutions for Reducing Urban Floods Considering Limited Space Availability. Environmental Process. (7), 297–319. https://doi.org/10.1007/s40710-019-00420-8

The methodology developed enables the assessment of both UGI implementation potential in different land use settings and the upscaling of these strategies, taking account of heterogeneous settlement characteristics. Due to its reproducibility, it can also be applied to new urban development projects and transferred to other regions of the world.

The assessment of NbS potential and the implementation and operation of prototypes also provided important insights for evaluating upscaling potential in the form of replicating measures at similar sites within the watershed. The NbS potential identified in the Real-World Lab (Fluhrer et al. 2021; Towsif Khan et al. 2020) was used to develop and model upscaling scenarios based on similar spatial typologies in other parts of the watershed.

For more information about how to estimate the NbS retrofitting potential of different urban areas and their hydrological performance please refer to:

Aparicio Uribe, C.H., Bonilla Brenes, R., Hack, J. (2022). Potential of retrofitted urban green infrastructure to reduce runoff - A model implementation with site-specific constraints at neighborhood scale. Urban Forestry & Urban Greening (69), 127499. https://doi.org/10.1016/j.ufug.2022.127499

Realistic upscaling of Urban Green Infrastructures based on empirical insights from the Real World Lab

Decentralized Nature-based Solutions in the form of Urban Green Infrastructures (UGI) are increasingly promoted to reduce flooding in urban areas. Many studies have shown the effectiveness of UGIs in controlling flooding at plot or neighborhood level. Modeling approaches extrapolating their flood-reducing impact to larger watershed scales are often based on the simplistic assumption of different percentages of UGI implementation. Moreover, such approaches typically do not consider the suitable space for UGI and potential implementation constraints. This study proposes a scenario development and modeling approach for a more realistic upscaling of UGIs based on empirical insights from the SUW project's Real-World Lab (RWL).

The principal aim of this methodological work was to define meaningful and realistic scenarios for retrofitted UGIs in urban watersheds. The project's Real-World Lab was considered as a representative neighborhood (Figure 5.10) as it had been studied and monitored in detail between March 2019 and February 2020 (Neumann and Hack 2019; Towsif Khan et al. 2020; Fluhrer et al. 2021). To assure the area's representativeness, several considerations were taken into account:

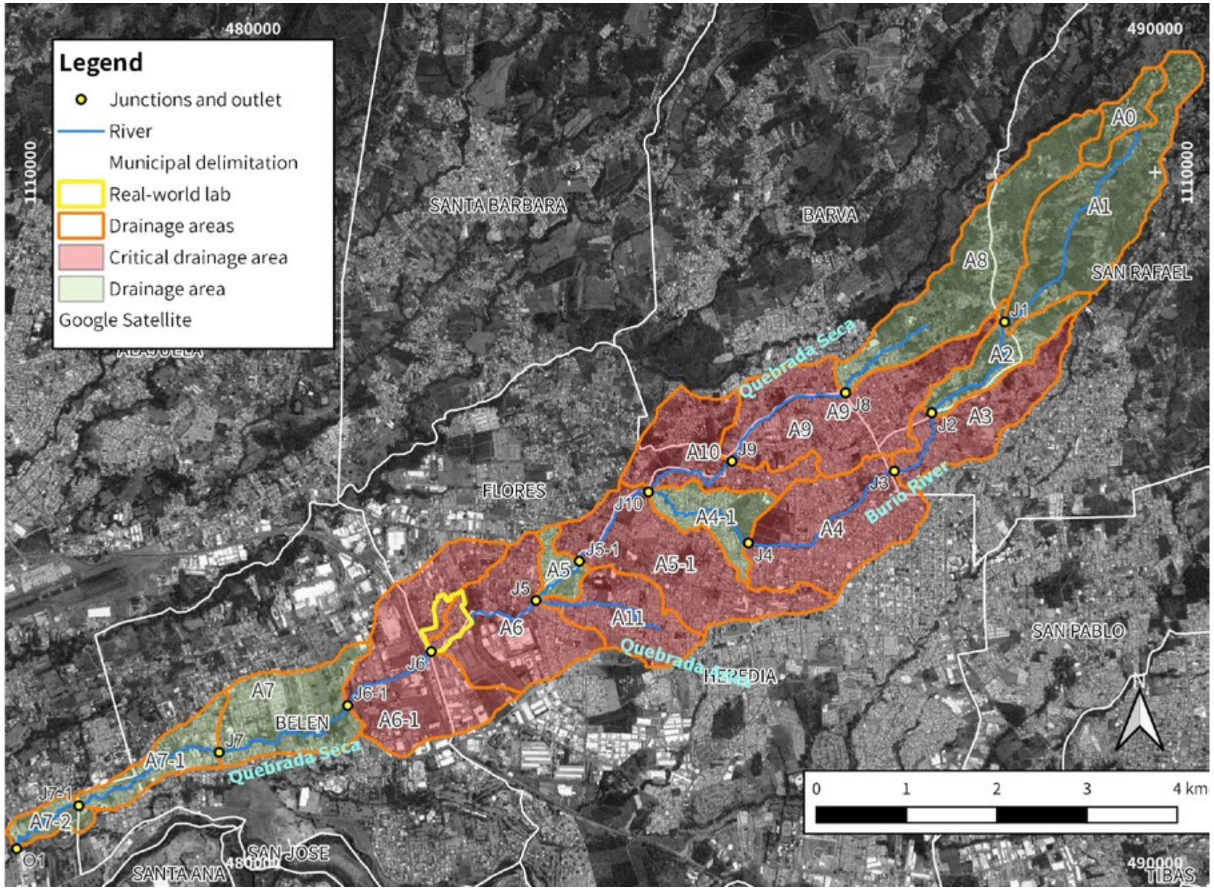

Figure 5.10. Sub-watersheds (Ai), stream network junctions (Ji) and outlet point (O1) used for hydrological modeling of the Quebrada Seca-Río Burío watershed. The SEE-URBAN-WATER Real-World Lab (highlighted in yellow) was used as the representative area for assessing the Urban Green Infrastructure implementation potential of the entire watershed.

1. The area makes up 2.4% of the entire watershed area,
2. on-site visits confirmed similar spatial characteristics at the site and the entire watershed, such as the width of streets, sidewalks and green verges, use of public space, building structures, the spatial distribution of roads of different hierarchies and unbuilt areas,
3. based on the analysis of remote sensing images, urbanization patterns developed similarly in time and space,
4. the Land use / Land cover (LULC) distribution is similar at site and watershed scale.

With these considerations, we believe that the area's representativeness can be assumed to a sufficient degree for the modeling purpose of upscaling Nature-based Solutions (NbS) to the watershed scale. Based on the empirical observations in the Real-World Lab, scenario S1 was defined in terms of constraints and potential for NbS implementation. This scenario is meant to be realistic in terms of its

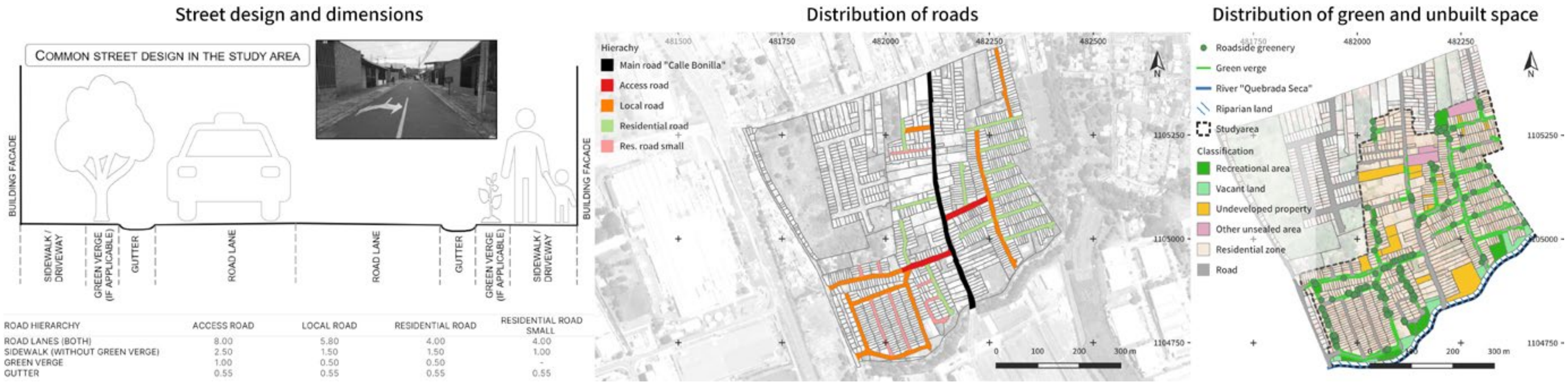

Figure 5.11. Landscape characteristics considered as constraints to a realistic implementation of Urban Green Infrastructure elements: Street design and dimensions of different-hierarchy roads (left), spatial distribution of road hierarchy (middle) and existing green network and available open space (right) for Urban Green Infrastructure in the representative neighborhood (Fluhrer et al. 2021).

technical implementation feasibility regarding space availability and the typical constraints of urban areas, but also as meaningful regarding its socio-political promotion.

UGI potential revealed in RWL as basis for upscaling modeling scenarios

The maximum potential for retrofitted UGIs in public spaces to reduce surface runoff peaks and volume identified in the Real-World Lab was the basis for upscaling to the watershed level (Section 4.3).

The maximum potential for retrofitted UGIs in public spaces (streets, sidewalks, unbuilt open spaces) to reduce surface runoff peaks and volume was investigated in the Real-World Lab (Fluhrer et al. 2021). The UGI scenario S1 resulting from this investigation considered four UGI options to be modeled with the Storm Water Management Model (SWMM): bio-retention cells, infiltration trenches, permeable pavements, and detention basins. To identify potential sites for these UGI options, available green and unbuilt space along streets, sidewalks, parcels, and the riverfront were evaluated. The potential of NbS sites, based on the empirical insights from the RWL, was limited by physical constraints associated with individual street designs (width of the street, gutters, green verges and sidewalks), road types based on the level of traffic intensity and road hierarchy (Figure 5.11), and driveways to properties. Property ownership for public properties and land-use and areas considered as suitable for the placement of UGIs within the representative neighborhood are illustrated in Figure 5.12.

Moreover, the following constraints to UGI implementation were also considered: driveways to private properties, space requirements defined in technical guidelines for the different UGI elements, regulations regarding the placement of street greenery in public space, and resident preferences for the placement of UGI elements.

To measure the latter, residents from the area were interviewed with regard to their opinion on using existing green verges for water treatment, the aesthetic upgrading of green verges with plants, and the appropriation of street space for additional green spaces (Rose, 2020).

While acceptance for the use of existing green verges for water treatment and the aesthetic upgrading of green verges with plants was high, the appropriation of street space for additional UGIs was rejected by almost two-thirds of the interviewed residents (N = 154). Consequently, only moderate UGI interventions at favorable sites in the street network, such as bioretention cells on street corners, and to a higher degree UGI options to be implemented without changing the current functionality of spaces (e.g., infiltration trenches along green verges) were considered (Fluhrer et al., 2021).

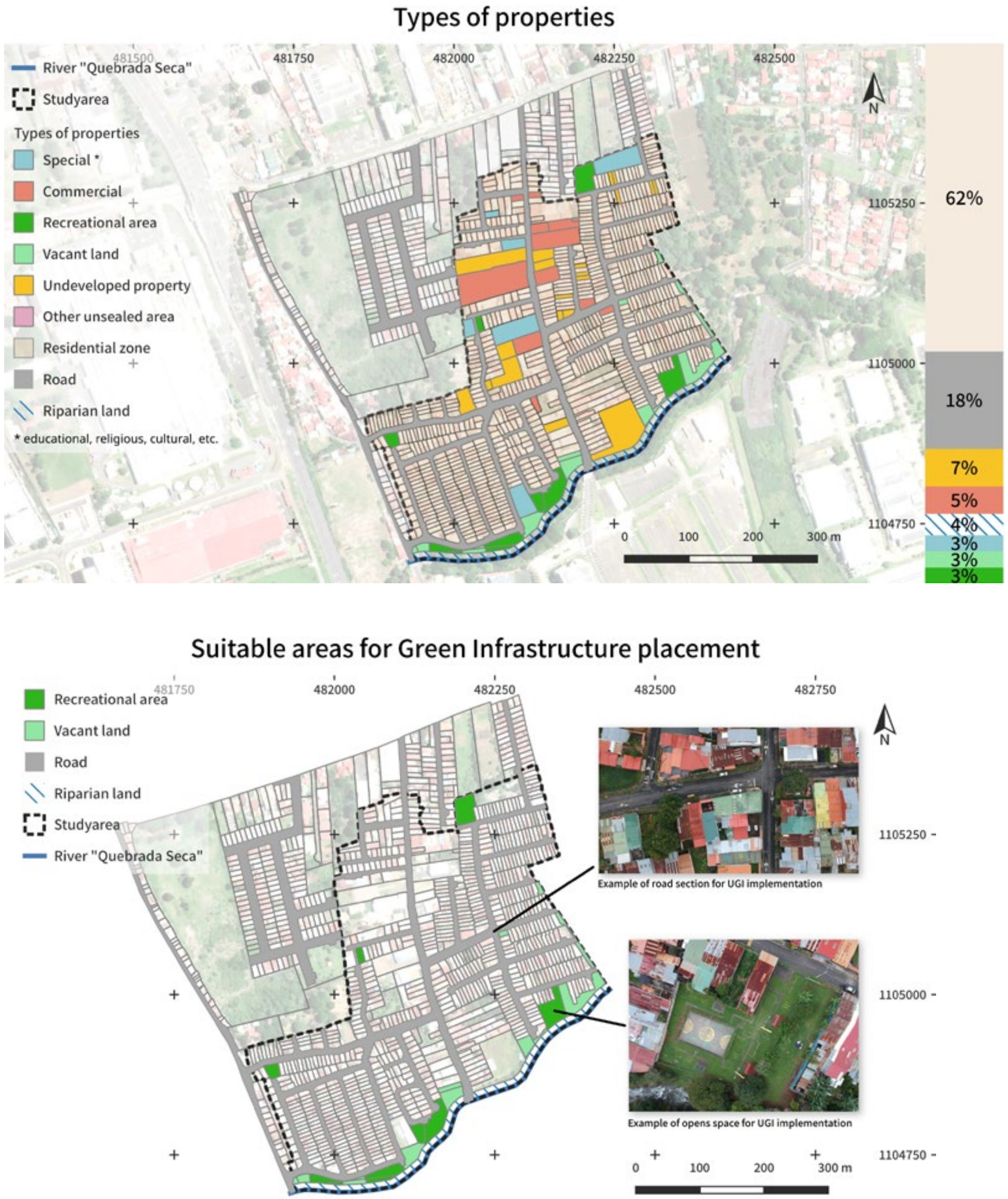

Figure 5.12. Land use distribution (top) and suitable areas (bottom) considered for the placement of Urban Green Infrastructure within the representative neighborhood (Fluhrer et al., 2021).

Based on these assessments, the potential space for implementing each UGI option was determined (Figure 5.13) and translated – taking account of the neighborhood's land-use classification – into representative percentages of land uses suitable for conversion into the four UGI options. These percentages constitute the maximum potential for the four UGI options for a given land-use distribution as retrofitted measures in public space, based on the assumption that all suitable and available space for UGI would be used.

These representative values were then upscaled to other urbanized sub-watersheds represented in the model used for the watershed-scale study. Eight of the seventeen sub-watersheds were considered for simulating UGI implementation. The upscaling was done by applying a linear relationship between the representative UGI percentages for the four UGI options from the experimental site to the land-use distribution of the eight sub-watersheds (47% of the entire watershed) identified as critical areas for flood generation since they produce around 77% of the total runoff volume in the baseline scenario. Hence, the assumption is that areas with similar LULC characteristics have a similar potential for implementing UGI. Since this UGI implementation scenario (S1) only considers public space, the principal agents to promote this transformation are public authorities.

UGI scenario S2 was developed to consider green roofs as the UGI option for private buildings. This scenario was not intended to represent a realistic scenario to the same degree as S1, because the technical suitability of roofs and social acceptance were not analyzed. The scenario considers that 25% of buildings will be converted to green roofs. Thus, 25% of the area classified as buildings was divided into 100 m^2 units representing the roof area of houses. Similarly, 75% of areas defined as buildings

Figure 5.13. Maximum realistic potential for implementing Urban Green Infrastructure in public space within the representative neighborhood, i.e., the Real-World Lab (Fluhrer et al., 2021).

are assumed to install cisterns with a respective volume of 10 m³. Here, 75% of the sub-watershed areas classified as buildings was divided into 150 m² properties. These values represent the typical property size identified in the RWL (Fluhrer et al. 2021). Finally, all UGI elements were modeled individually to compare individual performances (see Chen et al. 2021 for a detailed description). Table 5.3 summarizes the assumptions regarding land-use conversions into UGI for the two considered scenarios.

Our results show that upscaling the full UGI potential could significantly reduce surface runoff, peak flows, and flood volumes in downstream areas of the watershed (Table 5.4). Permeable pavements have the highest potential for reducing flooding in public space while cisterns perform best at property level. These results can guide the formulation of policies that promote UGI.

Our hydrological modeling results showed that permeable pavements were most effective in reducing peak runoff and volume due to their large application potential, followed by cisterns and bioretention cells. The combination of different UGI elements led to a maximum 57% volume and 58% peak reduction for a 10-year rainfall event.

Despite broad recognition of the benefits of UGI, its implementation has largely remained limited to quite small areas. Hence, the potential flood reduction impacts as a result of large-scale UGI implementation can only be investigated through the use of models. With the development of UGI scenarios based on detailed information on implementation constraints from an in-depth study in the SUW project's RWL, this study provides a more reliable and accurate estimation of how a watershed-wide UGI implementation in urban areas with similar characteristics could reduce flooding. With the proposed methodology, both the individual and combined effect of different UGI elements for different precipitation events can be assessed. The comparison of an UGI scenario limited to public space and an UGI scenario limited to properties reveals the potential of two different implementation strategies.

Used as the basis for their hydrological modeling, the detailed fieldwork in a Real-World Lab substantially helped to realistically estimate the Urban Green Infrastructure implementation potential in other urban areas with similar characteristics throughout the watershed.

In comparison to previous UGI implementation studies, this study takes account of site-specific constraints in retrofitting contexts of public space. These constraints reflect the urban neighborhood development characteristics of Latin American cities. This approach is of particular value for urban areas in the Global South where UGI implementation studies and strategies are still lacking. Given that a large share of present and future urban areas

UGI element	Scenario 1 (S1)		Scenario 2 (S2)	
	Area converted (%)	Land use converted	Area converted (%)	Land use converted
Permeable-pavement	17,5	Streets		
Bio retention cell	6,5			
Infiltration Trench	3,0			
Detention basin	0,015	Bare soil, low vegetation		
Cistern			75	Buildings
Green roof			25	Buildings

Table 5.3. Representative percentages of land uses suitable for conversion into the four Urban Green Infrastructure options.

Rainfall event	UGI scenario	Runoff volume (%)	Peak runoff (%)	Runoff coefficient (%)
1 (4-month duration)	S1	60,3	55,7	60,5
	S2	8	21,5	8
2 (10-year event)	S1	57,2	57,9	58,5
	S2	12,4	33,3	13,8
3 (50-year event)	S1	50,5	58,4	51
	S2	8,4	14,2	8,7

Table 5.4. Percentage reductions in terms of total runoff volume, average peak runoff and runoff coefficient when comparing the status quo to the Urban Green Infrastructure scenarios (S1 and S2) under three different rainfall events.

will be located in tropical countries with informal urbanization characteristics and the respective specific implementation constraints, there is a need to further study UGI potential and to develop realistic implementation strategies. Our results may guide policymakers to promote future UGI implementation strategies to reduce flooding.

For more information about NbS scenario development and upscaling to the watershed level please refer to:

Chen, V., Bonilla Brenes, J.R., Chapa, F., Hack, J. (2021). Development and modeling of realistic retrofitted Nature-based Solution scenarios to reduce flood occurrence at the catchment scale. Ambio (50), 1462–1476. https://doi.org/10.1007/s13280-020-01493-8

Off- and in-stream Nature-based Solutions

Nature-based Solutions (NbS) for river restoration include all in-stream and off-stream measures triggering or accelerating the recovery of degraded, damaged, or destroyed river ecosystems. In-stream measures are implemented within the river corridor, while off-stream measures are implemented within a river's drainage area. Examples for in-stream measures are wetland restoration, reconnection of seasonal streams, revitalization of floodplains, or the reestablishment of alluvial forest. Off-stream measures contribute to a more natural water balance and flow regime as well as controlling water quality and erosion. They include bioretention cells, vegetative swales, infiltration trenches, rain gardens, green roofs, or other elements of green stormwater infrastructures and water-sensitive urban design.

Especially in heavily urbanized river basins, the reestablishment of a more natural water balance in the form of off-stream measures is often necessary to achieve flow regimes (reduced runoff volumes and peak flows, augmented base flows) similar to their predevelopment state (Walsh et al. 2005). This implies measures to reduce surface runoff through reducing surface sealing and increasing infiltration and evapotranspiration, thereby providing water storage in soils and water bodies as vegetated space (Collentine and Futter 2016). Common concepts supporting the reestablishment of a more natural water balance and flow regimes are Water Sensitive Urban Design, Urban Green Infrastructures, Sustainable Urban Drainage Systems, or Low-Impact Development. In addition to NbS measures within a river's drainage area, other measures within the river corridor (in-stream) are essential for river restoration in urban areas.

These measures are related to the reestablishment of longitudinal and lateral connectivity – e.g., through the removal of weirs, the installation of fish passes, or the reconnection of floodplains – as well as to a general improvement of the morphology and ecological communities of rivers and their corridors.

The modeling of upscaling scenarios supports the identification of the most effective NbS types at watershed level and assesses the contribution of retrofitted NbS in already developed areas to river restoration (off-stream measures). In addition to retrofitted NbS, potential sites for multifunctional NbS as flood retention measures along the river corridor (in-stream measures) at the watershed scale were identified and modeled, as will be illustrated in the following sections. Since space is very limited in already urbanized areas, unbuilt areas will also be needed for NbS to restore the rivers of the Metropolitan Area.

For more information about different kinds of NbS for river restoration in Metropolitan Areas please refer to:

Hack, J., Schröter, B. (2022). Nature-Based Solutions for River Restoration in Metropolitan Areas: The Example of Costa Rica. In: Brears, R.C. (eds) The Palgrave Encyclopedia of Urban and Regional Futures. Palgrave Macmillan Cham. https://doi.org/10.1007/978-3-030-87745-3_166

Multi-criteria site selection and hydraulic modeling of in-stream Nature-based Solutions in a highly urbanized basin in Costa Rica

In previous studies, the SEE-URBAN-WATER (SUW) team demonstrated the hydrological control capabilities of Nature-based Solutions (NbS) retrofitting, considering different spatial scales and land uses. However, effective flood risk management within highly urbanized river basins requires the application of techniques that, in addition to promoting infiltration and evapotranspiration, are able to provide socio-ecological benefits increasing a site's resilience. An illustrative example of this approach is the implementation of in-stream NbS within the river corridor. Through a range of natural mechanisms such as retention, storage, infiltration, and conveyance, these solutions effectively regulate the onset of floodwaters, contribute to the restoration of river and floodplain ecosystems, and provide communal spaces enhancing residents' well-being.

The following study assessed the implementation of NbS as in-stream measures to reduce the risk of flooding during storm surge events in the Quebrada Seca-Rio Burio watershed. NbS performance was analyzed using the Open Source hydraulic modeling software HEC-RAS of the U.S. Army Corps of Engineers (USACE), quantifying the volume retained by the NbS measure and its impact on reducing the river's total flow.

The localization of in-stream NbS for flood retention as part of a watershed-wide Urban Green Infrastructure (UGI) network was defined using a two-step multi-criteria methodology based on a prioritization strategy that considers benefits in several dimensions. For instance, the main criteria relate to the hydraulic control benefits, i.e., flood storage and management, and runoff and sediment control. Additionally, the methodology includes the assessment of social and ecological benefits such as public green space accessibility, recreational opportunities, aesthetic/cultural value, habitat creation, and biodiversity enhancement.

The methodology is based on two analyses. In the first, a scoring criterion was created using a geographic information system to identify sites with the greatest potential to provide multifunctional benefits. The second analysis was performed using Google Earth satellite images to apply an exclusion criterion based on technical and legal requirements that need to be considered when implementing such measures. The site selection strategies are shown in Figure 5.14.

Critical flood generation areas

Drainage areas identified as critical for flood generation in watershed-scale hydrological modeling were considered as suitable for the placement of storage areas for flood retention (Section 5.1).

In Step 1, we developed a scoring strategy based on seven different criteria to prioritize potential implementation sites:

- Location within critical flood generating drainage areas identified by Chen et al, 2021.
- Location in flood-prone zones, according to Oreamuno and Villalobos, 2015.

- Bearing capacity of the soil, with a preference for loam and clay loam soils.
- Land use classification, considering only bare soil and vegetated lots.
- Site size in order to maximize multifunctionality (hydraulic, ecological, and social benefits).
- Reduction of deficits in public green space, considering the European Commission's standard of 5 m^2 per inhabitant.
- Promotion of recreational use and potential accessibility, considering the European Commission's standard of at least one 0.5 ha green area within not more than 300 m walking distance, or 5 min away from home.

High-resolution Urban Land Use Classification

The High-resolution Urban Land Use Classification developed for the Nicaraguan case study (Chapa et al., 2019) has been used for the study area in Costa Rica to provide a basis for modeling (Chapter 2).

Conversely, in Step 2, we developed an exclusion strategy to reduce possible inaccuracies introduced in the automated land use classification process (Arthur and Hack, 2022) used in point 4 above. Based on Google Earth satellite imagery, the exclusion criteria were used to verify that the sites were not located in areas with native or riparian vegetation or buildings to be preserved. Furthermore, the exclusion strategy considered sites that could provide inlet and outlet connections to the river (without having to cross streets or buildings) as well as geometry constraints such as a minimum length/width ratio of 2:1 as a technical requirement.

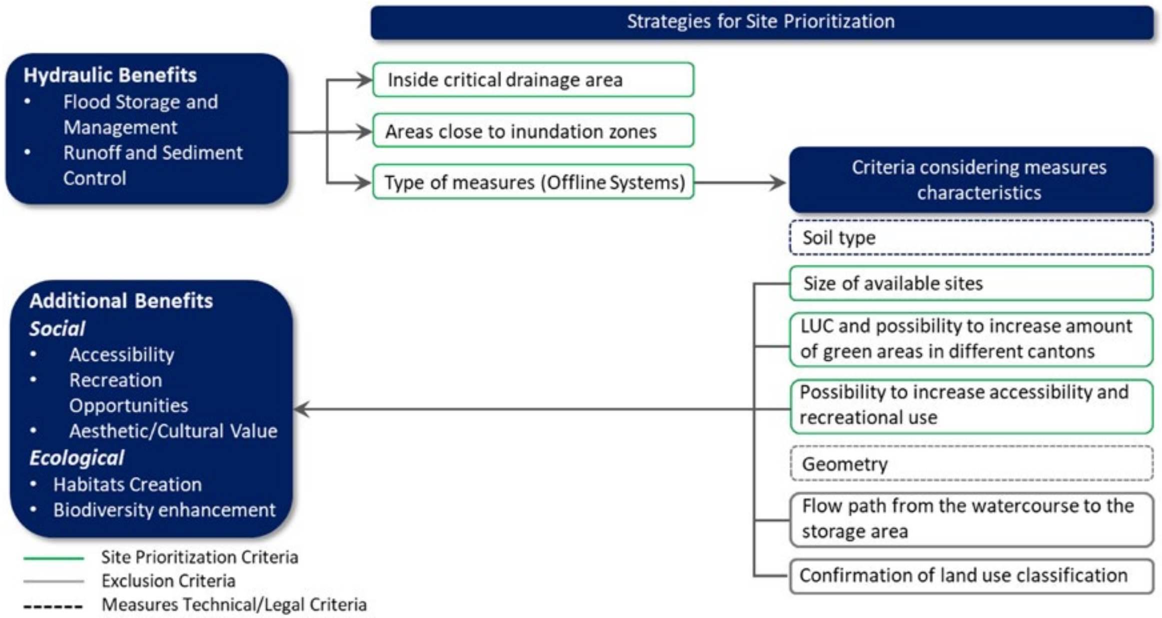

Figure 5.14. Illustration of the multi-criteria storage area site selection methodology.

After applying the two-step methodology to select the most suitable sites to maximize in-stream NbS multifunctionality, we developed a numerical model to quantify the hydraulic performance. A one-dimensional hydraulic model of steady flow was created with the HEC-RAS software, based on a digital elevation model. A total of 142 cross-sections were created at distances between 7 and 120 meters to simulate the river geometry. Furthermore, bridges over the river were added to simulate the flow pattern in the model.

A 10-year return period hydrograph was used (Oreamuno and Villalobos, 2015) to perform the unsteady flow simulation, while data from the Santa Lucia and Juan Santamaría Airport meteorological stations was used to estimate extreme events. For the hydrological modeling, the watershed was divided into 11 sub-watersheds, while three boundary conditions (BC-A, BC-B, BC-C) were defined as water inputs to the hydraulic model. Each boundary condition had a hydrograph representing the runoff volume from the drainage areas to the control point (Figure 5.15 and 5.16).

Figure 5.17 shows the most suitable sites for in-stream NbS implementation after applying the two-step methodology described above. Twelve sites (A-K, M, N, P and R in Figure 5.17) were identified as technically suitable for in-stream NbS implementation in accordance with their potential to increase hydraulic, ecological, and social benefits in the area. Six of these are located within the critical areas identified in Chen et al. (2020), thus allowing flood volumes to be

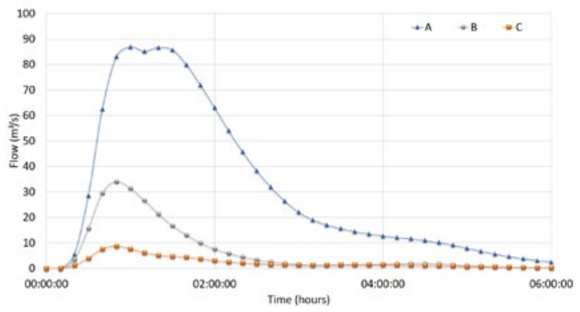

Figure 5.15. Hydrographs used as boundary conditions (BC) A, B and C for hydraulic modeling.

reduced in this zone. Average site size is 2.7 ha, three times the average size of all potential sites. Furthermore, four of the sites significantly increase accessibility to green spaces in the region, complying with the recommendations of the European Commission (2001). Regarding land cover, most of the sites are already green areas; thus, an adequate design for the storage areas could improve biodiversity, promote new habitats, and contribute to the aesthetic value of the area. Moreover, six of the sites are located in the lower part of the zone, which is the most vulnerable to flooding; therefore, the installation of the storage systems there would redirect the flow towards the structures, decreasing the risk of flooding.

Three of the twelve technically suitable sites (D, N and M) were selected for simulation with the hydraulic model HEC-RAS, based on their location, size, technical efficiency and implementation feasibility. The study area was limited to the sector downstream of boundary condition BC-A, due to the availability of runoff information. Site D (Figure 5.17) was selected as the first storage area (SA01) for the purpose of evaluating its impact on the entire drainage area, due to its proximity to boundary condition BC-A. SA01 is a green area 2.98 ha in size. Sites M and N were selected as storage areas (SA02 and SA03) due to their strategic position upstream of the area with the highest risk of flooding; their implementation thus allows an analysis of the direct effect on the most vulnerable areas. 0.92 ha in size, SA02 is classified as a green area, while SA03 has agricultural land cover and is 1.08 ha in size. It is important to highlight that, for these sites to be used as recreational areas, the storage systems should be equipped with an early warning system alerting visitors of any potential risk of flooding and/or closing access to them.

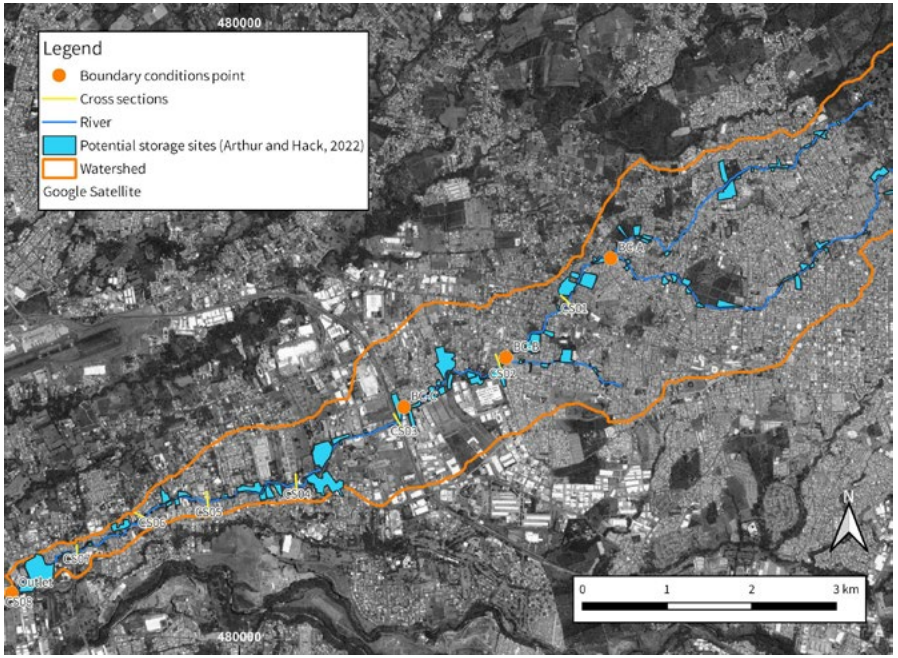

Figure 5.16. Potential storage sites, cross-sections and boundary conditions points within the watershed for use in the suitable site selection and in the hydraulic model.

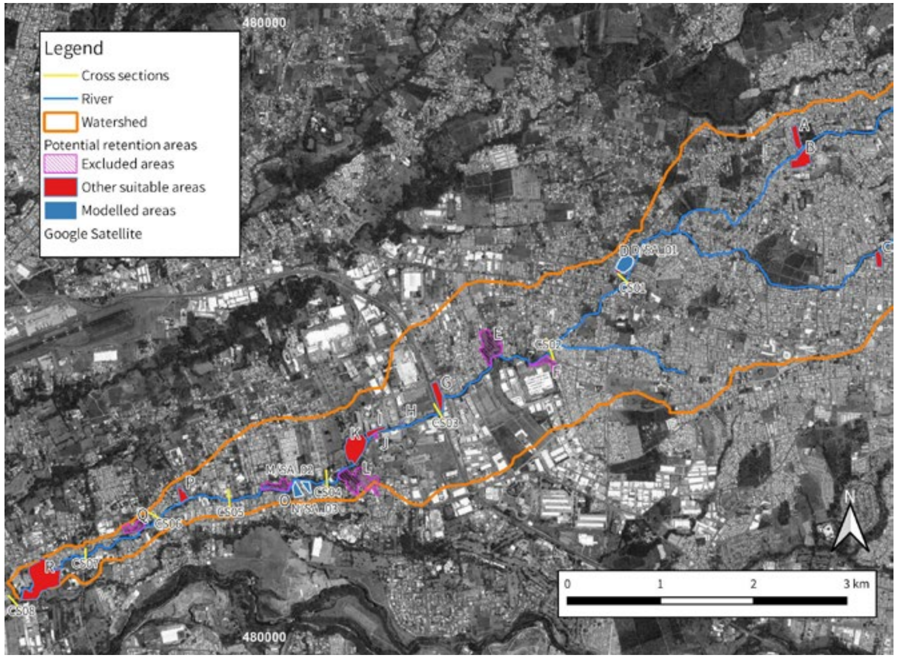

Figure 5.17. Final result of the site selection (blue), showing the areas modeled in HEC-RAS and the cross-sections (CS, yellow) used for the assessment of the hydraulic modeling results.

Once the baseline scenario was created, storage areas were added using the HEC-RAS Storage Area tool and connected to the river through culverts created with the Lateral Structure tool to simulate water inflow and outflow. The 3 m-deep storage areas were designed with a system of steps to stabilize the side slopes that reduce the flow energy at the inlet and allow access for people during the dry season.

Four simulations were developed to assess the storage areas' performance compared with the baseline scenario using the nine cross sections. For this assessment, we used the results at the different cross-sections (CS01 - CS08) shown in Figure 5.17:

- Simulation 01 – Baseline scenario: this shows the current river's hydraulic behavior without the implementation of any storage area. This scenario displays flooding conditions; volume and peak flow are observed in CS03 located in the upper part of the modeled area.
- Simulation 02 – SA01 implementation: SA01's capacity is 54200 m^3 and is located upstream of CS01. The effect of this measure is observed along the entire length of the river section analyzed, achieving a maximum reduction of peak flow and total volume of 10.6% and 8.9%, respectively.
- Simulation 03 – Combination of SA02 and SA03: This scheme has a total capacity of 43900 m^3. The sites are located downstream of CS04 (adjacent to each other); however, their potential is more significant in other cross-sections. For instance, the average reduction of peak flow (5%) and total volume (3.8%) was achieved at CS07 and CS08, respectively.
- Simulation 04 – Combination of SA01, SA02, and SA03: As expected, this scenario had the best performance for flood risk management. A maximum peak flow decrease of 15.3% was achieved at CS08, while the greatest volume reduction was achieved at CS07 at 9.7%.

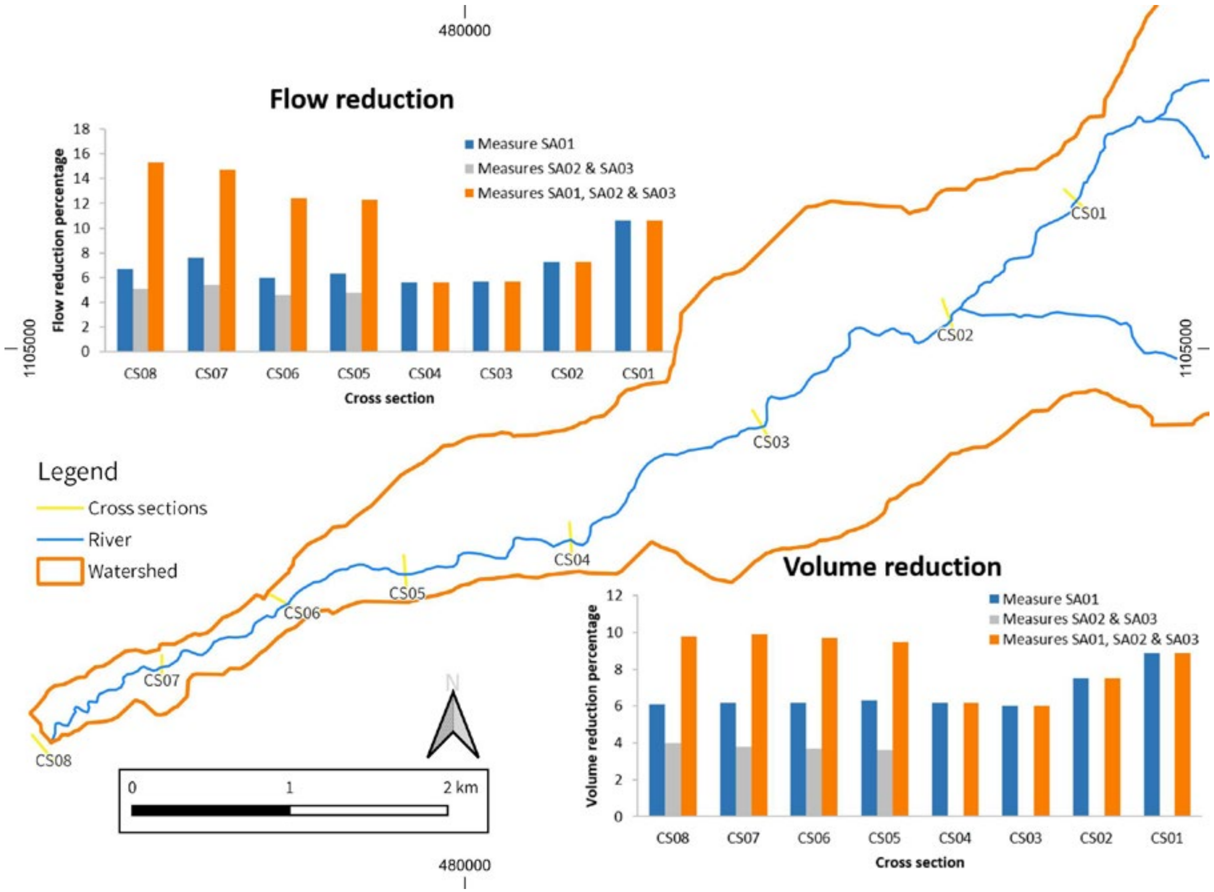

Figure 5.18. Hydraulic modeling results of maximum flow and volume reductions at different cross sections (CS) in the watershed as a result of storage areas (SA) implementation.

The results for flow and volume reductions for all CS are shown in Figure 5.18.

In terms of flooded area reduction (Figure 5.19), simulations showed that NbS implementation in the mid-watershed provides better results than their downstream implementation, since the effect is cumulative and benefits both the middle and lower zones of the watershed. For instance, SA01 alone reduced the flooded area by 3.7%, while the combined effect of SA02 and SA03 was only 1%. Conversely, simulation 04 displayed a 5.04% reduction in this regard. The decrease in flooded area is mostly noticeable in the lower part of the watershed.

We also assessed the influence of NbS implementation in terms of time-to-peak. At CS08, the baseline scenario had a time-to-peak value of 1:50 minutes, which was maintained in simulations 02 and 03 (Table 5.5). In turn, a time-to-peak of 2 minutes was obtained in simulation 04, demonstrating yet again that more storage areas result in better effectiveness.

A field verification was carried out to check the current status of the selected sites based on Google Earth images. This verification allowed us to corroborate that sites SA02 and SA03 maintained the original coverage of green area and agricultural use, respectively. However, site SA01 had since been used for the construction of a residential project, preventing its use for implementing in-stream NbS (Figure 5.20).

This study demonstrated the importance of the NbS location process when developing a multifunctional UGI network. The robust methodology proposed for site selection considered not only hydraulic control but also the promotion of a wide range of socio-ecological benefits. In addition, it is quite flexible. On the one hand, it enables decision-makers to base their final choice on local needs, allowing for the development of tailored solutions. On the other hand, although the scoring scheme was based on previous flood risk management research in the study area, the approach can serve as a methodological framework in other regions that want to integrate multifunctional UGI into urban planning. In any case, it is recommended to validate the results through field visits, as satellite images (in the exclusion strategy) may differ from on-the-ground conditions.

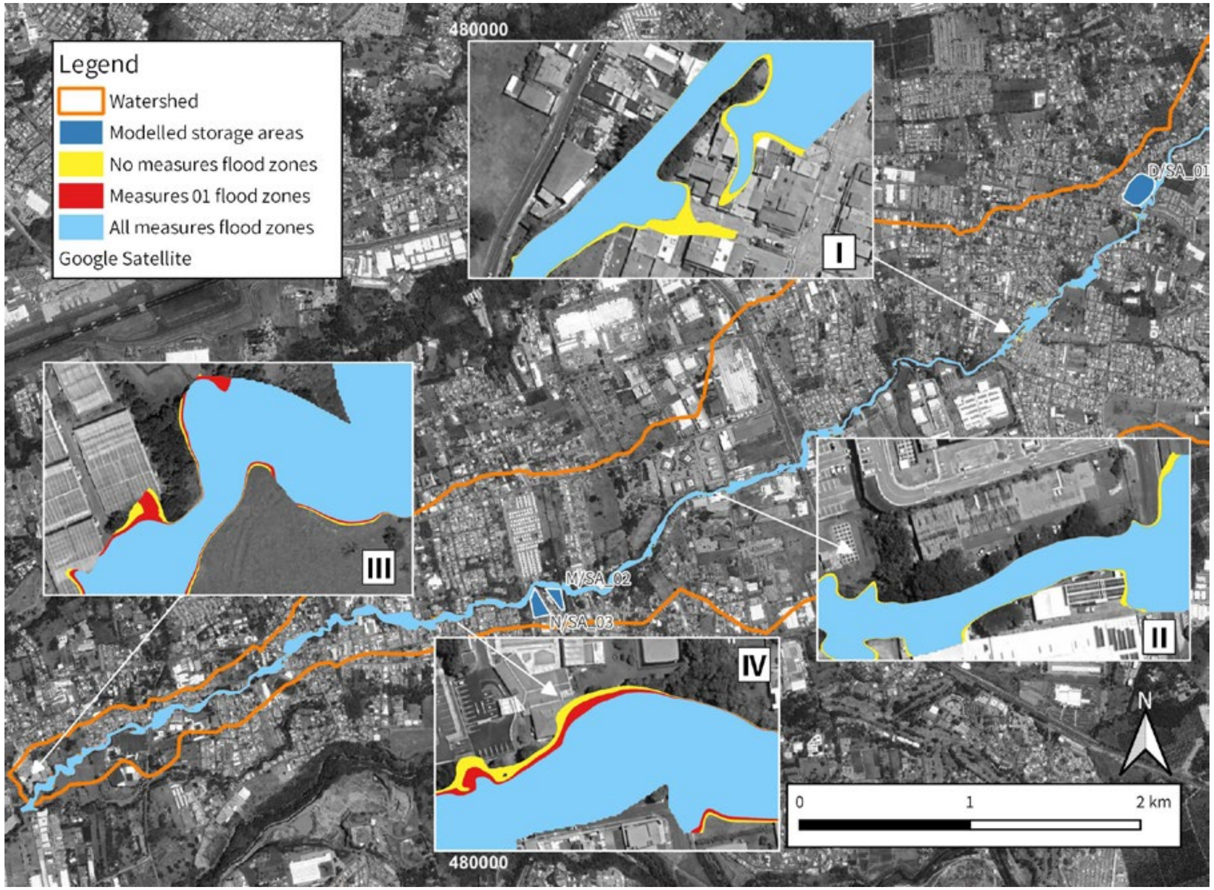

Figure 5.19. Modeled flooded areas for the baseline condition (yellow), for measure 01 (red), and for all measures (blue).

Figure 5.20. Current land use of the modeled sites SA01, SA02 and SA03.

Hydraulic modeling, in turn, revealed that, when distributed in the middle of the watershed, in-stream NbS can help improve effectiveness in terms of reducing flooding areas. This highlighted the significant impacts that downstream areas in highly urbanized environments may face.

	Without Measures (baseline Scenario)	Simulation 01 (Measure SA01)	Simulation 02 (Measures SA02 & SA03)	Simulation 03 (Measures SA01, SA02 & SA03)
Time-to-peak (h:min)	01:50	01:50	01:50	02:00
Peak Flow (m^3/s)	145.1	135.4	137.7	122.9
Peak Stage (m)	861.4	861.3	861.3	861.2
Volume (1000 m^3)	740.1	694.7	710.3	667.7
Flow Reduction (%)	–	6.7	5.1	15.3
Volume Reduction (%)	–	6.1	4.0	9.8

Table 5.5. Influence of Nature-based Solutions implementation (simulations 01, 02 and 03) on several hydrological and hydraulic parameters compared to the baseline scenario (without NbS implementation) at Cross-section 08 (outlet of the modelled watershed).

The recommendation is thus, as shown in the present study, that they should implement a combined scheme (of at least three storage areas) to obtain minimally higher reductions. Further research may be conducted for each individual site, encompassing social aspects fostering residents' willingness to embrace additional measures, particularly those intended to support supplementary recreational purposes.

For more information about hydraulic modeling of in-stream Nature-based Solutions as part of a comprehensive multifunctional Urban Green Infrastructure please refer to:

Lopes Monteiro, C., Bonilla Brenes, J.R., Serrano-Pacheco, A., Hack, J. (2023). Multi-criteria site selection and hydraulic modeling of green flood retention measures in a highly urbanized basin in Costa Rica. Urban Forestry & Urban Greening (85), 127957. https://doi.org/10.1016/j.ufug.2023.127957

5.2. Evaluation of the multifunctionality of Nature-based Solutions and Urban Green Infrastructure

As seen throughout Section 5.1, the SEE-URBAN-WATER (SUW) team explored the potential of Nature-based Solutions (NbS) and Urban Green Infrastructure (UGI) to address the major challenge of increased volumes and peak discharges in urbanized watersheds. However, cities are complex socio-ecological systems characterized by high competition for space. Hence, multifunctional solutions capable of taking these interactions into account, especially in the context of climate change and accelerated urbanization, are needed. Multifunctionality, along with connectivity, is regarded as a critical component in the promotion of UGI, with ecological, social, and economic functions needing to be explicitly examined. However, beyond mere consideration, the call today is to operationalize such multifunctionality, converting it from a theoretical cornerstone in UGI planning to a practical tool strengthening decision-making in urban water management.

Aside from surface runoff control, UGI's hydrological control capabilities include increasing groundwater infiltration capacity and improving water quality, both of which benefit the overall status of receiving water bodies. Moreover, depending on the NbS type, these infrastructures can serve as a decentralized water recycling and supply solution. The ecological benefits, in turn, include optimized microclimates, biodiversity augmentation, and the promotion of ecosystem connectivity, all of which represent not only advantages for the environment but also for the inhabitants that interact with these retrofitted spaces. Therefore, in addition to the benefits implicit in improving the urban environment, local communities may have access to better cultural, recreational, and educational opportunities, potentially positively impacting their health and well-being.

Quebrada Seca-Río Burío, Belen, Costa Rica.

As can be seen, all these benefits are interrelated, which is why the assessment and quantification of multifunctionality are key to building resilient cities. The following describes SUW's work addressing several hydrological, ecological, and social benefits from a conceptual and practical perspective.

Assessing multifunctionality of Urban Green Infrastructure in the Real-World Lab

The SEE-URBAN-WATER (SUW) research group investigates the role of Urban Green Infrastructure (UGI) in providing multiple benefits to society and ecosystems through implementing multifunctional Nature-based Solutions (NbS) for stormwater management, flood control, wastewater treatment, and urban river restoration. Besides these multi-dimensional advantages, society also benefits from improved habitat quality and recreational potential in urban green spaces, rivers, and riparian areas. A guiding idea is to take advantage of the existing ecological potential of urban open space, rivers and riparian areas by linking the targeted ecological improvement of these areas with the provision of additional benefits to society. Thereby, ecological improvement and protection become directly related to the sustainable use of these ecosystems by society. The development of possible NbS designs, geometries and placements as part of an Urban Green Infrastructure was the subject of various studies within the SEE-URBAN-WATER project. Alongside spatial suitability assessments and placement strategies for NbS and the modeling of their hydrological and hydraulic performances in different spatial contexts, we also assessed their potential to function in multiple ways. Apart from their hydrological functions, their climate-regulating function as well as their ecological and social functions were analyzed.

SUW previously (Lopes Monteiro, 2023) addressed NbS multifunctionality as a selection criterion in the in-stream NbS localization process. This work demonstrated that simply deploying NbS measures does not result in multifunctional schemes.

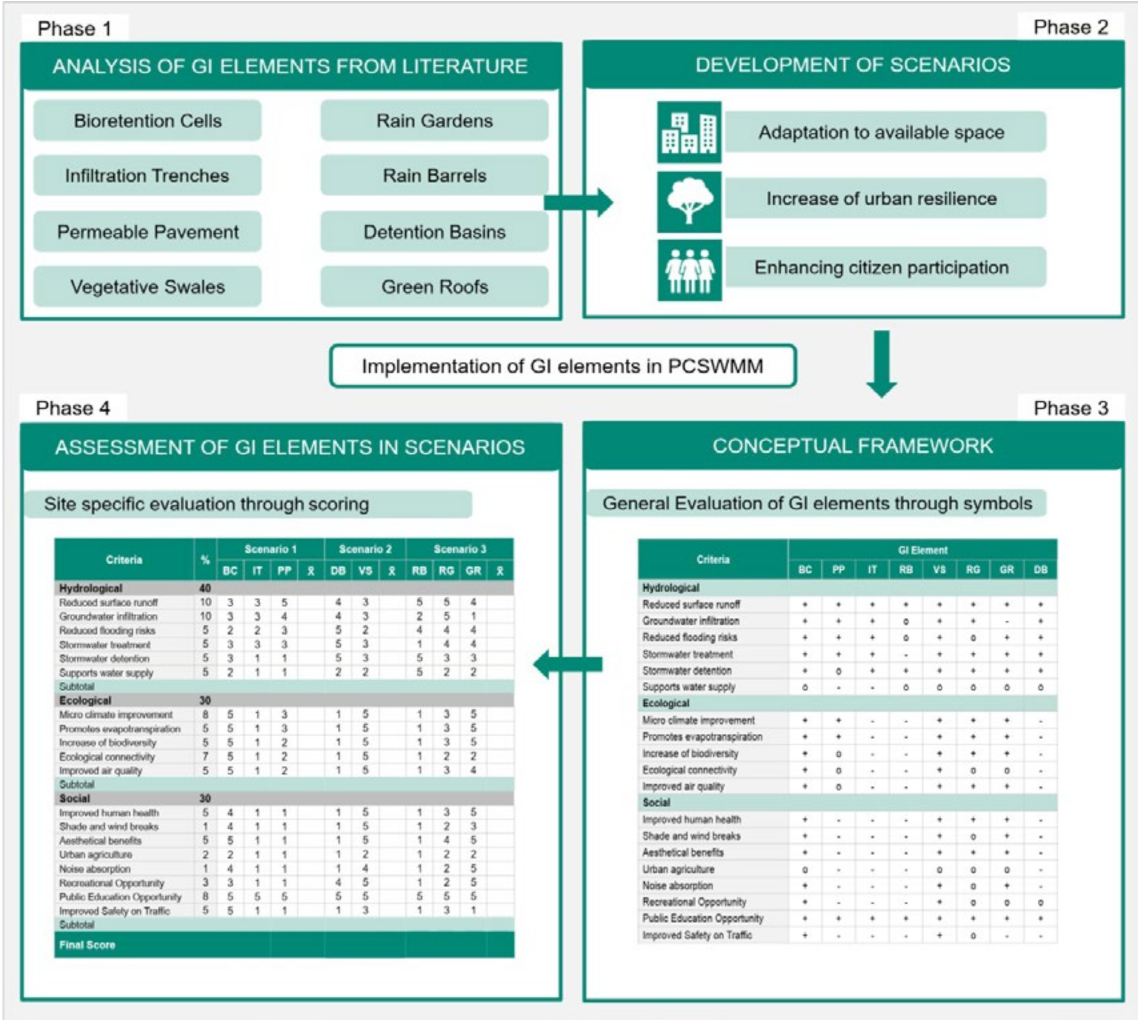

Figure 5.21. Four-phase methodology for assessing and quantifying the potential of different Urban Green Infrastructure elements to provide hydrological, social and ecological benefits under different implementation scenarios (Milagres, 2020). BC: bioretention cells; DB: detention basins; GR: green roofs; IT: infiltration trenches; PP: permeable pavements; RB: rain barrels; RG: rain gardens; VS: vegetative swales.

Far from being a “one-size-fits-all” installation, understanding local challenges is required in order to develop solutions tailored to a site’s technical and socio-ecological needs.

With this in mind, SUW developed a four-phase methodology for assessing and quantifying the potential of different UGI elements to provide hydrological, social, and ecological benefits under different implementation scenarios in the SUW Real-World Lab (Figure 5.21).

Figure 5.22. Urban Green Infrastructure elements analyzed with regard to their hydrological, social and ecological benefits (Milagres, 2020).

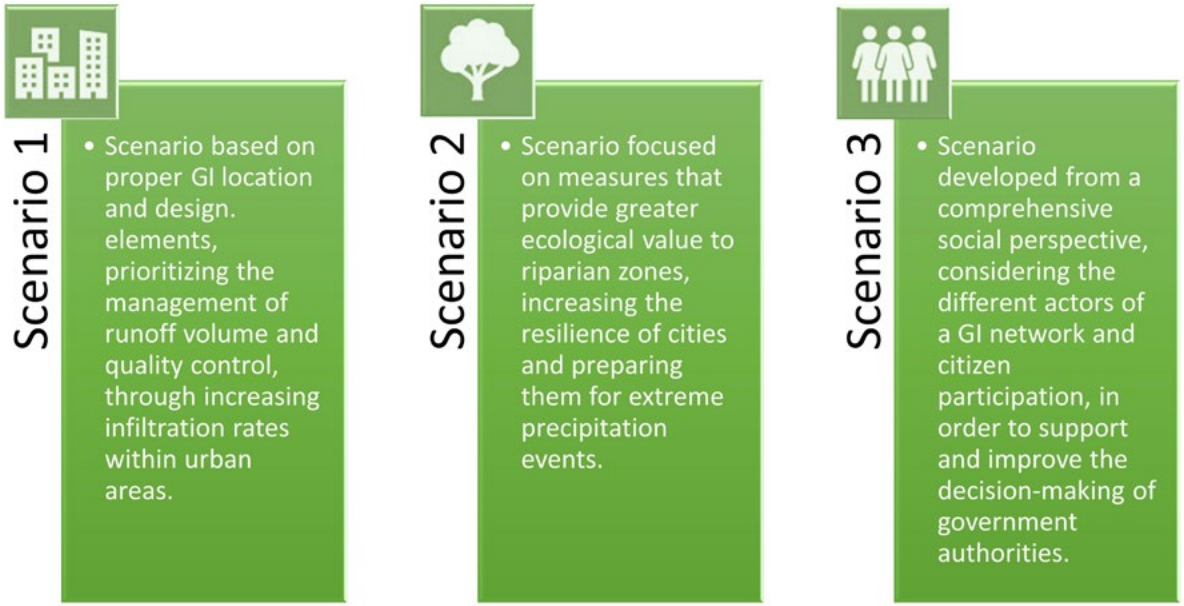

Figure 5.23. Scenarios assuming different development directions to represent the basis for types and placements of Urban Green Infrastructure elements.

First, an extensive and comprehensive literature review was conducted to examine the potential functions of different UGI elements in the three previously mentioned dimensions. The following UGI elements were considered for this assessment: bioretention cells, rain gardens, permeable pavements, infiltration trenches, green roofs, vegetative swales, rain barrels, and detention basins (Figure 5.22).

In the second phase, three UGI implementation scenarios for the RWL were developed, considering different suitable combinations of UGI elements. Each scenario assumes a different, feasible development direction for the area studied based on findings from both the RWL's transdisciplinary work and Fluhrer et al. (2021) (Figure 5.23).

The first scenario focuses on the best use of available street space by applying the design and placement strategies of Fluhrer et al. (2021) as well as NbS prototype development. This scenario combines bioretention cells, infiltration trenches, and permeable pavement. The second scenario prioritizes the improvement of urban resilience against climate extremes, favoring the most hydrologically effective UGI elements and ecological improvements, especially with regard to the RWL's riparian area. This scenario includes implementation of detention basins and vegetative swales. Finally, the third scenario assumes high stakeholder participation in UGI implementation, focusing only on measures suitable for privately or publicly owned developed properties (i.e., rain barrels, rain gardens and green roofs), while neglecting measures in public space. The comparative analysis of these three scenarios enabled us to identify the pros and cons of different development directions exemplified in two drainage areas of the SUW's RWL – the prototype implementation area (the Siglo XXI neighborhood) and the RWL's most densely urbanized neighborhood, El Rosario (Figure 5.24).

Figure 5.24. Location (top) and Urban Green Infrastructure scenarios (1 -3) for the El Rosario and Siglo XXI neighborhoods (bottom) within the SEE-URBAN-WATER Real-World Lab (Milagres, 2020).

In the third methodological phase, the potential of each individual UGI element to facilitate provisioning, regulating, and cultural ecosystem services was associated with the three hydrological, ecological, and social benefit categories (Table 5.6). To do so, we developed a matrix establishing the relationship between the eight selected UGI elements and their respective capabilities to deliver specific benefits. The matrix considered three distinct performance levels: viable (+), non-viable (-), or partially viable (o).

The fourth phase aimed at applying the general UGI performance matrix to the three scenarios. The qualitative performance indicator of the matrix was translated into a quantitative score ranging from 1 (lowest) to 5 (highest), as shown in Table 5.7. Here, the particular UGI types, designs, and spatial configurations in each of the scenarios matter. While the evaluation of the ecological and social benefits of each UGI element was based on the qualitative performance matrix shown in Table 5.7, the hydrological benefits were quantitatively assessed by simulating the UGI scenarios' performance using the hydrological modeling software SWMM.

General assessment	Specific assessment	Description
+	5	UGI element fulfills the observed criteria with an outstanding performance
	4	UGI element fulfills the observed criteria with a good performance
	3	UGI element fulfills the observed criteria with an average performance
o	2	UGI element fulfills the observed criteria by altering the design or technique applied
-	1	UGI element cannot fulfills the observed criteria

Table 5.7. Scoring system for the assessment of Urban Green Infrastructure (UGI) multifunctionality.

Criteria	Urban green infrastructure element							
Hydrological	**BC**	**IT**	**PP**	**DB**	**VS**	**RB**	**RG**	**GR**
Reduced surface runoff	+	+	+	+	+	+	+	+
Groundwater infiltration	+	+	+	+	+	o	+	-
Reduced flooding risks	+	+	+	+	+	+	+	+
Stormwater treatment	+	+	+	+	+	-	+	+
Stormwater detention	+	+	o	+	+	+	+	+
Supports water supply	o	-	-	o	o	o	o	o
Ecological								
Micro climate improvement	+	-	+	-	+	-	+	+
Promotes evapotranspiration	+	-	+	-	+	-	+	+
Increase of biodiversity	+	-	o	-	+	-	+	+
Ecological connectivity	+	-	o	-	+	-	o	o
Improved air quality	+	-	o	-	+	-	+	+
Social								
Improved human health	+	-	-	-	+	-	+	+
Shade and wind breaks	+	-	-	-	+	-	o	+
Aesthetical benefits	+	-	-	-	+	-	+	+
Urban agriculture	o	-	-	-	o	-	o	o
Noise absorption	+	-	-	-	+	-	o	+
Recreational Opportunity	+	-	-	o	+	-	o	+
Public Education Opportunity	+	+	+	+	+	+	+	+
Improved Safety on Traffic	+	-	-	-	+	-	o	-

Table 5.6. Assessment of Urban Green Infrastructure elements regarding the fulfillment [viable (+), non-viable (-), or partially viable (o)] of different hydrological, ecological and social criteria (based on literature research of Milagres, 2020). BC: bioretention cells; DB: detention basins; GR: green roofs; IT: infiltration trenches; PP: permeable pavements; RB: rain barrels; RG: rain gardens; VS: vegetative swales.

Multifunctional performance of individual Urban Green Infrastructure elements

HYDROLOGICAL PERFORMANCE

Among all considered UGI elements, green roofs had the best hydrological performance in terms of runoff control (Table 5.8). This is mainly due to the large area where these elements can be implemented in the El Rosario neighborhood. However, when considering all hydrological benefits, UGI elements with the highest performance scores were rain gardens (4.2), detention basins (4.0), and green roofs (3.7).

Since rain gardens are relatively simple to install on properties, it is reasonable to assume that this UGI type could be implemented to a greater extent in the study area. Therefore, these elements represent a significant opportunity to reduce surface runoff, besides promoting infiltration and stormwater quality enhancement. Moreover, detention basins (Figure 5.25) offer a great retention capacity which is useful in cases of extreme events, protecting the study area from flooding. In addition, due to the size of the basins, these elements enable the treatment of a significant volume of stormwater, thus reducing the pollutant load discharged into water bodies. Conversely, although green roofs' hydrological performance was comparatively high in controlling surface runoff, these elements do not allow the water to infiltrate into the soil for groundwater recharge.

Criteria	**%**		**Scenario 1**			**Scenario 2**			**Scenario 3**			
Hydrological	**40**	**BC**	**IT**	**PP**	**ø**	**DB**	**VS**	**X**	**RB**	**RG**	**GR**	**ø**
Reduced surface runoff	10	3	3	4	1.0	4	3	0.7	5	5	5	1.5
Groundwater infiltration	5	3	3	4	0.5	4	3	0.4	2	5	1	0.4
Reduced flooding risks	5	3	3	3	0.5	5	3	0.4	4	4	4	0.6
Stormwater treatment	10	3	3	3	0.9	4	3	0.7	1	5	5	1.1
Stormwater detention	5	3	3	3	0.5	5	3	0.4	5	4	5	0.7
Supports water supply	5	2	1	1	0.2	2	2	0.2	2	2	2	0.3
Subtotal		3	3	3	3.5	4	3	2.8	3	4	4	4.6
Ecological	**30**											
Micro climate improvement	8	5	1	3	0.7	1	3	0.3	1	4	5	0.8
Promotes evapotranspiration	7	5	1	3	0.6	1	3	0.3	1	4	5	0.7
Increase of biodiversity	5	5	1	2	0.4	1	3	0.2	1	4	5	0.5
Ecological connectivity	5	5	1	2	0.4	1	3	0.2	1	2	2	0.3
Improved air quality	5	5	1	2	0.4	1	3	0.2	1	4	5	0.5
Subtotal		5	1	2	2.6	1	3	1.2	1	4	4	2.8
Social	**30**											
Improved human health	5	4	1	1	0.3	1	3	0.2	1	5	5	0.6
Aesthetical benefits	7	5	1	1	0.5	1	4	0.4	1	3	5	0.6
Urban agriculture	2	2	1	1	0.1	1	2	0.1	1	2	2	0.1
Recreational Opportunity	3	3	1	1	0.2	2	4	0.2	1	2	5	0.2
Public Education Opportunity	8	5	5	5	1.2	5	5	0.8	5	5	5	1.2
Improved Safety on Traffic	5	5	1	1	0.4	1	3	0.2	1	2	1	0.2
Subtotal		4	2	2	2.6	2	4	1.8	2	3	4	2.9
Total		**4**	**2**	**2**	**2.9**	**2**	**3**	**1.9**	**2**	**4**	**4**	**3.4**

Table 5.8. Scoring matrix with the results of the individual Urban Green Infrastructure (UGI) assessment regarding hydrological, ecological and social benefits, as well as the multifunctionality potential (X) of the three scenarios combining sets of UGIs. BC: bioretention cells; DB: detention basins; GR: green roofs; IT: infiltration trenches; PP: permeable pavements; RB: rain barrels; RG: rain gardens; VS: vegetative swales.

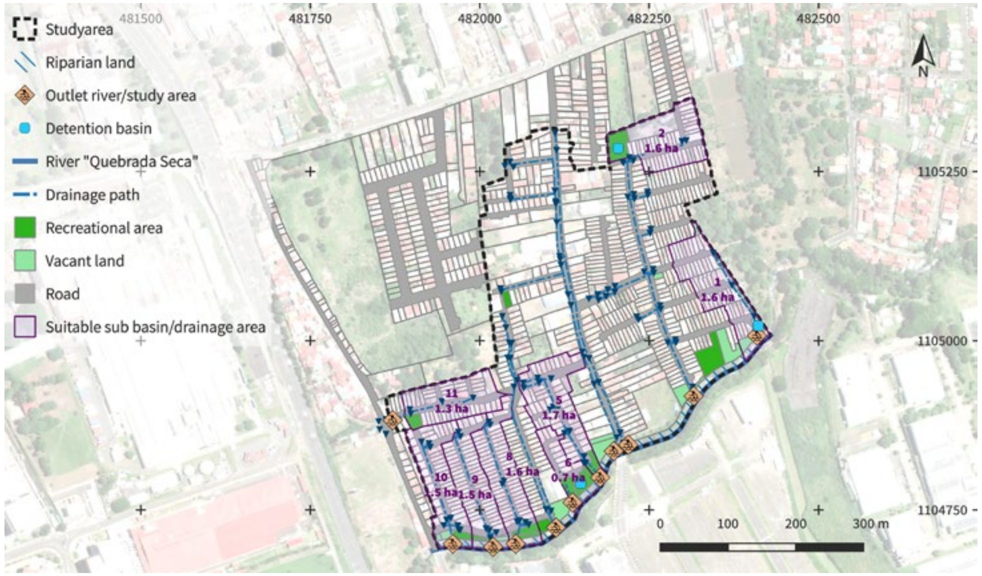

Figure 5.25. Potential placement sites for detention basins in the Real-World Lab according to Fluhrer et al., 2021.

Figure 5.26. Potential placement sites for vegetative swales in the Real-World Lab (Fluhrer et al., 2021).

The UGI elements with the lowest hydrological performance scores were bioretention cells (2.8), vegetative swales (2.8), and infiltration trenches (2.7). Compared to rain gardens, bioretention cells and vegetative swales perform similar hydrological functions. However, the study area offers greater implementation potential (available space) for rain gardens, resulting in better overall results. Since bioretention cells, vegetative swales and infiltration trenches were only considered for implementation in public space, their hydrological benefits are limited due to the lack of suitable implementation space in both neighborhoods, resulting in a low reduction of total surface runoff in the hydrological model. Even for low-intensity rainfall events, their performance was not satisfactory, restricting the main hydrological benefit of these elements in treating first-flush runoff.

ECOLOGICAL PERFORMANCE

Ecological benefits (Table 5.8) are mainly provided by bioretention cells (5.0), green roofs (4.4) and rain gardens (3.6). While the placement of bioretention cells in the study enabled the improvement of ecological connectivity, green roofs and rain gardens had lower chances of meeting this criterion since the locations of these elements were not directly connected to other urban greenery. Since green roofs are placed on buildings, it is possible to cover a large area with this type of UGI without compromising street space. Through the introduction of trees, as well as other medium- and large-size plants, it would be feasible to enhance the effects of CO_2 absorption and the capture of fine particulate matter. Moreover, bioretention cells, rain gardens and green roofs support biodiversity within an area since their respective vegetative layer attracts birds, insects, and possibly other animals. Although vegetative swales (Figure 5.26) were considered suitable only for a small area of El Rosario, they can potentially be implemented along the entire riparian zone, creating a better connection between urban spaces and green areas.

By contrast, infiltration trenches, detention basins and rain barrels (all with a score of 1.0) have little potential for adding ecological value to the evaluated areas. Although these elements foster storage and infiltration functions, their operation and nature (no vegetation included) are closely related to conventional gray infrastructure, limiting the provision of benefits in the ecological dimension.

Figure 5.27. Potential placement site and designs for bioretention cells (in green) in the Real-World Lab in accordance with Fluhrer et al., 2021.

SOCIAL PERFORMANCE

Social benefits (Table 5.8) mainly accrue through bioretention cells (4.0), green roofs (3.8) and vegetative swales (3.5 of 5). Bioretention cells can be implemented in a wide range of public spaces in both neighborhoods (Figure 5.27), thereby increasing the aesthetic value of the built environment while improving the well-being and health of residents. Moreover, this UGI type can be strategically placed at street crossings and traffic control elements, providing a safer environment for pedestrians.

In turn, when designed as common areas on buildings, green roofs can provide recreational, attractive and enjoyable spaces. Likewise, vegetative swales stand out as UGI elements capable of both increasing a neighborhood's aesthetic value and fostering environmental awareness among children and adults. However, they were only suitable for placement in the El Rosario neighborhood, near the riparian zone, therefore limiting their overall impact.

UGI elements not including vegetation in their design performed poorly in the provision of social benefits, i.e., infiltration trenches, permeable pavements, and rain barrels (all with a score of 1.7). The feeling of relaxation and the health benefits provided by UGI are mainly related to the inclusion of plants and nature-based elements. As a result, since these UGI elements operate more like traditional gray infrastructure, few social benefits are achieved. However, they all have a positive effect on natural resources and society by increasing environmental awareness. The UGI implementation potential of the entire RWL is illustrated in Figure 5.28.

Multifunctional UGIs

Following the individual dimension assessment, the multifunctionality of each UGI element was quantified by aggregating the scores based on different weights for each type of benefit, i.e., 40% for hydrological and 30% for social and ecological respectively. The hydrological dimension was assigned greater weight as the score assignation was supported by a numerical model yielding more accurate results. According to this evaluation, green roofs (4.0), bioretention cells (3.9), rain gardens (3.6), and vegetative swales (3.1) can be considered the most multifunctional UGIs (see Table 5.8).

Figure 5.28. Suitable sites for Urban Green Infrastructure placements within the SEE-URBAN-WATER Real-world Lab (Fluhrer et al., 2021).

While the best hydrological results in the hydrological modeling of all UGI scenarios were achieved by green roofs and rain gardens, with the highest total overall scores, green roofs (4.0 of 5), bioretention cells (3.9 of 5), rain gardens (3.6 of 5) and vegetative swales (3.1 of 5) can be considered the most multifunctional UGIs.

Despite their good hydrological performance (scores greater than 3 in all cases), rain barrels cannot be considered multifunctional UGI elements according to the applied methodology since they provide no direct ecological benefits to the study site. Furthermore, the social benefits achievable through this element are limited, being restricted practically to the opportunity of environmental education. The same applies to infiltration trenches, permeable pavements, and detention basins, with these also mainly providing hydrological benefits. While infiltration trenches and detention basins do not fulfil ecological and social criteria, different types of permeable pavements can increase their ecological impact.

For instance, if the pavement also contains a grass layer, these elements can help increase local evapotranspiration and provide new habitats for local fauna and flora. This type of design could provide further ecological impacts in the area.

Scenario assessment of combined NbS

For the scenario assessment, suitable UGI combinations for two neighborhoods of the project's RWL were analyzed, with a focus on the combined implementation potential in terms of the number and extents of UGI elements. The scenario assessment provides insights into feasible future UGI development scenarios based on the RWL's existing spatial characteristics. The scenario assessment was based on the average score of each scenario, considering the weights established for each criterion (Table 5.8). Scenario 1 reflects restricted hydrological characteristics for runoff control due to the high degree of urbanization and the limited size of the UGI elements able to be implemented along the streets without hindering traffic flows. Furthermore, the combination of elements chosen to represent this scenario (bioretention cells, infiltration trenches, and permeable pavements) achieved an average performance of 2.6 in both the ecological and social dimensions. It is worth noting that the bioretention cells were the most valuable elements in this scenario, as their implementation adds ecological and social value.

Through its implementation of detention basins, Scenario 2 proved to be effective in controlling runoff in the case of severe rainfall events. Besides the fact that these UGI elements can retain large amounts of rainwater and reduce downstream flood risks, they are also able to improve stormwater quality by removing particulates. However, while detention basins demonstrated a good hydrological performance in this scenario (4.0), they performed poorly in the ecological (1.0) and social (1.8) dimensions. To cope with this limitation, vegetative swales were considered in the El Rosario neighborhood scenario. Although these elements can increase the aesthetic value of the neighborhood, promote connectivity and create new habitats, their impact in the study area is limited to the riparian zones where they can be implemented.

Scenario 3 had the best overall rating after aggregating the scores by dimension, achieving a result of 3.4. Compared to the other scenarios, this result is most likely influenced by the larger area covered by UGI elements. Although the implementation of green roofs in the entire El Rosario neighborhood is unlikely in the near future, it is important to highlight the performance of this scenario in fulfilling the concept of multifunctionality through the combination of diverse UGI elements. This adds social and ecological value to the area, besides providing a remarkable hydrological performance in controlling runoff.

Recommendations for implementation strategies

The detailed individual performance analysis of eight different UGI elements in the El Rosario and Siglo XXI neighborhoods within the Real-World Lab highlighted the potential of this type of infrastructure for increasing the resilience of cities across three different dimensions: hydrological, ecological, and social. Furthermore, it was evident that overall UGI

UGI element	Benefits	Challenges
Bioretention cells	• Reduction of impervious surfaces. • Aesthetic value. • Creation of new habitats for local flora and fauna. • Microclimate regulation. • Creation of pleasant environments. • Improvement of the quality of life of the population. • When implemented in traffic control elements, enhancement of pedestrians' safety.	• Hydrological control potential may be constrained by a lack of suitable space for implementation.
Detention basins	• High flood control potential	• When designed as conventional gray infrastructure, lower social and ecological benefits. • Requires high degree of planning and financial investment.
Green roofs	• Multifunctional potential. • Microclimate regulation. • Increased evapotranspiration. • Carbon sequestration. • Promotion of urban farming projects. • Improvements in health and well-being, reduction of respiratory diseases (e.g., asthma). • Positive impacts on mental health, reducing stress. • Creation of new habitats for local flora and fauna.	• High implementation costs. • Reduced hydrological control potential if implemented on a small scale.
Infiltration trenches	• Potential for first-flush treatment, reducing pollutant load of stormwater.	• Weak runoff control performance. • Reduced provision of ecological and social benefits. • Need for frequent maintenance to avoid clogging.
Permeable pavements	• Satisfactory performance in runoff control. • Stormwater quality enhancement. • Increased infiltration rate and groundwater recharge.	• Reduced feasibility when replacing other types of pavements.
Rain barrels	• Environmental awareness enhancement. • Low implementation costs. • High availability of implementation area (buildings). • Reuse of stored water: gardening, cleaning tasks, toilet flushing.	• Reduced provision of ecological and social benefits. • Political will may be decisive for encouraging wider adoption.
Rain gardens	• Runoff control. • Increased infiltration rate and groundwater recharge. • Habitat provision for local flora and fauna. • Increased evapotranspiration helping to mitigate the urban heat island effect.	• Reduced provision of social benefits such as aesthetic value. • Expert supervision is required to ensure proper operation.
Vegetative swales	• Increased ecological connectivity along the riparian corridor. • Aesthetic value. • Conveyance functions (e.g., as gutter system)	• Highly dependent on the available space.

Table 5.9. Summary of the pros and cons of Urban Green Infrastructure implementation in the Real-World Lab.

performance is highly dependent on the urban environment in which it is implemented, in addition to other relevant geographic and climatic characteristics that influence its efficiency. Table 5.9 lists the different benefits of UGI and the challenges it faces in the study area. This information is relevant in other contexts as it lays the foundation for sustainable urban water management in similar densely populated areas. Nevertheless, it should be noted that multi-stakeholder engagement, including the participation of the public sector, the private sector and citizens, is key to enhancing the quality and legitimacy of urban water decision-making.

Conclusions

In the near future, climate change is projected to significantly amplify the impact of hydrometeorological hazards in urban environments. Central America, including Costa Rica, is set to experience a rise in the frequency of extreme rainfall events, increasing the risk of urban flooding. As a result, governments are challenged to find sustainable solutions promoting city resilience while mitigating the social, economic, and environmental damage caused by such events. The implementation of Urban Green Infrastructure (UGI) is gaining in popularity, primarily for hydrological control, i.e., as elements complementing a city's drainage system. As long as its design considers its multifunctional potential, this novel technology can provide several ecological and social benefits. In light of this, the SUW research group proposed a methodology to evaluate the multifunctionality of several UGI elements, looking at their hydrological, ecological, and social benefits. Different combinations of UGI elements are possible, depending on suitable implementation space and development strategies, thus promoting such a design at neighborhood or city level. For instance, green roofs, bioretention cells, rain gardens and vegetative swales proved to be the most multifunctional systems in the El Rosario neighborhood. Furthermore, the best results were obtained when a development scenario involving both public and private stakeholders was considered.

These results can serve as a basis for local planners and community organizers to determine local-level development goals and define what UGI elements contribute most to achieving them. Though the methodological framework proposed here provides orientation, it can be further improved to achieve a more accurate assessment of UGI multifunctionality, especially in quantitative terms, by establishing indicators to compare and evaluate these elements. Moreover, fulfilment of the proposed hydrological and ecological criteria can be investigated more accurately through field experiments. For instance, air quality improvement can be quantified through air pollution measurements, microclimate improvement through temperature measurements and evapotranspiration through daily changes in soil moisture. In addition, social criteria can be assessed through interviews and questionnaires with residents.

It is evident that UGI adoption represents a significant paradigm shift in urban water management where traditional gray infrastructure has been widely (and almost exclusively) promoted. Accordingly, strengthening the relationship between local government and the community is key to ensuring wider adoption and the long-term successful operation of these non-conventional approaches. For instance, thematic workshops or environmental awareness campaigns can both inform the community about the benefits of UGI and increase interest and willingness to implement this infrastructure at residential level. In terms of public-managed projects, it is recommended that local governments include citizens, not only in the design and planning stages but also in maintenance and supervision.

Impact of different degrees of urbanization and Urban Green Infrastructure scenarios on micro climate regulation in the Real-World Lab

Urbanization can have a significant impact on the local microclimate. Building density and increased surface sealing induce changes in outdoor climate, surface temperature, humidity, and wind speed and direction, affecting water and energy balances (Li et al., 2022). On the one hand, post-development conditions can reduce water infiltration into the ground, leading to increased surface runoff and decreased groundwater recharge. On-site and downstream hydrological processes may also be affected, inducing flood emergencies (Chen et al., 2022). On the other hand, drastic changes in land use can alter surface energy flows and reduce evapotranspiration, leading to an urban heat island effect. This, in addition to creating unpleasant environments for citizens, can have an impact on the amount of energy required to heat or cool buildings, thereby influencing normal local energy consumption patterns (Allen-Dumas et al., 2020).

Given these growing challenges, along with global urbanization trends, Urban Green Infrastructure (UGI) has received significant attention as a way to improve local microclimates. New greenery elements in built environments can improve evapotranspiration and on-site infiltration, positively impacting water and energy balances. Realizing the importance of quantifying these benefits, the SEE-URBAN-WATER (SUW) research team assessed the potential of various UGI elements, identified as suitable for the area in Fluhrer et al. (2021), to improve several neighborhood-level microclimate indicators in the SUW Real-World Lab (RWL).

To simulate water and energy balances, SUW applied the Surface Urban Energy and Water Balance Scheme (SUEWS) proposed by Järvi et al. (2011). SUEWS integrates several sub-models designed to minimize the number of input variables required, considering the surface (paved areas, roofs, shrubs, deciduous trees, irrigated grass, non-irrigated grass, and water) and the soil below, both treated as single-layer moisture stores. Each type of surface, except water, has a soil store below.

In terms of water balance, the SUEWS model employs the relationship of precipitation (P), external piped water supply (I), runoff (R), evapotranspiration (E), and net change in water storage (ΔS) proposed by Grimmond et al., 1986 (*Eq. 1*). These last three variables (ΔS, R and E) are fundamental to understanding the impact of urbanization on the hydrological response of the study area since they are directly related to changes in both land use and soil moisture.

$$P + I = R + E + \Delta S \ [\mathrm{mm\ h^{-1}}] \qquad \textit{Eq.1}$$

In addition, the model links both the energy balance and the water balance through evaporation, as proposed by Oke, 1987 (*Eq. 2*), where Q* is the net all-wave radiation, Q_F the anthropogenic heat emission, Q_E the latent heat flux, Q_H the turbulent sensible heat flux, and ΔQ_S the net storage heat flux which includes soil heat flux and also the heating and cooling of the complete urban fabric.

$$Q + Q_F = Q_E + Q_H + \Delta Q_S \ [\mathrm{W\ m^{-2}}] \qquad \textit{Eq.2}$$

In terms of energy balance, we also assessed the relationship between the turbulent sensible heat and the latent heat fluxes, Q_H/Q_E, defined as the Bowen Ratio (β). If $\beta < 1$, the latent heat flux is the dominant process, keeping the air cooler by converting energy into evaporating water. Conversely, the predominance of sensible heat ($\beta > 1$) indicates that more energy is being channeled to warming the lower atmosphere (Oke et al., 2017).

SUEWS is a grid-based model. For the RWL study area, SUW used a grid composed of 52 cells, each with a 100 x 100 m resolution. Site characteristics required for the model include population density and tree and building distribution. To model the effects of urbanization on water and energy balances, SUW developed two scenarios:

- Status quo, representing the current state of the study area.
- UGI scenario, with a spatially explicit representation of permeable pavements, stormwater trees, bioretention areas, swales, and constructed wetlands. Selection and placement of these UGI elements were based on Fluhrer et al. (2021).

Urbanization degree in the Real-World Lab

The degree of urbanization in the study area was determined before comparing the energy and water balances of the status quo and the UGI scenario. Each grid cell was categorized as one of four land cover types, i.e., not urbanized, sparsely urbanized, urbanized, and highly urbanized (Table 5.10). According to this assessment, 48% of the cells correspond to the urbanized category, while 13% are highly urbanized, implying that the status quo has a dominant urbanization condition of approximately 60% (Figure 5.29).

In turn, β results for the status quo agreed with the levels of urbanization in the study area (Figure 5.29). Accordingly, sensible heat flux was the dominant process, meaning that the surface dissipates more energy through conduction and convection than through evapotranspiration. This pattern is typical of dry surfaces such as buildings and asphalt roads. Moreover, the highest values of β (in red) correspond not only to the cells categorized as highly urbanized but also to those adjacent to them.

Category 1	**Category 2**	**Category 3**	**Category 4**
Non-urbanized >75% Non-urban ≤ 25% Urban	Sparsely urbanized 51–75% Non-urban 26–50% Urban	Urbanized 26–50% Non-urban 51–75% Urban	Highly urbanized ≤ 25% Non-urban >75% Urban
			

Table 5.10. Categorization of the grid cells of the study area based on the percentage of built-up land cover with Google Earth images for each category.

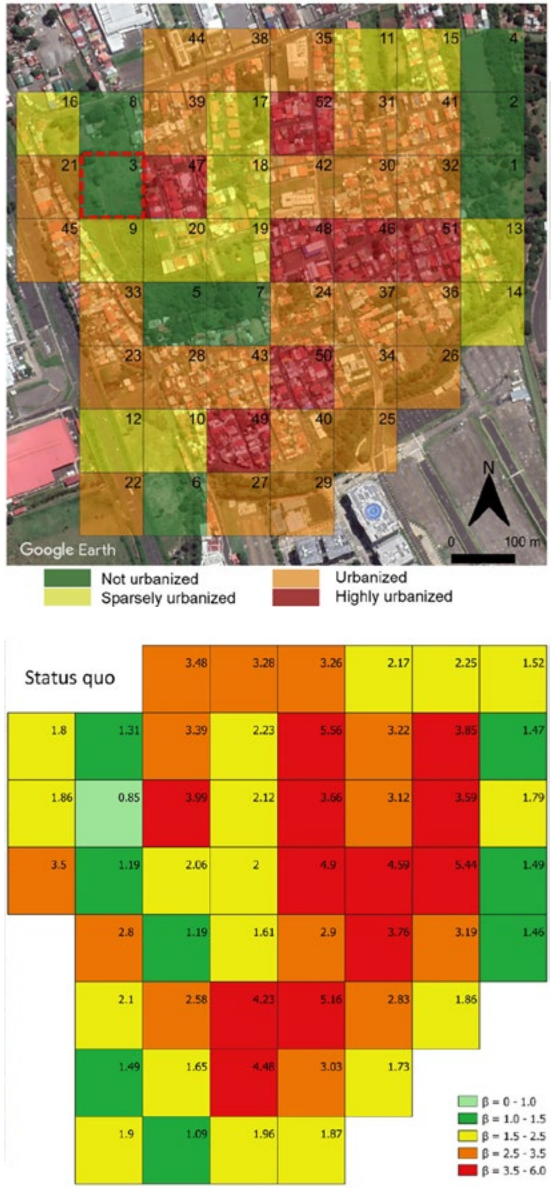

Figure 5.29. Top: Urbanization categorization and cell ID; the red dashed frame highlights the only cell with evaporation as its dominating process (β <1). Bottom: β distribution and values for the status quo. Source of background image: Google Earth.

UGI element	General placement strategy	Land cover change (status quo to UGI)
Permeable pavement	Low-traffic streets	Paved to bare soil
Swale	Unbuilt space next to river	Paved/ bare soil to grass
Constructed wetlands	Minimum of unbuilt space of 5 ha	Trees/shrubs/grass to water
Stormwater trees	Along streets with sufficient width and already existing trees	Paved to tree/shrub
Bioretention cells	Min. length of 10 m, excluding driveways, max. Width of 3 m	Paved to grass
Infiltration trenches	Street curb of min. Length of 10 m	Paved to grass

Table 5.11. Placement strategy (based on Fluhrer et al., 2021) to model multiple Urban Green Infrastructure elements in the Surface Urban Energy and Water Balance Scheme (SUEWS).

Water and energy balances: Status quo vs. UGI scenario

Because SUEWS is unable to explicitly model the multiple UGI elements considered in the RWL, SUW used a placement strategy that involved changing the land cover for the necessary (UGI) cells (Table 5.11). Figure 5.30 depicts the modifications made to the status quo condition to accurately simulate the UGI scenario.

Figure 5.30. Left: High-resolution land cover classification of the study area indicating the location and type of surface changes applied to simulate the Urban Green Infrastructure (UGI) scenario. Right: Surface fractions of the status quo and the UGI scenario.

To compare the two scenarios, SUW calculated the statistical distribution of the water balance (Figure 5.31a) in terms of change in water storage (ΔS), runoff (R), and evapotranspiration (E). In the case of the energy balance, the statistical distribution (Figure 5.31b) included the evaluation of net storage heat flux (ΔQ_S), latent heat flux (Q_E), and turbulent sensible heat flux (Q_H).

In terms of the water balance assessment (Figure 5.31a), the results showed that the maximum average grid cell values for total change in water storage (ΔS) increased specifically for a few cells. Moreover, the UGI scenario resulted in a higher storage capacity, with an average increase of 5% in comparison to the status quo. On average for all UGI scenario cells, evapotranspiration increased (+3%), while surface runoff decreased (–4%). By changing 11% of the impervious land cover to pervious, the UGI scenario resulted in a more natural water balance through increasing water storage in soils and evapotranspiration, thereby reducing surface runoff.

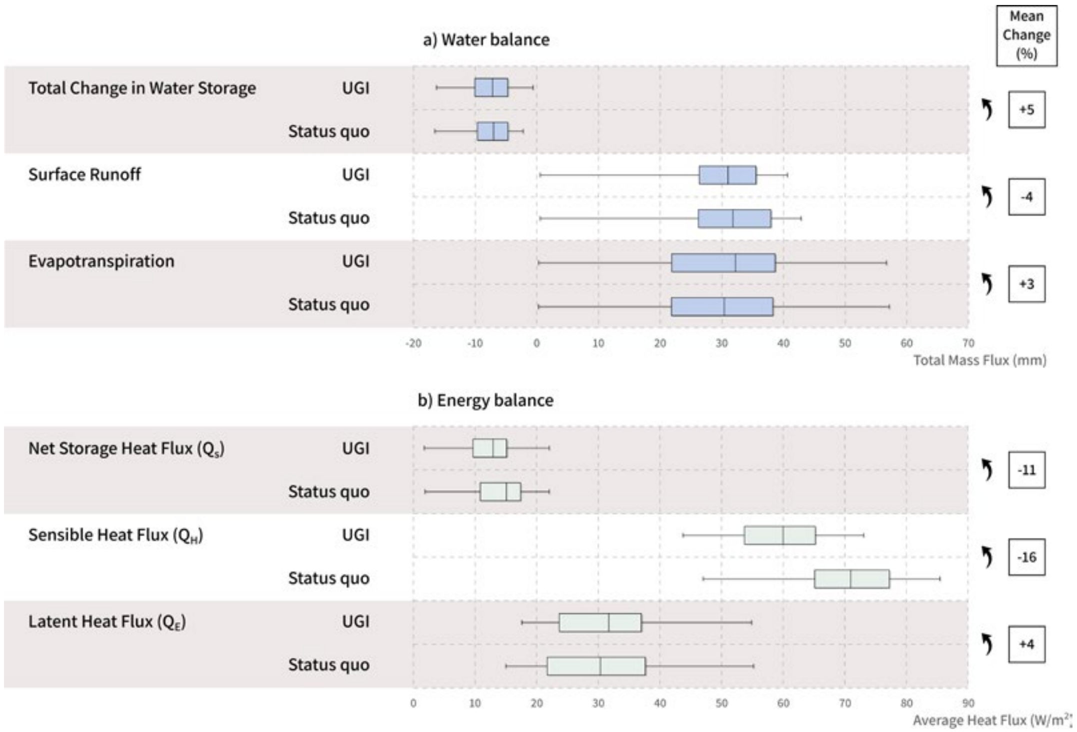

Figure 5.31. Box plots showing the statistical distribution of model output parameters for the water balance (a) and energy balance (b) of all grid cells, values on the right (in boxes) represent the mean relative change (reference scenario: status quo).

The microclimatic modeling of Urban Green Infrastructure in the project's Real-World Lab showed an increase in evapotranspiration and a reduction in surface runoff by increasing green and water spaces by just 5%. This resulted in a cooling effect at the site of UGI implementation, but also in other areas further away.

In turn, the energy balance results (Figure 5.31b) showed relatively small changes for the net storage heat flux (ΔQ_S) and the latent heat flux (Q_E). For instance, sensible heat flux values diminished from a range of 47–86 W/m^2 (status quo condition) to 44–73 W/m^2 (UGI scenario). The maximum and minimum latent heat flux remained at a similar level, only showing a change of about 1.5 W/m^2 (minimum and mean). In turn, the sensible heat flux (Q_H) diminished in the UGI case by on average 16%. These results showed that the land cover fraction conversion had an effective cooling impact in the UGI scenario.

In addition to the statistical distribution of water and energy balance results, SUW also analyzed the spatial distribution of the β values (Figure 5.32a) in accordance with the land cover changes for each cell displayed in Figure 5.32b. The color of each square illustrates the percentage change from urban to non-urban land cover classes (i.e., the percentage of total UGI implementation), while the white cells were not modified. The highest change occurred in cells 49 (+7.4%) and 40 (+10.6%). Numbers in blue indicate the percentage changed into water, as a representation of constructed wetlands, mostly in cells 40 and 34. In turn, numbers in brown represent the percentage of land cover changed into bare soil as permeable pavements.

Overall, increasing the percentage of greenspace from 48% to 53% resulted in a reduction of β (Figure 5.32a) from 2.7 to 2.1 (average).

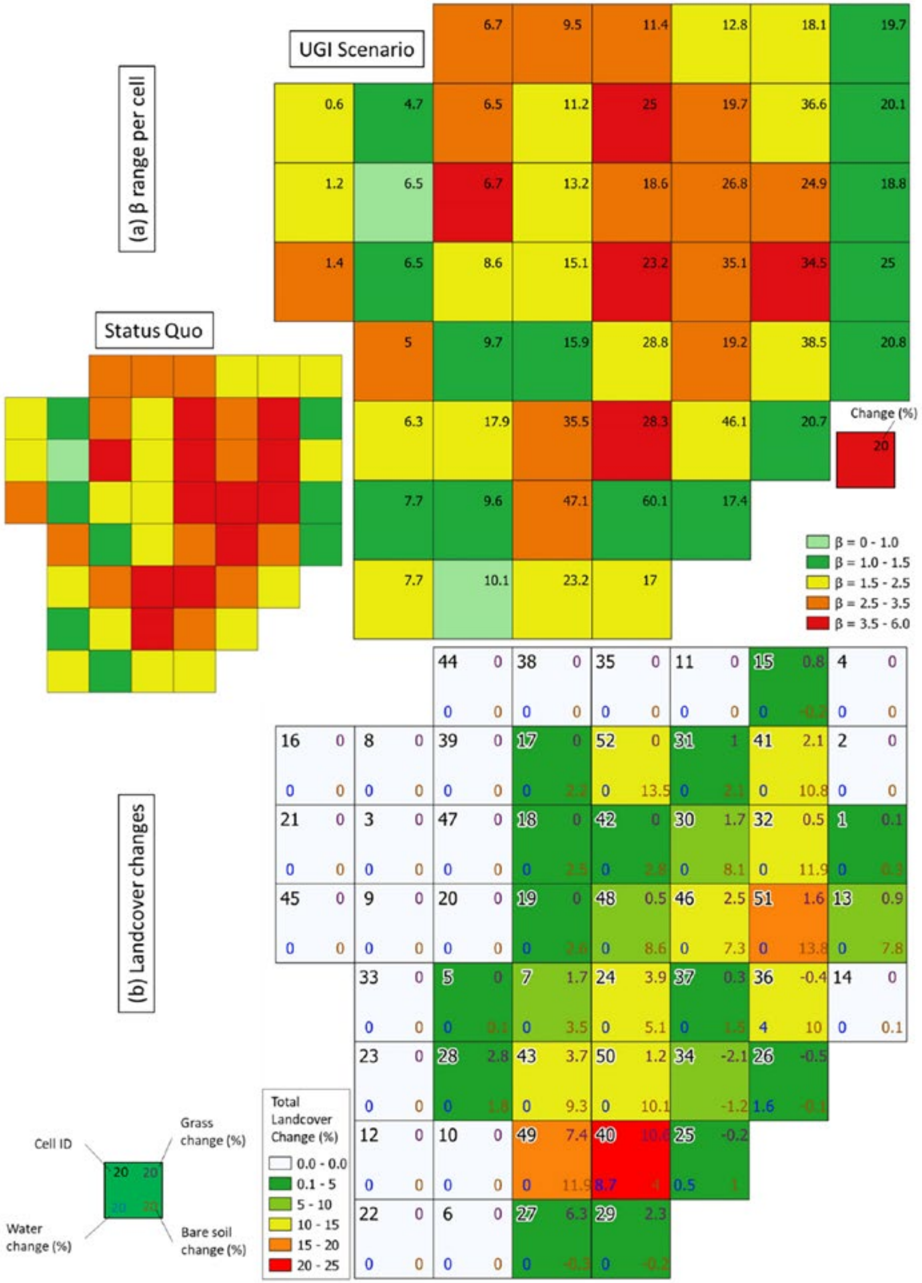

Figure 5.32. Top: Range and values of β per cell for the Status Quo (left) and the Urban Green Infrastructure scenario (right). Bottom: Land cover changes for each cell.

Moreover, cells in the center simulating UGI had the highest reduction of β (20–60%). With this assessment, it was evident that even implementing UGI in only certain cells can change the turbulent fluxes for all cells of the grid. Consequently, implementing green areas, green swales, or similar UGI elements can lead to a shift in the energy balance from sensible to latent heat fluxes.

Conclusions

This study showed that UGI implementation can have a positive impact on the water and energy balances in urban areas. Even small patches of water, vegetation, or unsealed surfaces can make a difference in the urban microclimate. For instance, considering a wide range of UGI elements may result in increased storage capacity and improved evapotranspiration, in turn helping reduce surface runoff. Moreover, the high-resolution distributed grid-based model demonstrated that reductions in sensible heat flux are also possible, even in cells where no previous surface changes were considered.

Even unsealing small patches of land and introducing vegetation as well as water elements make a difference in the urban microclimate. Urban Green Infrastructure effectively increases water storage capacity, reduces surface runoff, improves evapotranspiration, and supports the cooling of urban areas.

The findings of this analysis can be useful for decision-makers and urban planners in designing and implementing UGI in urban areas to mitigate the negative impacts of urbanization on the hydrological and energy balance. Nevertheless, while this study quantified the microclimate criteria associated with these assessments, improvements can be transposed to other cultural and regulating ecosystem services such as aesthetic and recreational value, as well as water purification.

Quebrada Seca-Rio Burio River flow during the dry season, Heredia, Costa Rica.

For more information about the evaluation of the multifunctionality of Nature-based Solutions and Urban Green Infrastructure please refer to:

Wiegels, R., Chapa, F., Hack, J. (2021). High resolution modeling of the impact of urbanization and green infrastructure on the water and energy balance. Urban Climate (39), 100961. https://doi.org/10.1016/j.uclim.2021.100961

5.3. Multifunctional Green Infrastructure Planning

Despite strong academic support, adoption of Urban Green Infrastructure (UGI) remains slow (e.g., Latin America, see Vásquez et al., 2019). One of the major impediments to its promotion and, as a consequence, to implementation willingness, is the lack of instruments and guidelines, both of which are critical for bridging the knowledge gap among citizens and decision-makers. In particular, there is a lack of methodological frameworks for assessing and improving the potential of existing UGI networks, mainly in developing contexts often characterized by insufficient recreational (e.g., parks and green spaces) and service (e.g., storm and wastewater conveyance and treatment) infrastructure.

Assessment and planning of multifunctional Green Infrastructure for urban watersheds

Considering the foregoing, we developed a comprehensive methodology (Figure 5.33) that considers three different spatial scales to:

- assess the multifunctional potential (or deficit) of existing UGI in urban environments (watershed and neighborhood scales) and
- identify potential UGI implementation sites to improve the existing UGI network (property scale).

To achieve these multi-spatial assessments, the SEE-URBAN-WATER (SUW) team first applied a land use / land cover classification (LULC) approach considering six different categories: buildings, low vegetation, high vegetation, bare soil, pavements, and shadow. Input data included satellite imagery from Google Earth and land use information from Open-Street-Maps, both considered valid and reliable sources for LULC in urban applications. After this, the landscape characteristics of the existing UGI were evaluated in terms of fragmentation and connectivity of vegetation patches. This was performed using the FRAGSTATS 4.2 software, assessing six parameters related to the enhancement of socio-ecological functions (further details can be found in Arthur and Hack, 2022). Larger and less fragmented urban landscapes promote increased local biodiversity, improved air quality, reduced heat island effect, and peak runoff management, all of which contribute to the multifunctional potential of UGI networks.

In addition to fragmentation and connectivity, we evaluated accessibility to public green spaces, thereby promoting UGI multifunctionality in terms of providing recreational spaces and amenities, improving the quality of life and well-being of citizens, and social cohesion. For this analysis, it was assumed that every resident should have a green space near their homes (300 m, 0.5 ha) and settlements (700 m, 10 ha). Studies from Latin America set the minimum park size at 0.5 ha, since these green spaces in Latin-American cities are often smaller than in Europe or the USA (Morales Cerdas et al., 2018; Reyes Päcke and Figueroa Aldunce, 2010; Wright Wendel et al., 2012).

In turn, to determine suitable sites for UGI implementation at the property scale and along the river corridor, we assessed the potential of additional green public spaces, flood retention areas, green roofs, and permeable pavements.

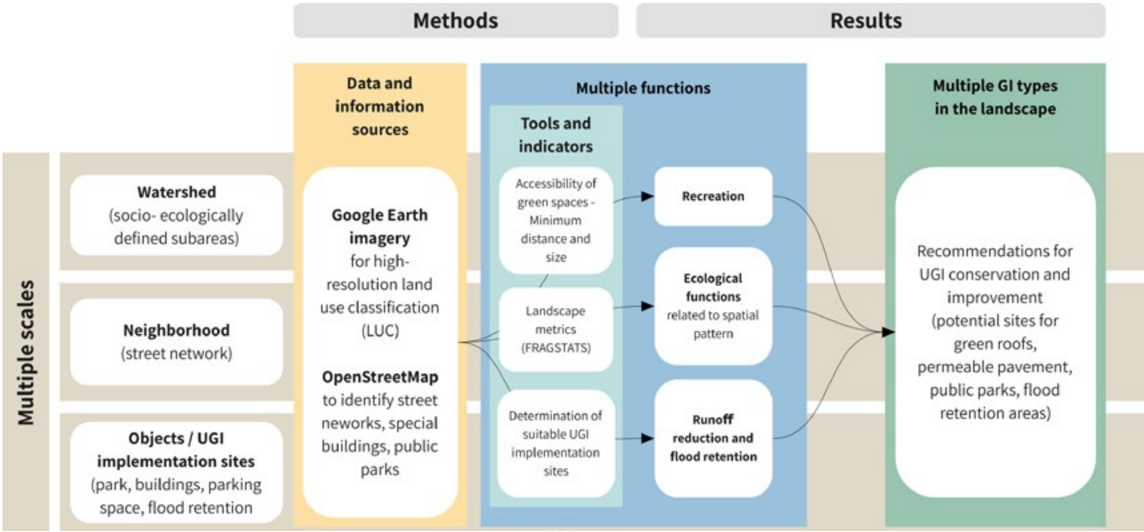

Figure 5.33. Methodological approach for assessing Urban Green Infrastructure (UGI) multifunctionality based on different scales, functions and types of UGI.

The QSRB case study was used to illustrate the UGI assessment methodology for already consolidated urban areas, to highlight deficits in the existing UGI, and to provide practical guidance for strategic improvements based on the prevailing characteristics, constraints, and opportunities of the particular area of investigation.

The SUW methodology is based on freely available data and software enabling the assessment of existing Urban Green Infrastructure and the development of improvement strategies at multiple scales.

Moreover, recommendations for developing green corridors and improving street greenery were developed to increase the connectivity of green spaces.

To apply this methodology, the Quebrada Seca-Río Burío (QSRB) watershed was divided into four sub-areas (Figure 5.34) to provide a more accurate comparison between the different parts of the study area:

1. Industrial-urban lower reach (IND-LOW) in Alajuela and Belén.
2. Industrial-urban middle reach (IND-MIDDLE) in Flores and Heredia.
3. Highly urbanized middle reach (URBAN-MIDDLE) in Heredia, Flores, Brava, and San Rafael.
4. Rural headwaters (RURAL) in Brava and San Rafael.

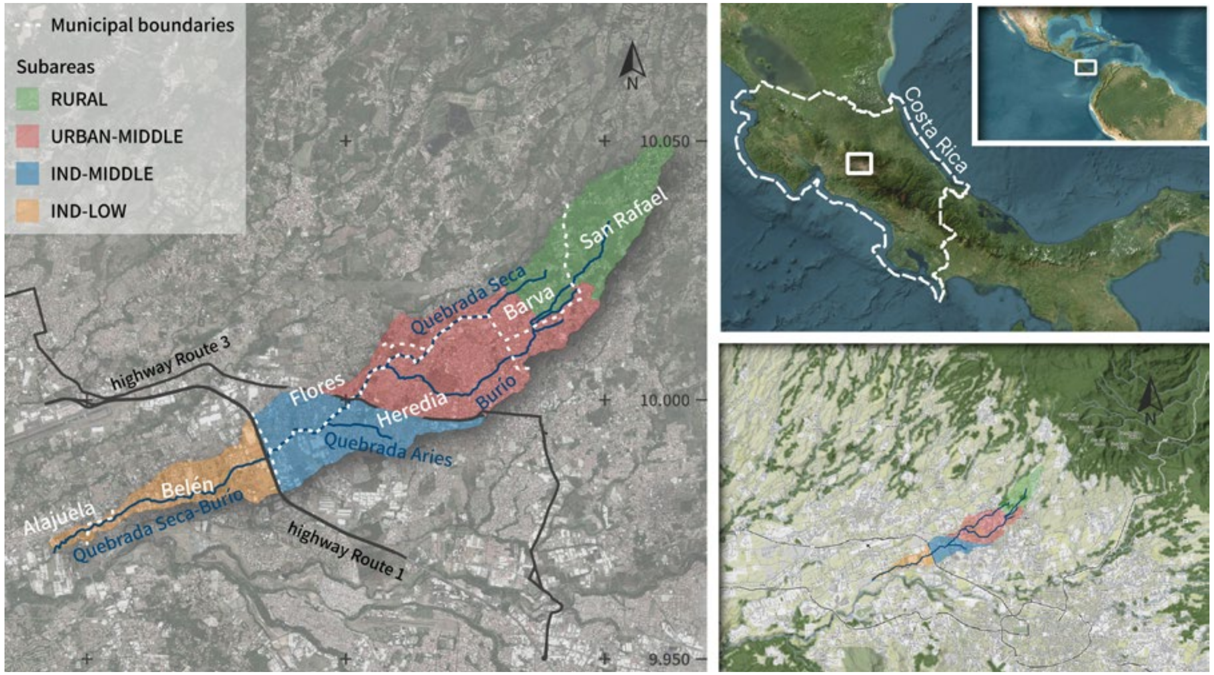

Figure 5.34. Location of the Quebrada Seca-Río Burío watershed and the four sub-areas used for the analysis of Urban Green Infrastructure.

Ecological fragmentation and connectivity within the watershed

To assess ecological fragmentation and connectivity within the QSRB watershed (Figure 5.35), only vegetation patches >1 ha were considered. According to Beninde et al. (2015), five sizes of vegetation patches with different ecological functions can be distinguished:

- patches <4.4 ha with no particular ecological function (red),
- patches of 4.4–10 ha as potential habitats for urban adapters (orange),
- patches of 10–27 ha that bear higher CO_2 storage (yellow),
- patches of 27–53 ha that have potential to sustain higher urban biodiversity (light green), and
- patches >53 ha that are potential habitats for urban avoiders (dark green).

In the three urban subareas, 29 green spaces larger than 4.4 ha exist. Only two of them are larger than 27 ha, located in the subareas IND-LOW (42.4 ha) and IND-MIDDLE (31.3 ha). Both feature the river corridor as a connecting element, potentially providing both terrestrial and aquatic habitats. However, the large vegetation patch in the IND-MIDDLE subarea is significantly frayed, featuring only a small core area and thus with a limited potential positive effect on biodiversity. Moreover, the patch extends to large parts of industrial and residential areas.

The 27.9 ha coffee plantation in the municipality of Heredia in the URBAN-MIDDLE subarea (Figure 5.35) is crisscrossed by a network of unpaved roads and was not analyzed as a contiguous green space. However, from an ecological or urban climatic perspective, it could be considered as one large green space. All potentially suitable habitats for urban avoiders (vegetation patches >53 ha) are located in the RURAL subarea of the upper part of the watershed. According to a UK study, CO_2 sequestration capacity increases most significantly up to an area of 10 ha (Grafius et al., 2018).

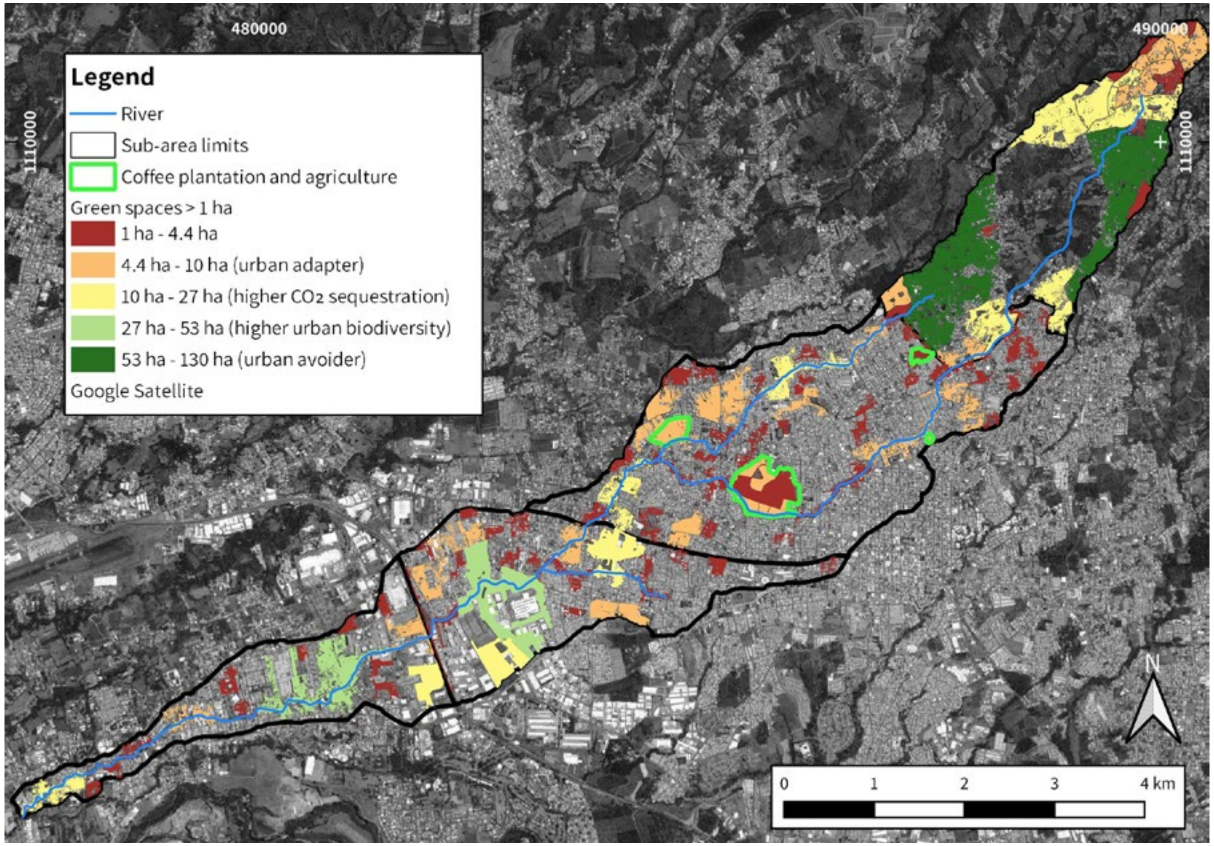

Figure 5.35. Larger vegetation patches and associated ecological functions within the Quebrada Seca-Río Burío watershed.

Accessibility of public green spaces

Public green spaces and parks are unevenly distributed throughout the QSRB watershed (Figure 5.36). Residents from several areas need to travel more than 300 m to benefit from parks or other public green spaces. Smaller public green spaces (0.5–10 ha) are too far away from the study area for inhabitants to travel to. Within the urban subareas, there is only one

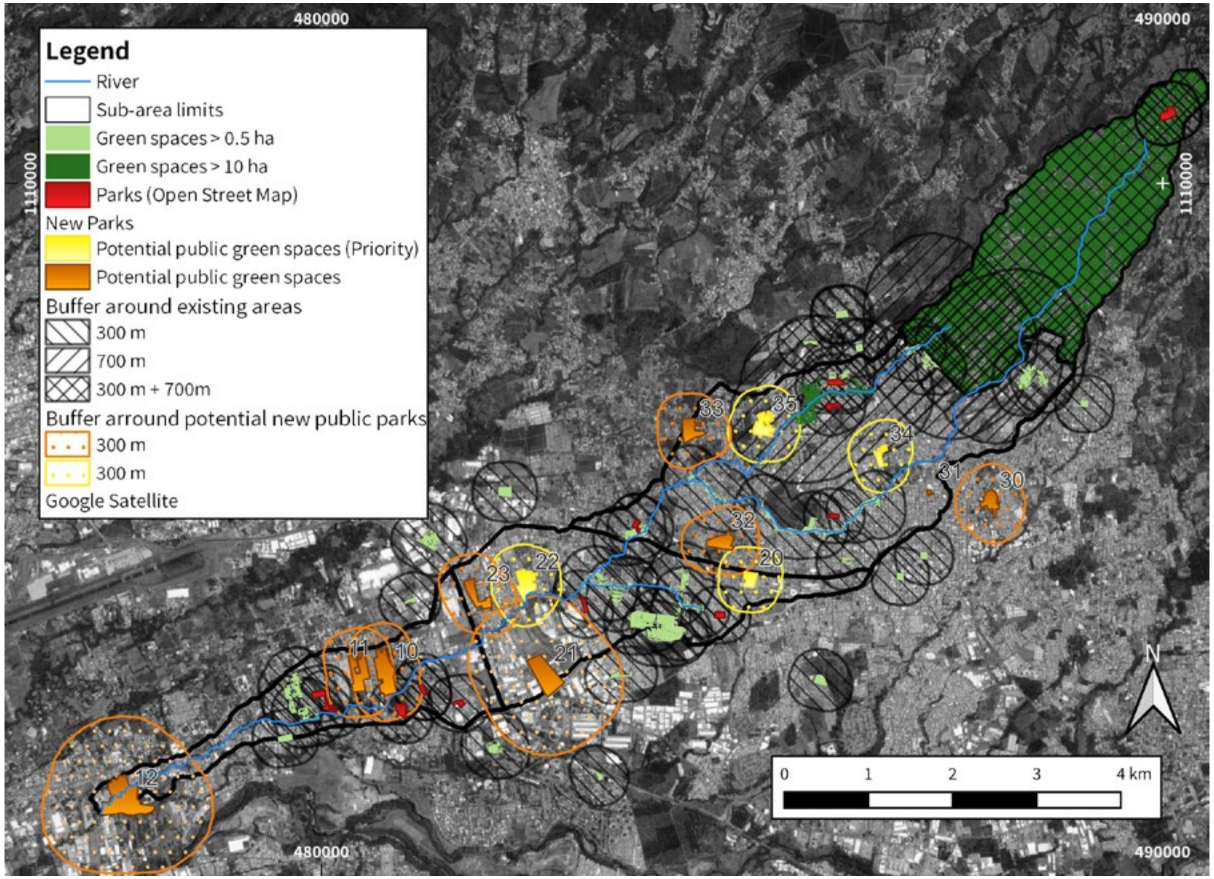

Figure 5.36. Accessibility and distribution of existing and identified potential new public green spaces of > 5 ha (300 m buffer) and >10 ha (700 m buffer).

public green space larger than 10 ha, located in the municipalities of Brava and Heredia (URBAN-MIDDLE) and comprising the Quebrada Seca River corridor.

The IND-LOW subarea is well-endowed with public green spaces and parks in some areas, although some residents have no green space available in their neighborhoods. Several public green spaces are concentrated in the middle of this subarea, i.e. along the banks of the Quebrada Seca River. Public parks are within reasonable walking distance, even for households outside the study area. Larger vegetation-covered areas are located in the downstream part of the subarea. However, these are not publicly accessible, meaning that this part of the subarea has a deficit of public green space. At least two smaller parks (<0.5 ha) are available in this area.

In the IND-MIDDLE subarea, public green spaces are also concentrated in a single zone. The area surrounding the Quebrada Aries tributary is well served, while the subarea's western part lacks accessible green spaces and parks. There are smaller parks in the Free Trade Zone outside the industrial area, but they do not have good accessibility or an area >0.5 ha. Crossing the northern boundary of the subarea, i.e., the Ruta 3 highway, residents have access to three other green areas belonging to the URBAN-MIDDLE subarea.

Public green spaces in the URBAN-MIDDLE subarea also showed deficits. Not all inhabitants have access to a public green space >0.5 ha within 300 m of their place of residence. While accessibility to public green spaces south of the Burío River is good, there is a lack of parks and green spaces in (i) the western part of the subarea, (ii) in the city center of Heredia, (iii) north of the coffee plantation, and (iv) in the municipality of Mercedes. Although the 700-m buffer of 13.4 ha of green space at the Brava-Heredia border extends across much of the northern URBAN-MIDDLE subarea, this portion almost entirely lacks public green space for residents (distance >300m, size 0.5–10 ha).

Approximately half of the green space in the URBAN-MIDDLE subarea is located along the two watercourses (Quebrada Seca and Burío River). In particular, the estuary and lower reaches of the Burío River are characterized by accessible green spaces. Furthermore, it is worth highlighting that there are 74 smaller parks in this subarea, with sizes ranging from 171 m^2 to 4723 m^2, more than half (45) of which are located south of the Burío River. In some cases, the small parks are also part of larger public green spaces. These small parks mitigate the deficit of public green spaces in some places, though public green space per inhabitant is still well below the WHO (2016) recommendations of 10 m^2/hab. (Table 5.12). The forests and green spaces of the RURAL subarea have a positive impact on the northern part of the subarea. In this area, a green space >10 ha is also available to the population at a distance <700 m.

Municipality	Inhabitants	Area (ha)	Public green space (ha)	Public green space per inhabitant (m^2/hab.)
Alajuela	2,355	31	-	-
Belén	14,969	336	11.6	7.7
Flores	13,005	212	4.1	3.2
Heredia	55,207	822	40.7	7.4
Barva	11,813	365	14.6	108.4
San Rafael	18,427	521	311.3	171.4

Table 5.12. Population, area, and public green space availability of each municipality.

INFO

For a quantitative statement about the provision of benefits of public green areas in cities, accessibility to the population is very important. However, different recommendations regarding the maximum distance and minimum size of public green spaces to assure accessibility exist (Grunewald et al., 2016; Handley et al., 2003; WHO Regional Office for Europe, 2016). We assumed that every resident should have a green space near their homes (300 m, 0.5 ha) and settlements (700 m, 10 ha) as studies from Latin America set the minimum park size at 0.5 ha, since parks in Latin American cities are often smaller than in Europe or the USA (Morales Cerdas et al., 2018; Reyes Päcke and Figueroa Aldunce, 2010; Wright Wendel et al., 2012). We used the availability of public parks per inhabitant (m^2/hab.) as an additional indicator to describe the public green space availability quantitatively.

The municipalities of San Rafael and Brava and a small part of Heredia are the only areas fulfilling the criteria of having a 0.5 ha green area close to the house units (<300 m) and a 10 ha green area close to the residential settlements (<700 m). These deficits are also reflected in the public green area per inhabitant ratios summarized in Table 5.12.

Potential for additional UGI at property scale

According to the LULC classification results (Figure 5.37), 631 hectares of the total QSRB watershed area are classified as buildings. However, the green roof implementation assessment only considered commercial and industrial uses characterized by flat roofs allowing installation of these UGI elements.

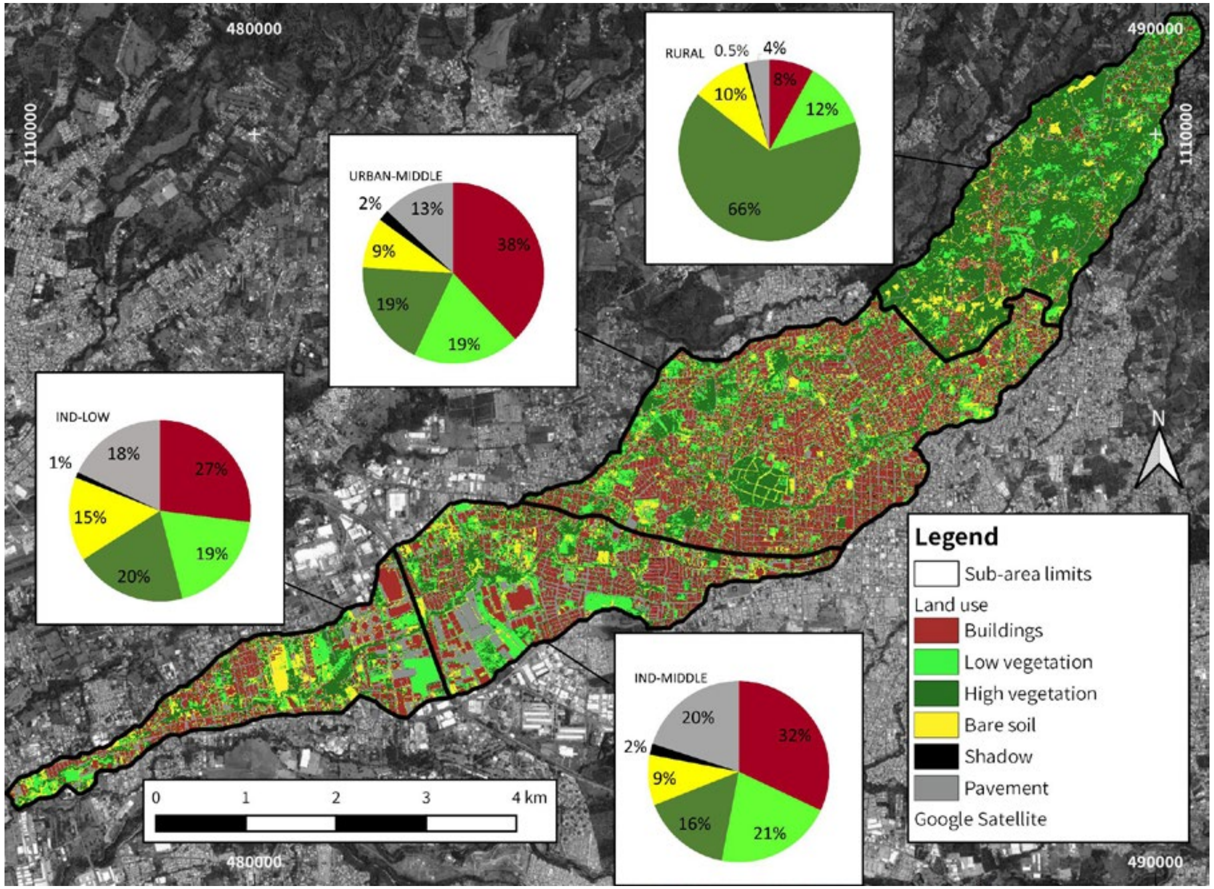

Figure 5.37. Results of the Land Use/Land Cover classification for the four sub-areas.

According to this analysis, 40,307 m^2 (aggregating the areas of 20 large supermarkets) have the potential to be converted to green roofs. Large industrial buildings belonging to the IND-LOW and IND-MIDDLE sub-areas also demonstrated potential to some extent, accounting for a total area of 478,988 m^2. Despite the high feasibility of green roof conversion, it should be noted that further suitability assessments need to be performed as some roofs are already used for photovoltaic panels, heliports, and cooling systems.

As an additional property-scale UGI analysis, we also evaluated the implementation of flood retention basins (Figure 5.38), considering the watercourse itself, riparian areas, vegetation adjacent to the watercourse, and undeveloped areas, for a total of 309 ha. However, only 85.3 ha were found to be suitable for conversion to retention basins or floodplains. For the purposes of this study, all areas covered by dense tall vegetation and coffee plantations were excluded due to low environmental feasibility.

In addition to these spatial limitations, we considered the critical flood generation zones as defined by the hydrological analysis in the QSRB watershed performed by Chen et al., 2021. As shown in Figure 5.38, there are only a few suitable areas of considerable size (30-50 ha) in these critical zones. However, as urban development is increasing along the watercourse, it is important to consider the use of multiple retention areas to achieve a runoff reduction effect in the river corridor. Accordingly, the potential for implementing retention areas is quite low in the URBAN-MIDDLE subarea.

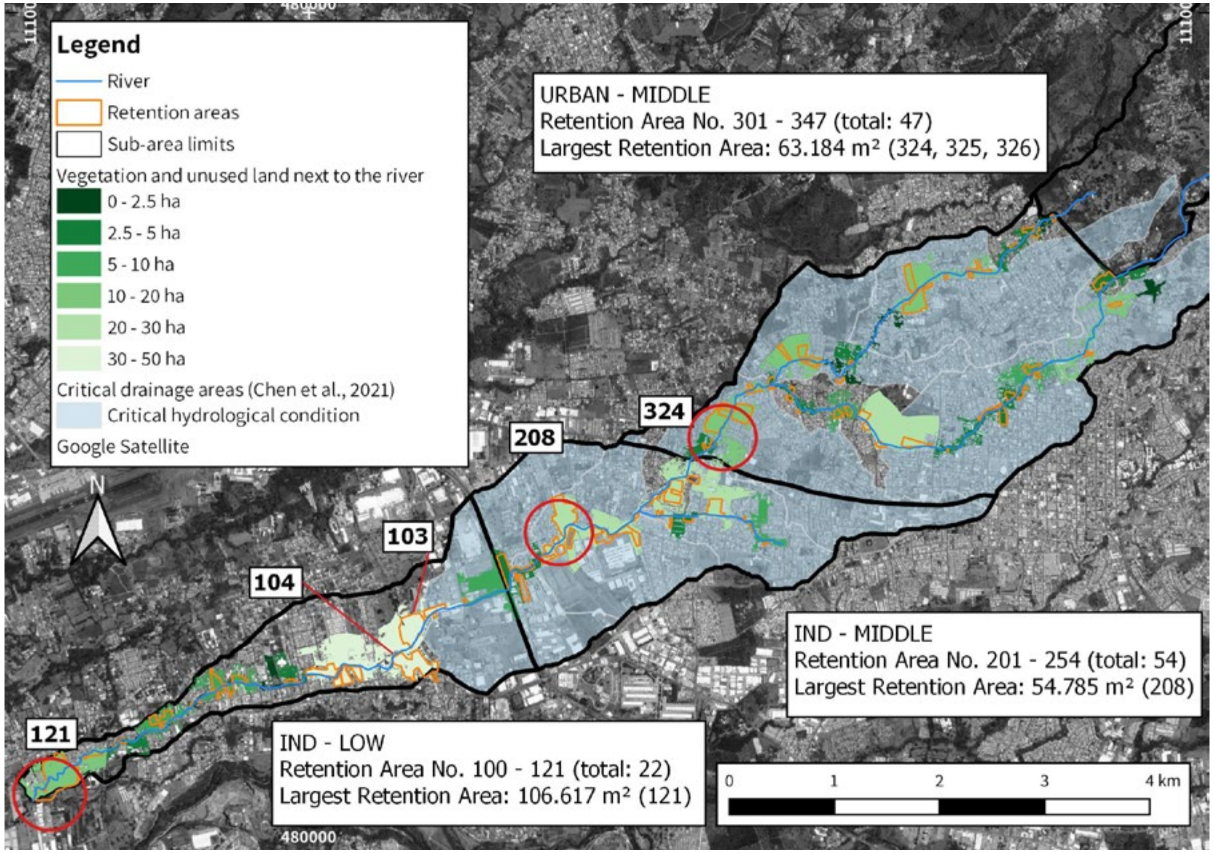

Figure 5.38. Undeveloped areas along the river corridor and potential locations for flood retention areas (RA). Numbering, total amount, and largest RA (red circles) indicated for each subarea.

Due to the scarcity of unoccupied land in the study area, the concept of Urban Green Infrastructure is a promising means for effectively enhancing the urban landscape in a multifunctional way.

Recommendations

Based on the high theoretical potential for UGI implementation at watershed, subarea, and property scales, the SUW group tabled a series of specific recommendations to amplify the multifunctionality of this type of infrastructure in the highly urbanized QSRB watershed. Table 5.13 summarizes how the functions of different types of UGI were determined and corresponding recommendations derived.

As seen in Figure 5.39, the total potential area of 230.1 ha includes additional public green space, retention

Function	GI type	Determination method and criteria	Recommendation to improve GI and multi-functionality
Ecological	Vegetation patches	Land use classification and landscape metrics: Vegetated areas > 1 ha.	Conservation of particular ecological functions: patches of 4.4–10 ha as potential habitats for urban adapters, patches of 10–27 ha for CO^2 storage, patches of 27–53 ha to sustain urban biodiversity, and patches > 53 ha as habitat for urban avoider species.
Ecological	Green corridors and street greenery	Land use classification and landscape metrics: High vegetation patches within street networks of different neighborhoods.	Prioritization of corridor increasing connectivity, street networks with ratios of high vegetation to sealed surface < 1:10.
Recreational	Vegetation patches	Land use classification, landscape metrics, and Open-Street Maps (OMS): Vegetation patches of low convolution (patch level metric FRACT < 1,6), > 0.5 ha within 300 m of buildings and >10 ha within 700 m of buildings identified as public green spaces.	Establishment of additional parks where accessibility is insufficient (absence of public parks within 700 m distance).
Runoff reduction	Roof tops of buildings	Land use classification and OSM: Large, flat- roofed commercial and industrial buildings, larger hotels, and supermarkets.	Conversion to green roofs.
Runoff reduction	Large parking lots	Land use classification and OSM: commercial and industrial parking lots in <300 m distance from the river.	Conversion to permeable pavement.
Flood retention	Large parking lots	Land use classification and OSM: commercial and industrial parking lots in <300 m distance from the river.	Use for temporal flood retention.
Flood retention	300 m wide river corridor	Land use classification and landscape metrics: Merged undeveloped areas of bare soil, low, and high vegetation (<10 %).	Prioritization of largest areas with critical location within the watershed (flood prone), multifunctional use of existing green spaces or multifunctional development as public parks.

Table 5.13. Functions of different Urban Green Infrastructure types, methods used for their determination and recommendations for multifunctional improvement.

areas, green roofs, and permeable pavements across all the three urban subareas, i.e., IND-LOW, IND-MIDDLE, and URBAN-MIDDLE. Moreover, the financial and environmental feasibility of implementing infiltration basins or constructed wetlands can be evaluated considering the availability of bare soil (11%) and low vegetation (19.6%).

The following are detailed recommendations for the IND-MIDDLE subarea (Figure 5.40) to improve accessibility and flood retention capacity, as well as the UGI network's multifunctionality (further details on the other subareas can be found in Arthur and Hack, 2022):

Accessibility:
The lack of public green spaces revealed by the watershed assessment highlighted the need to transform existing vegetated sectors into large open parks to improve local accessibility conditions. As shown in Figure 5.40, potential zones exist within the IND-MIDDLE sub-area with an extent between 0.5-9 ha and >10 ha. Leveraging these, the green coverage rate could be increased from 3.2 to 11.2 m^2/hab. in Flores and from 7.4 to 10.8 m^2/hab. in Heredia. This would have a significant positive impact on citizen well-being and local biodiversity.

In addition to harnessing existing green spaces, the analysis conducted by SUW revealed the potential for new green areas. In Figure 5.40, new public green spaces, namely 20, 21, 22, 23, and 32, could benefit a large portion of the population living in areas with restricted access to public parks within a 300-meter radius of their dwellings. In addition to the benefits listed above, the creation of new green spaces improves air quality, reduces the heat island effect, and provides recreational amenities.

Flood retention areas:
In some cases, potential flood retention areas may overlap with existing public green space. Given the high competition for space and flood risk in the QSRB watershed, it is recommended to prioritize flood risk mitigation. These zones, labeled 220-227 for the IND-MIDDLE subarea in Figure 5.40, could amplify the multifunctional nature of the proposed UGI network when combined with infiltration and retention basins.

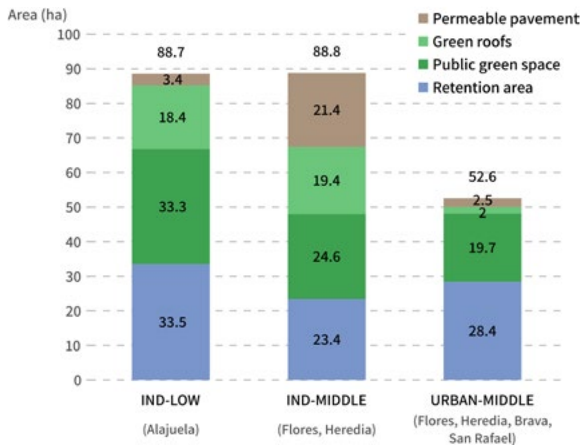

Figure 5.39. Potential for new Urban Green Infrastructures in the different sub-areas.

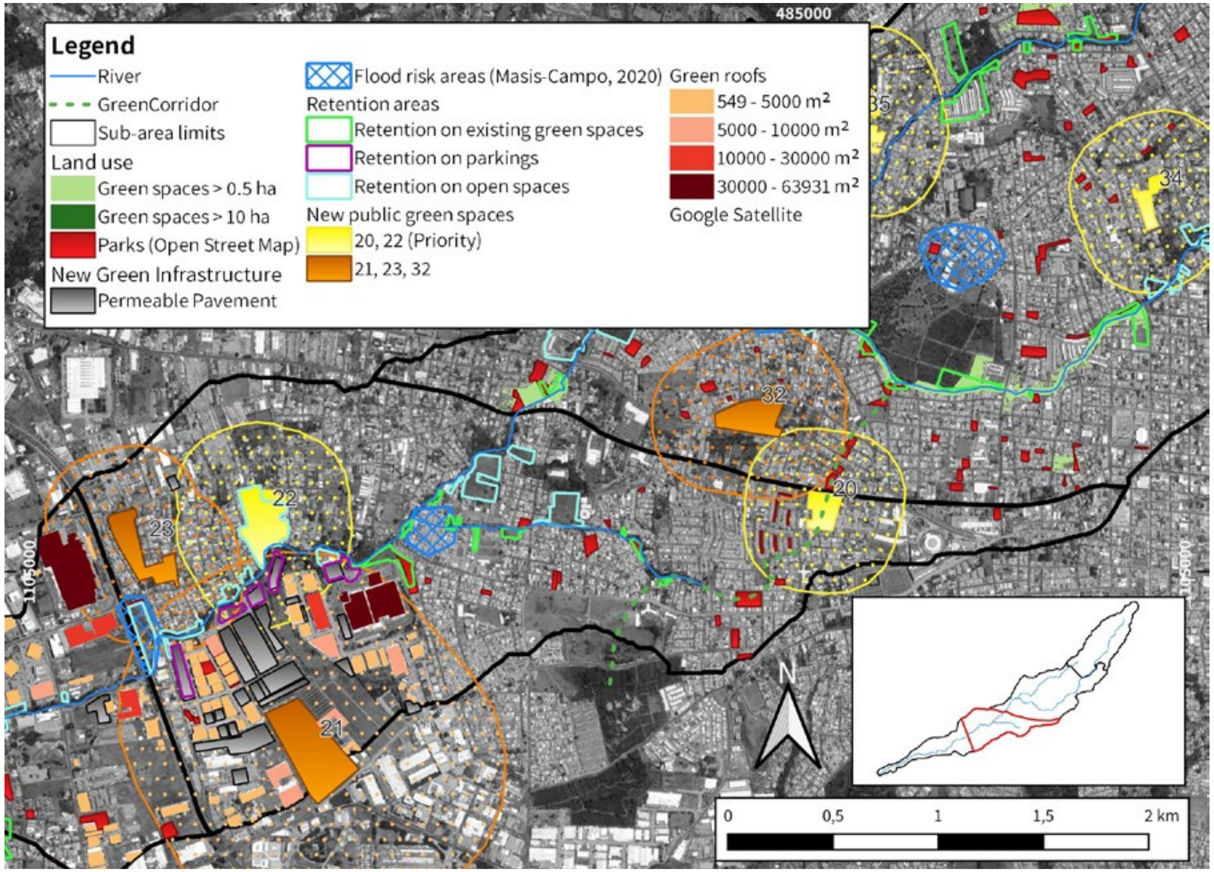

Figure 5.40. Detailed recommendations for Urban Green Infrastructure improvement for sub-area IND-MIDDLE.

When applying this open data and software method for evaluating multifunctional Urban Green Infrastructure in other parts of the world, other data sources (e.g., high resolution LULC, planning documents, green space inventories, etc.) may be available, providing an even better basis.

For more information about the multifunctional Green Infrastructure Planning please refer to:

Arthur, N., Hack, J. (2022). A multiple scale, function, and type approach to determine and improve Green Infrastructure of urban watersheds. Urban Forestry & Urban Greening (68), 127459. https://doi.org/10.1016/j.ufug.2022.127459

Conclusions

Urban Green Infrastructure (UGI) is considered a key instrument for city management and policy-making to achieve more resilient and sustainable development. Uncertainty about the relevance of implementing Nature-based Solutions (NbS) in highly urbanized contexts is decreasing in both developed and developing contexts. However, widespread adoption of such solutions is hampered by a lack of effective planning tools helping local decision-makers and managers move from assessment to robust implementation.

Understanding the need to overcome this limitation, the SUW team developed a comprehensive methodology to support the planning and evaluation of existing and new UGI, considering different scales of implementation, i.e., watershed, neighborhood and property, and covering a broad range of socio-ecological challenges related to climate change and sustainable urban water management. The methodology can be adapted to other spatial scales to promote comprehensive land management.

In addition to being a multi-scale methodology, the proposed approach supports the identification of the most suitable UGI types and locations, resulting in less fragmentation, greater habitat connectivity, and improved access to public green spaces. This promotes a variety of socio-ecological and hydrological functions such as recreation and sustainable flood risk management. However, the methodology is flexible enough to assess a wide range of ecosystem services (e.g., water quality improvement, carbon sequestration, and biodiversity support) depending on local priorities and needs.

The proposed cost-effective methodology is based on freely available spatial data and software. However, the accuracy and usefulness of the outcomes are contingent on the quality and availability of such information. For example, our land-use classification system relies on true-color satellite imagery which offers detailed insights even into small-scale objects such as individual trees and street greenery. However, since this approach operates on the basis of pixel colors, it is susceptible to potential misclassifications. In such instances, post-processing is critical to increasing accuracy. Moreover, it is recommended to validate the UGI location results with fieldwork to facilitate well-informed decision-making.

The spatially constrained Real-World Lab study area selected for application of the methodology demonstrated that the UGI concept is a promising means to improve the urban landscape in a multifunctional way. However, to establish a bridge between theory and practice, holistic approaches are needed where physical-spatial assessments and governmental (local and regional) synergies are integrated. Communication and visualization of results provided by the open source-based methodology are key to raising interest in UGI and a willingness to implement it.

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6

GOVERNANCE OF NATURE-BASED SOLUTIONS AND URBAN GREEN INFRASTRUCTURE

GOVERNANCE OF NATURE-BASED SOLUTIONS AND URBAN GREEN INFRASTRUCTURE

As relatively new concepts in urban water management, the widespread implementation of Nature-based Solutions (NbS) and Urban Green Infrastructure (UGI) faces numerous challenges. One of these is the establishment of a feasible governance model comprising robust regulatory frameworks, mechanisms to improve inter-institutional communication and cooperation, a clear assignment of responsibilities, funding programs, and incentives for the private sector to engage. Furthermore, the perspectives of a range of stakeholders need to be incorporated, an aspect crucial for the long-term operation and replication of alternative urban water management approaches.

In the following, the SEE-URBAN-WATER (SUW) team provides a comprehensive analysis of the institutional and policy factors influencing the planning and successful adoption of NbS in the context of the Real-World Lab (RWL) and, of course, Costa Rica. While NbS governance is obviously interwoven with the unique socio-spatial characteristics of the intended implementation location, this assessment yields valuable insights for other contexts at a methodological and practical level.

6.1. Municipal policy readiness for implementing Nature-based Solutions

In urban contexts of developing countries, the lack of evidence on NbS and UGI potential and performance often restricts wider adoption. This can become a vicious cycle: in the absence of pilot projects, there is a dearth of feedback essential for anchoring efficient legal frameworks, in turn impeding the reproduction of these sustainable approaches. In the face of this major challenge, the SUW team's RWL approach, as described in Chapter 4, promotes transdisciplinary learning for the technical experimentation while providing key, robust evidence for decision- and policymaking.

Policy-relevant transdisciplinary research in the Real-World Lab

SEE-URBAN-WATER used a Real-World Lab in Costa Rica to plan, design and implement Nature-based Solution prototypes in a transdisciplinary manner (Chapter 4).

Harnessing this representative socio-ecological, spatial, and institutional unit of analysis, the present study assessed the policy readiness of the municipality of Flores for implementing NbS projects. Readiness is understood as the gap between the existing and desired political context. As part of this analysis, the SUW team extracted the main policy insights from the successful New York City (NYC) Green Infrastructure Program (the desired context) using the policy feedback cycle (PFC), an analytical instrument recommended by the European Geosciences Union for such purposes.

The NYC Green Infrastructure Program was launched in 2011 and incorporated into the 2012 modified Consent Order between the NYC Department of Environmental Protection and the New York State Department of Environmental Conservation. Since then, the city has increased by over 930 hectares the green space available for stormwater management and combined sewer overflow reduction. This has been achieved through a range of measures alongside the NbS themselves (e.g., rain gardens and infiltration basins), including public agency partnerships, support for public on-site maintenance, improvement of stormwater control regulations, and financial incentives for private property owners.

In turn, the PFC is an idealized process explaining how policy should be drafted, implemented, and assessed to efficiently achieve expected goals. It consists of

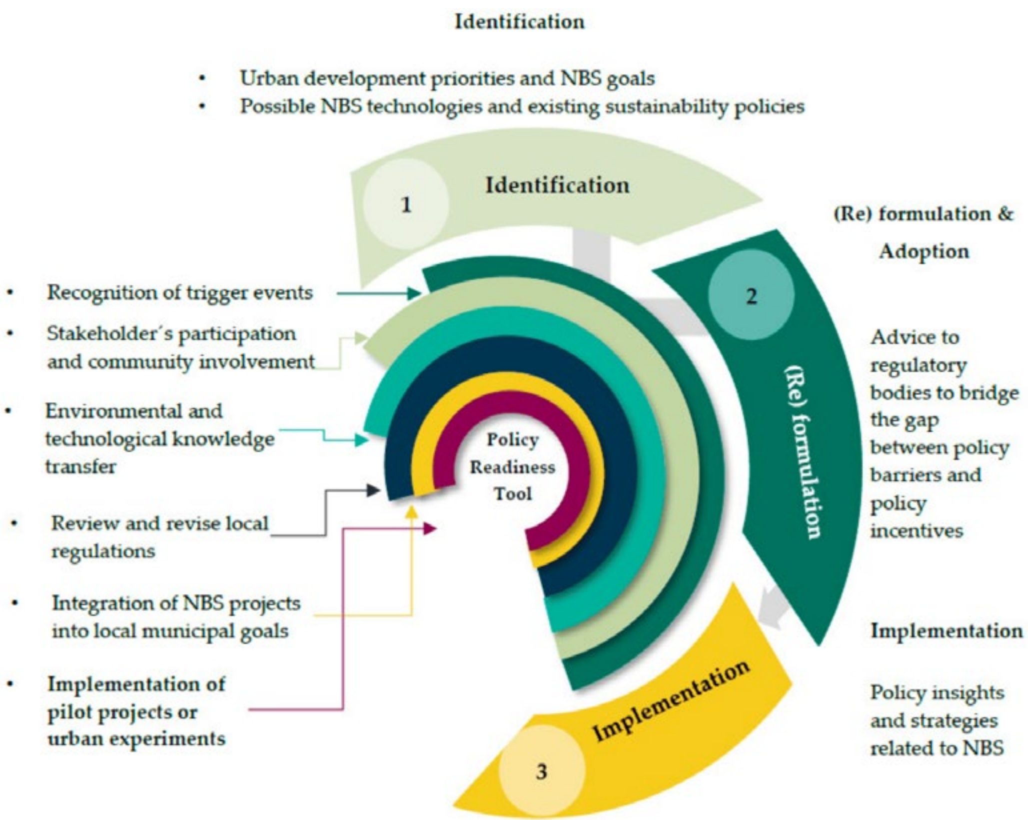


Figure 6.1. Proposed methodological approach to assess the municipal policy readiness for implementation of Nature-based Solution projects.

six stages: identification, formulation, design and adoption, implementation, evaluation, and support and maintenance. However, taking NYC's successful Green Infrastructure Program as a benchmark and considering the scope of the current analysis, the SUW team focused on the first three stages to develop a policy readiness analysis methodology to be applied to the RWL context. As illustrated in Figure 6.1, there are six key elements that should be integrated across these three phases to ensure greater success in implementing and operating NbS:

1. Recognition of trigger events,
2. Stakeholders' participation and community involvement,
3. Environmental and technical knowledge transfer,
4. Review of local regulations,
5. Integration of NbS projects into the local municipal goals, and
6. Implementation of pilot projects or urban experiments.

Although the Flores municipality has implemented several regulations to address urbanization problems and poor stormwater management, these instruments still need to capitalize more fully on the multiple benefits provided by NbS. Listed below are the main barriers that the municipality needs to tackle for the successful long-term implementation and operation of NbS:

- Conflictive political interests
- Reduced (or non-existent) budget for non-conventional measures (e.g., NbS)
- Sectoral silo mentality in policy development
- Vested interests in gray infrastructure
- Electoral/administrative changes

For more information about the proposed methodological approach for assessing policy readiness, please refer to:

Neumann, V. A. and Hack, J. (2020). A Methodology of Policy Assessment at the Municipal Level: Costa Rica´s Readiness for the Implementation of Nature-Based-Solutions for Urban Stormwater Management. Sustainability, 12(1). https://doi.org/10.3390/su12010230.

From this assessment, it became evident that overcoming policy barriers often hinges on the municipality's objectives and its interactions with other institutions and departments across various governance levels. Nevertheless, achieving broader adoption of NbS requires a balance between top-down and bottom-up approaches, ensuring that the needs and perspectives of diverse stakeholders and the local community are integrated into the policymaking process.

Achieving broader adoption of NbS requires a balance between top-down and bottom-up approaches, ensuring that the needs and perspectives of diverse stakeholders and the local community are integrated into the policymaking process.

Given these considerations and following the methodology outlined earlier, the SUW team proposed a series of measures that municipalities can implement to achieve a better integrated environmental management taking account of NbS multifunctionality:

- ✓ Financial incentives (e.g., grant programs, rebates, and tax abatement)
- ✓ Retrofit policies (e.g., regulation compliance assistance, and payment for environmental services)
- ✓ Emergency and safety codes
- ✓ Participatory planning and governance
- ✓ Regulations on biodiversity protection an increasing green space
- ✓ Public agency partnership programs
- ✓ Reformulation of current regulatory plans to include the full spectrum of stakeholders in the decision-making process

INFO

Currently, the Municipality of Curridabat, a municipality in the Greater Metropolitan Area of San José in Costa Rica, is pursuing a more ecological governance approach. The municipality grants a exception to the design of urban green spaces to enhance pollination, and encourages its citizens to adopt different types of UGI such as rain gardens or green roofs. A more inclusive regulatory plan where citizens can raise their voice and share their knowledge and perceptions with the various municipal officers has also contributed to this. For example, citizens can report cases where public green space is in a bad condition to a municipal official via a smartphone app.

6.2. Political barriers to the implementation of Nature-based Solutions

The technical feasibility of Nature-based Solutions (NbS) must be accompanied by a legal feasibility analysis in order to mainstream NbS application. As evidenced in Chapter 5, the built environment encompasses a variety of land uses (e.g., residential, public, commercial, industrial, etc.) governed by different urban, spatial and territorial planning regulations covering multiple institutional and political sectors as well as stakeholders. Given that the adoption of NbS and Urban Green Infrastructure (UGI) is still in its infancy in many parts of the world, their implementation implies a different level of legal complexity compared to that of the traditional gray below-ground systems currently still preferred in many cities. This is even more challenging considering the multifunctionality of NbS, which calls for a participatory and holistic vision capable of integrating various fields of knowledge and policies. Therefore, understanding the legal barriers is crucial for the successful transition to more socially and ecologically resilient cities.

SUW investigated the legal complexity constraining NbS retrofitting, considering separately

1. Their location on public or private land, and
2. Their functions of stormwater management and/or greywater treatment.

This assessment focused specifically on municipal-level management in Costa Rica when considering the implementation of permeable pavements, bio-retention cells, infiltration trenches, and detention basins.

As the implementation of NbS for stormwater and greywater management is not yet regulated in Costa Rica, the legal complexity analysis (shown in Figure 6.2) aimed to:

1. Determine the number of stakeholders involved in the necessary policy changes; and
2. Identify the number and types of regulations that need to undergo changes/adjustments in favor of NbS implementation.

Considering the multi-sectoral nature of NbS management, the SUW team conducted interviews and focus group discussions with water-related experts in Costa Rica at different levels of governance (national and local), the private sector, academics, and non-governmental organizations.

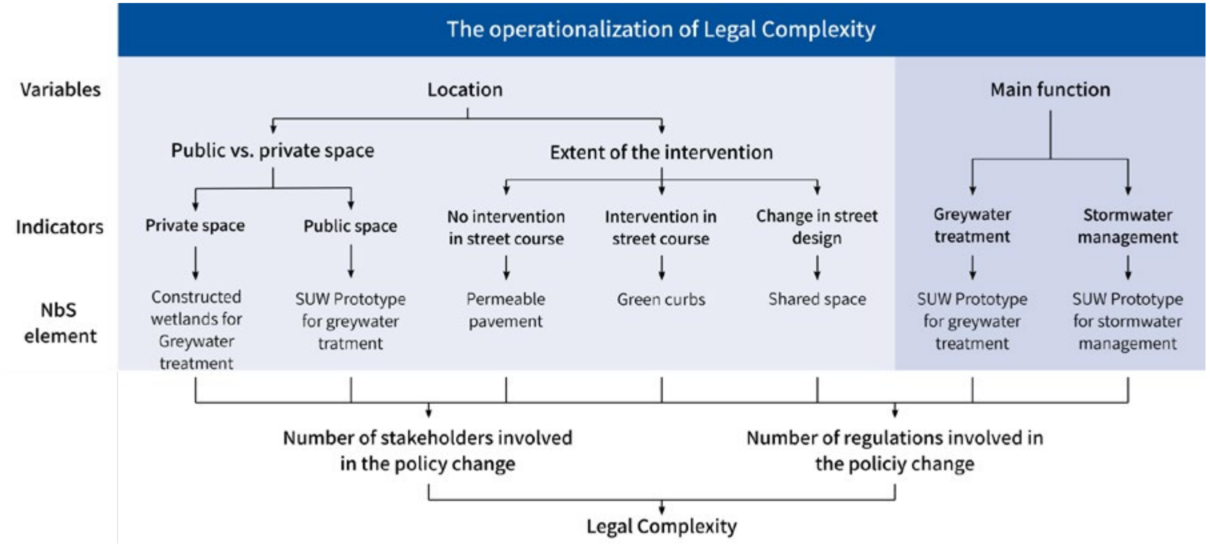


Figure 6.2. Variables and indicators used to analyze the legal complexity involved in adopting Nature-based Solutions for stormwater management and greywater treatment in the case study area.

Type of NbS	Regulations involved	Players involved
Permeable Pavement	• Costa Rican Manual for the construction of highways, roads, and bridges (Manual CR-2010). • Central American Road Manual	• Municipality (Local Government) • Ministry of Public Works and Transportation (MOPT)
Bioretention cells	• Regulation plan • Manual CR-2010 • General Public Health Law • Technical standard for the design and construction of drinking water supply, sanitation and storm water systems	• Municipality (Local Government and Local Parliament) • Ministry of Public Works and Transportation (MOPT) • Ministry of Health • National Environmental Technical Secretariat (SETENA) of the Ministry of Environment • National Water Authority (AyA)
Infiltration trenches	• Regulation plan • Manual CR-2010 • General Public Health Law • Technical Standard for the design and construction of drinking water supply, sanitation and storm water systems	• Municipality (Local Government and Local Parliament) • Ministry of Public Works and Transportation (MOPT) • National Water Authority (AyA)
Detention basin	• Technical Standard for the design and construction of drinking water supply, sanitation and storm water systems • River Protection Zone	• Municipality (Local Government) • National Water Authority (AyA) • National Institute of Housing and Urbanism

Table 6.1. Legal complexity in the adoption of Nature-based Solutions for stormwater management in the SEE-URBAN-WATER Real-World Lab context.

The questions were specifically designed to discuss the relevant regulatory frameworks and stakeholders involved in the planning, construction, operation, monitoring, and legal enforcement of NbS (Table 6.1). At the end, participants were asked to assess the feasibility (high or low) of implementing each type of NbS in the medium term. This was considered a control value to further verify and discuss the correlation between legal complexity and the likelihood of NbS adoption.

Although the legal complexity assessment was performed at municipal level, expert interviews and focus group discussions revealed that NbS implementation requires the simultaneous consideration of national laws and municipal regulatory plans. For example, while permeable pavement was the NbS type subject to the fewest constraints, compliance with both national and Central American durability and resistance provisions was the most important regulatory factor. In turn, NbS elements such as bioretention cells and infiltration trenches must comply with drinking water and sanitation standards, as well as with national riparian protection norms when located along river courses.

"I agree that regulation is the main issue, especially if national law is involved. And changing the general health law is a bigger challenge than changing a relay."
participant #1, 07.10.2021

Conversely, the adoption of bio-retention cells presented the greatest legal complexity. Although reducing roadway width was not a concern, the major constraint was the pollutant load of stormwater runoff and greywater flows.

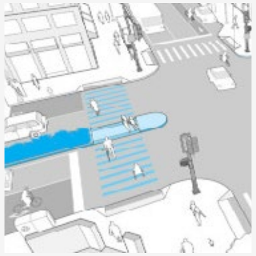
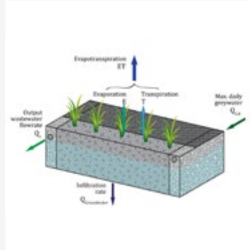
Design	 Change of the surface	 Green elements in streets	 New street design			
Type of NbS	Permeable pavement	Street curbs	Shared space	SUW Prototype: Household scale constructed wetland		SUW Prototype: Bioretention area
Location	**Public space**			**Public space**	**Private space**	**Public space**
Function	**Stormwater management**			**Greywater treatment**		**Stormwater management**
Regulations involved	• Regulation plan • Manual CR-2010			• General Law of Health • Decree 39887 • Decree 33601 • Law 7600 • Regulation plan	• Permission of construction	• Regulation plan • Manual CR-2010 • Law 7600
Stakeholders involved	• Municipality • Ministry of Public Works and Transportation (MOPT)			• National Parliament • Ministry of Health • Ministry of Environment and Energy • Costa Rican Institute of Aqueducts and Sewage Systems (AyA) • Municipality • Other administrators of Sewage treatment • Ministry of Public Works and Transportation • Costa Rican Association of Engineers and Architects (CFIA) • Homeowner	• Municipality	• Municipality • Ministry of Health • Costa Rican Association of Engineers and Architects (CFIA) • Ministry of Public Works and Transportation
Likelihood of implementation	High			Low	High	High

Table 6.2. Summary of the legal complexity analysis conducted with water-related experts to determine the likelihood of implementing different Nature-based Solutions (NbS) types in urban Costa Rica.

"The pluvial issue is simpler. You can even make a pluvial-only [NbS] pilot that still performs treatment. But it could be managed as a green stormwater management structure. Now it has a secondary effect that will improve the stormwater that goes to the river but without calling it a treatment system."
participant #6, 14.10.2021

In general terms, experts also emphasized that NbS implementation involving street layout redesign should be regulated in land use (i.e., regulatory) plans. This requires the involvement of the local administration (as the responsible management body) and the municipal council (as the responsible approval body).

"The municipality can change the [street] design as they want to. […] If the mayor gives his permission, you give him a team of technicians, and they will execute it".
participant #7, 17.10.2021

The legal complexity assessment of NbS adoption, considering both location and function as the main variables (Table 6.2), allowed us to better visualize the hindrances and opportunities of first-run implementation and upscaling. Results showed that legal enforcement depends on the primary function of the NbS element, rather than its particular location. This aspect is exacerbated when:

1. stakeholders relevant for reforming the regulation are not explicitly administratively related to the topic (cross-sectoral compliance),
2. cross-sectoral cooperation between different decision- and policymakers is required, and
3. regulations from different sectors/institutions are involved.

Legal complexity of SUW prototypes implementation

The legal complexity analysis integrated the results of both hydrologic modeling and expert interviews, offering an interdisciplinary readiness assessment for early implementation. For technical details of the RWL prototypes analyzed, refer to Section 4.4.

Although political will and institutional capacity have been identified as critical factors for transitioning from conventional infrastructure to sustainable alternative solutions, it is clear that there is still a lack of research on mechanisms to increase public-sector interest and motivation. This is most likely due to the novelty that concepts such as NbS and UGI continue to represent in developing country contexts where technological constraints have attracted most attention. However, the legal complexity analysis developed by the SUW team highlighted the relevance of including regulatory-institutional aspects in NbS planning.

Furthermore, it is imperative for the public sector to embrace institutional change by fostering more effective inter-sectoral cooperation, efficient decision-making and professional training. Given that budgetary challenges may limit the widespread adoption of NbS and UGI, maximizing socio-ecological and socio-economic benefits also plays a decisive role in raising interest among both public and private stakeholders.

Some of the necessary changes for the widespread adoption of NbS in urban areas include enhancing inter-sectoral cooperation, streamlining decision-making processes, providing professional training, and assessing socio-ecological and socio-economic benefits.

For more information about the legal complexity of Urban Green Infrastructure implementation in Costa Rica, please refer to:

Schiffmann, C., Bonilla Brenes, J. R., & Hack, J. (2022). A combined legal-hydrological evaluation method for Green Infrastructure in urban Costa Rica. Proceedings of the 39th IAHR World Congress. https://www.iahr.org/library/infor?pid=21663


Green corridor of Quebrada Seca-Río Burío river in Llorente, Flores, Costa Rica.

6.3. Attitudes of political-administrative players towards the implementation of Nature-based Solutions

In addition to investigating the legal complexities from a regulatory standpoint, the SEE-URBAN-WATER (SUW) team helped in exploring the perceptions of key institutional stakeholders on implementing Nature-based Solutions (NbS). The public sector can facilitate cross-sector collaboration and influence the allocation of funds to promote their wider adoption. Therefore, understanding the heterogeneity of views within this segment of society is highly relevant to the planning and successful long-term operation of NbS and Urban Green Infrastructure (UGI).

The collaborative study of Paetzke et al. (2023) aimed to explore the attitudes of influential political and administrative players on NbS decision- and policy-making in the Tárcoles River basin which includes the Quebrada Seca-Río Burío (QSRB) watershed (Figure 6.3). This study area was selected due to the relatively low influence of institutional barriers on the adoption of NbS. On the one hand, participants were familiar with the NbS concept as a result of the prototype development in SUW's Real-World Lab (RWL). On the other hand, since the Tárcoles River basin spans various political boundaries, there is a formal coordinating body, the Tárcoles River Basin Commission (in Spanish, Comisión de Gestión Integral de la Cuenca Río Grande de Tárcoles) which provides institutional robustness.

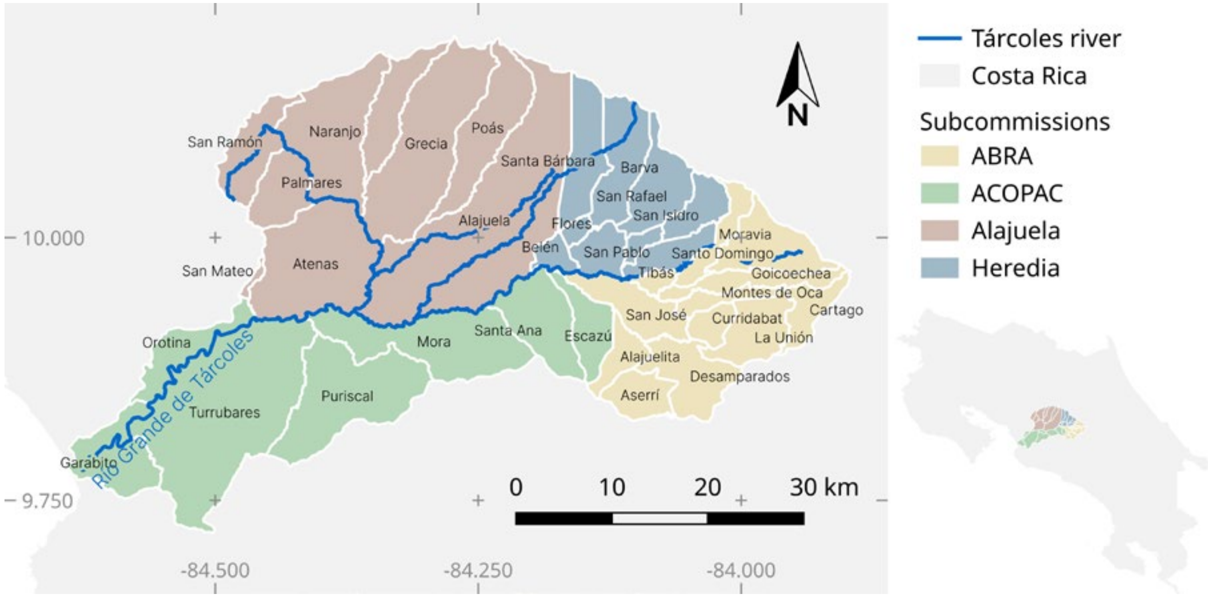


Figure 6.3. The Tárcoles River Basin and the subcommissions in charge of its decentralized management. The Quebrada Seca-Rio Burío watershed belongs to the subcommissions Heredia and, in its lower part, to Alajuela.

The study employed the Q-methodology to explore attitudes towards the hypothetical implementation of a constructed wetland for greywater treatment and flood risk reduction (SUW NbS prototype 3 and 4) in the Tárcoles River basin. Q-methodology is a qualitative-quantitative approach that combines subjective statements with a qualitative ranking analysis. The core elements are predefined opinion statements developed by the researcher based on expert discussions, scientific literature, and workshops. These statements were then discussed with participants and evaluated according to their agreement with them during interviews. Statements included engineering, environmental, political-institutional, economic, and social aspects, all linked to the hypothetical implementation and operation of the selected NbS.

All respondents (8 female and 12 male) belonged to the Tárcoles River Basin Commission and were chosen based on their level of influence in NbS decision-making. The group included representatives from ministries and local governments, non-governmental organizations (NGOs), universities, and other public institutions. The interviews were divided into two parts. Participants were first asked to indicate whether they agreed, disagreed, or were neutral regarding the researcher-prepared statements. Follow-up questions were employed to understand the interviewee's reasoning in each case. Respondents then categorized such opinions on a scale of -5 (I fully disagree) to +5 (I fully agree), allowing the answers to be quantified for further analysis.

The assessment of the public sector's perceptions revealed three very well-defined viewpoints on the planning and management of NbS: "the nature lover", "the cost concerned", and "the participation seeker".

Figure 6.4 illustrates these heterogeneous viewpoints according to the five categories of statements proposed for this assessment.

The nature lover:

- Presumably the highest intrinsic motivation
- Priority placed on the ecological benefits of NbS
- Engineering aspects highly relevant
- Promotes the implementation of NbS prototypes in order to demonstrate benefits and raise citizen trust

"We have already destroyed enough biodiversity. That's why it is important to try to recover some systems that are no longer there. If we take advantage [of NbS], we could improve wastewater treatment and increase biodiversity again."
participant #8, March, 2021

The cost concerned:

- Focused on cost and institutional feasibility
- Less priority on social participation
- Critical position to economic valuation of ecosystem services of NbS
- Strong agreement on the financial contribution of private companies

"If private companies do not participate, these projects cannot be implemented. Limited financial resources are a dire problem for the municipalities. Especially now with the pandemic, there are many businesses that are closing [...], there are people who are starving and unemployed. So, when budget cuts have to be made, this [watershed protection] is the part we are going to cut the most."
participant #19, May, 2021

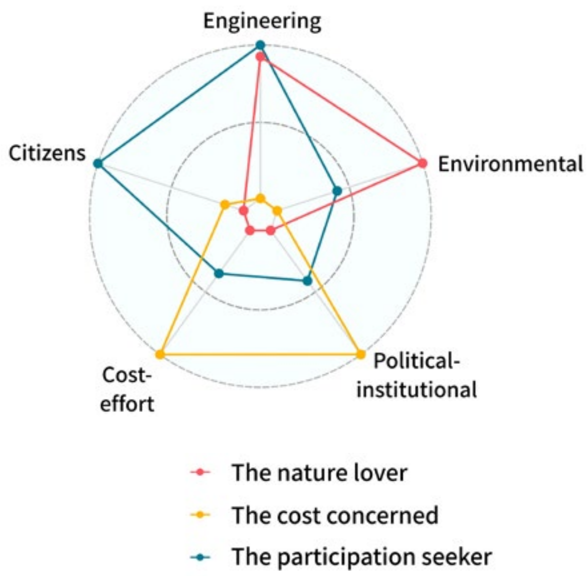


Figure 6.4. Categorized public sector perceptions regarding NbS implementation.

The participation seeker:

- The most pragmatic and balanced view
- Sceptical about the acceptance and recognition of NbS in society
- Urban infrastructure plays a major role
- Stakeholder participation and engineering aspects are highly relevant
- Does not believe in functional replacement of conventional treatment plants by the NbS in question

"I feel that having all parties involved in planning and implementation is very important for the success of the measure. I think that this is a good moment for a paradigm shift, as all the planning and implementation time can be used to demonstrate to everyone what an ecosystem-based model means and why it is so important to start implementing it."
participant #3, May, 2021

Despite their differences, the three types of viewpoints agreed on some aspects. For instance, there was consensus on the need for a shift in policymaking towards ecosystem-based approaches and closer transboundary cooperation in river basin decisions. On a smaller scale, "the cost concerned" advocated greater municipal cooperation, whereas "the participation seeker" and "the nature lover" emphasized the need for strong ties with the academic sector, seen as crucial for achieving the desired long-term establishment of more ecosystem-oriented governance.

Furthermore, all participants considered that NbS measures should not be exclusively public-funded and placed a high value on assessing the social functions of urban green spaces. Moreover, there was full agreement on the increasing relevance of NbS for urban water management and on embracing community participation in NbS implementation and operation to raise acceptance.

While Nature-based Solutions (NbS) are relevant for urban watershed management, the social functions provided by them should also be assessed. Community engagement and participation in NbS implementation and operation contribute to their acceptance.

The results showed that, despite the existence of a common vision among all participants regarding cooperation and participation, it was clear that their points of view and priorities differed according to their responsibilities, jobs and knowledge. Regarding the forms of NbS application, interviewees agreed on the urgency of a change in the design of policies in the country in favor of strategies considering the ecological dynamics of the ecosystem. Participants also highlighted the need for greater cooperation between administration agencies in watershed decision-making. Likewise, the importance of the social function of green spaces in urban areas and the need for greater citizen involvement in the design and construction of NbS were highlighted, with a view to increasing their acceptance in the population.

Regarding the barriers to implementing NbS, the participants highlighted as factors needing to be changed the lacking integration of NbS in regulatory plans and policies, the allocation of financial resources for implementing such solutions, the lack of knowledge, and institutional fragmentation. In particular, they highlighted how the lack of knowledge generated great uncertainty over the costs and benefits of NbS for the community and decisionmakers. Therefore, they considered it important to increase knowledge on NbS, thereby contributing to socially acceptable and sustainable solutions.

The financing of NbS is another obstacle: due to tight municipal budgets, participants considered it necessary to involve private companies able to provide financial resources. Since industry and agriculture were significant contributors to the pollution of the Tárcoles River basin, they were expected to fulfil this responsibility. Consequently, their participation in financing NbS should be considered to achieve effective and comprehensive wastewater treatment in the Tárcoles River basin.

On the other hand, institutional fragmentation is related to the way in which different departments assume different responsibilities based on their own objectives, frameworks and procedures. This not only generates conflicts and confusion between the institutions tasked with managing, operating, and maintaining the NbS, but also makes communication and collaboration between municipalities difficult. Consequently, it is important to promote a shared vision of NbS benefits, hopefully creating a mutual understanding between the state, private and civil society bodies involved in the management of the basin. This can lead to institutions working collaboratively toward a common objective.

Cross-cuttingly, comprehensive solutions potentially able to overcome these limitations include:

- ✓ Awareness-raising campaigns to increase the social acceptance of NbS and the long-term viability of public or private projects.
- ✓ Breaking up institutional/organizational silos by promoting a shared vision of NbS multifunctionality.
- ✓ Private-sector participation and financial engagement.

Urban green corridor of Quebrada Seca-Río Burío river in Heredia, Costa Rica.

As highlighted at the start of Chapter 6, the governance analysis conducted by the SUW team in the preceding sections was centered on the specific context of the project's Real-World Lab and the broader Costa Rican context, at various political-institutional levels. This assessment provided valuable tools for designing governance models tailored to local requirements. Expanding on this, we present a more comprehensive outlook in the following section, analyzing successful initiatives promoting NbS implementation in eight Latin American countries. Together with the earlier studies, we provide a solid foundation for the development of more socially and environmentally resilient cities.

For more information about the perceived barriers to NbS implementation from political and administrative actors in the Tárcoles River basin, please refer to:

Pätzke, F., Schulze, C., Hack, J., Castro-Arce, K., Neumann, V., and Schröter, B. (2023). Attitudes of Political-Administrative Actors Towards the Implementation of Nature-Based Solutions in Water Management - An Example of the Tárcoles River. Authorea. DOI: https://doi.org/10.22541/au.169774191.19879068/v1.

6.4. Advances in Urban Green Infrastructure for water management in Latin America

Research on Nature-based Solutions (NbS), and similar concepts, as strategies promoting sustainable development in cities has been concentrated in the Global North, with records dating back to the 1970s (Fletcher et al., 2015). In the case of Latin America, by contrast, the adoption of similar approaches has been slow-paced, featuring a mere handful of projects since the late 1990s (Quintero, 2007; Vásquez et al., 2019). Although sustainable development is far from systematic, all the examples previously discussed in this book are a clear example of the region's growing interest in sustainable urban planning strategies, with the protection of biodiversity and the promotion of ecosystem services serving as pillars for the construction of resilient cities.

NbS adoption in Latin American cities has been gaining momentum as a response to the impacts of rapid urbanization in recent years, as witnessed by abrupt changes in land use and the exacerbated loss of green areas. While it is estimated that 68 % of the world's population will live in cities by 2050, 81 % of Latin Americans already reside in urban centers (UNDESA, 2019). This is an alarming finding, given that more than 50 % of global biodiversity is contained in this region (UNEP, 2016). Moreover, the development of many cities is occurring in areas with high species richness and/or endemism (Liu et al., 2003).

Figure 6.5. Assessed examples of successful Urban Green Infrastructure (UGI) promotion and implementation in Latin America.

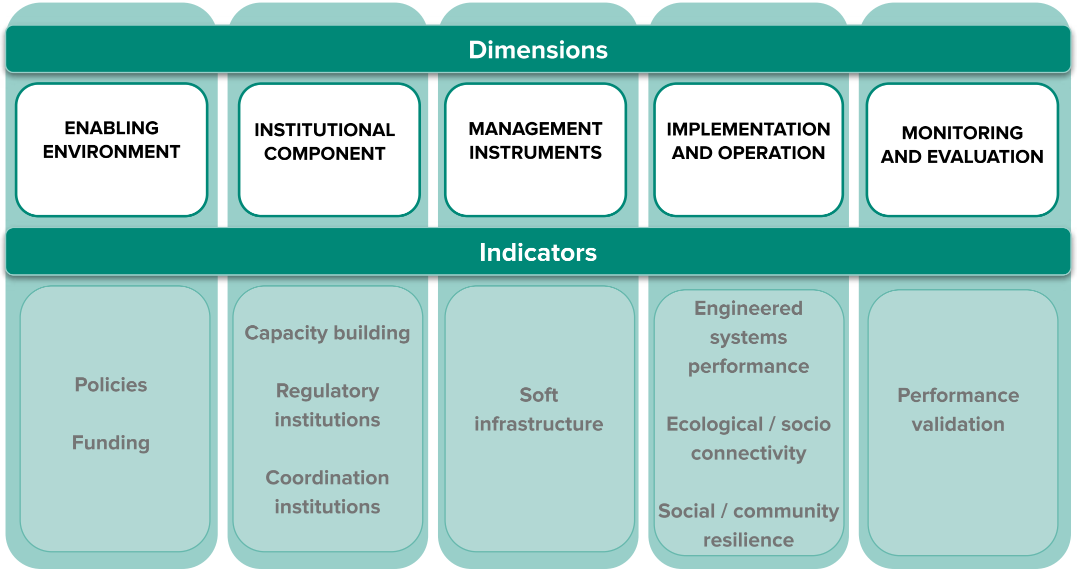


Figure 6.6. Proposed methodological framework to study the factors enabling and barriers constraining the wider implementation of Nature-based Solutions.

To achieve a more successful NbS implementation in cities, researchers insist on the importance of building a shared knowledge base to identify similarities and assess the factors enabling and barriers constraining its wider uptake (Kabisch et al., 2017). For this reason, we systematically analyzed ten successful examples of Urban Green Infrastructure (UGI) adoption, offering a robust analysis of the advances in the promotion and implementation of these infrastructures in eight Latin American countries (Figure 6.5).

To perform such a study, a methodology was developed to conceptualize the necessary transformative processes in five different dimensions, with at least one indicator in each (Figure 6.6).

The first three dimensions of the methodology originate from the three pillars of the Global Water Partnership (GWP) toolbox for promoting and implementing cross-sectoral, ecosystem-based policies for Integrated Water Resources Management (IWRM). IWRM is a globally recognized concept for the sustainable management of water resources that relies on ecosystem operation and has been used for developing effective cross-sectoral legal frameworks, establishing institutions and policies, and defining responsibilities. Therefore, the enabling environment, institutional component and management instruments dimensions are framed within the governance concept, allowing an understanding of the interrelationship between stakeholders and institutions to support collaborative NbS and UGI planning.

The other two dimensions, i.e., implementation & operation and monitoring & evaluation, are derived from the concept of 'coupled infrastructure systems' described by Zuniga-Teran et al. (2020). This term considers cities as socio-ecological systems due to the prominent role played by infrastructures – both hard/structural and soft (e.g., knowledge, social networks, and policies) – in urban system interactions. In this way, in addition to considering key advances in UGI governance, the methodology developed allows an evaluation of the contributions to improving urban resilience in aspects related to built, natural, and social infrastructures. The main results of the multi-dimensional and multi-case analysis are summarized in Table 6.3.

This assessment of UGI promotion and implementation in Latin America highlighted multiple opportunities explorable in other socio-environmental and governmental contexts in the region. For instance, in cases where political will plays a greater role (e.g., Curridabat/Costa Rica, Colombia, Guayaquil/Ecuador, and Mexico City initiatives), the "coordinated mix of different strategic planning instruments" (Pauleit et al., 2019) stands out rather than any establishment of new responsible organizations or particular instruments/mechanisms. Furthermore, capacity-building and -strengthening are the primary facilitators in the majority of the examples, underscoring the need to address a lack of adequate human resources as well as limited awareness and knowledge.

Coordination of existing strategic planning mechanisms can be more effective for the advancement of Urban Green Infrastructure implementation than creating new instruments or institutions. Capacity-building and -strengthening are key, underscoring the need to address a lack of adequate human resources, limited awareness, and knowledge.

Promoter	**Location**	**Advances in the promotion and implementation of UGI in LATAM**				
National government	Colombia	National guidelines	Centralized	Coordination of several existing planning mechanisms	Financing provision limitation	Insufficient planning and funds for monitoring and evaluation
State government	Mexico City	Leadership and political will	Centralized cooperation			
Municipal government	Curridabat, Costa Rica	National guidelines			Financing of UGI implementation in both small- and large-scale initiatives	
	Guayaquil, Ecuador	Constitutional law and local leadership				
Academia/ Local government	Santiago, Chile	Leadership	Multi-Stakeholder Platform			
	Buenos Aires, Argentina		Centralized cooperation			
Academia	Heredia, Costa Rica		Living lab			
	Tijuana, Mexico					Adequate planning and funding availability for monitoring and evaluation
Citizens/ Civil Society Organizations	Jarabacoa, Dominican Republic		Multi-Stakeholder Platform			
	São Paulo, Brazil		Civil society empowerment			
Transformative dimension		**Enabling environment**	**Institutional**	**Management instruments**	**Implementation and operation**	**Monitoring and evaluation**

Table 6.3. Advances in the promotion and implementation of ten Latin-American Urban Green Infrastructure projects across the transformative dimensions.

The diversity of stakeholders with different objectives was also evident in the analysis, demonstrating the wide range of interpretations and applications of the UGI concept. In the words of Pauleit et al. (2019) the diversity of stakeholders and socio-physical contexts "together determine the functioning and effectiveness of GI." This calls into question the notion of a one-size-fits-all approach and encourages the development of strategies that recognize the social, environmental, infrastructure, and economic challenges of the local context. Moreover, multifunctionality, as a fundamental principle of the effective implementation of UGI, was evident across a variety of spatial scales. This has the potential to improve social inclusion (Vásquez et al., 2019) as well as city environmental, social, and institutional resilience (Buijs et al., 2019).

Implementing multifunctional Urban Green Infrastructure at various spatial scales has the potential to improve environmental, social, and institutional resilience.

Along with the opportunities, this multi-scale study also revealed interesting challenges for the region. As seen in Table 6.3, most of the examples are driven by leadership and a will to succeed, whether political (e.g., local governments) or nongovernmental (e.g., NGOs and academia). Nevertheless, although guidance and supervision are crucial factors, they do not ensure the continuity of UGI-related projects when there is a change in government or when the UGI champion is no longer part of the initiative. On the other hand, a common shortcoming identified in most of the cases studied was at the monitoring and evaluation level. Indeed, such monitoring and evaluation were only visible in cases where the primary supporter was the academic sector (e.g., Heredia and Tijuana cases) or NGOs (Jarabacoa case). This can be attributed to the experimental nature of such initiatives and the time scale on which the projects were produced.

Monitoring and evaluation of Urban Green Infrastructure is often lacking, owing to insufficient funding and consolidation efforts. Academia and non-governmental initiatives are in the lead here, but usually only for a limited time until a project ends.

Furthermore, although the pilot initiatives (Ecopark and the SEE-URBAN-WATER projects) sought to be replicable and stimulate mutual learning, they also highlighted the gap between research and local government policies. This was evidenced by the lack of a "responsive and facilitating attitude towards initiatives of active citizens", "formal recognition" (Buijs et al., 2019), and the limited engagement of local practitioners (Pauleit et al., 2019). Another overarching challenge, regardless of the primary supporter of any initiative, is the dearth of financial resources. This limitation was mentioned in more than half of the examples and has been widely recognized as an obstacle to the implementation of UGI in earlier studies (Drosou et al., 2019; Gashu & Gebre-Egziabher, 2019; Kim et al., 2017).

In light of the above-mentioned prospects and limitations, the following recommendations (see Table 6.4) are made for each transformative dimension to better promote UGI implementation in LATAM.

For more information about this multi-dimensional and multi-case assessment of NbS and UGI implementation in Latin America, please refer to:

Hack, J., Ojeda-Revah, L., Pérez, M., Pradilla, G., Borbor-Cordova, M., Burgueño, G., Eleuterio, A., Rivera, D., and Vásquez, A. (2023). Progress in urban green infrastructure for water management in Latin America. Authorea. DOI: https://doi.org/10.22541/au.169081523.30339770/v1

Transformative dimension	Recommendations
Enabling environment	• Develop national guidelines to promote/motivate local leadership. • Include UGI in planning mechanisms and instruments, and national regulations. • Combine top-down and bottom-up initiatives to better coordinate the efforts of different stakeholders to preserve, restore, or develop UGI projects in urban contexts. • Coordinate the interests of diverse sectors and actors. • Foster a responsive and enabling attitude toward citizen initiatives.
Institutional	• Promote centralized cooperation as a successful governance model for UGI implementation. • Coordinate actions at the city/regional level across various institutions. • Create municipal or regional management structures around an integrative concept such as UGI. • Establish multi-stakeholder platforms (temporary or permanent) to reconcile divergent perspectives among stakeholders and develop a new set of common values. • Define clear responsibilities in conjunction with regulatory frameworks to ensure financial resources. • Develop trans-/multi-sectorial and multi-level governance schemes.
Management instruments	• Coordinate existing institutions and legal provisions. • Promote and sustainably finance capacity-building. • Promote the UGI principle of multifunctionality through coordination at local and interdepartmental level, and within the institutions. • Develop specific UGI planning instruments and enhance their integration with existing ones. • Develop and implement strategic plans with explicit UGI objectives and principles.
Implementation and operation	• Incorporate UGI connectivity and multifunctionality principles into UGI implementation. • Create demonstration environments or pilot projects to stimulate transdisciplinary learning and gain experience with alternative technologies. Take advantage of academia and CSO support. • Attend to the needs of the local context. • Support UGI implementation with communication and dissemination strategies.
Monitoring and evaluation	• Government stakeholders should promote/plan UGI monitoring and evaluation. • The active involvement of key stakeholders in the different implementation stages could influence greater ownership and willingness to participate in maintenance, monitoring, and long-term operation. • Take advantage of academia and CSO support.

Table 6.4. Recommendations for the promotion and wider implementation of Urban Green Infrastructure (UGI).

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PROJECT OUTPUTS AND PRODUCTS

PROJECT OUTPUTS AND PRODUCTS

As an inter- and transdisciplinary research project, SEE-URBAN-WATER (SUW) produced outputs and products targeting a variety of audiences in Latin America, Germany and globally, including the scientific community, practitioners, governmental and non-governmental groups as well as interested citizens.

On the one hand, the project generated traditional research output in terms of articles in scientific journals and presentations at international conferences addressing mainly academic and often specialized audiences. To broaden discussions and stimulate a more intensive knowledge transfer, SUW also organized and coordinated several Special Issues in collaboration with reputable research journals as well as Special Sessions related to Nature-based Solutions and Green Infrastructure in urban watersheds. The purpose of this book is to summarize the numerous scientific publications resulting from the project and to present them in a coherent, understandable, and contextualized manner.

On the other hand, the SUW team also produced tailor-made outputs and products using different media to transfer inter- and transdisciplinary knowledge to a variety of practitioners. One important product is “Guías Verdes” (Green Guidelines, in English) – a compendium of guidelines for promoting and implementing green infrastructure in urban areas, based on the transdisciplinary work and the exchange of experiences with other initiatives in the project’s Real-World Lab. The compendium is accessible through a web platform and in book format (printed and PDF versions). Another product is a web-based data and visualization platform to share geo-spatial data and modeling results using web maps, apps, dashboards, and other digital tools. This enables SUW to visualize scientific results usually presented as static maps and diagrams in publications in an interactive and user-defined manner. The web apps allow a range of datasets to be queried, combining different information for user-specified visualizations. Users can thus delve in detail into the results and the Nature-based Solutions developed by the SUW project within specific spatial application contexts.

All the aforementioned results were showcased at a two-day end-of-project event conducted in Spanish and hosted by the University of Costa Rica. Table 7.1 provides a summary of all project outputs and products, presented in detail in the following sections.

Project outputs and products	Description	Target groups
Guías Verdes, web platform and book (in Spanish)	Compendium of guidelines for promoting and implementing green infrastructure in urban areas, based on the transdisciplinary work in the project’s Real-World Lab and the exchange of experiences with other initiatives in the Greater Metropolitan Area of San José, Costa Rica.	Latin America: Practitioners Interested citizens Social activists/groups Non-governmental groups
Web-based data and visualization platform (in Spanish and English)	Online platform to share geo-spatial data and modeling results using web maps, apps, dashboards and other digital tools.	Costa Rica / Global: Administration/Municipalities Practitioners Interested citizens Non-governmental groups
Scientific publications and conference participation (in English and Spanish)	Dissemination of research work in peer-reviewed publications in scientific journals and through presentations at international conferences.	Global scientific community and research-oriented practitioners
End-of-project event (in Spanish)	Two-day hybrid conference held in Spanish at the University of Costa Rica. Presentation of project outputs and a summary of scientific results, complemented by thematically related talks by local experts from academia, administrations, practitioners and civil society; including two discussion forums.	Costa Rica and Latin America: Academics Practitioners Engaged citizens Non-governmental groups

Table 7.1. SEE-URBAN-WATER project outputs and products.

7.1. Web platform and book "Guías Verdes: Infraestructura verde para la ciudad, sus ciudadanos y sus ríos"

The six-year transdisciplinary work in the study area in Costa Rica enabled the co-production of new knowledge through identifying urban infrastructures, collecting hydrometeorological and hydrological data, holding community workshops, and co-designing and implementing of Nature-based Solution (NbS) prototypes. The knowledge generated contributed to improving public services such as urban drainage, wastewater treatment, microclimate regulation, public recreation, protection of water resources and disaster control. Furthermore, this knowledge is considered a foundation for proceeding towards a sustainable social-ecological transformation by virtue of the development and testing of nature-based urban drainage and greywater treatment infrastructures.

In its attempt to share this knowledge with others, the SEE-URBAN-WATER (SUW) research team compiled a compendium of guidelines, Guías Verdes (Green Guidelines, in English), for promoting and implementing Green Infrastructures in urban areas. Available in Spanish, it targets academic and non-academic stakeholders in Latin America who are either interested in or already engaged in NbS planning, implementation, operation, and monitoring. The guidelines are based on the activities conducted and experiences acquired during the development of the project in the Greater Metropolitan Area of San José, Costa Rica. They list actions to facilitate the creation of more green spaces, manage rainwater and improve water quality in cities. Acting as a procedure manual, each guideline describes the necessary steps for implementing a measure or solution in a structured and standardized format, making the knowledge accessible and available for replication.

Guías Verdes were developed within the framework of the SUW project, consolidating the results of an open and transparent process that involved different local stakeholders including universities, municipalities, and civil society organizations (Figure 7.1).

Figure 7.1. Guías Verdes: Participating organizations.

Guías Verdes

Front cover and QR code to access the book "Guías Verdes – Infraestructura verde para la ciudad, sus ciudadanos y sus ríos".

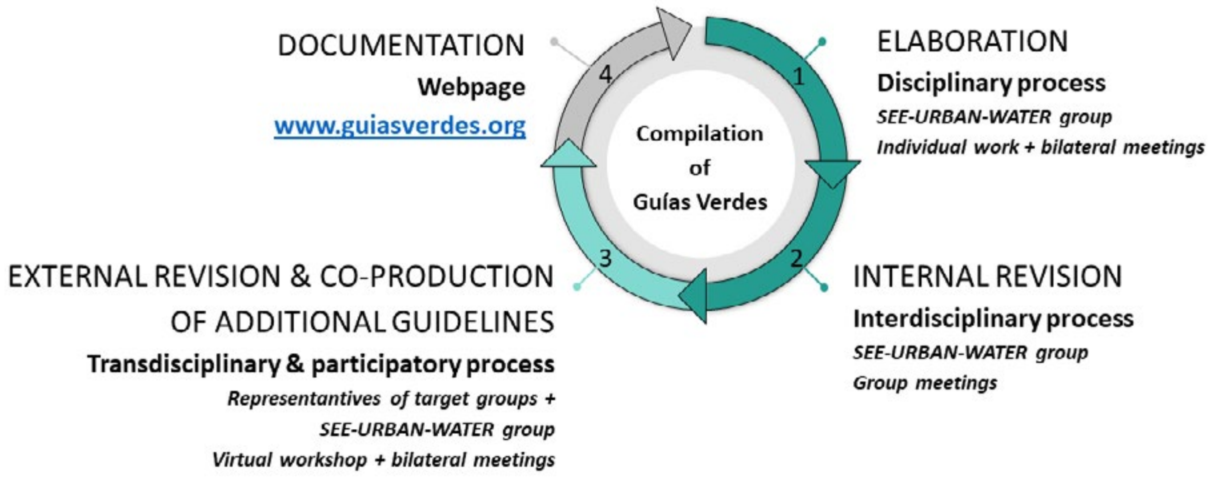
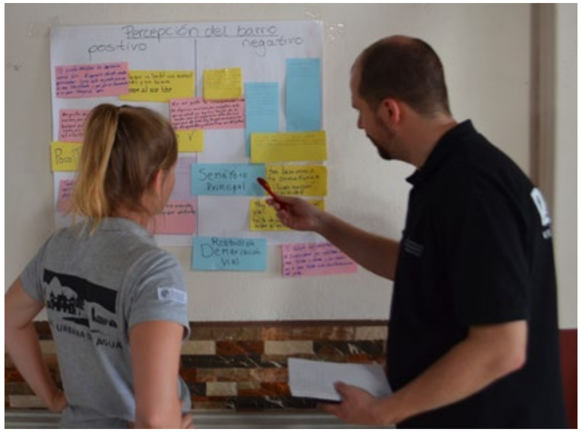


Figure 7.2. Compilation of Guías Verdes including methods.

Compilation involved four stages (Figure 7.2):

1. Drafting of guidelines by the SUW team members, drawing on the transdisciplinary knowledge acquired in the project's Real-World Lab.
2. Internal review conducted in an interdisciplinary manner.
3. External review performed in a transdisciplinary and participatory manner. This involved workshops with local stakeholders in Costa Rica and bilateral meetings.
4. Documentation and publication of the web platform and the book "Guías Verdes".

After more than one year of collaborative development with partners in Costa Rica, SUW launched the open-access web platform GUIASVERDES.ORG. This website offers guidance on promoting and implementing Nature-based Solutions to boost the development of Urban Green Infrastructures.



Transdisciplinary activities carried out by the SEE URBAN WATER Team in the Real-world Lab, described in Guias Verdes.

Alongside the aforementioned guidelines, it includes guidelines developed in collaboration with local partners, documenting other important experiences in the country. At the end of each guideline there is a short questionnaire for providing feedback or contacting the SUW team. This feedback feature is intended as a way to continuously improve website content and foster exchange with interested readers and practitioners. To improve accessibility, a PDF download function is available for each guideline.

Transdisciplinary activities carried out by the SEE URBAN WATER Team in the Real-world Lab, described in Guias Verdes.

As an additional outcome of the SUW research project, the web platform's content is also available in book format as 'Guías Verdes – Infraestructura verde para la ciudad, sus ciudadanos y sus ríos'. As is to be expected, the book encompasses all the developed guidelines, as well as documenting additional experiences gained within the context of NbS and UGI promotion in urban watersheds. Visit guiasverdes.org to access the book.

7.2. Web-based data and visualization platform

The traditional way of disseminating research findings is through scientific publications in journals or presentations at field-related conferences. However, this approach has significant limitations. For instance, the target audience is primarily associated with the academic community, excluding potential users with no access to these sources of information. Moreover, this presentation format lacks the ability to interact with data, visualize changes, or facilitate information exchange. Recognizing these constraints and considering the geo-spatial nature of the data and results generated through the project's place-based and transdisciplinary research, the SUW team developed a web-based data and visualization platform. This tool effectively presents all geo-spatial data related to the project's study area in an easily accessible, interactive, and user-oriented manner.

The aim of this platform, developed using the A rcGIS Experience Builder software, is to share geo-spatial data and modeling results of the project using web maps, apps, dashboards, and query tools. These enable the SUW team to visualize and present the project's results, typically displayed in non-interactive maps and diagrams within scientific publications, in a more dynamic and user-friendly format. Furthermore, the platform allows a variety of datasets to be queried, combining different information sources for user-specified tasks. Users (including project funders, project enthusiasts, individuals from the project area, and residents living within the project area) can thus delve in detail into both the results and Nature-based Solutions developed by SUW within specific spatial application contexts.

Aerial view of the Quebrada Seca-Rio Burío watershed, Llorente, Flores, Costa Rica.

Since our project data and results are linked to geographical information, resulting in numerous maps visualizing data and modeling results, the ArcGIS Experience Builder was chosen to create an online platform for presenting our work.

Through this web-based outcome-oriented application, we are able to provide an enriched and self-explanatory understanding of our project results through interactive content, storytelling and multimedia elements. This innovative approach goes beyond the conventional use of traditional maps and lengthy texts. For instance, our web apps are designed with intuitive interfaces and user-friendly features, allowing users to effortlessly experience our findings without the need for extensive explanations. By incorporating interactive elements and tools into our online resources, we invite users to delve into our project, explore the facts and findings of the study area, and directly engage with the research results. Furthermore, the creation of an online platform, incorporating web maps and layers, facilitates data sharing and exchange, fostering collaboration and supporting further research activities.

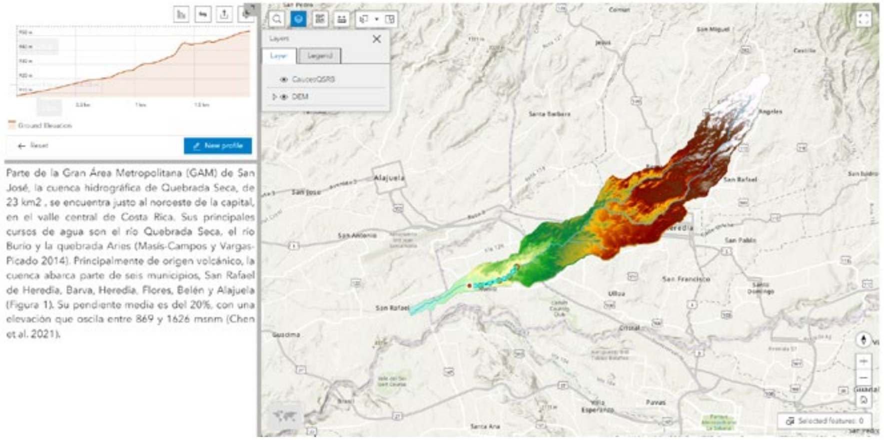
Would you like to know more about this tool? Visit our data and visualization platform:

https://experience.arcgis.com/experience/39b3b6d926f840c59e3879560d2e750f/

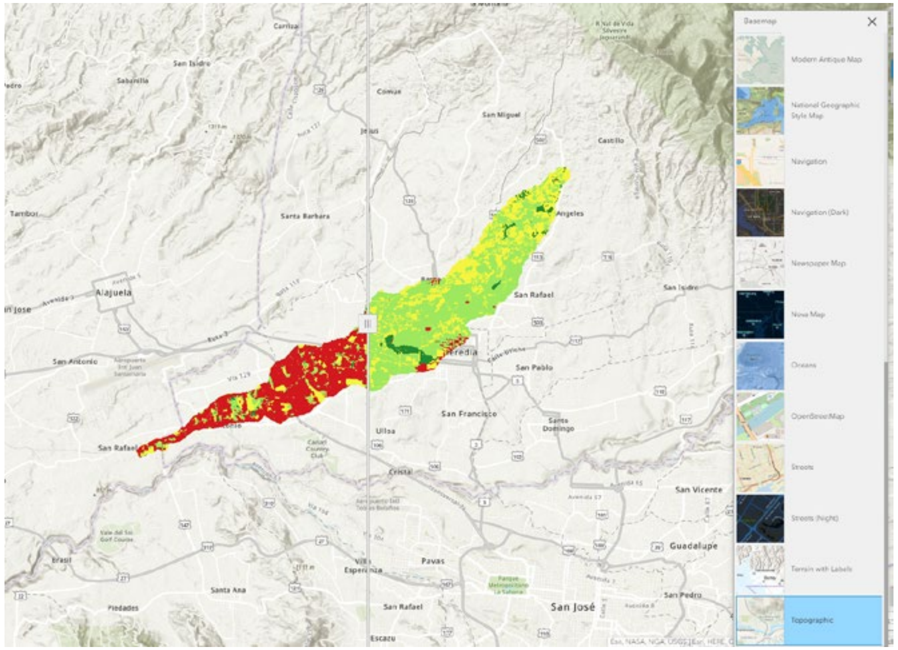
ArcGIS Experience Builder

Hydrometeorological station of Belén's Early Warning System.

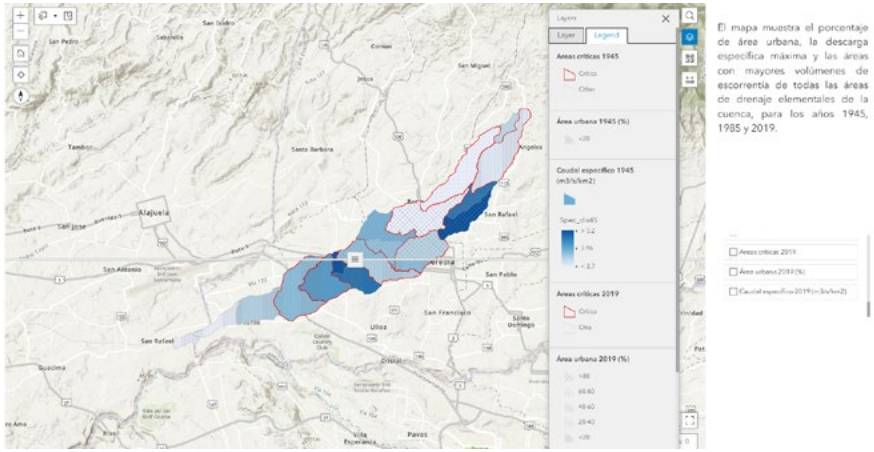
Screenshot of SUW's web-based data visualization and sharing platform



Interactive exploration of Quebrada Seca-Rió Burío watershed's topography.

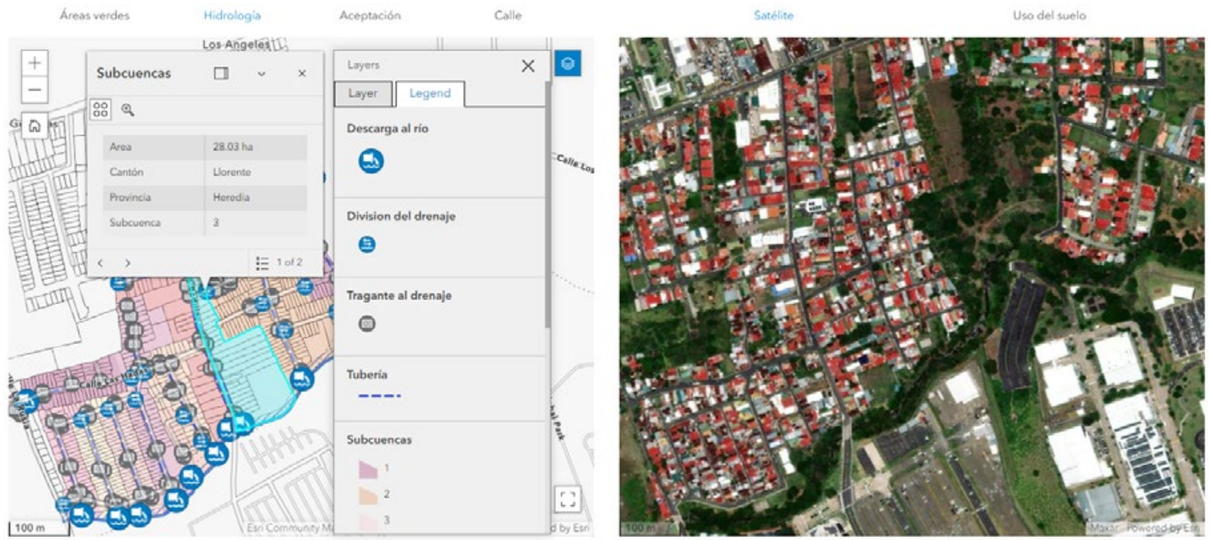


Historical land cover comparison tool for the Quebrada Seca-Rió Burío watershed.

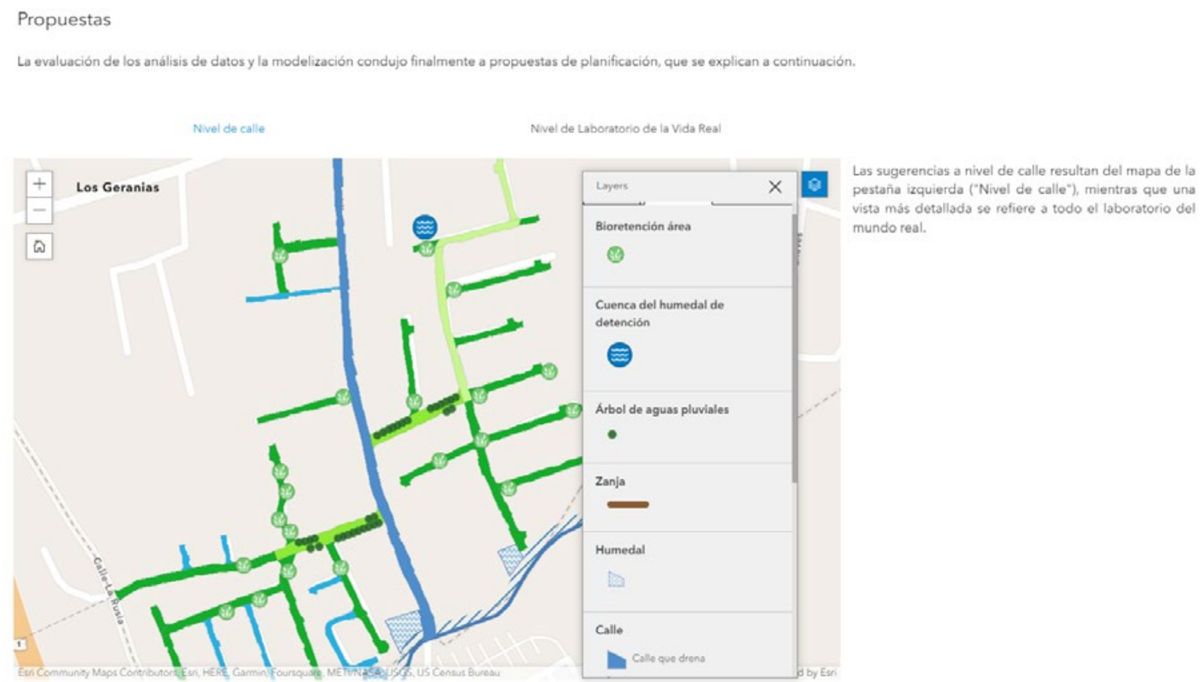


Data query tool for historical land cover and resulting hydrological model response of individual drainage areas of the Quebrada Seca-Rió Burío watershed.

Data query tool for historical land cover and resulting hydrological model response of individual drainage areas of the Quebrada Seca-Rió Burío watershed.



Visualization and interactive query of the data gathered in the SUW Real-World Lab



Visualization and interactive query of Urban Green Infrastructure options developed for the SUW Real-World Lab

We invite you to explore our innovative presentation of research results with queries reflecting your specific interest.

INFO

Good practices to share knowledge related to geospatial data?

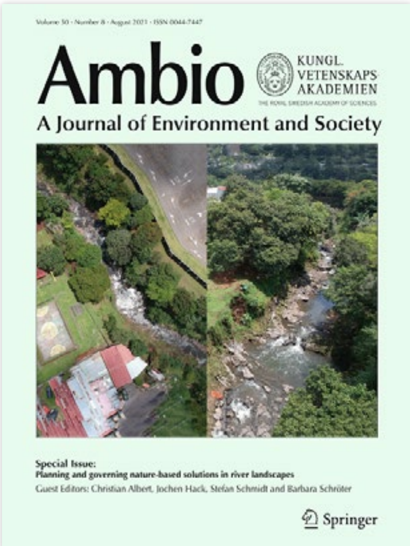
The Open Science movement promotes the freely accessible provision of scientific articles (open access) and the use and development of open-source software. The arguments for this development are manifold, ranging from transparency and reproducibility to the demand that publicly funded results should be a public good. As part of the SUW project, an open-source software tool was developed that uses maps to break down barriers in communication between practitioners and scientists with a view to enabling participatory approaches and mutual learning. This tool can be used in workshops and presentations for knowledge transfer. Since it is web-based it can be shared with different stakeholders after an event as a link, allowing them to interactively deepen or distribute the information. The advantage of the developed tool is that, even if it works interactively, it is technically a static tool. This makes the technical provision of the service very simple and inexpensive to realize, since there are various providers offering 'static' web space free of charge and in a relatively uncomplicated manner. In addition, the tool can be adapted to other purposes and used free of charge. This makes the service suitable for citizens' groups, NGOs or research projects with limited financial resources. The tool contains sample data and can be viewed at the following link: https://mi_barrio.codeberg.page.

7.3. Scientific outputs

Throughout the six-year project, a variety of peer-reviewed scientific journal articles have been published. SEE-URBAN-WATER has edited and contributed with research articles to several Special Issues dealing with Urban Green Infrastructures and Nature-based Solutions. Through the publications in Special Issues, SEE-URBAN-WATER participated in a more comprehensive manner in addressing certain topics, reflecting on the work performed in the project and putting it in context.

Scientific publications in special issues

Ambio – A Journal of Environment and Society - Special Issue: Planning and governing Nature-based Solutions in river landscapes



- Pérez Rubi, M., Hack, J. Co-design of experimental nature-based solutions for decentralized dry-weather runoff treatment retrofitted in a densely urbanized area in Central America. Ambio 2021. https://doi.org/10.1007/s13280-020-01457-y
- Chen, V.; Bonilla Brenes, J. R.; Chapa, F.; Hack, J. Development and modeling of realistic retrofitted Nature-based Solution scenarios to reduce flood occurrence at the catchment scale. Ambio 2021. https://doi.org/10.1007/s13280-020-01493-8
- Albert, C.; Hack, J.; Schmidt, S.; Schröter, B. Planning and governing nature-based solutions in river landscapes: Concepts, cases, and insights. Ambio 2021. https://doi.org/10.1007/s13280-021-01569-z

Journal of Remote Sensing - Special Issue: Mapping Ecosystem Services Flows and Dynamics Using Remote Sensing

Beißler, M. R.; Hack, J. A Combined Field and Remote-Sensing based Methodology to Assess the Ecosystem Service Potential of Urban Rivers in Developing Countries. Remote Sens. 2019, 11, 1697, https://doi.org/10.3390/rs11141697

Journal of Sustainability - Special Issue: Nature-Based Solutions—Concept, Evaluation, and Governance

Neumann, V. A.; Hack, J. A Methodology of Policy Assessment at the Municipal Level: Costa Rica´s Readiness for the Implementation of Nature-Based-Solutions for Urban Stormwater Management. Sustainability 2019, 12, 230, https://doi.org/10.3390/su12010230

Journal of Remote Sensing - Special Issue: Remote Sensing and GIS for Environmental Analysis and Cultural Heritage

Hack, J.; Molewijk, D.; Beißler, M. R. A Conceptual Approach to Modeling the Geospatial Impact of Typical Urban Threats on the Habitat Quality of River Corridors. Remote Sens. 2020, 12, 1345, https://doi.org/10.3390/rs12081345

Journal of Water - Special Issue: Stormwater Management in Urban and Rural Areas

Chapa, F.; Pérez, M.; Hack, J. Experimenting Transition to Sustainable Urban Drainage Systems—Identifying Constraints and Unintended Processes in a Tropical Highly Urbanized Watershed. Water. 2020, 12, 3554, https://doi.org/10.3390/w12123554

Journal of Sustainability - Special Issue: Nature-Based Solutions for Water Management from Pilot to Standard

Fluhrer, T.; Chapa, F.; Hack, J. A Methodology for Assessing the Implementation Potential for Retrofitted and Multifunctional Urban Green Infrastructure in Public Areas of the Global South. Sustainability. 2021, 13, 384, https://doi.org/10.3390/su13010384

Journal of Sustainability - Special Issue: Green Infrastructure and Sustainable Urban Water Management

Chapa, F.; Perez Rubi, M.; Hack, J. A Systematic Assessment for the Co-Design of Green Infrastructure Prototypes—A Case Study in Urban Costa Rica. Sustainability 2023, 15, 2478. https://doi.org/10.3390/su15032478

Several other research articles have been published in regular Journal Issues of different fields of research, documenting the broad interdisciplinary work of SEE-URBAN-WATER.

Title	Authors	Year	Journal & DOI
Avances de infraestructura verde urbana para la gestión de agua en América Latina	Hack, Jochen; Ojeda-Revah, Lina; Pérez Rubí, Maria; Pradilla, Gonzalo; Borbor-Cordova, Mercy; Burgueño, Gabriel; Eleuterio, Ana Alice; Rivera, Daniela; Vásquez, Alexis.	2024	Cuadernos de Geografía: Revista Colombiana de Geografía 33 (1): https://doi.org/10.15446/rcdg.v33n1.101947
Attitudes of Political-Administrative Actors Towards the Implementation of Nature-Based Solutions in Water Management - An Example of the Tárcoles River	Franka Pätzke, Christoph Schulze, Jochen Hack, et al.	2023	Authorea (Preprint) https://doi.org/10.22541/au.169774191.19879068/v1
Multi-criteria site selection and hydraulic modeling of green flood retention measures in a highly urbanized basin in Costa Rica	Carolina Lopes Monteiro, José Ricardo Bonilla Brenes, Alberto Serrano-Pacheco & Jochen Hack	2023	Urban Forestry & Urban Greening https://doi.org/10.1016/j.ufug.2023.127957
Variation in the hydrological response within the Quebrada Seca watershed in Costa Rica resulting from an increase of urban land cover	Ricardo Bonilla Brenes, Martín Morales, Rafael Oreamuno & Jochen Hack	2023	Urban Water Journal https://doi.org/10.1080/1573062X.2023.2204877
A Width Parameter Estimation Through Equivalent Rectangle Methodology for Hydraulic Modeling Applications	Jose Ricardo Bonilla Brenes, Rafael Oreamuno Vega & Jochen Hack	2022	Journal Water Management Modeling, https://doi.org/10.14796/JWMM.C493
Potential of retrofitted urban green infrastructure to reduce runoff - A model implementation with site-specific constraints at neighborhood scale	Carlos H. Aparicio Uribe, Ricardo Bonilla Brenes & Jochen Hack	2022	Urban Forestry & Urban Greenery https://doi.org/10.1016/j.ufug.2022.127499
Beyond Demonstrators—tackling fundamental problems in amplifying nature-based solutions for the post-COVID-19 world	Barbara Schröter, Jochen Hack, Frank Hüesker, Christian Kuhlicke & Christian Albert	2022	npj Urban Sustainability https://doi.org/10.1038/s42949-022-00047-z
A multiple scale, function, and type approach to determine and improve Green Infrastructure of urban watersheds	Nils Arthur & Jochen Hack	2022	Urban Forestry & Urban Greenery https://doi.org/10.1016/j.ufug.2022.127459
Revealing and assessing the costs and benefits of nature-based solutions within a real-world laboratory in Costa Rica	Veronica Alejandra Neumann & Jochen Hack	2022	Environmental Impact Assessment Review https://doi.org/10.1016/j.eiar.2022.106737
Nature-Based Solutions for River Restoration in Metropolitan Areas	Jochen Hack & Barbara Schröter	2022	In R. Bears (Ed.), The Palgrave Encyclopedia of Urban and Regional Futures. https://doi.org/10.1007/978-3-030-87745-3_166
Soluciones basadas en la naturaleza para la restauración de ríos en áreas metropolitanas: El proyecto Visión Urbana del Agua en la cuenca Quebrada SecaRío Burío, Costa Rica	Jochen Hack	2021	Ambientico https://www.ambientico.una.ac.cr/revista-ambientico/soluciones-basadas-en-la-naturaleza-para-la-restauracion-de-rios-en-areas-metropolitanas-el-proyecto-vision-urbana-del-agua-en-la-cuenca-quebrada-seca-rio-burio-costa-rica/
Crisis-induced disruptions in place-based social-ecological research - an opportunity for redirection	Kathleen Hermans, Elisabeth Berger, Lisa Biber-Freudenberger, Lisa Bossenbroek, Laura Ebeler, Juliane Groth, Hack, Jochen, et al.	2021	GAIA - Ecological Perspectives for Science and Society https://doi.org/10.14512/gaia.30.2.3
High resolution modeling of the impact of urbanization and green infrastructure on the water and energy balance	Rebecca Wiegels, Fernando Chapa, & Jochen Hack	2021	Urban Climate https://doi.org/10.1016/j.uclim.2021.100961

Title	Authors	Year	Journal & DOI
Preserving biodiverse river corridors for sustainable city development	Jochen Hack	2021	Research Outreach https://doi.org/https://doi.org/10.32907/RO-122-1289360226
Highly Resolved Rainfall-Runoff Simulation of Retrofitted Green Stormwater Infrastructure at the Micro-Watershed Scale	Sami Towsif Khan, Fernando Chapa & Jochen Hack	2020	Land https://doi.org/10.3390/land9090339
Cost-Effective Optimization of Nature-Based Solutions for Reducing Urban Floods Considering Limited Space Availability	Apoorva Singh, Arup Kumar Sarma & Jochen Hack	2020	Environmental Processes https://doi.org/10.1007/s40710-019-00420-8
A multi-parameter method to quantify the potential of roof rainwater harvesting at regional levels in areas with limited rainfalldata	Fernando Chapa, Manuel Krauss & Jochen Hack	2020	Resources, Conservation and Recycling https://doi.org/10.1016/j.resconrec.2020.104959
A Socio-Ecological System Analysis of Multilevel Water Governance in Nicaragua	Luis Montenegro & Jochen Hack	2020	Water https://doi.org/10.3390/w12061676
A New Approach to High-Resolution Urban Land Use Classification Using Open Access Software and True Color Satellite Images	Fernando Chapa, Srividya Hariharan & Jochen Hack	2019	Sustainability https://doi.org/10.3390/su11195266

Table 7.2. List of scientific publications in regular Journal Issues.

Aerial view of Quebrada Seca-Río Burío and remaining green areas in the river bank, Flores, Costa Rica.

Participation in international conferences

The SEE-URBAN-WATER team actively participated in international scientific conferences, delivering several Keynote Lectures and Invited Talks, and organizing Special Sessions, conference talks and poster presentations. These activities not only enabled a broader dissemination of results within the scientific community but also promoted intensive exchanges and discussions with other scientists and research-oriented practitioners.

Several Special Sessions and workshops addressing the promotion of Nature-based Solutions and Green Infrastructures in urban watersheds resulted from SUW's involvement in the Leadership Team of the Working Group on Nature-based Solutions of the International Association for Hydro-Environment Engineering and Research (IAHR), the Latin American Division of the Ecosystem Service Partnership (ESP) and the International Ecological Engineering Society (IEES). Table 7.3 summarizes the contributions to Special Sessions at international conferences, while Table 7.4 displays the regular contributions to conferences and special events.

SPECIAL SESSIONS AT CONFERENCES ORGANIZED BY SEE-URBAN-WATER

Conference - Place and Year	Contributions	Further details
IAHR 40th World Congress. Rivers – connecting mountains and coasts. Vienna, Austria. 2023	Prof. Dr.-Ing. Jochen Hack hosted the Special Session: "Nature-based Solutions for cities and urban watersheds". He presented a "SEE-URBAN-WATER project summary". Presentation by Ricardo Bonilla: Integrated development of Nature-based Solutions for tropical urban watershed restoration.	https://rivers.boku.ac.at/iahr/
4th ESP Europe Conference: Ecosystem Services empowering people and societies in times of crises. Heraklion, Greece. 2022	Prof. Dr.-Ing. Jochen Hack hosted two Special Sessions: • Beyond water: Understanding the role and co-benefits of NBS used for water management. • Integrative digital systems for planning and managing ecosystem services: State of the art and future prospects. Presentation by Maria Perez Rubi: Embracing a combination of bottom-up and top-down participatory approach to map the spatial distribution of potential Nature-Based Solutions in Costa Rica.	https://www.projectwaterways.eu/_news/ESP-4thEurope-2022-Conference-program-booklet.pdf
39th IAHR World Congress Granada, Spain. 2022	Prof. Dr.-Ing. Jochen Hack, member of the Leadership Team of the Working Group on Nature-based Solutions (NbS), hosted the Special Session "Implementing Nature Based Solutions – bringing science to practice", and organized a High-Level Panel of "Nature-based Solutions and Ecohydraulics", as well as a Technical Meeting of the Working Group. Prof. Dr.-Ing. Jochen Hack also presented: Advances in implementing and promoting Nature-based Solutions in urban areas – A real-world lab experience from Costa Rica. Conrad Schiffmann presented: A combined legal-hydrological evaluation method for Green Infrastructure in urban Costa Rica.	• Schiffmann, C., Bonilla Brenes, R., Hack, J., (2022). A combined legal-hydrological evaluation method for Green Infrastructure in urban Costa Rica. Proceedings of the IAHR World Congress. Granada, Spain. DOI: 10.3850/IAHR-39WC2521-71192022SS2039, https://www.iahr.org/library/infor?pid=21663 • Hack, J. (2022) Advances in implementing and promoting Nature-based Solutions in urban areas – A real-world lab experience from Costa Rica, Proceedings of the 39th IAHR World Congress, Granada, Spain. DOI: 10.3850/IAHR-39WC252171192022SS934, https://www.iahr.org/library/infor?pid=21662 • Penning, E. and Hack, J. High Level Panel 4: Nature-based Solutions and Ecohydraulics. Proceedings of the 39th IAHR World Congress. 19–24 June 2022, Granada, Spain. DOI: 10.3850/IAHR39WC252171192022panel4, https://www.iahr.org/library/infor?pid=21679

Conference - Place and Year	Contributions	Further details
3rd ESP Latin America and Caribbean Conference Mexico City, Mexico. Virtual 2020 w	In partnership with the Research Group PlanSmart, SEE URBAN WATER co-hosted the Special Session: “Nature-based Solutions for river landscapes in Latin America”. Prof. Dr.-Ing. Jochen Hack presented: Multifunctional Nature-based Solutions for urban drainage and wastewater treatment.	https://www.es-partnership.org/3rd-esp-latin-america-and-caribbean-conference/
Closed cycles and the circular society – The Power of Ecological Engineering. Conference of the International Ecological Engineering Society. Virtual - Zurich, Switzerland. 2020	Together with Prof. Dr. Petra Schneider, Prof. Dr.-Ing. Jochen Hack hosted the Special Session: Co-designed Multifunctional Urban Green Infrastructure Prof. Jochen Hack gave a talk on “Multifunctional Green Infrastructure for urban drainage and wastewater treatment – A Costa Rican Example” based on the SUW project work in Costa Rica. He also moderated the round table discussion with experts on “How to upscale and mainstream pilot measures?”	https://link.springer.com/article/10.1007/s43615-021-00125-x
6th Biennial Symposium of the International Society for River Science. Vienna, Austria. 2019	In partnership with the Research Group PlanSmart, Prof. Dr.-Ing. Jochen Hack co-hosted the Special Session: Nature-based Solutions at different scales in urban and rural river watersheds. He also organized a workshop about Nature-based Solutions.	Hack, J. (2019). Nature-based solutions of different spatial scales to improve the urban water cycle. In Riverine Landscapes as coupled socio-ecological systems, 6th Biennial Symposium of the International Society for River Science. September 8 - 13, 2019. Vienna, Austria. https://riversociety.org/isrs-conference/2019-vienna-austria/
Ecosystem Services Partnership World Conference 2019 Hannover, Germany. 2019	In partnership with the Research Group PlanSmart, Prof. Dr.-Ing. Jochen Hack co-hosted the Special Session: Frontiers in planning and implementing nature-based solutions in river landscapes. Veronica Neumann presented a poster about policy design of Nature-based Solutions in Costa Rica.	Hack, J. (2019). Dealing with different nature-society constellations in the co-design of urban green infrastructure. In Proceedings of the Ecosystem Service Partnership World Conference 2019: Session B2b - Frontiers in planning and implementing nature-based solutions in river landscapes. DOI:10.26083/tuprints-00019879

Table 7.3. Special Sessions organized by SEE-URBAN-WATER at international conferences.

SEE-URBAN-WATER AT CONFERENCES

Name of conference – City and Year	Contribution
4th International Ecosystem Services Partnership Latin America and Caribbean Conference, La Serena, Chile. 2023	Prof. Dr.-Ing. Jochen Hack presented the results from the publication "Advances in the application of Nature-based Solutions for urban water management in Latin America".
Closed cycles and the circular society 2023. International Ecological Engineering Society Chania, Greece. 2023	Poster presentation by Maria Perez Rubi: Scaling-up Nature-based Solutions for decentralized greywater treatment, retrofitted in urban areas of Costa Rica.
6 th IWA ecoSTP International Conference Girona, Spain. 2023	Poster presentation by Maria Peréz Rubí: Multidimensional Assessment of a Nature-based Solution for decentralized small-scale greywater treatment in Costa Rica.
IAHR 85th Anniversary Lectures. Online. 2021	At the invitation of the Technical Committee "Ecohydraulics" of the IAHR, Prof. Dr.-Ing. Jochen Hack presented the topic "Nature-based Solutions in the urban realm - Striving for multi-functionality and co-design" as a keynote lecturer.
Bioengineering in action online conferences at Universidad del Bosque, Colombia. 2021.	Prof. Dr.-Ing. Jochen Hack was invited as a guest speaker by the Universidad del Bosque (Colombia) to share the SUW experiences on "Implementation of Nature-based Solutions in urban areas of Latin America".
10th Conference on Fluvial Hydraulics - River Flow 2020, Delft, Netherlands (Online).	Dr. José Fernando Chapa presented the topic "Promoting multifunctional green infrastructures by implementing pilot projects. The study case of an urban watershed in a developing country."
International Conference on Urban Water Interfaces, 22 – 24 September 2020. Berlin, Germany.	Prof. Dr.-Ing. Jochen Hack presented the microclimatic modeling results of the potential impact of UGI in the SUW Real-World Lab: "Urbanization and Urban Green Infrastructure impact on the energy and water balance".
IAHR 85th Anniversary Summit. Beijing, China and Online. 2020	Prof. Dr.-Ing. Jochen Hack was a Keynote Lecturer in the session Ecohydraulics II: Nature-based Solutions. He presented "Nature-based Solutions in urban contexts – the fight for multifunctionality and co-design" sharing lessons learned from the SEE URBAN WATER project in Costa Rica.
19th Annual Meeting of the American Ecological Engineering Association. Asheville, NC, USA. 201	Prof. Dr.-Ing. Jochen Hack contributed with a presentation and a publication "A new Methodology to Assess the Ecosystem Service Potential of Urban Rivers in Developing Countries". DOI: 10.26083/tuprints-00024375
38th IAHR World Congress. Panama City. 2019.	Prof. Dr.-Ing. Jochen Hack contributed to the Special Session on Nature-based Solutions with the presentation "A Methodology to Quantify the Potential of Urban Rivers to Provide Ecosystem Services" and a publication "A Methodology to quantify the potential of urban rivers to provide ecosystem services based on remote sensing and field indicators – The Pochote River, Nicaragua" on the SUW project work in Nicaragua. DOI: 10.3850/38WC092019-1681 Prof. Dr.-Ing. Jochen Hack also participated in the conference workshop "Unlocking the Nature-based Solution potential for coasts, rivers and ports" – A Special IAHR Workshop on achieving implementation in Central and South America.
Lecture travel to Ecuador. Quito and Guayaquil. 2018.	At the invitation of the German federal government, Prof. Dr.-Ing. Jochen Hack participated as Keynote Lecturer in several academic events in Ecuador: • Water resources in cities and adaptation to climate change based on ecosystems, Universidad Andina Simón Bolívar, Quito • Water Resources in Cities and Strategies for Adaptation to Change Climate, Escuela Politécnica del litoral (ESPOL), Guayaquil

Table 7.4. Contributions of SEE-URBAN-WATER to international conferences and special events.

7.4. End-of-project event in Costa Rica, 2023

As part of the final phase of the SEE-URBAN-WATER (SUW) project, the SUW team, in collaboration with the Research Center for Sustainable Development Studies (abbreviated to CIEDES in Spanish) of the University of Costa Rica, organized a closing event. Its primary objective was to present the project's key findings and facilitate a space for discussion analyzing strategies for the development of Urban Green Infrastructure in Costa Rica. The event, themed 'Visión Urbana del Agua: Infraestructura Verde para la ciudad, sus ciudadanos y sus ríos', was held at the University of Costa Rica on 21–22 September 2023. Invitations to participate were extended to the project's counterparts in Costa Rica and representatives from academia, the public sector, the private sector, and civil society. A total of 94 individuals registered for the two-day event, while others took part online.

Members of SEE-URBAN-WATER and collaborators from CIEDES at the end-of-project event 2023 in Costa Rica. From left to right: Juan McGregor (CIEDES), Martín Morales (CIEDES), Julia Matecki, Alberto Serrano (Director de CIEDES), Adriana Araya, Jochen Hack, Manuel Beissler, Ricardo Bonilla, and María Pérez Rubí.

Announcement of the SEE-URBAN-WATER end-of-project event.

The first day of the event featured eight thematic presentations sharing the main results of the SUW project and presenting other experiences of local initiatives and projects related to urban water management, Nature-based Solutions and Urban Green Infrastructure.

The welcoming speech was delivered by Alberto Serrano, director of CIEDES. Prof. Dr.-Ing. Jochen Hack, leader of the SUW research group, followed, presenting the general background, context and development of the project and expanding on the challenges of urbanization in relation to water management. After stating the main project objective – the co-design and implementation of Nature-based Solutions in urban watersheds – Prof. Dr.-Ing. Hack outlined the presentation, aligning it with the project's main results and organizing it into three thematic blocks:

1. "Real-World Laboratory and co-design of Nature-based Solutions prototypes", by María Pérez Rubí.
2. "Hydrological-hydraulic studies of urban runoff and multifunctional green infrastructure solutions in urban basins", by Ricardo Bonilla.
3. "Governance for the development of Urban Green Infrastructure", by Manuel Beißler.

These presentations showcased not only the main results of the six-year project but also the challenges and lessons learned. Furthermore, each thematic block was followed by invited guest speakers sharing their own urban water management experiences in Costa Rica. Three corresponding discussion sessions were provided to encourage audience participation and the exchange of opinions.

The second day of the event started with Prof. Dr.-Ing. Jochen Hack presenting the key products of the SUW project, including the book “Guías Verdes – Infraestructura Verde para la ciudad, sus ciudadanos y sus ríos”, the web platform www.guiasverdes.org (described in section 7.1), and the present book summarizing the outcomes of the six-year project. This was followed by an interactive demonstration of SUW’s visualization and data exchange work in the Quebrada Seca-Río Burío watershed using the ArcGIS Experience Builder software (described in section 7.2).

Forums dynamics: Topic presentation, question and answer, and at the end, audience interaction.

This was followed by two discussion sessions involving local experts as guest panelists. Prior to each session, a keynote presentation set the stage for the discussion topic.

Forum 1 Opening: Citizen participation in urban water resource management.

The theme of the first forum was:

“Citizen Participation in water resource management processes in urban areas”.

Objective: To analyze the effective promotion of spaces for local community participation in water resource management based on previous experiences of citizen involvement.

Moderator: María José Bermúdez, ASADA Poás y Barrio Corazón de Jesús, Aserrí

Panelists:

- Yamileth Astorga, Estrategia Rios Limpios
- Hubert Méndez, Municipality of Curridabat
- Shirley Castillo, Observatorio Ciudadano del Agua Rio Poás

The moderator started by introducing, in a general way, the topic of citizen participation and water management. The ensuing discussion sought to intertwine the panelists’ valuable experiences with a view to getting to know their perspectives on three important dimensions related to citizen participation: public policies, local government and community engagement.

The valuable experiences and extensive knowledge shared by Yamileth Astorga, representing the ‘Public Policies’ dimension; Hubert Méndez, contributing from the ‘Local Government’ perspective; and Sheila Castillo, as a representative of ‘Community Engagement,’ gave rise to an exceptionally enriching and, at the same time, challenging discussion. In it, we explored the next steps required to achieve sustainable water management while ensuring active citizen participation and effective coordination among the aforementioned dimensions. The points raised and presented during the panel discussion were further enriched by audience interventions at the end of the session.

The second forum had the theme:

“Challenges, actions and perspectives for the implementation of Green Infrastructure in Costa Rica”.

Objective: To discuss the challenges and actions undertaken to implement Green Infrastructure in urban areas of Costa Rica, focusing on the current outlook.

Moderator: Paola Vidal, School of Civil Engineering, UCR

Panelists:

- Sabrina Geppert, German Development Cooperation Agency, GIZ
- Lenin Corrales, Centro Agronómico Tropical de Investigación y Enseñanza, CATIE
- Felipe Barrantes, School of Architecture, UCR
- Miriam Miranda, Proyecto Transición hacia una Economía Verde Urbana, TEVU
- Rubén Leandro, Wavin Company

Forum 2 Opening: Challenges, actions and perspectives of Green Infrastructure implementation in Costa Rica.

The moderator started by introducing, in a general way, the topic of urbanization processes and Green Infrastructure. The subsequent discussion was structured around three key questions, based on the experience and knowledge of each panelist: ‘Where are we?’ focusing on the current status, ‘Experiences and opportunities of Real-World Labs and Public Spaces,’ and ‘Where Are We Going?’—all in relation to the implementation of Green Infrastructure in Costa Rica.

The extensive experience and important contributions of each panelist provided diverse perspectives and insights into Urban Green Infrastructure, its implementation and the socio-institutional factors involved. The questions ‘why, what for, and for whom is Green Infrastructure implemented?’ were posed, inviting reflections on the efforts of everyone involved in promoting and developing Green Infrastructure, and their contributions to the necessary social transformation. Overall, the event presented a comprehensive vision of Nature-based Solutions and citizen participation and involvement.

LEGAL NOTICE

IMPLEMENTING NATURE-BASED SOLUTIONS AND GREEN INFRASTRUCTURE FOR CITIES, CITIZENS AND RIVERS -
The SEE-URBAN-WATER Project

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