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Article

Assessing Potential Effects of Nature-Based Solutions (NBS) on Water Ecosystem Service in the Interurban Micro-Watershed Río Torres, Costa Rica

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Abstract: The implementation of green infrastructure (GI) as Nature-Based Solutions (NBS) generates positive effects on the water ecosystem service in an urban context. Practices such as bioretention cells, green roofs, rain gardens, permeable pavements, and infiltration trenches contribute to treating large volumes of runoff and providing safe spaces for populations living in highly urbanized areas. With the aim to simulate these effects, a hydrological modeling was carried out using the i-Tree Hydro Plus model, which quantified the runoff generated from precipitation events and effective transformations (NBS) to cope with runoff. Eight scenarios were developed: a baseline scenario, five future scenarios with green infrastructure, a scenario with increased tree coverage, and a scenario with increased urbanization. Our hypothesis is that NBS would reduce runoff and increase permeable flow. The analysis of the feasibility of implementing the modeled green infrastructures was carried out through consultation with local stakeholders in the micro-watershed. We found that bioretention cells decrease runoff by 5%, green roofs by 4%, rain gardens by 4%, permeable pavements by 4.5%, and infiltration trenches by 7.5% compared to the baseline scenario where runoff accounts for 32% of water balance flows. The scenario of increased tree coverage had a similar behavior to the baseline scenario, indicating that efforts in this alternative would generate a limited impact on the reduction of runoff. With increased urbanization, impermeable flow increases up to 78%, which would generate floods. Implementing NBS would be feasible since this type of initiative is included in the agenda of many regulatory instruments of urban planning in Costa Rica.

Keywords: smart water cities; urban watersheds; i-Tree Hydro Plus; hydrological modeling; social perception

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1. Introduction

The study of urban watersheds has gained more attention in recent years as environmental factors such as change in land use and its relationship with climate variability are analyzed [1]. There is a close relationship between climate change and cities [2]. More evidence of the growing crisis of climate change and water insecurity is continually being released [3]. Since the middle of 20th century, changes have been observed in the intensity and frequency of extreme meteorological and events [4–6]. This crisis is currently accentuated by population growth, given that more than half of the world's population lives in cities with a marked trend of continuous population growth in future decades [7]. In Latin America, the levels of urbanization have increased since 1950, and 80% of the population lives in urban areas [8]. Meanwhile, in North and Central America, it is also estimated that 80% of the population lives in cities [9]. However, hydrological processes in urbanized watersheds are significantly altered due to human interventions; for example, gray infrastructure by construction activities increases the proportions of connected impervious surfaces that prevent natural water infiltration into the soil, decreases the evapotranspiration [10], and generates deficits in conventional drainage systems [11], causing environmental damage by dragging pollutants and by physical impacts of higher flows than in less urbanized basins [12]. According to the projections of the National Institute of Statistics and Censuses (INEC) in conjunction with the Central American Population Center (CCP), Costa Rica will continue to grow until approaching 6.2 million inhabitants in 2063 [13], meaning that there will be more demand for ecosystem services in the country. On the other hand, the Greater Metropolitan Area (GAM) of Costa Rica has shown a growth rate of urban area that increased 430 ha annually on average over the period 1997–2010, while from 2010–2018 urban growth decreased by 195 ha annually; this is explained by the depletion of the available land and the increase in vertical constructions, and, as a consequence, there is an increase in population density with less dispersion and greater compactness [14,15]. A clear example is the rapid rural–urban transition of the GAM of Costa Rica (Great Metropolitan Area) during the last century, which has generated intense environmental impacts throughout this region that are mainly associated with poorly planned land use planning [16]. According to the analysis by the International Union for Conservation of Nature (IUCN) for Latin America, the ecosystem approach to water resources has been consolidating as a strategy that integrates the different dimensions of development taking ecosystem management as the articulating axis, in addition to capacity building and investment in natural infrastructure [17]. Land use and land cover play a central role in defining the capacity of terrestrial ecosystems to provide environmental services [18]. However, land use change is one of the most important biophysical determinants of water regulation, such effects have been little studied until 2018 [19], and from this point, several studies have shown that watersheds with high vegetation cover improve hydrological functions by reducing surface runoff, increasing infiltration and recharge of aquifers, and therefore ensuring baseflow regulation among other hydrological services [20–22]. The alternatives to respond to the various challenges that society faces, such as climate change, food security, or disaster risk, can be faced under the new concept that encompasses all those actions that are supported by ecosystems and the services they provide: so-called Nature-based Solutions (NBS) [23]. The FAO points out that NBS are the key tool to achieve sustainable urban development [7]. In turn, a number of complementary approaches such as Ecosystem-Based Adaptation (EbA) have been explored, all with a common interest in using ecosystem functions to solve the problems society faces, rather than using conventional solutions [24]. The UN and the World Water Resources Assessment Program (WWAP) reveal that NBS are increasingly applied in the integrated management and planning of urban basins for conservation and ecological restoration, to prevent flooding problems or for the preservation of maximum flows in a basin [18]. Green infrastructures are a type of NBS that are used for the management of new ecosystems more extensively [25]. Hydrological modeling, including simulation of green infrastructure under different weather conditions, can support policy making for infrastructure development [26]. Unstructured management, policy, and educational actions that improve the use and conservation of ecosystem services in urban areas are also contemplated [27]. Human beings tend to generate problems by not applying existing regulations to prevent disasters [28]. Therefore, we need measurements both in space and time to assess the potential impact of future hydrological changes [29,30], and in that sense, the purpose of modeling is to simulate processes and understand a system, to project future behavior and support decision making [30]. There is a lack of prior research on the impact of reducing infiltration areas in the GAM through urbanization processes regarding an increase in impervious surfaces, decrease in quality, and increase of runoff. Added to this, human pressure, economic and industrial importance, urban growth, and planning and management of territory, among others, are elements that generate interest in carrying out studies and interventions aimed at dealing with said hydrological effects in the micro-basin. The proportion of precipitation that can be intercepted by vegetation and infiltrated to be stored in the subsoil, contributing to the constant flow of water as surface runoff, is known as the hydrological regulation ecosystem service [16]. To quantify the effect of NBS on the water ecosystem service through green infrastructure for the efficient management of stormwater, the i-Tree Hydro Plus model was used. This is a process-based forest management and research model which explicitly analyzes the effects of vegetation and soils on the urban hydrological cycle [31]. i-Tree Hydro Plus is a tool that has proven to be adequate and efficient enough to provide evidence of the hydrological impact of changes in land cover in urban environments [32]. In this sense, this research is considered an ecosystem service approach to climate regulation for the control and prevention of floods [33]. To determine the feasibility of implementation in the Torres River micro-watershed, this study addresses the perception of the key stakeholders of the Río Torres Interurban Biological Corridor, Biosphere Reserve (CBIRTRB), a corridor that corresponds to the limits of the micro-basin. This was established by the National System of Conservation Areas (SINAC) in 2017 through Executive Decree 40043-MINAE, where a steering committee called the Local Committee (CL) was appointed, made up of public and private entities, academia, and representatives of the civil society, with the aim of promoting ecological recovery, conservation of biodiversity and improving the quality of life of neighboring communities with an articulation of efforts that seek to gradually build a management process in the urban basin [34]. With this research we aim to answer the following questions: (a) What is the water balance in the urban watershed of the Torres River? (b) How will this water balance will change if we use some green infrastructure and/or increase gray infrastructure? (c) How feasible will it be to implement such GI in this watershed according to social perception of key stakeholders?

2. Materials and Methods

2.1. Study Area

The Río Torres micro-basin is located in the central sector of the Greater Metropolitan Area to the north of the province of San José, located within the limits of the Virilla river sub-basin. It belongs to the Grande de Tarcoles river basin, on the slope of the Pacific of Costa Rica (Figure 1). The Torres River presents a strong population pressure within the GAM. The GAM is called the Capital City mainly because it is an area of urban agglomeration. It has an area of 1779 km^2, includeing four historical cities (San José, Heredia, Alajuela and Cartago) and their peripheries [35]. The micro-basin is located between the geographic coordinates 9°57′42.71″ N Latitude and 84°2′34.67″ W Longitude, between the altitudinal gradient of 910 to 2040 m a.s.l., and it has an area of 50.24 km^2, which is equivalent to 2.82% of the surface of the GAM. Its main channel is of the fourth order, with a length of 31.7 km. The river originates in Rancho Redondo, Goicoechea, and its waters flow into the La Carpio district, in San José [36], ending at the Electriona Hydroelectric Plant in Pavas and the Belén Hydroelectric Plant [37,38]. Additionally, six station meteorological stations were identified in the study area, located in Tobias Bolaños Airport; the National Meteorological Institute of Cota Rica (IMN by its Spanish acronym), in Arajnjuez; the Geophysical Research Center (CIGEFI by its Spanish Acronym); the IMN in Jaboncillal, the IMN in Patio de Agua, and the IMN in Finca Los Macayas, Rancho Redondo.

2.2. Data Collection and Processing

The meteorological information (Table 1) to carry out the hydrological modeling consisted of daily data with hourly frequency for 2021, coming from 6 meteorological stations surrounding the study area generated by IMN and the CIGEFI.

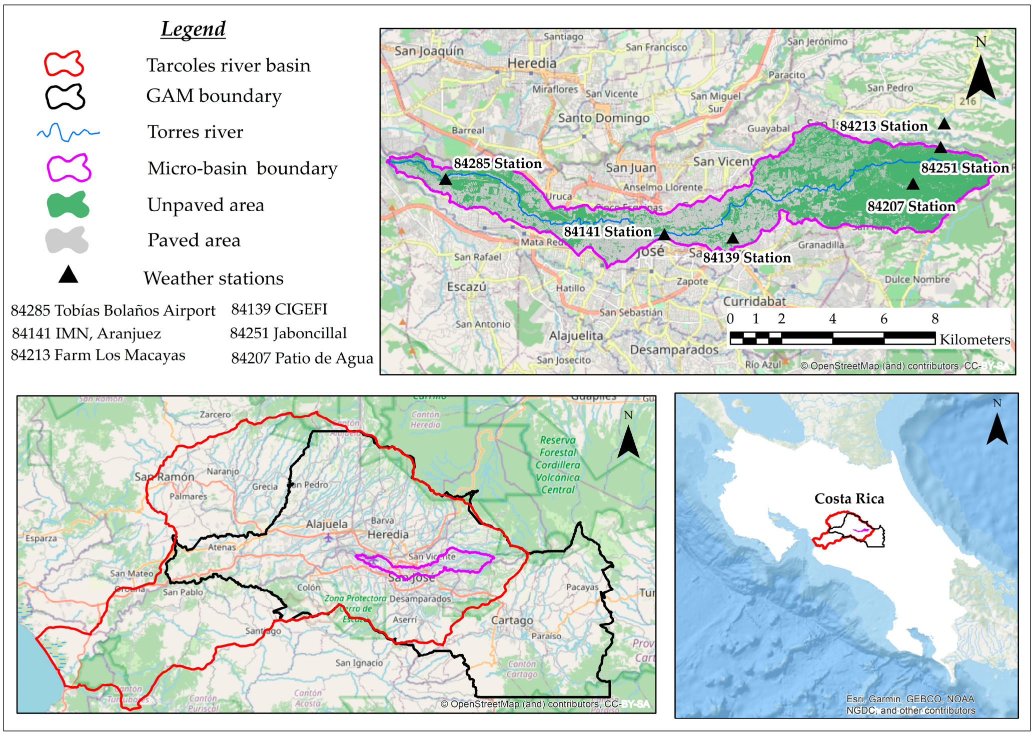

Figure 1. Location of the study area.

Table 1. Inputs used for research.

	Inputs	**Source**	**Format**
Morphometry	Micro-Basin Boundary	Own Delimitation	Shape (.shp)
Relief	Digital Elevation Model (DEM)	Project Biodiver_City	Tag Image File Format (.tif)
Drainage Network	Water network	Own elaboration based on DEM	Shape (.shp)
	Main channel	Own elaboration based on DEM	Shape (.shp)
	River order	Own elaboration based on DEM	Shape (.shp)
Soil	Land use	Atlas of Ecosystem Services in the GAM	Shape (.shp)
	Tree leaf area index (spatial resolution 30 × 30 m)	National Oceanic and Atmospheric Administration (NOAA)	-
	Shrub Leaf Area Index (spatial resolution 30 × 30 m)	National Oceanic and Atmospheric Administration (NOAA)	-
	Herbaceous leaf area index (spatial resolution 30 × 30 m)	National Oceanic and Atmospheric Administration (NOAA)	-
	Directly Connected Impervious Area (DCIA)	i-Tree 2019 [39]	-
Weather	Parameter	Source	Units
	Precipitation	IMN/CIGEFI	mm/h
	Solar radiation	Server of the NASA	$W/m^2/h$
	Maximum temperature	IMN	°F/h
	Minimum temperature	IMN	°F/h
	Average temperature	IMN	°F/h
	Relative humidity	IMN/CIGEFI	%
	Atmospheric pressure	IMN	Mbar/h
	Wind speed	IMN	m/h
	Wind direction	IMN	N/A
	Dew point temperature	IMN	°F/h
	Evaporation	IMN	mm/h

The information on the land cover of the micro-watershed was originally defined under the Corin Land Cover classification system for Costa Rica (Legend CLC-CR) developed by the Monitoring System for the Coverage and Use of Land and Ecosystems (SIMOCUTE) [40]. Based on this, Costa Rican institutions such as the Ministry of the Environment and Energy (MINAE) and the National System of Conservation Areas (SINAC) with the financial support of the German Society for International Cooperation (GIZ) within the framework of the Biodiver_City project have generated information on land use under the Green Infrastructure approach (Atlas of Ecosystem Services of the Greater Metropolitan Area of 2020) [41]. The soil cover is that which in a certain place contains biotic and abiotic elements, while land use refers to functional use with activities carried out of a biophysical or cultural nature carried out on the ground cover in a certain place [31]. Taking this definition into consideration, the relationship of land use with the types of land cover required by the i-Tree Hydro Plus model was made, as described in the Table 2.

Table 2. Classification of land uses according to equivalent coverage requirements of i-Tree Hydro Plus.

N°	Types of Land Cover and Land Use	Area (km^2)	Parameters of Coverage for i-Tree Hydro Plus
1	Trees along highways	0.02	Tree covers on permeable soil
2	Trees along railroad tracks	0.01	
3	Scattered trees	0.64	
4	Secondary forest	0.27	Tree covers on impervious soil
5	Forest and woodlands along riverbanks	6.98	
6	Peri-urban forests and woodlands	7.64	
7	Wooded coffee plantations	0.21	
8	Sports and recreational fields	0.18	Shrub Cover
9	Live fences	0.02	
10	Parks and small gardens with trees (<0.5 ha)	1.99	
11	Waste land (shrubs)	0.84	
12	Vacant land (predominantly herbaceous/grassland)	4.24	
13	Cultivated pastures	3.83	
14	Water bodies	0.05	Water cover
15	Annual Crops	0.11	Pervious cover
16	Unpaved area	2.91	
17	Paved surface	8.08	Impervious cover
18	Roofs/Buildings	12.22	
	Total	50.24	

I-Tree Hydro Plus uses the hydrological model "StatisticalHydro" that operates under a semi-distributed framework, also known as statistical distribution [42], based on physical rain-runoff processes combining concepts of urban and forest hydrology [43]. It is based on the topography that uniquely combines a set of algorithms for interception, storage, infiltration, evaporation and runoff, which allows representing the behaviors of permeable and impermeable surfaces [31].

This model version includes functions for modeling green infrastructure based on the Environmental Protection Agency (EPA) foundation of the Stormwater Management Model (SWMM) in collaboration with Addi Reza's 2019 work [44] on the development of computer algorithms to simulate nature-based restoration of urban river and stormwater systems. This SWMM model is being set up to reliably simulate rainfall and runoff characteristics with scenarios fitted with green infrastructure [26]. On the other hand, the i-Tree Hydro Plus model is an effective tool to simulate the reproduction of runoff volumes with a predictive capacity developed through the Nash–Sutcliffe coefficient calibration process [45]. To date, for the execution of the i-Tree Hydro Plus model there is no Graphical User Interface (GUI) that allows interactive manipulation of the tool since (it is currently under development). It is necessary to use different tools that operate in a computer programming framework written in C++ language [44]. In the first instance, the Visual Studio Windows SDK Version 10.0 software and the Visual Studio 2022 Platform Toolset (v143) were used to view, edit, and compile the C++ source code [42] using the C++ code to study of processes and simulation in hydrographic basins (soil responses in rain-runoff processes) for handling different types of data [45]. Next, we proceeded to update the configuration.xml files with the latest functions based on water statistics by executing the configuration files in batches in the Notepad++ editor 8.4.6 version. By performing all the above process and gathering the input files such as the weather database and land cover percentages, the HydroPlus.exe file is executed from the Command Line Interface (CLI) [42] of the operating system of the computer to carry out said hydrological modeling. In parallel, the programs used were Quantum GIS 3.22.3 version, SAGA GIS 7.8.2 version, and RStudio 2022.02.3 version for data processing, analysis, and transformation (graphs, hydromorphometry, and database formatting), respectively.

The following shows (Table 3) the relationship of the types of land cover obtained from the GAM Atlas of Ecosystem Services based on the input requirements of the i-Tree Hydro Plus model with areas and percentages of each of them [39].

Table 3. Land use classification according to the parameters required by i-Tree Hydro Plus.

Parameters of Coverage for i-Tree Hydro Plus	Area (km^2)	Area (%)	Source
Tree covers on permeable soil	15.09	30.04	Atlas of Ecosystem Services in the GAM
Tree covers on impermeable soil	0.67	1.33	
Shrub cover	11.11	22.11	
Soil cover	3.02	6.01	
Water cover	0.05	0.09	
Impervious cover	20.31	40.42	
Total	50.24	100.00	

2.3. Baseline Scenario

The baseline scenario approach consisted of carrying out a water balance to determine the magnitude of runoff generation, hydrologically modeling the conditions of land use and meteorological factors for 2021 in the micro-watershed. These land uses include surfaces with trees, shrubs, and grasses, impervious surfaces, water surfaces, and permeable soil surfaces (Table 4) as a reference point for modeling future scenarios with the implementation of green infrastructure. The land use percentages applied for the baseline scenario are shown below.

Table 4. Land cover parameters of the base scenario.

Parameters of Coverage for i-Tree Hydro Plus	Base Scenario Area (km^2)	%
Tree covers on pervious soil	15.09	30.04
Tree covers on impervious soil	0.67	1.33
Shrub cover	11.11	22.11
Soil cover	3.02	6.01
Water cover	0.05	0.09
Impervious cover	20.31	40.42
Total	50.24	100.00

The general water balance of the micro-basin was integrated by the explicit flows in the water cycle for i-Tree Hydro Plus: precipitation, evaporation from the vegetation surface, infiltration, runoff, flow, and base flow [31]. This was determined by the following equation:

$$\text{General water balance} = P - v - {}^{-}I - Q - Fb$$

where:

P = Precipitation

Ev = Evaporation
I = Infiltration
Q = Flow
Fb = Base Flow

2.4. Future Scenarios Based on Land Cover Changes

The parameterization of the alternative scenarios with green infrastructure was carried out using the configuration file specified for each type of green infrastructure. For the analysis of the future runoff generation potential of the micro-watershed, a runoff water balance was generated, composed of the components of water flow over the soil cover, resulting in a water balance that involves permeable flow, impermeable flow, and base flow. The water balance of the flow components was determined by the following equation:

$$\text{Runoff water balance (mm)} = Ft - Fi - Fp - Fb$$

where:

Ft = Total flow
Fi = impervious flow
Fp = permeable flow
Fb = Base flow

Seven future scenarios were designed in relation to the base scenario; each one was modeled separately over a 40% area with land cover changes to determine their individual contribution (Table 5). Of these, 5 scenarios corresponded to the implementation of green infrastructure to treat 40% of stormwater from impervious surfaces, a 40% increase scenario with canopy tree cover on permeable soil and, finally, a scenario with a 40% increase in sprawl of urbanization.

Table 5. Description of green infrastructure, tree cover and increased urbanization scenarios.

Scenario	Approach	Description
1	Implementation of bioretention cells	The behavior of the water ecosystem service was analyzed in a scenario with the implementation of bioretention cells for stormwater treatment in an area of 20.09 km^2, corresponding to 40%.
2	Implementation of rain gardens	The behavior of the water ecosystem service was analyzed in a scenario with the implementation of rain gardens for stormwater treatment in an area of 20.09 km^2, corresponding to 40%.
3	Implementation of infiltration trenches	The behavior of the water ecosystem service was analyzed in a scenario with the implementation of infiltration trenches for stormwater treatment in an area of 20.09 km^2, corresponding to 40%.
4	Implementation of green roofs	The behavior of the water ecosystem service was analyzed in a scenario with the implementation of green roofs for stormwater treatment in an area of 20.09 km^2, corresponding to 40%.
5	Implementation of permeable pavements	The behavior of the water ecosystem service was analyzed in a scenario with the implementation of permeable pavements for stormwater treatment in an area of 20.09 km^2, corresponding to 40%.
6	Increase in tree cover	The behavior of the water ecosystem service was analyzed with the increase of 40% of the total area with tree cover, prioritizing the distribution of these trees in agroforestry systems, the margin of the main riverbed, urban parks, and recreational areas.
7	Increased urbanization	The alteration of the hydrological cycle in a detrimental scenario was demonstrated, where urbanization increased massively by 40% without a vision of sustainable urban planning.

The modification of the percentages of land cover areas for future scenarios was also carried out. The parameterization of these coverages for future scenarios is described in Table 6.

Table 6. Land cover parameters for future scenarios.

Parameters of Coverage for i-Tree Hydro Plus	Alternative Scenarios Area (km^2)	%
Tree covers on pervious soil	15.09	30.04
Tree covers on impervious soil	0.67	1.33
Shrub cover	11.76	23.40
Soil cover	12.52	24.93
Water cover	0.05	0.09
Impervious cover	10.15	20.21
Total	50.24	100.00

2.5. Calibration of Predicted Flow versus Observed Flow

To determine the quality of the results of the hydrological modeling, the calibration was carried out by evaluating the behavior of the simulated flow and the observed flow from January to July 2022, since only observed flows of that temporality were available. The calculation of the Pearson "R^2" correlation coefficient was applied to determine the degree of linear association of the variables (simulated flow and the observed flow of the micro-basin) [46].

Calibration data through the observed flow from January to July 2022 were obtained through the gauging of the river in a site approximate to the water outlet point of the micro-basin (the gauging point is called "Los Conejos", located northeast of the Rohrmoser neighborhood, in San José). Measurements were made once a week from 26 March to 25 July, obtaining a total of 15 flow measurements, using the OTT MF pro (OTT Hydromet) novel inductive magnetic flow sensor for water [47].

2.6. Consultative Process with Key Stakeholders on NBS

Urban watershed management should be a participatory, interactive, and flexible process that integrates fundamental elements involved in the urban water cycle to maximize multiple benefits in an equitable manner [48]. Therefore, the feasibility of the implementation of the NBS was analyzed through the information provided by key actors of the micro-basin, members of the Local Committee (LC) of the Interurban Biological Corridor of Río Torres Biosphere Reserve (CBIRTRB). Combining a qualitative observational approach, including two meetings with members of the local committee and a site reconnaissance in the upper, middle, and lower parts of the micro-basin, we inferred the possible acceptance of the green infrastructure proposed in this research and the feasibility of future implementation considering the actions already being implemented in the area, as well as the management capacity of the local committee.

The validation process of the modeling results was carried out by reviewing the tools with which local actors currently work. For this, the material shared by the LC leaders was analyzed, in this case including the five-year management plan and the operative plan. The data analysis was an exploration process to identify which are the types of green infrastructure that have the greatest approval for their implementation based on the actions that are already being carried out in the micro-watershed. In addition to this, a review of the national legal framework of Costa Rica was carried out to identify the panorama that exists in relation to the viability of the future implementation of NBS in the country and especially in the interurban micro-basin of the Torres River.

3. Results

3.1. Hydrological Modeling of the Baseline Scenario

The necessary parameters required by the i-Tree Hydro Plus model to determine the main objective of this research are those that are directly involved in the water cycle, specifically in hydrological behavior: climate, soil, and observed flow [49]. The result of the water balance was generated from the hourly data of precipitation and evapotranspiration. Infiltration, flow, base flow, and evaporation are the components of the water balance originated through hydrological simulation (Figure 2).

$$\text{General water balance mm} = 2737.28\text{ mm} - 150.5\text{ mm} - 808.04\text{ mm} - 1401.13\text{ mm} - 377.61\text{ mm} = 0.00\text{ mm}$$

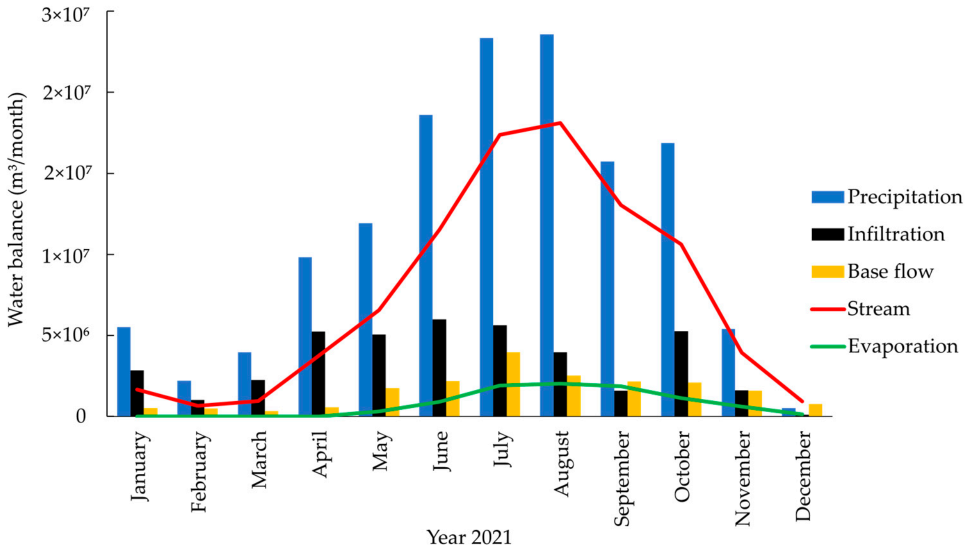

Figure 2. Result of the water balance of the base scenario.

The monthly average behavior of the water balance that varies throughout the year is manifested with greater accumulation of rain and generation of surface runoff in the months of July and August; in the same way, greater flows are experienced for the month of July. The highest values of infiltration and evaporation occur in the months of July and August, respectively.

For the conditions of land use and climate of the base scenario, the water balance resulted in a total volume of 89,175,455.51 m^3 (Table 7) that drained in the entire area of the micro-basin during 2021. This total volume was made up of 47% permeable flow, 32% impervious flow and 21% base flow.

Table 7. Results of the volume of the flow components for the base scenario.

Predictions Simulation	Flow Volume (m^3/year)	%
Base flow	1.90×10^7	21.00
Permeable flow	4.19×10^7	47.00
Impermeable flow	2.82×10^7	32.00
Total flow	8.92×10^7	100.00

The result of the flows for 2021 is directly related to land cover, the volume of precipitated water, and other climatic factors. The micro-basin has 40.4% impervious surfaces consisting of houses, buildings, and paved roads, and 59.6% of permeable surfaces such as tree cover on permeable soils, shrub cover, and permeable cover.

3.2. Hydrological Modeling of Alternative Scenarios

A change in the amounts of water flows was evidenced when implementing green infrastructures. The following figures in this section (Figure 3) show the behavior of the permeable, impermeable, and base flow throughout the modeled scenarios with changes in land cover with the implementation of green infrastructure.

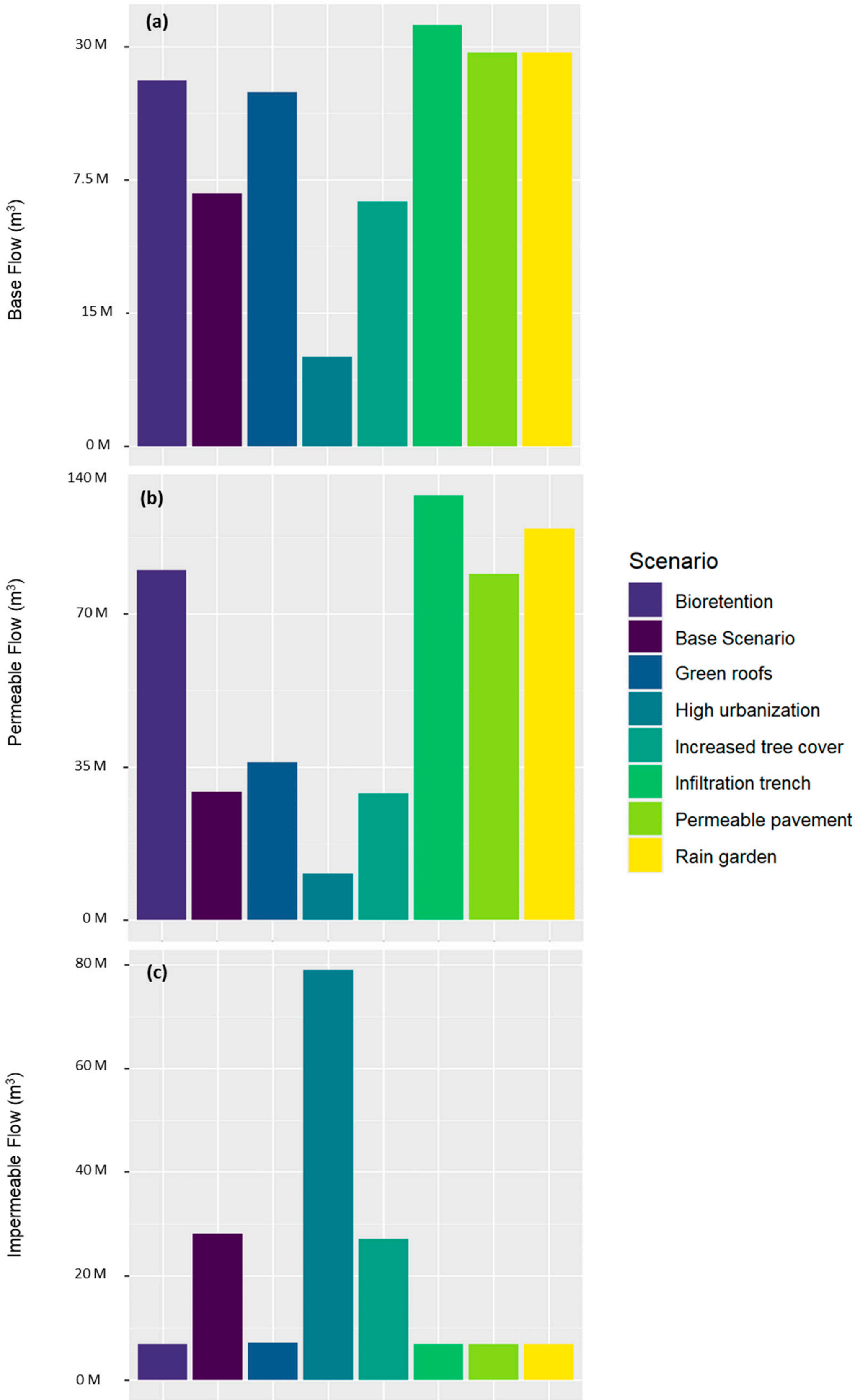

Figure 3. Base flow (**a**), permeable flow (**b**), and impermeable flow (**c**) volumes (m^3) generated by the scenario modeled with green infrastructure, the scenario of increased tree cover, and the scenario of increased urbanization in the Río Torres micro-watershed, San José, Costa Rica.

The results of the hydrological behavior show the base flow obtained by each modeled scenario. The annual base flow for each scenario reveals a different behavior, but all green infrastructures show a positive effect by increasing base flow volumes compared to the reference point (base scenario). It is estimated that in each scenario with green infrastructure there is a contribution to the base flow, obtaining a greater increase with infiltration ditches (21% of the base scenario to 35% with infiltration ditches) during the analyzed year. Otherwise, when the tree cover increases, the flow is maintained at 21%. When there is an increase in urbanization, the base flow decreases from 21% to 7%.

In relation to the permeable flow of the base scenario (47%), there is a greater generation of permeable flow (80%) in a scenario with the implementation of green roofs, followed by rain gardens and bioretention cells that produce 78% of the permeable flow. The other infrastructures that also increase the permeable flow are the permeable pavement and the infiltration ditches, with contributions of 75% and 57%, respectively. For the scenario of increased tree cover, the permeable flow decreases slightly, remaining within 47% in relation to the baseline scenario. The permeable flow is reduced to 15% in a scenario with increased urbanization.

The greatest impact on the reduction of impermeable flow is an average of 5% for each scenario with the implementation of green infrastructure: bioretention cells, infiltration ditches, green roofs, permeable pavements, and rain gardens. The tree cover increase scenario continues to behave in a similar way to the base scenario with a percentage of impermeable flow of 32%. However, in a scenario of uncontrolled urbanization growth, this flow increases to 78% in relation to the baseline scenario.

3.3. Model Calibration Results

The results of this analysis show a close relationship between the simulated and the observed flow (r^2 = 0.98) (Figure 4).

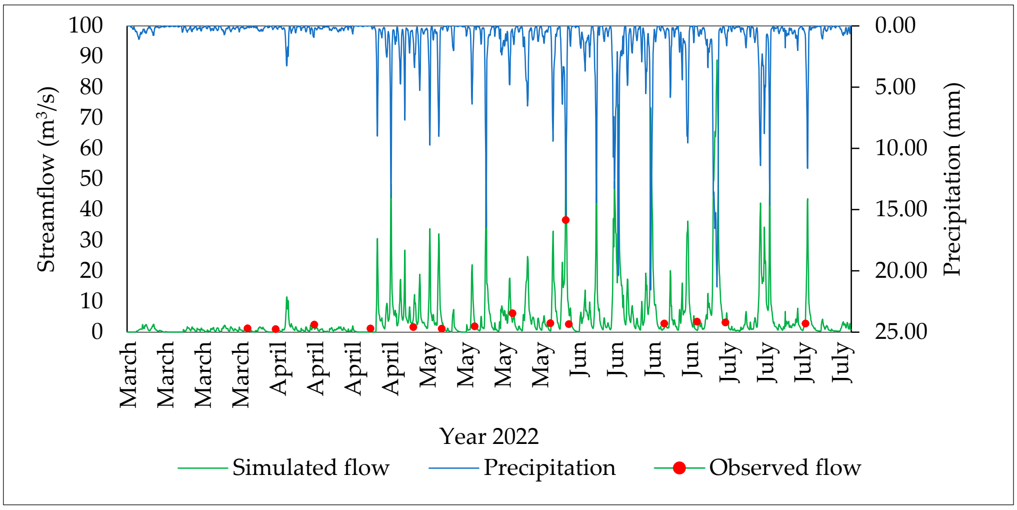

Figure 4. Precipitation and behavior of the simulated flow in relation to the observed flow from January to July 2022 in the Torres River micro-basin, San José, Costa Rica.

3.4. Feasibility of NBS Implementation

Currently there is much interest in sustainable development, allowing for management that already includes NBS in urban planning. The CL is a multidisciplinary group in which different institutions, such as municipalities, academies, non-governmental organizations, and international cooperation, participate (Table 8).

Table 8. CL sectors involved during data collection.

Institution/Organization	Sector
Huertas Donde Sea	NGO's
Pro-Zoológicos Foundation	NGO's
Municipality of San José	Public sector
Municipality of Tibás	Public sector
Municipality of Goicoechea	Public sector
National University (UNA)	Public sector
University of Costa Rica (UCR)	Public sector
University for International Cooperation (UCI)	Private sector
Technological University of Costa Rica (Tec-Costa Rica)	Public sector
German Development Cooperation (GIZ)	International cooperation/Technical specialist
Urban River	NGO's
Directorate of Environmental Quality Management, Ministry of Environment and Energy (DIGECA-MINAE)	Public sector

From the stakeholder's ongoing projects and goals, it is noted that they are already applying greening practices such as urban parks, tree planting on the banks of the Torres River, vertical gardens, bio-gardeners, green roofs, and rainwater harvesting, among others on a small scale. These practices have arisen from the need for protection from and risk prevention for water-based disasters, and to provide ecosystem services, giving way to the establishment of institutional environmental management policies and programs (Hydrographic Basin Program in municipalities, the National Program for Biological Corridors (PNCB) Strategic Plan 2018–2025, and the green plot concept) to improve the quality of life in cities. Most of the financing for these practices has been achieved through external cooperation projects that seek to strengthen the management of urban planners. About 82% of these practices are monitored by the institutions that managed or established them, while 18% of these NBS have an itinerant and slow follow-up due to financial limitations and deficiencies in budget management. On the other hand, the actors have had learnings and important results have been achieved, such as the recovery of protected areas, the construction of an Ecological Rehabilitation Protocol in Protected Areas in the GAM approved by SINAC in 2015, strengthening of the indicators of the Plan of Institutional Environmental Management (PGAI) of Executive Decree No. 36499-S-MINAET [50], awareness and cultural renewal of the population, and general strengthening of research projects. In addition, a good acceptance by the public and private sectors has emerged, causing a change in specific technological advances so that they are more friendly in different environmental aspects (water, fuel, energy, waste, etc.).

During our meetings, stakeholders indicated that bioretention cells, rain gardens, infiltration trenches, and permeable pavements are green infrastructures that would be feasible to implement, as well as good alternatives to tree planting. On the other hand, implementing green roofs has less acceptance in the context of River Torres micro-basin.

The stakeholders additionally suggested the implementation of alternatives such as bio-gardeners, pollinator gardens, wetlands to reduce the pollutant load, and strengthening urban trees with pioneer species that provide more and better ecosystem services. They also indicated the importance of strengthening the capabilities of the entities responsible for this management. However, even though the contribution of the evaluated green infrastructures to improve urban environments is positive, there are still many limitations to overcome, such as stable bases of financing or municipal budgets, technical training on green infrastructures, management of GI's implementation through use of law, regulation, or municipal ordinance, etc.

3.5. Social Validation Process

The primary information that was provided by one of the coordinators of the CL of Río Torres and the legal information in force in the constitutional framework analyzed allows us to infer that the CL has very solid foundations as a management model, allowing it to carry out its activities with great success, recognition, and acceptance in its space of action, for the most part. Its mission is to ensure comprehensive conservation and connectivity of the ecosystems of the Torres River micro-basin for the healthy and inclusive enjoyment of the benefits of the Urban NBS for different lifestyles [51]. It is important to highlight that the CL already works with innovative actions under the concept of Nature-Based Solutions (NBS). In this sense, the present investigation allows us to give added value by showing the effects that some representative green infrastructures have on the water ecosystem service with the results of hydrological modeling. Part of the municipal regulatory plans rule certain activities in favor of environmental conservation, allowing sustainable urban growth. As established in the institutional framework, there are many legal mechanisms (Urban Development Regulation, National Program for Biological Corridors-PNCB; National Strategy for Clean Rivers; Urban Planning Law No. 4240, National Urban Development Policy-PNDU 2018–2030 for the ordering of cities; National Urban-Environment Agenda, SDG) that seek to build sustainable cities, since they propose actions aimed at increasing existing green spaces and that have been generated under a broad participatory process of all sectors of society (civil society entities, public, private, economic, social, cultural, legislative, NGOs, local governments, and the United Nations System residing in the country, among others). Specifically, the result of this research is given at an opportune moment to contribute to SDG 11, where it is proposed to create resilient and sustainable cities and communities [52]. These tools indicate the presence of a concrete vital force to determine if there is a viability of future implementation of NBS in the micro-basin, with the ultimate goal of responding to various challenges arising from the growth of cities and the demand for urban ecosystem services for present and future generations.

4. Discussion

4.1. Water Effects of NBS Implementation

The water balance modeled with iTree Hydro Plus showed for 2021, firstly, that the proportion of permeable flow was higher, which is associated with areas integrated mostly by tree cover on permeable soils, shrub cover, and permeable cover. As the increase of permeable flow is desired, base flow, which should be kept in the river, is only reduced with the scenario of high urbanization.

Secondly, the proportion of impervious or impermeable runoff flow was lower than the pervious or permeable flow, associated with the proportion of impervious area in the micro-basin that is less than the pervious area. However, despite the lower percentage of impervious area, flooding incidents are becoming more common, mainly in the rainy season (May to October). Surfaces such as cement and asphalt decrease their infiltration capacity and limit plant cover to intercept rain [53] and in terms of flood threats for the years 2010–2025, it was urgent to create a sustained agenda in prevention measures and mitigation; otherwise further complications were foreseen due to disaster risks in Central America and Costa Rica [54]. The impermeable flow becomes detrimental from the point of view of flooding, since districts such as San Pedro, San José, and Guadalupe are areas mostly affected by floods caused by the Torres River with a frequency period of 2 years [55].

Thirdly, the result of the volume of water that becomes base flow reveals a positive behavior since it is responsible for the availability of flow in the channel, even during the dry period. This is characterized by being the portion of the flow that comes from groundwater, but which in turn can come from numerous sources [56]. In this sense, a great contribution to the flow can come from wastewater due to the population pressure presented by the Torres River tributary. The water balance resulted in greater infiltration in the month of June and greater evaporation in the month of August. This result coincides with the rainy season for the region of the Pacific slope from May to October, and a smaller amount of water volume in the water balance is reported for the dry season months from December to March, with April and November as the transition months [57].

Between the years 2000 to 2006 in the province of San José, most of the reports of floods and landslides in the country were concentrated; there were 914 events distributed in its different cantons, with 401 floods and 540 landslides, and of these, 29 were floods that occurred in the canton of San José [55]. The Torres River is increasingly affected by the growing urban development with settlements in sites with high risk of response to landslides and floods [55]. This behavior can also be attributed to the obstruction of the drainage system due to the mismanagement of solid waste, or the collapse of the storm sewer network due to not being able to drain large volumes of runoff. The results of the scenarios modeled in our study indicate that green infrastructures for runoff mitigation in urban environments have had good performance by reducing excess runoff on impervious surfaces generated in an urban micro-basin, favoring an increase in permeable flow and base flow.

In a neighborhood in the canton of Heredia, the result of a modeling of bioretention cells, infiltration ditches, and green roofs in the metropolitan area of Costa Rica with the Computerized Stormwater Management Model (PCSWMM) indicated that the generation of surface runoff is reduced compared to the current situation [26]; this result goes in the same direction as our research since on average green infrastructures have managed to reduce the volume of impermeable flow to 5%. However, this is an adequate contribution at the neighborhood scale, while in our research the implementation at the micro-watershed level has been considered, and therefore there are more green infrastructures analyzed. If significant changes are planned at the micro-basin level, the area should be considered for this purpose or complemented with other alternatives.

When contemplating the implementation of infiltration ditches, it is possible to infiltrate a large part of the volume of water, causing the impermeable flow to be reduced to a minimum in relation to the baseline scenario. These alternatives have a high contribution by infiltrating a large part of the drained volume from impermeable surfaces [58]. Green infrastructures behave the same or even better than gray infrastructure for water purification and protection against floods; additionally, it is highlighted that it has a similar cost and provides additional benefits [59]. In relation to its cost, the inhabitants of these environments, mainly in private areas, prefer natural systems for the wastewater disposal system instead of conventional ones because these are cheaper and provide green spaces and habitat for biodiversity [60]. Therefore, the implementation of green infrastructures in future constructions can contribute to reduce this type of costs in urbanization projects.

In the result of this modeling, it has also been shown that the increase in tree cover does not contribute significantly to reducing runoff volumes. A behavior of flows that is very similar to the base scenario has been observed; this means that a better impact would be achieved if a combination of alternatives that are better adapted to the conditions of the current environment (limited availability of spaces for restoration or plantations) is implemented. Our results differ from the study conducted in Fontibón, Bogotá, Colombia, where they found that an increase in permeable cover under trees (50% and 100% increase in cover under existing trees) provided the best strategy to mitigate the impacts of urbanization by reducing total, maximum, and average impervious flow by 3%, 4% and 8%, respectively [61]. However, large reforested areas are required to generate a significant decrease in maximum flows; likewise, this type of vegetation does not guarantee natural protection against flooding in return periods of more than one year [62]. However, trees significantly reduce runoff, and shorten the duration of extreme hydrometeorological events as the storage capacity of trees is regulated in part by the potential evaporation rate, which varies with changes in weather conditions arising from urban heat island effects, climate change, radiation variation with tree exposure, and wind speed variation with tree height [31].

The canton of San José presents extreme values of surface temperature of the land of the GAM, with a maximum of 51.2 °C and a minimum of 33.9 °C [41]; this is one of the factors that affect the performance of vegetation for water absorption. Additionally, urban trees provide benefits that are not necessarily related to stormwater management; for example, they help to reduce the environmental and socioeconomic challenges that humans face, such as air pollution and noise pollution, storage and carbon sequestration, and oxygen production, and all together provide several ecosystem services, such as water supply, soil formation, climate regulation, pollination, building resilience in cities and sustainable development [63,64]. The amount of carbon stored in the vegetation of the CBIRTRB contributes 2.2% of the total carbon stock of the GAM [65].

In another context, the high production of impermeable runoff has been evidenced in an uncontrolled increase in urbanization with respect to the base scenario, and as a consequence, a low proportion of permeable flow and a lower proportion in the base flow were evidenced. This is a result that would jeopardize the volume of water base flow supplied to the river throughout the year and even more so during the dry period. This would derive from the disorderly growth of the urban sprawl and poor planning [66]. The consequences of the replacement of vegetation by impervious surfaces have negative effects on the outflows of the hydrological cycle due to the reduction of infiltration [53] and evapotranspiration [67]. This indicates that the potentially available areas to install green infrastructures are those strategically located to specifically treat the water coming from impervious surfaces to stop the growth of the connected drainage network system, since this causes the increase of more impervious areas, with the ideal being to choose nature-based drainage for stormwater management. Given this, in urban contexts, the development of green infrastructure scenarios must consider existing spatial restrictions [26] because the implementation of green infrastructures is limited to public areas with non-impermeable surfaces [11]. In this sense, bioretention cells and infiltration ditches are among the most suitable types of Sustainable Urban Drainage Systems (SUDS) for public areas and green roofs among the most suitable for private areas such as residences and buildings [68]. Our research is the first to use the i-Tree Hydro tool in Central America, and follows the first study of its kind, which was implemented in Fontibón, Bogotá, Colombia [61].

4.2. Potential for Future NBS Implementation Feasibility

According to the CL, rain gardens, bioretention cells, permeable pavements, and increased tree cover are the most viable NBS. The results of this research support this perception since in the simulation a very acceptable result was obtained for these mentioned green infrastructures, except for the result of the increase in the area of tree cover, which does not prove to be a contributor to stormwater management.

In the case of green roofs, the perception of the implementation was not acceptable, since in the context of the CL an analysis of the structural capacity of the buildings is needed and the financial resources for the implementation are scarce. The economic factor has been one of the limitations frequently mentioned by the CL of the micro-basin. In this sense, it is important to mention that green infrastructures have a lower cost than traditional alternatives and it is necessary to insist to seek the profitability of both the investment and equity in the distribution of benefits [69]. However, the high economic influence to maximize development opportunities means that these benefits that we obtain from green infrastructure designs are not always going to be prioritized [60]. There is the Green city fund in Costa Rica, which is a NBS financing mechanism that has provided seed capital for the dissemination of said actions, and the results of this fund have been possible through multisectoral alliances [70]. The economic and political sectors play an important role in favoring the feasibility of NBS implementation, which can be achieved if there is political will and the collaboration of interested parties [71]. It is known that the incorporation of ecosystem services in urban planning is low in Latin America and the Caribbean, but at the same time, there are promising developments related to the application of innovative actions such as NBS and in support of the new agenda global urban [72].

To promote these spaces and that they are safe, inclusive, and accessible, it is important to recognize the importance of achieving and assuming the commitment established in the goals of SDG 11 of the United Nations (UN) agenda to promote the creation of green spaces and improve the quality of life in cities [7]. Costa Rica is among the countries committed to implement actions related to the UN 2030 Agenda to meet the goals, since it was the first country in the world to sign the national pact in favor of the SDGs [73]. In order to assess the potential for green infrastructure implementation in the metropolitan region of San José, Costa Rica, more site-specific analyses are needed to reveal relevant social and technical aspects, since there is a feasibility at different dimensions to improve hydrological, ecological, and environmental conditions of the inhabitants of said region [74]. Not knowing these aspects could limit the acceptance and sustainability of NBS infrastructures [11]. In this case, it is necessary to install and monitor the operation of the NBS in the hydrometeorological conditions of Costa Rica, which will contribute to the improvement of models such as i-Tree Hydro Plus. This is a challenge that must be addressed mainly by making known in a participatory manner what happens with urban hydrology when the natural conditions of the micro-basin are altered.

An adaptive methodology for the design of NBS should be a disaggregated system for urban runoff, but there is a reason that hinders the implementation of NBS and these are the same local inhabitants. The solution is to involve them in monitoring and evaluation processes to overcome the uncertainties that exist around NBS [11]. For the actors of the micro-basin, social management has become a strength, since they have a strong performance of multisectoral involvement in urban sustainability processes which is evidenced by the work they have been carrying out over the years [51]. There is a very marked trend that will come to recognize civil society actors as transcendental entities for the analysis of policies that promote the potential benefits of urban forestry [7]. They can also become important stakeholders for the creation of legislative guidelines that promote the integration of NBS and better governance in the city.

The evolution of urbanism clearly requires a discipline of legislation that is responsible for an effective analysis to establish models of intervention under systematic guidelines with a broad vision of the city [75]. Likewise, the Clean Rivers Strategy in Costa Rica for the recovery of urban watersheds aims to promote the creation of a culture around water through social participation and the formation of strategic alliances to contribute to the improvement of ecosystems and the quality of life of people around urban watersheds [37]. However, the absence of the effective applicability of conservation spaces, the cultural order in urban and territorial planning are more important contributing elements that generate problems that threaten conservation in urban areas [51]. Costa Rica, based on Law No. 4240, has the National Urban Development Plan as a planning instrument for the efficient development of urban areas, with the aim of improving the use of natural and human resources [76].

In the same way, the Metropolitan Regulatory Plan 2013–2030 seeks to promote adequate urban planning to improve the quality of life of the population, which generates competitive economic development in urban centers and which, in addition, seeks to generate an emphasis on the balance of the natural, agro-productive, and urban environments [77]. This Regulatory Plan is the main tool to influence the territory in Costa Rica [33]. The base of a high technical and socioeconomic viability specifically of green infrastructure generates the capacity to provide solutions to various problems offering a wide range of benefits, which is why they become an essential tool [78]. In Costa Rica there is a broad regulatory framework in the context of NBS and it is aimed at decision makers from the political and economic sector in the urban context of the GAM [79]. Consequently, this compendium of the legal framework related to NBS gives a fairly solid picture and a very broad vision for the feasibility of NBS implementation in Costa Rica.

5. Conclusions

The future implementation of NBS of the green infrastructure type in the Torres River micro-basin provides a notable contribution to reduce excess runoff generated on impervious surfaces, favoring the increase in the volume of permeable and base flow. The increase in tree cover as an alternative to mitigate stormwater problems is not an effective alternative for this purpose, since the contribution is conditioned by the limited availability of plantable area; therefore, the actions should be oriented to the combination with most innovative practices and NBS. The i-Tree Hydro model can be adapted to the climatic conditions of the region to which it is applied, since information from the study site can be integrated. With the analysis of social viability (legal and regulatory support, perception of local actors), the CL is recognized as the key governance mechanism or platform for decision-making in the micro-basin, and the viability of the implementation of the NBS is determined by the need to provide ecosystem services in urban environments in the face of a trend of urban growth and reduction of flood risks. The CL has the potential to influence the creation of legislative guidelines that promote the integration of NBS and better governance in the city.

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