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Original article

Multi-criteria site selection and hydraulic modeling of green flood retention measures in a highly urbanized basin in Costa Rica

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ABSTRACT

Green flood retention measures (GFRMs) are nature-based solutions applied to. mitigate floods by slowing and storing floodwater. This study employed a hydraulic, model developed in HEC-RAS to analyze the effects of GFRMs in the Quebrada Seca-Burío basin in Costa Rica. A multi-criteria methodology was developed to select. suitable sites for implementing the measures. A baseline representing the status quo, scenarios with individually assessed measures implemented at different sites, and a scenario with all measures combined were compared concerning their flood retention. potential. Twelve suitable sites capable of providing multiple socio-ecological benefits. were identified, of which three were implemented in the model to evaluate their. hydraulic performance. The results indicate that all scenarios are effective in reducing. peak flow, volume, and inundation areas, but to varying degrees. The combination of. all measures presented the most effective results, with peak flow reductions of 5.6 –15.3% and flood volume reductions of 3.6 – 9.9%.

1. Introduction

Urbanization is a global phenomenon (UN DESA, 2022) leading to increased runoff generation and a high flood vulnerability of populations. As the most frequent natural disasters, floods are particularly severe in urban areas (Chen et al., 2015; UNISDR and CRED, 2015). Engineering solutions commonly focus on increasing the hydraulic capacity of drainage systems and urban rivers often aggravate flooding problems downstream while deteriorating the ecological status of rivers through artificial embankments and disconnected floodplains (Vietz et al., 2016). The latter aspect is also causing a continuous loss of natural or nature-like features that help maintain biodiversity in urban areas and provide recreational opportunities for citizens (Hack, 2021).

While in most industrialized countries any further deterioration of the ecological status of rivers and riparian areas is no longer an option (e.g., due to the Clean Water Act in the USA or the Water Framework Directive in the European Union), in less industrialized countries nature conservation has not yet become a dominant political priority (Neumann and Hack, 2020). Particularly in regions with high levels of urban populations, like Latin America, urban flooding has become a serious problem, as has the lack of urban green spaces and the loss of urban biodiversity (Arthur and Hack, 2022). With the concept of nature-based solutions (NBSs), new approaches are being fostered that build on natural processes simultaneously serving nature conservation and social functions (Nesshöver et al., 2017). Natural water retention measures (NWRMs) and natural flood management (NFM) are examples of NBSs. While NWRMs aim to reduce runoff generation by intercepting and retaining water and allowing it to filter into the ground, NFM focuses on altering, restoring or using landscape features to manage flood risk (Hartmann et al., 2019). Both concepts present advantages over traditional grey solutions as they are designed to fulfil multiple functions (e. g., flood control, carbon sequestration, pollution control, recreation; (Meerow and Newell, 2017). The effectiveness of NWRMs in reducing surface runoff, avoiding local flooding, and at the same time addressing other urban challenges, such as pollution or the urban heat island effect, has been widely studied and proven (Oral et al., 2020; Orta-Ortiz and Geneletti, 2021; Towsif Khan et al., 2020; Singh et al., 2020; Chen et al., 2021). However, their performance during extreme precipitation events and on larger scales is less effective (Towsif Khan et al., 2020; Chen et al., 2021; Aparicio Uribe et al., 2022). In such cases, NFM measures

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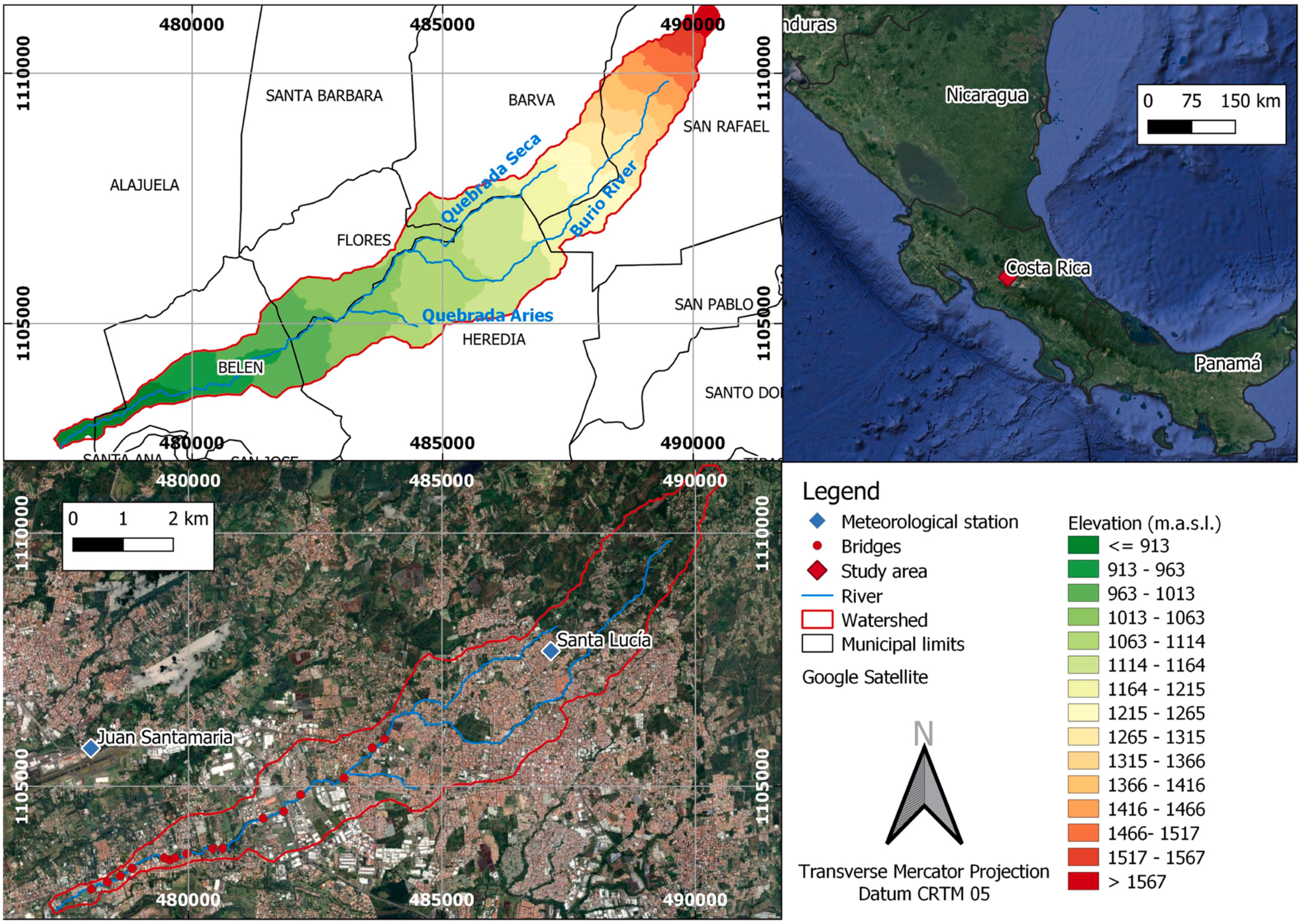

Fig. 1. Location of the Quebrada Seca-Burío basin.

that modify and restore the river landscape to manage fluvial flood risk can present a complementary solution (Holstead et al., 2017). Specifically, green flood retention measures (GFRMs) or offline storage areas are NFM solutions commonly used to address inundation issues (Hartmann et al., 2019). These techniques use natural features and properties to manage the origin and route of floodwaters, focusing on environmental processes that also provide socio-ecological benefits and help in the restoration and enhancement of rivers and floodplains (SEPA, 2015).

In urban contexts, high competition for space is a significant limitation for implementing GFRMs (Chen et al., 2021). To become a feasible option, the suitability of a site and the provision of multiple functions to serve different social demands are of great importance (Arthur and Hack, 2022). This present case study uses the Quebrada Seca-Burío basin in the Metropolitan Area of Costa Rica. The basin has experienced significant urbanization in the past decades, resulting in severe pluvial and fluvial flooding (Masís-Campos and Vargas Picado, 2014; Oreamuno Vega and Villalobos Herrera, 2015). In the context of the SEE-URBAN-WATER research project (www.see-urban-water.uni-hannover.de), the potential for implementing NWRM options on different spatial scales was previously investigated, with it being shown that potential existed to reduce flooding, albeit limited for higher-intensity precipitation events (Towsif Khan et al., 2020; Aparicio Uribe et al., 2022). This present study investigates the potential for GFRMs in the form of multifunctional offline storage areas as complementary solutions to reduce downstream fluvial flooding issues in the Quebrada Seca-Burío basin. In an initial step, a multi-criteria assessment, based on basin characteristics, such as potential storage areas, green space availability and accessibility for residents, identified in a previous study (Arthur and Hack, 2022), was performed to identify suitable implementation sites. These were then hydraulically modelled using the River Analysis System (HEC-RAS) developed by the Hydrologic Engineering Center of the US Army Corps of Engineers (USACE) to quantify their effectiveness regarding downstream flood reduction (USACE, 2022). The principal research questions were:

- What are potential sites for multi-functional green flood retention measures along the Quebrada Seca-Burío?
- What is the potential of using green flood retention measures to mitigate inundation problems in downstream areas of the Quebrada Seca-Burío basin?

The aim of this contribution is to present a multi-criteria methodology for identifying suitable GFRM sites in densely urbanized basins and to evaluate their hydraulic effectiveness in reducing downstream flooding. The results provide guidance to decision-makers in complex, multi-objective planning situations.

2. Materials and methods

2.1. Study area

The Quebrada Seca-Burío basin is located in the Central Valley of Costa Rica within the Greater Metropolitan Area (GAM) on the country's central plateau (Fig. 1). The highest point of the basin is 1617.5 m.a.s.l. and the outlet is at 861.8 m.a.s.l. The gradient is generally moderate to high, varying between 4% and 8%.

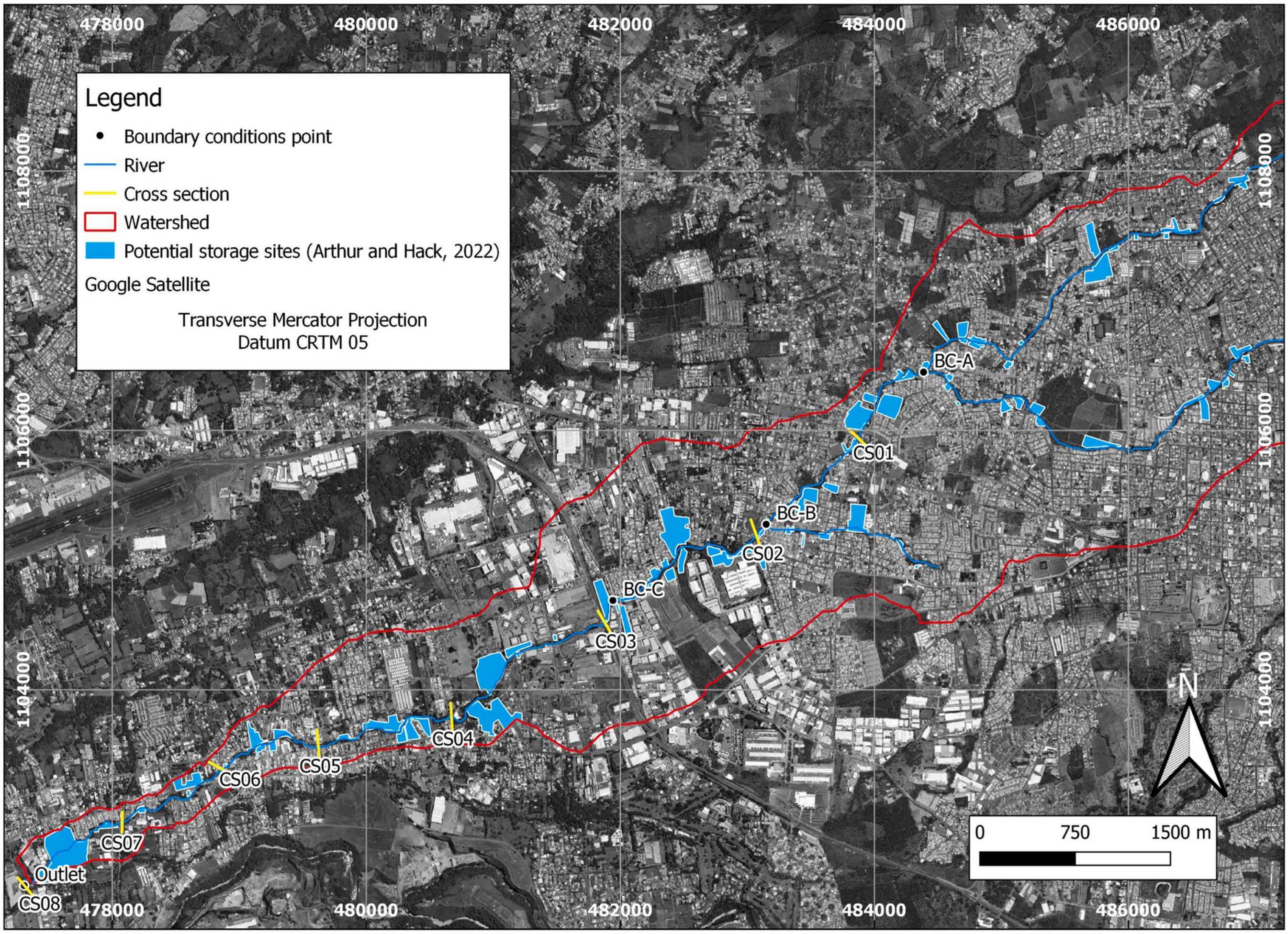

Fig. 2. Storage sites, cross-sections and boundary conditions points within the basin for use in the suitable site selection and in the hydraulic model.

The climate in Costa Rica is influenced by its location in Central America, mainly classified as tropical wet-dry and humid subtropical. The Quebrada Seca-Burío basin is influenced by the climatic characteristics of the Pacific slope, specifically those of the rainy and dry tropical climate, the rainy temperate climate, and the humid temperate climate, the maximum rainfall occurs between September and

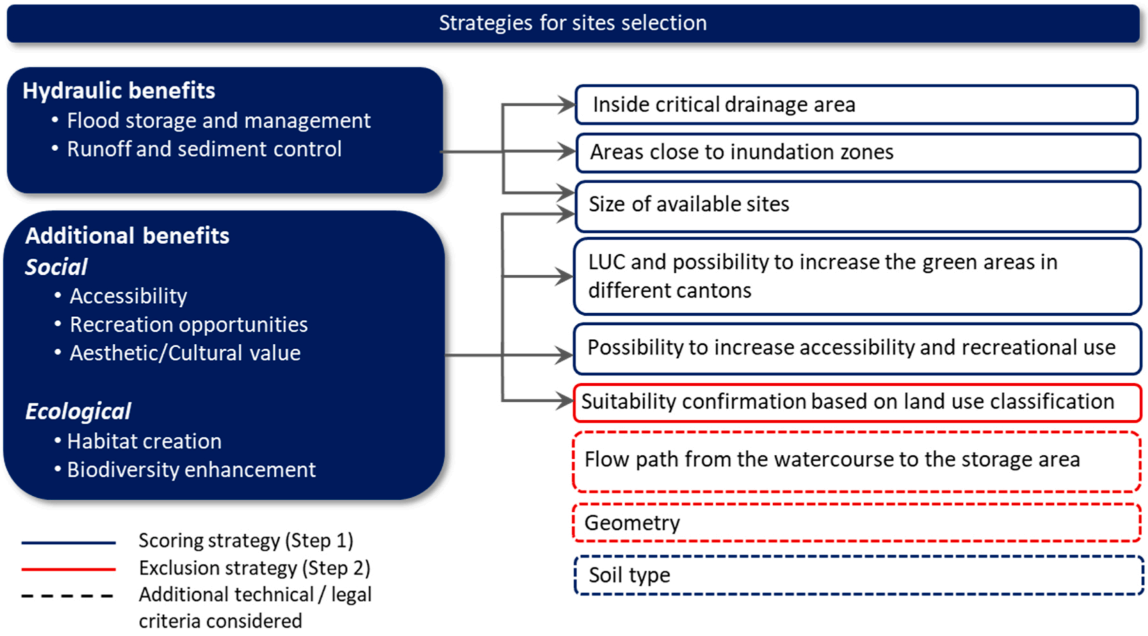

Fig. 3. Illustration of the methodology for suitable site selection.

Table 1
Resume of the scoring strategy (step 1) with the criteria analysed and the points given Based on the benefits classification.

Criteria applied in the scoring strategy	Points	Description of expected benefits and degree	Explanations
Areas close to inundation zones based on areas identified in Oreamuno Vega and Villalobos Herrera (2015)	Yes - 20 points No – 0 points	**Very high benefit** - Possibility of reducing and managing flood occurrence in the canton most susceptible to inundations.	The inundation zones presented in Oreamuno Vega and Villalobos Herrera (2015) show that Belén is the canton in the basin most susceptible to inundations. Areas located in this canton received max. punctuation.
Size of the site in relation to the average size of all potential multifunctional sites identified in Arthur and Hack (2022)	Above average (0.9 ha) - 20 points < 0.9 ha and > 0.5 ha - 10 points < 0.5 ha – 0 points	**Very high benefit** (hydraulic, ecological and social consideration) - Larger areas allow the implementation of offline systems capable of storing larger volumes of flood water as well as to provide more ecological and social benefits (Grafius et al., 2018). **Medium benefit** (recreational consideration) - Recommendation of at least one 0.5 ha green area within not more than 300 m walking distance, or 5 min away from home (European Commission, 2001).	
Areas inside the critical area for flood generation as identified in Chen et al. (2021)	Yes - 10 points No - 0 points	**Medium benefit** - Runoff reduction.	Medium benefit was considered due to the size of the area (47% of the basin). Assuming that most of the sites would receive the points, considering this as a parameter of very high or high benefit would not be beneficial to the site selection as it would hinder the ranking process.
Land use classification (Arthur and Hack, 2022)	Bare Soil – 15 points Vegetation – 10 points	**High benefit** - Possibility of increasing green areas in the basin **Medium benefit** - Possibility to improve and adapt the area to provide greater social and ecological benefits.	
Reduction of deficit of public green spaces (Arthur and Hack, 2022)	Yes – 15 points No – 0 points	**High benefit** – Possibility of increase of public green spaces in cantons with smaller green space/inhabitant values (Alajuela and Flores).	Arthur and Hack (2021) shows that Alajuela and Flores are cantons featuring greenspace/inhabitant ratios lower than 5 m^2, the minimum recommended by European Commission (2001).
Possibility of recreational use including improvement of accessibility of public green spaces (Arthur and Hack, 2022)	Yes - 15 points Recreational possibility but no accessibility improvement – 10 points No – 0 points	**High benefit** - Recreation opportunity based on identified land use and potential accessibility improvement. **Medium benefit** - Only recreation opportunity.	Arthur and Hack (2022) show that some potential sites identified correspond to areas used for agriculture or as parking lots and, therefore, bear higher resistance to be turned into recreational spaces.Green space accessibility evaluated based on the European Commission's (2001) recommendation of at least one 0.5 ha green area within not more than 300 m walking distance, or 5 min away from home
Areas with soil type Alajuela (mix of loam and clay loam) considering foundation conditions (Oreamuno Vega and Villalobos Herrera, 2015)	Yes – 5 points No – 0 points	**Low benefit** - Technical criteria for implementation of GFRM.	

December.

The problem of flooding in these cantons is mainly due to hasty and disorganized changes in land use, with much agricultural (mainly coffee production) land now urbanized, resulting in a loss of special protection zones and floodplains (Bonilla Brenes et al., 2023). In the study area, 28% of land was used for urban or industrial uses in 1979, a figure that has now risen to more than 66%.

According to Masís-Campos et al. (2020), the population of the Quebrada Seca-Burío basin is 115,776, living in approximately 35,411 buildings. While average demographic density is 4160 inhabitants per km^2, almost 50% of inhabitants are concentrated in the canton of Heredia and/or peripheral areas where density can reach almost 10,000 inhabitants per km^2. These highly populated areas frequently present economic, social and environmental challenges, and correspond to areas with larger runoff generation (Chen et al., 2021). The study area also has a significant deficit of green spaces of higher social and ecological value (Arthur and Hack, 2022).

2.2. Selection of suitable sites for green flood retention measures

The determination of locations to implement Nature-based Solutions (NBSs) is an important task belonging to urban planning policies (Ustaoglu and Aydınoglu, 2019). Solutions commonly focus on particular benefits such as reducing rainfall runoff. Nevertheless, further analyses of potential sites can optimize their multi-functionality with the services provided by them (Meerow and Newell, 2017) becoming part of a more comprehensive urban blue and green infrastructure (Arthur and Hack, 2022). Therefore, in a first analytical step prior to developing the hydraulic model, a multi-criteria decision methodology was used to identify suitable GFRM sites. Multi-criteria methodologies are widely used to support the selection of suitable areas (Ustaoglu and Aydınoglu, 2019; Meerow and Newell, 2017; Li et al., 2020; Hasala et al., 2020), but have yet not been combined with hydraulic models.

In this study, the selection of suitable sites was based on the potential sites for green infrastructures (Fig. 2) previously presented in Arthur and Hack (2022). In application of the multi-criteria methodology, a selection strategy with two steps (Fig. 3) was used, considering hydraulic, social, and ecological benefits.

In a first step, a scoring strategy was used together with the geo-information software QGIS (Version 3.12) to identify suitable sites with a higher potential for providing multifunctional benefits in accordance with Arthur and Hack (2022). Scoring strategies include the distribution of points for different aspects in accordance with knowledge, data availability and selection goals (Ustaoglu and Aydınoglu, 2019). In a second step, satellite images provided by Google Earth were used to apply an exclusion strategy based on specific technical and legal requirements to be considered for the implementation of the measures and to identify suitable areas for modeling. The exclusion strategy is applied in the second step of the methodology to not discard valuable analyses of the sites identified by Arthur and Hack (2022). The parameters used to exclude sites take into consideration the particularities and expected effects of GFRM, but the results of the scoring strategy are still beneficial for the implementation of other green infrastructures that could have different exclusion parameters than the ones applied in this study.

2.2.1. *Scoring strategy of the multi-criteria assessment (Step 1)*

The distribution of points (scoring) considered that each site could receive a maximum of one hundred points (100% suitable). The criteria analyzed were classified as parameters of very high benefit (20 points), high benefit (15 points), medium benefit (10 points) and low benefit (5 points) based on the objectives of this study and the data available for analysis (Table 1).

Offline storage systems in the form of green flood retention measures (GFRMs) were the solutions selected to be investigated in this study, as they best suit the specific topographic and land use conditions in the area belonging to the river corridor. Such measures can be implemented in the floodplain region to retain water during flood events (SEPA, 2015) and can be modeled by the tools available in the software used in this study to develop the hydraulic model (Morris et al., 2004). The design, advantages and limitations of offline storage systems were aspects evaluated during site selection. Their versatility allows the production of social and ecological benefits while reducing flooding impacts (Patterson et al., 2016).

As the development of a hydraulic model to assess the potential of GFRM to mitigate inundations is one of the objectives of this study, the primary criteria established (very high benefit) were related to hydraulic performance directly affecting the occurrence and intensity of floods, i.e. providing flood storage, management and control of runoff and sediments. For the social and ecological impacts, the criteria considered were accessibility, recreational opportunities, aesthetic/cultural value, habitat creation and biodiversity enhancement (Fig. 3).

The inundation zones presented in Oreamuno Vega and Villalobos Herrera (2015) were analyzed. According to their study, Belén is the canton in the basin most susceptible to inundations. Hence, based on the possibility of reducing and managing flooding, very high benefits was considered for sites in this canton.

The critical drainage area of the basin identified in Chen et al. (2021), was established as a parameter of medium benefit. According to Chen et al., (2021), this area produces approximately 77% of the total runoff volume and is, therefore, critical for surface runoff generation. The implementation of retention measures within this area has the potential of reducing runoff and bringing hydraulic benefits. Nevertheless, this critical zone corresponds to about 47% of the basin and is located where most of the potential sites lie. As part of the objectives of applying a scoring strategy is to rank the options, and assuming that the majority of the sites would receive the points from the critical drainage area criterion, classifying this parameter as of very high or high benefit would not be very favourable to the sites selection. Therefore, assigning it with 10 points (medium benefit) was the solution applied to still consider this important criterion while turning the decision-making process more efficient.

The size of the available areas was another aspect considered in the strategy. Very high benefit was considered to sites larger than the average area of all potential locations (0.9 ha). Larger areas allow the implementation of offline systems capable of storing larger volumes of flood water. Furthermore, considering the potential use of the sites as public green spaces, larger areas increase the provision of social and ecological benefits (Grafius et al., 2018).

This study is based on the recommendation of a minimum green space per inhabitant of 5 m^2, and at least one 0.5 ha green area within not more than 300 m walking distance, or 5 min away from home (European Commission, 2001). Hence, areas smaller than 0.9 ha but larger than 0.5 ha received 10 points (medium benefit) considering their potential to comply with the European Commission's recommendations. Arthur and Hack (2022) presented a high-resolution land use classification (LUC) for the basin, the public green space per inhabitant ratio of each canton, and the accessibility to green spaces. This data was used in the scoring strategy to analyze the possibility of increasing green areas in the basin - especially in cantons with smaller green space/inhabitant values - and of enhancing accessibility and recreational opportunities. Alajuela and Flores were the two cantons featuring green-space/inhabitant ratios lower than 5 m^2. Hence, potential sites classified as bare soil (assumed suitable for public green space development) in the LUC received 15 points (high benefit) and areas classified as vegetation received 10 points. Furthermore, sites with the potential of reducing green space/habitant deficit i.e. located in Alajuela or Flores received 15 points (high benefit). Even without the potential of enlarging the green spaces in the basin, medium benefit was given to areas classified as vegetation as they can still be improved and adapted to provide greater social and ecological impacts. When considering design possibilities and different types of vegetation, for example, the implementation of GFRM in a green area can be an opportunity for environmental and ecological improvement and nature conservation (Patterson et al., 2016). The potential for recreation was measured based on the use status presented by Arthur and Hack (2022). The authors show that some of the potential sites identified correspond to areas used for agriculture or parking lots. Although these areas are suitable for the implementation of GFRM, they cannot be easily turned into recreational spaces such as green parks or children`s playgrounds. In addition, Arthur and Hack (2022) used social accessibility as an indicator for recreational functions of these areas. Therefore, the combination of possibility for recreation use with social accessibility enhancement (potential sites located in areas with no public green spaces within a 300 m radius) was considered a parameter of high benefit. For sites providing only recreational possibilities, 10 points (medium benefit) were given.

Suitable foundation conditions are among the aspects to be considered when implementing a GFRM (Patterson et al., 2016). The soil type was evaluated in the scoring strategy as a criterion of low benefit (5 points) taking into consideration that modern engineering solutions are capable of addressing foundation treatment needs but require high investments and time for implementation. The potential sites analyzed were in areas with soils classified as Alajuela and Heredia. Alajuela soil is a mix of loam and clay loam, while Heredia soil is composed of clay loam and clay (Oreamuno Vega and Villalobos Herrera, 2015). Load-bearing strength and impermeability were the soil properties evaluated in the selection of the locations. The sites classified as having Alajuela soil presented characteristics better complying with foundation requirements.

The soil type was evaluated in the scoring strategy as of low benefit criterion taking into consideration that modern engineering solutions are capable of addressing foundation treatment needs but require high investments and time for implementation.

Table 1 shows the points and benefits assignment for each scoring criterion. Sites achieving a score of at least fifty points (50%) of the maximum of one hundred points were then re-analyzed in a second step applying the exclusion strategy (Fig. 3, see also 2.2.2).

2.2.2. *Exclusion strategy (Step 2)*

Although the analyzed LUC was developed using high-resolution spatial information, some inaccuracy was expected due to the automated classification process (Arthur and Hack, 2022). Hence, the second step of the methodology used images provided by Google Earth to visually study the sites selected in the first step on an individual basis and to ensure that they were not located in areas with native/riparian vegetation or constructions/properties to be preserved. In addition, the exclusion strategy was used to evaluate the geometry of the sites and the

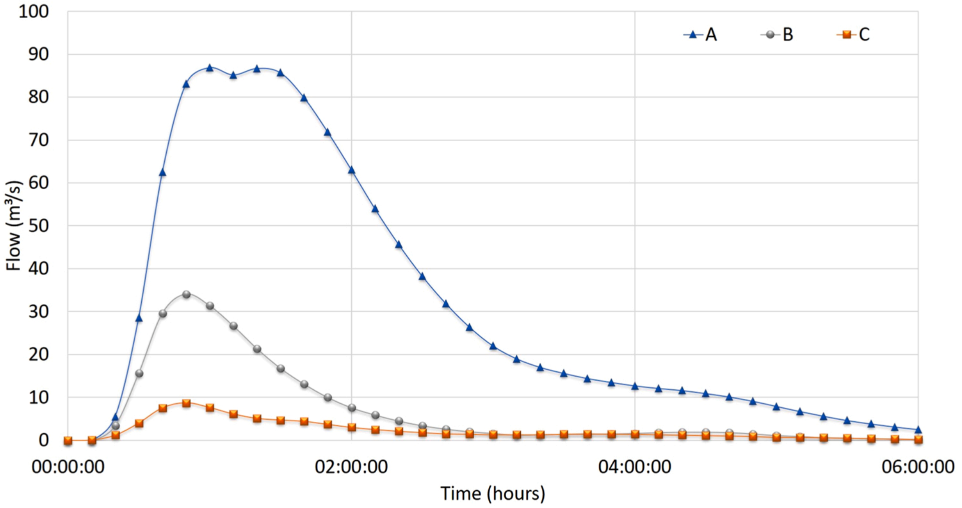

Fig. 4. Hydrographs for the boundary condition points BC-A, BC-B and BC-C (A, B and C in the diagram).

feasibility of creating an inlet connecting the watercourse to the storage area. Based on the design requirements, offline systems needed to have a minimum length/width ratio of 2:1 (Woods Ballard et al., 2015). Moreover, considering that GFRMs need inlet and outlet structures connecting to the river, the sites needed to be located in regions allowing them to be implemented without crossing streets or buildings. Potential sites not complying with these criteria were excluded.

2.3. Hydraulic modelling

The River Analysis System (HEC-RAS) software developed by the Hydrologic Engineering Center of the US Army Corps of Engineers

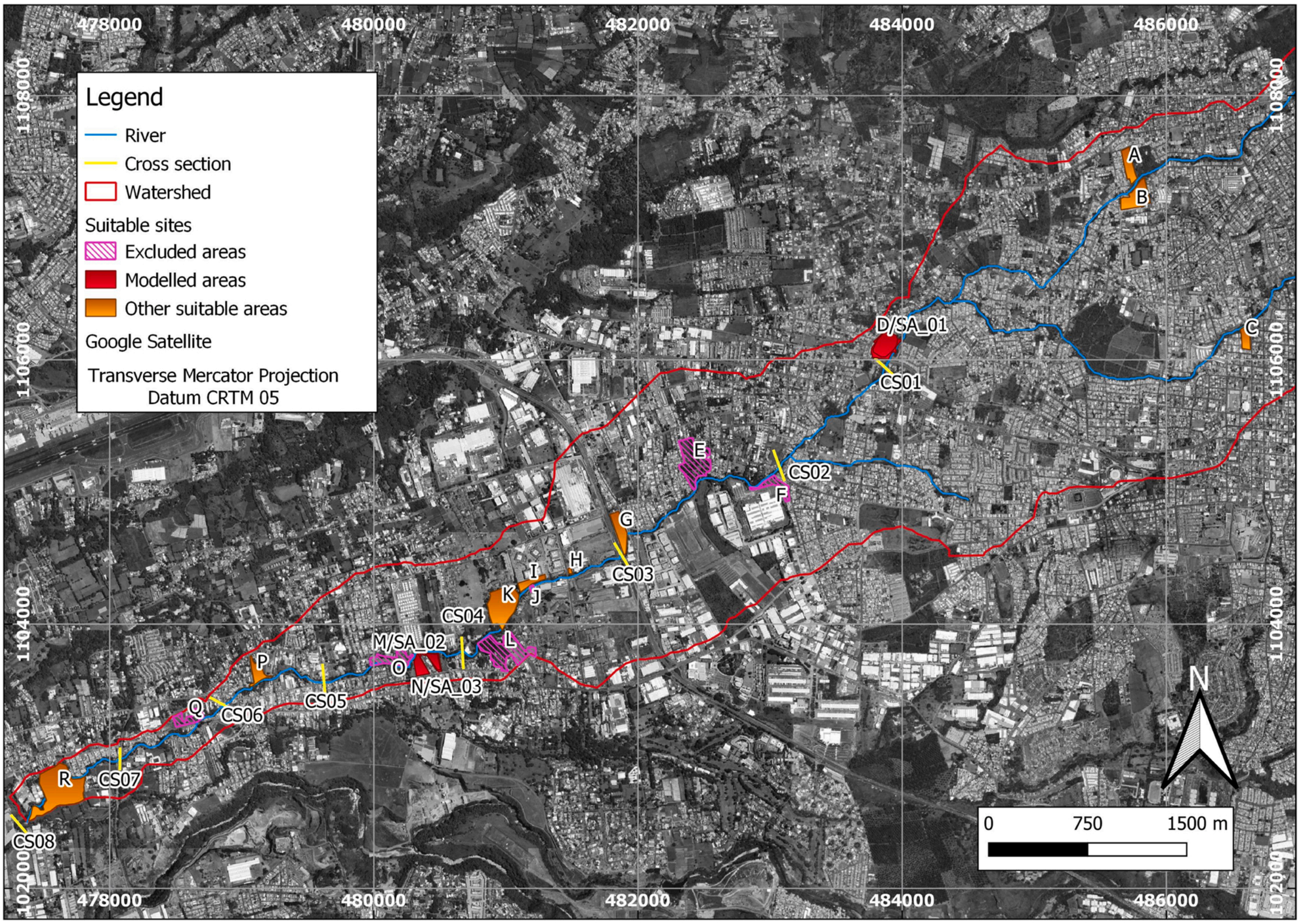

Fig. 5. Final result of the suitable site selection, highlighting the areas modeled in HEC-RAS in red and the cross-sections used for the analyses of the hydraulic modelling results.

Table 2
Summary of the site selection scores, including all sites selected after the scoring strategy, the sites excluded based on the exclusion strategy, and the finally selected sites for modeling. The observations at the table bottom describe the reasons for exclusion and information identified by the inspection of satellite images that were considered in the final selection.

Criteria	ID - Selected Sites																		
	A	B	C	D/SA01	E	F	G	H	I	J	K	L	M/SA02	N/SA03	O	P	Q	R	S
Size of the site	20	20	20	20	20	20	20	0	10	0	20	20	20	20	20	10	20	20	20
Areas close to inundation zones	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	0	0	0
Land use classification (excluding high vegetation)	10	15	10	10	10	10	10	10	10	15	10	10	15	10	10	10	10	10	10
Reduction of deficit of green spaces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Areas inside the critical area for flood generation	10	10	10	10	10	10	10	10	10	10	0	0	0	0	0	0	0	0	0
Possibility to recreational use including accessibility improvement	10	10	10	10	15	10	15	15	10	10	10	10	10	0	10	15	15	15	15
Areas with soil type Alajuela	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5
Total points	**50** 🟨	**55** 🟨	**50** 🟨	**50** 🟦	**55** 🟧	**50** 🟧	**75** 🟨	**60** 🟧	**65** 🟧	**60** 🟨	**65** 🟨	**65** 🟧	**70** 🟦	**55** 🟦	**65** 🟧	**60** 🟨	**50** 🟧	**50** 🟨	**50** 🟨
Canton	Barva	Heredia	Heredia	Flores	Flores	Heredia	Belén	Belén	Belén	Belén	Belén	Belén	Belén	Belén	Belén	Belén	Alajuela	Alajuela	Alajuela
Observations	Outside modeled area	Outside modeled area	Outside modeled area		Native/ Riparian Veg.	Inadequate Geometry	Next to Pan American Highway	Native/ Riparian Veg.	Inadequate Geometry	0.12 ha	Golf field	Native/ Riparian Veg.		Agriculture	Native/ Riparian Veg.	DS Site	Excluded considering flow path	DS Site	DS Site

🟧 Excluded based on the exclusion strategy
🟦 Sites modeled in HEC-RAS (Final Selection)
🟨 Sites not selected as potential storage areas based on visual inspection of satellite images
DS Downstream

(USACE, 2022) was used to create a one-dimensional unsteady flow hydraulic model. The topography for the model was constructed using a Digital Elevation Model (DEM) with the coordinate system Costa Rica Traverse Mercator (CRTM05). The river geometry was drawn manually based on the terrain created and satellite images available in the HEC-RAS system. One hundred and forty-two cross-sections were manually added perpendicular to the channel in intervals that vary between 7 and 120 m depending on the geometry of the river. Sinuous curves and areas close to bridges were populated with more cross-sections i.e. cross-sections distributed in smaller intervals. On the other hand, for the parts of the channel presenting straight morphology, fewer cross-sections were included. Manning's coefficient for natural open channels varies between 0.025 and 0.150 (Chow, 1959). After a calibration analysis, it was verified that 0.06 was the value generating the smallest software computational errors, providing greater stability and water volume conservation in the developed model. The bridges crossing the Quebrada Seca river were added to the model, representing structural flow-limiting elements along the river course (Oreamuno Vega and Villalobos Herrera, 2015). To perform an unsteady flow simulation, 10-year return period flow hydrographs from Oreamuno Vega and Villalobos Herrera (2015) were used as boundary conditions for the model, while the Santa Lucia and Juan Santamaria Airport meteorological stations were used to estimate the extreme events (Fig. 1).

The basin was divided into eleven drainage areas. Three boundary condition points were established as inflow points of surface runoff from the drainage areas to the river channel (Fig. 2). Boundary condition point A corresponds to the beginning of the river modelled in this study, i.e., the confluence of the Burío and Quebrada Seca rivers. This inflow point accumulates the runoff generated in seven drainage areas. In boundary condition B, the runoff from two drainage areas is discharged into the river, while in boundary condition C, the runoff from one drainage area is discharged. The area located downstream from boundary condition C corresponds to one sub-catchment, the surface runoff of which is not considered in the model.

Hydrograph A was implemented as the boundary condition at the first cross-section of the model, corresponding to the beginning of the modelled river or boundary condition point A (Fig. 4). Hydrographs B and C were considered as lateral inflow hydrographs, representing the flows added at boundary condition points B and C (Fig. 4). In addition, a normal depth boundary condition was added to the cross-section furthest downstream (Outlet point in Fig. 2). For the normal depth, a friction slope of 0.02 was used, based on the elevation difference between the first and last cross-sections.

After setting up the baseline scenario, the measures previously selected in the suitability analysis were added to the model as offline storage areas. To build an offline storage area in HEC-RAS, the storage area (SA) tool was used, while the lateral structure tool was applied by adding culverts to connect the river to the storage area for in- and outflow.

Table 3
Peak flow and volume results in cross sections for each scenario.

	Without Measures (baseline Scenario)	Measure SA01	Measures SA02 & SA03	Measures SA01, SA02 & SA03
Cross-section 01				
Time to Peak	01:10	01:10	01:10	01:10
Peak Flow (m^3/s)	86.1	77.0	86.1	77.0
Peak Stage (m)	1050.2	1049.8	1050.2	1049.8
Volume (1000 m^3)	589.0	536.4	589.0	536.4
Flow Reduction (%)	-	10.6	-	10.6
Volume Reduction (%)	-	8.9	-	8.9
Cross-section 02				
Time to Peak	01:00	01:00	01:00	01:00
Peak Flow (m^3/s)	117.4	108.9	117.4	108.9
Peak Stage (m)	1019.4	1019.2	1019.4	1019.2
Volume (1000 m^3)	709.2	656.0	709.2	656.0
Flow Reduction (%)	-	7.3	-	7.3
Volume Reduction (%)	-	7.5	-	7.5
Cross-section 03				
Time to Peak	01:10	01:10	01:10	01:10
Peak Flow (m^3/s)	151.8	143.1	151.8	143.1
Peak Stage (m)	970.1	970.0	970.1	970.0
Volume (1000 m^3)	873.5	820.9	873.5	820.9
Flow Reduction (%)	-	5.7	-	5.7
Volume Reduction (%)	-	6.0	-	6.0
Cross-section 04				
Time to Peak	01:20	01:20	01:20	01:20
Peak Flow (m^3/s)	149.5	141.2	149.5	141.2
Peak Stage (m)	929.1	929.0	929.1	929.0
Volume (1000 m^3)	854.2	801.1	854.2	801.1
Flow Reduction (%)	-	5.6	-	5.6
Volume Reduction (%)	-	6.2	-	6.2
Cross-section 05				
Time to Peak	01:20	01:30	01:20	01:30
Peak Flow (m^3/s)	147.9	138.6	140.8	129.7
Peak Stage (m)	910.3	910.2	910.2	910.0
Volume (1000 m^3)	833.6	781.5	803.6	754.8
Flow Reduction (%)	-	6.3	4.8	12.3
Volume Reduction (%)	-	6.3	3.6	9.5
Cross-section 06				
Time to Peak	01:30	01:30	01:30	01:30
Peak Flow (m^3/s)	146.8	138.0	140.1	128.7
Peak Stage (m)	897.0	896.9	897.0	896.9
Volume (1000 m^3)	806.8	757.2	776.9	728.7
Flow Reduction (%)	-	6.0	4.6	12.4
Volume Reduction (%)	-	6.2	3.7	9.7
Cross-section 07				
Time to Peak	01:40	01:40	01:40	01:50
Peak Flow (m^3/s)	146.2	135.1	138.3	124.7
Peak Stage (m)	874.4	874.3	874.3	874.1
Volume (1000 m^3)	769.3	721.6	739.7	692.8
Flow Reduction (%)	-	7.6	5.4	14.7
Volume Reduction (%)	-	6.2	3.8	9.9
Cross-section 08				
Time to Peak	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

Fig. 5 shows the locations and geometries of the storage areas. These areas were implemented with a 3.0-meter depth to permit the construction of large reservoirs without necessitating massive excavations in densely urbanized areas. Taking soil stability aspects into account, a stair design tolerates earthworks with high slopes, allowing reservoirs to be constructed with higher storage capacity using the same area. Moreover, the stairs can be used to access areas during dry periods, and also to dissipate the energy of water entering the reservoir. Four simulations were conducted to evaluate the performance of different combinations of measures, comparing them with the baseline scenario.

The unsteady flow simulations were conducted with a computation interval of 12 s based on calibration analyses achieving the smallest software computational errors and maintaining the model's stability. The intervals for mapping, hydrograph generation and detailed outputs were set to 10 min. Performance evaluations and comparisons were carried out in the cross-sections shown in Fig. 5 that were selected in accordance with the storage area locations, enabling an analysis of the entire downstream stretch of the river.

3. Results

3.1. Selection of suitable sites

Nineteen sites were found to be suitable after applying the scoring strategy (Step 1; Table 2). They are located throughout the basin and featured sizes varying from 0.12 ha to 10 ha. Belén, the canton most affected by flooding, featured the largest number of suitable areas. All nineteen sites were then individually evaluated in a second step by applying the exclusion strategy to ensure an appropriate design and location, and to confirm the LUC evaluated in step 1.

Fig. 5 shows the results of both analyses and the final decision on the sites for the measures. Sites F and I were excluded from the selection during the second step of the methodology based on their length/width geometry straighter than 2:1. According to the images provided by Google Earth, sites E, H, L and O were located in areas of perennial vegetation not identified during the LUC process by Arthur and Hack (2022). A street was located between the channel and site Q, impeding the implementation an offline system there. In total, seven areas were thus excluded in this second analytical step of the multi-criteria methodology.

Of the twelve sites finally identified, six were within the critical drainage area and had the potential to increase runoff retention in this region and thus reduce the downstream flood risk. Seven of them featured soil type Alajuela and five Heredia. Even though Alajuela soil is more appropriate as a foundation, geotechnical investigations are always needed to better assess the soil conditions and to check whether engineering interventions are necessary (Patterson et al., 2016). The smallest site had an area of 0.12 ha and the largest 6.0 ha. Average size was 2.66 ha. Eleven sites were larger than 0.5 ha and four would increase the accessibility to green space in the region, hence complying with the green space and accessibility recommendations of the European Commission (2001).

Nine sites were classified as green areas, three as bare soil, and one as agricultural land. As most of the selected sites were already green spaces, they had no great potential for increasing the green area per inhabitant ratio in Alajuela or Flores, the cantons with a ratio below the recommended level. However, the proper design of an offline storage system could enhance biodiversity, create habitats and contribute to aesthetic value.

Six sites were located in Belén, two in Heredia, two in Alajuela, one in Flores, and one in Barva. As the majority of them were located in Belén and therefore close to the inundation zones, the installation of flood reservoirs in this municipality has the potential to attenuate the impacts of floods. In operation, the system would redirect water to the storage areas instead of flooding houses, streets and other urban structures.

The main objective of the multi-criteria methodology (Step 1) was to identify the most suitable locations for the implementation of GFRM in the basin. Nevertheless, to assess the relative hydraulic impact of GFRMs in the basin, it is not necessary to develop a model including measures for all selected areas. It suffices to implement some of them as a starting point to analyze their effects and predict the potential impacts generated by measures installed in other suitable sites. This also reduces complexity as the interaction of individual measures and measure combinations are easier to understand. Based on that and the data available for the development of this study, three of the selected sites were chosen to be modelled as offline systems in HEC-RAS. In addition to data availability, their choice considered their location within the basin, possible effects on the efficiency of the storage areas, and the difficulty to implement them. The data available for developing the model was assessed after the sites selection was finalized, and was restricted to the area downstream of the point named boundary condition point A (Fig. 2). Hence, sites A, B and C were outside the modelled area. The hydraulic effects of GFRM are evaluated downstream of the implemented measures. Considering that the area modelled in the hydraulic model corresponds only to the Quebrada Seca basin, with the data available for the model development it would not possible to assess the impact of retention measures implemented in the lower part of the basin (sites P, R and S). It was chosen to not implement a measure on site J to prioritize the largest sites among those selected, as they have the potential to store higher volumes. Moreover, site G is located next to a highway and site K is currently a golf course in the backyard of a hotel. Considering technical requirements, GFRM could be implemented in these two areas. However, the measures can highly impact roads, services, and users (Patterson et al., 2016). In the case of a hotel facility and a highway, the impacts can include logistical issues and the non-acceptance from users that can directly cause economic losses to the hotel. These last considerations resulted in the final selection of the sites D, M and N for implementation.

Table 4
Percentage of flooded area reduction.

	Area (x 1000 m^2)	Area Reduction (%)
Without Measures (baseline scenario)	319.60	-
Measure SA01	307.80	3.69
Measures SA02 & SA03	316.57	0.95
Measures SA01, SA02 & SA03	303.50	5.04

3.2. Hydraulic modelling

3.2.1. Volume and peak flow

The baseline scenario (simulation 01) was simulated to analyze the fluvial flood occurrence within the basin without any storage structures. As flooding occurs in this scenario, peak flows and volumes for evaluated cross-sections (CS) do not continuously increase in downstream direction. The highest volume and peak flow were observed in cross-section CS03 in the upper half of the modelled river course.

In simulation 02, solely storage area SA01 was modelled. Featuring a capacity of 54,200 m^3 , it is located upstream of cross-section CS01. The results showed that this measure would decrease the volume and peak flow along the entire channel (Table 3), due to the volume taken up by the storage structure and its delayed release. SA01 reduces peak flow by 7% on average, with the main reduction (10.6%) observed at CS01. Volume reduction averages 6.7%, with CS01 again presenting the biggest reduction (8.9%). The full results are shown in Table 3.

Simulation 03 represented the simultaneous implementation of SA02 and SA03 with a combined capacity of 43,900 m^3 . The two sites are next to each other, downstream of CS04. They were modeled together, as their individual impacts were negligible. Due to their location, the decrease in volume and peak flow is appreciable from CS05 onwards (Table 3). Peak flow reduction averages 5%, with the main reduction occurring at CS07. Volume reduction averages 3.8%, with the main reduction occurring at CS08.

Implemented all three storage structures, simulation 04 was the scenario with the greatest impact in terms of volume and peak flow reduction. Table 3 shows the results obtained with respect to the baseline modeling (no measures implemented). For the first four cross-sections, the results are the same as the ones observed in simulation 02. In simulation 04, peak flow reduction averages 10.5%, with the greatest reduction occurring at CS08 (15.3%). Volume reduction averages 8.4%, peaking at 9.7% at CS07.

3.2.2. Flood zones

Comparing the individual measures, implementing offline systems in the upper part of the channel showed better results than designing

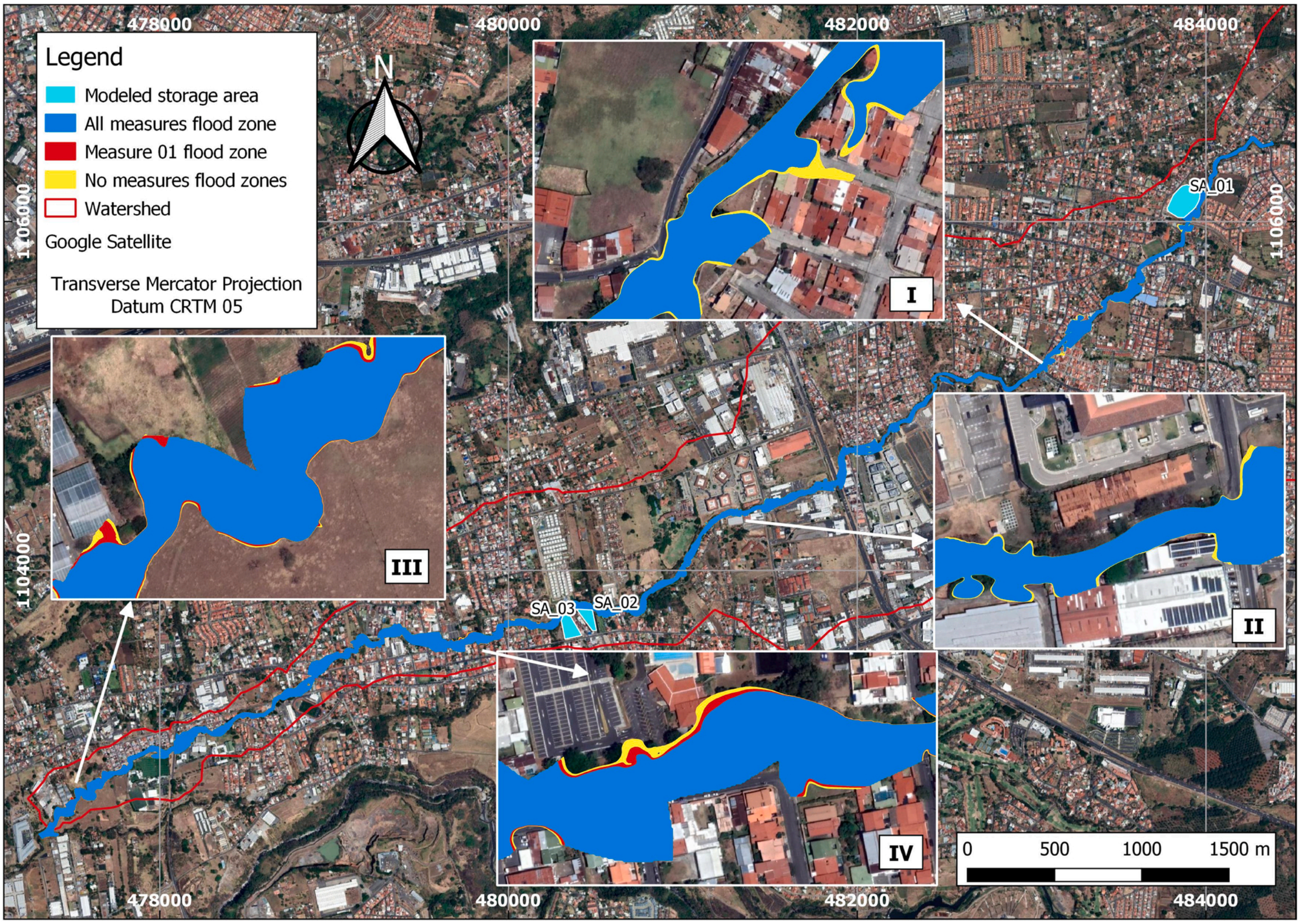

Fig. 6. Modelled flood zones for the baseline condition (yellow), for measure 01 (red), and for all measures (blue).

solutions in the lower sector. SA01 has greater potential to reduce the scale of flood events than SA02 & 03. Even though SA02 & 03 are located in Belén, which has a higher risk of flooding due to its location, they still show flood reduction potential in this canton. The effects of SA01 are also visible in this location, reducing peak flow and volume to a greater extent. In addition to SA01′s larger volume capacity, reductions in the flow and volume in the upper part of the channel can cause a cumulative effect benefiting the lower part of the basin. The largest effects of SA01 are also visible in flood zones, demonstrating that site selection targeting flood risk reduction does not need to be considered specifically in flood zones. Instead, wider areas and upstream sites may generate more significant benefits (Table 4). Implementation of SA01 would lead to a 3.7% reduction in the total flooded area mapped in the baseline scenario. The results of implementing SA02 & 03 show the lowest effect, with merely a 1% reduction in the flooded area. Implementing all three measures exhibits the larger reduction (5.04%) in flooded area. Fig. 6 presents the flood zones for the baseline scenario, the SA01 scenario and the scenario with all measures. A greater decrease in the flooded area can be seen in the lower part of the basin, as shown in the extended images III and IV. The middle part of the basin features minor decreases difficult to visually appreciate, as shown in the enlarged images I and II of Fig. 6.

4. Discussion

4.1. Selection of suitable sites and sites for modeling

The application of the multi-criteria methodology indicated twelve sites as the most suitable for implementing green flood retention measures and potentially providing hydraulic, social and ecological benefits. The accuracy of the results is highly dependent on data availability and quality. When satellite images are used for such analyses, the presence of clouds and the season of the year can influence the outcome, especially in regions with wet and dry periods affecting land cover and vegetation (Arthur and Hack, 2022).

Site D was implemented in the model as SA01. The implementation of a retention area near boundary condition point A allowed its effect on the entire region downstream to be assessed, including the impacts on the river flow and volume, range, and time of the flood.

Belén is the canton experiencing the largest and most frequent inundations. Implementing measures in nearby upstream areas to this region allows their direct effect on the inundation areas to be assessed. The areas most impacted are in the middle-lower part of the canton, which in addition to large inundation ranges (Oreamuno Vega and Villalobos Herrera, 2015), also featured a high population density (Masís-Campos et al., 2020). Sites M and N were located in this part of Belén and their implementation in HEC-RAS as SA02 and SA03, respectively, allowed the assessment of flood mitigation possibilities in this critical region.

SA01 has a surface area of 2.98 ha, is located in Flores, and was classified as a green space with Heredia soil type. Implementing a retention measure there would neither improve accessibility nor increase the green area per inhabitant ratio (Arthur and Hack, 2022). Nevertheless, in conjunction with an appropriate warning system, the measure could be designed as a recreational area during dry periods and to improve biodiversity, thereby providing additional social and ecological benefits.

The two offline solutions in Belén were areas with 0.92 and 1.08 ha and classified as having Alajuela soil. One was classified as a green area (SA02), the other as a space used for agriculture (SA03). Similar to SA01, the measure in site M (SA02) could also be designed for recreational use, even without improving accessibility to green space in the region. On the other hand, implementing a measure in an agricultural area (SA03) is a valid approach to show how sites already in use for other purposes can act as retention areas during flood events. One of the advantages of offline systems is their potential multi-functionality, which can be exploited in urbanized regions where space availability is limited.

The final three sites fulfil the targeted multi-functional goals and allow the influence of the storage areas over the entire modelled channel to be assessed by comparing the impacts of the measures in the upper and middle part of the basin, and in the areas with more intense inundation issues. The results of the multi-criteria methodology bring diverse benefits. After the application of the scoring strategy, it was shown that nineteen sites have the potential to provide hydraulic, social and ecological benefits and can, therefore, be used for the implementation of green infrastructures or Nature-based Solutions. The criteria considered in the exclusion strategy narrowed down the number of suitable sites as they were related to specific requirements for the implementation of green flood retention measures. However, it still resulted in twelve potential sites for the implementation of GFRM or similar Natural Flood Management solutions. With further data and disregarding possible non-acceptance from users and economic impacts, for example, the implementation of measures in these twelve sites can be further investigated in other studies.

4.2. Hydraulic modelling

4.2.1. Volume and peak flow

Comparing the individual measures, implementing systems in the upper part of the channel showed better results than designing solutions in the lower sector. SA01 has greater potential to reduce the scale of flood events than SA02 & SA03. Even though SA02 & SA03 are located in Belén, which has a higher risk of flooding due to its location, they still show flood reduction potential in this canton. The effects of SA01 are also visible in this location, reducing peak flow and volume to a greater extent. In addition to SA01′s larger volume capacity, reductions in the flow and volume in the upper part of the channel can cause a cumulative effect benefiting the lower part of the basin.

An unexpected phenomenon occurred in the downstream part of the model. As already mentioned, it is predictable that the effects of the offline systems are greater in adjoining areas, as high volumes of water are being deviated. However, the last four analyzed cross-sections do not feature such behavior. Depending on the simulation, peak flow and volume increase or fluctuate in line with the distance between the CS and the storage areas. It is known that the downstream region features a large number of flooding areas, and that these also have an influence on the flow and volume parameters. The inundated areas represent an enlargement of the river cross-section. According to the volumetric flow equation, for the same discharge, a larger area will result in a lower flow velocity. Hence, inundation zones could result in a reduced peak flow. Moreover, these areas may act as an unintended storage system, slowing down or accumulating the water.

4.2.2. Flood zones

Masís-Campos et al. (2020) developed a map of historical flood zones for the Quebrada Seca-Burío basin based on a comprehensive community survey as part of a larger socio-economic and housing profile study with the aim of facilitating restoration, conservation, and mitigation solutions for the basin's fluvial system. In their survey, the population were asked to report the occurrence and location of environmental problems such as floods, deforestation or landslides. Similar to the ones presented in this study, the resulting map revealed flooding zones showing that the social aspect is highly connected to flooding issues. Areas with a higher population corresponded to those with larger inundation problems. Masís-Campos et al. (2020) stress that the proper management of organic and solid waste negatively influences the issues, as solid material in the river frequently obstructs bridges and reduces their hydraulic capacity, leading to flooding. This aspect needs to be considered in future studies in the context of a more thorough restoration of the basin.

In our study, the hydraulic simulation with all measures combined showed the best results in reducing flooding intensity in the lower part of the basin, with peak flow reductions corresponding to values greater than the sum of the reductions for the individual solutions. This indicates that the measures interact, improving their individual efficacy. Hence, designing storage systems along the entire stretch of the river could generate better results and reduce inundation impacts in the basin. To achieve more precise results, more accurate and up-to-date data is needed, such as a digital elevation model (DEM) including data from in-site topographic studies combined with further information on bridge dimensions and drainage areas. Even though the potential for mitigating flooding can be increased by implementing several storage areas along the river, implementing just one measure can be a more acceptable approach when considering policies, approval and investments. The selection of a large upstream site produced better individual results in managing the inundation area close to the storage area, reducing river flow and volume for the entire downstream channel.

4.2.3. Time to peak

Time to peak is another parameter potentially influenced by the storage areas. In CS05, a delay of 10 min occurred for simulations 02 and 04. CS07 and CS08 also showed a delay of the same magnitude, but only for the scenario with all measures combined. As all parameters are influenced by the river morphology and its interactions, we can conclude that other river characteristics such as pronounced curves and watercourse width may also impact the time when peak flows occur. In addition, the model output interval of 10 min and the distance between cross sections can result in uncertainties and inaccuracies.

4.3. Discussion of results in the context to previous studies

Among the previous studies in the area of interest, that of Peralta (2014) on the hydraulic capacity of the Quebrada Seca-Burío riverbed should be mentioned. Peralta (2014) developed a hydrological model using the HEC-HMS model, dividing the basin into 20 drainage areas and obtaining hydrographs for different return periods (2 – 100 years). For the floods defined in the hydrological analysis, hydraulic modelling was carried out in permanent flow using the HEC-RAS model. To construct the model, a topographical survey carried out by the Municipality of Belén was used. Actions proposed by him included the instrumentation of the basin, refurbishment or replacement of bridges, zoning and urban planning, diversion of flows and channel modifications (increasing its hydraulic capacity).

Oreamuno Vega and Villalobos Herrera (2015) carried out a hydrological and hydraulic diagnosis of the Quebrada Seca-Burío basin, identifying conservation measures and the use and sustainable exploitation of existing natural resources, using a territorial ordering approach. This study built on the work previously performed by Peralta (2014). Likewise, through the HEC-RAS model, the flow conditions for the calculated floods were obtained and entered into a model consisting of 267 cross sections distributed over approximately 8 km. This analysis revealed the existence of hydraulic capacity problems in various hydraulic structures (bridges and culverts). The conclusion was that, to solve the problem of flooding in the area, large-volume structures were needed to cushion the volume of water from the flood. The use of retention gaps was considered a requirement. However, neither volumes nor their location were identified. However, these solutions in combination with infrastructure improvements (culverts and bridges) need to be analyzed on a case-by-case basis.

The above two studies did not identify possible sites for storage areas, but made just general recommendations for measures to be carried out in the basin.

Our study took these previous insights and recommendations into account to develop an updated hydraulic model of the basin and to enable the identification of flood zones for the status quo (baseline). In addition, green flood retention measures in the form of multi-functional offline storage areas were analyzed and compared to the baseline. Only suitable areas along the river corridor were considered for flood retention and assessed with regard to their multifunctional potential.

In their study, Oreamuno Vega and Villalobos Herrera (2015) recommended inter alia implementing retention measures to attenuate flooding events and reduce peak flow in the river. In this regard, the authors investigated the storage volume needed to address the flooding issues at one critical bridge and two culverts along the river channel. For a 10-year return period event, the same event used in our study, their results showed that a volume reduction of 1.55% could potentially avoid inundation at the bridge and one of the culverts, and that 24.33% of the volume needed to be reduced to prevent flooding at the second culvert. However, the authors did not evaluate space availability, design possibilities, or the social and ecological benefits of the measures. The model presented in our study also considers these additional aspects. The hydraulic results show that a volume reduction of 1.55% is possible through the implementation of one storage area. However, a volume decrease of 24.33% is not achievable with the three measures modelled in this study which potentially could lead to a reduction of close to 10% in the lower part of the basin. Hence, for an effective solution to the inundation issues in the basin, more than the three modelled storages would be needed. The analysis of suitable sites in this study identified four additional sites in between the modelled ones and two further sites upstream of site SA01. Four of them could provide a similar or larger storage volume than the modelled ones and could suffice to achieve $> 24\%$ of volume reduction. This study revealed the flood reduction potential of three potential storage sites and the results provide valuable insights regarding the potential of additional sites, but further studies are needed to evaluate the additional potential.

There are of course uncertainties in the presented modelling results regarding the impact of the modelled measures. These uncertainties arise from several sources: inaccuracy in model structure, parameter estimation, initial conditions, and observational data used to drive and evaluate the model. With regard to the modelling of the off-line storage systems, the in- and outlet structures were not designed and modelled in detail so were not the storage system itself. To reduce uncertainty regarding the measures impact, such detailed studies that enable a precise study of, for instance, inflow and outflow processes when the system is filling up or emptying are needed.

In other previous studies in the same study area, natural water retention measures (NWRMs) within the urban drainage areas were analyzed based on available suitable space. Chen et al. (2021) used the hydrological rainfall-runoff model PCSWMM to simulate two NWRM scenarios and assess their impacts on flood reduction: (1) modelling of permeable pavements, bio-retention cells, infiltration trenches and detention basins in public spaces, and (2) cisterns and green roofs on private properties. The results show that scenario 1 generates greater reductions in the volume (80%) and peak runoff (55%) when simulating a 10-year rainfall event. When comparing the simulation results of Chen et al. (2021) with our study for the same control point (CS08) and the same rainfall event, the offline storage areas considered in our study resulted in a river peak flow reduction of 15.3%, while the NWRM measures showed a decrease of up to 40% in the peak runoff. However, these reductions cannot be directly compared with the reductions documented in our study's results since the Chen et al. (2021) study modelled a full NWRM implementation at all potentially suitable sites, thereby representing a hypothetical maximum retention potential. Whereas NWRMs aim to control generation of surface runoff to reduce potential flooding, storage systems act as flood managers by reducing flood intensity and impacts.

Aparicio Uribe et al. (2022) used the PCSWMM software to model NWRM scenarios (infiltration trenches, stormwater tree pits, swales, retention ponds) for different neighborhoods within the Quebrada Seca-Burío basin with more detail on the actual implementation potential with regard to available space. Assuming the full-scale implementation of all measures, their results show peak runoff reductions at neighborhood outlets (points of discharge to the Quebrada Seca river) between 14.4% and 23.7% for the same 10-year rainfall event, hence demonstrating a diverse runoff reduction potential among the considered neighborhoods and a generally smaller reduction than that achieved for the entire basin in the study of Chen et al. (2021).

A further study by Towsif Khan et al. (2020) performed a high-resolution rainfall-runoff simulation with PCSWMM, considering only prioritized NWRM measures (infiltration trenches, stormwater tree pits, retention ponds) identified as feasible during field work in a residential area (SEE-URBAN-WATER real world lab; Chapa et al., 2023; Hack and Schröter, 2021; Peréz Rubí and Hack, 2021; Chapa et al. 2020). For a 5-year rainfall event, the peak runoff reduction achieved was 7.1%, again showing decreasing runoff reduction potential when considering NWRM implementation on a smaller scale and with more detailed consideration of implementation constraints.

Hence, these NWRM studies on different spatial scales (basin, sub-basin/neighborhood, residential area) reveal an area-specific decreasing runoff volume and peak flow reduction potential with decreasing spatial scale and more detailed accounting for actually available space and the integration of measures into the existing (drainage) infrastructure. While the basin-scale study features the highest heterogeneity of urban spatial organization, the neighborhood and residential area scales consider specific urban characteristics that may differ from other parts of the basin. The neighborhoods and residential area considered in the studies of Aparicio Uribe et al. (2022) and Towsif Khan et al. (2020) are characterized by a relatively high degree of urbanization compared to other areas in the basin. Hence, the resulting runoff reduction potential in these areas is probably low in comparison. It can be assumed that the

Fig. 7. Current land use of the modelled sites SA01, SA02 and SA03.

area-specific potential of peak runoff reduction through NWRMs varies, depending on the prevailing land-use characteristics, from areas where < 10% reductions are possible up to areas with around 40% reductions across the basin when the full implementation potential for NWRM measures in the specific area is exploited. This shows that there is potential for NWRMs across the basin that complement GFRM measures. It would be advantageous to sequence such measures: 1) reducing surface runoff through NWRMs and thereby reducing the accumulated discharge into the river, and 2) further reducing peak flows and the resulting flooding through GFRMs as offline systems.

NWRM implementation also shows particular advantages in comparison with offline storage systems. NWRMs include a larger variety of solutions that can be installed in public and private sites (e.g., streets, sidewalks and buildings). They could also be used to collect and treat water for different purposes – such as irrigating green spaces or washing cars – common in the urban environment. On the other hand, implementing NFM measures faces limitations in the selection of suitable locations. The HEC-RAS results show that the impacts of GFRMs are more pronounced when higher volumes are stored. Hence, their effectiveness is also related to the availability of large areas. The floodwater is stored during the event period and later released into the watercourse, without treatment or further use. Moreover, the storage areas are connected to the river and manage fluvial flooding. Installable throughout the basin, NWRMs can reduce runoff production and flow, thereby addressing pluvial flooding.

Another disadvantage of GFRM solutions is the need to evacuate a storage area when the system is in operation, thus reducing its social use and acceptance and also increasing implementation costs as an alarm system would need to be installed and regularly tested. Nevertheless, as such storage areas require larger available areas, GFRMs offer greater potential for creating habitats, enhancing green spaces and biodiversity, and providing recreational opportunities. While NWRMs aim to avoid inundations (i.e., *ex ante*), offline storage systems operate when flooding occurs (i.e., *ex post*). These measures are therefore capable of preventing the consequences of sometimes inevitable natural disasters. The different characteristics of the two solutions are not to be seen as better or worse, but as complementary.

One particular constraint of this study was the use of Google Earth images to identify possible sites and ensure their appropriate design and location. Comparing the images with existing conditions in the field, we were able to verify that the selected areas SA02 and SA03 were suitable for implementation, see Fig. 7(a) and (b). However, as can be seen in Fig. 7(c), a construction project is set to be developed in SA01, making this site unavailable.

Offline storage systems feature lower potential for mitigating flooding events than runoff-controlling measures. In addition, NWRMs present further advantages, including the use of the collected water and the possibility of implementing them in various public and private areas. On the other hand, NFM measures can provide larger ecological benefits and reduce the consequences of high-magnitude events. Further investigations are needed to analyze the combination of flood storage and runoff-controlling measures, as the characteristics of the different solutions can complement each other, thereby enhancing the hydraulic, social, and, ecological benefits.

5. Conclusions

By using hydraulic modeling it could be shown that offline storage systems at sites with potential for additional social and ecological functions along a river can reduce downstream flooding. Large upstream sites produced better results in reducing river flow and volume. Overall, peak flow reductions of 5.6 – 15.3% and flood volume reductions of 3.6 – 9.9%, depending on the location and number of measures, are achievable with combinations of three potential sites. This study considered hydraulic, ecological and social benefits for the selection of sites to model GFRMs. Spaces classified as bare soil, agricultural land, vegetation and carparks were assessed. In addition, inundation zones, runoff production, soil type and the distribution of green spaces were considered. Application of the methodology using data from previous studies combined with analyses of satellite images resulted in three sites being identified. A site visit carried out in the final stages of the study revealed the limitation of using remote sensing systems for this purpose. Now earmarked for a construction project, one of the selected sites was not previously identified as being unavailable due to a lack of updated satellite images.

Furthermore, additional analyses are needed to assess in greater depth site feasibility. Considering the social aspect, it is necessary to evaluate the local population's acceptance of the green flood retention measures, especially when the areas are used for recreation or other activities. Where it is found that citizens will be hesitant to frequent such spaces, the selection and design of sites should consider ecological and hydraulic benefits as the main priorities. Wide-ranging surveys can be carried out to access the opinions and the functioning and benefits of the GFRMs using simple and non-technical language. Regular maintenance of evacuation systems should be carried out by testing alarms and instructing users on how to proceed before a storage area starts to fill up.

CRediT authorship contribution statement

All persons who meet authorship criteria are listed as authors and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this manuscript has not be submitted to or published in any other journal before.

Lopes Monteiro Carolina: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Bonilla Brenes José Ricrado:** Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Serrano-Pacheco Alberto**: Supervision, Writing – original draft, Writing – review & editing. **Hack Jochen:** Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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