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Evaluation of nature-based solutions for flood risk management in the Oitavén-Verdugo River Basin (NW Spain)

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ABSTRACT

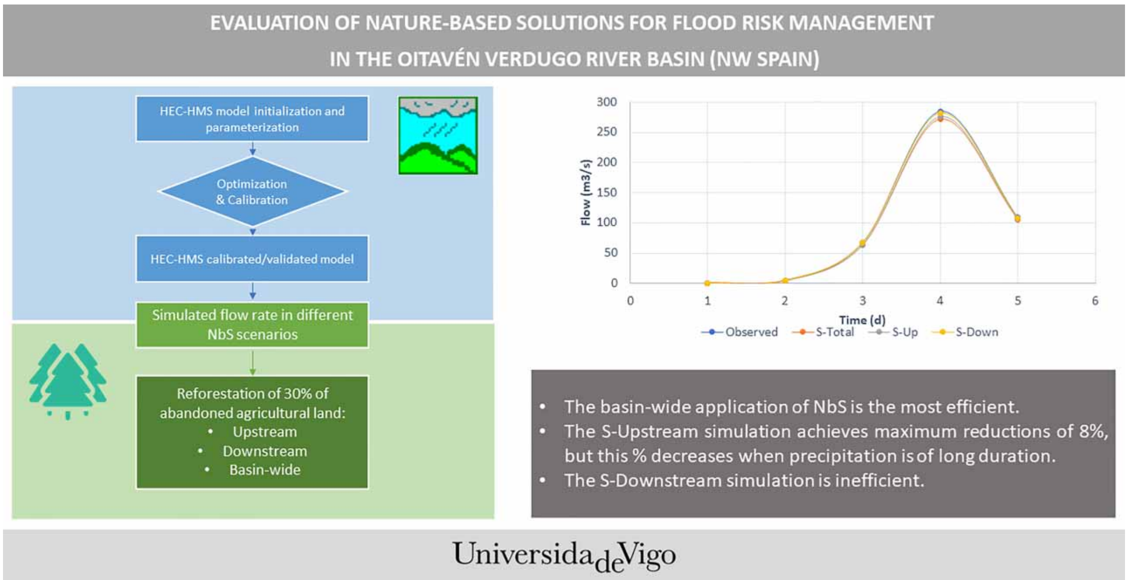
Floods are recurrent phenomena with significant environmental and socio-economic impacts. The risk of flooding can increase when land use changes. The objective of this research has been to obtain an integrative methodology based on the development of a model in HEC-HMS, calibrated and validated from events between 2018 and 2022, and to apply simulations employing the use of Nature-Based Solutions (NbS) tools. This model has been applied in Verdugo-Oitavén River Basin (NW Spain). Three different scenarios propose (1) the reforestation of 30% of abandoned agricultural land across the basin, (2) reforestation upstream (S-Upstream), and (3) reforestation in two sub-basins (S-Downstream). Upstream afforestation provided a similar reduction to catchment-wide afforestation for both peak discharge and hydrograph volumes. The S-Upstream simulation reaches peak reductions of 8%, but this percentage decreases when precipitation events are long lasting, reaching a reduction of 3.3% for events of 5 days or more. On the other hand, downstream reforestation has minimal effect (1%) in reducing maximum discharge of events. The use of NbS-based strategies would improve integrated watershed management, reduce flood risk, and improve environmental governance.

Key words: curve number, flood hazard management, HEC-HMS, nature-based solutions, reforestation

HIGHLIGHTS

- First hydrological modelling of the Verdugo-Oitavén Basin.
- Proposed change of land use from abandoned agricultural land to reforested land.
- Simulation of reforestation upstream almost as effective as in the whole catchment.
- Land use change from abandoned land to forested land is a promising tool.
- Ensuring watershed water security through the development of new strategies is key to environmental governance.

GRAPHICAL ABSTRACT



EVALUATION OF NATURE-BASED SOLUTIONS FOR FLOOD RISK MANAGEMENT IN THE OITAVÉN VERDUGO RIVER BASIN (NW SPAIN)

HEC-HMS model initialization and parameterization

Optimization & Calibration

HEC-HMS calibrated/validated model

Simulated flow rate in different NbS scenarios

Reforestation of 30% of abandoned agricultural land:
- Upstream
- Downstream
- Basin-wide

- The basin-wide application of NbS is the most efficient.
- The S-Upstream simulation achieves maximum reductions of 8%, but this % decreases when precipitation is of long duration.
- The S-Downstream simulation is inefficient.

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1. INTRODUCTION

Globally, floods are one of the natural phenomena that affect the most people in the world, generating a large number of fatalities and a high socio-economic impact. In addition, climate change has caused hydrological changes around the world, increasing the likelihood of extreme weather events such as floods (Rajkhowa & Sarma 2021). The impacts caused by flooding are expected to increase dramatically over time, prompting policy makers to implement innovative risk management strategies and solutions (Pagano *et al.* 2019).

In recent decades, the most common approach to reducing flood impacts has been based on the use of 'grey' solutions (e.g. dams, embankments, levees, etc.) (Muller *et al.* 2015). However, there are also some limitations: they are capital intensive, often responsible for damaging or eliminating biophysical processes necessary to sustain both people and ecosystems, and even associated with a misleading sense of security that could condition the behaviour of communities (Palmer *et al.* 2015; Infrastructure 2017). In addition to other direct impacts, such as altering fish migration, altering seasonal cycles, blocking nutrient transport, they can also accumulate heavy metals and other pollutants, such as cyanobacteria (Adefemi *et al.* 2007; Dugan *et al.* 2010; Acuña-Alonso *et al.* 2022a). Recent years have seen an increase in the study of nature-based solutions (NbS), in other words, 'solutions inspired and supported by nature, which are cost-effective, provide simultaneous environmental, social and economic benefits and help build resilience' (Pagano *et al.* 2019). The NbS being studied are manifold, e.g. wetland restoration, reforestation, watershed renaturation (Giordano *et al.* 2020; Acuña-Alonso *et al.* 2022b). The capacity of these actions to reduce vulnerability to flood disasters has been analysed, but also the use of these tools provides other ecosystem services compared to the use of grey infrastructure, in addition to promoting mitigation and adaptation to disturbances generated by climate extremes and urbanization (Dong *et al.* 2017), they can be considered multi-objective tools.

On the other hand, the frequency as well as the magnitude of floods can lead to an increase in areas with environmental conflicts caused by land use change (Janizadeh *et al.* 2021). These occur when there are conflicting views on land-use policies, for example, when a growing population creates competing demands that negatively impact land uses nearby (Brown & Raymond 2014). In Galicia, the privatisation of public forests led to a decrease in forest cover, as the forests acquired by the new owners were cleared and replaced by agricultural land and pastures, and riparian vegetation was reduced or eliminated (Guadilla-Sáez *et al.* 2020). In addition, there is a serious problem of land abandonment within Galicia, which has led to the promotion of agricultural use over forestry, to recover these areas. All these changes reduce soil permeability, which decreases the stability of the soil itself and its ability to maintain its structure under water pressure (Wheater & Evans 2009).

The Hydrologic Modelling System (HEC-HMS), software developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC), is a numerical, semi-distributed hydrologic model used for event-based and continuous runoff simulation (Ford *et al.* 2002). Previous studies using the model demonstrated its ability to simulate and forecast water flows based on different datasets and different types of catchments (Chu & Steinman 2009).

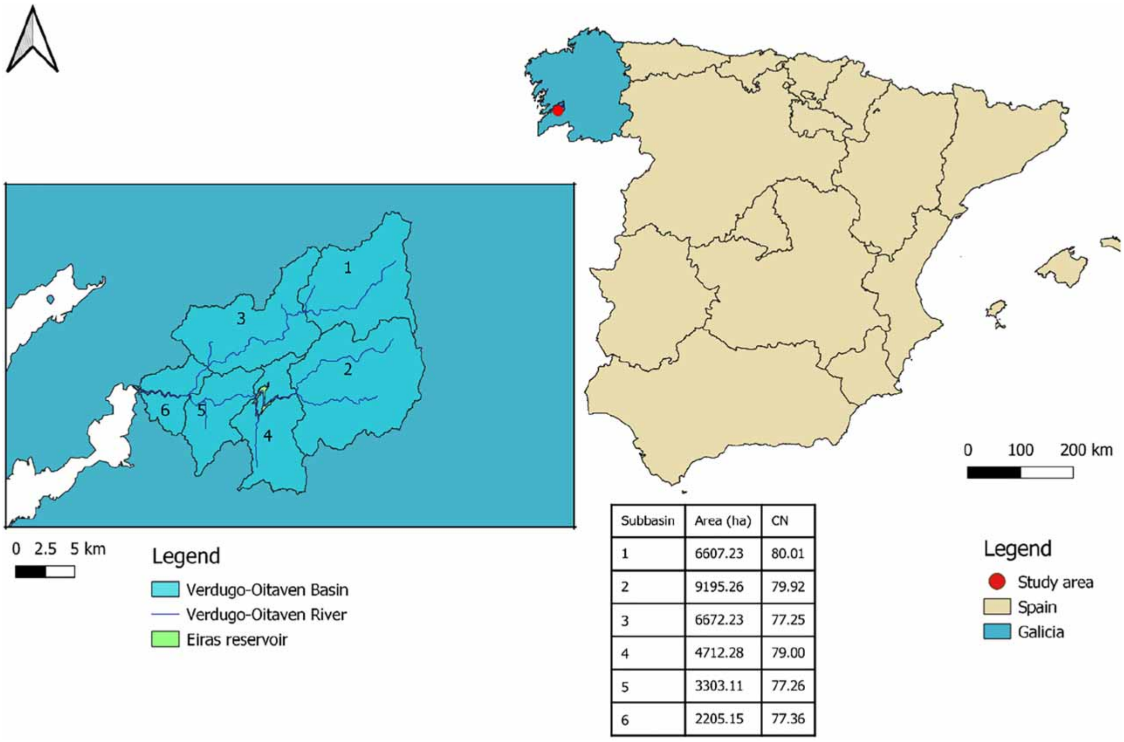
The purpose of this study is firstly to model the Verdugo and Oitavén River Basin. Up to date, rainfall-runoff modelling of this catchment has not been carried out using HEC-HMS. This catchment is one of the areas with the highest risk of flooding, and also has a large area of urban centres and floods often involve high economic costs. Therefore, the second objective of this study is to carry out a simulation to test NbS use, in this case changing land use from abandoned agricultural land to reforested land.

2. MATERIALS AND METHODS

2.1. Study area

The study was done on the Verdugo and Oitavén rivers, in Pontevedra Province, Galicia, Spain. The rivers are confluent 7 km from the Vigo estuary. They are considered a single hydrographic system, the so-called Verdugo-Oitavén. The Verdugo River, the main riverbed, rises on the slope of Outeiro Grande, Cernadelo village, at 760 m. It flows through deep, V-shaped valleys for most of its 41-km course, and gradually narrows (Figure 1).

The 32-km River Oitavén, the Verdugo's main tributary, rises at the confluence of Regato de las Ermitas (which rises at 720 m altitude) and the River Xesta (which rises at 920 m), 360 m above sea level. It supplies water to the city of Vigo, as well as Mos, Porriño, Redondela, and Salceda. The total Verdugo-Oitavén Basin covers approximately 335 km^2, of which 177 km^2 correspond to the Oitavén Basin. The absolute flow at the mouth of the Verdugo River is on average 17 m^3/s (with flows of approximately 1.2 m^3/s in dry periods and flows of 170 m^3/s in rainfall events), while the flow of the Oitavén River before its confluence is around 10.5 m^3/s (with minimum flows of approximately 0.2 m^3/s and around 90 m^3/s in rainfall events). Both basins are rainfed, and the average annual rainfall in them is approximately 1,884 mm, reaching 2,000 and 2,500 mm in the upper reaches (period 2006–2019).



Subbasin	Area (ha)	CN
1	6607.23	80.01
2	9195.26	79.92
3	6672.23	77.25
4	4712.28	79.00
5	3303.11	77.26
6	2205.15	77.36

Figure 1 | Location of Verdugo-Oitaven Basin and the sub-basins in Pontevedra province; location of the study area on the Spain map. The map coordinate system is EPSG:25829 ETRS89/UTM zone 29 N.

Every year precipitation events in the autumn–winter season cause the Verdugo River to overflow, potentially affecting the city centre of Ponte Caldelas, while overflows of the Oitavén River affect the city of Soutomaior. These events cause significant material damage, flooding streets, commercial premises, basements, and houses.

In 2019, a major catastrophe occurred in the Eiras reservoir (on the Oitavén River), which supplies Galicia's most populous city, Vigo. Due to heavy precipitation the dam overflowed, forcing the gates to be opened, and causing major economic impacts in the area.

2.2. Model simulations

In this study, different hydrologic simulations of the Verdugo-Oitavén River Basin were run and analysed. They were calculated from a HEC-HMS software (V.4.9.0) hydrologic model, and calibrated and validated with data from 2017 to 2019. To obtain the study area model, a digital terrain model was obtained from the National Centre for Geographic Information, specifically from the National Aerial Orthophotography Programme (PNOA) (Spanish National Geographic Institute 2021). Land uses were obtained from SIOSE (Gobierno de España 2016). Precipitation and evaporation data were obtained from Meteogalicia (Xunta de Galicia 2021), calculating the weighted average precipitation of each station using the Thiessen polygon method (Table 1). Flow data were obtained from the website of the Ministry for Ecological Transition (Ministerio Para La Transición Ecológica 2020; Table 2).

Table 1 | Meteorological stations in Verdugo-Oitaven Basin

Station name, location	Coordinates		Type of rain gauge
Ponte Caldelas	Latitude	42.39316, WGS84 (EPSG:4326)	Lambrecht, Model 00.15189.002000
	Longitude	– 8.506196, WGS84 (EPSG:4326)	
	Altitude (m.s.n.m.)	350	
Soutomaior	Latitude	42.327152, WGS84 (EPSG:4326)	Tipping bucket rain gauge, Model 52202/52203
	Longitude	– 8.568357, WGS84 (EPSG:4326)	
	Altitude (m.s.n.m.)	169	
O Viso (Redondela)	Latitude	42.3207, WGS84 (EPSG:4326)	Tipping bucket rain gauge, Model 52202/52203
	Longitude	– 8.601872, WGS84 (EPSG:4326)	
	Altitude (m.s.n.m.)	260	
Fornelos de Montes	Latitude	42.315304, WGS84 (EPSG:4326)	Lambrecht, Model 00.15189.002000
	Longitude	– 8.400214, WGS84 (EPSG:4326)	
	Altitude (m.s.n.m.)	705	
Amiudal	Latitude	42.414585, WGS84 (EPSG:4326)	Lambrecht, Model 00.15189.002000
	Longitude	– 8.238242, WGS84 (EPSG:4326)	
	Altitude (m.s.n.m.)	553	
Rebordelo	Latitude	42.467537, WGS84 (EPSG:4326)	Lambrecht, Model 00.15189.002000
	Longitude	– 8.502887, WGS84 (EPSG:4326)	
	Altitude (m.s.n.m.)	367	
Gargamala	Latitude	42.246513, WGS84 (EPSG:4326)	Lambrecht, Model 00.15189.002000
	Longitude	– 8.454067, WGS84 (EPSG:4326)	
	Altitude (m.s.n.m.)	235	

The model was calibrated using the Soil Conservation Service-Curve Number and the Clark methods, but on the same dates, to check which gave better results. Other parameters were calculated: The time of concentration was added to the data for the corresponding sub-basin (hours), while the lag time was added to the data for each

Table 2 | Gauging stations in the Verdugo-Oitavén Basin

Gauging station	Coordinates		Observation
Ponte Caldelas	Latitude	42.2329, WGS84	Verdugo River
	Longitude	−8.2955, WGS84	
	Altitude (m)	288	
O Sobral	Latitude	42.2029, WGS84	Oitavén River
	Longitude	−8.3319, WGS84	
	Altitude (m)	88	
Soutomaior	Latitude	42.2029, WGS84	Oitavén River
	Longitude	−8.3319, WGS84	
	Altitude (m)	10	

corresponding reach (minutes). Finally, a robustness check of the developed model was performed to confirm that the results obtained were reasonable and consistent with expectations. The model was calibrated and validated, by calibrating model parameters by sub-basin from upstream to downstream according to Zhang *et al.* (2022).

For the simulations, the infiltration capacity was quantified in a parameter derived by the Soil Conservation Service (SCS) called CN (curve number), which determines the runoff over an area based on soil type and cover, and the soil's hydrological group (Cronshey 1986).

$$\mathrm{CN} = \frac{\sum A_i \mathrm{CN}_i}{\sum A_i} \tag{1}$$

The values calculated for the sub-basins are 80.1 (sub-basin 1), 78.5 (sub-basin 2), 77.3 (3), 74.0 (4), 76.1 (5), and 81.0 (6). To assess the possible effects of using NbS, four hypothetical scenarios were chosen. These were based on the change of agricultural land use from abandoned to forestry. According to Perpiña Castillo *et al.* (2020), Galicia has one of the highest proportions of abandoned agricultural land in Spain, at around 44%. Therefore, assuming that it is not always possible to use all, a change of 30% of the agricultural area to forest was simulated, prioritizing the least permeable soils. The hydrographs simulated in HEC-HMS were carried out for two flood events in the Verdugo-Oitavén catchment to provide for different simulations. Event 1 took place from 12 to 17/10/2019, and event 2 from 09 to 13/12/2019. The aim was to analyse different scenarios reflecting different options, to reduce flood hazards through NbS and, particularly, afforestation. Afforestation was first simulated upstream (S-Upstream) of the catchment headwaters, and designed for sub-basins 1 and 2, increasing their forested areas from 1,733.09 to 3,133.33 ha and 2,458.63 to 4,495.26 ha, respectively. Subsequently, afforestation was simulated in the basin centre, in the downstream scenario (S-Downstream), reforesting sub-basins 3 and 4, increasing their areas from 2,987.13 to 3,849.67 ha and 1,818.52 to 2,538.84 ha, respectively. The last scenario (S-Total) evaluated reforestation throughout the basin, where sub-basin 5's forested area was increased from 1,485.01 to 1,959.61 ha and sub-basin 6's from 992.12 to 1,268.33 ha. Different assumptions were also simulated to assess whether the use of reforestation would be sufficient in this catchment.

2.3. Statistical analysis

In this study, the statistical error between simulated and observed runoff was evaluated by the Coefficient of Determination (R^2), the Percentage of bias (PBIAS), and Nash–Sutcliffe Efficiency (NSE). PBIAS and NSE are included in the HEC-HMS software. R^2 indicates how well the simulated data correlates to the observed values (Di Bucchianico 2008).

PBIAS measures the average tendency of the simulated data to be higher or lower than the observed values (Kumarasamy & Belmont 2018). The optimal value of PBIAS is zero, indicating a perfect match between simulated and observed runoff, whereas positive values show that the simulation is underestimated and negative values overestimation (Belayneh *et al.* 2020).

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n} [Q_{oi} - Q_{si}]}{\sum_{i=1}^{n} Q_i} \times 100 \tag{2}$$

NSE measures the model's efficiency by relating the goodness of fit of the simulated data to the variance of the measured data. NSE can range from $-\infty$ to 1, the latter corresponding to a perfect match of the modelled discharge to the observed data.

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} [Q_{\mathrm{o}i} - Q_{si}]^2}{\sum_{i=1}^{n} [Q_{\mathrm{o}i} - Q'_{\mathrm{o}}]^2} \tag{3}$$

where Q_{o} is the observed flow (m^3/s), Q_{s} is the simulated flow (m^3/s), Q_{o}' is the average observed flow, i is the time step, and n is the total number of time steps.

2.4. Environmental and economic analysis of NBS scenarios

A preliminary analysis was carried out in order to evaluate the cost of afforestation scenarios and the benefits that the use of these NbS could bring. The benefits evaluated were: (1) carbon sequestration rates based on the removal rate database for Spain and Galicia with the restoration type 'Oak'), which was 9.5 CO_2/ha/year (Bernal *et al.* 2018). (2) Quantification of the benefits of afforestation on surface and groundwater quality, estimated at 187 €/ha, according to Müller *et al.* (2019). (3) Valuation of biodiversity use and non-use services, estimated at 281.05 €/ha/year (Dittrich *et al.* 2019; Johnen *et al.* 2020).

Afforestation costs were calculated on the basis of (1) rental of plots from the 'Banco de Tierras' (Ley 11/2021, 2021) with a price of 105 €/ha/year. These plots can be rented with the aim of providing climate change mitigation measures. The Xunta de Galicia (the public administration with competence for land management in Galicia) makes the land available to the public at a symbolic price. (2) A value of 2,526.45 €/ha was obtained for land preparation actions, including the reforestation itself. (3) A cost of 474.76 €/ha each was estimated for forestry work. These calculations were made for the first 20 years of afforestation, due to the fact that the estimated CO_2 sequestration rate is reduced thereafter.

3. RESULTS AND DISCUSSION

3.1. HEC-HMS model

The calibration process using the SCS curve number method gives a result of $R^2 = 0.96$, while Clark's method gives $R^2 = 0.91$. Both figures are very high. In the validation check for both the SCS curve number and Clark methods, $R^2 = 0.99$. Different studies suggested this common method for the assessment of time series agreement by examining the sum of squared differences (Najim *et al.* 2006). The results indicate that the HEC-HMS model is well optimized in this study, and that it is generally reliable and robust for flood simulation in the study area. The PBIAS ranged from -2.2 to -11.7%, suggesting some overestimation of simulated runoff, and the Nash–Sutcliffe values ranged from 0.80 to 0.93.

The mean CN of the Verdugo-Oitavén watershed is 78.5, indicating that the study area's general conditions favour runoff over infiltration. In fact, 59% of the study area corresponds to hydrological soil group type D (very slow infiltration, <13 mm/h), with 35% corresponding to group type C (slow infiltration, 36–13 mm/h), while 5 and 1% correspond to infiltration B (medium infiltration 37–75 mm/h) and A (fast infiltration >76 mm/h) (Bradbury *et al.* 2000), respectively. In other words, slow or very slow infiltration predominates. Depending on the needs for land use change from forest to agricultural or vice versa, CN decreases or increases (Singh *et al.* 2022). Taking into account the permeability of the area to apply NbS could facilitate decision making, as well as the optimization of resources.

3.2. Simulations on the Verdugo-Oitavén River Basin

The different simulated scenarios provide small changes in CN (Table 3). The basin has a low representation of soils with higher permeability (types A and B), so the number hardly drops. When simulating the change from agriculture to forestry, CN decreases, the basin's permeability increases. Thus CN could provide information about the effect of changes in land use on the watershed's permeability and, therefore, flood risk.

The hydrographs simulated with the data obtained from the model were run for a first event that reached an observed flow rate of 320 m^3/s (Figure 2) and for a second event that reached a flow rate of 285 m^3/s (Figure 3). This maximum flow was reduced for all the scenarios presented in this study, through the reforestation of

Table 3 | Observed and simulated curve number for the sub-basins that form the Verdugo-Oitavén River Basin

CN	Sub-basin 1	Sub-basin 2	Sub-basin 3	Sub-basin 4	Sub-basin 5	Sub-basin 6
Observed	80.01	79.93	77.26	79.01	77.27	77.37
Simulated	77.57	77.38	75.61	77.18	75.54	75.85

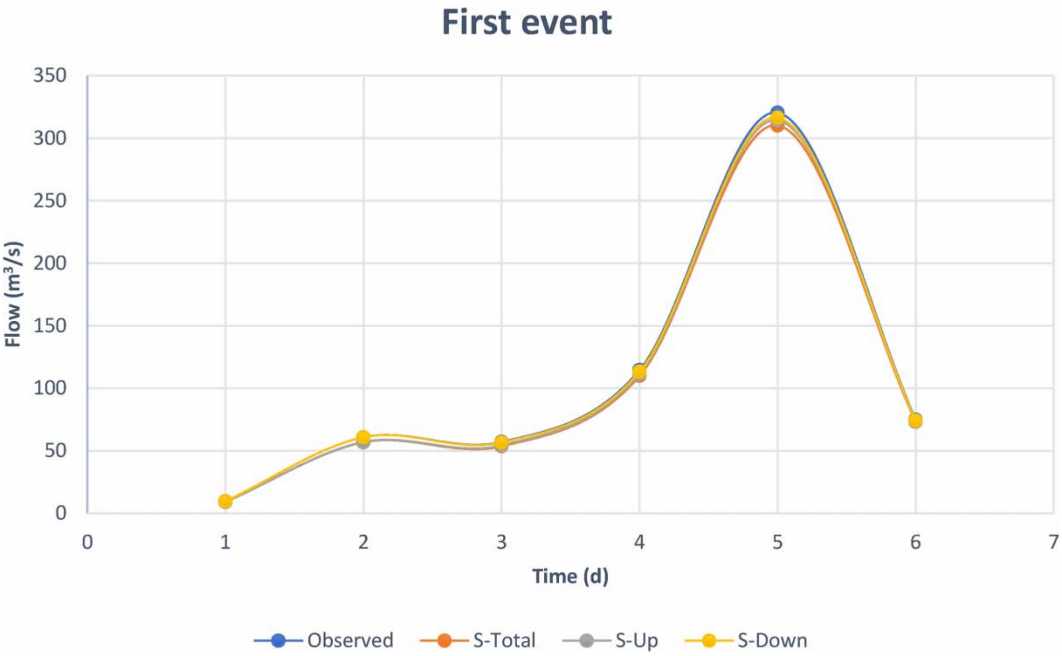


Figure 2 | Flood event hydrographs (12 to 17/10/2019) from the model output considering the different scenarios.

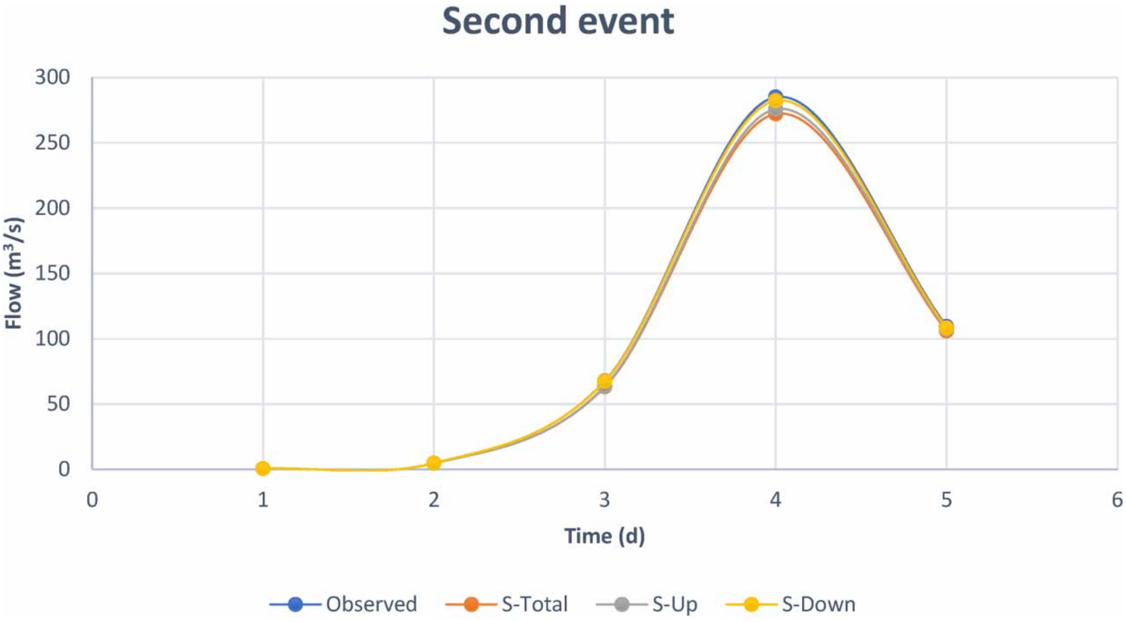


Figure 3 | Hydrographs obtained for a flooding event (09 to 13/12/2019) from the model output considering the different scenarios.

abandoned agricultural areas. For the first scenario, where reforestation was simulated throughout the basin (S-Total), the maximum discharge (m^3/s) was reduced by 3.9% for the first event, and by 4.5% for the second. For the scenarios where only the upstream sub-basins were changed (S-Upstream), the reductions were 2.7 and 3.3% for the first and second events, respectively. However, the third scenario (S-Downstream) achieved a much smaller reduction of only 0.9%. These results are similar to those of other studies, although studies such as Johnen *et al.* (2020) increased the forest area indiscriminately, without taking into account the real capacities to accommodate different land uses in the watershed. Factors such as the need for agricultural use, and its link to water security (water, energy, food), were not taken into account (de Amorim *et al.* 2018; Acuña-Alonso *et al.* 2021). In our case, the proportional reduction ratio increases for specific days within each event, reaching 8% reduction for the first day in S-Total and S-Upstream 7% reduction for both simulations on the first event's second day. Similarly, in the second event, 7 and 6% were achieved for the second day for the S-Total and S-Upstream scenarios, respectively. However, for the same day, the scenario simulating reforestation in sub-basins 3 and 4 did not reduce the maximum discharge.

This improves infiltration due to forest cover, which intercepts and captures rainwater, providing social benefits by reducing flood risk (Brody *et al.* 2014), in addition to increasing groundwater reserves. This last factor is key in a scenario where drought periods are expected to be longer lasting and more extreme. Other study such as Kabeja *et al.* (2020) analysed how increasing reforested land by 18 and 16% decreased peak flood discharge by 14 and 6%, respectively. This highlights how land use changes affect catchment flood risk. Revell *et al.* (2021) found that forest planting reduced peak flow intensity compared to impervious land cover by averages of 6, 2, and 1% for 6-, 24-, and 96-h winter storms. The increased forest area has a limited effect (Danáčová *et al.* 2020), in contrast to the very intensive agricultural and livestock use of the area (Álvarez *et al.* 2017). There is a reservoir in sub-basin 4 of the Verdugo-Oitavén Basin, but this does not prevent flooding in the area. It was overwhelmed in 2018 and 2019 after extreme precipitation events, during which it deteriorated, worrying the administrations about possible breakage. Moreover, compared to reservoir and water diversion canal construction, the use of NbS offers the advantages of reforestation, wetland restoration, and rainwater harvesting, which improve water supply security in an environmentally friendly way (Van Wesenbeeck *et al.* 2017; Huang *et al.* 2020), thus providing multi-objective solutions.

The intensity of floods is expected to increase due to climate change, so it is necessary to implement management and control measures to minimize their impact. The impact caused depends on several variables, such as the magnitude of rainfall, or the different characteristics of the catchment (e.g. land use, geomorphological features). In the study catchment, with multiple small plots, much of the agricultural land abandoned and much of the riparian vegetation zone removed, the development of adaptation and mitigation strategies is key for society. The strategies must be supported by the administration to be successful. However, the Galician Forestry Law (Ley 7/2012, de 28 de Junio, de Montes de Galicia 2012) allows, under certain conditions, the change of forest use towards agriculture, trying to avoid rural abandonment. On the other hand, conversion from agriculture to forestry is only allowed on rustic land classified as agricultural, but abandoned and destined for an agricultural land bank (at least 2 years), and only after prior notification to the forestry management body, and when (1) it is adjacent to forest land and (2) enclaves of up to 5 ha of trees are formed (Ley 11/2021, de 14 de Mayo, de Recuperación de La Tierra Agraria de Galicia 2021). It is necessary to continue working on regulations that support the right tools to improve adaptation to climate change, in relation both to floods and other types of events that affect river basin hydrologic security, such as droughts or eutrophication (Viso-Vázquez *et al.* 2021). The use of HEC-HMS can provide key information to stakeholders, but the scenarios used must be realistic. For example, if a land use change is simulated in sub-basin 3 by setting a CN of 50 (increasing the forested area), the total volume in sub-basin 3 for a studied rainfall event would decrease from 63 to 51 mm, and the peak flow from 16 to 13 m^3/s. However, making sub-basin 3 reach CN 50 would be impossible due to the characteristics of the study area, for example it would not be feasible to optimize forestry use over residential use.

This work provides a basis for assessing flood risk in the basin with the highest anthropogenic pressure in the autonomous community of Galicia. These first approaches should be incorporated into more complex models, including groundwater, sediment, and pollutant transport, in addition to models combining pluvial and fluvial floods, as well as the analysis of the effect of multiple floods in an area in a concentrated manner. The development of multi-level models for flood forecasting will facilitate a new holistic framework for flood mitigation and warning. Rubinato *et al.* (2019) highlight how the integration of mitigation efforts across multiple scales will be essential for optimizing damage reduction and public protection.

3.3. Benefits and costs of applying NbS

Parts of the environmental, economic, and social impacts of the proposed scenarios were analysed. The total costs depend directly on the area of land involved, so that the S-Downstream scenario has the lowest total cost, with €25,907,005, followed by the S-Upstream scenario, with €30,952,060, and finally, the S-Total scenario, in which it is assumed that the entire watershed is reforested, with €69,949,169. Some of the benefits are estimated at €72,898,867 for the S-Upstream scenario, €61,016,659 for the S-Downstream scenario, and finally, a benefit of €164,745,581 for the S-Total scenario. For each of the scenarios, the benefits are higher than the costs.

The use of NbS is estimated to be between 15 and 63% less expensive than the use of grey solutions (Le Coent *et al.* 2021). Moreover, these tools, in addition to promoting flood risk reduction, provide other environmental and social benefits, compared to the use of conventional structures. In a socio-political context where public resources are very limited, economic valuation is essential to identify the most appropriate solution to address water risks.

4. CONCLUSIONS

Climate and land use change, and lack of land management and planning, have increased the danger of floods, which has put pressure on governments to develop measures to mitigate their effect on river basins. Simulation of the change from abandoned agricultural use – very small (average 0.26 ha), heterogeneous plots – to forestry in the Verdugo-Oitavén River Basin enabled study of flow reduction.

Reforestation as NbS is effective in reducing flood hazard in the catchment. In the Verdugo-Oitavén River Basin, upstream afforestation has effects similar to those obtained from catchment-wide afforestation for both peak discharge and hydrograph volumes. Scenario ‘S-Upstream’ achieves peak reductions of 8%, but when precipitation events are continuous and their duration exceeds two days, this falls to around 3%. However, the effect of the ‘S-Downstream’ simulation is minimal, with a reduction of about 1%. It would therefore be advisable to apply more stringent measures (NbS or hard engineering) to cope with the flood risk in the future. The use of NbS tools to increase water retention in watersheds is sustainable for improving territorial planning.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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