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Modelling the impact land use change on flood risk: Umia (Spain) and Voglajna (Slovenia) case studies

Carolina Acuña-Alonso [a,*], Xana Álvarez [a], Nejc Bezak [b], Vesna Zupanc [c]

[a] University of Vigo, Agroforestry Group, School of Forestry Engineering, 36005 Pontevedra, Spain
[b] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia
[c] Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia

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ABSTRACT

Accurate quantification and assessment flood hazards is critical for mitigation and prevention. This study proposes a methodological framework for analysing this hazard and its relationship to agricultural and forestry land use. The objective is to obtain an integrative methodology based on the HEC-HMS model and to apply different simulations, with land use changes as indicator in two different study areas, taking into account the different characteristics of each basin and the different regulations of each area. This was done in two river basins, the Umia Basin (north-western Spain) and the Voglajna Basin (eastern Slovenia). The hydrological models obtained showed a very high performance in the calibration and validation periods. In the Umia River Basin agricultural use has priority over forestry, with food security taking precedence over water security. Reforestation only upstream has been shown to be almost as beneficial as reforestation throughout the basin. However, the use of abandoned land currently limits the reduction of peak discharge. Nevertheless, for an event designed with a 100-years return period, a reduction of about 12% was achieved. The increase in agricultural use promoted by the administration could increase this peak by about 6%, thus increasing the flood hazard, but it has been shown that this use on less permeable soils and upstream would not significantly increase this peak (<1% for the event studied). On the other hand, the Voglajna Basin has a smaller catchment area and fragmented land use, and a mosaic landscape. For the 100-years return period the reduction in peak discharge is only few percent compared to the baseline scenario even if 30% of the agricultural land (about 7% of the total area) is changed to forest land use. The information provided by the simulations is a useful indicator that can be incorporated into management plans to ensure appropriate decision making by the administration. Not only for the application of nature-based solutions (NBS) and providing evidence-base for the NBS and the reduction of flood risk, but such information is key when the use changes from forestry to agriculture and vice versa, as it provides tools to ensure food and water security. In both case studies it was demonstrated how stakeholders need to undertake optimal and strategic planning and management in order to reduce the risk of flooding. In turn, the use of this modelling, as well as the calculation of scenarios from a perspective that not only evaluates different land use changes, but also incorporates different regulations, is presented as an innovative and realistic analysis.

1. Introduction

Floods are among the most devastating natural disasters in small watersheds, inflicting loss of life, enormous damage to property in urban and peri-urban areas and causing a serious threat to the economy (Ben Khélifa and Mosbahi, 2021). According to the Centre for Research on the Epidemiology of Disasters (CRED) and the United Nations Office for Disaster Risk Reduction (UNISDR) in the period between 1998 and 2017 (CRED and UNISDR, 2018), floods were the events that caused the greatest number of disasters (3148 cases, accounting for 43.4% of registered disasters), affecting 2 billion people, of whom 142,088 died. In reaction to this serious problem, the European Union (EU) has made flood risk assessment a central issue (Directive 2007/60/EC, 2007). However, flood risk reduction is not one of the main objectives of this Directive, nor does it take into account future changes in flood risk that will result from climate change. Instead, it imposes the development of

* Corresponding author.
E-mail addresses: carolina.alonso@uvigo.es (C. Acuña-Alonso), xaalvarez@uvigo.es (X. Álvarez), Nejc.Bezak@fgg.uni-lj.si (N. Bezak), Vesna.Zupanc@bf.uni-lj.si (V. Zupanc).

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river basin management plans for each river basin district, with the aim of achieving a good chemical and ecological status, which will help to mitigate the effects of flooding.

Another aspect of the impact of floods that needs to be considered is the increase in extreme weather events associated with global warming, which increase the virulence of floods and its dangerousness (Tabari, 2020). Due to urban sprawl and widespread inundation of floodplains, as well as the increasing frequency of extreme events that cause flooding, it is important to study and simulate floods in order to mitigate the consequences they cause. In general, different dimensions of impacts caused by floods are identified, including social impacts, which include human, material and cultural heritage losses (da Silva et al., 2020). In addition, there are environmental impacts that result in biodiversity losses, as well as geophysical impacts (Stammel et al., 2021). These impacts also include financial or institutional impacts, such as the availability of human, technical, and financial resources and the capacity to effectively manage this risk. Jongman et al. (2014) predicted that by 2050 extreme floods will become more frequent, every 30 years rather than every 50, while damage cycles will occur every 10 years rather than every 16 years, increasing economic losses from € 4.9 billion in the last decade to € 23.5 billion in 2050.

On the other hand, the frequency and magnitude of flooding may increase where environmental conflicts caused by land use change have developed (Janizadeh et al., 2021). Land use conflicts occur when there are contradictory views on land use policies, such as when an increasing population creates competing demands on land use that negatively impact on other nearby land uses (Brown and Raymond, 2014). In this context, an environmental land use conflict develops where the current use differs from a natural use established based on certain morphometric parameters, namely drainage density and hill slope (Caldas et al., 2018). In this case, specifically in one of the proposed study areas (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). All of these changes reduce the permeability of the soil, which reduces the stability of the soil itself and its ability to maintain its structure under water pressure (Wheater and Evans, 2009).

Currently, flood risk management in the EU relies not only on infrastructure development, but also on governmental and non-governmental actors applying legal, economic and communicative water management instruments (Akter et al., 2018). Therefore, key to mitigating flood risk lies in establishing governance in flood management. Water is handled by water managers, while spatial planning determines land use. This clear division and separation of competences is notable in most European countries and is a key factor for successful management (Handayani et al., 2020). This highlights the need to develop new governance models that opt for spatial integration of land use and water issues, which would lead to more sustainable and viable land and water management (Hartmann and Driessen, 2017). Such governance must address the inadequacy of regulations, and structural measures, as well as take into account social and economic inequalities and the geographies of climate change (Winter and Karvonen, 2022), and it should be based on a reliable metric.

Nowadays, the development and implementation of a flood disaster management plan, as well as the development of hydrological risk maps to inform the public, has become more than a necessity. Hydrologic rainfall-runoff models are key to the study and future analysis for the prevention and prediction of hydrometeorological disasters, including flood simulation, flood risk assessment, hydraulic flood control projects and social and environmental impact prediction studies (Dawod et al., 2012). Hydrological models can be classified as lumped models, which assess the response only at the basin outlet, semi-distributed models, which allow the model to change partially in space with a division of the basin into a number of sub-basins, and the distributed model, which allows its parameters to change in place at a commonly chosen resolution (Acuña-Alonso et al., 2022). The Hydrologic Engineering Center - Hydrologic Modelling System (HEC-HMS), developed by the US Army Corps of Engineers (USACE) (Engineers, 2000), is a widely used and powerful modelling tool for hydrologic studies, and is one of the most widely used distributed models. This software is specialised in simulating the hydrologic process of precipitation transformation in urban and rural watersheds and has been used to predict critical events and their potential impacts. The implementation of hydrological models in a given area is always a challenging task. This model has been tested several times in climate conditions and scales similar to the ones used within this study both in Slovenia (e.g., Bezak et al., 2018, 2021; Šraj et al., 2010) and Spain (e.g., Acuña Alonso et al., 2023; Bodoque et al., 2016; García et al., 2008).

In this context, two hydrological models have been applied to two catchments with significant flooding problems, one in the Umia River Basin (northwest Spain), the other in the Voglajna River Basin (eastern Slovenia). The first catchment is larger, but both have a fragmented land use and a mosaic landscape, with an average plot size of 0.26 ha. The second area, the Voglajna River Basin, has extensive agricultural use with an average plot size of 0.33 ha. The main objective of this work was to analyse if land use changes can be used as environmental indicators in flood risk management. For this purpose, we evaluated different land use change scenarios based on the regulations of each catchment and their impact on flood risk were evaluated. Our initial hypothesis is that the current planning model does not adequately integrate land use management into the associated potential risk, especially flood risk. Therefore, management could be designed for each specific area based on its determining factors and characteristics through multi-objective planning.

2. Materials and methods

2.1. Study area

The study was conducted in the Umia River (Galicia, Spain) and the Voglajna River (Slovenia). The study area includes the Umia Basin (Galicia region), located in northwestern Spain (Fig. 1). The total area of the basin is 445.9 km^2. The predominant climate in the study area is oceanic, with an average annual rainfall of 143.72 L/m^2, reaching maximum peaks above 700 L/m^2, and an average temperature of 13.6 °C. The Land Cover and Use Information System of Spain (SIOSE in Spanish) shows that 35% deciduous broadleaved forest, 24.4% complex cropping patterns, 15.6% marsh and heathland, 10% coniferous forest and 15% for other land uses (Gobierno de España, 2016) (Appendix Fig. A.3). The main tributary of the Umia is the Gallo River with a sub-basin of 44.3 km^2 (Álvarez et al., 2017). The Umia reservoir has a maximum capacity (normal maximum level) of 8.05 hm^3 with a surface area of 506,027 m^2. However, this reservoir presents constant eutrophication problems (Acuña-Alonso et al., 2020a; Acuña-Alonso et al., 2020b), which is why the water supply to the population has been interrupted. The elevations of the river basins range from 99 m above sea level in the reservoir area to 798 m in the headwaters of the Umia River. In this first study area, there are problems with land abandonment, which has accelerated the poor condition of agricultural land and the increase of fast-growing forest species, in fact, it is estimated that about 44% of the agricultural land is in a state of abandonment. In agriculture, the farm size is limited due to the small farms typical of this area, which leads to an intensification of land use. The average area of each plot is 0.17 ha, with >5 owners per plot. All this leads to serious environmental problems such as the removal of riparian vegetation, the increase of pollutants in the water and the increased risk of flooding. Floods in the Umia River Basin recur every year, with significant economic and social impacts with the flooding of agricultural land, inundation of commercial premises and homes, and damage to infrastructure and occasional accidents (Xunta de Galicia: Augas de Galicia, 2015). The soils in the upper reaches of the Umia river basin predominantly consist

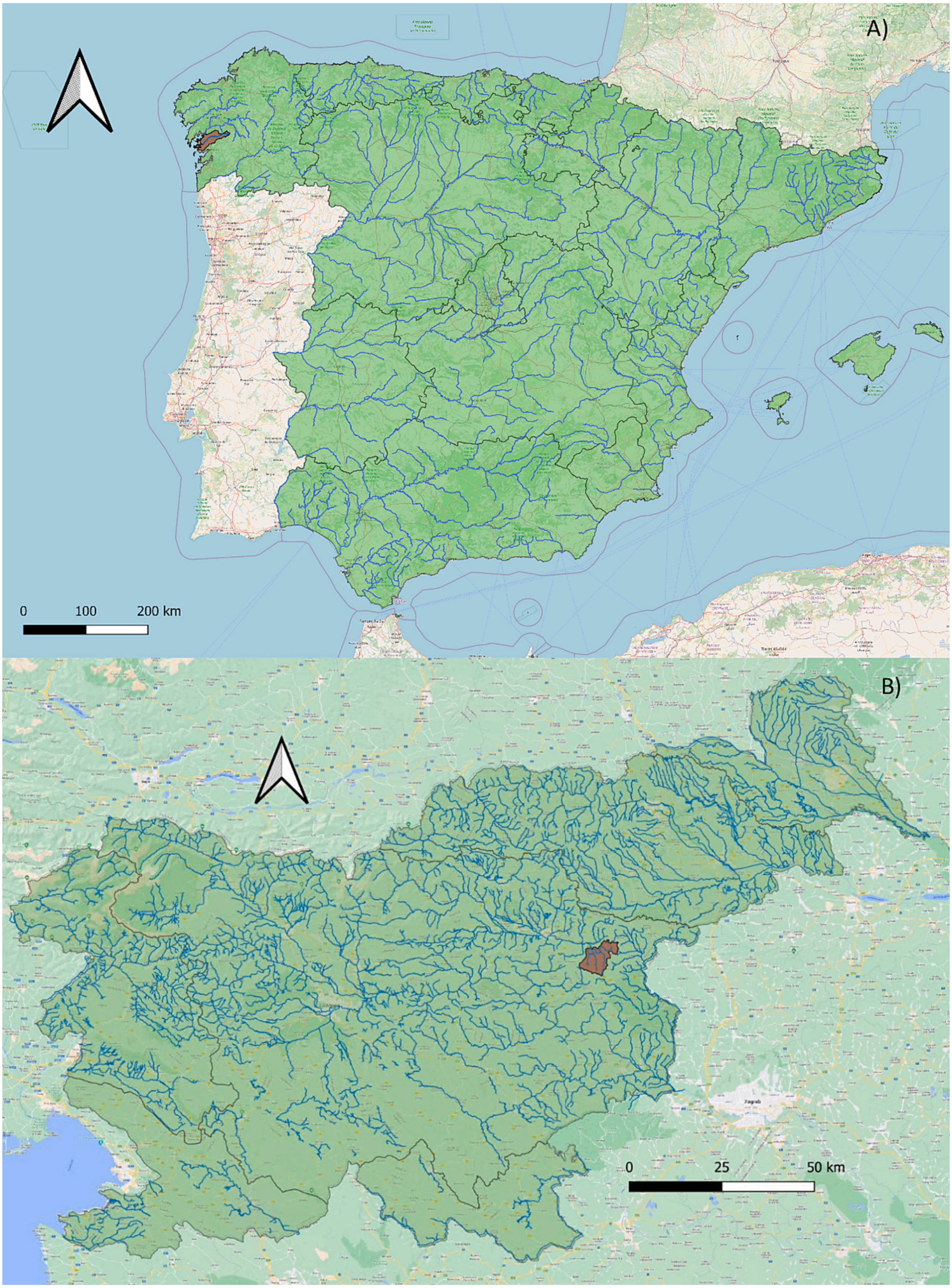

Fig. 1. (a). Location of the Umia Basin (brown polygon) on the Google Road background with a river network in Spain (blue lines). (b). Location of the Voglajna Basin (brown polygon) on the Google Road background with a river network in Slovenia (blue lines).

of granitic formations. As we move downstream, the terrain continues to feature granitic soils, but also incorporates sections characterized by phyllonian rocks and quaternary deposits.

As a second case study, we examined the Voglajna River Basin in Slovenia up to the gauging station Črnolica (54.7 km^2) (Herman, 2012). This gauging station is located at 46.1948° latitude and 15.4136° longitude at 264 m above sea level. The maximum catchment elevation is 700 m a.s.l. and mean catchment elevation is 390 m a.s.l. The average slope of the catchment is about 30% with maximum values exceeding 120%. Moreover, mean annual precipitation in the area is around 1100 mm. The Voglajna River can be characterized by the Panonnian pluvial-nival water regime, which means that minimum water flows can usually be measured in summer and maximum flows in autumn or spring. What makes the Voglajna an interesting case study, is that it is an (albeit small) tributary of the Savinja River and the confluence of the two rivers takes place in the town of Celje (Brilly and Polic, 2005). Therefore, even a small change in discharge can be significant in improving flood mitigation.

There is a relatively large amount of agricultural or similar land in this area, accounting for >60% of the total area according to the 2018 CLC Corine map. Originally, the mountainous area was covered with wet meadows, pastures and fields, but today the lower areas are urbanised with scattered settlements (Panagopoulos et al., 2019). The Voglajna River watershed is extensively farmed. The source of the Voglajna River is Lake Slivniško, which was created for industrial use in 1975, but never used for its original purpose. Instead, Lake Slivniško developed into a multifunctional lake (wet retention basin) that has a low water retention effect during floods, has rich habitats, and is used for recreational purposes. Although irrigation is not planned, there are proposals to use it for irrigation in the future. There are 294 ha in the area that are potentially suitable for irrigation. The soils are distric brown soils and eutric brown soils on soft carbonate rock that are highly susceptible to erosion (Prosen, 2015). Together with the lack of an adequate sewage system in nearby villages and settlements, this contributes to the pollution of Lake Slivniško by nutrients from fish ponds, sediments, and surface runoff.

2.2. Data selection and calculation of parameters

2.2.1. Model setup

HEC-HMS (Hydrologic Engineering Center - Hydrologic Modelling System) model was developed by the U.S. Army Corps of Engineers (Feldman, 2000). The HEC-HMS model can be applied to analyse urban flooding, flood frequency, flood warning system planning, reservoir spillway capacity, stream restoration, etc. (Ford et al., 2002). For the modelling carried out in the Umia Basin study area, the digital terrain model was obtained from the National Aerial Orthophotography Plan (PNOA) (Spanish National Geographic Institute, 2021). Precipitation data were obtained from Meteogalicia (Xunta de Galicia, 2021b), and data from nearby stations, 6 atmospheric stations in total, were downloaded (Appendix Table A.1). The Thiessen polygon method was used to calculate the weighted mean precipitation for each station (Thiessen, 1911). Daily precipitation data were downloaded between 1 January 2014 and 31 December 2016, and the weighted precipitation was calculated using the Thiessen polygon surface values. In cases where the data had a reading error, it was replaced with data from the nearest station. The flow data were obtained from the website of the Ministry of Ecological Transition (*Ministerio para la Transición Ecológica,* 2020). There are two gauging stations in the study area, one dow/nstream and one upstream (Appendix Table A.2). Evapotranspiration data were obtained from four Meteogalicia stations (Xunta de Galicia: Augas de Galicia, 2021). The weighted evapotranspiration of each sub-basin was calculated using the Thiesen polygon. In HEC-HMS, evapotranspiration data were entered in units of monthly total millimetres, and a coefficient of 0.7 (Brunner, 2010). The obtained basin was subdivided into sub-basins with the QGis 3.12.0 program using a layer in shapefile format from Augas de Galicia. The set of sub-basins forming the Umia River Basin were grouped into 6 sub-basins to simplify the subsequent simulations in HEC-HMS 3.5 (Appendix A Fig. 1A, Fig. 2A) in the same way as in the Flood Management Plan carried out by the responsible administration (Xunta de Galicia: Augas de Galicia, 2015, 2021). The city of Caldas de Reis is located in sub-basin 4, as is the A Baxe reservoir. The HEC-HMS has been employed multiple times in various watersheds in the northwest of Spain, and the model's performance was acknowledged as acceptable following the execution of model calibration and validation (Acuña-Alonso et al., 2022; Acuña Alonso et al., 2023; González-Cao et al., 2019).

Since the Voglajna River Basin is much smaller compared to the Umia River Basin, only one sub-basin was used to describe the entire catchment area (54.7 km^2) within the HEC-HMS model. Hourly discharge data from the Črnolica gauging station for the period from 2010 to 2019 was used. For model calibration and evaluation, the five largest flood hydrographs were selected based on peak discharge values. In addition, hourly precipitation data from the nearest station Slovenske Konjice was used to extract the rainfall data. This station is located at 314 m a.s.l. and is about 10 km away from the studied catchment. The HEC-HMS was already applied several times in different catchments in Slovenia and performance of the model was recognized as acceptable after the model calibration and validation was performed (e.g., Bezak et al., 2018; Bezak et al., 2021; Šraj et al., 2010).

2.2.2. Concentration time, the lag time and storage coefficient

The time of concentration was calculated from the Témez formula (Témez, 1978)(Eq. 1).

$$Tc = 0.3\left(\frac{L}{S_0^{0.25}}\right)^{0.75} \quad (1)$$

where Tc is the time of concentration (hours), L is the length of the main channel (km) and.

S_0 is the difference in elevation between the end points of the channel L (%).

The lag time (Tlag) is the time that elapses from reaching the centre of gravity of the net precipitation hietogram until the tip of the hietogram is reached. To calculate Tlag, the time of concentration value is multiplied by 0.6 (Pascual and Díaz-Martín, 2016). The storage coefficient is the result of multiplying the time of concentration by 0.6. This value is used because the storage coefficient takes a value equal or similar to that of the delay time (San Román, 1993).

The time of concentration was added to the data for the corresponding sub-basin (hours) (5.9 h Sub-1, 2.8 h Sub-2, 3.5 h Sub-3, 3.3 h Sub-4, 4.9 h Sub-5, 4.5 h Sub-6) while the lag time was added to the data for each corresponding reach (minutes).

For the Voglajna River Basin the initial value of the lag time parameter was calculated using the equation developed specifically for Slovene catchments (Mavri, 2022):

$$Tlag = 0.11^*\left(\frac{A_g{}^*L_c}{\left(\sqrt{I_0}\right)^{2.45}}\right)^{0.21} \quad (2)$$

where A_g is extent of agricultural areas in km^2 and L_C is river distance from the location closest the catchment centroid to the catchment outlet, I_0 is river slope in m/m. The initial estimation of the Tlag parameter (Eq. 2) for the Voglajna River Basin up to the Črnolica gauging station was 5.1 h. During the model calibration process, the lag time parameter and peaking coefficient parameters were calibrated with aim to minimize the mean of the squared residuals.

2.2.3. Curve number

The calculation for the Umia River Basin, curve number (*CN*) was made from the 2011 Land Occupancy System (SIOSE) data. The CN determines runoff over an area based on soil type, soil cover and soil hydrologic group (Cronshey, 1986). The attributes of the different land uses were regrouped into the 4 main land uses (water, residential, forest and agriculture) using QGis 3.12.0 software. The *CN* values for each sub-basin were calculated by using formula (Cronshey, 1986):

$$CN = \frac{\sum A_i CN_i}{\sum A_i} \quad (3)$$

where A_i is the area (km^2) of the sub-basin and CNi is the corresponding curve number.

Two criteria were used to calculate the impervious area of each sub-basin. In the first, soil permeability was calculated from the data of Información Xeografica de Galicia (Xunta de Galicia, 2021a). The attributes were dissolved according to their degree of permeability: high permeability (to which the letter A was assigned), medium-low (letter B), low (letter C) and very low or very low or impermeable (letter D). Sandy soils correspond to those with high permeability, loamy soils to those with medium-low permeability, sandy-clay soils to those with low permeability and clayey soils to those with very low or very low or impermeable permeability. Finally, the fields were dissolved and classified according to (Pascual and Díaz-Martín, 2016),and based on the area of each curve number in each sub-basin, the weighted curve numbers were calculated. The second mode was calculated from SIOSE 2011. In this case, the percentage of area of a particular land use (urban, industrial, or aquatic) in each sub-basin was calculated. Once these two values were calculated, the criterion of selecting the higher value as valid for the simulations in HEC-HMS was followed (Table 1).

For the Voglajna River Basin the initial CN parameter was estimated using the 2018 CLC Corine land use map and considering the runoff potential map of that basin (Appendix B). Thus, a corresponding runoff potential was determined for each specific land use polygon, and CN coefficients were determined according to the Soil Conservation Service (SCS) methodology. Therefore, the initial average CN value for the Voglajna River Basin was equal to 77.7. During model calibration, the CN parameter was also calibrated, as described in the following subsection.

2.3. Model calibration and validation

Calibration of the hydrological model using HEC-HMS 3.5. for the Umia River Basin study area of was performed by comparing simulated and previously observed values for each of the eight major rainfall events between the years 2014 and 2016 (Appendix Table A.3). The model was calibrated using two different methods, but on the same data, to test which produced better results, these two methods were the Soil Conservation Service-Curve Number Method (SCS-CN) (Mishra and Singh, 2003) and the Clark Method (Clark, 1945). Finally, a validation was performed to confirm the robustness of the developed model and to establish that the results obtained were reasonable and consistent with expectations (Razi et al., 2010) (Table 2).

The calibration and evaluation for the Voglajna River Basin was somewhat different because hourly discharge and precipitation data were also available. Therefore, model calibration was performed for five events (Table 3) with the aim of minimizing the mean of the squared residuals for all five events. Therefore, manual calibration was selected because only two parameters were calibrated (i.e., CN and Tp), which simplified model for the Voglajna River catchment compared to the Umia River catchment.

Table 1
Impervious area of each sub-basin.

Sub-basin (N°)	Impervious area		
	According to soil permeability (%)	According to land use (%)	Final value (%)
1	9.47	4.32	9.47
2	0.85	4.8	4.8
3	0.01	3.66	3.66
4	0.8	6.24	6.24
5	4.58	3.31	4.58
6	22.7	1.79	22.7

Table 2
Main characteristics of events used for model calibration dates used in the development of the flood model in the Umia Basin.

Start date	End date	Peak discharge [m3/s]	Rainfall amount [mm]	Rainfall duration [h]
01/01/2014	05/01/2014	161.5	192.1	51
11/11/2014	15/11/2014	148.6	203.4	47
28/02/2015	03/03/2015	46.1	123.1	38
30/03/2015	04/04/2015	63.1	169.7	44
25/10/2015	28/10/2015	85.5	81.9	36

Table 3
Main characteristics of selected events used for model calibration and evaluation in case of the Voglajna River Basin.

Event	Peak discharge [m^3/s]	Rainfall amount [mm]	Rainfall duration [h]
13/09/2014	56.6	84.5	18
19/09/2010	48.5	70.1	20
23/11/2013	20.3	35.1	16
15/10/2015	18.7	38.6	11
23/05/2015	14.9	51.6	24

2.4. Statistical analysis

For the study, the statistical error between the simulated and observed runoff was measured by the Coefficient of Determination (R^2), the Percentage of bias (PBIAS) and Nash-Sutcliffe Efficiency (NSE) performance metrics. PBIAS and NSE are included in the HEC-HMS software.

The Coefficient of Determination (R^2) indicates how the simulated data correlates to the observed values of data. The range of R^2 extends from zero (unacceptable) to one (perfectly correlated) (Di Bucchianico, 2008).

The NSE measures the efficiency of the model by relating the goodness of fit of the simulated data to the variance of the measured data. NSE can range from - ∞ to 1. The NSE value of one corresponds to a perfect match of the modelled discharge to the observed data.

$$NSE = 1 - \frac{\sum_{i=1}^{n} [Qoi - Qsi]^2}{\sum_{i=1}^{n} [Qoi - Qo\acute{}]^2} \quad (4)$$

where *Qo* is the observed flow (m^3/s), *Qs* is the simulated flow (m^3/s), $Q_O\acute{}$ is the average of the observed flow, *i* is the time step, and n is the total number of time steps.

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

$$PBIAS = \frac{\sum_{i=1}^{n}[Qoi - Qsi]}{\sum_{i=1}^{n} Qi} x100 \quad (5)$$

Where *Qoi* represents observed runoff, *Qsi* represents simulated runoff, and *Qi* represents the observed runoff for each time step i.

2.5. Land-cover change scenarios

In this study, different simulations based on two hydrological models are carried out and analysed, the first in the Umia River Basin and the Voglajna River Basin.

2.5.1. Land-cover change scenarios in the Umia River Basin

Simulations in the Umia River Basin were calculated using a hydrological model created with the HEC-HMS software (V.4.9.0), calibrated and validated with data from 2014 to 2016. Infiltration capacity was quantified by a Soil Conservation Service (SCS) derived CN (Curve Number). According to Perpiña Castillo et al. (2020) Galicia is one of the regions in Spain with the highest percentage of abandoned agricultural land, with an estimated value of about 44%. The recovery of these lands is a priority for the Autonomous Government, which prioritises agricultural use over forestry and offers leasing opportunities for these lands, as well as aid to those interested their reclamation.

For this reason, in this study, different scenarios have been carried out, with the aim of making them as realistic as possible. Of these 44% brownfields, 30% were used (ensuring its availability to other small stakeholders). First, the CN of the Umia River Basin has been studied according to the changes from agriculture to forestry, and from forestry to agriculture, using 30% of the area. Due to the nature of the CN, two strategies were carried out (Table 4): a) Total Use (T), where 30% of the land is used regardless of permeability (A, B, C, D), b) the second strategy (Partial Use, P) where the less permeable soils (C, D) are given priority. Simulation one (S1), "Upstream Umia Agr-For" scenario, where the change of land use from Agricultural to Forestry is applied to 30% of the total area, in sub-basins 6 and 5 (Upstream). Next, the simulation (S2) corresponding to the "Downstream Umia Agr-For" scenario was carried out, where the change was applied to sub-basins 4 and 3 (Downstream). Simulation 3 (S3) "Everywhere Umia Agr-For" scenario, where the change is applied in all sub-basins. The second set of scenarios was based on increasing forest use over agricultural use. Three simulations were also run: Simulation four (S4), "Upstream Umi For-Agr" scenario (sub-basins 6 and 5), followed by simulation five (S5) corresponding to "Downstream Umia For-Agr" scenario (change in sub-basins 4 and 3), and simulation six (S6), "Everywhere Umia For-Agr" scenario (change in all sub-basins). These simulations were tested on an event that caused flooding in the area, event 1 (01/02/2017–06/02/2017), which, according to the Insurance Compensation Consortium, caused practically exclusively material damages of about €260,000, and led to several alerts in the area and the closure of roads.

In addition, a design event was calculated from the time of concentration of the catchment (approximately 18 h), intensity-duration-frequency curves, in the same way as in the Voglajna River case study (Section 2.5.2). They were designed for a return period of 10- and 100 -year, and the design rainfall amounts obtained were 47.5 mm and 86.9 mm, respectively.

2.5.2. Land-cover change scenarios in Voglajna River Basin

Using the calibrated and validated rainfall-runoff model land use change simulations were performed for the Voglajna River Basin. Using calibrated parameters (i.e. CN, lag time, peaking coefficient) different land use scenarios were investigated. In all scenarios, land that is primarily used for agriculture and has significant areas of natural vegetation (CLC ID 243) was predicted to be converted to forest land. This specific land use type covers 13.8 km^2 of the Voglajna River Basin (i.e., about 25%). Therefore, the following scenarios were considered: 10%, 30%, 50% and 70% of this land use type converted to forest.

In addition, we used the design rainfall events with a return period of 10 and 100 years for simulations. The design rainfall event was determined considering the catchment time of concentration (i.e., about 6 h) and the Huff curves available for the nearby Celje station. in addition, intensity-duration-frequency curves were used to extract the information about the design rainfall for both return periods. This resulted in design rainfall amounts of 69 mm, 82 mm, 92 mm and 103 mm for the 10-, 25-, 50- and 100-year return periods, respectively. Fig. 2 shows such a design rainfall event for the 100-year return period.

3. Results and discussion

3.1. Flood risk analysis: Umia River Basin

The calibration process based on SCS-CN gives a result of $R^2 = 0.959$, while the calibration process based on Clark Method gives a result of $R^2 = 0.964$, both of which are very high. The model based on the HEC-HMS calibration has obtained similar results in other studies, e.g., Hamidon et al. (2020), where they obtained an R^2 of 0.90 (SCS-CN), or higher than other models, e.g., in the study of Singh et al. (2022) where the calibration value of R^2 was 0.80 (SCS-CN), or Gharib et al. (2018) where they obtained an R^2 of 0.84 (Clark Method). When validated with the SCS-CN Method, the R^2 result is 0.995, while when validated with the Clark Method the R^2 result is 0.993. Both results, for the both Clark

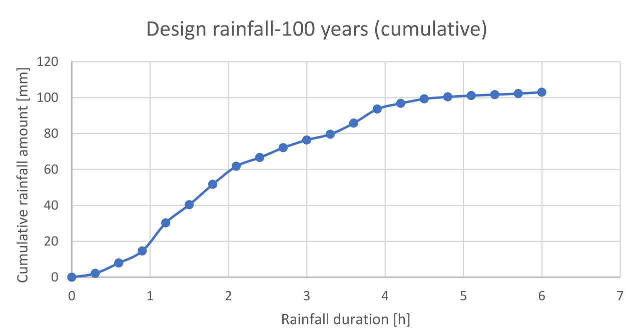

Fig. 2. Cumulative design rainfall event with 100-years return period used for the simulations for the Voglajna River Basin.

Table 4
Summary table of land use changes specifying the simulation codes for the proposed changes in the Umia River Basin.

Simulations	Total Use (T)			Partial Use (P)		
	Upstream	Downstream	Total	Upstream	Downstream	Total
From agronomy to forestry	S1T	S2T	S3T	S1P	S2P	S3P
From forestry to agronomy	S4T	S5T	S6T	S4P	S5P	S6P

Design event 10- and 100-year return period: 10 and 30% from agricultural to forestry

Method and the SCS loss method, were high compared to other studies, e.g. Zelelew and Langon (2020) obtained a value of 0.71 and 0.89, respectively. The PBIAS ranged from −1.5% to −8.7% and the Nash-Sutcliffe values ranged from 0.84 to 0.94.

The average CN for the Umia River Basin had a value of 75, indicating that general conditions in the area favoured runoff over infiltration. Specifically, 76% of the study area corresponds to soil hydrological group type C (slow infiltration, 36–13 mm/h), 10% type D (very slow infiltration, <13 mm/h), while only 14% is type A (fast infiltration >76 mm/h) (Bradbury et al., 2000), which also affects the effective capacity of the selected NBS. The possibility of alteration was evaluated by giving priority to the least permeable soil type (priority alteration of type D, followed by C) and without assessing permeability (Table 5). Depending on the requirement of land use change from forestry to agriculture or vice versa the CN decreases or increases (Singh et al., 2022). In the Umia River Basin case study, the CN increased by about 3% when conversion from forestry to agriculture occurred and conversion occurred regardless of permeability. This value varies greatly between sub-basins, reaching, for example, an increase of 3.3% for sub-basin 3, and a value of 1.2% for sub-basin 1. However, due to the low representativeness of the higher permeability soils (type A) in the Umia River Basin, the changes between methods are hardly noticeable. However, it can be highlighted that the upstream sub-basin 6, has a higher CN value when the less permeable soils are prioritized. Nevertheless, when the change from agriculture to forestry is simulated, the CN decreases further for the permeability-independent method. Therefore, to reduce the flood risk in the basin, measures should be taken to reduce the values of the CN to control runoff, such as reforestation of degraded areas, expansion of forested areas, introduction of silvopastoral systems instead of livestock farming the typical of the region, or priority use of abandoned land. The hydrological impacts of these actions can be easily assessed by monitoring spatial and temporal changes in the CN. When implementing these measures, the development of a strategic approach that takes the CN into account would facilitate decision-making as well as the optimisation of resources by the responsible management organisation. Therefore, analyses such as the one presented in Table 5 optimize the improvement of decision making by the administration. Planning and land management from a strategic point of view is key to reducing both the risk of flooding and other possible phenomena that impact water security and the health of ecosystems (Alonso, 2023). Furthermore, incorporating this information into the regulations that regulate these uses would improve territorial planning.

The hydrographs simulated in HEC-HMS were run for a first event that reached an observed flow of 221.7 m^3/s. This peak flow was reduced for the simulations based on the change from agriculture to forestry and increased for the forestry to agriculture simulations (Appendix A, Table A.4). The percentage reduction depends directly on the peak flow, however the total flow is reduced by about 6.0% when the change is from Agriculture to Forestry (without prioritising the less permeable soils), and by about 3.5% when the less permeable soils are prioritized. On the other hand, this change in peak discharge (m^3/s) also depends on where the land use change is applied, this was reduced by 5.6% (Agr-For T, S3T), 1.2% (Agr-For Up, S1T) and 3.4% (Agr-For M, S2T) for the flood event (Fig. 3). These results are similar to those obtained in Johnen et al. (2020) where it was found that an increase in tree cover (by 15–60%) resulted in a 9–13% reduction in flood peak. In all cases, the reduction in peak discharge was higher in the forest to agriculture conversion simulations, when land use change was applied equally across the different soil permeabilities (Total). However, when it is necessary to apply a forest to agriculture change, this peak discharge will be higher. For example, although the priority use of the less permeable soils (C and D) reduces the increase in this peak, e.g. in increases it by 3.5% in the For-Agr T (S6T) simulation, and by 3.2% in the For-Agr P (S6P) simulation. This information could be incorporated into the corresponding management plans. Currently, the central government has drafted a Recovery, Transformation and Resilience Plan for the management of abandoned land. Government registered >1500 initiatives to apply for these funds in 2021, 62% of the funds applied for were for recultivation of abandoned land, 9% for agriculture, 7% for forestry, and 22% for mixed production. Incorporating information on soil permeability in basins particularly prone to flooding and adapting it to land use needs would provide key information for the correct management of the territory.

Table 5
Curve number (CN) calculated from Forest to Agricultural (For-Agr) and from Agricultural to Forest (Agr-For). From 30% total (T, distributed between permeabilities), and partial (P, prioritising the less permeable soil).

Sub-basin (N°)	1	2	3	4	5	6
Original	74.38	72.58	72.98	73.05	75.32	80.61
For-Agr T0.3	75.82	74.52	75.10	75.49	77.25	81.57
For-Agr P0.3	75.55	74.31	74.91	75.25	77.07	81.60
Agr-For T0.3	70.31	69.18	70.14	71.17	73.15	78.05
Agr-For P0.3	72.27	70.81	71.34	71.79	73.67	78.64

The reduction in peak runoff that occurs in watersheds, due to forest cover, which intercepts, captures and infiltrates rainwater, thereby reducing surface runoff, provides social benefits by reducing the risk of flood events (Brody et al., 2014), increasing the availability of groundwater and its reserves. The increase in forested 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). The Umia River Basin has a reservoir located in sub-basin 4 (Appendix A, Fig. 1A), however, as obtained in this study and coinciding with the Paleo (2010) study, this reservoir hardly mitigates the risk of flooding. Despite the fact that it was conceived by the administration to mitigate the frequent flooding in Caldas de Reis and, in addition, to produce electricity and facilitate the supply of drinking water to the communities in the area. Paleo (2010) points out that this reservoir has a lower capacity to laminate floods downstream, reducing but not eliminating the risk.

With the model obtained for the Umia River Basin, final scenarios for the return periods of 10-, 25-,50- and 100 years were carried out (Table 6). The scenarios that the administration could carry out were investigated. As can be seen, in the hypothetical changes proposed, the maximum simulated discharge hardly decreases, with the exception of scenario 2 (30) where this peak is reduced by 12.8%. However, due to logistical limitations, as well as regulatory limitations, this scenario seems unrealistic. Therefore, Scenario 1, where the maximum discharge is reduced by 2.5% for the 10-year return period, would be a more realistic and promising scenario. Finally, it should be noted that the reduction in the volume of the flood hydrograph shows similar ranges to the maximum discharge values.

3.2. *Flood risk analysis: Voglajna River*

As indicated in the Materials and Methods section the model calibration was performed for five selected events. The percent bias ranged from −0.4% to −11.7% and the Nash-Sutcliffe values ranged from 0.82 to 0.95 for the selected events. Hence, after the calibration process, the calibrated parameters were determined as the mean values of the most suited parameters for specific model runs. Hence, the calibrated parameters were 86.1, 4.3 h and 0.55 for the CN, lag time, and peak coefficient parameters, respectively. These parameters were used to evaluate different scenarios for the 10-, 25, 50- and 100- year return period. The comparison of the results of the simulations with the calibrated parameters with the results of the flood frequency analysis for the Črnolica gauging station shows relatively good agreement between both approaches (simulated values as shown in Table 7 is within the ranges of the confidence intervals). Hence, this means that the set-up model can be considered as suitable for the study of different land use scenarios.

In the next step of the study, 4 scenarios of land use change were investigated, and in all cases the changed land use resulted in changed

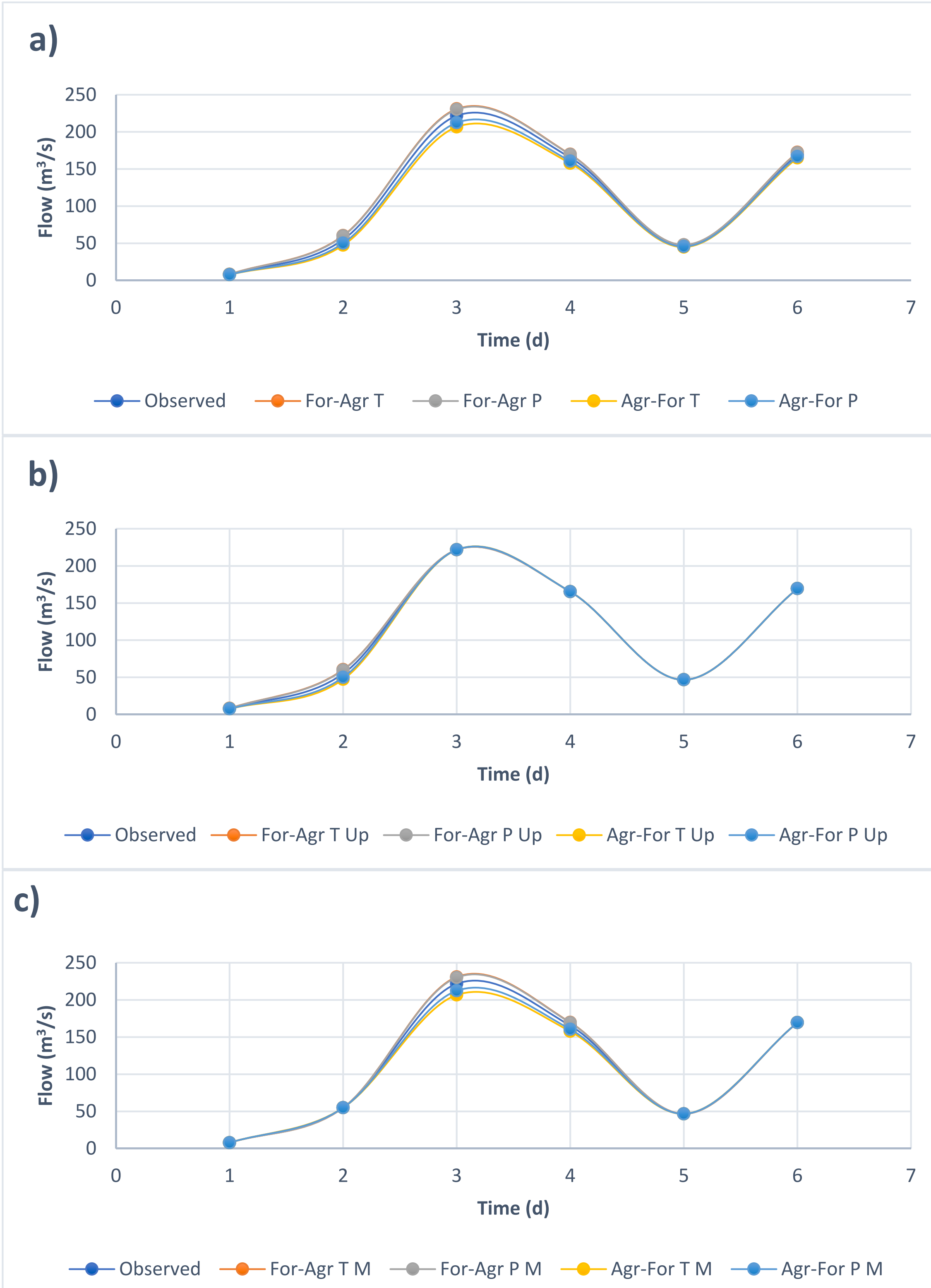

Fig. 3. Hydrographs obtained for a flooding event from the model output considering the different scenarios, a) applying the simulations in the whole catchment, b) changes applied in the upstream catchments, c) changes applied in the catchments located in the middle.

values of the CN parameter. The results are presented in Table 7. It can be seen that the proposed hypothetical land use changes have relatively small impact on the simulated peak discharge values. More specifically, for the 10-year, 25-year, 50-year and 100-year return period event the maximum decrease was obtained for Scenario 4 (between 8% and 6%). However, in this case, 70% of the specific land use would have to be changed, which logistically can be considered a nearly unrealistic scenario. A more realistic option would be Scenario 1, which results in only about a 1% reduction in the peak discharge for all tested return periods (Table 7). Moreover, the reductions in flood hydrograph volume are in a

Table 6
Simulation results for different scenarios of changing specific land use type (SIOSE ID 200) to forest areas with the consideration of the 10-, 25-, 50–100 years return period in the Umia River Basin.

Scenario	Q 10 [m^3/s]	V 10 [1000 m^3]	Q 25 [m^3/s]	V 25 [1000 m^3]	Q 50 [m^3/s]	V 50 [1000 m^3]	Q 100 [m^3/s]	V 100 [1000m^3]
Baseline	47.5	1767.8	58.9	1937.9	68.7	2093.6	86.9	2437.8
Scenario 1 (10%)	46.3	1725.1	55.3	1880.7	65.1	2036.4	76.6	2200.4
Scenario 2 (30%)	41.5	1683.3	51.1	1813.9	62.0	1987.1	74.2	2124.7

Table 7
Simulation results for different scenarios of changing specific land use type (CLC Corine ID 243) to forest areas with the consideration of the 10-, 25-, 50- and 100- year return period in the Voglajna River Basin.

Scenario	Q 10 [m^3/s]	V 10 [1000 m^3]	Q 25 [m^3/s]	V 25 [1000 m^3]	Q 50 [m^3/s]	V 50 [1000 m^3]	Q 100 [m^3/s]	V 100 [1000 m^3]
Baseline	60.4	1976.3	78.8	2583.9	93.4	3066	110.9	3607.2
Scenario 1 (10%)	59.5	1947.1	77.9	2553.6	92.4	3033.4	109.7	3569.8
Scenario 2 (30%)	58.0	1899.1	76.2	2499.3	90.5	2975.2	107.9	3507.9
Scenario 3 (50%)	56.3	1842.6	74.3	2435.6	88.5	2906.6	105.6	3433.5
Scenario 4 (70%)	55.5	1814.9	73.7	2406.6	87.7	2875.4	104.5	3398.1

similar range as the values for peak discharge values (Table 7). Despite small reduction, the results indicate that if afforestation is extended to the upstream tributaries of the Savinja (Glavan et al., 2020), a small but important reduction in peak discharge during flood waves can be expected.

This opens another perspective on upstream afforestation phenomena as a means to reduce flood risk and their potential positive effects. The drivers of afforestation in the Voglajna watershed and other Savinja tributaries are more of a socio-economic nature, as the upstream areas have poor demographic indicators (afforestation results from land abandonment). Valuing these drivers would require a different modelling approach based on land-society interaction (e.g. Verburg et al., 2013) to properly assess ecosystem services and assign benefits to those that provide one or more ecosystem services - in this case, reducing flooding and improving biodiversity of natural habitats.

3.3. General discussion

The intensity of floods, whose increase is imminent due to climate change, should trigger management and control measures to minimize the impact of these hazards. The impact of these more extreme events depends not only on the magnitude of precipitation, but also on the characteristics of the catchment, land use, vegetation cover and other geomorphological features. This study explored various mitigation strategies that will allow the development of a more resilient model and contribute to long-term solutions. This requires an assessment of current policies and the extent to which they will allow adaption to new changes caused by a climate change.

In the Umia River case study, the small size of the plots, as well as the culture and tradition of the region, have reduced the area of riparian vegetation, and replaced it with agricultural use. This is covered by current regulations, which do not require prior authorization for cultivation of land subject to an easement (5 m from the riverbank), but such land must be forested (Ministerio de Obras Públicas y Urbanismo, 1986). In addition, the Galician Forestry Law (Ley 7/2012 et al., 2012), allows, under certain conditions, the change of forest use to agriculture to increase the viability of farms. However, the conversion from agricultural to forest use is allowed only on rural land classified as agricultural use but in a state of abandonment and destined for an agricultural land bank (at least 2 years), and then only after prior communication to the forest management body and when 1) they are adjacent to forest land; and 2) enclaves of up to 5 ha of woodland are formed (Ley 11/2021, 2021,in force until May 2021). In both cases, it is indicated that deciduous broadleaf trees must be used as the reforestation species. The regulations in this case study make it difficult to use reforestation as a NBS. However, this push by the administration to increase agricultural areas, compared to forest areas, would be detrimental to the risk of flooding, as analysed in Tables 5 and 6. The development of the proposed strategies to improve the effectiveness of this NBS in the area, based on the permeable characteristics of the area, and on the area of application (e.g., difference between the effectiveness of reduction of applying NBS in the whole catchment or in the headwater area), would ensure a substantial improvement in flood risk management in the area.

Afforestation as a management measure to reduce flood risk requires a change in perception, as land abandonment and afforestation of fertile areas has been viewed as negative development (e.g., EU, 2004; Katayama et al., 2015; MacDonald et al., 2000) and can have impact on water cycle (e.g. Luan et al., 2022). In Slovenia, for example, afforestation of agricultural land is addressed by a policy (Decree implementing the measure to combat the overgrowing of agricultural land, 2021) that encourages farmers, especially in hilly areas, to preserve agricultural land, although the policy applies nationwide. Although certain land elements are exempted from this measure in order to preserve important small habitat elements (e.g., windbreaks, small groves of trees), government support for preserving agricultural land against afforestation is evident. Establishing dry retention reservoirs is a clear priority (Bezak et al., 2021; Glavan et al., 2020).

In both case studies, the simulation results for the different scenarios of land use change from agriculture to forestry for return periods of 10-, 25-, 50- and 100- year have a minor impact on the simulated peak discharge and hydrograph volume. Therefore, the development of other NBS or hybrid tools (Anderson et al., 2022) adapted to each catchment is needed, such as floodplain restoration, detention basins, retention ponds and river enlargement (Acuña Alonso et al., 2023; Bezak et al., 2021). These measures have proven to be very effective in reducing flood risk in river basins (Mubeen et al., 2021). Understanding the environmental management and policy implementation aspects of flood impacts is key to developing new tools to improve resilience to extreme events caused by climate change. Hence, the simulations conducted within this study provide an evidence base about possible functioning of the NBS in various environmental conditions and somehow confirm the scepticism about NBS effectiveness (Anderson et al., 2022) since relatively big land-use changes should be conducted in order to obtain a notable peak discharge decrease.

The simulations carried out highlight the lack of integration between current land use management and river resource management. In the future, the use of land use change as an indicator in such scenarios could provide information on where certain land changes (from forestry to agriculture or vice versa) should be made according to the needs of the population, without losing sight of the danger posed by such floods. The comparison of such a methodology in two areas in different countries, but both with fragmentation problems, is presented as an innovative research, due to the different casuistry that different regulations make possible. The analysis of these changes in different river basins would provide holistic and integrated information that would favour an adequate environmental management of the basins and could be integrated into the process of water control and management in the study areas. It also highlights the need for the EU to integrate new governance models that spatially integrate land and water use.

3.4. Study limitations

It should be noted that this study has several limitations that should be mentioned to provide a basis for further studies that would further improve the robust knowledge of the effects of land use change on flood risk. First, the modelling and watershed delineation performed with the HEC-HMS software should be considered a simplification of rainfall-runoff processes at the catchment scale; the use of a detailed, fully distributed model could provide more accurate results, but at the same time would require additional field measurements to collect the data. Second, according to theoretical tables found in the literature, the link between land use, soil data and CN parameters could be affected by the spatial resolution of these datasets, which could lead to uncertainties in the model results. Third, model calibration and validation was performed for selected rainfall-runoff events to test model behaviour, but a truly extreme catastrophic flood event could result in different hydrologic dynamics and potentially model could fail in reproducing this behaviour. Finally, the predefined scenarios represent the theoretical changes that could occur in these two watersheds and were not derived based on predicted future land use changes and there are other factors (e.g., effects of air temperature on soil properties) that could change in the future along with land use and that could have an important influence on flood risk in the studied watersheds.

4. Conclusions

Climate change has increased the risk of flooding, putting pressure on governments to invest in measures to mitigate its effect. Developing these measures is a challenge for administrations around the world. Reliable, unambiguous environmental indicators are needed to gain the political support necessary to implement new, area-specific measures and to ensure water supply security and optimal watershed management. In this study, two river basins were analysed: the Umia River Basin (Spain), and the Voglajna River Basin (Slovenia). In the Umia River catchment, reforestation upstream reduces the peak discharge by about 6%. However, current policies promote agricultural use over forestry, and it has been concluded that its use upstream and in the least permeable soils is the one that least increases the peak discharge. In the Voglajna River, various land use change scenarios result in only a small percentage decrease in peak discharge and hydrograph volume. Therefore, it is clear that land use change is an important indicator that emphasizes that measures (NBS, hard-engineering or hybrid) need to be applied to manage flood risk in the future. In both cases, for simulated events with a return period of 100- year, the tested NBS are not sufficient. Thus, scepticism about NBS effectiveness is somehow confirmed. Measures need to be developed to adapt and mitigate the impacts of the effects of extreme events, through new policies and coordinated multi-sectoral strategies. The use of these new tools will be critical in water management to mitigate the impacts of climate change on people and ecosystems. Furthermore, it is necessary to highlight that incorporating the methodology analysed in the different management plans, as well as in the regulations, is key to guarantee the reduction of the impact of this phenomenon.

CRediT authorship contribution statement

Carolina Acuña-Alonso: Conceptualization, Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Methodology. **Xana Álvarez:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft. **Nejc Bezak:** Conceptualization, Software, Writing – original draft, Writing – review & editing, Formal analysis, Investigation. **Vesna Zupanc:** Conceptualization, Formal analysis, Investigation, Software, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2024.107185.

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