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Analysing Coastal Flood Risk: Assessing the Impact on Critical Water Infrastructures

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Abstract
There is a need to enhance the resilience of critical infrastructures. The effects of climate change have already led to increased flooding of critical water infrastructure. Furthermore, predictions indicate that more infrastructures will be affected in the future. Currently, methods for accurately quantifying the economic losses resulting from sea level rise and extreme weather events are lacking. This article proposes a risk assessment methodology for coastal flooding in the Galicia region of Spain. The method estimates the losses incurred by water infrastructure and indirect industry losses due to the interruption of water infrastructure services. The results indicate that losses currently exceed 90 million euros due to extreme weather events. In the most pessimistic scenario, these losses increase to 127 million euros in 2050 and 451 million euros in 2100. In both cases, indirect industry losses account for more than 80% of the total losses.

Keywords Critical water tnfrastructures · Climate change · Economic losses due to flooding · Risk assessment

1 Introduction

One of the most relevant problems that policy-makers will have to manage in the coming decades is the increase in the frequency and intensity of extreme weather events (EWEs) and sea level rise (SLR) due to the effects of climate change (IPCC 2022). As a consequence of such events, floods are considered the cause of most of the losses caused by natural disasters in recent decades (Navarro-Hernandez et al. 2023; Peng et al. 2024). Furthermore, the

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climate models used by the Intergovernmental Panel on Climate Change (IPCC) suggest that the severity of these floods will increase in the future. Thus, it is projected that if the global warning level rises by 1.5° by the end of the 21st century, the global mean SLR will be 0.15 m compared to the 2020 level. This SLR could reach 2.4 m in the most pessimistic scenario (IPCC 2022). This problem is worsened because coastal areas have high concentrations of water infrastructure (Qiang 2019) and are often located in low-lying areas or in rivers close to the sea (Allen et al. 2019).

All these circumstances make it necessary, without further delay, to manage the risk of water infrastructures for several reasons. First, the impact on these infrastructures entails catastrophic damage and high economic costs (IPCC 2019202320232023). Second, water supply and sanitation are vital because they affect the health and well-being of people and are also essential for the proper functioning of the economy (Navarro-Hernández et al. 2023). Finally, water infrastructures are interconnected with other critical infrastructures, which increases their vulnerability (Mikellidou et al. 2018). Thus, the failure of water infrastructures will cause cascading disruptions in other infrastructures (e.g., electricity, transport, health or industry), even if the latter are not affected by floods (Arrighi et al. 2021).

Against this backdrop, there is a need for risk assessment methods. However, most risk assessment methods are qualitative (Allen et al. 2019). Regarding quantitative methods, few studies have assessed economic losses, both direct losses to water infrastructures and indirect losses to other infrastructures (Arrighi et al. 2021). For example, direct losses due to the repair, replacement or rehabilitation of pipes, water pumping systems and wastewater treatment plants have been quantified (Martínez et al. 2018). Indirect losses to citizens due to the lack of drinking water services have been quantified (Tarani et al. 2019). To the best of our knowledge, indirect industry losses have not been quantified.

Thus, we propose a method that quantifies the economic losses caused by flooding in water infrastructures and the economic losses to industries due to the interruption of water infrastructure services. This method makes several contributions. First, we analyse the risk in 10 hazard scenarios, including an optimistic and a pessimistic scenario. In these scenarios, we analyse their degree of exposure and vulnerability. Second, we assess risk in monetary terms, taking into account intergenerational solidarity by updating values through the social discount rate (Nesticó and Maselli 2020). Third, we reflect on the economic consequences of not taking action to reduce greenhouse gas emissions (Becher et al. 2023).

2 Study Area

The study area is Galicia, a region of Spain heavily affected by coastal flood risk (Fig. 1). This area is suitable for several reasons.

Galicia has 1,498 km of coastline along the Atlantic Ocean and the Cantabrian Sea (IGN 2022).

Furthermore, the region is located in the North Atlantic storm track, which produces extreme precipitation and anomalous winds in the region (Eiras-Barca et al. 2018). In addition, projections indicate an increase in frequency and intensity (Des et al. 2021).

Finally, during the period 1948–2019, the sea level rose along the Galician coast by approximately 2.29 mm per year (Vargas-Yáñez et al. 2023). Predictions forecast that it will continue to rise given its location on the west coast of Europe.

Fig. 1 Geographical location of the study area

3 Data and Methods

The method of economically estimating flood losses to water infrastructures and their effect on industries comprises 2 parts: risk analysis and risk assessment. Figure 2 shows the methodology used.

3.1 Risk Analysis

3.1.1 Hazard

Risk analysis requires determining different hazard scenarios to estimate the occurrence of floods caused by EWEs, SLR or a combination of the two (Alabbad et al. 2021). We use two scenarios defined by the IPCC (2014): representative concentration pathways (RCPs) 4.5 and 8.5. These scenarios are recommended by the European Union in Flood Risk Assessment and Management Directive 2007/60/EC (EU 2007) and have been widely used (Becher et al. 2023).

Having finalised the scenarios, we define the return periods of EWEs. For this purpose, we choose two return periods: 100 and 500 years (Arrighi et al. 2021).

With these RCPs and return periods, we establish 10 hazard scenarios. For each of these scenarios, we estimate the areas affected by floods (flood map) (Pant et al. 2018).

3.1.2 Exposure

Exposure makes it possible to analyse the presence of water infrastructures and industries in areas affected by floods (IPCC 2023).

First, we determine the infrastructures analysed: (1) water supply infrastructures, which include drinking water treatment plants, water tanks, water harvesting systems and water

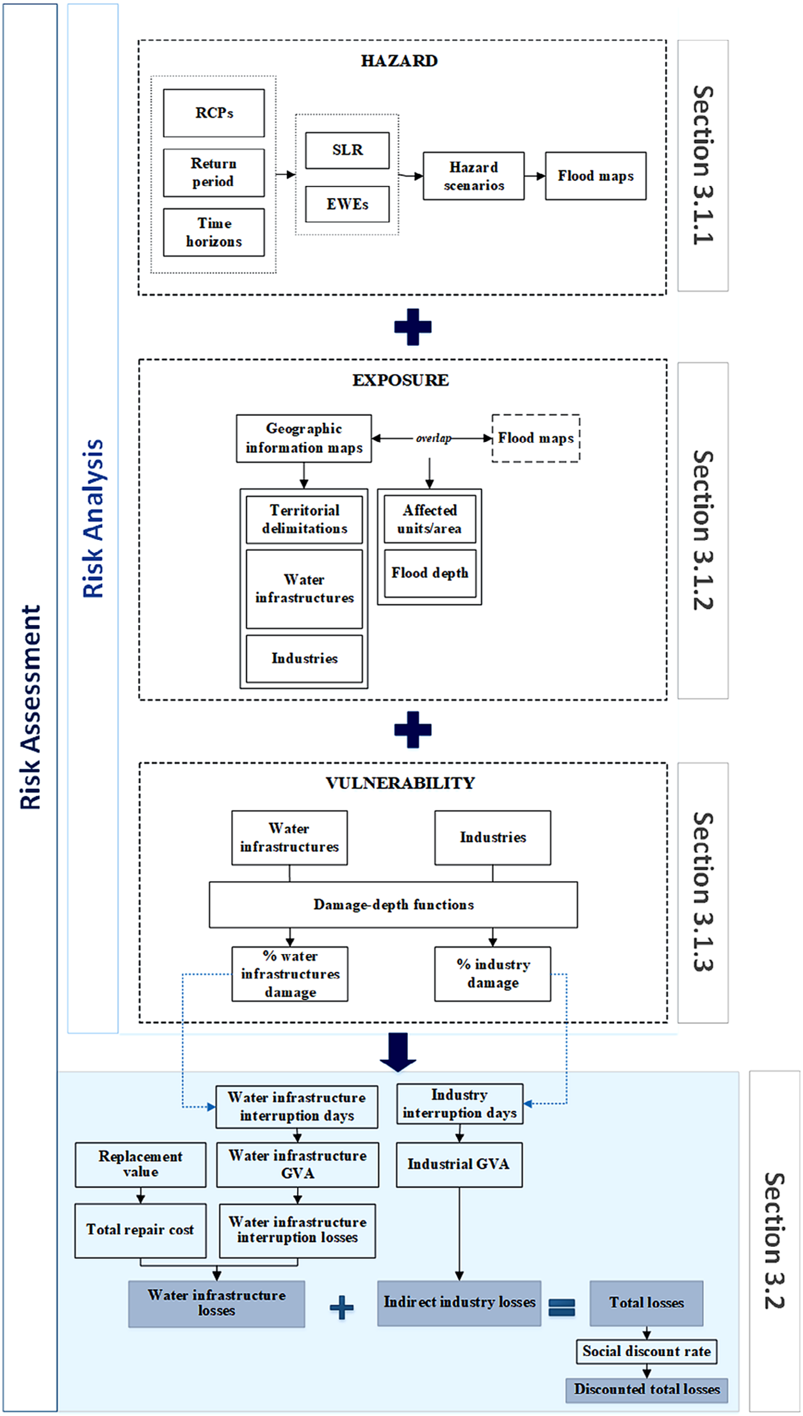

Fig. 2 Flowchart of the methodology used

distribution pipes (Qiang 2019); (2) sanitation infrastructures, which include wastewater treatment plants (Nofal and van de Lindt 2020); and (3) industries that will be affected by the disruption of water infrastructures (Karagiannis et al. 2019).

Then, in collaboration with the Instituto de Estudios del Territorio de Galicia, we determine the location of these infrastructures. Between April 2021 and July 2022, geographic information maps were collected. These maps collect the following information: (1) the territorial delimitation of the 82 coastal municipalities of Galicia; (2) the location and area of 93 wastewater treatment plants, 33 drinking water treatment plants, 581 water tanks and 700 water distribution systems, including 153 water pumping systems; (3) the longitudinal disposition of the 4,825.02 km that make up the water distribution pipes; and (4) the industrial area of 5,575.09 hectares, which accounts for 563 industries.

Finally, the flood maps overlap with the geographic information maps in the different hazard scenarios. As a result, we obtain the flood units and areas and the flood depth for each hazard scenario and for each municipality. For example, Fig. 3 shows how this overlap occurs for a wastewater treatment plant. The map on the left shows the location of the plant delimited by a blue line (geographic information map). The middle map shows the flooded part of the land in light blue (flood map). Finally, the map on the right shows the part of the wastewater treatment plant affected by the flood with a red line.

3.1.3 Vulnerability

The vulnerability of an infrastructure is its propensity to be negatively affected by floods (Roukounis and Tsihrintzis 2022). To estimate vulnerability, we apply damage-depth functions, which relate flood depth to the expected percentage of damage to water infrastructures and industries (Nofal and van de Lindt 2020). We use those developed by the Department of Homeland Security and the Federal Emergency Management Agency through the Hazus program (FEMA 2020).

Regarding water infrastructures, Fig. 4 graphically represents the damage-depth functions for drinking water treatment plants, wastewater treatment plants and water pumping systems. In the case of water tanks, the damage percentages are equal to 0 regardless of the flood depth reached. The reason is that they are all above ground level. Finally, in the case of water distribution pipes, the damage percentages are also equal to 0, regardless of the flood depth.

For industries, we use the damage-depth function shown in Fig. 4.

Fig. 3 Example of overlap

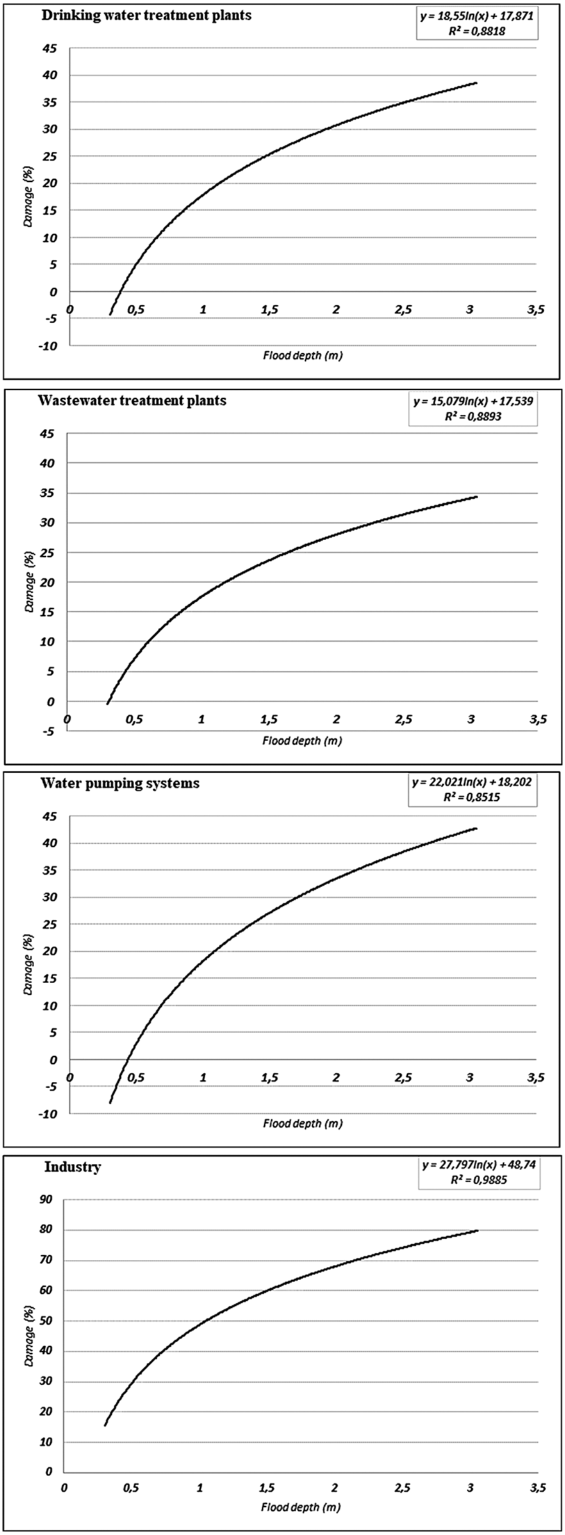

Fig. 4 Representation of damage-depth functions

3.2 Risk Assessment

3.2.1 Water Infrastructure Losses

This type of loss refers to the economic consequences for water infrastructures directly caused by flooding. These losses are calculated by summing the total repair cost and the economic losses generated by the interruption of water infrastructure services. The formula is as follows:

$$WIL = TRC + WIIL \tag{1}$$

where:

WIL = Water infrastructure losses.

TRC = Total repair cost.

WIIL = Water infrastructure interruption losses.

First, we estimate the cost of floods to water infrastructures. To do so, we use the total repair cost incurred to recover their normal operation (Martínez et al. 2018). This cost is calculated based on two parameters: the replacement value of the affected infrastructure and the depth-damage function (Karagiannis et al. 2019).

The replacement value is estimated in the case of supply infrastructures (drinking water treatment plants, water tanks, water harvesting systems and water distribution pipes) through the values budgeted for new public works (Augas de Galicia 2023). In the case of sanitation infrastructures (wastewater treatment plants), this cost is estimated by assigning a cost based on the equivalent inhabitants that these infrastructures serve (Pinheiro et al. 2018). Finally, both values are validated through consultation with experts. These values are detailed in Supplementary annex.

$$TRC = \sum_{i=1}^{n} f_{(x_i)RV_i} \tag{2}$$

where:

$i: 1,2,\ldots,n:$ Water infrastructure belonging to each category

$RV_i:$ Replacement value of each water infrastructure

$f(x_i):$ Depth-damage function of the water infrastructure category

$x_i:$ Flood depth at each facility i

Second, water infrastructure interruption losses are calculated by relating the gross value added (GVA) of water infrastructures to the days of interruption of their activity (Toimil et al. 2017). The latter are calculated based on the damage percentage and business-as-usual recovery data used in the risk models (Becher et al. 2023) (Table 1).

With the data obtained, we calculate the water infrastructure interruption losses according to the following formula:

$$WIIL = \frac{GVA_{WI_i}}{365} \times t_{intWII_i} \tag{3}$$

Table 1 Example of days of interruption

Damage percentage	Estimated days of interruption of water infrastructure services	Estimated days of industry disruption
1.7	1	2
40.2	10	5
54.8	14	10
>64.2	17	15

where:

GVA_{WI_i}: GVA generated by the water infrastructures of municipality *i*.

t_{intWII_i}: Estimated days of interruption of water infrastructures in municipality i

3.2.2 Indirect Industry Losses

These losses refer to the economic consequences for industries of the interruption of water infrastructure services. They are calculated by relating the GVA generated by the industry to the days that the industry sees its activity interrupted due to the lack of water supply and/or treatment.

These days are calculated as the difference between the days of service interruption of water infrastructures and the days of interruption of the industry due to flooding (Table 1). In the case of industries, these days are calculated from the damage percentage function proposed by Nirwansyah and Braun (2021).

The formula is as follows:

$$IIL = \frac{GVA_{ind_i} \times TIIInt_i}{365} \tag{4}$$

where:

IIL : indirect industry losses

GVA_{ind_i}: GVA generated by industries in municipality *i*.

$TIIInt_i$: days of indirect disruption of industries in municipality *i*.

They are calculated as the sum of water infrastructure losses and indirect industry losses according to the following formula:

$$TotalLosses = WIL + IIL \tag{5}$$

Finally, these total losses are updated to compare the estimates made in the base year (2018) with those for the medium term (year 2050) and the long term (year 2100) (Du et al. 2020). To do so, we use the social discount rate, which allows us to evaluate investments through the maximisation of the social welfare function (Hurst 2019). We apply a social discount rate of 2% for 2050 and 1% for the 2100 horizon (Toimil et al. 2017).

Table 2 SLRs in the different hazard scenarios

Hazard scenarios	Time horizon	CPR	Return period	SLR
S1	Present	-	100	-
S2	Present	-	500	-
S3	2050	4.5	100	0.23 m
S4	2050	4.5	500	0.23 m
S5	2050	8.5	100	0.26 m
S6	2050	8.5	500	0.26 m
S7	2100	4.5	100	0.51 m
S8	2100	4.5	500	0.51 m
S9	2100	8.5	100	0.69 m
S10	2100	8.5	500	0.69 m

Fig. 5 Example flood scenario

4 Results

4.1 Risk Analysis

The SLR data for the 10 hazard scenarios were estimated based on the global mean sea level increase values provided by the IPCC, adapted to Galicia. As a result, we obtain increases in SLR of 0.23 m (RCP 4.5) and 0.26 m (RCP 8.5) for 2050 and 0.51 m (RCP 4.5) and 0.69 m (RCP 8.5) for 2100 (Table 2).

Next, we obtain flood maps in vector format. These maps are developed from a digital terrain model created based on data extracted from a LiDAR flight of the coast of Galicia. For example, Fig. 5 shows, on the map on the left, a flood scenario vectorised and merged into a single entity and, on the map on the right, a detailed view of a flood zone.

Regarding exposure, we estimate that in all the scenarios, wastewater treatment plants and industries are affected by flood depths greater than 2 m. Moreover, the percentage of area affected by this flood depth increases as the scenarios become more pessimistic. Thus, for example, this type of infrastructure has a potential impact ranging from 0.04% in the present (S1) to 0.44% in 2100 (S10).

Water pumping systems are the next most affected infrastructures. We estimate that some are affected by flood depths of between 1.5 and 2 m in the two most pessimistic scenarios in 2100 (S9 and S10). However, the flood depths of affected water tanks do not exceed 1 m in any scenario, and the flood depths of drinking water treatment plants exceed 0.5 m only in the two most pessimistic scenarios in 2100 (S9 and S10).

Finally, regarding vulnerability, we find that the most potentially damaged water infrastructures are wastewater treatment plants (Table 3). Thus, in the present, 19.4% of these plants are potentially damaged (S1 and S2), and in 2100, 31.2% of them are potentially damaged in the most pessimistic scenario (S10).

In contrast, less than 3.3% of the remaining infrastructures would be damaged in all hazard scenarios. For example, the next most damaged infrastructures are water pumping systems, among which at present only 1.3% are damaged (S1 and S2). By 2100, this figure reaches 3.3% in the most pessimistic scenarios (S9 and S10). This type of infrastructure is followed by water distribution pipes, which almost double to 1.5% in 2100 (S10). In the case of drinking water treatment plants and water tanks, neither are affected at present (S1 and S2), but the percentages reach 3% and 0.7%, respectively, in 2100 (S9 and S10).

Finally, more than 12% of industries are potentially damaged in the current scenarios (S1 and S2). This percentage rises to 16.7% and 18.7% in the most pessimistic scenarios in 2050 (S4 and S6). In addition, almost a quarter of the industries, 23.6%, will be damaged in 2100 in the most pessimistic scenario (S10).

4.2 Risk Assessment

4.2.1 Water Infrastructure Losses

The discounted water infrastructure losses amount to 7.7 million euros in scenario S1 and 8.4 million euros in scenario S2 (Table 4). In the most optimistic scenarios, the water infrastructure losses are 13.4 and 75.2 million euros in 2050 and 2100, respectively (S3 and S7). Water infrastructure losses amount to 89.8 million euros in the most pessimistic 2100 scenario (S10).

In detail, the total repair cost also increases as the scenarios become more pessimistic. Thus, in the most optimistic scenarios, the cost is 8.2 and 36.9 million euros in 2050 and 2100 (S3 and S7), respectively, but in the most pessimistic scenarios, it exceeds 10.5 and 50.1 million euros in 2050 and 2100 (S6 and S10), respectively. Furthermore, the total repair cost increases by up to 858% in scenario S10 compared to scenario S1.

The same holds true for interruption losses. These losses increase from 2.5 million euros today to approximately 5.5 million euros in 2050 and to approximately 39 million euros in

Table 3 Percentage of water infrastructures and industries potentially affected

Time horizon	Present	Present	2050	2050	2050	2050	2100	2100	2100	2100
CPR	-	-	4.5	4.5	8.5	8.5	4.5	4.5	8.5	8.5
SLR	-	-	0.23	0.23	0.26	0.26	0.51	0.51	0.69	0.69
Return period	100	500	100	500	100	500	100	500	100	500
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Drinking water treatment plants	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.0
Wastewater treatment plants	19.4	19.4	19.4	20.4	20.4	25.8	26.9	26.9	30.1	31.2
Water pumping systems	1.3	1.3	1.3	1.3	1.3	2.0	2.6	2.6	3.3	3.3
Water tanks	0.0	0.0	0.0	0.3	0.3	0.5	0.5	0.5	0.7	0.7
Water distribution pipes	0.8	0.9	1.0	1.0	1.0	1.1	1.2	1.2	1.4	1.5
Industries	12.3	12.4	14.2	16.7	16.7	18.7	21.1	21.7	23.1	23.6

Table 4 Economic losses discounted (in millions of euros)

Time horizon	Present	Present	2050	2050	2050	2050	2100	2100	2100	2100
CPR	-	-	4.5	4.5	8.5	8.5	4.5	4.5	8.5	8.5
SLR	-	-	0.23	0.23	0.26	0.26	0.51	0.51	0.69	0.69
Return period	100	500	100	500	100	500	100	500	100	500
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Total repair cost	5.2	5.9	8.2	9.3	9.3	10.5	36.9	40.9	47.2	50.1
Interruption losses	2.5	2.5	5.2	5.3	5.3	5.6	38.3	38.3	39.0	39.7
Water infrastructure losses	**7.7**	**8.4**	**13.3**	**14.5**	**14.6**	**16.0**	**75.2**	**79.2**	**86.1**	**89.8**
Indirect industry losses	82.7	82.8	106.3	106.6	106.9	111.0	356.4	354.2	355.6	361.2
Total losses	**90.4**	**91.2**	**119.7**	**121.1**	**121.5**	**127.0**	**431.6**	**433.4**	**441.8**	**451.0**

Table 5 Days of interruption of water infrastructures and industries

Time horizon	Present	Present	2050	2050	2050	2050	2100	2100	2100	2100
CPR	-	-	4.5	4.5	8.5	8.5	4.5	4.5	8.5	8.5
SLR	-	-	0.23	0.23	0.26	0.26	0.51	0.51	0.69	0.69
Return period	100	500	100	500	100	500	100	500	100	500
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Water infrastructure interruption days (mean)	6.3	6.7	8.5	8.7	8.8	8.9	10.0	10.1	11.2	12.8
St. dev.	9.3	9.2	10.2	10.0	9.9	9.9	10.1	10.0	10.0	10.3
Indirect interruption days of industries (mean)	6.2	6.5	8.3	8.5	8.6	8.6	9.7	9.7	10.7	12.3
St. dev.	9.2	9.0	10.0	9.8	9.8	9.7	9.8	9.7	9.7	10.1

2100. This represents an increase of 1560% from the present to 2100. The average number of days of interruption is 6.3 in the present, rising to 12.8 in scenario S10 (Table 5).

4.2.2 Indirect Industry Losses

The discounted indirect industry losses range from 82.7 million euros in the present (S1) to 361.2 million euros in 2100 in the most pessimistic scenario (S10). The latter value is four times greater than that of water infrastructure losses (Table 4). To calculate indirect industry losses, we use the industry days of interruption from Table 1. These average 6.2 days in the present (S1), rising to 12.3 days in scenario S10.

4.3 Total Losses

The total discounted losses are 90.4 million euros in the most optimistic present scenario (S1). In the most pessimistic 2100 scenario (S10), these losses are 451 million euros. In both cases, more than 80% of the losses are indirect industry losses (Table 4). Furthermore, this methodology makes it possible to disaggregate discounted total losses at the municipality level. Figure 6 shows the results for all scenarios.

According to the results obtained, the maps show that at present, there are losses in southern municipalities due to the occurrence of EWEs for both scenarios S1 and S2. In addition, 3 municipalities out of the 82 analysed represent 85.3% of the total losses in the

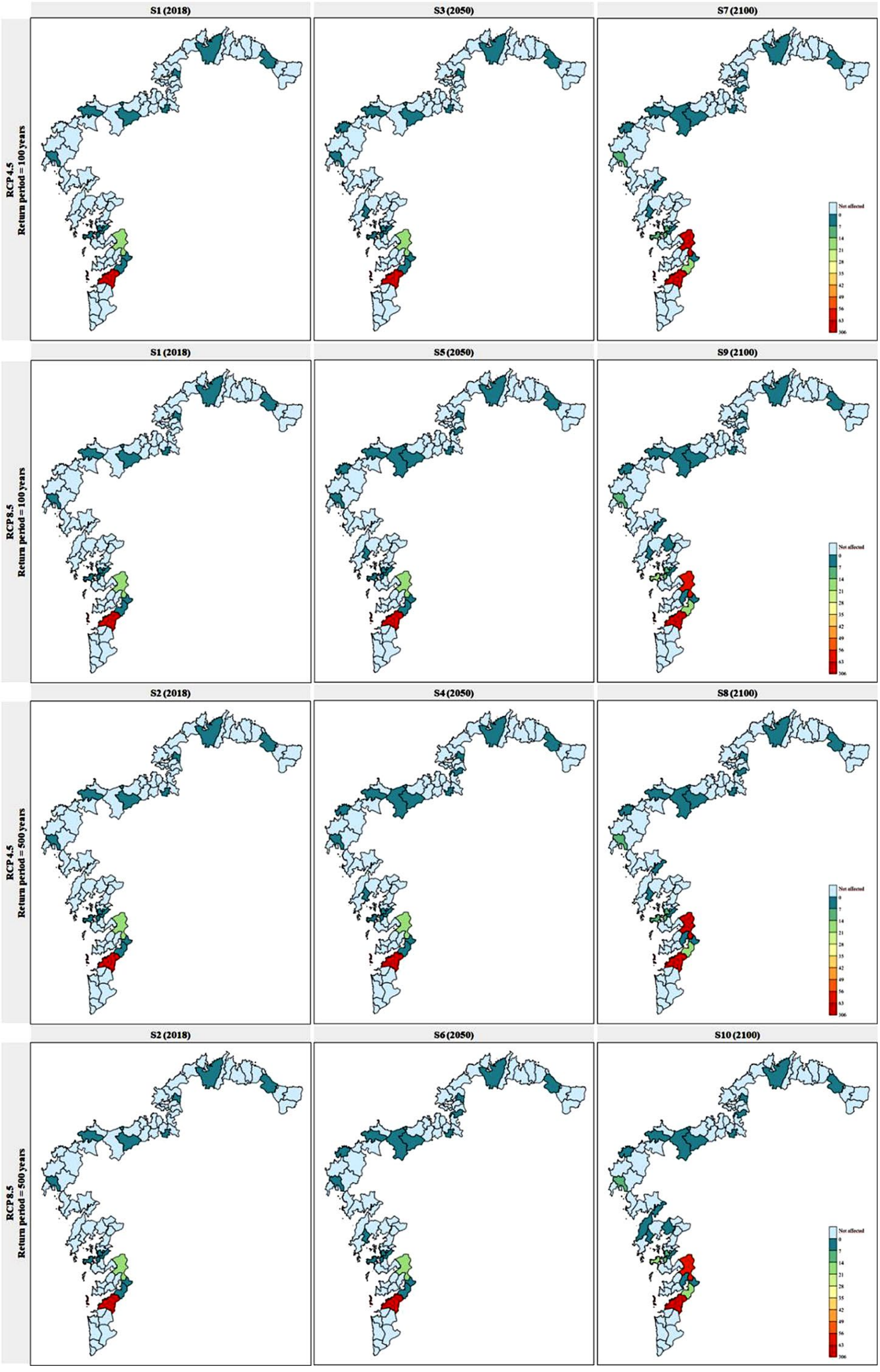

Fig. 6 Discounted total losses by municipality

region in scenario S1. The losses in these 3 municipalities reach 305.2, 62.8 and 16.8 million euros in 2100 in the most pessimistic scenario (S10).

5 Discussion

Our study shows that the total losses at present may be more than 90 million euros. The reason is that if an EWE occurs, almost 1 out of 5 wastewater treatment plants are affected, as is 1 out of 8 industries (Table 3). These results are similar to those obtained by other studies. Thus, Arrighi et al. (2021) estimated that all water distribution pipes in all municipalities of Florence are affected. Qiang (2019) also estimated that 27.1% of water facilities in the United States are affected. Nevertheless, drinking water treatment plants and water tanks are not affected because they are located at higher elevations.

However, the problem does not stop at the present. The predictions are grim (Razmi et al. 2022; IPCC 2023). In our case, by 2100, almost one-third of wastewater treatment plants and one-quarter of all industries will be disrupted by EWEs and SLR (Table 3). This will lead to economic losses of more than 430 million euros in any of the scenarios (Table 4). Thus, for example, in the most optimistic scenario (S7), these losses will amount to 431.6 million euros. Of this amount, 356.4 million euros are losses to industries due to the interruption of water-related services.

For these reasons, it is important to have works, such as the present study, that propose a quantification methodology that is as complete as possible. Thus, most previous studies estimated water infrastructure losses (Arrighi et al. 2017; Martínez et al. 2018). Although there are other works that analyse the effects of the disruption of water infrastructures, only their effects on the population are considered. For example, Becher et al. (2023) estimated that an EWE would affect 5% of Jamaica's water infrastructures, with an average of 5 days of outage. This would result in an impact of 40 million customer disruption days. However, to the best of our knowledge, there is no work that considers the effects on industries. In this regard, our work makes its greatest contribution.

Furthermore, at the micro level, this methodology makes it possible to disaggregate the results to the municipal level. This possibility facilitates identifying those areas that will be most affected and where action is needed (Peng et al. 2024). In our work, we see that currently, 1 of the 82 municipalities is already heavily affected by flooding. As of today, if an EWE were to occur, the losses would be 65.8 million euros in scenario S1 and 66.2 million euros in scenario S2. In this municipality, there is an urgent need to take protective measures, without further delay, involving natural or artificial barriers, such as coastal dikes, dams or retaining walls (Yereseme et al. 2022). In addition, in 2100, the economic losses in this municipality are predicted to reach 305.2 million euros (S10).

Finally, this methodology can be extrapolated not only to other critical infrastructures (ports, telecommunications, etc.) but also to other sectors, both in the economic sphere (agriculture, transport, tourism, etc.) and in the social sphere (health, emergency services, etc.). The versatility of this method also allows it to be applied to other natural hazards, such as droughts and earthquakes.

6 Conclusions

In this study, we propose and test a methodology to assess the risk of water infrastructures and industries from coastal flooding. To the best of our knowledge, this quantification for industries has not been included in previous methodologies.

The application of this methodology reveals that EWEs in Galicia can cause economic losses. Our estimates suggest that these losses will amount to €119 million in 2050 and over €431 million in 2100 under optimal conditions. These results are because our projections indicate possible increases in SLR by 0.23 m in 2050 and 0.51 m in 2100. With these results, policy-makers can make decisions on the design of both mitigation and adaptation policies to address the challenges of climate change in coastal infrastructures.

In terms of limitations, given that the methodology has been tested through a case study, further empirical studies are needed to confirm its validity.

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Author Contributions All authors contributed to the study's conception and design. E. C. performed conceptualization, formal analysis, methodology and results. A. G.-P. performed conceptualization, writing, review and editing, supervision phases. G. C. performed conceptualization, writing, review and editing, supervision phases. F. L.-M. performed conceptualization, formal analysis, methodology and results. All authors have read and approved the final manuscript.

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Data Availability Data are available on request due to privacy or other restrictions.

Declarations

Ethical Approval Compliance with ethical standards.

Consent to Participate All authors give their permission.

Consent to Publish The authors consent with the publication of the manuscript.

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

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