Are we preventing flood damage eco-efficiently? An integrated method applied to post-disaster emergency actions

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ABSTRACT

Flood damage results in economic and environmental losses in the society, but flood prevention also entails an initial investment in infrastructure. This study presents an integrated eco-efficiency approach for assessing flood prevention and avoided damage. We focused on ephemeral streams in the Maresme region (Catalonia, Spain), which is an urbanized area affected by damaging torrential events. Our goal was to determine the feasibility of post-disaster emergency actions implemented after a major event through an integrated hydrologic, environmental and economic approach. Life cycle assessment (LCA) and costing (LCC) were used to determine the eco-efficiency of these actions, and their net impact and payback were calculated by integrating avoided flood damage. Results showed that the actions effectively reduced damage generation when compared to the water flows and rainfall intensities registered. The eco-efficiency of the emergency actions resulted in 1.2 kg CO_2eq. per invested euro. When integrating the avoided damage into the initial investment, negative net impacts were obtained (e.g., -5.2E+05 € and -2.9E+04 kg CO_2 eq. per event), which suggests that these interventions contributed with environmental and economic benefits to the society. The economic investment was recovered in two years, whereas the design could be improved to reduce their environmental footprint, which is recovered in 25 years. Our method and results highlight the effects of integrating the environmental and economic consequences of decisions at an urban scale and might help the administration and insurance companies in the design of prevention plans and climate change adaptation.

KEYWORDS: risk management, life cycle assessment, life cycle costing, damage prevention, climate change

1. INTRODUCTION

Climate change and the increase in urban population pose a problem to flood risk management. By 2050 cities are expected to host 70% of the world's population (UN, 2012), resulting in more urban infrastructure and altering soil infiltration and natural watercourses. Floods are responsible for 34% of the global natural disasters (Guha-Sapir et al., 2009), and their management is especially complex in urban areas. The Spanish Mediterranean coast is an example. In this region, ephemeral streams are common hydrologic features that are typically dry except during torrential rainfall events that result in flooding. Some of the factors that increase the occurrence of these events are land use change, vegetation and soil removal and the construction of drainage networks. Therefore, prevention and mitigation strategies are essential for managing floods and reducing urban and natural damage (Barbosa et al., 2012). In the case of Spanish ephemeral streams, some engineering solutions include channeling or undergrounding the stream or regular maintenance activities. Still, flood damage amounts to 3E+09 USD/year worldwide (around 2.6E+09 euros - €)(Guha-Sapir et al., 2009). In Spain, the average insurance compensations for flood damage (e.g., lost properties, vehicles, etc.) reached 150 million euros/year from 1990 to 2014 (Insurance Compensation Consortium, 2015).

In the framework of sustainability, the consequences of flooding result in environmental and economic impacts at two different scales. On the one hand, damaged goods such as buildings or personal properties must be replaced or re-constructed, which requires materials, energy and money. On the other hand, prevention and mitigation strategies are often associated with investing physical and monetary resources for designing and constructing infrastructure. At this point, it is interesting to determine the environmental and economic balance of prevention and mitigation strategies with respect to the damage that they might prevent.

Existing articles proposed methods for integrating flood risk, prevention and damage. Most of the analyses simulated the hydrologic performance of different scenarios based on climate change predictions, control policies or alternative management systems and provided socio-economic results (Brouwer and van Ek, 2004; Haynes et al., 2008; Jonkman et al., 2008; Kubal et al., 2009; Zhou et al., 2012). These might include physical (e.g., building damage) and/or intangible costs (e.g., traffic delays or impacts on health). Cost-benefit analysis was usually the method applied to determine the economic feasibility of management alternatives (Jonkman et al., 2008; Zhou et al., 2012). The integration of environmental or ecological damage is more complex, but some studies attempted to include this dimension by estimating the potential damage to groundwater or biodiversity, for example (Brouwer and van Ek, 2004; Kubal et al., 2009). However, we still need to clearly define the environmental and economic impacts of flood prevention strategies in terms of investment and damage generation. In this context, post-disaster emergency actions are a field to explore, as the urgent need for urban restoration might lead to the application of economically and environmentally inefficient strategies.

To determine the environmental and economic investment in infrastructure, life cycle assessment (LCA) and life cycle costing (LCC) are commonly applied. Several studies on best management practices dealt with innovative systems, such as green roofs and retention systems (see for instance Flynn and Traver, 2013; Kosareo and Ries, 2007; Petit-Boix et al., 2015), but rehabilitation or post-disaster restoration strategies were not assessed, and neither were flood damage costs. However, this analysis is essential to provide an estimation of the eco-efficiency of the strategies, which is a measure of the environmental performance of a system in relation to its value (ISO 14045:2012) that helps to determine its feasibility through a bi-dimensional approach. When dealing with post-disaster emergency actions, this assessment should help reduce the economic investment while generating fewer environmental impacts. To our knowledge, the eco-efficiency approach was not applied to flood studies in the past.

This paper seeks to integrate post-disaster emergency actions and flood damage generation in hydrologic, environmental and economic terms with the aim of eco-efficiently planning prevention strategies in the future. We try to answer the following question: Are post-disaster emergency actions feasible when compared to the economic and environmental damage generated by floods? Our goal was to provide a method for estimating the environmental and economic balance and payback period of flood prevention from an eco-efficiency standpoint. This approach might facilitate and foster eco-innovation in the field of disaster management. We tested this method in the coast of Catalonia (Spain), where the combination of torrential rainfall and urbanized ephemeral streams poses a significant risk. This analysis was based on historical data and specific torrential events, as previous hydrologic analyses identified the need to focus on particular damaging events and their associated consequences instead of providing general inaccurate statistics (Olcina and Rico, 2000).

2. METHODS

Figure 1 illustrates the method applied for estimating the environmental and economic balance and payback period of implementing post-disaster emergency actions. The application of the method is detailed in the following sections.

<Figure 1>

2.1 Case study

The ephemeral streams under analysis are located in the Maresme region (Barcelona) (**Table 1)**. The streams are called Vilassar, Cabrils and Cintet – hereinafter, streams A, B and C, respectively. Stream A rises from the city of Vilassar de Dalt, and streams B and C, from the city of Cabrils. All of them flow into the city of Vilassar de Mar and, finally, into the Mediterranean Sea. These streams are composed of granitic bedrock with a depth of fifteen meters, covered by an intermediate substrate of altered granites and sublevels of quaternary alluvial sands coming from the stream itself. The areas affected by streams A, B and C are 557, 569 and 445 hectares, respectively (Junta d'Aigües, 1992).

Since the early 90s, these cities have experienced an intense urban growth (see **Supporting Information 1**) and the population has doubled. In 2015, Vilassar de Dalt, Vilassar de Mar and Cabrils had a population of 8,964, 20,447 and 7,250, respectively (Idescat, 2016). Some consequences that resulted from this process include land use changes, construction of low-density neighborhoods, and a shift from agriculture to intensive greenhouse production and industries. As a result, between 1986 and 1996 the surface water flow increased by 4.5% and 54% in streams B and C, respectively (Lleonart and Tarruella, 2010).

In the last 20 years, flood prevention plans became more relevant, especially since the great torrential event that took place in September 1996, which resulted in almost 3 million euros of damage compensations and casualties (Insurance Compensation Consortium, 2015). In November/December 1996 a set of post-disaster emergency actions were implemented to improve the channels and complement previous interventions. These actions affected the three cities and mainly consisted of adapting the existing channels by (re)constructing concrete walls and ripraps in strategic areas (**Table 1**). In addition to these interventions, there were improvements at a smaller scale and certain areas of the streams were buried when located in urbanized areas.

<Table 1>

2.2 Hydrologic characterization

Historical data were used to assess water flows and rainfall intensity. A total of 50 damaging events were considered for the period from 1996 to 2014. This information should be handled with care, as the flash floods that result from torrential events in this area do not perfectly fit in the methodologies developed for estimating water flows (Barrera et al., 2006). In the Mediterranean coast, floods are produced by torrential events, not by series of precipitations. These are sudden events that do not require previous or subsequent days of rainfall and which occur punctually and with localized torrentiality.

The methodology applied by the Catalan Water Agency (2003) was used to identify the hydrologic features of the streams and determine their behavior during flooding events. First, the maximum daily rainfall was calculated following the guidelines published by the Spanish Ministry of Development (1999) and applying **Equation (1)** with a regional correction factor of 1.2 for the area under study (Junta d'Aigües, 1992).

$X_t = Y_t \times P$ **Equation (1)**

where X_t: maximum rainfall (in mm) for the return period considered; Y_t: regional quantile resulting from a tabulated value obtained by Cv (coefficient of variation; dimensionless) and T (return period; in years); P: maximum annual daily rainfall (in mm).

Second, using the data obtained through **Equation (1)**, we calculated the peak flows (Q_p) for different return periods (i.e., 50, 100 and 500 years), according to an update of the Rational Method by Témez (1991) (**Equation (2)** – for detailed equations, see **Supporting Information 2)**. With Q_p we can identify whether the water flow estimated for each event (Q) was above or below the expected flows of the watershed.

$$Q_p = k \times \frac{RC \times I \times A}{3.6}$$ **Equation (2)**

where Q_p: the maximum flow (m^3/s); k: uniformity coefficient (adimensional), based on Témez (1991); RC: threshold runoff coefficient (due to data availability, we calculated C for streams A and C and applying an interval between 0.4 and 0.6 according to literature values (Aparicio, 1999); I: rainfall intensity (mm/h), and A: watershed area (km^2).

In addition, the features of the channels constructed in some sections of the streams were reviewed (Junta d'Aigües, 1992). Note that these values might be underestimated given the lack of hourly rainfall intensity data and rain gauges (Catalan Water Agency, 2016; RuralCat, 2016), which is a shortcoming of this type of analysis (Camarasa Belmonte and Segura Beltrán, 2001). Given data availability, most of the collected hydrologic parameters correspond to stream B, whereas peak flows for streams A and C were extrapolated based on stream B. As a result, flow ranges were obtained depending on the threshold runoff, considering the maximum flow rate range as worst case scenario (see **Supporting Information 2**).

2.3 Post-disaster emergency actions: environmental and economic assessment

The environmental and economic performance of the emergency actions was estimated from a life cycle perspective. The environmental impacts were calculated using the LCA methodology (ISO 14040:2006), whereas the economic costs were provided through LCC (ISO 15686-5:2008). Based on the ISO standards, we describe the assessment phases in the following sections, i.e., goal and scope definition, inventory assessment, impact assessment and interpretation. The eco-efficiency of the system was obtained by combining the environmental and economic results (ISO 14045:2012).

2.3.1 Goal and Scope of the LCA and LCC

The functional unit (FU) of this analysis was the implementation of a set of post-disaster emergency actions (A1 to A7) for re-constructing and conditioning ephemeral streams A, B and C after a destructive flooding event. The lifespan of these actions was set at 50 years, which was the minimum return period considered.

For each of the emergency actions implemented in the area, the system boundaries considered were the preparation of the affected site, raw material extraction and transport to the construction site, (re)construction of the infrastructure, and transport and disposal of the demolition waste resulting from the preparation phase (**Figure 2**). The operation and maintenance were considered negligible because the infrastructure typically requires little maintenance.

<Figure 2>

2.3.2 Life cycle inventory (LCI)

An inventory of the materials, energy and processes involved in each life cycle stage was composed considering physical quantities and economic costs (a breakdown of the quantities and costs is provided in **Supporting Information 3**). In the case of the LCC, the labor costs were also included. Data were retrieved from the original projects, expenditure records and project files provided by the archive of the Catalan Water Agency (2015). Additional data for some missing construction items were obtained from MetaBase ITeC (2010) and CYPE Ingenieros (2015) and validated with the expenditure records. An average distance of 30 km was considered for the transport of local materials, such as concrete, cement or wood (Petit-Boix et al., 2016; Sanjuan-Delmás et al., 2014). Plastics and metals covered 100 km until the construction site. The distance to the landfill was 10 km (Petit-Boix et al., 2016). Note that the economic cost of material transport was embedded in the cost of material procurement and is not shown in the results. The ecoinvent v3 database (Weidema et al., 2013) was used for retrieving background data on the environmental life cycle of materials and processes.

2.3.3 Life cycle impact assessment (LCIA) and economic analysis

For calculating the environmental impacts related to the LCI, the classification and characterization processes included in the LCIA step were considered. The ReCiPe (H) method was applied (Goedkoop et al., 2009) through the Simapro 8.0.4 software (PRé Consultants, 2014). The midpoint indicators included were Climate Change Potential (CCP, kg CO_2 eq.), Ozone Depletion Potential (ODP, kg CFC-11 eq.), Human Toxicity Potential (HTP, kg 1,4-DB eq.), Photochemical Oxidant Formation Potential (PCOP, kg NMVOC), Terrestrial Acidification Potential (TAP, kg SO_2 eq.), Freshwater Eutrophication Potential (FEP, kg P eq.), Marine Eutrophication Potential (MEP, kg N eq.), Water Depletion Potential (WDP, m^3), Metal Depletion Potential (MDP, kg Fe eq.) and Fossil Depletion Potential (FDP, kg oil eq.). The Cumulative Energy Demand V1.08 (CED, MJ)(Hischier et al., 2010) was also selected to evaluate energy issues.

In the economic analysis, we estimated the Total Cost (TC, euros - €) associated with the emergency actions. Because the original projects were based on the year 1996, we calculated the TC for 2015 by applying the Spanish inflation rates for the period from 1996 to 2015 (IMF, 2015). According to BOE (2001b), 19% of indirect costs and 16% of value-added tax were added to the life cycle costs to obtain the TC value.

2.4 Flood damage: environmental and economic assessment

A series of flood damage data were supplied by the Spanish Insurance Compensation Consortium. These covered the events that occurred after implementing the emergency actions described in Section 2.3. Data accounted for physical damage, but resulting intangible damage, such as traffic delays or health issues, was not included due to its complexity. Physical damage was divided into damage to vehicles, residential buildings, industries and businesses and warehouses, and referred to the three cities affected by Streams A, B and C. This information was the result of expert appraisals conducted by insurance companies and was supposed to compensate insurance holders for flood damage. Because uninsured population was not included in the assessment, the economic loss was probably underestimated.

As opposed to the emergency actions (Section 2.3), damage compensations were recorded in economic terms and no physical or environmental data were available. In this approach, we used national input-output tables (INE, 2015) and related greenhouse gas emission tables (INE, 2014) to convert the economic compensations into environmental impacts. To do so, we selected the economic sectors involved in the life cycle of each damage category (**Table 2**) and averaged their impact factor (i.e., kg CO_2eq./€). This value was applied to the economic compensation data, as illustrated in **Supporting Information 4**.

<Table 2>

2.5 Eco-efficiency metric and environmental and economic balance

The indicators that resulted from this assessment were a set of eco-efficiency ratios related to the investment in infrastructure, and the net impact and payback period that combined the investment and flood damage prevention.

The eco-efficiency of the post-disaster emergency actions was assessed by selecting one of the eco-efficiency indicators proposed by ISO 14045:2012. We chose an eco-efficiency ratio that depicts the environmental performance divided by the product system value, which might represent the environmental intensity of production (Huppes and Ishikawa, 2005). This metric was only applied to the investment assessment.

The net impact and payback period were estimated in environmental and economic terms. We assumed that the implementation of the emergency actions avoided material damage. The damage resulting from a hypothetical do-nothing scenario was estimated by applying the ratio damage-water flow of 1996 to the water flow of each registered event (see **Supporting Information 5**). The avoided damage was obtained by subtracting the recorded damage from the do-nothing scenario. **Equations (3)** and **(4)** were applied to estimate the net impact and payback period.

$$NIE = \frac{TII}{L \times E} - (DND\text{-}RD) \qquad \textbf{Equation (3)}$$

$$PP = \frac{TII}{DND\text{-}RD} \qquad \textbf{Equation (4)}$$

where NIE: net impact per event; TII: total initial investment; L: lifespan of the system (years); E: average number of events per year; DND: average do-nothing damage per event; RD: average recorded damage per event; PP: payback time (in number of events).

3. RESULTS AND DISCUSSION

In this section we present the hydrologic evaluation of the watershed (Section 3.1), the impacts associated with the investment in infrastructure (Section 3.2) and damage compensation (Section 3.3) and the economic and environmental feasibility of the actions (Section 3.4).

3.1 Hydrologic performance of the watershed

Using **Equation (2)**, we calculated the water flow in Stream B, which is the main stream in the area. A flow of 78.2 m^3/s would be expected for a return period of 50 years (**Table 3**). This is the return period considered in Spanish regulations (BOE, 2001b) and flood studies conducted in the same area (San Millán, 2008). None of the observed events with the greatest flows exceeded this value (**Table 3**), and yet damage was registered in the three cities. However, this is not surprising, as the localized torrential events that affect the Mediterranean coast not always relate to the return periods (Olcina and Rico, 2000). Thus far, flooding has not generated as much damage as the 1996 event, mainly because the post-disaster interventions might have mitigated its effects.

<Table 3>

Another aspect to consider is the rainfall intensity. The magnitude of the rainfall intensity becomes more important than the amount of water accumulated during the event, as higher intensities generated greater economic losses. Heavy precipitation in a short period of time results in the inability of the soil to absorb water, thereby increasing runoff that might cause more damage (Barrera et al., 2006; Olcina, 1994). This fact is aggravated by the increase in artificial urbanized surface. In light of the results, the emergency actions seemed to be effective when reducing the effects of flooding, albeit the land use changes that took place in the past.

3.2 The investment: impacts and costs of the emergency actions

The LCA and LCC provided with overall impact and eco-efficiency results (**Table 4**) related to the implementation of the emergency actions. In general terms, these actions resulted in 3.9E+06 kg of CO_2 eq. emissions and an economic investment of 3.2E+06 €. These values lead to an eco-efficiency ratio of 1.2 kg of CO_2 per invested euro.

<Table 4>

The major contributors to the environmental impacts were concrete and related steel reinforcements (**Figure 3**), which were the main materials applied in the (re)construction of walls and other structural elements. Their joint impacts accounted for 30-90% of the impacts, depending on the impact indicator. Another relevant process was the use of construction machinery, which had a maximum contribution of 50% in the Photochemical Oxidant Formation Potential due to the emissions that result from burning diesel. Machinery was also relevant in economic terms (33% of the costs) because of the time dedicated to each engineering process. These results might vary depending on the type of machinery used in the projects. Labor represented 20% of the total costs and was the third main contributor to TC after the machinery and reinforced concrete.

<Figure 3>

3.3 The loss: impacts and costs of flood damage

According to the data provided by the Insurance Compensation Consortium, the losses from 1996 that led to the implementation of the emergency actions amounted to 2.6E+06 € and 2.7E+05 kg of CO_2 eq., when a maximum rainfall intensity of 176 mm/h was registered (see **Supporting Information 5**). The historical damage recorded afterwards is shown in **Figure 4**. In general, events that resulted in more than 20,000 € of losses mainly consist of damage to residential buildings, which accounted for a minimum of 40% of the economic compensations. Vehicle damage was also relevant in these events (15-35% of the costs). Because ephemeral streams are usually dry, vehicles are occasionally parked in the streambeds and water drags them during torrential events.

This pattern was similar when analyzing the environmental results, but the contribution of vehicles was barely noticeable. This outcome is related to the CO_2 conversion factors that we estimated for the car production. The impact factor applied in this case was between eight and ten times lower than that applied to the other damage categories (**Table 2**). In the latter, damage to electricity and gas networks was considered, which resulted in the highest impact (0.86 kg CO_2eq./€) compared to other affected sectors.

Figure 4 also illustrates the evolution of flood damage after implementing the emergency actions. As mentioned in Section 3.1, the water flow did not surpass the design flow in any of the cases. The hydrologic data presented in **Figure 4** are related to accumulated water flows, but intensity plays a key role in damage generation. For instance, in 1998 and 1999 two events resulted in similar water flows, but the maximum intensity was greater in 1999 (132 mm/h) than in 1998 (55.2 mm/h). Nonetheless, during this 17-year period, it seems that damage generation was lower when compared to 1996. The event that led to these measures registered an estimated water flow of 42.7 m^3/s. To date, some events resulted in water flows that ranged from 20 to 30 m^3/s (see **Supporting Information 5**), but the damage generated was lower than the previous registers. This outcome could be related to the rainfall intensity, which was lower, and the implementation of the emergency actions (Section 3.1). However, some of the events that generated damage could not be associated with rainfall data due to data availability and the location of the rain gauges.

<Figure 4>

3.4 The balance: investment versus loss

The data generated in Sections 3.2 and 3.3 was used to estimate the net environmental balance of the emergency actions implemented in the area (**Table 5**). When accounting for the net impacts, the negative values (-5.2E+05 € and -2.9E+04 kg CO_2 eq.) suggest that these emergency actions contribute with environmental and economic benefits. The average damage recorded after the interventions represented 2.5% of the loss estimated for the do-nothing scenario. With regard to the payback period, the initial economic investment was recovered two years after the intervention. In this sense, this set of emergency actions was economically feasible with respect to the damage they prevented.

In environmental terms, results differed, as 25 years were needed to offset the initial CO_2 emissions resulting from the project. However, different factors might affect these values and their associated uncertainty. We did not include potential ecosystem services that might result from the emergency actions, such as social or natural benefits. These might reduce the environmental investment because of their positive effect on the system. Future analyses should improve this aspect to better depict the absolute environmental impacts of emergency actions. Other aspects that might increase the environmental payback and related uncertainty are lifespan and material intensity of the infrastructure and damaged products. For instance, vehicles and electric appliances generally have a shorter lifespan than built infrastructure. In the latter, the use of materials tends to be intensive to increase their durability and, thus, the initial investment might be higher than that of a car. This might lead to re-thinking the type and quantity of materials and designs applied in the reconstruction of this type of infrastructure or to implementing green systems with a shorter environmental payback. Finally, the environmental impacts of losses might be underestimated because average characterization factors were applied using input-output tables. In this case, data on specific damaged items within the damage categories is needed, such as basement furniture, household appliances, etc. Future assessments should consider this limitation and provide particular environmental values for these items.

<Table 5>

4. CONCLUSIONS

The results obtained in this paper highlight the effects of integrating the consequences of decisions into the life cycle of urban interventions, such as flood prevention strategies. Accounting for costs and benefits is especially common in companies, where revenue can easily be calculated and balanced with the investment. However, it is also interesting to couple these parameters at an urban scale, as they might be responsible for a share of the total impacts of cities. Thus, this type of assessment might offer data to the local administration and insurance companies for improving the sustainability of cities. In this particular case, communicating the economic and environment payback of the emergency actions, i.e., 2 and 25 years, respectively, might have an impact on their future decisions once they are aware of the actual feasibility of their systems. Additionally, eco-efficiency indicators will give them information about the impacts related to each invested euro (e.g., 1.2 kg of CO_2/€). In the field of environmental management, this approach is yet to be explored in detail, but it is key to ensure the sustainability of any action and decision made at an urban scale. This study is thus a first step towards integrating the environmental and economic dimensions for assessing flood prevention and we believe this can be applied and adapted to different types of infrastructure.

Furthermore, adapting to climate change is essential for dealing with future extreme events. When emergencies occur, damage restoration and risk prevention are a priority and any action is acceptable to recover from a disaster. However, if emergency situations need to be dealt with very often, the eco-efficiency of the solutions should be considered to reduce the resource consumption, impact generation and economic investment.

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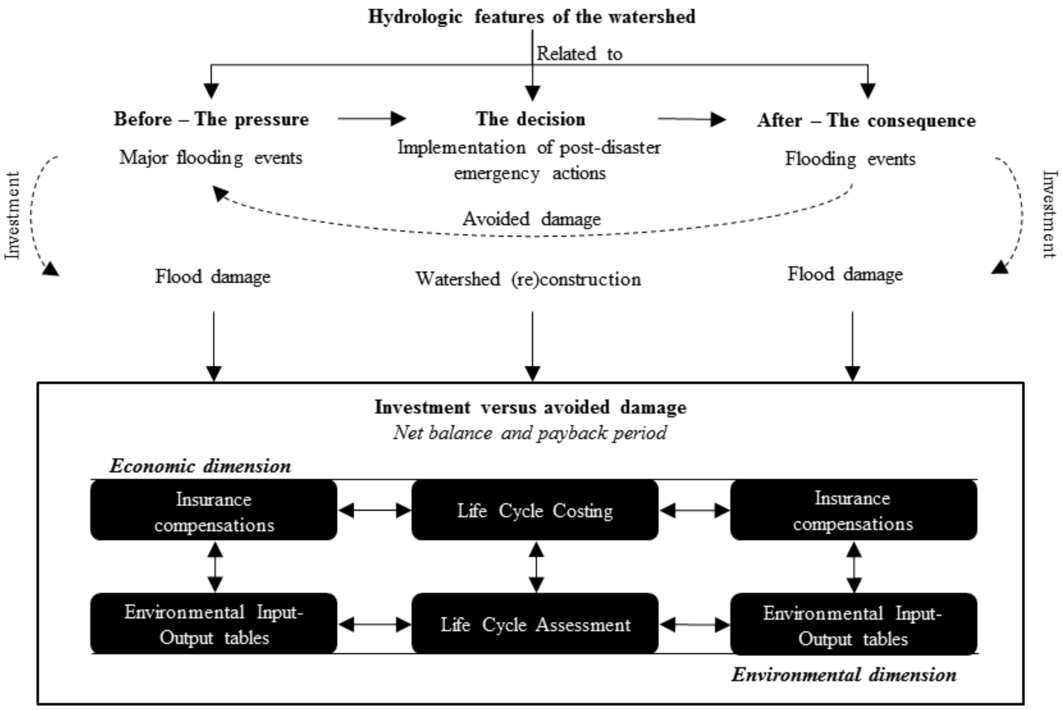

Figure 1 Integrated method for estimating the net impacts and payback period of flood post-disaster emergency actions

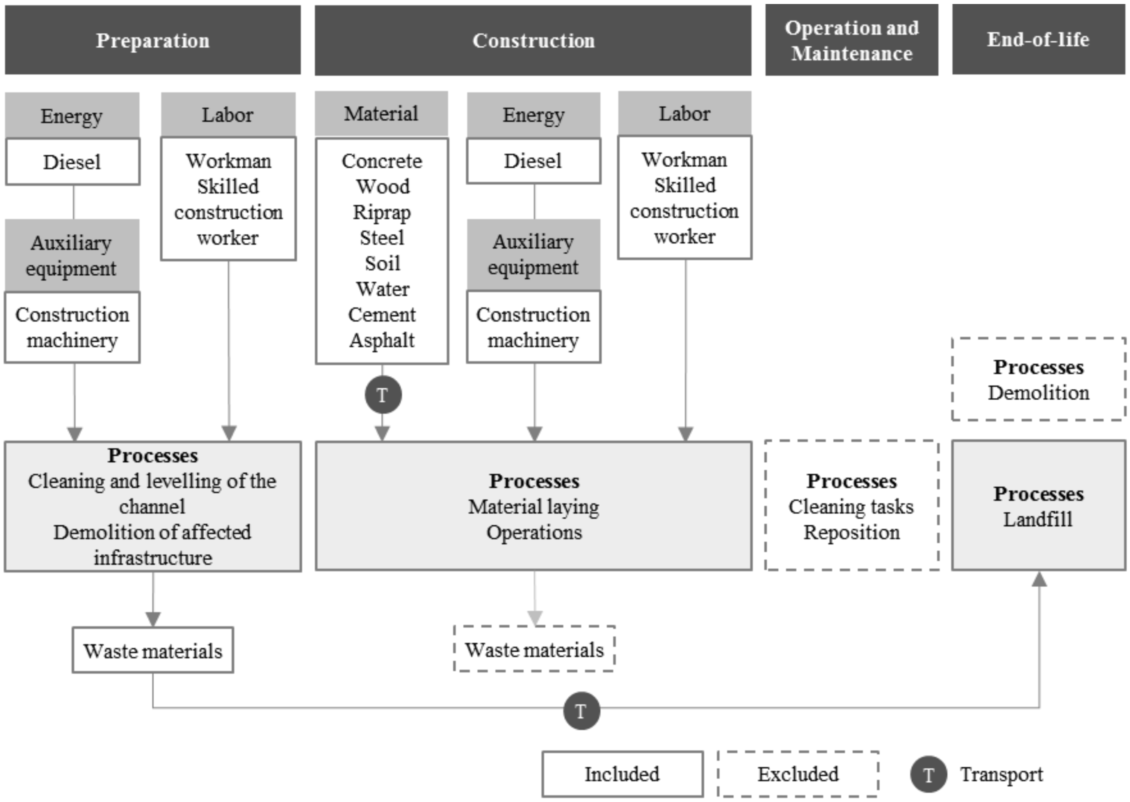

Figure 2 System boundaries of the life cycle of the emergency actions analyzed

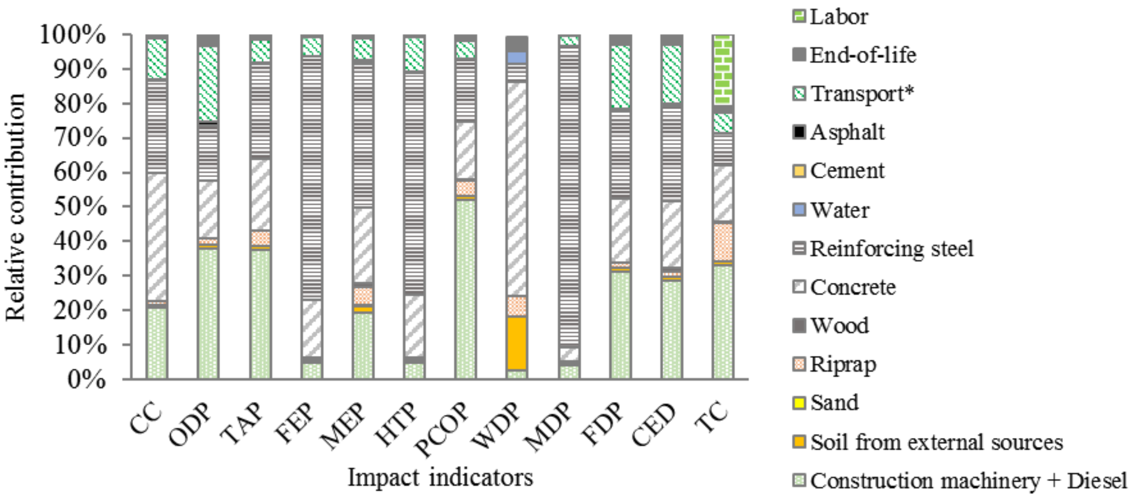

Figure 3 Breakdown of the relative contribution of the processes involved in the emergency actions to the impact indicators. *In TC, the transport cost is related to material transfers within the construction site; material transport costs are embedded in the cost of each material

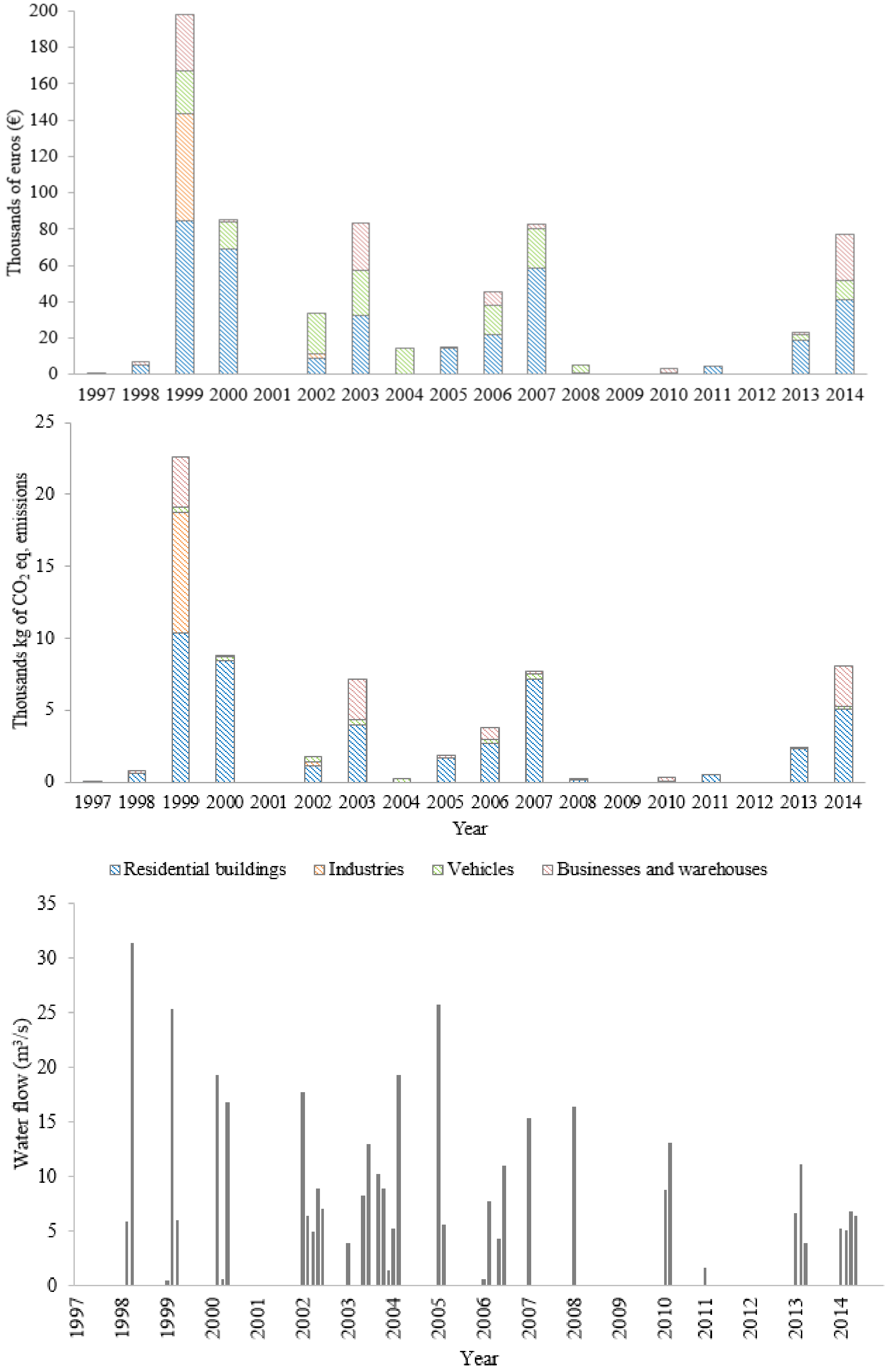

Figure 4 Environmental and economic impacts related to different types of flood damage recorded in the study area, and evolution of the water flow for each event with recorded damage

Table 1 Features and location of the post-disaster emergency actions implemented after the 1996 flooding. Data from the archive of the Catalan Water Agency (2015). Basemap from ICGC (2016). Vilassar: Stream A; Cabrils: Stream B; and Cintet: Stream C

	Stream	**City**	**Post-disaster emergency actions**
A1	Stream B	Cabrils	Reconstruction of 54 m of wall
A2	Torrent Roldós (Stream C)	Cabrils	Construction of 9 downstream concrete sleepers and riprap
A3	Torrent Cal Xinxe (Stream B)	Cabrils	Cleaning and wall reconstruction
A4	Stream B	Vilassar de Mar	Canalization
A5	Riera Targa (Stream A)	Vilassar de Dalt	Cleaning and construction of 3 concrete sleepers
A6	Stream B	Cabrils and Vilassar de Mar	Wall reparation on the left margin and right margin protection
A7	Torrent d'en Cuyàs (Stream A)	Vilassar de Mar	Canalization

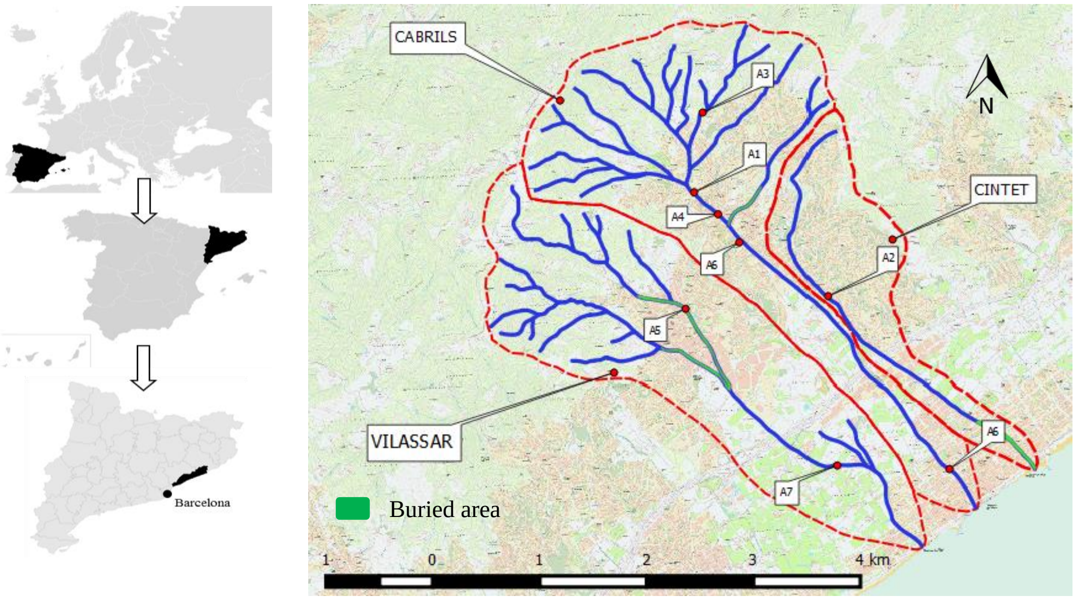

Table 2 Estimation of the CO$_2$eq. emissions of the damage categories through input-output tables. Based on data from the Spanish Statistical Office (INE, 2015, 2014)

	Damage categories				**Input-output values**		
Selected economic sectors	**Residential buildings**	**Industries**	**Vehicles**	**Businesses and warehouses**	**Total output (x 10^6 €)**	**Total greenhouse gas emissions (x 10^3 tons of CO$_2$eq.)**	**Sectorial impact factor (kg CO$_2$ eq./€)**
Food products and beverages	×			×	1.8E+05	5.9E+03	0.032
Textile products	×			×	6.0E+04	6.8E+02	0.011
Paper and related products	×	×		×	1.8E+04	2.8E+03	0.153
Electronics	×	×		×	3.9E+04	1.4E+02	0.004
Electric equipment	×	×	×	×	3.4E+04	6.6E+02	0.019
Furniture	×				3.6E+04	4.7E+02	0.013
Repair services and installation of machinery and equipment	×	×	×	×	2.0E+04	9.4E+01	0.005
Electricity, gas, vapor and air conditioning	×	×		×	8.5E+04	7.3E+04	0.863
Construction activities	×	×		×	2.3E+05	1.1E+03	0.005
Wood and cork and related products		×			1.1E+04	7.6E+02	0.067
Machinery		×	×		4.1E+04	6.6E+02	0.016
Motorized vehicles			×		8.1E+04	1.5E+03	0.018
Lodging services				×	1.1E+05	1.9E+03	0.017
Sports and leisure centers				×	1.7E+04	4.5E+01	0.003
Average impact factor (kg CO$_2$ eq./€)	**0.123**	**0.142**	**0.015**	**0.111**			

Table 3 Events with relevant water flows and associated damage. T: return period; RC: Threshold runoff coefficient at intervals

Date	Expected water flow in the watershed (Q_p) (T=50 years)	Water flow (Q) (RC=0.4) (m^3/s)	Water flow (Q) (RC=0.6) (m^3/s)	Accumulated rainfall (mm/day)	Maximum rainfall intensity (I) (mm/h)	Economic compensation (€)
2-Sep-1996	78.2	42	64	158	176	2,533,267
3-Dec-1998		31	47	116	55	4,372
14-Sep-1999		25	38	93	132	116,892
19-Sep-2000		16	25	62	175	54,162

Table 4 Total environmental and economic impacts of the emergency actions given a lifespan of 50 years

Impact category	Unit	Acronym	Result	Eco-efficiency ratio
Climate Change Potential	kg CO_2 eq.	CC	3.9E+06	1.2E+00
Ozone Depletion Potential	kg CFC-11 eq.	ODP	3.8E-01	1.2E-07
Terrestrial Acidification Potential	kg SO_2 eq.	TAP	1.7E+04	5.3E-03
Freshwater Eutrophication Potential	kg P eq.	FEP	6.6E+02	2.1E-04
Marine Eutrophication Potential	kg N eq.	MEP	2.3E+03	7.2E-04
Human Toxicity Potential	kg 1,4-DB eq.	HTP	9.1E+05	2.8E-01
Photochemical Oxidant Formation Potential	kg NMVOC	PCOP	2.1E+04	6.6E-03
Water Depletion Potential	m^3	WDP	2.4E+04	7.5E-03
Metal Depletion Potential	kg Fe eq.	MDP	7.1E+05	2.2E-01
Fossil Depletion Potential	kg oil eq.	FDP	8.9E+05	2.8E-01
Cumulative Energy Demand	MJ	CED	4.4E+07	1.4E+01
Total Cost	€	TC	3.2E+06	-

Table 5 Environmental and economic balance of the emergency actions based on the avoided flood events

	Economic balance		**Environmental balance**	
Parameters	**Value**	**Units**	**Value**	**Units**
Average # events per year	2.7	u	2.7	u
Lifespan of the actions	50	years	50	years
Initial investment	3.2E+06	€	3.9E+06	kg CO_2 eq.
Average recorded damage per event	1.4E+04	€	1.4E+03	kg CO_2 eq.
Estimated average do-nothing damage per event	5.6E+05	€	5.9E+04	kg CO_2 eq.
Estimated avoided damage per event	5.4E+05	€	5.8E+04	kg CO_2 eq.
Net impact per event	-5.2E+05	€	-2.9E+04	kg CO_2 eq.
Payback period	5 2	events years	67 25	events years