

Vulnerability of transport infrastructure to extreme weather events in small rural catchments

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Across the Mediterranean region, extreme weather events (EWE), such as high-intensity storms causing flooding in small river basins, are one of the most common types of hydro-meteorological hazards. Flooding has been associated with severe effects on road networks and a significant number of vehicle-related fatalities, raising concerns regarding the performance of transportation infrastructure during EWEs. Given the expected increase in frequency of such events within the context of climate change, an assessment of its vulnerability is particularly crucial. The work presented herein evaluates the performance of transportation infrastructure during high-intensity storms. This research focuses on small rural catchments, examining the impact of five extreme storm events in five rural basins in Greece. Post-flood surveys were conducted, to record the impact of inundation on each infrastructure element in the five catchments. Overall, findings showed that road infrastructure, especially river crossings, performed poorly, restricting access to large areas during and after the events, affecting the safety of commuters and sustaining extensive damages. On average, it was found that 73% of the river crossings and 11.5% of the total length of the road network were inundated or damaged, while a total of 12 individuals died during the events. The results revealed that the impact of flooding in the transportation infrastructure of small rural basins was severe and a threat to human life. The findings of this study indicate that authorities should consider taking measures during EWEs, re-examine the safety features of the relevant infrastructure and assess the risk related to its failure.

Keywords: *flash floods, extreme weather events, climate change, transportation infrastructure, vehicle accidents.*

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1. Introduction

Transportation has been shown to be a crucial aspect of development and economic growth (Vickerman, 2008; Lakshmanan, 2011; Chatman & Noland, 2011; Deng, 2013). Land-based transport of goods and passengers depends on a network of infrastructure, vulnerable to adverse weather conditions and prone to damages from weather extremes (Koetse & Rietveld, 2009). Across the Mediterranean region, extreme weather events (EWEs), such as high-intensity storms, often cause catastrophic flash flooding in ephemeral torrents and rivers, thus draining small rural basins (Bull et al., 2004; Lana et al., 2004; Belmonte & Beltra, 2001). Previous research has shown that during extreme weather events, the integrity and the safety of road infrastructure can be compromised, often leading to severe accidents (Maurer et al., 2012; Mitsaklis et al., 2014a). Specifically, it has been shown that flood-related disruptions in the operation and performance of transport networks often result in undesirable impacts for the road users endangering their safety or leading to trip alternations and/or cancellations (Stamos et al., 2015a; Mitsakis et al., 2014b). This has been also reflected in the European Truck Accident Causation report, which states that extreme weather conditions (among which severe precipitation leading to flooding) are ranked among the main causes for road accidents, with a total of 4.4% attributed accidents in the European Union (ETAC, 2007). Similarly, studies from the U.S. and Europe (French et al., 1983; Jonkman & Kelman, 2005; Ashley & Ashley, 2008) show that a significant number of fatalities caused by flooding is related to the use of vehicles and transportation networks. In Greece, 60 out of 151 individuals who lost their lives due to flooding between 1970 and 2010 were vehicle occupants using the transportation network (Diakakis & Deligiannakis, 2013). In Saxony, about 8.5% of the total direct, tangible damage from weather events occurred on streets and bridges and about 13% on railways (Freistaat Sachsen, 2003).

Climate change studies show that the frequency of EWEs, such as high intensity storms, is expected to increase in the near future (Stamos et al., 2015b). Combined with the recorded impact of EWEs on infrastructure and human life, these predictions raise concerns regarding the performance of transportation infrastructure. We suggest that an assessment of the vulnerability of transportation infrastructure under extreme conditions is a particularly pressing matter. Existing studies that attempt to quantify the impact of flooding in transportation focus only on large urban areas (Changnon, 1999; Suarez, 2005; Mitsakis et al., 2014c), although a large percentage of flood damages and fatalities is recorded in small flash flood-prone basins (Gaume et al. 2009, French et al. 1983), which are particularly common across the Mediterranean. Given the importance of transportation infrastructure and the anecdotal evidence of the impact of EWEs on them, this work examines the performance of transportation infrastructure during EWEs and their effects in small rural catchments. To this aim, this study examines the effects of five extreme storm events and subsequent flooding in the Greek territory, in an effort to assess the infrastructure and provide a better understanding of the way safety is affected during EWEs. To the authors' knowledge, limited literature exists on the field of evaluating the performance of road infrastructure during the occurrence of EWEs. This paper attempts to shed some light on our understanding of the nature and extent of the impact of EWEs on transportation infrastructure.

2. Materials and methodology

This work uses a case-study approach to collect data and examine the effects of extreme weather events in small flash flood-prone basins.

2.1 Case studies

Data were collected from five river basins in Greece that suffered flash flooding after high-intensity storm events. The first river basin is situated in northeast Attica, in central Greece,

approximately 25 km northeast of the capital, Athens. In this case Vranas torrent drains a mountainous area of 25 km², through the Marathon plain and into south Euboikos Gulf (Figure 1a). The second is situated on the island of Euboea, in central Greece. Lilas River drains a coastal but mountainous rural area (259.4 km²) of central Euboea (Figure 1b). The third, Kremasti River basin, is situated on the northern part of the island of Rhodes in southeast Greece. The river drains a coastal rural area of 22.9 km², around the villages of Pastida and Kremasti (Figure 1c). The fourth lies in western Greece, 15 km northeast of Agrinio. Platanorema River drains an area of 26.1 km² around the village of Potamoula (Figure 1d). The fifth, Xerias River basin, is situated in north Peloponnese, draining a mountainous area of 155.9 km² in the Gulf of Corinth. Corinth, the biggest town in the catchment, is built around the river's outlet (Figure 1e).

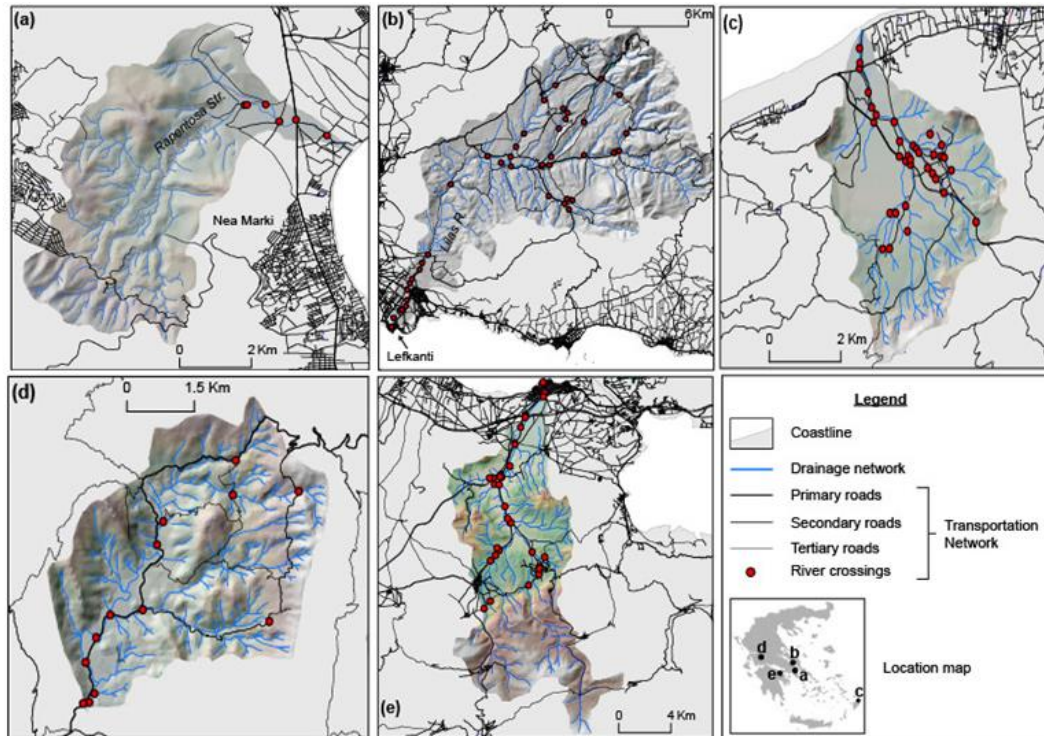


Figure 1. Maps of (a) Rapentosa, (b) Lilas, (c) Kremasti, (d) Potamoula and (e) Xerias river basins, illustrating the local drainage and the paved transportation network along with the established river crossings

In all five basins, the watercourses are ephemeral with little or no water at all for most of the year. Built areas constitute only a small part of the basins, which are dominated by agricultural or natural vegetation land (EEA, 2006). In all cases, a long paved road network has been established. The basic attributes of the five basins are illustrated in Table 1.

Table 1. Basic attributes of the examined basins

Attributes	Lilas Basin	Rapentosa Basin	Xerias Basin	Kremasti Basin	Potamoula Basin	Average
Basin size (km ²)	259.4	37.2	155.9	22.9	26.1	100.3
Nr. of towns/villages	21	3	14	3	4	-
% of built areas within the basin	0.35	4.12	1.63	5.02	0	2.22
Total length of roads (in km)	187.6	42.1	233.3	70.7	32.2	113.18
Nr. of river crossings	40	6	37	35	13	-

In all five study sites, extreme precipitation events induced flash flooding with substantial consequences on human life, property and infrastructure (Table 2).

Table 2. Attributes of extreme weather events in the examined basins

Attributes	Lilas Basin	Rapentosa Basin	Xerias Basin	Kremasti Basin	Potamoula Basin
Date of extreme precipitation event	12/09/2009	27/10/198	19/01/199	22/11/201	02/10/2008
Total rainfall accumulation (in mm)	203.4	114	123-358	104.6	280
Storm duration (in hours)	24	11	43	4.5	0
Recurrence interval (in years)	155	70	10-1000	10	13

2.2 Approach

To examine the effects of the above extreme precipitation events on the transportation infrastructure of the five river basins, post-flood field investigations were conducted. In the course of these field surveys the following elements were recorded:

- the type and location of each transportation infrastructure element
- the extent of inundation
- the height of flood waters above ground
- the effects of flooding on the road network, with detailed description of damages and their location
- the effects of flooding on each river crossing, with detailed description of the type of damage
- the impact on human life and the circumstances under which fatal incidents occurred
- the impact of flooding on the accessibility of parts of the road network

A database was developed to store information on the type and location of each infrastructure element and the possible impact of flooding on them. Each element was photographed and a detailed description of damages (if any) was stored in the database. The spatial extent of flooding was mapped based on field evidence (e.g. deposited debris) using GPS and satellite imagery. Data from reports and interviews with eyewitnesses were collected regarding vehicle-related accidents during the extreme events, in an effort to determine the conditions under which they occurred. River crossings were grouped in three categories depending on their type:

- Low water crossings: Pathways constructed out of asphalt or concrete with shallow foundation, used as a bridge when water flow is low (Figure 2a).
- Single-span bridges (no piers): Concrete structures, single-span bridges have abutments at each end that support the weight of the bridge and serve as retaining walls (Figure 2b).
- Multi-span bridges (with piers): Concrete structures, which use piers to support the weight of the structure at the end of each span and between the abutments (Figure 2c).



Figure 2. Types of river crossings: (a) low water crossings, (b) single-span bridges and (c) multi-span bridges

Using the delineation of the flooded area, the affected part of the road network was accurately mapped (Figure 3). The damages on the roads and the river crossings were categorized in different groups according to their type. Simple mathematical operations were carried out to quantify the extent of the effects on the road network and particularly on the river crossings.



Figure 3. Maps of Xerias river basin near its outlet at the town of Corinth, illustrating the extent of flooding as mapped during the post-flood fieldwork, and the affected part of the road network

3. Research results

The findings showed that extreme precipitation events had a significant impact on the transportation network of the study sites in four different aspects:

- effects on paved roads
- damages on river crossing infrastructure (i.e. bridges and low water crossings)
- effects on the accessibility of parts of the road network
- the safety of travelers.

3.1 Effects on the road network

Extensive road flooding was recorded in all events, hindering vehicle circulation and access to parts of the study areas. In addition, in certain cases, floodwaters inflicted various types of damage on parts of the paved road network itself. Six different types of such effects were identified, namely:

- a. Inundation of parts of the road network causing no permanent damage or effect of a structural nature, but restricting vehicle circulation during the flood and up to several hours after it, by making these parts of the network impassable (Figures 4a, b).
- b. Inundation of parts of the road network accompanied by debris and sediment accumulation or deposition on parts of the road network, restricting access (Figure 4c) and vehicle circulation during and after the flood (sometimes for 1 or 2 days) and immobilizing vehicles (Figure 4d).
- c. Inundation of parts of the road network accompanied by erosion and scouring of the road fill material, its embankments or its foundations and subsidence of the road surface (Figure 4e).
- d. Inundation of parts of the road network accompanied by surficial scouring limited to the asphalt, the road pavement or the shoulders (Figure 4f).
- e. Inundation of parts of the road network accompanied by damages on various road installations such as street lighting, road signs, traffic lights, guardrails and others (Figure 4g).
- f. Inundation of parts of the road network accompanied by complete collapse of whole parts of the road network due to erosion and scouring, together with the foundation material and the asphalt deck (Figure 4h).



Figure 4. Effects of flash flooding caused by extreme precipitation events on the road network including: inundated parts (a, b), deposits of debris (c, d), eroded road fill and scoured roads (e), asphalt scouring (f), damages on road equipment (e.g. lighting installations) and (g) complete erosion and road collapse (h)

Significant parts of the paved road network of the five study areas experienced the above effects during extreme precipitation events and the subsequent flooding (Figure 5). Results showed that:

- the length of roads that suffered both inundation and damages ranged between 0.4 and 9.7 km (1.6% - 5.1% of the total road length) depending on the basin
- the length of roads that experienced only inundation ranged between 3.5 and 16.2km (5.9% - 13.3% of the total road length) depending on the basin
- the length of roads that experienced either inundation or inundation and damages ranged between 3.9 and 25.9 km (8.2%-13.8% of the total road length) depending on the basin
- On average 2.9% of the total length of the road network of a basin experienced both inundation and damages and 11.5% experienced either inundation or inundation and damages. An average of 88.4% did not experience any effects (Figure 5).

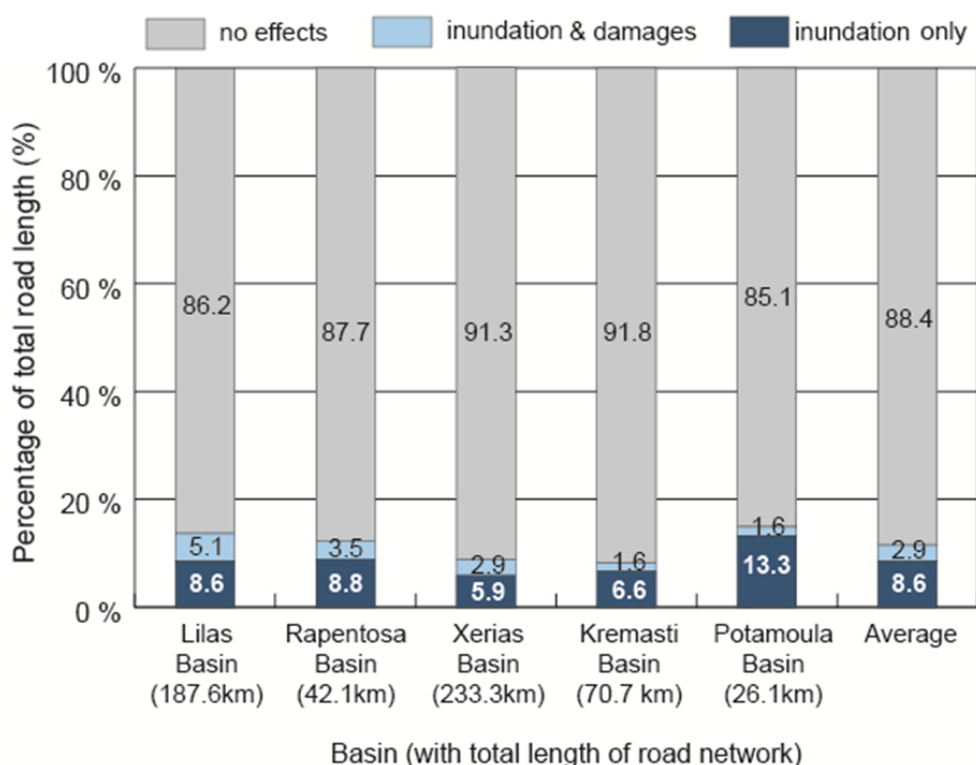


Figure 5. Percentage of total road length of the examined basins that experienced temporary inundation and damages during the EWEs

3.2 Effects on river crossings

As far as river crossings are concerned, it was found that a significant percentage was affected by the extreme precipitation events mainly due to under-capacity, blockage or scouring of foundations. Their performance was grouped in five categories depending on the effects recorded, namely:

- Type 1: River crossing operated normally during and after the precipitation event, experiencing no inundation or any type of structural damage, allowing vehicle circulation.
- Type 2: River crossing experienced inundation, cutting access to vehicles, but with no structural damages on any element of the infrastructure (Figure 6a).
- Type 3: River crossing experienced inundation after clogging of its culverts or other waterways. Access across the watercourse was restricted after the flood (for hours and up to 1-2 days), as water continued to overflow due to the blocked pathways. No further structural damages on any element of the infrastructure was present in this case (Figures 6b, c).
- Type 4: River crossing experienced inundation accompanied by damages on parts of the infrastructure such as: destroyed guardrails, debris accumulation on the bridge deck, partial scouring on the bridge foundations, damage on street lighting / road signs / traffic lights, scouring on the asphalt deck, scouring and erosion of embankments or fill material. In this category, all effects and damages were fully restorable without the complete demolition of the river crossing in question. However, the functionality of the infrastructure was restored after a considerable amount of time, ranging from 3 days up to a few weeks (Figures 6d, f, h).

- e. Type 5: River crossing experienced inundation accompanied by critical damages that caused the complete collapse of its structure or damages that cancelled the functionality of infrastructure permanently. In most cases, the collapse or critical damage came with scouring or erosion of foundations of the bridge (abutments or piers) followed by substantial subsidence of the bridge deck and its support. In this category, the effects and damages were not restorable. The functionality of the infrastructure was restored after weeks or months (Figures 6e, g).



Figure 6. Types of damages on river crossing infrastructure, ranging from inundation only (a), clogging of waterways (b, c), damages on parts of a bridge (d, f, h) and complete collapse of the infrastructure (e, g)

In total, it was found that a significant percentage of river crossings experienced the above types of effects and damages. The percentage of river crossings that suffered inundation or any other type of effect ranges from 54.3% to 83.3% depending on the basin (Table 3). In fact, out of 131 river crossings mapped in the five basins, 92 (or 70.2%) experienced effect types 2 to 5, whereas only 39 (29.8%) of them were not affected at all.

Table 3. Effects of flooding in river crossing infrastructure in the examined basins

	Lilas Basin	Rapentos a Basin	Xerias Basin	Kremasti Basin	Potamoula Basin	Total
Total nr. of river crossings	40	6	37	35	13	131
Nr. and % (in brackets) of river crossings affected	28 (70)	5 (83.3)	30 (81.1)	19 (54.3)	10 (76.9)	92 (70.2)

Based on these results, an average 73.1% of river crossings in each basin was found to experience inundation, making these passages impossible to cross. On the contrary, an average of only 26.9% experienced no effects from the precipitation events and the subsequent flooding. In a significant part of these river crossings (50.1% on average), in addition to inundation, the floodwaters also caused damages to the road deck, culverts, guardrails, street lights and other installations. However, the particular damage to infrastructure did not lead to collapse, and was restorable (Figure 7).

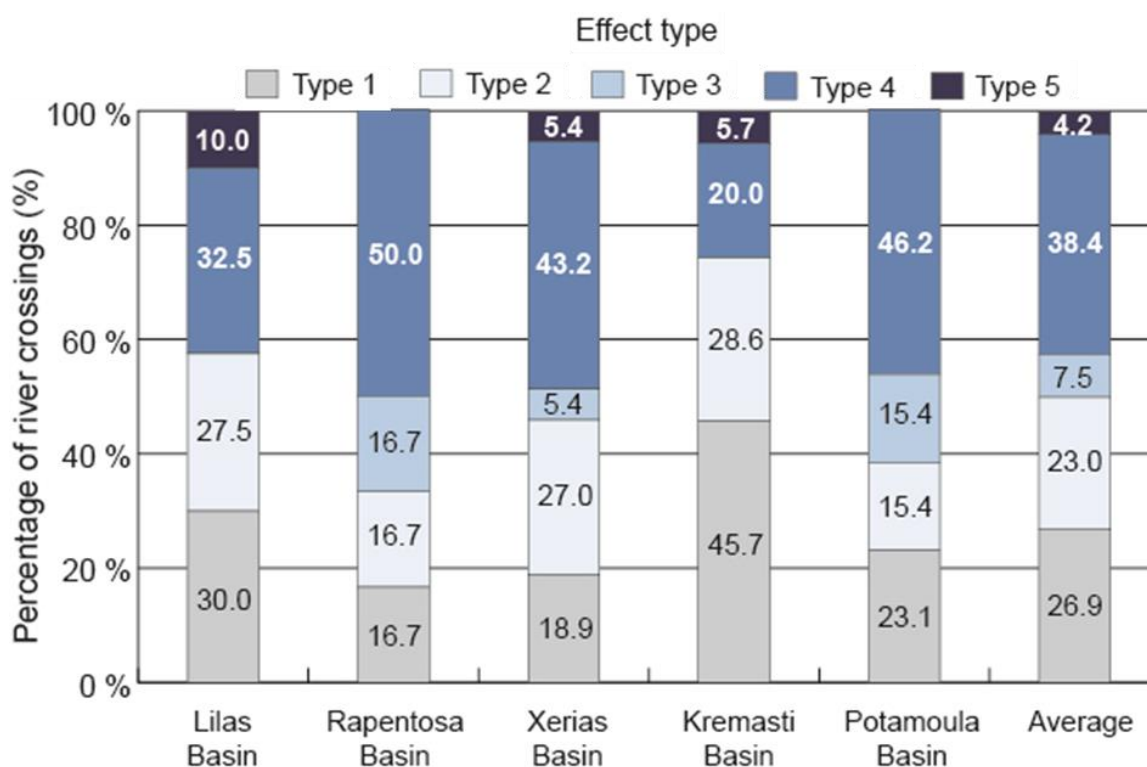


Figure 7. Percentages of effect type per examined basin

The type of damage appeared to be related with the type of infrastructure (Figure 8). Out of 38 cases of "low water crossings", 86.8% were inundated, 42.1% experienced damages and 7.9% suffered non-restorable damages or collapsed. Out of 87 cases of single-span bridges, 65.5% were inundated, 36.8% were damaged and 5.7% suffered non-restorable damages or collapsed. In 6 cases of multi-span bridges, 33% were flooded and damaged, but none of them collapsed or suffered critical damage. Low water crossings were found to be more vulnerable to inundation and to damages from extreme precipitation events and subsequent flash flooding, as only 13.2% of them were not affected (Figure 8). On the contrary, multi-span bridges presented less vulnerability than the other two types, with 66.7% not suffering any effect from flooding. This difference can probably be attributed to the larger cross sectional areas.

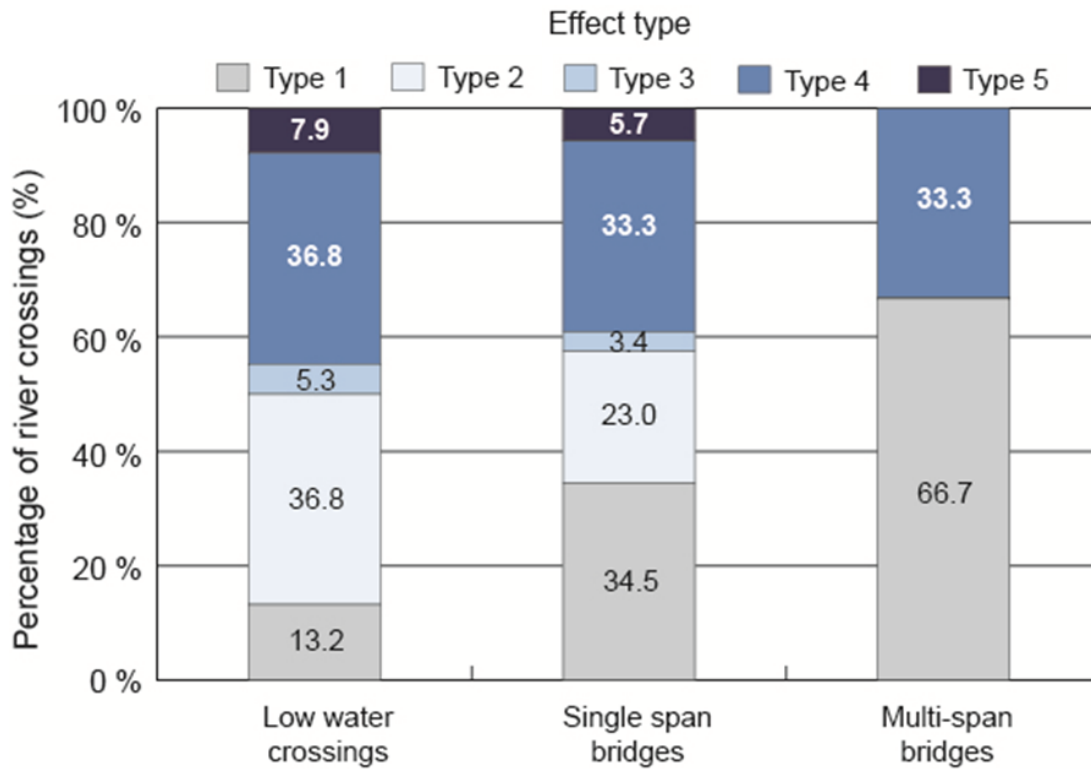


Figure 8. Percentages of effect type on river crossings

3.3 Impact on road access

Post-event field visits showed that parts of the road network in all five basins had to close for hours and up to weeks so that restoration works could be carried out. Although specific data for vehicle circulation were not available for the study areas, closed parts of the road lead to changes (detours) of vehicle itineraries.

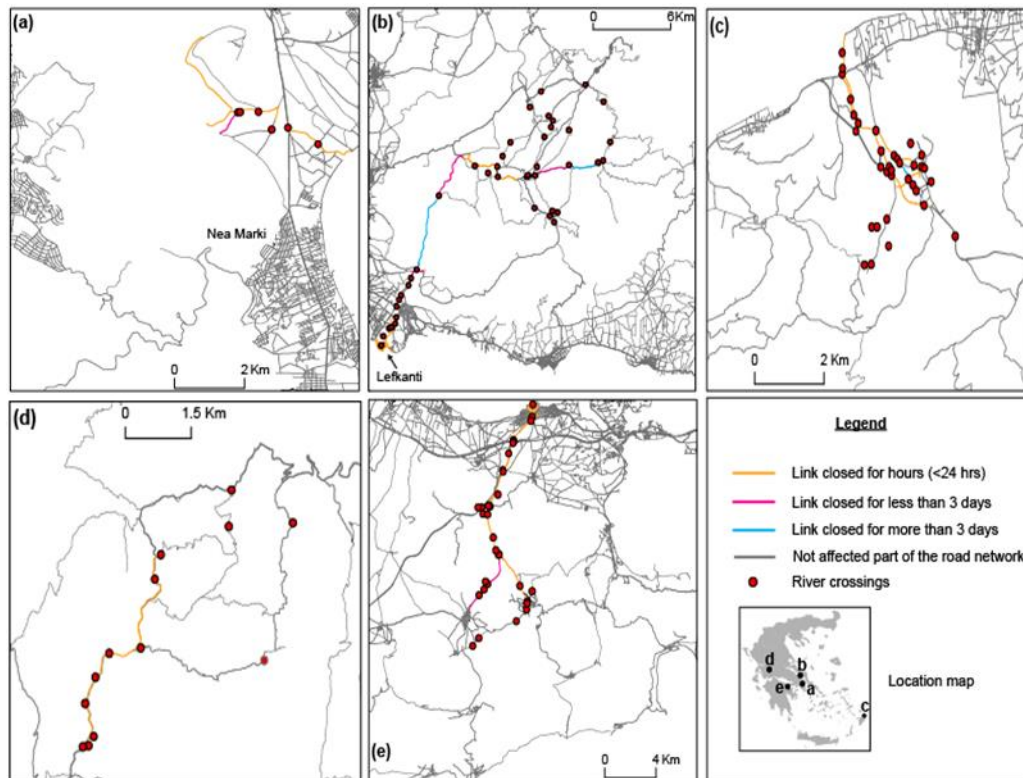


Figure 9. Closed road network after the extreme precipitation events per examined basin

3.4 Impact on safety of travellers

Six fatal car accidents were caused by floodwaters in the five events, resulting in 12 fatalities in total. In all cases, accidents occurred as vehicle occupants were trying to travel across inundated or damaged parts of the road network. At Kremasti basin, occupants of two cars tried to cross the torrent through a single span bridge and a low water crossing during the flood resulting in 4 fatalities. At Rapentosa basin, a family tried to cross a flooded torrent using a car, resulting in the loss of their daughter. At Potamoula, a couple tried to cross an inundated small single-span bridge to get to their house. Their car was swept away by the flooded torrent killing both passengers. At Lilas basin, an off-duty police officer tried to cross an inundated bridge during the storm, causing his car to be swept away. Finally, at Xerias basin, a motor coach was swept away by floodwaters when the driver tried to travel across a multi-span bridge, leading to the death of 5 people. Post-flood surveys did not record any road signs restricting traffic or alerting vehicle occupants to a potential risk.

Table 4. Details of fatal incidents caused by the extreme precipitation events

Location of incident	Fatalities	Type of infrastructure used by deceased	Type of impact on infrastructure
Kremasti basin	2	Single-span bridge	Type 5 (suffered inundation and irreparable damage on the deck)
Kremasti basin	2	Low water crossing	Type 2 (flooded with no damages)
Rapentosa basin	1	Single-span bridge	Type 4 (flooded with damaged guardrails)
Potamoula basin	2	Single-span bridge	Type 4 (flooded with damaged guardrails)
Lilas basin	1	Single-span bridge	Type 2 (flooded with no damages)
Xerias basin	4	Multi-span bridge	Type 4 (flooded with damaged guardrails and other installations)

4. Conclusions

The present study provides insight on the performance of land transport infrastructure of flash flood prone areas during extreme precipitation events. The study assesses how roads and river crossings perform by quantifying the extent to which they are affected by these events. To the authors' knowledge, these are the first findings to quantify in a holistic way the degree to which the road network is affected by the flooding that follows an extreme precipitation event.

In the five basins studied, 8.2%-13.8% of the roads suffered submergence during and a few hours after the storm, restricting vehicle circulation and leading to unsafe conditions. Furthermore, a small but noteworthy part of the networks (1.6% - 5.1%) suffered damages ranging from simple asphalt scouring, to complete collapse of the road foundations all of which required road closures to restore.

As far as the river crossings are concerned, findings show that the types of infrastructure identified in the five study basins were on average more vulnerable than the road network itself. Low water crossings and single-span bridges were affected on higher percentages (86.8% and 65.5% respectively) than multi-span bridges, which presented far lower figures (33.3%). These notably high percentages have not been previously recorded and show that the impact of EWEs in small flash flood-prone basins may have been overlooked by authorities and professionals.

Fatal incidents involving commuters were recorded in multiple occasions, indicating that the safety of the transportation network was compromised during the EWEs. The findings indicate that authorities should take steps to improve the resiliency of infrastructure to EWEs and its safety. Infrastructure elements should be examined in conjunction with flood risk maps at local level, to map the all elements that are under risk. Emergency measures should be taken during extreme storms to restrict traffic and warn commuters about the imminent risk. River crossings should be examined for safety features such as permanent warning signs, adequate lighting and guardrails. Authorities should also remove vegetation and other debris from channels and culverts to prevent clogging. The drainage capacity of single-span bridges should be re-examined in comparison with design flood discharges to estimate the probability of flooding. Finally, local authorities should enhance local awareness campaigns focusing on the risk of flooding as far as vehicle occupants' safety is concerned.

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