

Review Article

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Risk Assessment of Flood-Prone Roads Using Digital Models

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ABSTRACT

Climate change and extreme weather events constitute a major threat to the integrity and the operability of every transportation system. Storm surges, wildfires, floods and hurricanes may produce unforeseeable damage to passengers, vehicles, goods and roads. Among these climate hazards, floods are the most damaging and hard to confront. With respect to traffic and the road infrastructure, devastating floods are observed every year all over the globe, inundating roadways, ruining bridges and causing fatalities. At international level, the concern about flood risk has gradually been amplified and respective action plans have been elaborated and implemented in Europe and elsewhere. It seems, however, that these action plans are hardly sufficient to prevent road flooding.

On a scale of a region or a town, it is very important to identify proactively the safest road corridors, as well as those of uncertain operability under flood conditions. By contrast to the general methods proposed by most research institutions and associations, what is really needed is the assessment of the submersion risk for the road/street network by segment and of the effectiveness of some proactive measures, either of current practice or totally innovative. In this regard, low-cost engineering operations over unsafe road corridors, such as profile uplift, drilled wells, lateral protection boards or additional drainage systems, may prove beneficial, once these low-level segments are identified. The dual digital concept may prove very effective in the fight against roadway inundation and traffic blockage. The concept consists of two digital models, the digital testing model and the digital twin model and is meant for Road Operators willing to safeguard the infrastructure and to protect travelers. It consists of a digital flood-testing model and a digital twin model.

The digital flood-testing model makes possible a virtual inundation of the road corridor and the surroundings by rainfall water over a return period of >250 years. Every proactive measure or set of measures against flooding, to be potentially taken, can thus be tested proactively using this model and the respective outcome, in terms of flood impact alleviation, can be assessed.

The digital twin model is an interactive tool providing real-time information, in case of flood. It observes constantly and evaluates the rate of the water level rise and forecasts eventual emergency situation by means of these digital tools. Road Operators can identify the most vulnerable and the safest Road Corridors, as well as to spot low-lying and flood-prone road segments along Critical Corridors. Accordingly, they will be able to plan actions to upgrade and reinforce the deficient infrastructure but also to elaborate suitable emergency plans in order to effectively face aggressive events of extreme severity. The paper presents the layout of this dual digital concept and some measures to upgrade low-lying road segments by conventional as well as by innovative techniques.

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Background

During the last decades, the frequency and the intensity of extreme weather events marked a net increase worldwide. Aggressive events, such as, floods, storm surges, wildfires and snowstorms, constitute a big threat to the integrity of the road transport system, since they can severely harm critical road assets and the infrastructure. The threat may become even more severe to drivers and travelers, unexpectedly obliged to face harsh weather events. In the field of road adaptation to climate hazards, multiple scientific approaches and protection measures taken have not produced yet the expected results. The road transport sector still suffers from climatic hazards and undergoes severe deterioration in the advent of extreme weather events, often turning into disasters. The need for a method of reliable risk assessment leading to effective proactive and reactive measures, with view to reinforcing the

road infrastructure and to protecting travelers and vehicles, still remains [1].

Among all climate hazards, flooding is certainly the most common and the most disastrous, since global temperature rise produces heavier and more frequent rainstorms. Consequently, devastating floods occur every year worldwide. In 2024, disastrous floods were reported to have taken place in India, Bangladesh, Chad, Niger, Brazil, as well as in many European countries, namely in Spain, Germany, Belgium, Czech Republic, Poland and other. Such flood events produce severe damage, fatalities and a totally helpless situation. Recovery is always long and full of impediments [2-4].

Road infrastructure is typically designed to withstand high rainfall intensity. Road engineers take into account historical data on weather events, to design drainage assets, culverts and pipes of sufficient strength and capacity. However, it seems that, recently, the historical record on natural hazards is no longer a reliable

predictor of future disasters Harsh events of extreme severity become more frequent and the rate of return period for the design of drainage assets climbs from 100 to 250 and, possibly, to 500 years [5,6].

The serious concern about the vulnerability of roads and streets with regard to climate hazards has driven Road Authorities and Institutions to conduct research on the subject and to develop guidelines for the protection of road infrastructure Moreover, individual scientists and researchers have proposed risk assessment methods and reinforcement measures to fight against climate threats [7-16].

Since the early 2000', road adaptation to climate change has been a persistent challenge to National Road Authorities in Europe and in other industrialized countries. Gradually, the concern about climate hazards has been amplified and respective action plans have been elaborated by national and international Institutions. Protection measures against flooding, implemented in various countries, United Kingdom, Denmark, France and other, are reported to have produced beneficial effects on the road network integrity.

However, it must be clearly stressed that the current situation in the industrialized world is far from being ideal, since incessantly and every year devastating floods occur worldwide ruining properties and causing fatalities. A method for flooding risk assessment on local scale and an emergency tool for timely alert about the oncoming flood are persistent challenges and fields for further research.

Road and Floods

Climate stressors are climatic events likely to generate extreme hazards. Long and heavy precipitation, rainstorms, snowstorms, high temperature, tornados, storm surges and other climate

stressors are generating hazards of harmful impact on road infrastructure. Hazards associated with climate stressors are floods, landslides, wildfires, droughts and sea level rise, which have multiple negative impact on roads, traffic and the environment. While it is very difficult to annihilate a climatic stressor, it is possible and mandatory to fight effectively against a hazard.

Plains, valleys and flat terrain may be submerged under heavy rain or under rainstorm conditions if the runoff volume exceeds the discharge capacity of drainage assets. An extreme rainstorm is likely to generate a flash flood while a heavy and persistent rainfall will probably produce permanent flood. In either case, the road infrastructure risks getting inactive. It takes only a local submersion of short- length segment to cut off an important road corridor of many kilometers [Fig.1].

In this regard, research institutions and scientists developed methods of flood risk assessment and proposed measures to fight against flood impact on roads.

The first operational European system monitoring and forecasting floods, across Europe, is the European Flood Awareness System (EFAS). According to its internet site, the aim of EFAS is to support preparatory measures before major flood events strike, particularly, in the large trans-national river basins and throughout Europe, in general. Since 2012, EFAS is running fully operational as part of the Copernicus Emergency Management Service [17].

Some international institutions strive to elaborate methods of proactive intervention to protect the road infrastructure and assets Most of them are of general character, that is, methods which are not specifically elaborated for application in specific areas at risk of flooding (Table 3). Nevertheless, these methods may be a powerful tool in the fight against flood hazards [18].

Table 1: Flood Risk Assessment Methods and Models (from literature search)

Institution	Flood Risk Assessment of Roads	Area / Network	Proactive Measures		Reactive Measures
			General	Specific	
PIARC 2015, All Hazards [6]	Assessment of impact severity and probability	Road network	Structural and green	Using algorithms	-
EU / Van Ginkel et al, 2021, Floods [16]	Inundation maps and digital models	Assessment by region	-	-	-
AUTH 2020 / Mouratidis, All Hazards [5]	-	Road network	Structural, green and digital	-	-
FHWA 2024 / Leung, Floods [17]	Digital model + AI	Street network	-	-	-
EU ROADAPT 2016, All Hazards, [1]	Vulnerability assessment	TEN-T network	Structural and green	Using algorithms	-
WORLD BANK All Hazards [12]	Vulnerability and road assessment	Road assets	-	-	Emergency planning
EFAS 2011 Floods [19]	Forecast model	Post-event & precipitation maps	-	-	-
EEA 2017 Floods [4]	-	Vulnerability by region	Structural and green	-	-
UK, Univ. of Huddersfield 2024, Floods [20]	-	Roads, streets pavements	Structural and green	-	-

Floods, Traffic and Road Infrastructure

Floods may overflow a significant part of land, properties, habitations and the road infrastructure, namely roads and streets, usually those constructed on low embankments or on the ground surface. Considering human life and health as the first priority in case of flooding, the road infrastructure has a very important role to play in a concerted public action for the safeguard of citizens and the safe movement of emergency vehicles. Therefore, it is important to perceive not only the risks to the integrity of road assets generated by flooding, but also the risks related to traffic safety during or in the aftermath of a flood event [19,20].

Several flood-induced risks, related to the integrity of the infrastructure (Table 1) and to traffic safety after excessive flooding (Table 2), are displayed and classified by level of severity.

Table 2: Flood-Induced Risks to the Road Infrastructure

High	Significant	Low
• Approach embankments • Abutments • Bridge piers • Wing walls	• Embankments (no surfacing on slopes) • Retaining walls • Earth shoulders • Gravity walls • Embankments on steep slopes	• Cutting sections • Natural slopes • Rigid pavements • Embankments with slope surfacing • Vegetated slopes
• Heavy trucks on saturated embankments • Heavy trucks on unstable bridges • Unsuspended traffic before post-hazard inspection and placement of signage	• High-speed on littered / wet asphalt courses • Heavy trucks on distressed pavements	• Traffic on road with weathered markings • Traffic on roadway at cutting sections after landslide debris removal but prior to soil stability measures

Engineering structures, including drainage systems, bridges and culverts, are designed to withstand flood conditions over a return period of 50 and, rarely, 100 years. However, recent catastrophic events, all over the world, prove that rainfall intensity and height may overrun these assumptions.

Digital Models to Fight Against Roadway Submersion and to Minimize Flood Impact on Traffic

On a scale of a region or a town, it is very important to identify proactively the safest road corridors, as well as, those of uncertain operability under flood conditions. By contrast to the general methods and guidelines proposed by most research institutions and associations, what is really needed is the assessment of the submersion risk for the road/street network and of the effectiveness of some proactive measures. In this regard, low-cost engineering operations over unsafe road corridors, such as profile uplift or additional drainage systems, may prove beneficial, once these flood-prone segments are identified.

Moreover, the real-time observation of a flood event, with respect to the road/street network, may prove decisive in an emergency plan of evacuation and intervention. Roads need to remain open and traffic must be directed to safe corridors.

The innovative hereby method consists of.

a) A digital flood-testing model, that is, of a Digital Ground Model (DGM), where the advent of a flood incident is investigated, in terms of road/ street corridors submersion. Moreover, every potential measure or set of measures is tested over the DGM and the respective outcome, in terms of flood impact alleviation, is evaluated. Thus, the beneficial impact of every measure or set of measures and the respective cost is evaluated.

b) A digital twin model, consisting of a set of sensors, floating balls and CCTV, adequately placed on riverbanks, drainage pipes and culverts to identify the rate of groundwater rise and the probability of flooding, likely to affect the road and the street network.

The Digital Flood-Testing Model

The development and the implementation of the Digital Flood-Testing Model constitute the first stage of the hereby outlined method. It consists of a digital ground model (DGM) of the area and the road/street network under investigation, were peak runoff volume, for different scenarios, over a return period of 250 or 500 years, may create full or partial submersion of roadways. Reasonably, the digital ground model must simulate realistic conditions with regard to riverbed and banks, bridges, culverts and drainage systems, while it must accurately delineate the flood-prone plain under investigation.

The implementation of the Digital Flood-Testing Model aims at 2 distinct objectives:

1. Perform a Road/ Street Vulnerability Assessment (risk of submersion) and classify road corridors and road segments by flooding susceptibility over different rainfall return periods.
2. Determine the most effective Engineering Intervention at Deficient/ Low-Lying Short Road Segments (widening riverbeds, construct new drainage canals and assets, proceed to red line uplift at short, low-lying, road segments).

The Digital Testing Concept is designed to provide answers to crucial questions regarding risk of flooding over road and street networks:

- Which corridors and road segments are at high risk of flooding?
- How deep and how long would this submersion be by corridor?
- What are the most effective engineering measures (widening riverbed, raise red line, construct artificial ponds, vertical wells) required to prevent this submersion?
- What is the cost of these measures?

On a scale of a catchment area, it is important to examine and check on the impact of extreme rainfall events on the road infrastructure and its eventual submersion. This may be carried out using digital ground models, simulating the terrain and the road corridors. For each increment of return period of rainfall, the runoff volume flowing into the examined area is compared to the total discharge capacity. On a scale of a road corridor, the water level of a flooded area may be juxtaposed to the profile and the red line of roads and streets, thus unveiling the overflowed parts/ segments and the rate of water level rise until submersion over each road corridor. Since extreme rainfall events are so frequent nowadays, this search and checking must attain, at least, a return period of 250, and, possibly, 500 years.

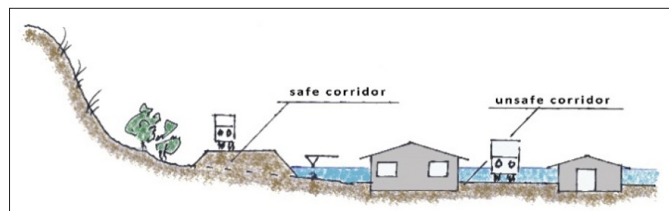


Figure 2: Visualization of the Digital Flood-Testing Model

The Digital-Twin Model

The Digital-Twin Model (DTM) is the reactive tool in the case of a potential flood event. It consists of physical indicators, namely, sensors, floating balls and CCTV, adequately placed on river and watercourse banks, culverts, bridge piers, sign posts and drainage systems (hardware of the Model) to provide real-time measurements of the water level. The signal from the physical asset is transmitted to the processing software through a “physical asset-edge device- digital network- processing software” chain (Fig.3).

The DTM is equipped with a processing mathematical algorithm, able to interpret the water level measurements, and to deduce the rate of water level rise. Reasonably, the time of concentration, gradual land saturation and other hydrological parameters must be taken into account for precise estimates. This mathematical process leads to an estimate of the remaining time for eventual submersion of each road or street corridor and provides the Competent Authorities with reliable information about the time remaining to set forth actions directing traffic to safe road links. In case of a flood emergency, Competent Authorities, local, regional or other, must proceed to the following actions:

- Inform drivers, travelers and individuals. A water height of 30cm renders a roadway unsafe.
- Suspend traffic and proceed to road closures, where water level is about to overflow road/street corridors
- Direct traffic to safe road links
- Evacuate residential areas risking submersion
- Launch auxiliary drainage measures (if any, retention basins, emergency water gates).

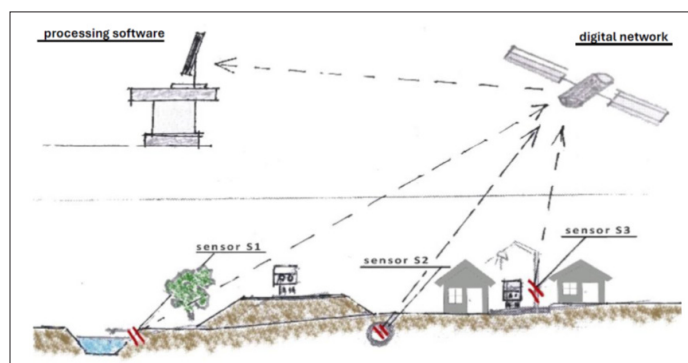


Figure 3: Visualization of the Digital-Twin Model

Proactive and Reactive Measures

Setting in operation a strategic plan consisting of proactive and reactive measures to fight against flood hazards is the best option to protect individuals and properties, traffic and the road infrastructure. Even if, in many cases, this plan may prove insufficient or ineffective, it is certain that, under extreme rainfall conditions, the overall road infrastructure would turn up less accessible without proactive or reactive measures. Generally, measures can be classified into proactive and reactive, although, even reactive measures should be planned in advance.

Proactive measures are classified into two categories: a) preventive measures, aiming to reduce runoff water volume and to prevent submersion of the road structure (Table 4) and b) protection measures, intended to reinforce the road structure in case of upcoming inundation (Table 5).

Table 4: Preventive Measures Against Flooding [8]

Preventive measures	Objective
Widen and deepen riverbed	Increase outflow discharge capacity
Construct additional culverts	Increase discharge capacity
Allow for enhanced vegetation uphill	Reduce runoff inflow
Drill vertical wells	Increase infiltration volume
Create small dams and artificial ponds uphill	Reduce runoff inflow
Artificial watercourses/channels	Increase outflow discharge capacity

Table 5: Protection Measures Against Flooding [8]

Protection measures	Objective
Install lateral concrete barriers	Prevent roadway flooding
Lay Rip-rap on slopes	Protect road infrastructure
Deepen toe ditch	Prevent water level rise
Check drainage network	Enhance surface drainage
Raise roadway profile	Prevent roadway flooding
Remove debris from culvert inlets	Prevent erosion

On the other hand, reactive measures may be effective and decisive, in case of a flood, especially these planned in advance (Table 6).

Table 6: Reactive Measures to Ensure Smooth Traffic

Reactive measures	Comment
Remove on-street parking	In the beginning of the flood event
Debris removal from culverts, inlets	Emergency patrols
Proceed to traffic diversion to safe corridors	Traffic management
Continuous check on bridges, overpasses	Structural integrity of piers, abutments
Divert (part of) rainwater runoff volume to high capacity watercourses	Wherever possible
Install lateral barriers and pump the blocked runoff water	Wherever possible

Conclusion

Flood-induced risks to the road infrastructure constitute a persistent challenge to road engineers and operators. Even more important are risks related to traffic on roads and streets, damaged by flood events after extreme rainfall. Protection measures, in this case, are obligatory and crucial.

The present approach, introducing two digital models for investigation and alertness, goes beyond the well- established methods of flood risk assessment for road networks. The objective is to identify the most vulnerable road segments and to determine

the most suitable measures, specifically tailored for each road or street network. Moreover, through the digital-twin technology, the gradual water level rise may be monitored, in case of a flood event, and a set of reactive measures to enhance trafficability may be implemented.

The proactive checking on the effectiveness of measures can produce risk mitigation and save resources. It may be combined with green measures uphill which are meant to reduce runoff discharge downward.

Although, in several cases, the disaster produced by a flood event is immense and makes any measure seem pointless, this, in fact, is hardly true. Even in case of extreme hazards, engineering and green measures taken proactively may alleviate the impact of the disastrous event. They must observe the fundamental triptych of fighting against floods: a) Reduce runoff water inflow, b) Increase discharge capacity, c) Protect vulnerable assets and consider human life and survival as the utmost priority.

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