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GCRF-OSIRIS LITERATURE REVIEW

Optimal Investment Strategies to Minimize Flood Impact on Road Infrastructure in Vietnam

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1. Background

The literature, discussed below, comes in several forms. Some is written for academic purposes, published in academic journals. Other literature relates directly to specific international development and Disaster Risk Reduction (DRR) programmes/projects, in the form of policy guidance, project documents, evaluations, and public information materials. Some literature comes from Vietnamese government agencies relating to urban development plans and strategies. Most is written in English, and some specific items for Vietnam are written in Vietnamese. This review examines the most useful literature available to inform the GCRF-OSIRIS project, highlighting specific points of relevance.

The project focuses on Hanoi, the capital city of Vietnam, which is regularly impacted by pluvial flooding. In recent years the city's authorities have attempted to reduce the economic and social impacts of flooding by improving drainage systems, but their efforts have been more than counter-acted by the combined negative effects of rapid urbanisation and climate change. In 2016, a summary of key urban flood risk management challenges in Vietnam provided by Vietnamese officials at the international Technical Deep Dive on Integrated Urban Flood Risk Management conference in Tokyo (Newman & Jain, 2017), included the following points:

> *"Consistent coordination between state agencies needed for integrated flood management is lacking. The lack of coordination between the ministries and localities causes functions to overlap. Vietnam does not have tools or a system for monitoring flooding, nor has it developed guidelines on safety criteria; Vietnam's urban planning method is obsolete and needs to be updated with new methodologies. New technology is not integrated in urban water management."*

The impacts of flooding in Hanoi are most profoundly experienced along the city's road infrastructure system, effecting traffic, markets, the local economy, and pubic services. Yet, when writing about the challenges and solutions for sustainable urban transport in Vietnam (Tran, 2016), the General Director of Vietnam's Department of Transport did not mention the issue of flooding. This is itself informative, demonstrating that other challenges, especially to increase the size and reach of the city transport system, and increasing the speed at which that development is achieved, take higher priority for government officials. Unfortunately, these priorities are likely to exacerbate flood risks, without careful attention.

The Climate Action Plan for Hue City (Phong & M-BRACE, 2014) – a city in central Vietnam – demonstrates the need to mainstream climate change into city planning, including transport planning. In common with many Vietnamese cities, during the preparation of the Action Plan, transport infrastructure was assessed to be the category of infrastructure most vulnerable to the impacts of climate change (including increasing flood risk).

(Tran, et al., 2016) note the different future climate scenarios for temperature and rainfall in Hanoi as follows.

Change in average annual degrees celcius compared to the period 1986 to 2005:

RCP 4.5 scenarios			RCP 8.5 scenarios		
2016-2035	2046-2065	2080-2099	2016-2035	2046-2065	2080-2099
0.6	1.7	2.4	1.1	2.2	3.9

% Change in annual rainfall compared to the period 1986 to 2005:

RCP 4.5 scenarios			RCP 8.5 scenarios		
2016-2035	2046-2065	2080-2099	2016-2035	2046-2065	2080-2099
12.6	17.0	24.0	9.9	17.8	29.8

The report's findings on sea level rise for Vietnam, which would be (worst case scenario) up to 73cm by 2100, would affect the Red River Delta and would require revised planning for the main dyke protecting Hanoi from flooding from the Red River. But this dyke is not within the scope of the OSIRIS project.

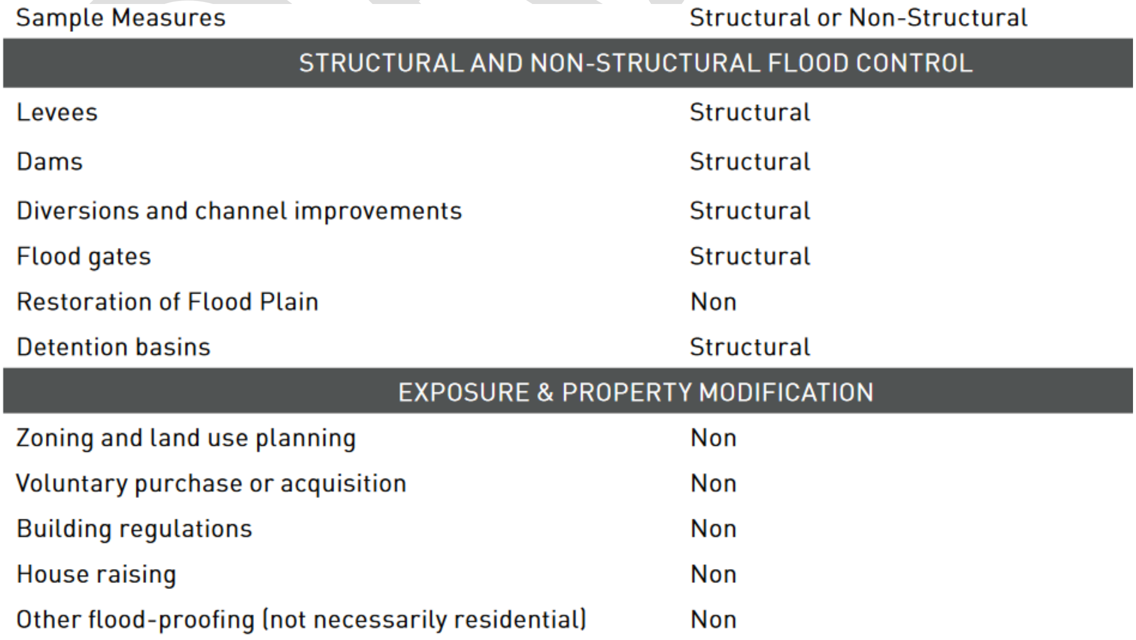
2. Challenges

There is a lack of OR research focusing on optimizing investment strategies to mitigate the impact of floods on the road infrastructure, in any country. There is no literature specifically on the application of OR in this field, and therefore the GCRF-OSIRIS project is forging a new path.

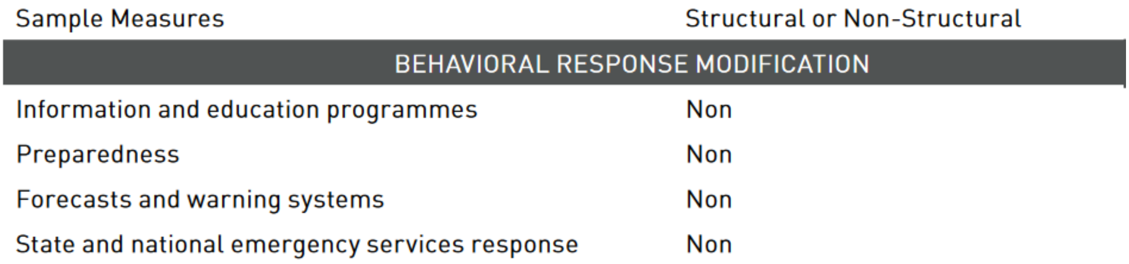
There are several issues within relevant literature, which require consideration when selecting how to optimize investment strategies.

First there is a focus on whether investments are for structural or non-structural measures (UNISDR, 2017). Structural measures are also sometimes described as 'hard' measures, typically, improved roads and drainage systems, while non-structural measures can be referred to as 'soft' measures, that is, measures which do not include construction, such as raising community awareness and capacities, development of early warning systems, etc. The World Bank (Jha, et al., 2012) provides a detailed overview of urban flood risk management, making clear the division and the complementarity of structural and non-structural investment measures (Chapters 3 and 4), and stressing the advantages of integrating the various measures to produce optimum results. This approach is challenging for optimization modelling because it rightly implies that the more variables and constraints which can be introduced to an optimization model – including variables for both structural and non-structural measures – the better the model will reflect reality and identify the most cost-effective investment options. (Hawley, et al., 2012) make a classification of 15 types of measure, labelling them as structural or non-structural, as below.

Figure 1- Samples of structural and non-structural measures (Hawley, et al., 2012)



Sample Measures	Structural or Non-Structural
STRUCTURAL AND NON-STRUCTURAL FLOOD CONTROL	
Levees	Structural
Dams	Structural
Diversions and channel improvements	Structural
Flood gates	Structural
Restoration of Flood Plain	Non
Detention basins	Structural
EXPOSURE & PROPERTY MODIFICATION	
Zoning and land use planning	Non
Voluntary purchase or acquisition	Non
Building regulations	Non
House raising	Non
Other flood-proofing (not necessarily residential)	Non



Sample Measures	Structural or Non-Structural
BEHAVIORAL RESPONSE MODIFICATION	
Information and education programmes	Non
Preparedness	Non
Forecasts and warning systems	Non
State and national emergency services response	Non

Their analysis found that most economic research had focussed on those measures classified as structural, (dams, levees etc), and very few studies were available on the benefits of institutional or other ‘softer’ investments in flood risk reduction. Little documentary evidence was available, for example, on the costs versus benefits of property modification, and very few studies were also found on the costs and benefits of behavioural modification, such as early warning systems, although these are expected to have high economic returns. They also found no significant studies on ‘portfolio approaches’ – “*the combined use of early warnings systems, zoning, and drainage improvements”.* Their review suggested that such portfolio approaches *“should result in a much greater reduction in flood losses when implemented as a package rather than as stand-alone activities. The gap in evidence on this is, as a result, a significant limitation for decision-makers.”* They concluded that: “*The wider literature suggests that softer strategies for flood risk management are more technically effective, particularly under conditions of uncertainty, and are likely to be much more cost-effective [than hard structural measures].”*

Second, there is the issue of whether measures aim to reduce the level of flood waters, or reduce the human or economic impacts of given levels of flood waters. Often this duality corresponds with the structural/non-structural duality, but not always. For example, improved planning (to incorporate climate change scenarios into transport network planning) is itself a soft measure, but it would probably lead to reducing the level of flood waters; and raising the base levels of buildings is a hard measure which would reduce the impacts of given levels of flooding.

Third, is the question of whether ‘Optimal Investment Strategies’ should include only consideration of public/government investments versus public/government returns, or whether optimization should include consideration of private/household investments and returns, such as those documented by the Asian Cities Climate Change Resilience Network (Danh, 2014). Most studies typically only consider public infrastructure and public returns. But the fact is that economic and social costs of the impacts of floods are largely absorbed at household level, often by relatively poor households who are unable to travel to work, or unable to take children to school, during intense flood situations. The costs of such household level impacts are often not included in analysis, and support to household-level investment is normally not considered among government investment strategies.

Fourth and generally, the issue of distribution of benefits is missing from many calculations of assessment of benefits of flood risk management interventions. This is highlighted in a study of the Rohini River Basin in India (Kull, et al., 2008). It notes: *“Cost-benefit analysis is a useful support tool for decision-making, but it does not capture distributional (who benefits?) and non-monetizable aspects of disaster risk reduction well. It should, thus, not be used alone, but rather concurrently with more vulnerability and stakeholder-driven processes.”* In fact, most investment decision-making tools disregard any gender differentiated impacts of flooding, and in instances where government investment reaches household level, they is unlikely to be any consideration of whether optimal investments will be those channelled through women or through men.

Fifth is the issue that some measures, and the effect of some measures in reducing the impacts of flooding, are more easily quantified than others. Economic damages are more quantifiable and therefore often labelled ‘tangible’, whereas social and environmental impacts are difficult to quantify consistently, and hence often labelled ‘intangible’ (Dutta, et al., 2003) (Smith & Ward, 1998). Table 1 shows a categorization of tangible and intangible impacts (Penning-Rowsell, et al., 2005).

Table 1- Classification of a sample of measurements

			Measurement	
			Tangible	Intangible
Form of Loss	Direct	Social	Damage to household assets	Health impacts Injury and casualties
		Economic	Damage to infrastructure, roads, housing	Inability to travel to work
		Environmental		Contamination of water supplies
	Indirect	Social	Loss of Industrial Production	Mental health/stress Reduced time in education for children
		Economic	Stock and produce are unavailable for sale and purchase	Absorption of flood impacts by other development goals, e.g. reduced poverty alleviation
		Environmental		Increased pollution from disrupted garbage

Sixth is the problem that developing countries typically lack the volume and types of data required for accurate modelling of the effects of a range of investment options. This issue has been highlighted in Nepal (Dixit, et al., 2008) as follows:

> “*There is little data on the effectiveness of either these structural measures or the informal self-initiated responses of individuals or communities. There is a dearth of even the most basic of data, such as precipitation within the basin, river flow levels, areas of flooding, and investment in the construction of flood control structures, whatever data is available is often incomplete or of uncertain quality. With so little information, making effective decisions regarding flood control strategies is difficult. Because there is so little quantitative information, it is essential to turn to qualitative approaches to identifying and evaluating alternative strategies as a first most basic step towards making informed decisions*.”

As a result, the study recommends a “*qualitative CBA methodology*” which comprises participatory workshops with stakeholders at all levels, including communities, and ranking of costs and benefits of flood risk reduction interventions. The situation is different from Hanoi as a capital city, but the process and the reasoning behind it is informative. The same lack of data issue is included in a study of disaster risk (Roy, 2018). The document describes a typical urban flood risk assessment in Myanmar: *“None of the models also incorporated the urban drainage network. and consequently, flood risk due to intense storms in urban areas could not be accurately modelled. Additionally, tidal surge effects have not been simulated and there may be additional flood risk, particularly in coastal areas. Climate change scenarios have not been modelled as well. Data on flood velocity were not available for any of the flood model simulations. Such modelling parameters and boundary conditions used in the modelling need to be clearly understood by DUHD and the city government, and considered when interpreting the results. Any inferences drawn from the modelling result should be treated with caution and refined when additional data becomes available.”*

Seventh is the emerging issue of climate change. Models cannot now rely entirely on existing data, but need to consider how variables will change, according to downscaled climate change scenarios, and extrapolate relevant data under such scenarios. (Moench, et al., 2009) notes:

> *"Moving beyond general projections requires familiarity with the scientific literature on climate change and the ability to scale the scenarios that can be generated using large-scale General Circulation Models (GCMs) to the specific area and hazard of concern."*
>
> *"The ability of cost-benefit analysis and other techniques to assess the economic viability of DRR investments requires probabilistic information (frequencies and magnitudes) of potential events such as floods and droughts."*

Eighth, lack of broad participation in the assessment of disaster risk impacts and measures is often a critical issue (Roy, 2018):

> *"Disaster risk assessment is not a one-off exercise. Longer-term in-country/local capacity is needed to update such assessments regularly. Moving forward, there is an urgent need to include local technical organizations, such as universities, in leading disaster risk assessment processes. Faculties involved in environmental sciences, geography, water resources, and structural engineering, among others, should be capacitated to lead disaster risk assessments, and guide masters and PhD students in undertaking research."*

The OSIRIS project successfully addresses this issue, with broad participation from local stakeholder groups, including government, academic, and civil society.

Finally, there are certain limitations to what the OSIRIS project can achieve in terms of modelling, because these OR tools have not been applied to this problem any similar circumstances before. Not all lessons from the literature can be immediately incorporated within the OSIRIS model, but if OSIRIS can demonstrate its utility, then remaining lessons can be used later, to evolve the model to a more advanced stage.

3. Existing Projects in Vietnam

In practice, among the largest recent investments in flood mitigation in Hanoi has been the Hanoi Drainage Project, which cost a little more than £140 million over a period of 10 years, from 1995 to 2005. The report (Vietnam-Japan Joint Evaluation Team, 2009) had positive results, and led to a second phase of the project which took place from 2009 to 2016. The high cost of both phases was justified by the project's ambitious objective, *"To control the floods in Hanoi city and improve the water quality of the rivers, lakes and reservoirs by the construction of flood works and the rehabilitation of the channel and sewage system"*. All stakeholders, especially the Vietnamese government which borrowed the funds from Japan, had a strong interest in optimizing the investment to ensure that it was wisely spent. The evaluation document at the end of the first phase, contains useful technical information and data on the drainage system, and on the factors required to upgrade the system. It contains a useful map of the flood gates and pumping stations which take water out of the city to the Red River (Figure 1 on page 8). Additional, more detailed information about the project can probably be found within the project design documents which may be possible to access if needed. But again, referring to data issues, the document states that "*due to the unavailability of statistical data for the costs of damage and loss caused by floods in Hanoi, the degree of impact [of floods in Hanoi] cannot be analysed in a quantitative manner*."

Overall, after identifying its evidence, the evaluation concludes that *"This project has largely achieved its objectives, therefore its effectiveness is high."* However, outside observers may have doubted this conclusion, partly because the evaluation team comprised mainly government officers and Japanese colleagues with a clear interest in promoting positive outcomes, and partly because Hanoi's roads have continued to flood each year (VietNamNet Bridge, 2017). This demonstrates that: a) official pre-project cost-benefit analyses cannot always be trusted to provide accurate estimates of the financial value of benefits of an investment; and b) new methods to assess and compare flood mitigation interventions, especially methods which rely on objective, mathematical processes such as OR, should be in demand.

(Tran & Tran, 2014) report on a relatively small study carried out in mid-2013, which used simulated future 'Digital Elevation Maps' (DEMs) to identify major flaws in the Da Nang (third biggest city in Vietnam) City Development Plan up to 2050. This study provided a clear example of how city planning in Vietnam lacks flood sensitivity, and needs further attention to incorporate flood sensitivity into zoning and construction planning.

(Dang & Hieu, 2013) review the extent of major flooding across all areas and districts of Hanoi in 2008. The study compares different areas of the city.

(Leducq & Scarwell, 2018) outline some of the big picture changes in the Hanoi Master Plan to 2030, including the creation of a 'Green Corridor' to the west of the current urban core, and a so-called Blue Corridor corresponding to the valleys of the Day and Tich Rivers, to take the overflow of the Red River in the event of potentially catastrophic floods.

The World Bank's city profile of Hanoi (Prasad, et al., 2009) focuses on large scale, structural measures to reduce flooding, and lists existing projects/programmes (at that time in 2009) which were enabling the city to adapt and prepare for future impacts of climate change. Among the measures being taken was the 5 million hectares forestation programme, which planted and protected forests upstream from Hanoi. The project was a success in terms of tree planting, but its effect on flood risk reduction in Hanoi remains unclear.

(Luo, et al., 2018) propose an acceptable model to simulate flooding in central areas of Hanoi based on four historical and extreme rainfall events and to identify sustainable approaches for urban flood management under present and climate change conditions. Their flood analysis shows that reservoirs, pump systems, green roofs and vertical greening systems, and underground water storage systems are potential measures to reduce water depth and flooded areas.

(Duy, et al., 2019) propose to simulate the flood vulnerability in 2020 of Ho Chi Minh city to show that the road network of the city is not resilient to floods. In 2020, they state that the extent of vulnerable roads will increase by 41.32% in the city. The authors propose to improve the resilience of the road network through a conceptual model based on flood vulnerability assessment. However, due to a lack of data, their model has to be improved.

4. Existing Tools and Methods

When considering tools to comparatively assess the value of different investment options, most literature focuses on Cost Benefit Analysis (CBA), although other tools are sometimes used, and in some situations may be more useful.

(Mechler, et al., 2014) compare the use of CBA with other tools, to assess whether or when different tools might be most practically useful to assess and select from among different flood reduction measures. The review makes a tabula comparison of CBA, cost-effectiveness analysis, multi-criteria analysis and robust decision-making approaches (see Table 2).

Table 2 - Comparison of the CBA with other tools (Mechler, et al., 2014)

Tool	Opportunities	Challenges	Typical Application
CBA Cost-Benefit Analysis	Rigorous framework based on comparing costs with benefits	Need to monetize all benefits, difficulty in representing benefits such as value of life.	Well-specified hard resilience projects with economic benefits
CEA Cost-Effectiveness Analysis	Ambition level fixed, only costs compared. Intangible benefits (eg. loss of life) do not need to be monetized.	Ambition level needs to be fixed and agreed upon.	Well-specified interventions with important intangible impacts (e.g. loss of life)
MCA Multi-Criteria Analysis	Consideration of multiple objectives and plural values	Subjective judgments of values required, which hinder replication	Multiple and systemic interventions involving plural benefits (e.g. infrastructure plus education)
RDMA Robust Decision-Making Approaches	Address uncertainty and robustness of decisions	Technical and computing skills required	Projects with large uncertainties and long timeframes (eg. climate change, where flood return periods become more uncertain)

Similarly, (Price, 2018) describes the same set of tools (in comparison to CBA) as follows: *"Cost-Effectiveness Analysis (CEA): identifies least-cost options to meet a certain predefined target or policy objective (which, in effect, represents the project benefit measured in monetary terms). CEA does not require the quantification of benefits, as the project costs are the key variable of consideration to be minimised. Multi-Criteria Analysis (MCA): assesses how well DRR investments achieve multiple objectives such as economic, social, environmental and fiscal goals, as well as co-benefits. Using selected criteria and indicators as verifiable measures for monitoring across time and space, MCA observes and evaluates DRR investment performance in quantitative or qualitative terms. Because MCA does not require the monetisation of all values, it is seen as potentially more palatable and flexible than CBA and CEA. A major challenge, however, is assigning weights to the criteria. Robust Decision-Making Approaches (RDMA) has received increasing emphasis recently, particularly in the context of climate change adaptation. Comprising both quantitative and qualitative methodologies, RDMA draws the focus away from optimal decisions (such as those supported with CBA and CEA) and aim to identify options with minimum regret, that is, minimal losses in benefits of a chosen strategy under alternative scenarios where some parameters are highly uncertain, and impacts are potentially devastating or irreversible."*

The Institute for Social & Environmental Transition (ISET) (Institute for Social & Environmental Transition, s.d.) – a US-based agency – has developed insightful studies on CBA related to flood risk mitigation or climate change adaptation interventions in developing countries. For example, (Mechler & Team, 2008) introduce key concepts of risk, vulnerability, disaster, and the evaluation of social, economic and environmental impacts.

Whilst most analysis of economic losses due to flooding focuses on losses to infrastructure and GDP, there are studies such as (Danh, 2014) which succeed in quantifying the economic losses absorbed at household level as a result of floods, and which are often omitted from official figures used to evaluate the financial value of flood damage and loss. The methodology used in this study, in Can Tho City in the Mekong Delta region of Vietnam, is relevant broadly, and especially relevant in Vietnam's context. The study used an 'opportunity cost' method to show that an average household's total annual economic losses due to flooding in Can Tho was about USD 642 per household, representing on average, 11% of each household's income. The study also succeeded in putting financial values on common flood risk management measures taken at household level, such as installing sandbags, moving furniture to higher places, and elevating the base of the house. The methodologies used in this case study would be useful to produce fully comprehensive assessments of the economic costs of flood damage and loss, including both public costs and those costs absorbed by households. The methodologies would also be useful to assess the extent to which public finances should be distributed to households impacted by floods, where household spending on relief and mitigation measures could be more cost-effective than government spending. The survey materials used by study appear to be gender-responsive, but gender is not an issue covered in the report.

Mathematical modelling is also used to optimize benefits of different courses of action. An initial step is to determine which objective function to optimize. The OSIRIS project considers estimation of flood damages. Damage functions are used to evaluate costs and losses caused by floods to the infrastructures or the environment. The flood-depth damage function which links the water-depth to direct damages is the most used in mathematical modelling (Tariq, et al., 2014). However, these functions need real data during flood events, implying that there are specific to an area and highly dependent on the availability of the data.

Damage functions have been developed to estimate losses due to floods (Dutta, et al., 2003), (Jonkman & Vrijling, 2008), (Hammond, et al., 2015), (Kefi, et al., 2018). (Dutta, et al., 2003) present different damage functions for urban, rural and infrastructure losses. In (Kefi, et al., 2018), the authors evaluate the tangible damage caused by floods in the urban area of To Lich river in Hanoi city. Based on data collected from surveys, they develop an accurate function which correlates the flood-depth and the damage for buildings in residential and non-residential areas from a regression analysis. In (Win, 2018), flood damage functions are provided for house and agricultural damage from a regression analysis. However, their results show that these functions are not accurate compared to the observed damages. (Jonkman & Vrijling, 2008) provide a function which correlates the flood depth to the mortality rate.

Regarding the impact of floods on congestion and traffic flow, it is difficult to capture and to understand the link between flood events and these impacts (Suarez, et al., 2005), (Sohn, 2006), (Pyatkova, et al., 2019). Road damage due to floods can be either direct, such as physical damage to infrastructure, or indirect, such as increases in carbon emissions due to congestion (Hammond, et al., 2015). Several works have focused on the impacts of disaster on road networks (Hammond, et al., 2015), (Faturechi & Miller-Hooks, 2015). In 1964, the U.S. Bureau of Public Roads (BPR) provided a function to compute the travel time on a road according to the traffic volume which is widely used to evaluate congestion or traffic delay in the literature. In order to take account of urban traffic which is different from the US, (Li, et al., 2018) consider an adapted BPR function to evaluate the impact of floods on traffic delays and congestions in Shanghai. (Faturechi & Miller-Hooks, 2015) propose a review on transportation system performance during disaster events. They also provide insights to assess the measurement of network performance based on risk, reliability, robustness, vulnerability, survivability and resilience. Recently, (Pregnolato, et al., 2017) first propose a function to link vehicle speed and standing water derived from video analysis and quantitative analysis from the literature review. They use their function to estimate the travel time delay caused by the flood of June 2012 in Newcastle in the UK.

5. Operational Research

Disaster management aims to optimize pre-disaster (preparedness, mitigation) and post-disaster (response, recovery) decisions (Galindo & Batta, 2013). In the OSIRIS project, the OR team focuses on the flood mitigation decisions in Hanoi, that is, planning decisions which will minimize the impact of flooding on road infrastructure.

OR has proved its utility in enabling industry to save costs in fields such as supply chain, logistics and transport management. The OSIRIS project transfers this utility to flood mitigation management, by determining the most efficient mitigation measures for implementation over the long-term, under several constraints such as budget, to optimize mitigation outcomes. Currently in Hanoi, the benefits of flood mitigation measures are often considered independently. Methods used in OR help to answer the questions of when, how much and where to implement measures across the city. These methods also determine which subset of the available mitigation measures should be implemented, to minimize overall costs and damages.

OR problems can be solved by commercial solvers such as CPLEX, GUROBI, XPRESS among others. However, for large-scale problems, using these solvers without improvements may not be efficient in terms of computational time. Hence, other resolution methods such as heuristic algorithms can be implemented to improve the computational time or the quality of the solution. Briefly, a heuristic is an algorithm which does not guarantee any optimality criteria, but enables users to reach good and feasible solutions in a reasonable time for large-scale problems. The OSIRIS project uses heuristic algorithms to show the efficiency of OR for flood mitigation.

This review focuses on mathematical formulation of pre-disaster management. Several papers have studied pre-disaster network management to strengthen transport networks and to optimize the allocation of resources, but few works have considered this problem in relation to flooding.

5.1. OR in Disaster Management

In recent years, disaster management has been increasingly investigated by academics and practitioners in OR (Altay & Green, 2006), (Galindo & Batta, 2013), (Grass & Fischer, 2016), (Besiou, et al., 2018). However, only a few have focused on mitigation measures in flood management. (Besiou, et al., 2018) review several papers to discuss the gap between the requirements in practice and the results obtained in research, in order to motivate further studies in disaster management. (Galindo & Batta, 2013) have reviewed literature on OR and management science in the field of disaster management. They found mathematical programming to be the most used OR methodology to tackle disaster management. Table 3 shows statistics according to the contribution and the operational stage of papers from the literature.

Table 3 - Statistics on disaster management works in the literature review

	Statistics (%) (Galindo & Batta, 2013)	**Statistics (%)** (Altay & Green, 2006)
Operational stage		
Mitigation	23.9	44.0
Preparedness	28.4	21.1
Response	33.5	23.9
Recovery	3.2	11.0
Multi-stages	11.0	0.0
Research contribution		
Theory	19.3	26.6
Model	75.5	57.8
Application	5.2	15.6

The North Sea Flood of 1953 in the Netherlands caused catastrophic damages. Following this event, the government created the Delta Programme to protect the Netherlands against flooding, to ensure a sufficient supply of fresh water, and to contribute to a climate-proof, water-resilient spatial design for the country[1,2]. In 2008, The Delta Committee recommended to increase flood protection standards on dikes to compensate for growth of population and the economy since 1953 (Eijgenraam, 2014). Initial propositions were to invest 11.5 billion euros in dike improvements around the country. However, a research group in OR showed that the best solution consisted of improving standards in three critical areas only, which allowed the government to save 7.8 billion euros. The mixed integer non-linear programming model developed by the researchers is presented in (Brekelmans, et al., 2012). The authors studied investment planning in a multi-period setting with uncertain parameters to determine the optimal height of nonhomogeneous dikes to reinforce and to prevent floods. Their heuristic algorithm continues to be used by the Netherlands government. Dikes are not a mitigation measure in the OSIRIS project, but this case suggests other relevant mitigation measures for Hanoi, such as determining the optimal capacity of reservoirs. (Zwaneveld, et al., 2018) extend the results of (Brekelmans, et al., 2012) by proposing an integer programming model to determine optimal dike heights and strengths where time periods and possible heightening are discretized. (Postek, et al., 2019) consider the study of dike height where the required height of dikes depends on sea level. The authors assume a realistic case where sea level is unknown, implying that their mathematical model is not deterministic. They apply their model to the Rhine Estuary-Dretchsteden region in the Netherlands.

5.2. Increasing Resilience of Road Networks

There are several criteria for evaluation of the resilience of a network, such as the travel time, connectivity, resistance and reliability.

Several papers have examined road strengthening, to increase accessibility following disasters, in a stochastic setting. The model described by (Liu, et al., 2009) aims at strengthening a network by determining a set of bridges for retrofitting, such that the expected risk and total costs are minimized under a finite set of disaster scenarios. The authors propose to model this problem using bi-level stochastic programming. (Peeta, et al., 2010) introduce a pre-disaster problem of determining a set of links to retrofit in a network subject to random failures, to maximize the survival and connectivity of the network and to minimize the travel cost. The authors propose a bi-level stochastic programming and an equivalent deterministic model based on a shortest-path problem. The approximation algorithm developed in this paper has been applied to the Istanbul highway network. In contrast with the other studies, (Du & Peeta, 2014) consider how links can be repaired at different levels. In addition to the link failure randomness, disaster randomness is also built into their model. Their aim is to determine the optimal allocation of pre-disaster resources so that post-disaster response time is minimized. A sensitive analysis of the effect of the network structure, traffic demand distribution, and upgrading costs of the pre-disaster investment decisions, are proposed in this paper. (Miller-Hooks, et al., 2012) provide a network resilience measurement tool to assess the vulnerability of a network under disaster. They include both preparedness and the post-disaster recovery actions. The network resilience level is defined as the expected number of post-disaster journeys that can be achieved. (Dehghani & Sherali, 2016) incorporate the value of a shortest path between origins and destinations as a network measure, in addition to the connectivity. They also consider that the state of a link is not binary but is ranged between full functionality and complete failure. They propose a linear mixed integer programming model that could be solved efficiently for Istanbul's highway network.

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[1] https://english.deltacommissaris.nl/

[2] https://www.pathlms.com/informs/events/260/thumbnail_video_presentations/6877

Unlike the papers presented previously, the following literature deals specifically with road protection against flood. (Suarez, et al., 2005), state that time wasted in traffic congestion due to flood is a significant impact. Most literature considers the impact of flood on the road network itself, with only a few authors studying mitigation measures for road protection. (Sohn, 2006) proposes an accessibility index which includes the traffic volume and the decrease of distance to determine critical links to retrofit. (Starita, et al., 2016) tackle investment decisions for protecting roads against flooding in a multi-period dimension. They propose mixed integer linear programming to determine the optimal subset of links, subject to flood disruption scenarios, to build resilience over a discrete time horizon, so that the expected shortest paths cost is minimized. They develop a heuristic, based on the greedy randomised adaptive search procedure meta-heuristic and the local search heuristic, to solve large instances efficiently. The case study of Hertfordshire in the UK gives several insights about road protection measures. (Amin, et al., 2018) focus on pavement management, which consists of planning the repair and maintenance of a paved network, to optimize pavement conditions. Floods and prolonged standing water accelerate the deterioration of pavements and increase the repair and maintenance costs. The authors consider the problem of determining the optimal maintenance and rehabilitation operations as a mitigation measure to reduce the damage caused by flood on paved roads in Bangladesh, under a budget constraint. First, the authors propose to estimate two criteria: the geo-physical risk (probability of hazard occurrence and level of consequences after a hazard) and vulnerability of a road and pavement performance based on the duration of standing water (defined as the performance of pavements in terms of roughness progression by Bangladeshi transport authorities). Finally, they propose a mathematical formulation to minimize these two criteria under budget constraints.

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