FloodProBE

Technologies for Flood Protection of the Built Environment

Guidance based on findings from the EU-funded project FloodProBE

SEVENTH FRAMEWORK PROGRAMME

Technologies for the Cost-effective Flood Protection of the Built Environment

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Chapter 1 Introduction

1.1 Floods create a large risk to people and assets

Floods are considered the major natural hazard in the European Union (EU) in terms of risk to people and assets (Figure 1.1). Global warming is expected to lead to more severe storm and rainfall events as well as to increasing river discharges and sea level rise. This means that flood risk is likely to increase significantly. Provoked by several severe flood disasters within Europe causing the death of people and large sums of damages, the EU Floods Directive (2007/60/EG) was issued in October 2007 by the European Parliament and Council. Its aim is to reduce and manage the risks that floods pose to human health, the environment, cultural heritage and economic activity.

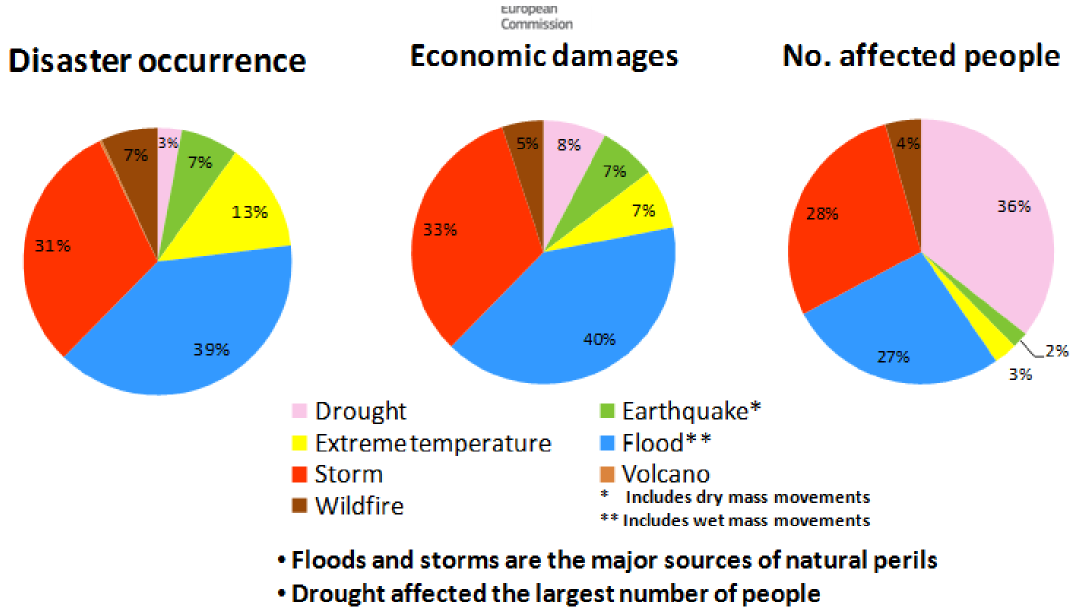


Figure 1.1 Natural hazards in Europe (1998-2008)

Source: Guha-Sapir, D., Below, R., EMDAT International Disaster Database, Centre for Research on the Epidemiology of Disasters, University of Louvain Institute for Health and Society, Brussels, Belgium

1.2 The majority of people and assets are located in urban areas

Climate change and the concentration of population and assets in urban areas are main factors likely to affect flood risk in the future. Urban systems contain assets of high value and complex and interdependent infrastructure networks (i.e. power supplies, communications, water, transport etc.). The infrastructure networks are critical for the continuity of economic activities as well as for the people's basic living needs. Their availability is also required for fast and effective recovery after flood disasters.

1.3 There is a need for knowledge to manage these flood risks

Flood Risk Management (FRM) is defined in the FLOODsite EU Project (www.floodsite.net) as the 'continuous and holistic societal analysis, assessment and mitigation of flood risk'. In line with this definition, flood risk management can be roughly divided into two parts: flood risk analysis on the one hand and risk mitigation on the other.

Various knowledge gaps were identified through the FLOODsite project which stand in the way of an improved flood risk management. These knowledge gaps are in the field of a *Better understanding of risk* as well as a *Better understanding of interventions.*

Many flood research projects funded by the EU Framework Programs in the last two decades (such as FLOODsite) have developed tools, models and best practices which are most relevant for the implementation of the Floods Directive. However, our current understanding in this emerging domain of flood risk management still lacks a fundamental comprehension of the complexity of socio-economic systems such as societal vulnerability towards flood disasters, and the governance needed to integrate the efforts of organisations at all levels needed to effectively implement these integrated approaches. It is becoming increasingly clear that flood risk management is only one of the many challenges of our society to deal with and that there are opportunities to incorporate flood risk management into other policy domains such urban planning leading to significant societal and economic benefits. In addition to this, innovative interventions to minimise flood impacts are required. FloodProBE "Technologies for the cost effective Flood Protection of the Built Environment" is acknowledging and addressing these research gaps that could help turn flood risk into opportunities.

1.4 FloodProBE focuses on developing knowledge on urban flood defences and critical infrastructure

The principal aim of FloodProBE is *to provide cost-effective means for flood risk reduction in urban areas*. FloodProBE focussed on:

- improvement of knowledge on identification and upgrading of weak links in flood defence systems and
- flood-induced failure of particular critical infrastructure, assessment of damages caused by these failures and development of new interventions.

This focus provided methodologies and interventions which allow decision makers to focus their investments and efforts on addressing risk areas in flood defences and urban critical infrastructure. Within the context of this guidance, critical infrastructure is defined as the urban assets which are essential for the functioning of society and encompass utility networks, transport networks and (tele) communication networks as well as the buildings which house elements of the infrastructure ("hotspot buildings" or "critical infrastructure buildings"). Examples of these are electricity and pumping stations as well as hospitals, fire brigade buildings, communication hubs and shelters.

1.5 Critical infrastructure and secondary impacts: terra incognita

Damage to critical infrastructure assets during flooding can result in significant secondary consequences which, on many occasions such as during the 2007 floods in England and the 2011 floods in Queensland, may be more serious than the direct damage caused by the flood. More recently, the destruction power and widespread disruption to infrastructure caused by Sandy on the east coast of North America and the Caribbean has ranked this hurricane one of the costliest storm events for insurers. The large electric and utility losses that left millions without power will probably cause more insured losses than were foreseen from a typical Category 1 event. Much damage could have been avoided if New York's most vulnerable critical infrastructure assets were protected ahead of time. This event has prompted to reconsider the impacts of flooding on the functioning of essential services and the management practices used to alleviate these risks. Damage to one type of infrastructure can cascade to disruption to other infrastructure, e.g. loss of power supply can impact on the health service of an urban community. Flood vulnerability therefore largely depends on the degree in which both hotspot buildings and infrastructure networks are affected by flooding and as a consequence are generating damage either directly or indirectly or both. Retrofitting techniques to protect flood prone residential buildings are widely applied and well documented. There is however limited experience with retrofitting techniques to reduce the impact of flooding to critical infrastructure assets and guidance and best practices to flood proofing these assets are lacking.

Figure 1.2 Flood marks, Prague, Czech Republic

Source: Meindert Van, 2012

1.6 An extensive ‘toolbox’ to support flood risk management

To this end, FloodProBE developed technologies, methods, concepts and tools for assessment purposes and for the adaptation of new and existing buildings and infrastructure networks, as well as for flood defences. The products of FloodProBE therefore aid in flood risk management and support the implementation of the EU Flood Directive. This is illustrated in Figure 1.3.

1.7 This guidance provides information and signposting to technologies arising from the FloodProBE project

This FloodProBE overall guidance provides end users with an overview and a first insight into the products, methods and knowledge developed within the context of the FloodProBE project. It aims at public authorities responsible for flood protection and water management as well as other asset managers and practitioners.

Through Chapter 2 further insight is given into the design process in urban flood management. Chapters 3 and 4 give a summary of the developed FloodProBE technologies, methods, concepts and tools aimed at improving flood risk analysis, where Chapter 3 focuses on flood defences and Chapter 4 on critical infrastructure. Chapter 5 gives an overview of the interventions developed within the FloodProBE context. Chapter 6 provides a summary of sources of complementary information.

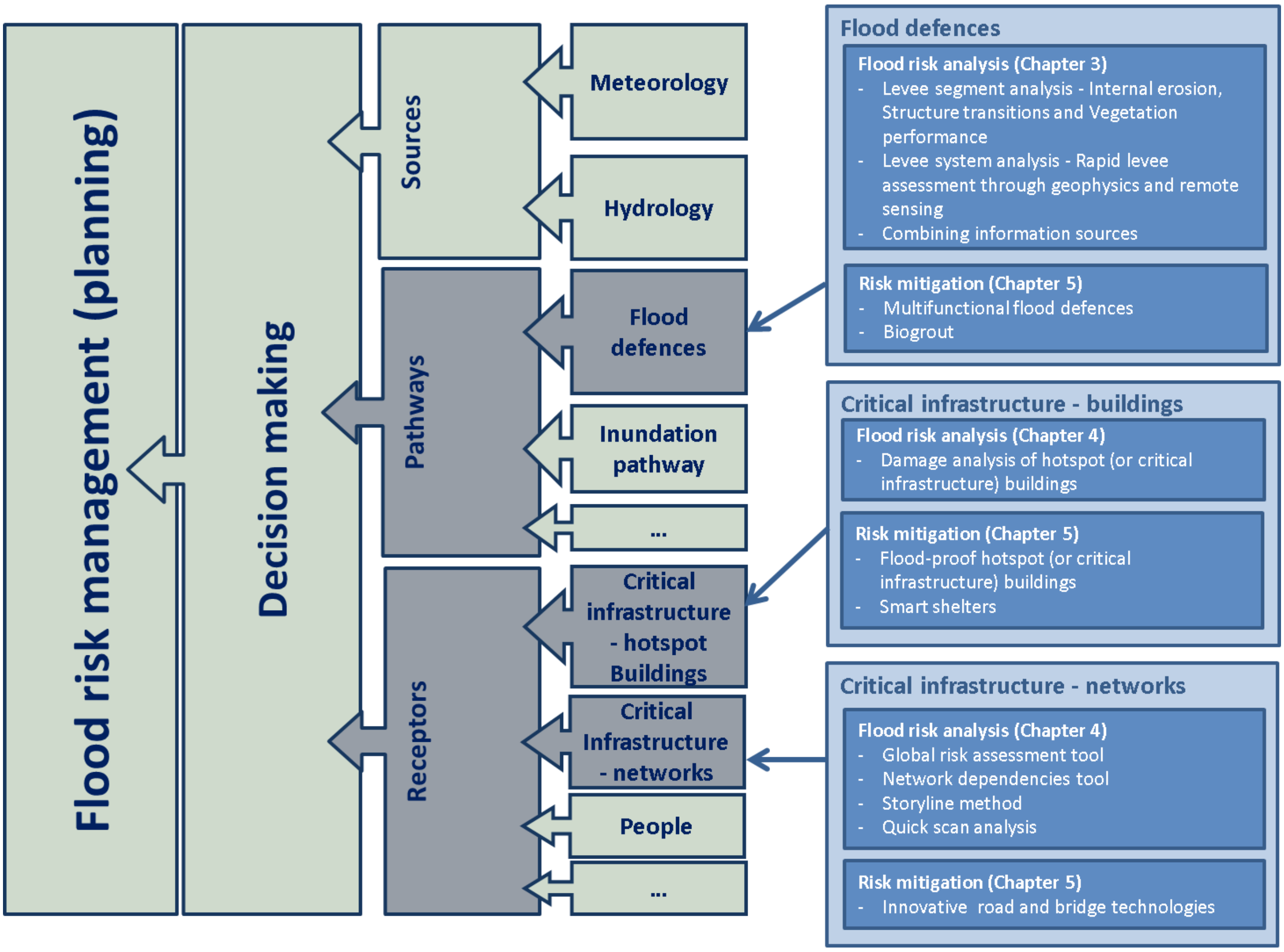


Figure 1.3 Overview of technologies developed within the FloodProBE project

The technologies developed within FloodProBE are listed on the right in relation to the Flood Risk Management process; the dark grey boxes indicate the Flood Risk Management areas to which FloodProBE contributed

Chapter 2 The Design Process in Urban Flood Management

2.1 Introduction

The development and implementation of Flood Risk Management plans should enhance the capacity of the flooding system to cope with an uncertain future and unforeseen events due to social economic developments and climate change. Consequently, Flood Risk Management plans are established through a continuous process of design, engineering, implementation, monitoring and adaptation, a multi-step process which is often initiated or triggered by a policy need, e.g. the Floods Directive or a situation where flooding is high on the political agenda due to a flood event. The value of a flood resilient system is its capacity to cope with unforeseen events and longer term drivers such as global environmental change.

The first phase within the design process is one of gathering insight and information through an analysis of the present and future flood risks within an area (phase 1 – Systems analysis). If it is concluded that there is a need to decrease the flood risk, the next phase (phase 2 – Design and engineering) will involve the evaluation of interventions and planning, leading to a selection of appropriate interventions and the development of a flood risk management plan. These plans should then keep options 'open' by adopting flexible, multiple use interventions which may involve development of adaptable engineering techniques in construction and refurbishment.

It follows from the above that the engineering design process does not end when a plan is put into action. The flooding system is a dynamic and complex one which is affected by continuous changing of natural and human induced processes such as climate change, urban growth and economic development. When the interventions are in place, a phase of monitoring of the flood risk and, where required, adjusting and adapting is entered into (phase 3 – Monitoring and adaptation). If adaptation is required, the process could be started from phase 1 and so on. Figure 2.1 illustrates this general process.

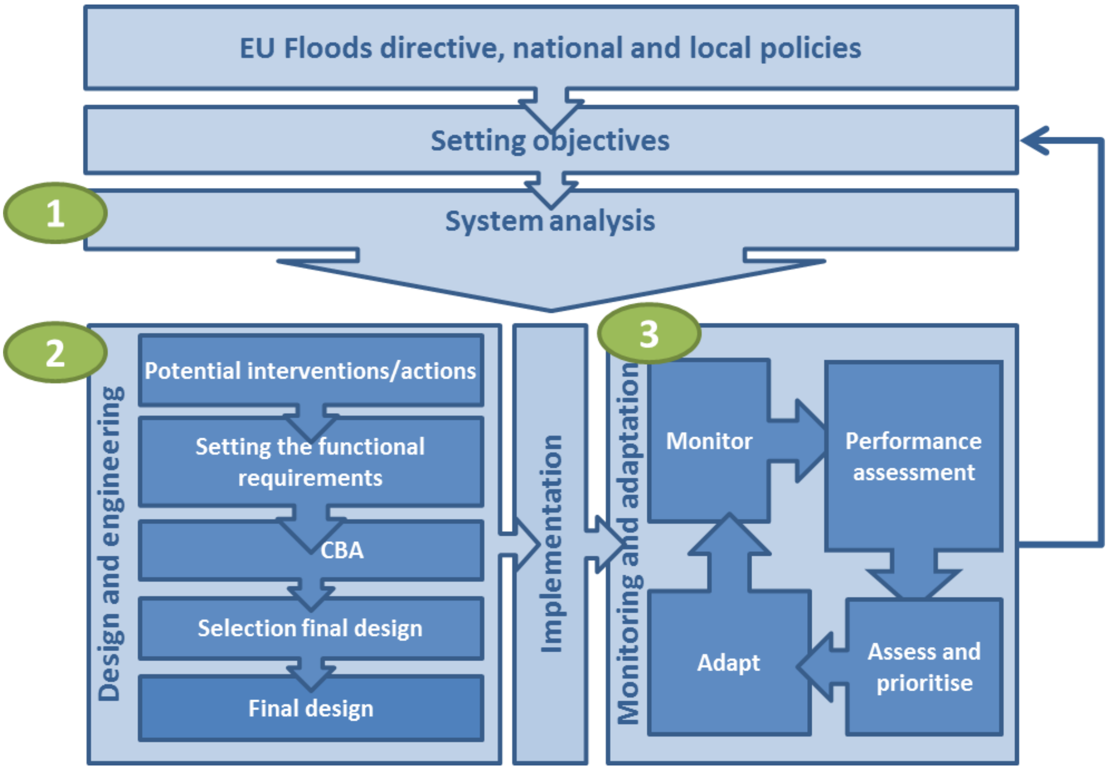


Figure 2.1 The design process as a continuous process

The process is based upon the following three major phases: (1) System analysis, (2) Design & engineering and (3) Monitoring and adaptation

An important element is the setting of objectives which plays a role throughout all phases. At first the systems performance is assessed according to these objectives to define if interventions are required. Within the design and engineering phase, when interventions are selected, their effectiveness is tested by assessing to what extent they contribute to reaching the objectives, and in the monitoring phase the flood risks are checked according to the set objectives. Design performance standards are often set as objectives. Design performance standards vary internationally and can relate to the probability of occurrence of certain water levels or even flow rate or velocity of flow, normally expressed as a return period. Attempts are also being made to deal with risk by defining combinations of probability and consequence, and nowadays these performance standards need also to take climate change into account.

FloodProBE aimed at filling some of the knowledge and implementation gaps of urban flood risk management identified by FLOODsite. Within the context of the FloodProBE project, a selection of emerging methods and innovative technologies have been further investigated and tested. The selected methods and technologies focus on a better assessment of the flood risks through improved risk analysis, the mitigation of flood risks through design and engineering of innovative technologies and improved techniques for monitoring the condition of flood defences, respectively. Figure 1.2 (in Chapter 1) gives an overview of the technologies developed in FloodProBE. The following section explains the three phases of the design process in more detail.

2.2 System analysis

In order to be able to manage the (flooding) system, an understanding of its functioning is a prerequisite. A system analysis is often performed to further unravel its complexity. To analyse the urban flood system, the physical system is best described through the conceptual source-pathway-receptor model. The source describes the hazard source such as a river, a sea or direct rainfall; the pathway is about the route the water flows when a flood occurs and the receptors are the elements which are susceptible to flood water such as people, buildings and infrastructure, which could be injured or damaged (see Figure 2.2).

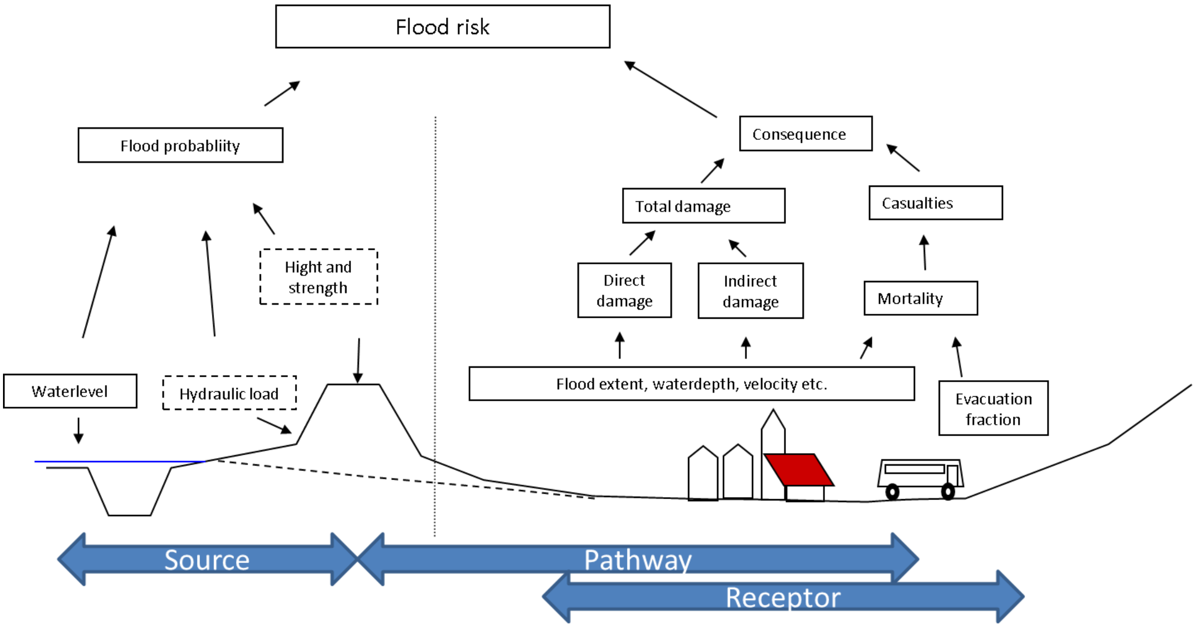


Figure 2.2 The Source-Pathway-Receptor model

The first key point for avoiding serious damage and the high cost of a failure and its consequences lies in the knowledge of the safety level and reliability of the flood defence system. Since flood defence systems are only as strong as the weakest links, the weak spots need to be identified, assessed and strengthened. In the urban context, many embedded constructions are encountered within the levees. These levees are often old elements and little is known about the material within the levee. A flood defence assessment is a process that has the objective of identifying these weak spots and evaluating the performance of a levee system.

The flooding system is a dynamic and complex system, which is affected by continuous changing natural and human induced processes. The urban flooding system is composed of interaction between subsystems such as nodes and networks and the urban system itself is part of a bigger (supra-) system. There is still limited understanding of the complex linkages between subsystems and services and the cascading effects of one subsystem upon another, such as for example between water supply, energy production and transportation. This limitation may partly explain the present lack of guidance on how to ensure the adoption of consistent approaches and on quantification of the benefits which arise from increasing the flood resilience of the critical infrastructure.

2.3 Design & engineering; working towards a flood risk management plan

The design and engineering phase works towards a flood risk management plan. It is an interactive process which requires the involvement of different stakeholders and encompasses design and engineering of interventions and spatial planning. This phase can be split into five steps:

Potential interventions: In order to manage the flooding system, a portfolio of interventions is required to protect economic, social, and environmental assets against flooding. In principle, at each spatial level, there are different types of measure to reduce the overall system's flood vulnerability. These interventions can aim at increasing the protection level or reducing the system's sensitivity by increased coping or recovery capacity. Being able to apply the interventions requires adaptation capacity of the system. When considering urban flood risk, the flooding system should be represented as multi-(spatial) level interacting systems which are made up of various components that act as input–output units, including positive or negative feedback loops (see Figure 2.3).

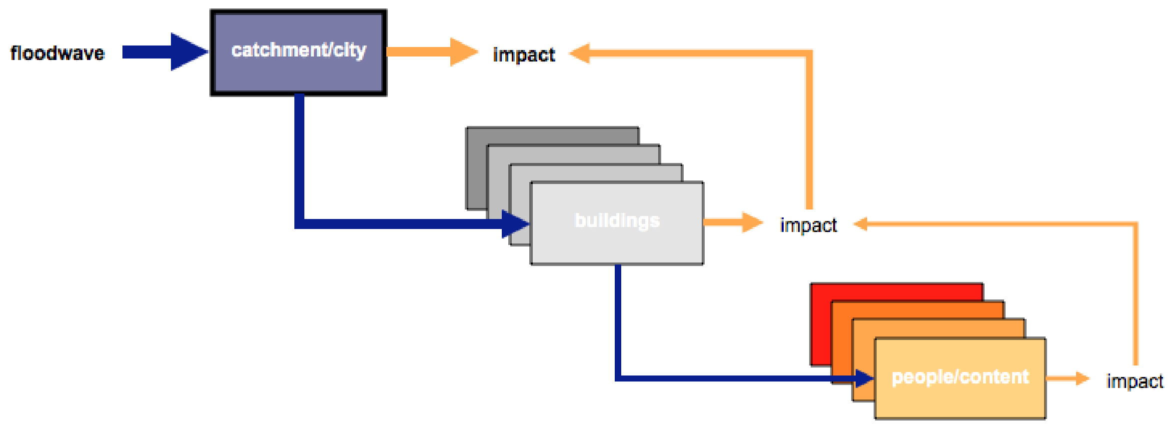


Figure 2.3 The different scales of the urban flooding system

At a low spatial level, the system is composed of interacting parts or subsystems such as buildings, roads and a supporting social economic environment for agents to interact. At the highest level, it is part of a supra system, 'the catchment'. Flood exposure at the urban scale is directly related to the physical mechanism underlying the flood propagation throughout the catchment system and the propagation of a flood wave to lower spatial levels is buffered by thresholds that can be set at each scale level, e.g. flood barriers that protect the entire catchment or a flood wall protecting a neighbourhood. Flood risk at a certain spatial level is dependent on the interventions implemented at a higher level. In other words, managing flood risks involves a feedback process initiated from a top-down perspective.

Functional requirement: It is increasingly recognised that responses need to be based on adaptable approaches leading to greater resilience for the system as a whole and should, where feasible, be incremental, reversible and 'no-regret'. This requires a new way of looking at responses, especially those that entail 'hard' engineering and are seldom reversible. In future these need to be able to accommodate changes (adaptations) in response to new knowledge, demands and expectations, and in the assessment of performance, with attendant flexibility in standards and codes of practice.

Cost benefit analysis (CBA): Responses need to provide the appropriate level of performance. Decision-making following a risk based analysis is based on either implicit design standards or on explicit cost benefit and multi-criteria considerations. CBA involves the comparison of the construction, operation and maintenance costs with benefits such as victims and damage prevented over the life of the project.

Selection of final design and flood risk management plan: Implementing technologies should be timed to coincide with autonomous planning cycles wherever possible (e.g. scheduled refurbishing or new developments) to minimise costs. Wherever feasible, win–win (i.e. benefits across multiple sectors) or no-regret approaches should be sought, although there will frequently be tensions and competing objectives. Development of integrated portfolios requires coordinating the activities of more than one organisation and multiple stakeholders. Whilst ageing infrastructure and building stock in the developed world pose a risk due to increasing vulnerability, this also provides an opportunity to introduce new technologies in the redevelopment process and to adapt infrastructure and buildings to enhance flood resilience. Urban restoration, regeneration and modernisation can be a key driver of economic development; both as a result of the initial investment required and the benefits that it will accrue over time (e.g. formerly flood-prone areas may become available for productive use).

2.4 Monitoring and adaptation; maintaining the flood risk levels

Once a flood risk management plan is implemented and interventions are in place, the phase of monitoring and adaptation is entered which focuses on maintaining the flood risk levels. This is done by monitoring the development of the flood risk and, where required, adapting to changing circumstances. Monitoring and adaptation of the performance of the implemented technologies will be critically important for judging their effectiveness and making decisions on which efforts are needed to adjust to changing conditions. In the context of climate adaptation, continuous monitoring and adaptation activities also need to recognise the longer time horizon of potential climate change impacts.

Monitoring can lead to the re-setting of objectives, as illustrated in Figure 2.4. In traditional flood-risk management policies, flood risk is generally managed through structural interventions such as strengthening of flood defences, and restricted to measures adopted at the catchment level only (increasing protection levels). At present, the focus is therefore on gaining an improved insight into the state of flood defences. In future when more emphasis is given on implementation of interventions other than flood protection measures, the monitoring phase could include receptors and monitoring of overall flood risk.

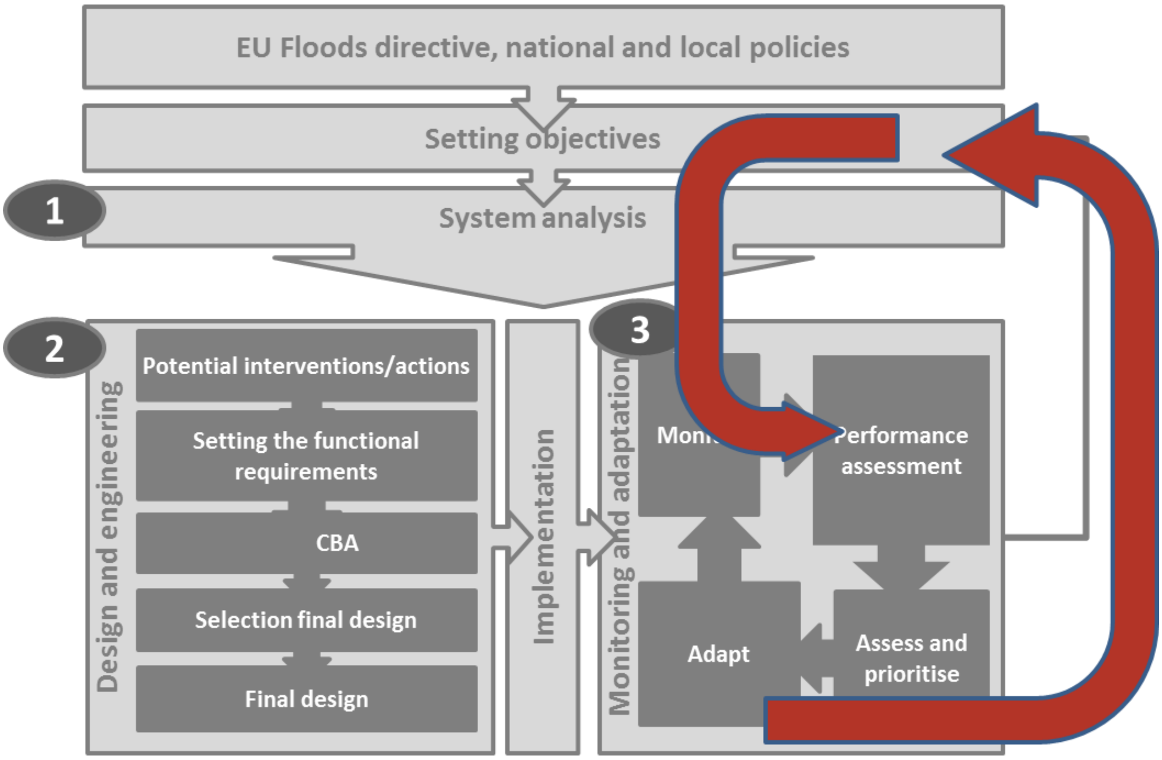


Figure 2.4 The re-setting of objectives as a consequence of monitoring and adaptation

Chapter 3 System Analysis – Flood Defence Reliability

3.1 Introduction

Most of the levees are old structures built several centuries ago, then rebuilt or repaired (after a breach), modified, heightened several times, with some materials that do not necessarily match the original conception of the structure. The levee foundations are naturally heterogeneous and in general were not properly treated to improve their water-tightness or strength properties. Other factors such as roots or animals introduce weaknesses in a levee.

In the urban context, the levees present many additional singularities, such as embedded networks, pipes, human constructions like houses, gardens and walls. Urban flood defences comprise both soft soil embankments and hard structures. Failures are often caused by internal and/or external erosion processes, particularly at transitions between materials or between defence types. Complex combinations of defence types are typical in urban areas.

A flood defence assessment, as part of the system analysis or monitoring phase, has the objective to evaluate the performance of a levee system and should include a diagnosis of the actual or possible causes of failure. In current practice, a levee assessment almost always involves determination of the so-called reliability of a levee for all main types of failure mechanism. Conventional site investigation techniques for assessing geotechnical properties do assess soil properties at specific locations quite accurately; however due to natural and man-made heterogeneity, determining the soil properties over long lengths of embankment is more difficult. In between measured subsurface points, properties have to be interpreted or interpolated, introducing large uncertainties. Considering the stretch of hundreds of kilometres and the heterogeneity of the levees, both good assessment methods, based on sturdy fundamental knowledge of the failure mechanisms and the strength of the levee components, and rapid, cost-effective and reliable techniques for data acquisition and surveying the defence system over long lengths are necessary. Figure 3.1 illustrates the decision process based on the assessment of flood defences.

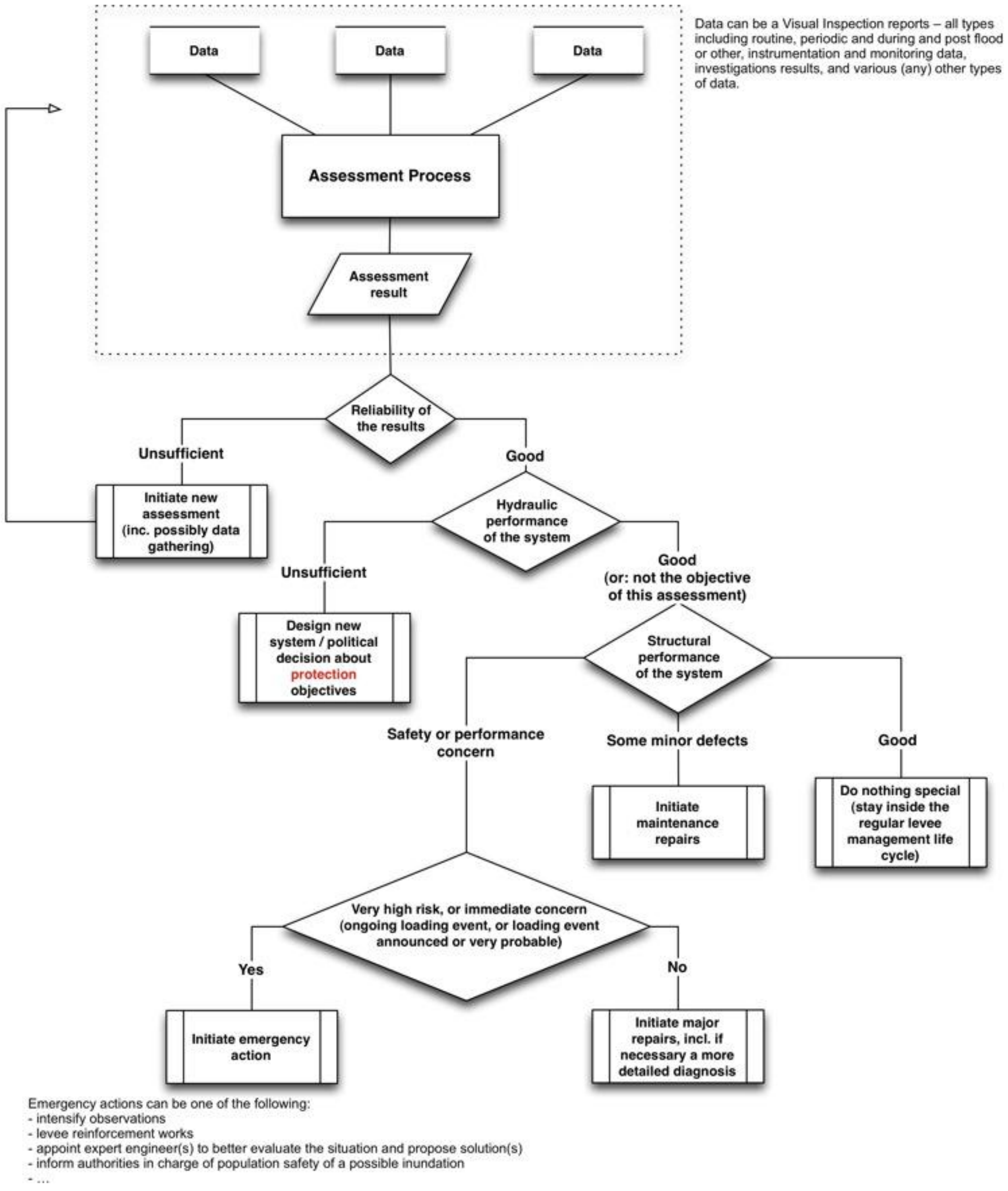


Figure 3.1 Flow chart on the decision making process related to flood defences, based on the assessment (or diagnosis) of flood defences

The FloodProBE project has produced a better understanding for several knowledge gaps in the safety assessment of flood defences. The research focused on improving the understanding of, on the one hand the failure modes at the scale of a levee segment, and on the other hand the use of techniques to assess large stretches of levees on the scale of the levee system. FloodProBE also looked into the use of GIS for combining these data sources with insights gathered, i.e. by visual inspection, at these different scale levels for a full levee system assessment (Figure 3.2).

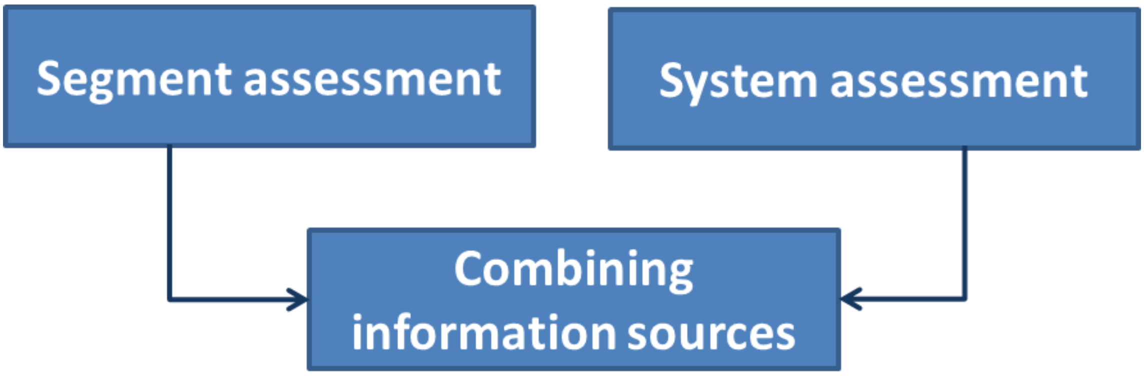


Figure 3.2 General framework for assessment of levees

The present chapter describes new methodologies and tools for assessing the reliability of flood defence systems:

- An improved understanding and clear guidance on assessing erosion processes; internal erosion, surface erosion (grass cover) and erosion around transitions associated with embankments, in particular against hard structures (FloodProBE D3.1 'Guidance on improved performance of urban flood defences', 2012)
- Standardised overview and new guidance for these rapid and cost-effective methods to deal with large lengths of heterogeneous levees and subsoil (FloodProBE D3.2 'Rapid and cost-effective dike condition assessment methods: geophysics and remote sensing', 2013)
- Tools to improve the levee assessment by combining multiple sources and different types of available information (FloodProBE D3.3 'Combining information for urban levee assessment', 2013).

3.2 Levee segment assessment

For a complete levee assessment, insight is required into the conditions of a levee system. These insights are gained on the one hand through large scale information gathering and on the other hand by gaining a better understanding of the small scale local conditions and the possible failure processes associated with these local conditions. Both scale levels of information gathering have been researched through the FloodProBE project. This section focuses on the FloodProBE results which provide a better understanding of the local levee conditions. Section 3.3 deals with the large scale information gathering techniques.

Soil erosion is the cause of failure of the majority of levees and composite flood defence structures, whether through internal erosion, wave overtopping, overflow or contact erosion. The research focus has been placed on the three failure processes (or modes) that have proven to be critical in recent major flood events: internal erosion, erosion around transitions and surface erosion (grass cover). These erosion processes are the most dominant failure mechanisms in safety assessments in urban areas but also require an improvement of knowledge to be able to perform a proper performance assessment of urban flood defences.

3.2.1 Internal erosion processes

Internal erosion is the “downstream transport of soil particles within a levee or its foundation by seepage flow”. Through an extensive literature review and analysis of test results on soil erodibility, a better understanding was gained on the parameters which contribute to the internal erosion processes (Figure 3.3). The knowledge on internal erosion has been bundled and presented in a way easily understandable and act as guidance for the analysis of internal erosion processes. This framework was developed for levee managers, engineers and technicians working on the safety of hydraulic structures and (urban) flood defences, and includes the following:

1. A framework for a practical description of erosion assessment tools with link to identification parameters of soils and in-situ investigations. This framework consists of:
    - A description of the different types of physical processes of erosion.
    - A description of the different scenarios of failure by internal erosion through four successive phases leading (or not) to a breach, with a matrix representation.
    - And a description of key soil parameters reflecting internal erosion susceptibility.

2. Information about testing facilities available in Europe and some other countries for measuring erodibility parameters: parameters of erosion that can be measured, types of soils that can be tested.

3. Results of cross-tests on two pilot sites of the project (Orléans and Humber) and overview of existing data bases for erodibility parameters.

A summary of the framework is provided in this section. Items 2 and 3 are elaborated further within the technical reports.

Framework on internal erosion

In Table 3.1 the internal erosion processes are defined and unified in a general overview. The FloodProBE project research focused on four internal erosion mechanisms, since these types of erosion (except suffusion) are known to be dominant for the urban areas in France, Great Britain and the Netherlands. The information in the table can be used to determine the potential types of internal erosion for a certain levee segment.

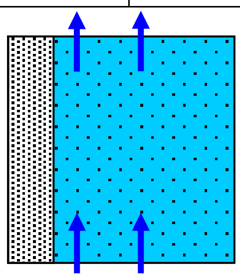
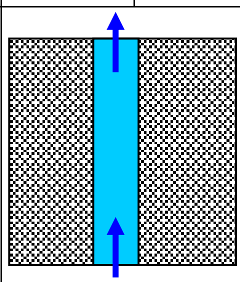
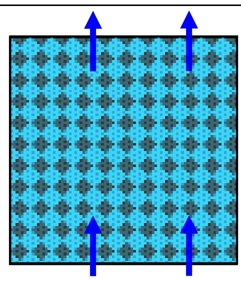
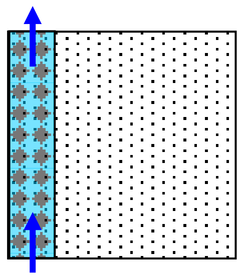
The table distinguishes between two soil classes as the nature of the soil in the embankment determines its vulnerability to erosion:

1. *Granular non-cohesive soils*: erosion resistance is related to particle buoyant weight and friction; hydro-mechanical transport criterion is linked to rolling and sliding resistance of the grains and

2. *Cohesive soils*: erosion resistance is mainly related to attractive contact forces in between soil's particles; the main transport mode is suspension flow.

Figure 3.3 Failure due to backwards erosion; piping test at Ijkdijk, The Netherlands
Source: Deltares

Table 3.1 Basic mechanisms of internal erosion in dams and levees

Type of internal erosion		Type of soil	Presence of a boundary layer		Location of erosion
			Coarse filter	Impermeable layer	
Backward erosion: Detachment of soil particles when the seepage exits to an unfiltered surface and leading to retrogressively growing pipes and sand boils		Non-cohesive	No	Roof (parallel to flow)	Downstream along the roof
		Cohesive	No	No	In volume
Concentrated leak erosion: Detachment of soil particles through a pre-existing path in the embankment or foundation		Non-cohesive	No	Roof	Along the roof
		Cohesive	No	No	In volume
Suffusion: Selective erosion of the fine particles from the matrix of coarse particles		Fine enough particles (cohesive or not) for transport through the fixed granular skeleton	Possible	No	In volume
Contact erosion: Selective erosion of the fine particles from the contact with a coarser layer		Fine enough particles cohesive or not) for transport through the coarse layer	No	No	Along the contact zone

Breaching of a levee is in fact a process which in a first stage is initiated through a failure mode, causing the first signs of the degradation process of the levee. The onset of this initial failure mode often triggers one or more other failure modes and finally ends with the actual failure of the levee through breaching or overtopping, resulting in letting uncontrolled water into the protected area. Failure modes are commonly named after the leading or originating mechanism; for example, overtopping, internal or external erosion, sliding of the slope, etc.

On levees, different types of internal erosion and the actual phase of the process can be hardly distinguished by visual inspection. The usual field observations of internal erosion are: vegetation or soaked area (related to seepage outflow); fine particles deposit on the downstream slope of the levee; deformation of the levee (settlement, sinkhole); seepage flow with fine particles in suspension (observation during floods); etc. For a better understanding of internal erosion processes, a summary description is presented in Table 3.2. For this description of the process of internal erosion of embankment dams or levees and their foundations, FloodProBE chose to represent these by four phases:

- *Initiation*: first phase of internal erosion, when one of the phenomena of detachment of particles occurs.
- *Continuation*: phase where the relationship of the particle size distribution between the base (core) material and the filter controls whether or not erosion will continue.
- *Progression*: phase of internal erosion, where hydraulic shear stresses within the eroding soil may or may not lead to the erosion process being on-going and in case of backward and concentrated leak erosion to formation of a pipe. The main issues are whether the pipe will collapse, or whether upstream zones may control the erosion process by flow limitation.
- *Breach*: final phase of internal erosion. It may occur by: 1) Gross enlargement of the pipe, which may include the development of a sinkhole from the pipe to the crest of the embankment, 2) Slope instability of the downstream slope, 3) Static liquefaction, which may include increase of pore pressure and sudden collapse in eroded zone, 4) Unravelling of the downstream face, 5) Overtopping for example due to settlement of the crest from suffusion and/or due to the formation of a sinkhole from a pipe in the embankment.

The following table (Table 3.2) aids in identifying signs of internal erosion at different stages of the process.

To be able to predict internal erosion through modelling, insight is required on the characteristics of the soil layers of which a levee is composed of. These characteristics such as grain size distribution, compaction or erodibility act as input for the erosion models. The dominant internal erosion mode is predominately dependent upon the characteristics and configuration of the soil layers, especially the grain size distribution and compaction.

Table 3.2 Main scenarios of embankment failure by internal erosion

Type of internal erosion	Initiation	Continuation	Progression	Failure
Backward erosion	Uplift (at toe) Local defect (hole, root) Induced concentrated leakage (suffusion,	Beginning of pipe extension (parallel to flow)	Acceleration of pipe extension	Roof collapse Sinkholes
			→ Concentrated leak erosion	
Suffusion	Self-filtering condition not fulfilled	Without filter downstream	Yes	Settlement, Sinkholes
			→ Backward erosion	
			→ Contact erosion	
		With filter downstream	Clogging, pore pressure increase	Diffuse instability (liquefaction)
Contact erosion	Tangential flow erosion	Cavities settlements (locally)	→ Concentrated leak erosion	
			→ Backward (or forward) erosion	
Concentrated leak erosion	Pre-existing opening (settlement, structure transition, layering) Induced opening (contact erosion, settlement, backward erosion)	Beginning of pipe enlargement (normal to flow	Acceleration of pipe enlargement	Roof collapse Sinkholes

In Table 3.3 a summarized overview is given of the basic mechanisms of internal erosion and the most used assessment models with the methods for determining the involved parameters.

Table 3.3 Matrix of models of internal erosion and parameters to be determined

Type of internal erosion	Models	Parameters	Methods of determination	Domains of validity	Key soils' parameters
Backward erosion (in non-cohesive material)	Threshold: $\Delta H_c = F_{res} F_{scale} F_{geo} L$ (Sellmeijer)	κ: aquifer permeability	Permeameter, grain size distribution	d_{70}:150 – 450 µm; d_{60}/d_{10}< 2,6; roundness: 35 – 70; relative density > 50%; Silt fraction (<63 µm) < 10%	Grain size distribution
		d_{70} of aquifer	Grain size distribution		
	Threshold(Bligh) $\Delta H_c = L/C_{Bligh}$; $\Delta H_c = (L/3+L_v)/C_{Lane}$	C_{Bligh}: creep factor C_{Lane}: weighted creep factor	Grain size distribution and empirical table	d_{50}: from very fine (<105 µm) to very coarse (>16 mm)	
Concentrated leak erosion	Excess shear stress erosion law: $\varepsilon = k_{er}(\tau - \tau_c)$ (Bonelli)	Critical stress: τ_c	Hole Erosion Test (by adjustment of the erosion law)	Cohesive soils (sufficient cohesion to hold up drilling a cylindrical hole for testing)	Water content; Compaction Fine content; Chemical activity
		Erosion coefficient: k_{er}			
Suffusion	Self-filtration rules *H>15* (Kezdi); *H>F* (Kenney & Lau)	*F*: mass passing (size *d*) *H*: increment of mass passing (size *D=4d*)	Grain size distribution	Non-cohesive soils	Grain size distribution
Contact erosion	Threshold (Beguin) $U_c = Fr_c n_D((s-1)gd_{50})^{1/2}$ $Fr_c = f(d_{50}, D_{15}, Re_D)$	*k* and n_D: coarse soil permeability and porosity; d_{50} and D_{15}	Grain size distributions	Non-cohesive soils	Grain size distribution
	Excess shear stress erosion law $\varepsilon = k_{er}(\tau - \tau_c)$ (Beguin)	Similar to concentrated leak erosion	Contact Erosion Test (adjustment)	Cohesive soils	Similar to concentrated leak erosion

In the case of non-cohesive materials where erosion is the result of local destabilizations of particles at the interface induced by the hydraulic flow, it is obviously the grain size distribution of the material that determines the resistance of soil to erosion. The main parameters are typical particle diameters as d_{70} or d_{50}, permeability and more complex parameters deduced from the grain size distribution.

No simple relationship was found between soil characteristics and erodibility parameters determined from direct testing of cohesive soils. However, soil parameters with the most significant influences on erodibility have been clearly identified. For a given soil, the more influencing parameters are compaction density, water content and degree of saturation. An increase of these parameters leads to an improvement of soil resistance against erosion phenomenon. For a given nature of fines (i.e. for a unique chemical activity), the fines content in soil has obviously an important impact on erosion parameters; the critical shear stress of erosion increases significantly as the percentage of fine content present in the soil increases. For different types of clay, chemical activity is fundamental for erodibility and a very strong discrepancy is observed from one clay to another, even within the same “class” of clays (kaolins for instance). The dispersivity of soil has a significant impact on erodibility. It is also noteworthy that the aging effect plays a significant role on soil erodibility parameters with strong differences between intact and reconstituted soil samples; some erosion experimental results have shown that intact samples are more resistant than reconstituted samples; this is certainly due to the remoulding of soil in case of reconstituted samples.

3.2.2 Structure transitions

Analysis of recent flood events such as at Arles (France) and New Orleans (USA) have demonstrated the weaknesses in urban flood defences that can occur at transitions between structure types or at specific locations. In particular, the contact zone between two types of structure can be a preferred seepage path, where erosion can be initiated or developed. Those transitions create weak points within a defence and undermine the performance of the overall system of flood defences. In particular, internal erosion processes at structure transitions or below historical structures such as sluices, are poorly understood, since information on the current state of the subterranean part of the structure, e.g. foundation or sheet pile cut-offs, is often lacking. Whilst flood defence asset managers, who routinely inspect and manage defences, are typically aware of the practical risks posed by transitions between structures, these risks are not yet routinely included within system flood risk analyses. The broad aim of the work in FloodProBE was to identify typical weak designs for structure transitions and specific points and provide guidance on repair or retrofit solutions.

There is a need for methods for safety assessment of transition structures, being preferably fast, cost-effective and non-destructive methods, as well as providing a clear understanding of the erosion processes that lead to inundation failure. FloodProBE has built upon the state-of-the-art to advance the fundamental knowledge on soil erosion along structures and at structure transitions. This knowledge is used to extend or introduce failure mode descriptions of transitions for the risk analysis of urban flood defences in particular.

Typical problems that might occur, alone or as part of a process (or scenario) at different types of structure transitions have been investigated in flood experiences in France, USA, Thailand, The Netherlands and UK. Based on this study, Figure 3.4 was developed with a flow chart for the assessment of the different types of structure transitions and the processes that might occur at those transitions (red boxes) as well as short recommendations as to how such transitions should be managed, assessed, designed and repaired to limit flood risk (green boxes).

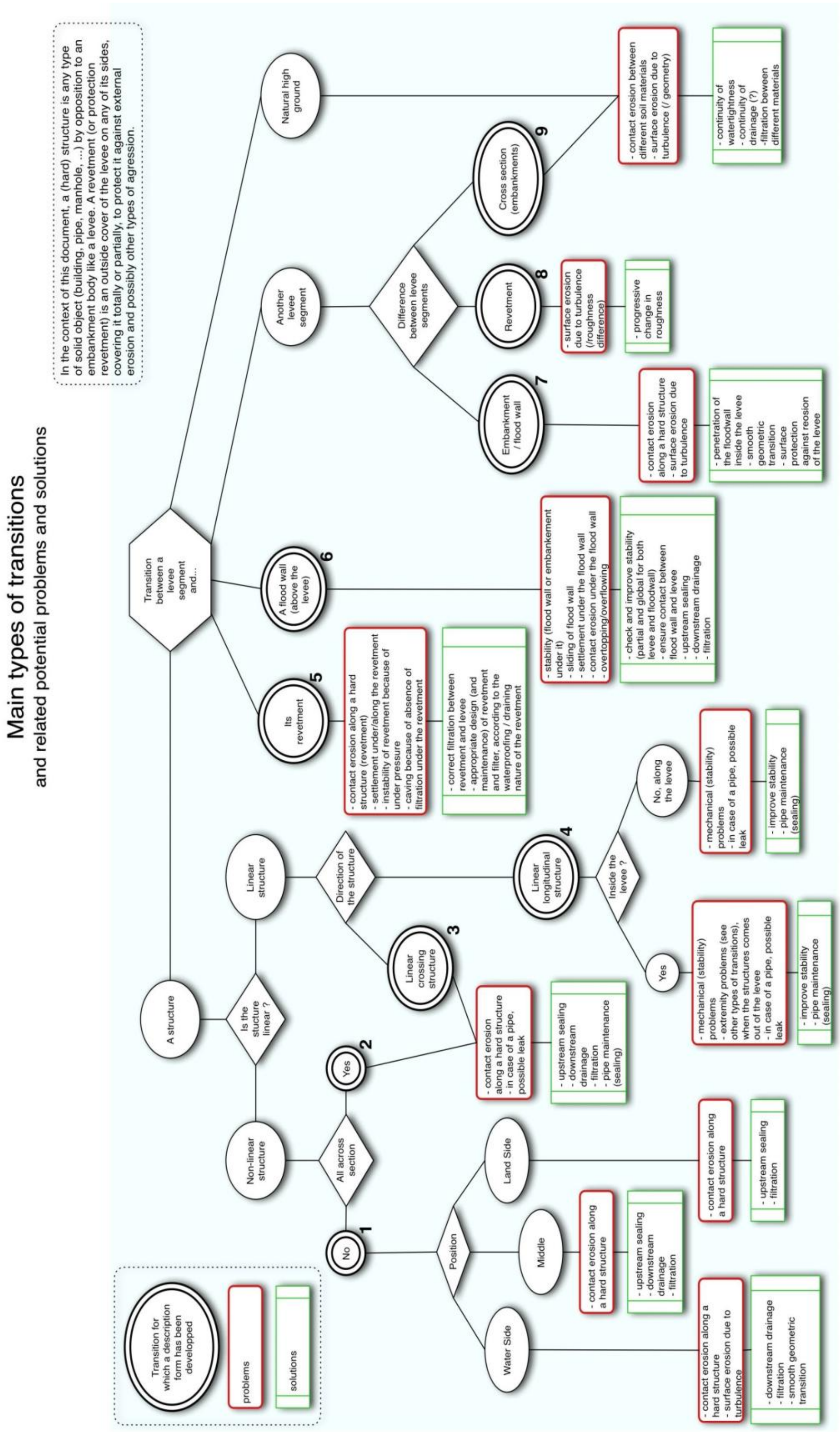


Figure 3.4 Flow chart to identify types of transition and potential associated problems

The research resulted in the following lessons learned:

- The contact zone between the different materials in the transitions can be defined as "rough" or "smooth" or even "loose", allowing more or less water flow and so giving more or less internal erosion. The physics of the phenomena are not yet well understood at the microscopic scale, or characterised well by means of numerical models. The physics of contact erosion probably differ in the case of a transition between a hard structure and an embankment or in the case of a transition between two embankments, for instance at the limit of two stretches of the same levee, with different geotechnical cross sections.
- External erosion occurring at the surface area of a transition can be caused either by contact erosion occurring inside, or by an external cause, such as for instance turbulence caused by a difference in roughness coefficient across a transition between two materials. Also a simple geometric irregularity can lead to concentrated flow, turbulence and external erosion.
- Sometimes the function of the structure or the way it has been built can cause specific erosion problems, for example: leakage from pipes (or into pipes) or poor levee soil conditions around a good condition structure (e.g. sand around a pipe through a levee). As pipes are the most common type of "hard" structures found in a levee in many countries (FloodProBE Orleans pilot), it is particularly important to consider this specific transition structure. Problems could be avoided or detected through close cooperation between the levee managing organisation, and the pipe managing organisation.
- Another type of problem is related to settlement under or near a hard structure, causing a preferred area for water flow, which will then result in erosion or increased internal pressures leading to uplift or sliding.
- In some cases, the presence of a structure or a transition can also induce sliding (shear), because of additional forces not taken into account in the initial stability analysis.
- The failure and collapse of an included structure may lead to either settlement in the levee, causing a potential overflow, or a loss of cohesion of the levee material in the structure area and hence internal erosion during a flood. Due to the presence of the structure, or because of its failure, mechanical failure (e.g. collapse or sliding) may also happen.
- Solutions/interventions, for improving the management of transitions can be proposed in terms of: 1) management of the encroachments, i.e. organisation (coordination) of the management of the levee and the structure, 2) inspections (pre, during or post flood), 3) assessment methods, 4) improvement works (decide between rebuild/remove/act on the soil or act on the structure, propose technical options). It should be recognised, though, that the best option remains to avoid creating transitions wherever possible.
- Reviewing and developing the information on transitions was to provide guidance on how to identify and manage the risks posed. It also became clear that identifying where transitions existed was a problem. For the situations where transitions arise from interfaces between structures buried within or even under the levee, records do not always exist and a visual inspection does not always show any signs of the transition. In this situation a review of historic records and asset manager’s field experience is often the only initial method that asset managers could employ in order to develop a long list of transition structures for assessment.

Historically, the analysis and inclusion of risks generated from transitions has not been undertaken – at least within the UK and Dutch frameworks for flood risk analysis. Inclusion of transitions within a modelling framework for risk assessment then poses a number of challenges. For a rigorous assessment it is necessary to include transitions as point or individual structures, against which performance data has to be attributed. This requires adaptation of the analysis framework to incorporate such structures plus sufficient knowledge of the potential failure mechanisms as to allow performance curves (fragility curves) to be produced for each transition structure under a range of load conditions. Currently the understanding and characterisation of some of the processes is not at a sufficiently developed stage to provide a reliable numerical representation of the processes. However, in the absence of numerical models of the failure process, engineering judgement may be used to develop initial estimates of performance based upon field experience. See also Section 3.4 on how to combine engineering judgement and numerical data.

3.2.3 The performance of vegetation (grass) on flood embankments

The erosion resistance of levees is partly determined by the performance of the grass cover. Grass is considered to have good performance if it prevents erosion of the underlying soil and ultimately any damage to the flood defence. Determining the loading(s) up to which grass remains in place, offering protection to the structure, is one of the primary aims of the designer and asset manager. The hydraulic performance of grass on flood embankments can be assessed by the loading(s) to which the grass and embankment are subjected. These loadings fall mainly into the following categories: wave impact and overtopping, overflow and rainfall runoff.

In general the hydraulic performance of grass can be considered in terms of:

1. Its *erosion resistance*, by means of a “maximum permissible velocity” of the flow or the “effective shear stress” that a grass lined structure can withstand; the erosion resistance indicates if the grass cover can protect the underlying soil.

2. The *resistance to the flow* (caused friction), usually by means of a coefficient of frictional resistance such as Manning’s n, which allows calculation of the flow depth/velocity/rate.

Both concepts are useful and complementary. For the case of flood embankments, determining the erosion resistance is the primary aim, whereas the resistance to the flow becomes more relevant to the design of grassed channels because it allows the determination of the conveyance (i.e. flow capacity) of a channel. However, knowledge of the resistance of grass is also important in the context of flood embankments as it is required in certain methodologies for the determination of the effective shear stress, and allows estimation of how much flow can reach areas behind the defences and how fast it will reach them.

Existing design guidance on the performance of grass on levees is limited and typically based upon data and analyses from the 1980s. The data sets used are fairly limited, and also appear to contain in built factors of safety which, whilst these maybe appropriate for use in design methods, can cause problems when the performance curves are used for levee reliability analysis. Based upon a review of international research results and grass performance data from the last 25 years, guidance has been developed regarding the use of existing guidance for the performance assessment of grass cover. Specific research actions on grass performance within FloodProBE were:

- A review of project initiatives related to the performance of grass;
- Investigation into grass performance data collected at the USDA Stillwater centre over the past 20 years, to identify what aspects might be relevant to European practice;
- Confirmation of existing European and US guidance on grass performance followed by identification of either (i) updates to guidance using existing international research findings or (ii) clarification of longer term R&D needs to improve knowledge and performance of embankment grass cover layers.

The review of initiatives, guidance and literature relating to overflow conditions identified a range of projects that appeared (initially) to provide guidance or advance the state of knowledge. The review of current guidance, and the data upon which this guidance is based, highlighted some noteworthy issues:

1. As a <u>general</u> indication, from the literature review by FloodProBE it has been suggested that permissible velocities (which depend on the soil, the density of grass cover and the longitudinal gradient of the channel/slope) are in the range 1.2m/s and 2.1m/s for good grass cover. It has been found that the duration of the flow is a relevant parameter in the erosion of channels that are intermittently subjected to flow, which is the case of flood embankments. Even without reinforcement, grassed surfaces can withstand considerably high velocities for short durations: almost 4m/s for 1 hour or 3m/s for 2 hours. However, long term stability is generally achieved if flow velocities remain below 1m/s.

2. Practical and detailed quantitative guidance on performance of grass under overflow conditions is quite hard to find. There appear to be many research initiatives, but little generic guidance with actual methods provided for the design or performance analysis of grass cover. To the contrary there seems to be plenty of general guidance on the maintenance and use of vegetation.

3. A lot of research initiatives seem to focus on the hydraulic resistance of grass / vegetation to flow, rather than the performance of the grass in protecting soil from erosion.

4. Based upon the literature review undertaken, the main sources of guidance on erosion protection from grass cover seem to be limited to:

a. A guide to the use of grass in hydraulic engineering practice, further referred to as CIRIA Technical Note 71.

b. Design of reinforced grass waterways, further referred to as CIRIA Report 116.

c. Stability Design of Grass-Lined Open Channels, further referred to as Agriculture Handbook 667.

It should be noted that the CIRIA 116 method builds from the Technical Note 71 data. It also incorporates USDA data; hence all three methods are related to some degree.

5. The extent to which US grass performance data is valid in Europe remains unclear. Where grass performance is related to root density, soil strength etc. it would seem 'transferable', but research looking at this issue does not appear to have been undertaken. The CIRIA 116 report does incorporate US data within the analysis.

The relatively recent development of the wave overtopping simulator in The Netherlands has encouraged testing of real flood embankments, in-situ, by the controlled release of water down the embankment face (Figure 3.5). In the future, this will help to clarify how the in-situ performance of grass varies with a range of factors relating to the design and state of the flood embankment.

Figure 3.5 Some examples of levee grass protection testing using a wave overtopping simulator

The FloodProBE review highlighted two interesting issues in relation to grass performance assessment:

- Use of the CIRIA 116 design curves repeatedly predicted quicker grass failure times than use of the CIRIA Technical Note 71 data. This is consistent with the inclusion of a factor of safety within the CIRIA 116 design curves. Users of the CIRIA 116 curves should recognise this fact since it affects the acceptability of the results, depending upon whether the curves are used for design or performance / reliability assessment (with a design application leading to a safer design, whilst with performance assessment, leading to a pessimistic assessment of behaviour).
- The USDA approach incorporates the plasticity index, which reflects to a degree, the soil erodibility. This shows a significant variation in performance, as soil erodibility reduces, whereas the CIRIA methods show no variation, because soil parameters are not considered.

Hence, whilst improvement in the reliability of performance assessment can be made by using the USDA approach instead of CIRIA methods, there still remains a number of ‘gaps in knowledge’ relating to grass performance. These include:

- The appropriateness of using test data from grasses in the USA for application within Europe.
- The performance of grass during the initial hour or so of overflow – this period is missing from the CIRIA 116 and Technical Note 71 work.
- Much of the data used relates to flow in steep grass lined channels, as might be used for embankment dam spillways. The applicability to small earth flood embankments is not completely clear.
- The effect of variation in grass type across Europe is unclear. In addition, as climate change effects start to change the rainfall and soil moisture content of levees, variations in grass type may also occur.
- Analysis of any link between grass type and performance in conjunction with underlying soil type and performance is also required. For example, where the underlying soils are highly erosion resistant, do they prevent growth and maintenance of an effective grass layer? Conversely do weak erodible soils promote stronger grass growth? Subsequently, which combination of soil and grass cover offers the best solution for flood embankment protection and performance?

It was noted that in recent years there have been a number of initiatives looking at (i) the management of grass (i.e. cutting frequency), (ii) soil erodibility and (iii) wave overtopping on grassed embankments. The missing piece to this jigsaw of research is quality data relating to the performance of a range of grass types, on a range of soil types under steady overflowing conditions. Such data would permit most of the gaps in knowledge listed above to be answered and for more reliable performance guidance to be given.

It would seem logical that the physical process of grass erosion, with the removal of roots from the soil, would also relate to the resistance of the underlying soil to erosion. The trend in levee breach analysis is towards the use of soil erodibility in order to improve representation of the embankment performance. Similarly, with the likely trend being towards design or planning for acceptable overflow during increasingly extreme flood events, adoption of a method that includes representation of soil erodibility for grass performance assessment would seem sensible.

3.3 Levee system assessment

Levee systems consist of large stretches of flood defences which have to be assessed in a rapid and cost-effective manner. Geophysical methods and remote sensing are assessment tools that are specifically applicable for large areas. Within FloodProBE, an overview of these techniques which are applicable for risk assessment of levees is compiled and presented in a uniform way. Especially within FloodProBE, its applicability focus is the use of these techniques in urban areas. This is studied as well as tested in pilots. The results are summarised in the following sections. Section 3.3.1 gives an overview of geophysical methods and how those can be used in levee assessments. In section 3.3.2 an overview is given of all available remote sensing techniques, which could be used for levee assessment, but especially the so-called LIDAR technique is presented in much more detail and was tested in a pilot since this technique is the most useful method for a cost-effective risk assessment of urban levees.

3.3.1 Geophysical methods for rapid levee condition assessment

Geophysical investigation is based on a reflection of a physical or electromagnetic wave on the subsurface materials - see Figure 3.6. These reflections are sensitive to material properties, its nature and parameters such as i.e. bulk density or moisture content. Therefore, geophysical investigations have shown great potential to inform on subsoil features such as: structure (layering), nature (geology), condition and spatial variations of soil properties.

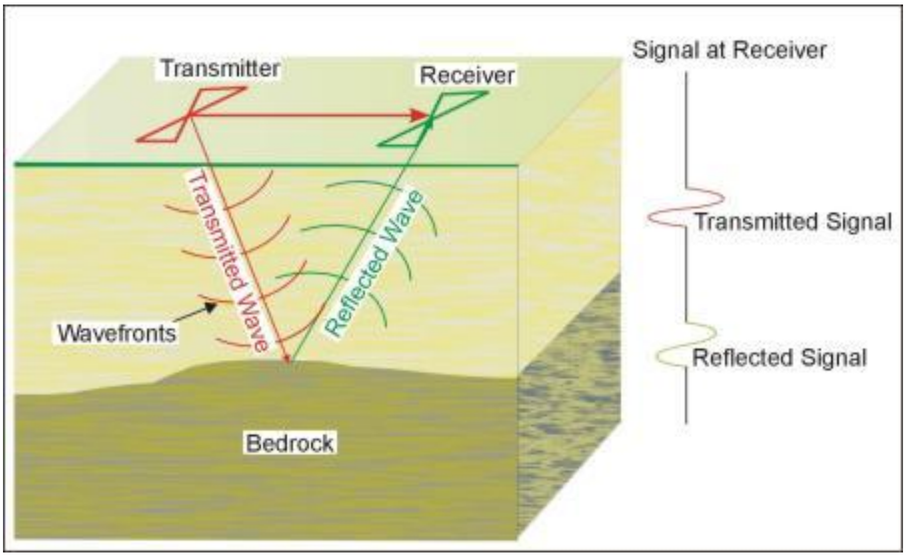


Figure 3.6 Geophysical principle for ground investigation
Source: www.cflhd.gov

The geophysical interpretation requires signal processing and noise reduction, then data processing, calibration, modelling and result quality assessment (reliability or uncertainty level), (see Figure 3.7). Interpretation of data from various sources (combination of geophysical methods with borehole / cone penetration test data, geologic data and / or historical data) is needed for interpretation and calibration of the resulted subsoil model.

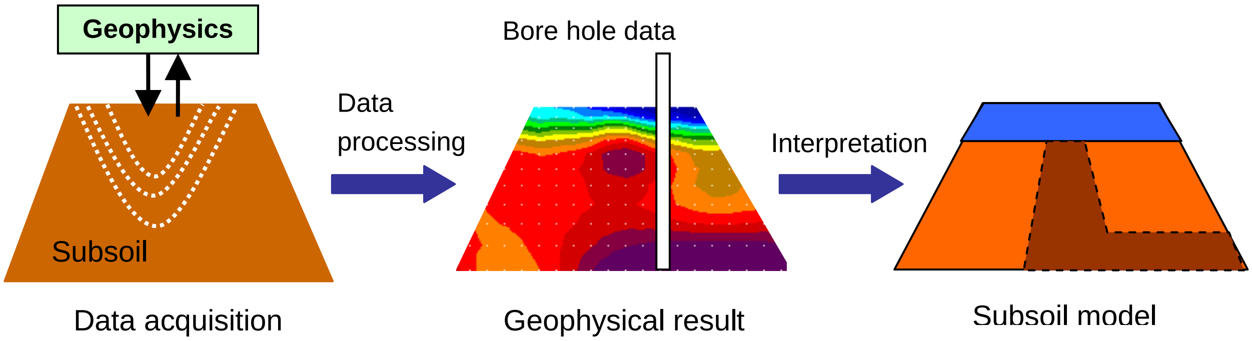


Figure 3.7 General scheme of a geophysical investigation process

Geophysics provides a variety of methods and technologies with different performances to investigate subsoil from the surface. A geophysical survey is designed on the basis of available site information and the aims and constraints of the investigation. This process implies the selection of one (or more) geophysical methods applicable to the case study. There are several types of data acquisition techniques (e.g. profiling, sounding, mapping, imaging, monitoring), depending on the investigation goals, the selected method, the equipment used and the required depth of investigation and spatial resolution. Two examples of devices are shown in Figure 3.8.

a) 

b) 

Figure 3.8 Examples of geophysical methods

Examples shown are: (a) Dipole electromagnetic profiling (GEM2 © METCENAS, G IMPULS PRAHA s.r.o.), (b) Electrical Resistivity Tomography (© ERINOH, Ifsttar)

In Table 3.4 an overview is produced of geophysical method features that are important for asset managers to evaluate their usefulness and cost-effectiveness. The geophysical methods considered here are the most popular methods for investigating embankment levees and they were discussed during a European wide FloodProBE-workshop to gain agreement on their applicability, limitations and cost-effectiveness.

Table 3.5 matches levee manager (stakeholder) investigation requirements with geophysical method applicability. It was compiled and agreed on during the aforementioned European workshop.

Table 3.4 An overview of the performance of geophysical methods in levee assessments

Geophysical methods	Mainly used in which investigation phase?	Sensitive to which geophysical and geomechanical soil properties?	Which features within dike and foundation can be detected?	Type of dike model or dike information produced:	Additional advantages	Conditions / Limitations	Applicable in urban areas?	Acquisition speed	Minimum recommended data processing and interpretation time (in engineer days) for the amount of profile surveyed per day	Estimated cost per km of profile (see 'Description of table contents' for details)
Slingram profiling	Overall	Soil electrical conductivity: Soil nature, moisture content, clay content	Material transitions along dike Buried metallic objects	Longitudinal dike segmentation into 'homogeneous' blocks, roughly material type	Acquisition for several depths of investigation is possible; Suitable for monitoring (requires GPS and accurate procedure) Metal pipe detection	Qualitative; Low resolution Needs calibration Disturbance by metallic objects; Effects of dike geometry	Possibly, have to run a test to confirm; Signal disturbed in dense urban areas (metal, networks, power lines); May require traffic disruption or work at night	5 to 10 km/day	0,5	A
Radio Magnetotellurics profiling	Overall	Soil electrical resistivity: Soil nature, soil grain size, moisture content	Material transitions along dike	Longitudinal dike segmentation into 'homogeneous' blocks Roughly: material type (needs calibration)	Applicable to dikes made of resistive or conductive materials	Needs steady signal reception Low resolution; Interpretation uncertainties; Field diffraction on dike geometry (source field incidence on dike); Disturbance by metallic structures	Rarely, but have to run a test; Signal disturbed in dense urban areas (field diffraction)	5 to 10 km/day	0,5	A
Lateral Resistivity profiling	Overall or Detailed (fast)	Soil electrical resistivity: Soil nature, moisture content, clay content, temperature	Material transitions along dike	Longitudinal dike segmentation into 'homogeneous' blocks, roughly material type	Applicable to all types of dikes and soils; Investigation depth usually adaptable; Continuous Resistivity Profiling (CRP) is faster (spike wheels or 'capacitive' device)	Qualitative; Disturbed by metallic structures; Soft soil: use ground stakes or spike wheells; Paved surfaces: use 'capacitive' device (faster, noisier)	Yes, depending on noise level On sealed or paved surfaces: use 'capacitive' (but noisier and lesser resolution)	2 to 4km/day	0,5	C (point measurements) B (continuous profiling)
Electrical Resistivity Tomography	Detailed or Overall (slow)	Soil electrical resistivity: Soil nature, moisture content, clay content, temperature	Structure; Depth of layers and foundation; Water table; Soil: type, condition (moisture, compaction, clay content) and transitions; Signs of internal erosion and seepage	Lateral and vertical segmentation of dike and foundation into identified blocks (material type and condition, anomalies)	Quantitative; Applicable to all types of dikes and soils; Investigation depth is very adaptable; Suitable for monitoring time changes	Artifacts due to 3D effects; Interpretation sometimes ambiguous: needs calibration; Temperature effects; Disturbed by metallic structures	Yes, depending on noise level and networks; Paved surfaces: drill holes through road paving (slower output rate and may require traffic disruption) or use 'capacitive' device (faster, but noisier and lesser resolution)	0.6 to 1.2 km/day	2,5	E
Ground Penetrating Radar profiling	Overall or Detailed	Contrasts in material dielectric permittivity: Material type, moisture and density	Structures and material transitions: Voids; Networks; Built-in elements; Layers; Water table; Damaged zones; Metallic features	Dike segmentation: Layer depths (needs calibration) Location of material transitions	Detection of metallic pipes and structures	Limited investigation in conducitve materials e.g. clayey soils Signal scattering in heterogeneous conditions Disturbed by presence of metal	Yes (see limitations)	5 km/day	2,5	B
Multichannel Analysis of Surface Waves	Overall	Mechanical properties; Direct link to shear strength of material	Voids (e.g. karstic cavities) Zones of deconsolidated soil	Dike segmentation into zones of homogeneous mechanical condition, including mechanically weak zone location	Potentially quantitative and high resolution method; Use of towed land streamers enables faster acquisition	False anomalies; Topography effects; Affected by vibrations; Slow acquistion when not towed	Depending on traffic and vibrations (test signal to noise ratio, measure overnight)	2 to 3 km/day	5	D
Seismic Refraction	Detailed	Soil mechanical condition; Layer thickness and hardness; Direct link to shear strength of material	Layer thicknesses; Depth of foundation; Water table level	Horizontally layered model of identified materials (needs calibration); Depth to foundation (or water table) all along dike	Quantitative	Slow acquistion; 1D model; Upper layers have to be softer than lower ones; Resolution for dike body is weak; Limited to 20m depth (without using explosive);	Depending on traffic and vibrations (test signal to noise ratio, measure overnight); May require drilling of road paving and traffic disruption	0.2 to 0.4 km/day	2	F
Micro-Gravimetry	Detailed	Earth gravimetric field, bulk density variations; Absence of mass	Cavities in dike body; Karsts in foundation; Washed zones; Relative changes in soil density; Variations in substratum depth	Relative density variation profiles; Location of zones of probable absence of mass	Directly linked to density variations Potentially: weak zone monitoring (when density changes are significant)	Information is not continuous, may miss target unless station offset sufficiently small; Procedure is delicate (drifting of device and gravity field corrections)	Yes, potentially; Built environment: strong limitations (requires delicate and significant correction of mass distribution)	0.1/day (assuming 2m spacing between stations)	1	G
Magnetic profiling	Overall (Detailed: potentially in the near future)	Induced and/or remanent magnetization; Lithology of soils and rocks	Buried iron manmade structures (and ammunition); Potentially: repaired zones, disturbed soil (requires mapping: slower)	Accurate location of metallic elements; Image of soil magnetization within dike body and foundation	Provides crucial information for assisting interpretation of methods disturbed by buried metal targets	Requires recording of temporal variation or gradiometry if presence of aerial metallic structures, power lines, industrial activity	Yes (may depend on surronding infrastructure, see limitations)	10 to 20 km/day	1	A
Self-Potential methods	Overall (waterborne profiling) Detailed (on land imaging)	Electrical properties Seepage intensity	Water seepage (estimation of depth and velocity) Signs of internal erosion Leakage location	Seepage flow distribution in dike body and foundation	Applicable to dike (dam) of any dimensions	Only during flood Not applicable if presence of reinforced concrete, nor if salted water Competing sources of SP signal	Possibly, depending on disturbance by other sources of SP signal	2 km/day (waterborne profiling) 0.5 km/day (on land imaging)	0.5 (waterborne profiling) 1 (on land imaging)	C (waterborne profiling) E (on land imaging)
Temperature sounding method	Overall (slow) or Detailed	Soil thermal conductivity Temperature contrasts	Water seepage, cracks, signs of internal erosion	Thermal model of dike body and foundation, showing seepage anomalies	Directly linked with flow-tracer technique; Applicable to all types of dikes/materials and up to 35m depth	Only in flooding conditions (or high tide); Needs temperature contrast between water and medium; Short range 'Intrusive': Needs holes (passive) or initial installation (active)	Yes	0.5 km/day (depending on sounding spacing, a few days for a complete estimation)	1	E

This table is explained in detail in the FloodProBE deliverable report; see Chapter 6 for links to more information.

Table 3.5 Geophysical method applicability with respect to stakeholder requirements

Green = Recommended method or even preferred method; Yellow = Conditionally applicable method; Red = Not applicable or not recommended economically.

	Material property and condition identification				Weak spot and anomaly detection								Zoning and structure delineation	
Detection requirements / Geophysical methods	Seepage flow velocities	Monitoring of time changes (dry season/flood conditions)	Soil geotechnical properties (porosity, consolidation, permeability)	Soil type, moisture content, clay content	Buried metallic structures	Embedded manmade structures	Seepage areas; Potential erosion and piping	Buried channels (in foundation)	Voids, animal burrows (in dike body); Subsidence, cavities (karsts in foundation)	Cracks	Contact surfaces between layers of contrasting material or condition (compaction, permeability etc.)	Structural anomalies (e.g. breach repairs, transitions)	Vertical structure: layers, depth to foundation, water table	Horizontal segmentation of dike into 'homogeneous' blocks
Slingram profiling	Red	Yellow	Red	Green	Green	Green	Red	Red	Red	Red	Red	Green	Red	Green
Radio Magnetotellurics	Red	Yellow	Red	Green	Yellow	Green	Red	Red	Red	Red	Red	Green	Red	Green
Lateral Resistivity profiling	Red	Yellow	Red	Green	Yellow	Green	Red	Red	Red	Red	Red	Green	Red	Green
Electrical Resistivity Tomography	Red	Green	Yellow	Green	Green	Green	Green	Yellow	Yellow	Yellow	Green	Green	Green	Green
Ground Penetrating Radar	Red	Yellow	Red	Red	Green	Green	Red	Red	Yellow	Yellow	Yellow	Green	Yellow	Yellow
Multichannel Analysis of Surface Waves	Red	Yellow	Green	Red	Red	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Green	Yellow	Green
Seismic Refraction	Red	Red	Yellow	Red	Red	Yellow	Red	Red	Red	Red	Yellow	Red	Green	Red
Micro-Gravimetry	Red	Yellow	Red	Red	Red	Red	Yellow	Red	Green	Red	Red	Red	Red	Red
Magnetic profiling	Red	Red	Red	Yellow	Green	Yellow	Red	Red	Red	Red	Red	Yellow	Red	Yellow

Geophysical methods are specifically useful for long stretches of levees. The assessment of levees, including diagnosis of the (potential) problems, should identify the weaknesses of the structure (zoning) and provide the level of safety. The phase in which geophysical methods are commonly applied in a general assessment process is shown in Figure 3.9.

General methodology for levee assessment
including geophysical and geotechnical methods

I – Preliminary studies

1 – Historical research
2 – Geological study
3 – Topography
4 – Hydrology and hydraulics
5 – Morphodynamic analysis of watercourse
6 - Visual inspection

II – Geophysical studies

1 - *Efficient survey:* ***first zoning***

Methods: **Slingram, AEM or RMT**
Result : **First dike zoning**

And/Or

2 – ***Efficient and local survey** : **local zoning***

Method : **Electrical Resistivity Tomography**
Result **local zoning**

3 – ***Other methods, other targets***

Method	Result
Seismic reflexion	Mechanical impedances
Multy-Channel Analysis of Surface Waves	Contact dike body/substratum
Seismic refraction	Contact dike body/substratum
Ground Penetrating Radar	Networks, layers
Seismic reflexion	Mechanical impedances

III – Geotechnical studies

Method	Result
Penetrometric tests	Dynamic resistance / depth
Loggings of Boreholes permeability	Permeability /depth
Mechanical shovel	Ponctual visual controle
Destructive drillings	Materila repartition / depth
Core drillings	Materila repartition / depth and samples for laboratory tests

IV – Diagnosis, stability studies, improvement of levee model…

Figure 3.9 Place of geophysics in general assessment

Source: Fauchard & Mériaux, 2007

This assessment process begins with so-called ‘preliminary studies’ to collect all available data of the area. It is of primary importance that the levee manager provides all information of the preliminary studies to the geophysics expert before the geophysical investigation phase starts. Then geophysics is used for an efficient survey of long stretches and defining zones (or levee sections) with similar subsoil profiles. It is recommended to execute first a longitudinal zoning, resulting in stronger and weaker subsoil zones. And then in a second phase measure cross-sections, especially in the weak areas, which in Figure 3.3 is called ‘local zoning’. However, in some countries longitudinal and cross-sections are measured in one survey. After these geophysical studies, further local geotechnical studies with field tests and laboratory testing are needed for each relevant zone in the safety assessment.

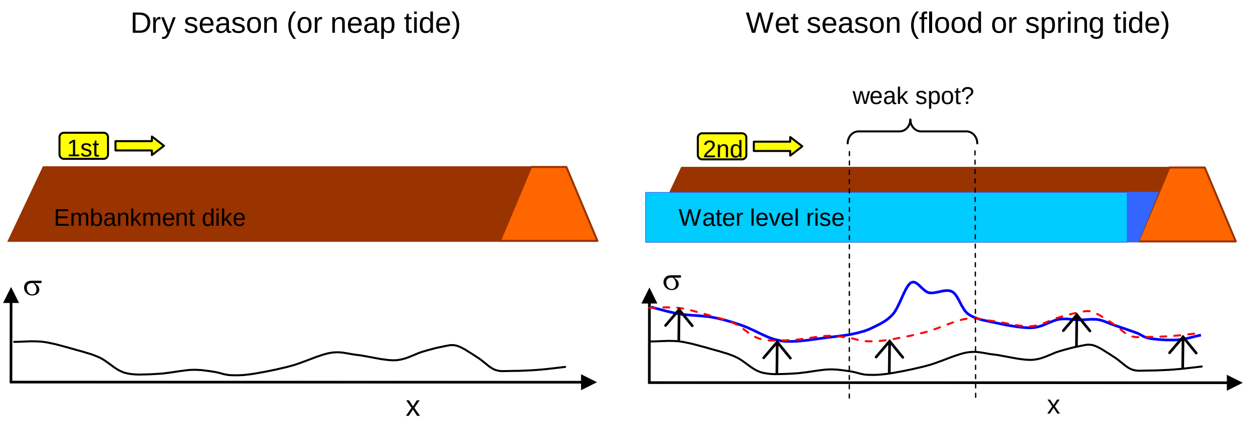


Figure 3.10 Principle of a weak-spot detection by a repeated survey

The geophysical survey can be repeated for additional information. For example the transition from a dry season to a wet season causes changing of soil properties and water tables within levee. In weak zones, significant property changes may occur and be a sign of progressive disorders (e.g. water infiltration, seepage, internal erosion, etc). Soil property and water table variations induce geophysical response variations. Therefore, measured seasonal differences could indicate weak zones, for an illustration see Figure 3.10.

3.3.2 Remote sensing for rapid levee condition assessment

Remote sensing, in its broadest sense, refers the use, from a distance (for instance an aircraft, a spacecraft, a satellite or a boat), of any type of instrument capable of acquiring information on the environment. For the levees, the most frequently used techniques include: aerial photography or satellite imagery; mono- or multispectral photogrammetry; traditional Lidar and bathymetric Lidar; radar; high resolution infrared thermography; sonar. These various techniques, either passive (photography, thermography) or active (Lidar, Radar, Sonar), and their potential applications to levee assessment is summarized in a table in Table 3.6. Lidar technologies are very relevant for levee assessments and how to perform these assessments, especially in urban areas, is elaborated in details within FloodProBE.

Table 3.6 Remote sensing techniques for levees

Type of technique	Sensor or technology	Technology description	Remote sensing technique	Details on the sensor	Technique used for processing data or signal	Platform carrying the sensor	Regular applications	Known applications to levees (sources, references)	Measurement precision (planimetry and altimetry)	Sensor-driven spatial sampling frequency	Output	Costs	Limits
passive	Optical	Black-and-white, false color or color photos or videos	Traditional aerial photography (nadir or vertical sighting)	Typically a visible sensor with RGB (red, green, blue) or panchromatic matrix, and less frequently a linear sensor (still camera with only one sensor line)	Camera, GPS and IMU (Inertial Measurement Unit) are used to produce orthocorrected images (geo-referenced photograph) With manual corrections, photogrammetry may help detect items that are unidentifiable by lidar Requires more post-processing than the lidar	Airplane, helicopter, satellite, balloon, ULM, drone	- Imagery-driven topographical maps and field analysis - Orthocorrected aerial photographs (orthophotographs) commonly found in geomorphological mapping - Primary method for studying objects down the water bed	- Overall vegetation mapping - Recent instance of application to CNR levee with 1 cm anticipated resolution - Example of application to torrential geomorphology (CEMAGREF and CEREGE)	High: >1 with a few pixels/m² precision highly dependent on flight altitude and technologies used for geo-referencing images	Depends on sensor and flight altitude	Different output according to sensor, resolution, acquisition type (surface, linear, etc.) and restricted by weather conditions, desired contrasts, etc.	Highly variable, according to measured surface. Although high fixed costs for sensor and aircraft procurement. For very high aerial resolution in optical application (from 3 to 30 cm), average costs range from 20 to 100 €/m²	Requires unobstructed view of the surface Limited by weather conditions (clouds, fog, heavy rain, shade) Unable to cross vegetation
			Oblique aerial photography	Often a video sensor, typically a visible sensor with RGB or panchromatic matrix, and less frequently a linear sensor		Airplane, helicopter, satellite, balloon, ULM, drone, oblique ground platform	Used to produce images for communication purposes (impact reviews, landscape analysis)		Low: panning effects induce larger pixels as the horizon is approached The viewing angle reduces underwater visibility (refraction)				
			Stereophotogrammetry	At least doubled images vs traditional aerial photography (for stereo or multiview)		Aerial images taken by airplane; ground platform or onboard a vehicle	- To retrieve relief and topography - To identify potential small-scale changes or strains	Geometrical properties of an object on a levee	High precision planimetry; lower for altimetry (~half lower)				
			Near infrared photogrammetry	The sensor is sensible to near infrared spectrum (most frequently 0.7 to 1µm)		Airplane, helicopter, satellite, balloon, ULM, drone, oblique ground platform	To determine crop types	- To determine vegetation (water and vegetation are identified with near IR spectral reflection factor) - Bare soils are more visible (FRMRC)	High precision				
			Multispectral photogrammetry	Captures an image in several wavelengths (multi, super or hyper, depending on the number) of the visible or infrared electromagnetic spectrum (0.3 to 30µm)		Any ground, aerial or satellite vector	Refined determination of ground, water or vegetation properties (depending on the wavelengths used)		Variable according to wavelengths				
			Satellite imagery			Satellite	Numerous scientific, civil and military applications: meteorology, environment evaluation and monitoring, global climatic and environmental change assessment	Used for break hazards in the event of a crisis (flooded area)	Low precision	Suitable for large surfaces			Unable to produce images underneath cloud cover
			Video	For visible, black-and-white and color images		Helicopter, balloon, ULM, drone: low altitude devices		To determine vegetation					
	Passive microwave	Passive micro wave detection for moisture content sub soil	microwaves			Helicopter, balloon, ULM, drone: low altitude devices		Soil moisure detection on levee	Low precision				
	Thermal	Infrared photographs or videos to identify areas with thermal anomaly (temperature discrepancy between the surface ground and resurgence areas)	High resolution thermography	Can reach the far end of the spectral infrared strip		Helicopter, balloon, ULM, drone, mobile or fixed ground platform	- To identify subsurface issues in a great number of materials (concrete and masonry) - EDF to determine the hot water network impact downstream the plants	- Application tests for hydroelectric installation levees (EDF, CNR) and waterway levees (DREAL Centre) - Application to identify damp areas on levees	Precision affected by material properties (thickness and dampness)	Depends on flight altitude, sensor optics and resolution; resolutions are 10 times rougher than in optical application	Different output according to sensor, resolution, acquisition type (surface, linear, etc.)	Expensive	
active	Topographic and bathymetric Lidar	From an aircraft or a ground station which position is precisely known (DGPS + IMU for onboard systems), a laser beam is transmitted towards the relevant area and an analysis of the backscattered signal (route duration between transmission and return signal reception is analyzed, as well as specific features thereof) will derive information on the topography Can fly over non-navigable channels NB: lidar technology may be used for other applications (DIAL, doppler...)	General	Wavelengths used from green, UV and NIR (near infrared)	The main steps for deriving information on topography include: 1- Achieving a geo-referenced scatter diagram (X,Y,Z) 2- Treatments to produce digital models for raster surface from the raw scatter diagram 3- A field digital model may be generated following the classification of points that helps identify points on the ground (frequently semi-automatic step during production: automatic treatments are manually reprocessed)	Helicopter / airplane / ground platform / onboard a vehicle	Topographic and bathymetric lidars help determine all natural and anthropogenic items (surfaces and water): topography, erosion, volcanism, faults, infrastructure follow-up, archaeology, urban items, vegetation and water, etc.	- To map areas liable to flooding by coupling hydraulic models and lidar DTM - Levee geometry - To localize small items such as walls - Multitemporal surveys for determining the river geomorphological processes (e.g.: identification of changing altitudes through 2 sequences of Lidar surveys over a braided river in New-Zealand - Lidar survey over Petit Rhône river in Arles	High precision, depending on aircraft altitude and path as based on the overflown area and the desired precision. 5 to 25 cm for altimetry and tens of cm for planimetry. Far more precise than Radar technique.	Point density depends on the lidar transmission frequency, the scanning system and the airplane or helicopter height or velocity.	Fast: hundreds of km² over a few days	More expensive than standard Lidar	Depends on weather conditions
			Helicopter-borne topography	NIR		Helicopter	Primary application: linear infrastructure topography and survey (for example: electric lines) (source: Fugro Geoid)	- To identify and determine small-sized items on levees, vegetation, irregular works, etc. (source: CEMAGREF and CEREGE) - To determine geomorphological changes in a braided river section near Digne	More precise in high density lidar such as FLIMAP 5 cm for altimetry 25 mm/pixel (with 150 m flight height)	Over 50 points/m² if helicopter flies at low altitude and slow pace Lower density: 1 to 10 points/m²			Requires a great number of aircraft flights across the area (limited scan swath)
			Airborne topography (Airborne Laser Scanning)	Laser wavelength ranges from 1,064 to 1,550 nm		Airplane flying 200 to 6,100m high	Topography, DTM, particularly for river valleys	- Val de Loire 2002 - Rhône River Valley, late 2000's	15 to 20 cm for altimetry and 0.3 to 1 m for planimetry	Point density lower than 10 points/m², and sometimes lower than 1 point/m²		Fixed costs: €12,000 per site + €200/km² (estimated in 2006)	
			Static (Terrestrial Laser Scanning)	Green or NIR		Tripod	To specify small-scale structures such as slope and dam operation, architecture, forestry, civil engineering, etc.	- To survey cross-sections over river beds - To determine the root system for levee woodland	Far more precise than on helicopter; airborne or onboard a vehicle	Density is very different according to the distance between the system and the object of interest Riegl minimum angular pitch is 0.0024°	About 1 ha/day	€1,000/day	Requires time for broad surfaces
			Land vehicle (Mobile Laser Scanning)	Green or NIR		Car	Urban 3D mapping,	- Levee strain in New Orleans: precise measurement of ground movements on levees	Distance from scanner to target is a precision factor		Extended spatial coverage		Requires access road for vehicles
			Airborne bathymetry	Laser beam operates with two frequencies: one is in the green (532 nm), so that the signal is not blocked by water, and the other frequency is reflected from the water so as to record other topographical data	The recorded waveform (signal) results from the interaction between the signal (gaussian pulse), the water surface (gaussian surface echo) and the bed when the beam reaches the bottom (depends on depth and turbidity, bottom echo). The water column that is crossed back and forth by the beam also contributes to the return signal. Adjusting models to waveforms helps retrieve the various components and specifically determine the depth.	Airplane / helicopter	Technique used to measure a coastal area topography and bathymetry; developed on the coastline, specifically through 3D mapping with depth ranging from 0.5 and 60 m	- Not much developed over continental watercourses - To continuously determine damp bed geometry (e.g.: hawkeye Gardon experiment) - Applications to levee control	15 cm deep (Z), although low depths are overestimated and great depths are underestimated	1 point/10m², and up to 1 point/4m² when altitude and velocity are optimized	20 km²/hour spatial coverage	Fixed costs: €20,000 per site + €250/km² (estimated in 2006)	Identification is contingent upon the wavelength used (green seems to be more suitable) and the environment features (sediments, etc). Bathymetry is not easily estimated for lower than 50 cm depths. Constraints in rapid flow rivers,
	Radar	Synthetic Aperture Radar (SAR): produces a DEM on large-scale grounds	InSAR (radar interferometry), PS INSAR(deformation)	Microwave frequency sensor (with long wavelength: from 1mm to 1m)	Can produce a digital elevation model (DEM)	Satellite, airplane or ground platform	- To examine the ground surface and provide topographical information - Ability to identify ground movements over time	- Watercourse and flood mapping - May ensure levee elevation or slump monitoring through InSAR-	Depends on the platform: satellite/airplane/ground platform. Altimetric precision > 50 cm. Precision by a couple of cm for elevation change through inSAR - deformation on mm scale by PS Insar	- TerraSAR: 1mx1m spatial resolution - RADARSAT-2: 3mx3m spatial resolution	Can produce 24 hour images (depends on platform)	€2,500/image - TerraSAR: 10kmx10km - RADARSAT-2: 30kmx30km In future for free (SENTINEL Program)	No limits : sensor under any weather conditions and at anytime Unaffected by cloud cover or darkness Limit : satellite image once a week/month
	Sonar	Sonar and ultrasound scanner are used for measuring underwater topography	Sound Navigation and Ranging	Uses specific sound propagation properties in water to identify objects under water and sandwaves	The sonar sounds a tone burst and listens to its echo on any obstructing objects on its path. Distance is calculated by measuring the time lapse from transmission to echo reception (sound propagation speed in sea water being 1,500m/s)	Boat	- Navy: submarine and mine detection - Fishery management - Sea and river navigation: watercourse longitudinal profiles or ocean floor mapping - windmillpark: forcasting of seabed changes in time		High precision			Rather cheap equipment compared to other systems, but expensive compared to low water visual inspection	Can only identify underwater objects Speed of sound is different according to depth (change in temperature and pressure)

Figure 3.11 Lidar acquisition (left) and multiple return (right) principle

Source : Fugro Geoid©

Lidar (Light Detection And Ranging) is an “active” remote sensing technique based on light transmission from a transmitter to a receiver. The light is partly radiated or absorbed into the target environment while the remaining light is backscattered towards the receiver. The technique is based on measuring the lengths between the laser source and the object or environment (typically the earth surface). The signal is transmitted from a laser attached to an airborne (helicopter or airplane) or on a ground platform. The signal wavelength ranges, depending on its applications, from 500 nm (e.g. bathymetric Lidar) to 1,550 nm (e.g. Airborne Laser Scanning). Traditional ground resolutions are provided in decimetres with densities amounting to a few points per square meter. This type of Lidar survey is commonly used in Levee management for acquiring topographical data on river valleys, and for studying coastal areas. Compared to airplanes, helicopters offer the advantage of flying at lower altitudes and slower velocity, allowing the measurement of high point densities on the ground (> 50 points/m^2) and are particularly suitable for performing surveys or following up linear infrastructures such as levees. Additional to Lidar, taking also aerial photographs or videos of the levees is very helpful to identify and specify any visually indicated damages (external erosion, etc.), specific works (walls, water discharge or intake, etc.) and irregular surfaces (woodlands), and to map then on a large scale plan.

As part of levee assessment procedures, Lidar techniques were first used in the United States and The Netherlands. In France, the first experimental application dates back to 2006. As part of FloodProBE-project, the very high resolution helicopter-borne laser remote sensing technology has been identified as suitable for contributing to the assessment process (topography, determination of embedded structures within the levee and vegetation) of urban and suburban levees, see the textbox for some results of this pilot in Val D’ Orléans in France.

The laser performs three scans forward, nadir and backward, respectively, on the helicopter (Figure 3.11). The flight path and laser source position can be known using onboard GPS systems. The measurement principle is based on recording all data stemming from the first pulse or first echo, and from the last pulse or last echo. First echo data will show, for instance, the vegetation top whereas last echo data will show the ground underneath this vegetation. The different returns can be used in the analysis i.e. in digital terrain model (DTM) also known as surface digital model

(SDM) or digital elevation model (DEM) and from the different returns in layers with or without vegetation. In Figure 3.12 an overview is given of which echo data can be used for assessing risks of internal erosion, overflow, instability external erosion and scour or former breaches. Vegetation heights may be classified for a better determination of forest canopy strata or structures (trees, bushes, hedges, etc.). In the text box some examples of the Orleans pilot site are shown, but for more examples and details of the assessment guidance is referred to the FloodProBE deliverable, see Chapter 6.

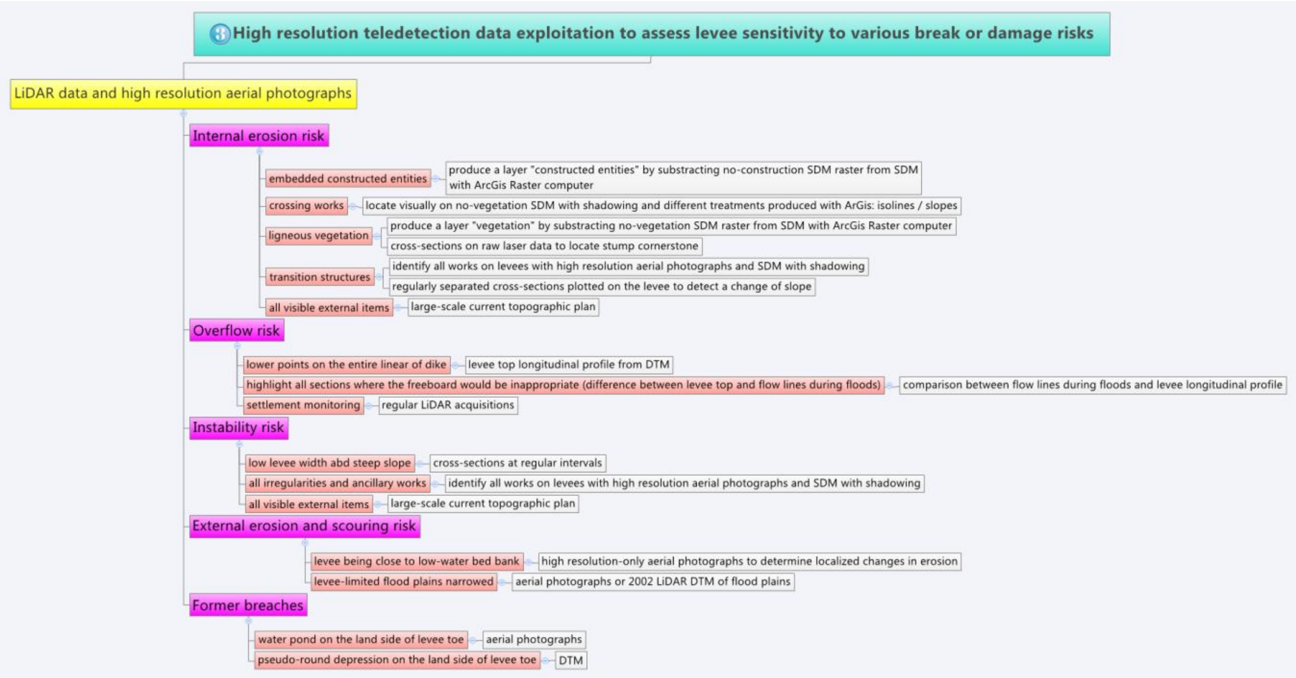


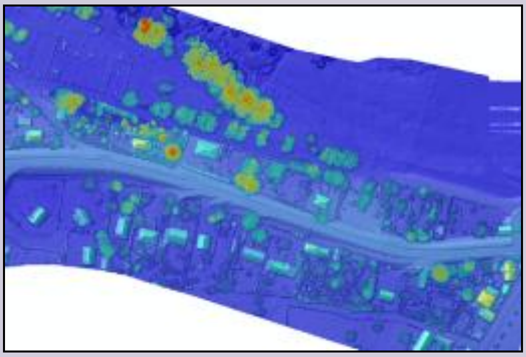
Figure 3.12 Lidar data and failure modes detection

Potential levee settlement issues may be identified by comparing topographical data recorded over time. These types of movements usually change, at a more or less slow pace, over several years. In order to identify and follow them up, high resolution Lidar acquisitions should be repeated at regular intervals, every 2 to 5 years for instance. Follow-up processes of this type are regularly applied in management for levees in the Netherlands.

Box 3.1 Helicopter-borne survey of levees

The French pilot site selected for performing and operating an experimental helicopter-borne survey over levees and related works in urban and suburban environments is Val d' Orléans. This is one of the most challenging dales along the Loire River, with several Orléans districts or boroughs located on areas liable to flooding by the river (65,000 inhabitants).

The digital elevation model (further referred to as SDM) contains information transmitted by the radar first echo from the vegetation and frame cover. Items such as cars and people are filtered. Underwater topography is not shown on the SDM as this type of laser does not reflect water. Especially for the FloodProBE experiment, other SDM products were created: a no-vegetation SDM to show only the constructions; and conversely a no-construction SDM to show only the vegetation (Figure 3.13). This will help improve the levee assessment with constructions and vegetation analyses with a GIS.



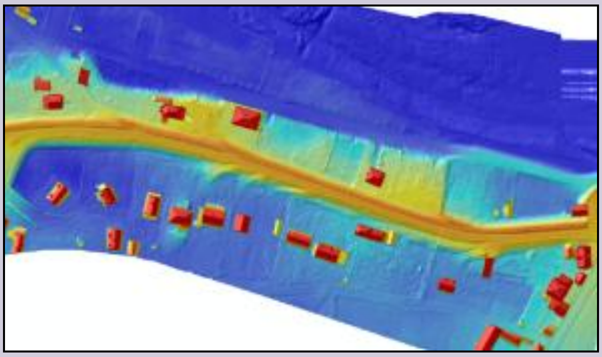


Figure 3.13 Left to right, SDM and no-vegetation SDM from the same area

As recalled in paragraph 3.3 (structure transitions), main internal erosion risk factors are as follows: buildings embedded in levees, pipes crossing the levee, woodland and interface or transition areas. SDM data are provided as 100x150 metre raster plates. To produce a layer showing only constructed entities, each no-construction SDM raster (including vegetation) must be subtracted from SDM (including vegetation and constructed entities). Below is an example of a house embedded in the levee slope on the land side (orange circle). It is located in Guilly, just before the levee separates from the river downstream. In this instance, only one house is identified.

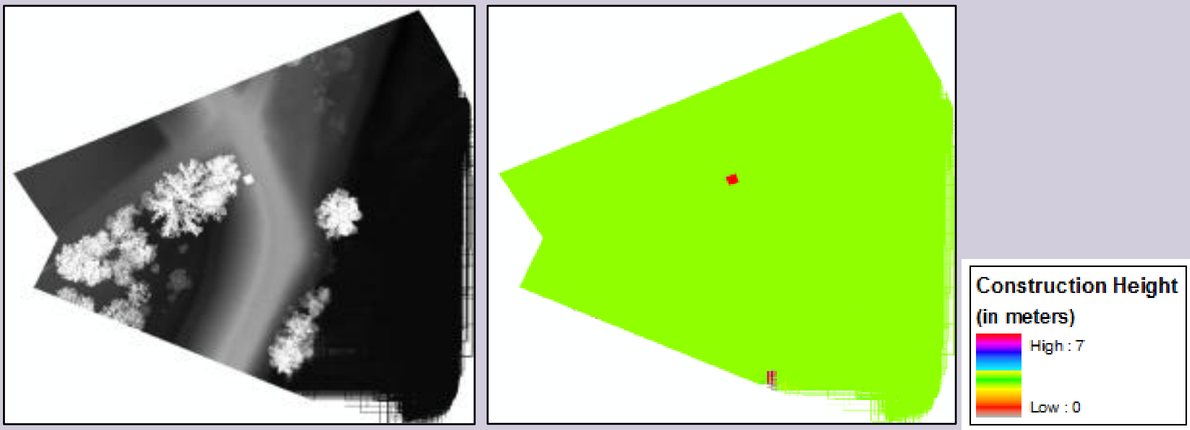


Figure 3.14 SDM (Left) Result from SDM/No-construction SDM raster subtraction

Another filter treatment may be carried out on SDM raster to make the relief more visible: this is referred to as shadowing. The figure below results from superimposing SDM over shadowing raster.

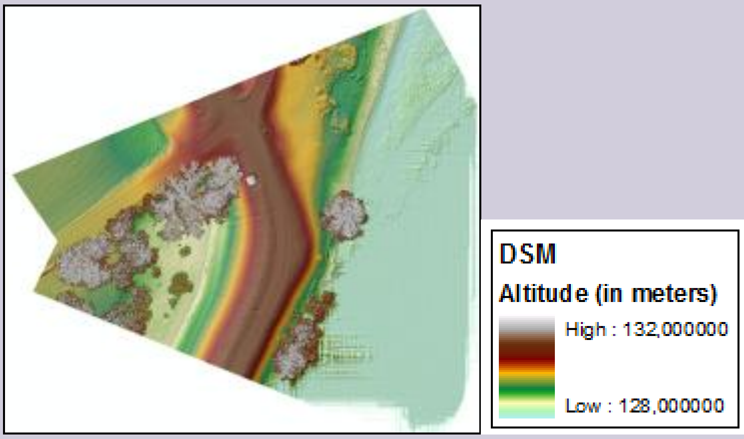


Figure 3.15 SDM with colour shadowing

Figure 3.16 below shows the result obtained from no-vegetation SDM being subtracted from the SDM.

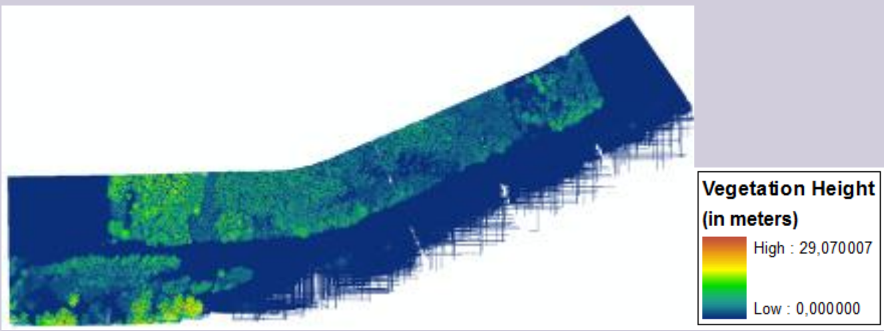


Figure 3.16 Example of SDM/No-Vegetation SDM subtraction to display vegetation

Combination of information sources - GIS-based diagnosis of levees

Levee management has changed rapidly over the past few years towards a more structured and transparent data oriented process. This change is largely driven by the evolving presence of information technology at all steps of the assessment. This applies to the traditional “hard” data (that goes directly into the performance models), but also to the softer information that experts observe whilst inspecting levees. A significant improvement in performance assessment can be made if these fundamentally different data types (hard data as well as softer information like observations or experiences) are combined and used in the assessment. As most of the information is linked to a location, more and more information regarding levees is stored within GIS databases. GIS is therefore more and more applied as part of a performance assessment.

Incorporating the softer information in the assessment models is not always straight-forward as our traditional assessment tools are not designed to deal with different data types. FloodProBE investigated how data is used to assess flood defence performance and how data and softer information might be combined to provide more reliable performance assessments. The report elaborates on assessment methods and mathematical techniques to combine data types and gives practical examples.

The way in which system performance is assessed varies between countries and according to specific assessment; national policy and cultural approaches have a significant impact on the approaches taken. However, analysis of system performance typically requires the assessment of each component of the system in a methodical manner. Historically, this has evolved by summing the analysis of each of the individual structures or structure lengths. Within UK and The Netherlands, probabilistic methods are used to analyse system flood risk. Fundamentally, the approach considers how the flood defence structure performs over a range of load conditions and what might happen when failure occurs. The FloodProBE-research differentiates between the purpose of the assessment (policy analyses, routine maintenance, emergencies and regular safety assessment), the type of data (data nature, type, source, format) and the stage (in the assessment process) in which the data can be combined – for example, refining the input versus refining the model.

3.3.3 Methods for analysing performance of the levee

The assessment process can be described, in a very simple way; as the use of one or more methods for treating and combining data in order to evaluate the performance of the levee or levee system, according to its main function (to protect against a flood) and/or its reliability (possible failure modes). This can be done in a variety of ways, as there are different assessment methods used in different countries, all based upon a combination of data processing, using expert judgment, index based methods, empirical models, physical and/or mathematical models. Simple models often suffice with simple data like indexes while more complex models often need large amounts of data assimilation. Four types of methods for analysing levee safety modes are listed from relatively simple (expert judgment) to very complex (mathematical models):

- A flood safety expert has experience to assess whether a flood defence can withstand a certain water level. The quality of the assessment stands with the quality of the expert. This also implies that the process leading to the conclusion is not always transparent and could be questioned.

- In index based assessment methods, a number of performance features determines the safety level. An example of such a method is a check on erosion of the inner slope of the levee based on several observations such as the angle of the slope and the quality of the grass. A check list with scores is normally used.
- If there is a clear relationship between a number of parameters and the performance of a levee (for different failure modes), empirical models for failure modes can be set up in order to evaluate the performance. Such a correlation leads to a relationship between measurable/predictable parameters and the safety of the levee. An example of such a model is Bligh's model for backward erosion.
- Physical and mathematical models for failure modes are detailed assessment tools. Then an investigation of the critical situation, the so-called limit state, is a method of determining the safety level of a levee solely based on physics. In this situation, the loading and the mobilized strength is in equilibrium. This is the maximum load the levee can withstand. By dealing with uncertainties, a probability of failure as a function of the water level can be deduced. Most physical and mathematical models can be presented in a limit state equilibrium equation.

3.3.4 Combining data techniques

In every step of an assessment – from gathering data to reporting the assessment result – there are sources of uncertainty. Uncertainties found in parameters are caused by imperfections and omissions in the physical models and are the result of the fact that models are schematisations. At every step of the safety assessment, information is left out because it did not fit the assessment methodology. In order to decide on the strategy of combining data one should address the main uncertainties, and then determine what data can help to reduce the uncertainty and finally look for a technique that combines this data type with the existing model. With the increasing availability of GIS data, more opportunities arise to use multiple sources of data in the assessment. Up to now, this happens mainly through expert judgment. But several techniques exist to fully utilize all available GIS data in a more reproducible way. Data can be combined at three points during the steps of the analysis process. Each of these three points will be elaborated on in this section.

Point 1: Refining the input data.

Integration can be performed at the start of any analysis in order to have the correct input data or to refine or improve the input data. The prediction model remains unchanged. Observations of the levee behaviour or performance are combined with the results of the prediction model. Many techniques already exist to perform calibration Of the input data The techniques vary from rather straight forward averaging and least squares analysis to be applied in data-sparse areas, to more complex time series analysis and Kalman filtering techniques applicable in data-rich areas.

Point 2: Improving the (performance) model.

At a later stage in the assessment process, data can be combined to improve the precision of the model through calibration or by incorporating additional effects. If the uncertainty due to the model is relatively large compared to the uncertainty of the input parameters, updating the model is an efficient way of improving the assessment.

The simplest updating method comprises standard mathematical techniques. A more advanced method to upgrade the probability density function is by adding survived loads (high water labels in the past) to the analysis. More advanced mathematical techniques comprise a group of methods that rely on computational intelligence. Such methods can address complex problems to which the previously mentioned methodologies and approaches are ineffective or infeasible because of the complexity of the data. Another possibility in data rich areas is the use of an artificial neural network (ANN) to simulate the behaviour of a system. ANNs are very efficient to simulate the behaviour of a slow, complex mathematical model with few input parameters. If experts have knowledge about processes, but are unable to quantify them mathematically, fuzzy logic can be a tool to translate this knowledge to an assessment tool. E.g. knowledge like “clogging of a drain is a small risk to the safety” can be combined with other such statements to construct a fuzzy system that relates and quantifies the risks of a levee system.

Point 3: Adjusting the output.

In the final stage, one or several assessment results can be updated based on additional information.

An assessment result can be adjusted based on information that has not been taken into account in the parameters or model yet. Understanding the influence of data types like animal burrowing, historic plan form data or visual inspection data on failure modes provides valuable information. This understanding makes it possible to include information into the assessment that has not been taken into account initially.

The combining and integration of data sources is complex and manifold. Within the FloodProBE project several examples have been drawn up to illustrate and explain different data combining techniques. Table 3.7 gives an overview of these examples which are elaborated further in the FloodProBE deliverables (see Chapter 6). The first column names the example; the second column shows the point (data, model or output) at which the data is combined. The third column is the applied (mathematical) combining technique and the final column gives a short description of the example and the data types.

Table 3.7 Overview of the examples of data combining techniques

Example	*Combination level point*	*Analysis method*	*Description of data combination technique and data types*
1. Back calculating settlement parameters during construction	Input	Maximum posterior estimate	Field observations (measurements) with laboratory results
2. Using a stochastic subsoil model for risk analysis	Input	Risk analysis	Geological knowledge with mathematical models for risk assessment.
3. Improve backward erosion model based on observations	Model	Bayesian Belief Network	Expert knowledge, mathematical models and field observations to improve assessment of backward erosion.
4. Updating probability density functions for backward erosion using survived loads	Model	Bayesian updating based on survived loads	Field observations like uplift or sand boils with Sellmeijer model
3. Back-calculate stability parameters	Input and model	Genetic algorithm	Field observations (measurements) with mathematical model
6. Updating the input with observations	Input	Updated models	Updating fragility curves on internal erosion
7. Risk analysis	Model	Risk analysis	Combining probabilities of failure

3.3.5 Analysing and designing the GIS-based data system for levee assessment

The need to register all information within a GIS system is also considered within FloodProBE and how such a system should be set up. The architecture of the data, the accessibility of the data and the user interface are crucial for an intuitive, functional system.

The first step is to consider the most suitable information system for collecting and maintaining all the data sources. Vast amounts of data relating to plans, cross-sections, geotechnical survey, structural survey, condition inspections, design and as-built drawings, photographs, reliability and many more aspects of the levee systems ought to be referred to whenever an assessment needs to be made. In order to access these data efficiently, it is important to have a well organised data acquisition and data storage system in place, which could combine both a classic paper based system (e.g. for paper reports, plans), a digital computer file system (e.g. for CAD files, digital pictures, digital aerial photographs) and a GIS-based digital platform. Since many of these data are spatially related, there are clear advantages to such a system being accessible via a GIS combined with a Data Base Management System (DBMS). Examples of existing GIS & DBMS's are the NFCDD in the UK Environment Agency, the IRIS in the Netherlands, the SIRS Digues in France. One of the challenges is to design a conceptual data model which allows combining both the representation of linear items (e.g. type of surface material of the landside part of the levee) and point items (e.g. trees, animal burrows).

This GIS / DMBS system can be loosely or tightly coupled to specific levee assessment tools based on some of the techniques presented in the previous section. In such a case, a GIS with an underlying DBMS can serve as central data source for input to analysis software for levee assessment. By automating this link, it is ensured that the most recent information is used in the safety analysis. New visual observations from regular inspections can be used to tune the input data, the model or the output data or a combination hereof.

Chapter 4 System Analysis – Vulnerability of Critical Infrastructure

4.1 Introduction

Urban critical infrastructure includes those assets that are crucial for the continuity of economic activities in cities as well as for the urban population basic living needs. Examples of critical infrastructure are technological networks of energy supply, transport services, water supply, information and communication services, as well as the so-called “Hotspot buildings” (or critical infrastructure buildings) such as power stations, water and wastewater treatment plants, control centres of public transport, communication hubs, fire stations and hospitals.

Damage to one type of infrastructure can cascade to cause disruption to other infrastructure, e.g. loss of power supply can impact on the health service of an urban community (see Figure 4.1). Besides the financial damages associated with this cascading, the execution of the crisis management is also hindered as is the recovery from the flood event. Flood vulnerability therefore largely depends on the degree in which both hotspot buildings and network critical urban infrastructure are affected by flooding and as a consequence are generating damage either directly or indirectly, or both.

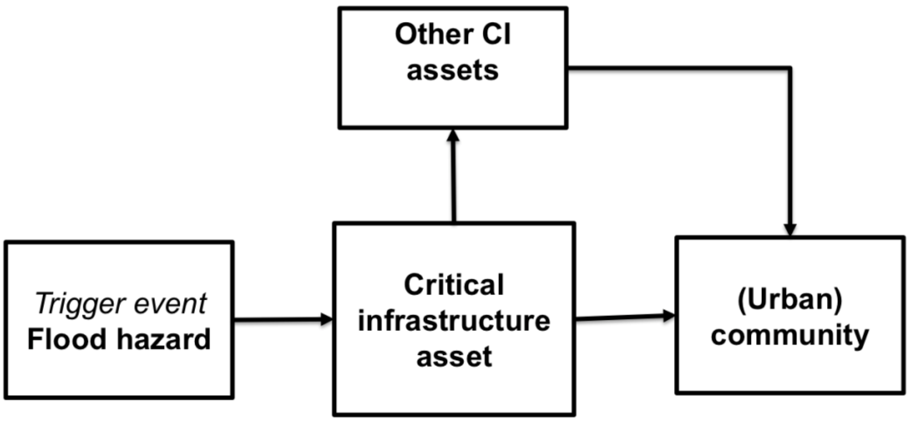


Figure 4.1 Schematic representation of cascading effects of flood damage to infrastructure

In any vulnerability assessment of critical infrastructure it is therefore essential to have an understanding of these cascading effects and inter-linkages between the organisations and systems involved in providing these essential services.

The framework suggested here consists of four elements: (1) criticality, (2) vulnerability, (3) severity and (4) alleviation - see Figure 4.2.

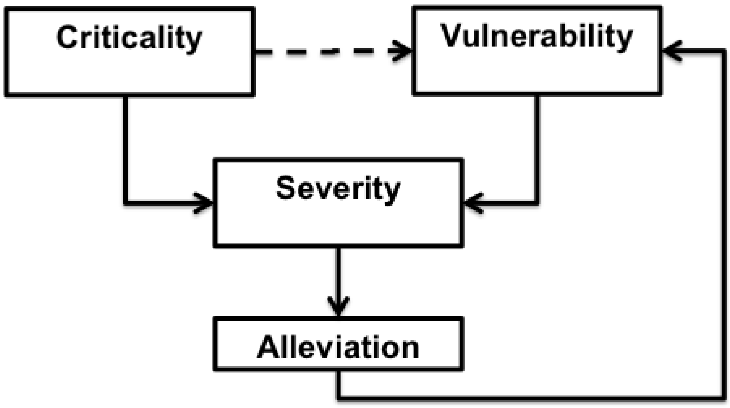


Figure 4.2 General framework underlying the Quick Scan method

Criticality can be expressed by:

- the severity of the effect (number of fatalities/wounded or monetary damage),
- the extent of the area or the number of people affected,
- the rate of recovery from the outage.

Vulnerability relates here to the exposure and sensitivity to disruption or (direct) losses which, in case of critical infrastructure assets, are dependent on the features of the location (frequency and extent of flooding) and the 'condition' of the asset (e.g. susceptibility to flooding, state or repair, design features)

Severity stands for the extent of socio-economic impact on society due to the reduced serviceability level of infrastructure (i.e. 2nd or 3rd order impacts).

Alleviation entails all the pro-active interventions available to reduce the vulnerability of the critical infrastructure asset (feedback mechanism) and by doing so sustain the level of serviceability of an infrastructure during and after a flood disaster.

The present chapter describes new methodologies and tools for assessing the vulnerability of urban environments to floods that were developed under FloodProBE to fill some existing gaps in this area (e.g. modelling of interactions between critical infrastructure networks):

- Step-wise approach framework for networks and tools (FloodProBE D2.1 - 'Task 2.1 Identification and analysis of most vulnerable infrastructure in respect to floods', 2012), including
  - Risk Assessment Tool
  - Advanced Analysis Tool
- The Storyline method (FloodProBE D5.1 – 'Report detailing integrated pilot results and lessons learned', 2013)
- Assessment methodology and tool to identify likely level of damage to critical buildings (FloodProBE D2.2 - 'Assessment of the vulnerability of critical infrastructure buildings to floods', 2012)

- The ‘Quick Scan method’, a pragmatic assessment and ranking procedure of the consequences of flooding which attempts to capture second and third order consequences.

4.2 Step-wise approach for networks and tools

To offer guidance for the flood vulnerability analysis of critical infrastructure networks, the FloodProBE project developed a framework based on a stepwise approach, from a simple coarse assessment to advanced modelling. This approach is oriented towards the stakeholders involved in critical infrastructure and flood vulnerability in urban areas, be them public entities, private consultants or researchers. Two tools were developed in strong collaboration with the pilot areas Trondheim (Norway), Orleans (France) and Dordrecht (The Netherlands).

The methodology proposed consists of four steps that cover a spectrum of possible approaches for the flood event. It goes from step 1 (a coarse overview) to step 4 (the most sophisticated analysis) - Figure 4.3. In many situations not all steps are possible to undertake (or required) but in the case where they are performed, the final result is a thorough insight into the critical infrastructure present, and its vulnerability towards flooding of the area under assessment.

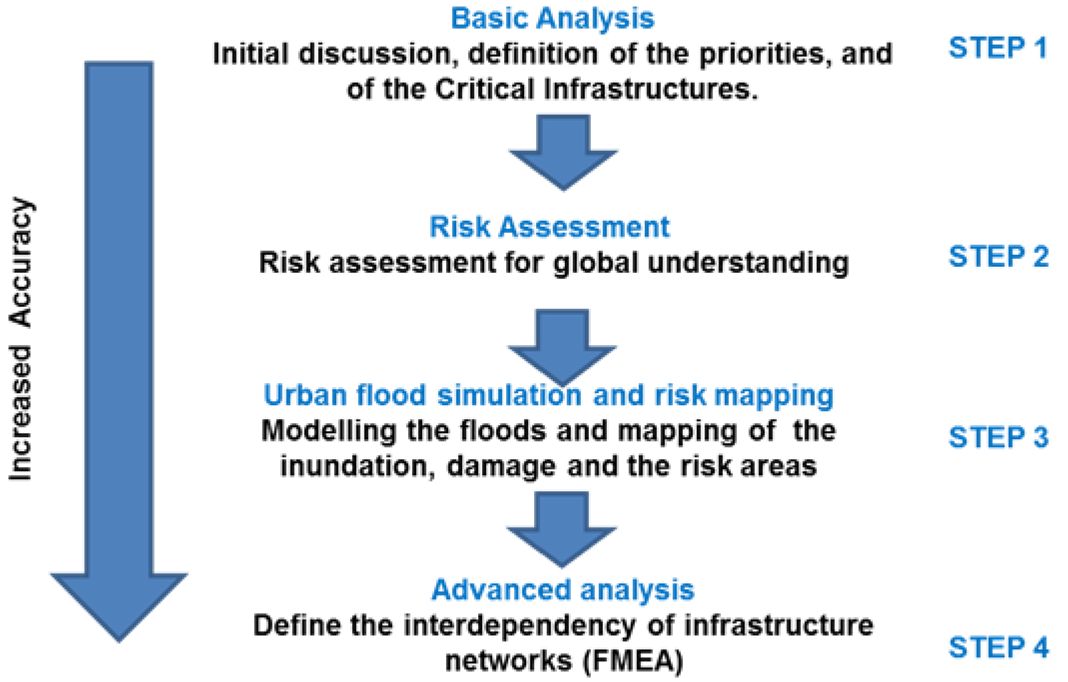


Figure 4.3 Framework for risk assessment

Note: FMEA - Failure Modes and Effects Analysis

Steps 2 and 4 are not covered by existing tools and were therefore developed within the frame of FloodProBE to fill these gaps.

4.2.1 The Risk Assessment tool for global understanding

Based on existing methodology and software tools for risk and vulnerability assessment in Norway (covering various types of hazard) an Excel based tool for global risk assessment has been developed focusing on the flood hazard. This tool which allows fulfilling step 2 in the framework for risk assessment consists of a coarse analysis resulting in the generation of risk matrices (Figure 4.4). A risk matrix is produced for six different categories, which represent as many perspectives for the calculation of the risks:

- People
- Environment
- Infrastructure: water network, transportation, electricity, telecommunications.

These matrices are handy tools which support discussions and the decision process for the stakeholders (municipalities, planners, flood professionals, etc). The main area of improvement for the stakeholders can be defined by the sections "Some damage", "Serious" and "Critical". If the risk calculated for the event is located in the red part "Catastrophic", it should be understood that maybe even the most significant mitigating measures are not able to bring about a real improvement. In this case, the focus may be preferably focused on the recovery from the extreme event, or on reducing vulnerability.

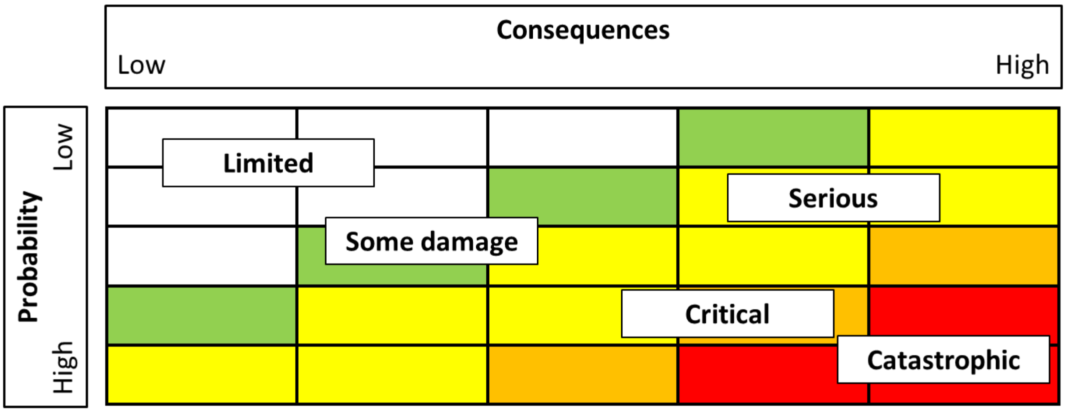


Figure 4.4 Sample of risk matrix

The tool only requires basic knowledge of the area under investigation and can be performed by users from different backgrounds. The method starts with expert interviews to identify undesired events, their likelihood and the consequences in the case of an incident. These are discussed and registered in a risk matrix. The analysis then provides a first risk picture on a coarse scale. In most cases, more detailed standard risk analyses and model-based risk analyses have to follow. An example of application is given for the case of Trondheim, Norway (see Box 4.1).

BOX 4.1 – Application of Risk Assessment tool - for global understanding to the city of Trondheim, Norway

The Trondheim Municipality is situated in central Norway beside the Trondheim Fjord, in the county of Trøndelag. With around 170.000 inhabitants, Trondheim is the third biggest city of Norway and is exposed to three different sources of flood risk:

Flooding from the river Nidelva

Flooding from the sea during storm events

Flooding of urban drainage systems - the sewer system consists of about 50% combined system built before 1965, 40% separate system and 10% non-active separate system.

For a large number of possible flood events the risk has been evaluated and placed within the matrices showing the vulnerability to People and to the Environment. The results are presented in Figure 4.5. Each number represents one possible flood event. For example, the event numbered 42 is in the red zone for risks on people, but only in the yellow zone when it concerns the environment.

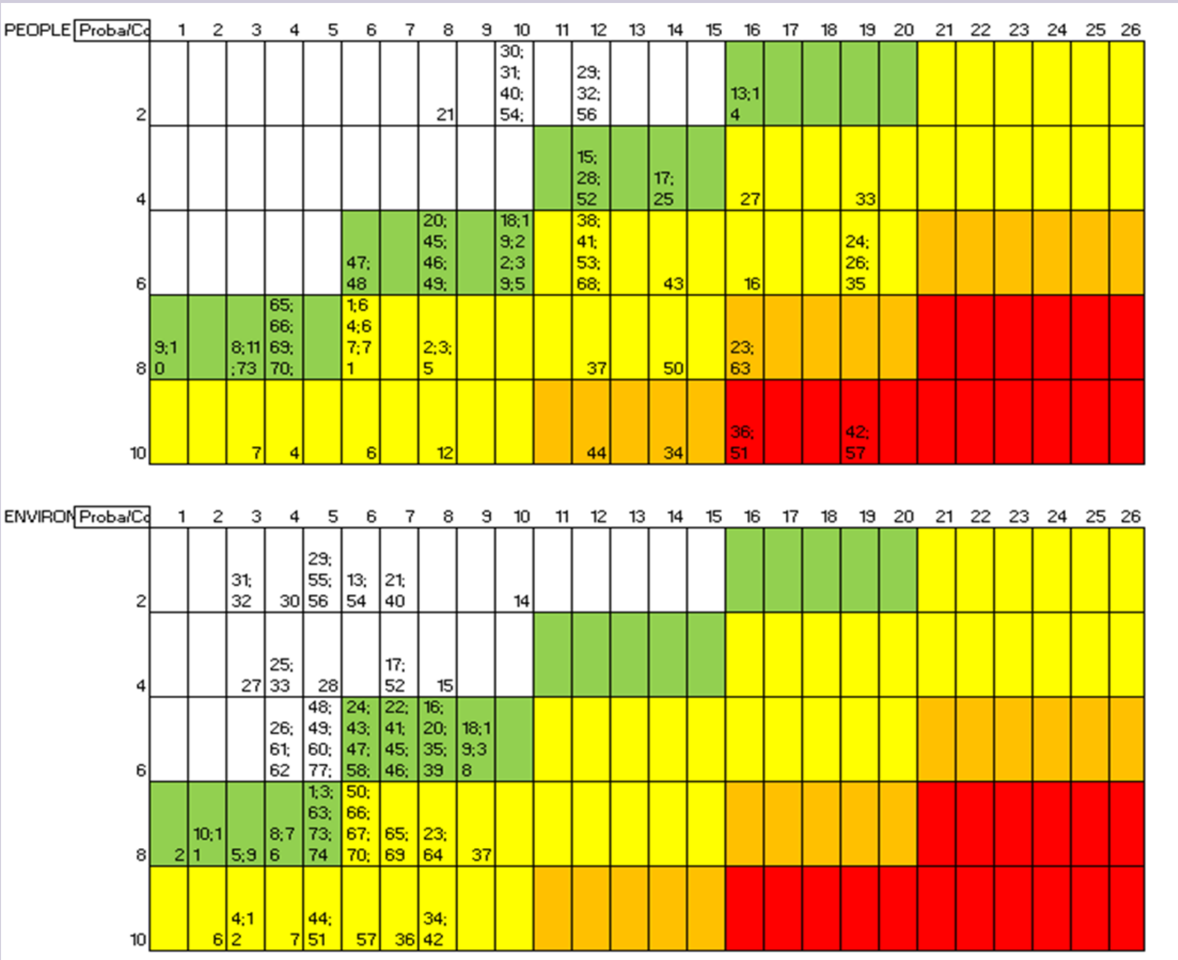


Figure 4.5 Output of the program

4.2.2 Advanced Analysis tool – defining the interdependencies of infrastructure networks

A sophisticated modelling tool based on Failure Modes and Effects Analysis (FMEA) on a GIS architecture has been developed enabling the study of interdependencies between networks subsequent to a disaster. Two interdependency levels must be taken into account: *components interdependency level* and *networks interdependency level*. The combination of components and/or function failures generates such a large number of scenarios that a computer tool is needed to automate the design of these scenarios and fully apply FMEA (Figure 4.6).

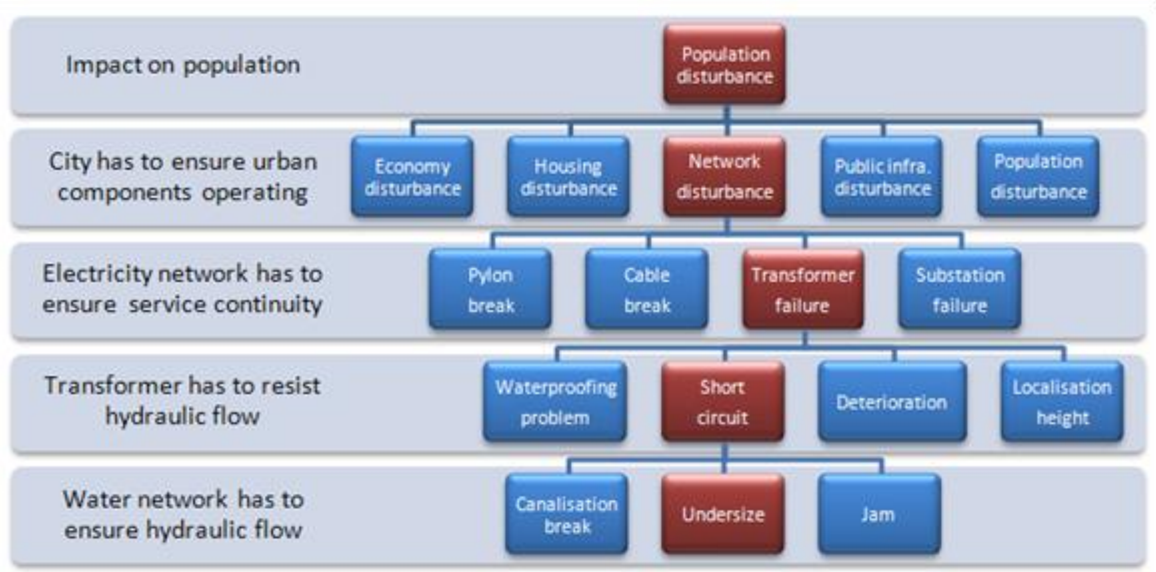


Figure 4.6 Failure scenario example

Note: this type of scenario can be identified without an automation process but it is impossible to produce all imaginable scenarios

The software addresses three main objectives. The first is to allow visualisation and update of the FMEA; the second is to design failure scenarios; the third objective is to analyse the results and allow an overall understanding of interdependent network failure modes thanks to diagram representation of the results (Figure 4.7).

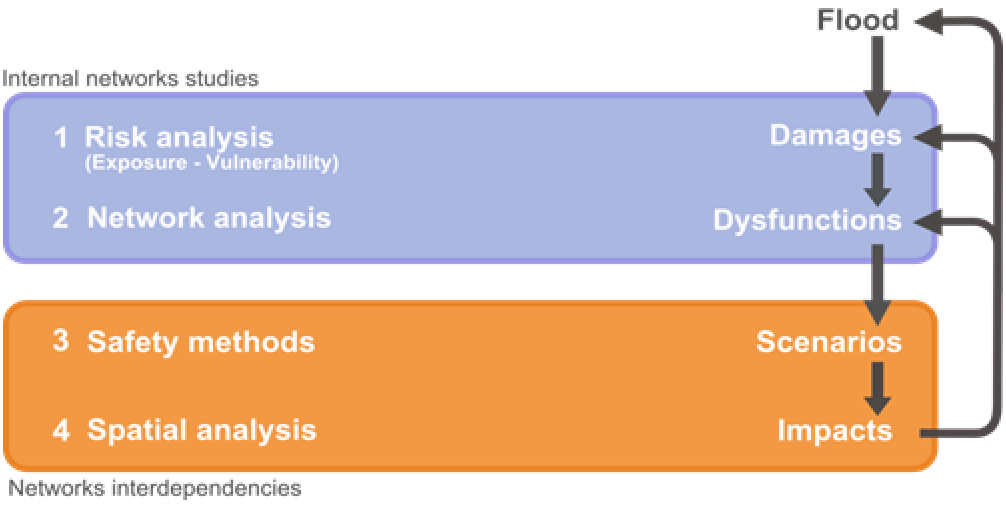


Figure 4.7 Approach for studying network disruptions caused by floods accounting for interdependencies between networks

An example of application of the tool is given in Figure 4.8 - as data on technical networks are difficult to obtain especially at city level (due to commercial sensitivities), this example used fictional data. The example involves three networks and demonstrates the importance of considering interdependencies (in orange dashed lines). For instance, the electrical network does not suffer direct damage (in red) and direct dysfunction (in pink) from flood hazard but it is damaged by the sanitation network. As time goes on, the initial failures further generate new dysfunctions (in orange) on sanitation and drinking water networks (by pumping station dysfunctions).

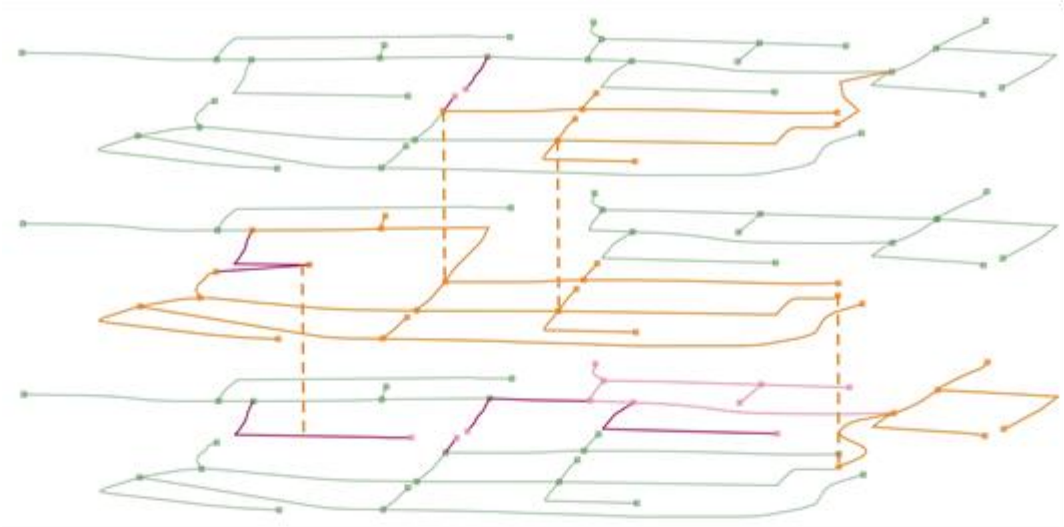


Figure 4.8 Example of application of the tool for three types of network

Upper level is the drinking water network; middle is the electricity network; lower is the sanitation network

It should be noted that most of the frequent disruptions are locally absorbed by the networks and the end users remain unaware of their occurrence. This fact results from the ability of the networks to redistribute the flow at the location of the disruption – to a certain extent. This is a typical resilience capacity that allows networks to operate in a degraded mode. However, the geometric properties of the network can limit the adaptive capacity of the network. Indeed the network configuration determines the number of alternative paths to disruption of one or several components, or in other words the redundancy of the networks.

The web GIS tool developed is composed of different modules (Figure 4.9):

- The map with the main components for navigation and switch layers
- The menu with the different levels of analysis: redundancy analysis, recovery analysis, disturbance analysis and synthesis of the results
- The options with the different steps for calculation: from data import to visualization
- Different tools in order to: print maps, interact with maps, and interact with the display area.
- Display area: area to display information about objects or to display statistic about map.

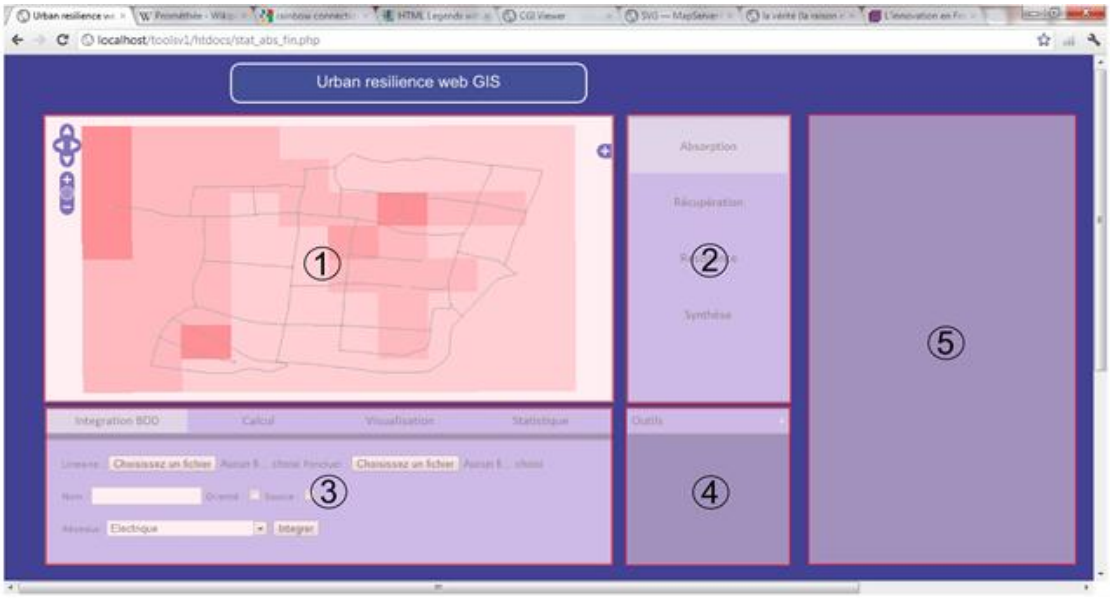


Figure 4.9 View of the GIS tool (French version)

4.3 The Storyline Method

A storyline is a realistic sequence of incidents and human responses that may happen during a flood event. Three phases of a flood are analysed: the rising of the flood threat, the flooding itself and the recovery from the flood. Storylines are an addition to commonly used impact analyses and a good tool to support the analysis of CI vulnerability as they provide a clear basis for discussions and are illustrative. They help in flood event management and strategy development.

The storyline aids in analysing the consequences of a flood on critical infrastructure including the effects of outfall of a network or part of a network on other networks and on society (number of people affected, costs, etc.). Applying the storyline method provides a clear mutual basis for discussion on what may happen and what could be done. It shows interdependencies and complexities between the water system, critical infrastructure and actors; it allows analysis of CI in relation to flood event management, recovery and measures and provides insight on which assumptions are relevant and into knowledge gaps. Storylines can also be developed for a situation with interventions in place, providing insight into the effect of the selected interventions.

A storyline is developed through the following steps:

1. Setting up a framework to comprise all information that can contribute to the sequence of incidents and human responses during a flood. The components of this framework are based on the Source-Pathway-Receptor-Consequence S-P-R-C approach. Information is gained from literature, studies on the area and talking with experts on the subject and the area.
2. Based on this knowledge, the elements that need to be incorporated to form a realistic storyline are selected. Furthermore, the flooding scenarios that are most relevant to describe in a storyline are determined. Once these elements are determined, the methods and information needed to develop and analyse storylines with different realistic options are described.
3. The resulting storylines are analysed. The number of fatalities, the damage, the number of people affected and the number of evacuees are determined. These results are then used to compare different measures that may be taken at all layers/levels of the Multi Level Safety approach and to develop new strategies.

It should be understood though that applying a storyline method does require time and a sufficient set of data. The method cannot be used to compare areas and is not very suitable to use for larger areas. Storylines must be realistic, but no precise probability can be assigned to them.

An example of application is given in Box 4.2.

Box 4.2 Application of the Storyline Method to the city of Dordrecht, The Netherlands

A case study was carried out for the Island of Dordrecht, in the Netherlands to test the storyline method. The island of Dordrecht contains various types of land use (urban, industrial and rural) and the governmental structure is relatively simple: the city is part of one municipality, one water board, one safety region, one province and has one safety standard. This makes it an ideal prototype case for a delta region at risk. Three storylines were developed for Dordrecht: two for flood events under the current flood risk management situation and one for flood events for a future flood risk management situation with interventions taken.

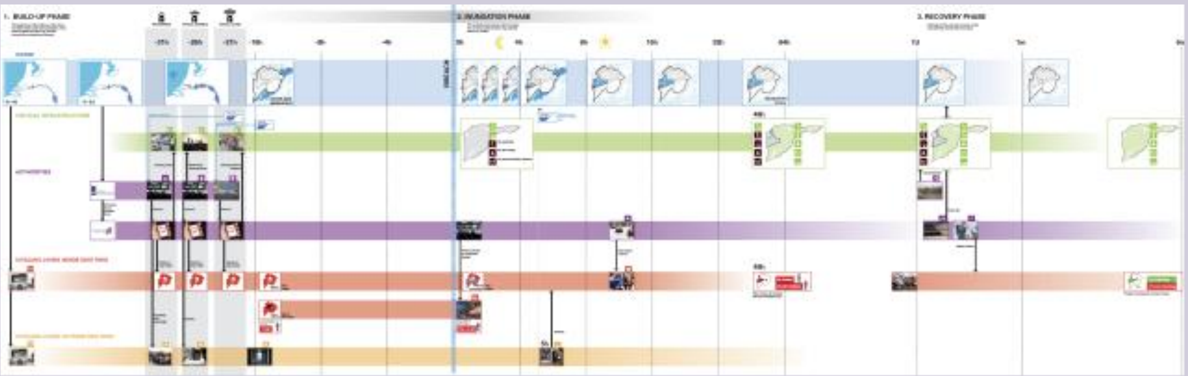


Figure 4.10 Storyline method applied to the island of Dordrecht, The Netherlands

The analysis showed that the flooding pattern is the most important characteristic for the end result of the storylines. This flooding pattern determines:

- The (total) flooded area which determines the total damage
- The (total) depth which determines the total damage and fatalities
- The time available to flee or evacuate from water which determines the number of fatalities
- Rising rate and speed of water which determines the number of fatalities
- The time needed to get the area dry which is important for the recovery phase
- The disruption extent for critical infrastructure which is important for the recovery phase.

As the flooding pattern is an important characteristic, the model used to develop the flooding pattern should be as accurate as possible. Other factors that determine the results such as the behaviour of humans are uncertain. Often there are many options for the assumptions made on these factors and more different storylines should be considered in order to develop a strategy. The storylines developed for the island of Dordrecht showed that much is not known yet for the island and blanks need to be filled to select a feasible flood risk management strategy. However, the method shows in which component there is a knowledge gap and it also gives an indication of the factors that will always be uncertain, such as human behaviour.

The aforementioned knowledge gap was (partly) addressed in a workshop where all experts on the different components were present, so as to enable them to study and fill in the blanks themselves. At this workshop the three storylines developed in the research were presented. The storyline method was received positively. During the workshop it also became clear that the storyline method has the advantage of enhancing and steering the discussion on strategy development directly at the important details and knowledge gaps.

4.4 Assessment methodology and tool to identify likely level of damage to critical buildings

Critical infrastructure includes not only the physical networks of cables, pipes and roads, but also the organisational networks of health, security and emergency services. Buildings play an important role in protecting the equipment and personnel related to these networks (e.g. hospitals, fire stations, communications centres, power stations, etc.). However, the variety of designs and constructions of these buildings make it unrealistic to categorise them into meaningful types when considering their vulnerability to flooding. In order to be able to predict the effects of flooding and costs of reinstatement of these buildings, an individual approach needs to be taken, taking into account the specific characteristics of each building.

At present there is no reliable way of anticipating and estimating post flood remedial works to buildings at an individual scale. This is problematic in that plans need to be developed in advance of flooding to ensure expeditious rehabilitation of buildings. The need for such plans is particularly relevant for critical infrastructure buildings. In the majority of cases, the production of a site-specific remediation plan only occurs following a major flood event.

Therefore, an assessment methodology that identifies the likely level of damage to individual buildings in the case of flooding was developed, the results being expressed as the predicted costs of remedial works. The assessment methodology distinguishes between buildings built using different constructions and materials and is relevant to critical as well as non-critical buildings. A damage prediction tool was developed based on the methodology. This damage prediction tool facilitates:

- Forward planning of rehabilitation responses
- Identification of key risks in order that buildings can be retrofitted to improve their robustness against flooding
- Target investment for reducing future vulnerability
- Better land-use planning for new build and re-development of brown field sites.

The tool is designed for use by people with sufficient technical knowledge of the planning and construction of buildings in question, such as surveyors, architects and other building designers, quantity surveyors and property managers. The purpose of the tool is to enable building professionals who have no specialist knowledge of the effects of flooding on buildings to predict the cost of flood damage to individual buildings depending on the nature of the flood event and the individual constructional characteristics of a particular building. This will enable them to foresee the likely consequences of flooding and to make a cost/benefit analysis of different measures that could be undertaken to protect the building from these consequences. The tool is designed to be used by building professionals throughout Europe. Although the cost data is based on UK prices in 2012, there are conversion factors built in to the tool to make adjustments for the different building costs in the EU countries. The prices and the conversion factors would have to be updated regularly to reflect changes in these over time.

This tool is a simple-to-use system that encompasses the elements of individual buildings likely to be affected by flood water, namely the basement and foundations, the external walls, the ground floor, the internal partitions including the internal doors and joinery, the external doors and windows, as well as the associated services such as electrics, plumbing and ventilation.

The tool calculates the actual cost of flood damage to individual building elements according to their construction and materials, the types of services and the nature of the flooding. The initial output, based on the database contained within the tool, predicts the cost of cleaning, repair or replacement and is expressed as a percentage of the new-build cost of each element. Additional percentages are added for pollution clean-up and sterilization and mechanically assisted drying. An adjustment for regional factors (i.e. different countries) can then be made. An approximate indication of the actual cost of returning the building to use, depending on where it is and when the flooding occurs, can then be produced by the tool when it is combined with calculations using the areas, lengths or numbers of affected elements, the current or predicted rates of construction prices. It should be noted that the way in which the flood depth is taken into account with regard to repairs of building elements depends to a large extent on the different approaches in each country and on different individual practices within a country. For this reason the tool is flexible enough to allow tailoring to the practices in each country.

A simple diagram of the principles of the tool is presented in Figure 4.11.

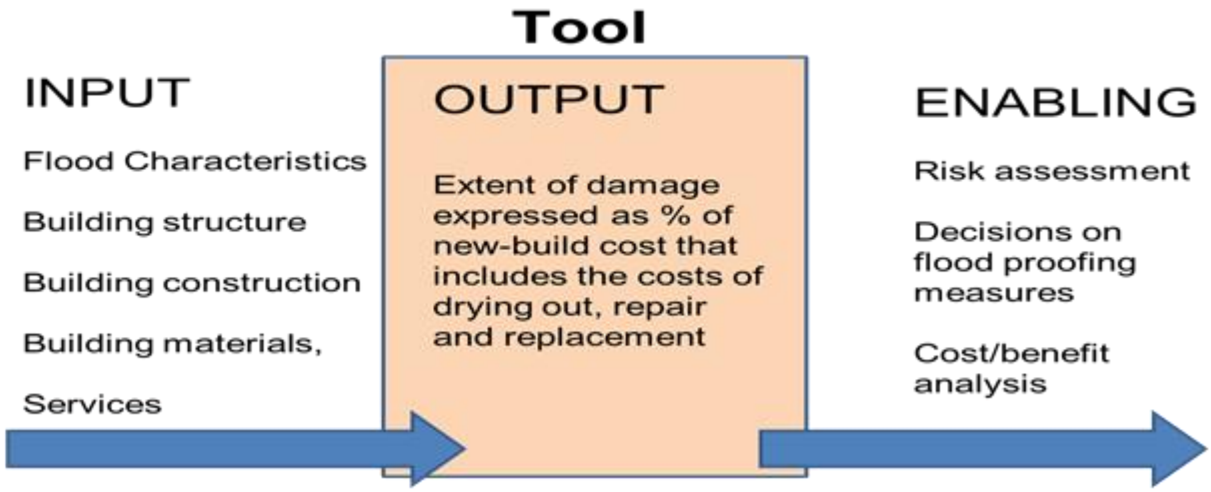


Figure 4.11 Building damage estimation tool principles

The basic data required to be input into the tool by the user are:

- The flood characteristics of the event that is predicted
- Floodwater depth
- Flow velocity and debris
- Contaminant content
- Flood duration
- Identification of the main structural system

- The building divided by elements (external walls, floors, internal partitions, windows and doors, electrics, mechanical services, communications etc.). Each element is analysed according to the materials used and the layering of them. To simplify the range of options, a list of typical constructions has been devised from which a choice can be made.
- Dimensions of walls, floors etc. and numbers of doors and windows that are affected by the selected flooding event.
- Types of services, their positions and layout and the extent of these that are affected by the selected flooding event.

The basic data that are contained in the tool are:

- A database of common elements of different constructions and materials
- A database of effects of flood damage to each construction and the % new build cost incurred by clearing up costs, repair/replacement of the affected area of the construction, assuming clean water
- An additional cost to add for mechanically assisted drying
- An additional percentage calculated to add for pollution of different types, i.e. hazardous and non-hazardous
- An additional percentage calculated to account for the effects of high velocity and debris
- An additional percentage calculated to account for the duration of the flood
- A database of effects of flood damage to each of the different services
- An adjustment factor calculated for regional differences (i.e. different countries).

Before calculating the damage to the building, it is worth checking that the building is not prone to collapse due to the flooding, as this will make the damage calculations superfluous. The likelihood of collapse can be determined either by calculation or by depth/collapse curves (curves are available for wood, metal and masonry constructions for single and multi-storey buildings).

This tool can be used to compare the implications of flooding for different types of building construction, and to assess the value/cost of installing flood protection installations to the building to reduce the damage from future flooding. Various solutions using dry proofing and wet proofing techniques (see Chapter 5) can be explored and run through the tool to gauge their cost effectiveness. Of course, decisions on protecting the building against floods will also be affected by the function and contents of the building – in some cases the fabric of the building and its protection might only be a relatively small economic consideration. The tool does not calculate the damage to contents and secondary costs associated with these.

Validation of the tool was carried out using three case studies in order to gauge the accuracy of the predictions made by the tool. These were selected from data supplied by AXA insurance on three premises that were flooded in 2007 in the Sheffield area of the UK.

The tool as presented here should be regarded as a demonstration of the methodology for calculation of flood damage costs based on flood characteristics, detailed constructional information and associated damage factors. It will provide a springboard for the development of a fully functional tool that can be used for buildings of all types throughout Europe.

The flood damage estimation tool relies on a range of expert assessments of the scale of damage and costs of repair/replacement of a wide range of building constructions. These assessments can be made more robust by repeated testing against real situations, both in the laboratory and in real life as experienced in past flood events. In order to do this, much more specific information of flood events is required, including detailed data about the effects of different flood characteristics on different building constructions and materials, and itemised costs of necessary repair/replacement works. It has proved difficult to gain this level of detail during this research, partly due to issues of confidentiality, to lack of detailed records of past events, and division of responsibilities during and after the event.

The range of different constructions and materials presented by the prototype tool is still limited compared with what is available and used throughout Europe. In order for the tool to be widely applicable, a far greater choice of these should be offered in the menus. To provide this requires a major exercise in cataloguing and assessing typical construction methods and materials in the various countries.

4.5 The 'Quick Scan' method

The objective of the Quick Scan is (i) to assist operators and decision makers to identify, rate, and protect their (existing) critical infrastructure assets servicing urban communities, which may be at most risk from flooding and (ii) to support them in developing effective interventions to alleviate the damage to these assets which are relatively easily achievable and most cost beneficial (i.e. 'low hanging fruit').

The Quick Scan is concerned with urban infrastructure networks including the essential nodes or high value assets (referred to as "hotspot buildings") of these networks. Both are critical for the continuity of economic activities in cities as well as for the urban population's basic living needs. Examples of critical infrastructure are technological networks of energy supply, transport services, water supply, information and communication services. Hotspot buildings within these networks include power stations, water treatment plants, control centres of public transport, communication hubs, waste water treatment plants, fire fighting stations and hospitals.

The Quick Scan method aims to provide a pragmatic and rapid assessment and ranking procedure taking specifically into account rough estimates of the consequences and damages; the method attempts to capture indirect (second and third order) consequences. It complements the Storyline method in the sense that the Quick Scan also includes indicative estimates of the cost and time required for implemenation of the options with the highest severity rating. It is important to note that the point of departure of the Quick Scan is the urban community (defined here as a neighbourhood or city district with a clear cut boundary based on density, age composition of the buildings, geographic location, or socio-economic status). This implies that the focus of the assessment is on 'upstream' rather than on 'downstream' dependencies (in other words: the focus is on the effect of flood damage to a node or network, located either inside or outside the community, on the delivery of a service to that same community (and not to other communities).

The following procedure comprising five consecutive steps has been developed (see Figure 4.12):

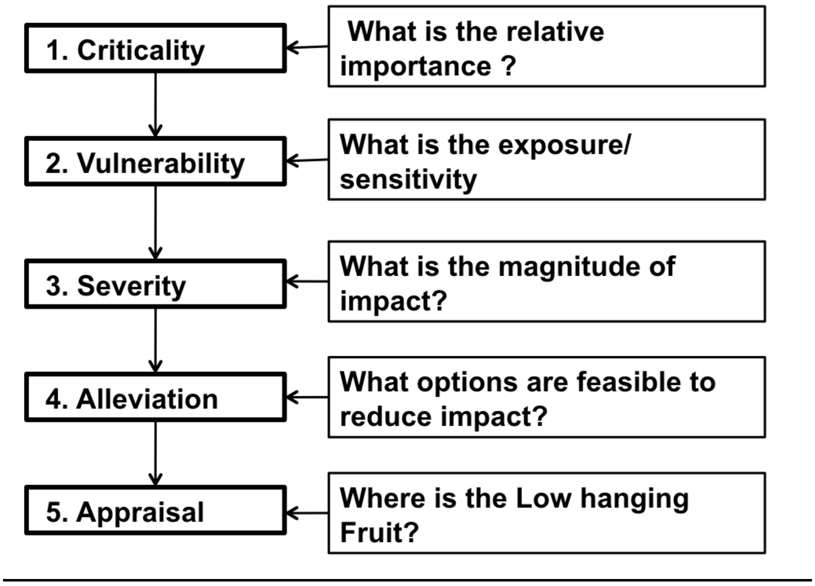


Figure 4.12 Basic steps of the Quick Scan method

Step 1 - Identify and analyse critical infrastructure assets and rank their criticality. Firstly, the assets relevant for the area of concern (in this case the community) should be identified including both the nodes (e.g. transformer and substations, water works) and connections (roads, water supply network, electricity cables). In this step the relationship between networks has to be taken into account. If electricity fails, pumps, communication, traffic control systems and most of the infrastructure will not function, unless they have their own power supply (see Figure). To carry out this step a network analysis is done by describing the critical networks and the elements they consist of, by studying the effects of outfall of one element on the functioning of the network and by the effect of outfall of the network on other networks. Finally, the effect of outfall of one or more networks on the community must be assessed. As described earlier, the focus is on 'upstream' dependencies, which implies that the assets of concern may be located outside the boundaries of the community in question.

Step 2 - Analyse both the exposure and sensitivity of the critical assets defined in step 1. For some infrastructure types clear thresholds define the sensitivity of elements e.g. transformer stations in Dordrecht, The Netherlands, will fail if water depths exceed 30 cm. Based on such thresholds, a focused analysis of potential flood parameters and probabilities ('the exposure') can be carried out. In other cases these thresholds will be less clear. Generally, the principal flood parameter is depth, though duration, salt/fresh water, and flow velocity may be relevant. Flood exposure analysis is normally based on historical data and / or model simulation of potential floods.

The sensitivity depends on the flood resistance and resilience of the critical assets. An asset is defined here as resistant if it can withstand a particular flood water depth without any damage or failure. An asset is resilient if, when it comes into contact with floodwater during floods, no permanent damage is caused, structural integrity is maintained and, if operational disruption does occur, normal operation can resume rapidly after the flood has receded. Vulnerability can be expressed in monetary terms or be based upon indicators such as the duration of outage, the number of people affected and combinations of those.

Step 3 - Based on the results of step 1 (criticality) and 2 (vulnerability) the severity can be assessed taking into account (i) the effect of failure of the assets (nodes and connections) on the delivery of service (first order), (ii) the effect of failure of a (part of one) network or node on other networks (2nd and 3rd order affects such as electricity outage which may impact the functioning of communication and traffic control systems) and (iii) the likelihood of failure (flood exposure and sensitivity).

Step 4 - The aim of this step is to identify the options available to alleviate the effects of flooding on the functioning of the critical infrastructure and at what cost. The options comprise flood proofing (resilient and resistant) construction and retrofitting techniques ranging from simple interventions such as temporary closures to permanent elevation. Much information which is available for traditional buildings is also applicable to critical infrastructure assets, albeit that the underlying CBA (Cost Benefit Analysis) may require a different approach. It is also possible to alleviate impacts from failure by reducing the criticality of the sensitive elements e.g. by making the network more redundant in order to make sure that if one node fails, the network will still function.

Step 5 - The final step comprises the appraisal phase in which the so called “Low Hanging Fruit” will be identified. Based on the severity ranking (where are the highest impacts?) of step 3 on the one hand and the identification of the options and cost to alleviate these impacts of step 4 to the other, the actions that can be undertaken at (relatively) low cost and with high impact as part of a wider range of interventions to further protect the urban critical infrastructure can be identified.

Chapter 5 Design and Engineering

5.1 Introduction

A wide range of engineering options is available to flood risk professionals to help manage flood risk in the urban environment. For the purpose of providing guidance, it is helpful to distinguish between flood defences, critical networks and critical buildings, although these are obviously interlinked and the individual categories should be considered as part of a holistic approach to flood management.

The present chapter describes new methodologies and tools to minimise the impact of floods that were developed under FloodProBE to fill some existing gaps in this area:

- “BioGrout”, a technique to strengthen flood defences (FloodProBE D4.1 – ‘Report on bio-technological strengthening on flood embankments, including the applicability based on experiments, and concepts close to industrial application’, 2013)
- Concepts for Multifunctional Flood Defences (FloodProBE D4.2 - ‘Design concepts of Multifunctional Flood Defence Structures’, 2013)
- Innovative road and bridge technologies (FloodProBE D4.3c – ‘Construction and Technologies for flood-proofing Buildings and Infrastructures; Concepts and Technologies for flood-proof Road Infrastructure’, 2013)
- Hotspot Buildings (FloodProBE D4.3 ‘Construction Technologies for flood proof buildings and infrastructures; Technologies for flood-proofing hotspot buildings, 2012; FloodProBE D4.4 ‘Building resilience measures; outline design guidance and roadmap for accelerated acceptance’, 2013).

5.2 Flood defences

A number of options are available to improve the quality and/or take advantage of existing flood defences (also termed embankments, dikes, levees in different countries) or to design new structures. Some innovative options developed under FloodProBE are presented in the following sections as examples to be considered within the portfolio of options.

5.2.1 Strengthening of earth flood defences

For urban flood defences internal erosion, involving the removal of sand is an important potential type of failure that eventually leads to inundation of the areas protected. Internal erosion occurs when groundwater velocity, driven by a hydraulic head difference over the water defence during a flood or storm surge, exceeds a critical value. In case internal erosion below a point structure is suspected to threaten the stability of the structure, costly measures are usually undertaken: leak detection monitoring techniques (e.g. tracer, temperature or self-potential methods) or traditional measures for mitigating (potential) internal erosion problems, such as reduction of the groundwater flow velocity by means of installation of sheet piles or (local) grout injection. However, as well as costly these can be undesirable in cases where flood defences have historical value.

BioGrout is an innovative technology for in situ strengthening of unconsolidated sediments using bacteria. This technique enables sustainable improvement of sandy soils by building calcium carbonate bridges between the sand grains through microbial processes (Figure 5.1).

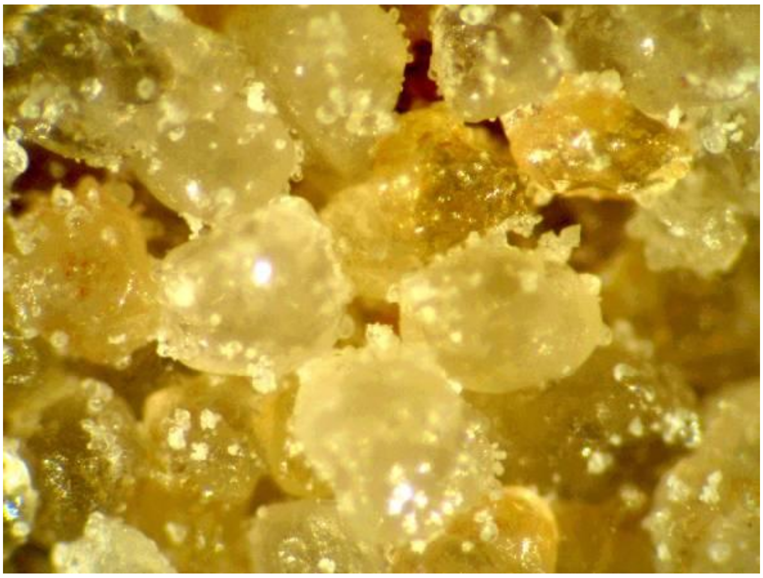


Figure 5.1 Sand grains treated with BioGrout

Contrary to (traditional) grout injection methods, BioGrout can be applied without significant reduction of the permeability of the sand. This technique is still in development stage but laboratory experiments have demonstrated its feasibility with regard to prevention of backward erosion in flood defences. By applying BioGrout the critical head is increased several times, sufficient to withstand high water in rivers and rise in sea level (Figure 5.2). BioGrout has the following advantages compared to conventional techniques:

- Applied in situ, without soil displacement or influencing surrounding constructions
- Large injection distance, at least 5 m between injection and extraction wells
- Fast process: within 5-10 days, sufficient strength is obtained
- Strength and stiffness are adjustable between 0.2 MPa and 50 MPa
- Permeability is more or less maintained up to 10 MPa, hardly influencing the (ground) water flow
- Light application material, making it usable at locations with difficult access
- Only calcite, a natural mineral, is left in the soil.

Figure 5.2 Cementing gravel for the horizontal drilling pilot near Nijmegen, 2010

The costs to apply BioGrout are substantial, making it a high grade technology. Also the production of ammonium chloride means that only limited volumes of BioGrout can be produced. This technique is recommended at locations where other techniques cannot offer a solution, as can be the case of multifunctional flood defences (see Section 5.2.2).

5.2.2 Multifunctional flood defences

The search for multi-functionality in flood defences has been gaining relevance by the long-term trends of urbanisation and climate change. These two factors will have a large influence on (urban) flood defences as well as on the spatial quality of cities and landscapes, which will need to be adjusted in the next decades.

Multifunctional Flood Defences (MFD) is a newly developed concept to optimise allocation of urban space rather than constructing stand-alone dikes. MFD are flood defences that combine the function of flood protection with other functions such as provision of housing, recreation and leisure, commercial buildings, ecology, mobility and transport, underground infrastructure. The biggest advantage of multi-functionality is that it can generate financial, social and environmental benefits.

The main difference between traditional flood defences and MFD is that instead of modifying the surrounding area for a traditional flood defence, the MFD are modified for the surrounding area. Functions in the surrounding area do not disappear; rather they remain or are enhanced.

Decisions in the area of policy and governance (cooperation), regulation and land development (real estate) often dictate whether or not a particular type of MFD is possible and which of the various alternatives may be feasible. Involving local stakeholders is an important contribution to this. Therefore in the design process it is essential to take into account the needs and requirements of current and future stakeholders, such as the local population, municipality and the relevant environmental/water authorities. Equally important is that the exchange of information takes place in a transparent way. These issues relate to the policy, system analysis and setting of objectives stages.

The diagram below (Figure 5.3) gives the steps required to assist in the process of designing a multifunctional defence.

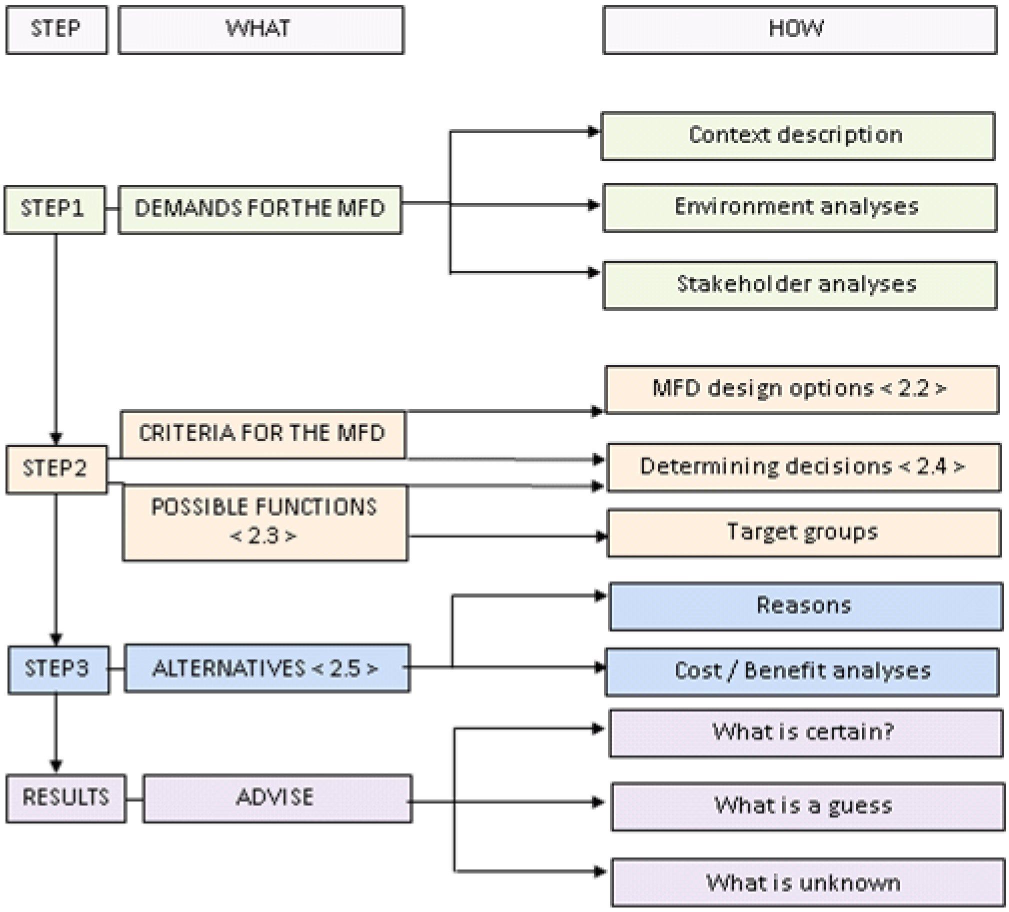


Figure 5.3 Choosing and developing a design for a multifunctional flood defence

In Figure 5.4 an overview is given of six possible concepts for MFD and how the concepts relate to one another. The various concepts (which are illustrated in Figure 5.4) are briefly described below.

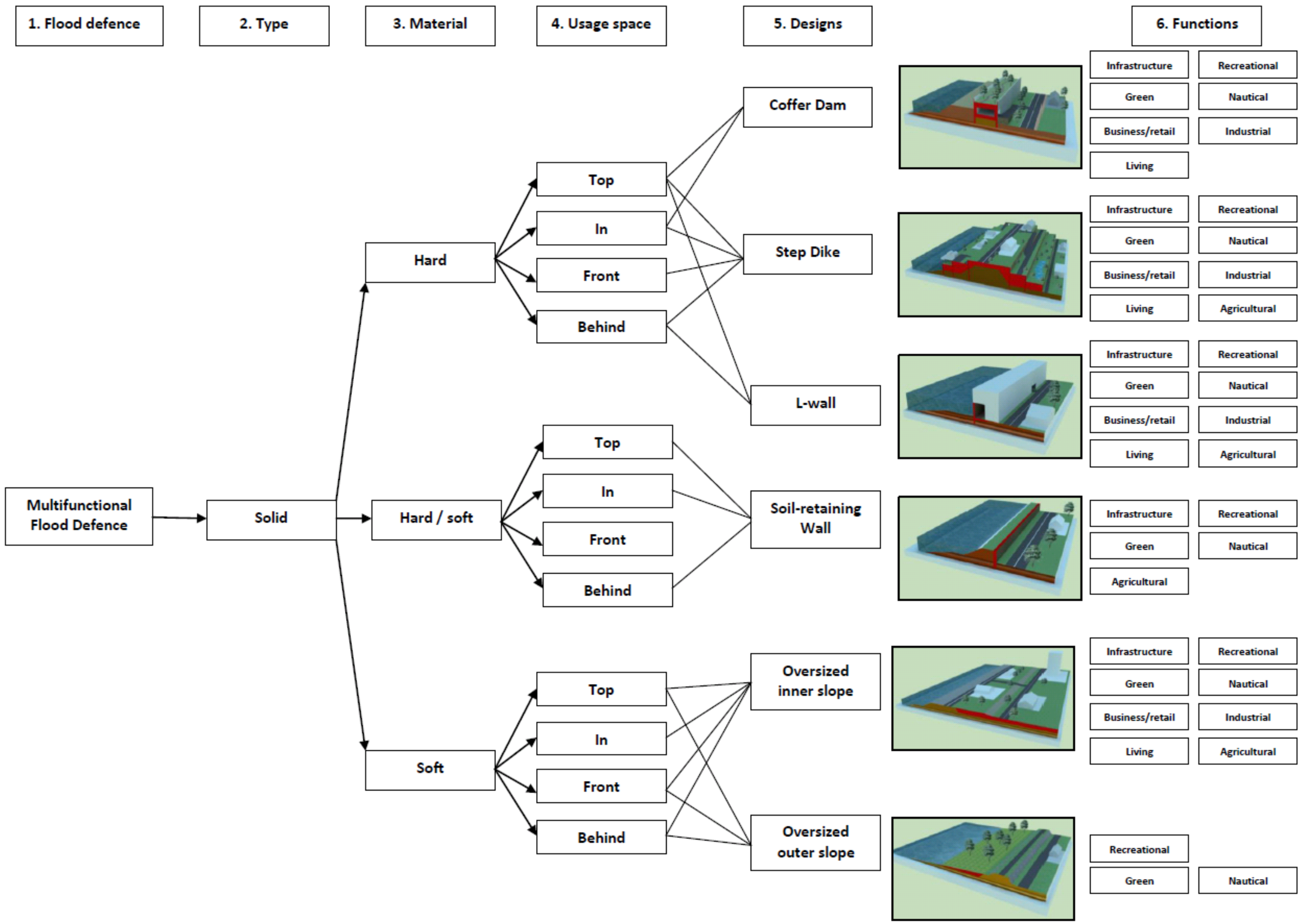


Figure 5.4 Features of six concepts of multifunctional flood defences

Coffer dam

The coffer dam is a concept that can either be a freestanding construction or combined with a traditional dike body. When building this construction, two deep steel walls are placed at least 7 m apart from each other. The space between these deep walls can either be filled with soil or used as a tunnel, parking garage, etc. The top of the coffer dam can be used for several functions such as a boulevard/promenade or park.

Step Dike

The Step Dike is a concept that can be combined with a traditional dike body where this serves as the base. This concept can use space efficiently as there are a number of horizontal flat surfaces that can be used for several functions and is constructed as follows. Deep walls are placed alongside a traditional dike body, all walls go equally deep into the ground but differ in length above ground. If necessary, the step dike can be constructed much wider and higher than required, making it safer. The spaces between the deep walls are filled with soil, creating the characteristic steps.

L-wall

The L-wall is a freestanding concept that does not need a traditional dike body. It is a concrete construction with horizontal and vertical parts equal in length, giving it the characteristic L shape. Additional functions can be place behind this wall. An important consideration is that the walls must always be kept accessible for inspections. The L-wall can also be constructed in such a way that a tunnel can be built below ground, with additional functions on top. When the horizontal part is constructed deep enough into the ground, it can also help prevent piping thus reducing the chance of the construction failing. Because it is a hard construction that directly stands in contact with the water, waves react more intensively to the presence of the wall; this is in contrast with traditional dike bodies which have slopes that attenuate the energy of the water and also the waves.

Soil Retaining Wall

This is a concept that can be combined with a traditional dike body. The construction can be applied either behind the dike or in front of it. When placed behind the dike, it creates space for additional functions. To build this construction the traditional dike body has to be excavated until only a half (in plan) remains. The remaining part of the dike body is kept in place by a steel or concrete wall, allowing time and space to create a soil retaining wall. This construction does not only demand certain height requirements, but the excavated dike body has to be at least 3 m wide at the top.

Oversized Inner Slope

Over sizing the inner or outer slope of a dike are concepts that have to be combined with a traditional dike body. When constructing, both concepts need considerable space but when built they create a lot of space and are believed to be unbreakable. When the inner side of the slope is over dimensioned, all potential functions can be applied. Land is simply raised. The greatest limitation of over dimensioning the inner slope is that all existing functions have to be removed.

This is a major undertaking and will also incur a large financial cost. The inner or outer slope of an existing dike body is extended by adding soil to the slope, giving the slope a very shallow angle. Because of the shallow angle, waves have less influence on the dike body and the height can be decreased which is positive for the visual aspect of the surrounding area. A slope angle of 1:6 is only suitable for green functions or infrastructure. When the slope is flatter than 1:9 buildings can be constructed on the slopes.

Oversized Outer Slope

Over sizing the outer slope of the existing dike makes the front of the dike higher and longer, and practically unbreakable. For example trees can be planted resulting in a 'park dike'. Vegetation or other functions on the outer slope of the dike will have a wave-breaking effect. This concept may negatively impact on the width of watercourses as their width is reduced. Over sizing the front slope does not allow many functions, as tides and currents affect this. Only recreational and green functions can be applied, such as parks and aquatic nature. If applied correctly, these functions can stop or slow down the height and speed of waves making it possible to lower the crest of the dike body. Buildings can be constructed on the front of the dike although these have to be floating.

Figure 5.5 shows an example of a matrix that brings the various types of concept and possible functions together, helping the selection process. This matrix provides indication of the most appropriate location of a particular function in relation to the dike (top T, front F, behind B, in I) for each design. The matrix shown in Figure 5.5 was developed for a rural location; in this case not every function fits into the MFD as it would for an urban location. For this MFD if the focus is on functions like green and recreation (see below) the MFD is better connected with the environment. The ‘Over sized inner slope’ appears the most obvious choice for adding green functions. The ‘Cofferdam’ or the ‘Step dike’ are unable to easily add any recreational functions at the flood defence.

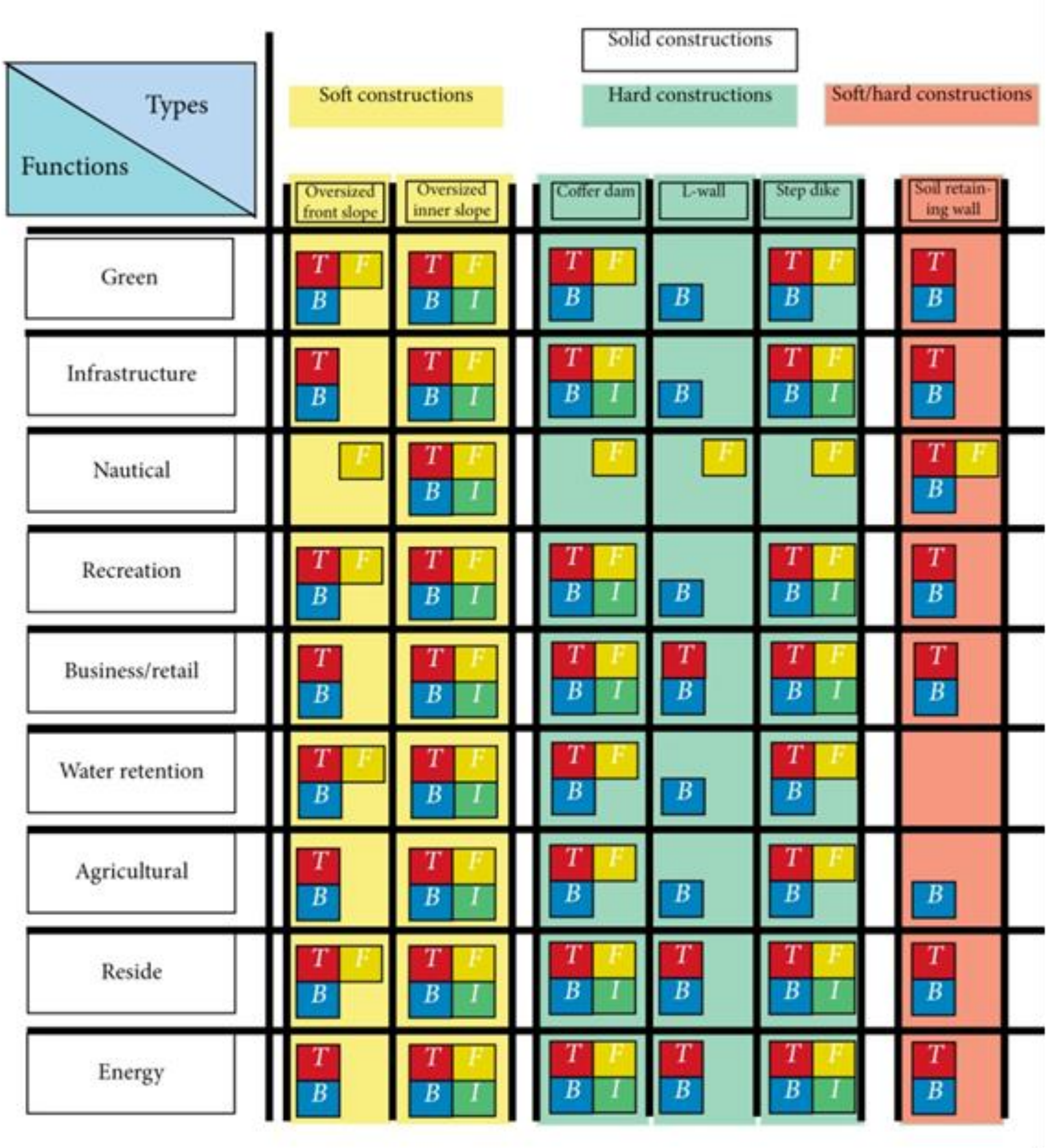


Figure 5.5 Example of catalogue of MFD options

Note: MFD is Multifunctional Flood Defences

The additional functions in a flood defence have an impact on engineering, economics, society and the environment. The potential integration of a specific function also affects the design of the flood defence. For example, a green function, such as a park, will result in a different dike profile than the integration of parking garages. Choosing a particular function has impacts in terms of economics. This has to do with the distinction between public and private functions. Certain functions, like infrastructure, can potentially be funded from public funds, whereas other functions, like businesses, can be financially more interesting from a commercial perspective. The available financial resources from the public and private domains are often limited and decisions must be taken to use these in the best way. It is, therefore, important that all costs and benefits of the interventions for water safety and other functions are included in an integrated assessment. A Cost Benefit Analysis (CBA) method has been developed that can be used for the analysis of the possible alternatives for MFDs. The CBA method is a dynamic process in which it might often be needed to return to previous steps during the design process, so the sequences of the steps are not necessarily linear. Furthermore, a CBA is able to provide both a quantitative and qualitative comparison of the possible alternatives.

Once an MFD is constructed, the Monitoring & Adaptation stage is based primarily on the procedures/measures for flood defences (see Chapter 3), complemented by necessary actions related to the functions included in the structure (e.g. buildings, recreational).

The most significant advantage of multi-functionality is that it can generate financial, social and environmental benefits. In contrast with MFDs, traditional dike strengthening only generates financial costs with non-monetary benefits (i.e., increased flood safety / reduced flood risk). By designing MFDs, the costs for dike strengthening can in some cases be partially funded with the revenues from the secondary functions.

5.3 Critical networks - Innovative road and bridge technologies

This section addresses a range of innovative technologies related to critical nodes and networks. These technologies are installed just before or during a flood event with the objective to sustain functioning of the critical node or network and will be removed completely when water levels have receded. These technologies comprise floating road infrastructure and bridges, light weight bridges, floating storage facilities and emergency bases. At present there is very limited practical experience in the use of these technologies and specific guidance on their application is lacking.

Road infrastructure forms a lifeline for inhabitants in a flood prone area, allowing evacuation as well as access to emergency response services to affected areas, and the continuation of the provision of essential services such as supply of food, bottled water and maintenance of communications. To alleviate this impact it is important to have back-up solutions.. Flood proof structures are therefore proposed in circumstances of flooding and post-flooding, for interoperability and connection.

5.3.1 Innovative technologies

Floating Bridge Technology

Floating bridges are those bridges that rest on the surface of water instead of crossing it, as is usual, and one of their main characteristics is that they do not present a barrier to the passage of water Figure 5.6). The fact that these bridges do not have foundations on the ground makes its global stability dependent on its buoyancy and not on the resistance and characteristics of their supports and foundations.

Promptly assembled floating bridges consist of prefabricated cubic composite elements. A connection of a dozen or so elements using mechanical connectors will become the floating base. In order to stabilize the bridge structure, this should be anchored using stays in the quay. For compensation of fluctuations in the water level and to facilitate movement from bank to the bridge, deflection constructions should be placed on its ends. On the side surfaces of the bridge there are handles for slinging installations with various types of utility.

Figure 5.6 Pedestrian floating bridge by Eco-Dock Inc

Temporary Lightweight Composite Bridge Technology

This technology consists of extremely light sections that are assembled on site. The load-bearing parts consist of fibreglass beams that are reinforced with carbon fibres on the underside. The bridge interacts with a thin bridge deck that is prefabricated out of composite-fibre-reinforced concrete with extremely high strength. Since these materials are very durable and demountable, they are advantageous in a life-cycle perspective, and they are highly suitable for temporary construction, see Figure 5.7.

Figure 5.7 Lightweight bridge placements

Source: Construction by ACCIONA, Asturias, Spain, 2004

The implementation of this technology follows a series of analysis and decision making process, that are carried out by competent authorities involved in planning and design of buildings, infrastructure, disaster management and maintenance of key infrastructure (central, provincial, and local government agencies sharing the responsibilities with local stakeholders).

Floating Storage Facilities

Having access to fuel during flood events (and other disasters) is complementary to providing access and is therefore relevant to mention techniques for storage. Very large floating structures have been used for storing fuel. Constructed like flat tankers (box-shaped) parked side by side, they form an ideal oil storage facility, keeping the explosive, inflammable fluid from populated areas on land. Japan has two major floating oil storage systems. One oil storage facility is located in Shirashima with a capacity of 5.6 million kilolitres while the other is at Kamigoto (see Figure 5.8) with a capacity of 4.4 million kilolitres.

Figure 5.8 Examples of floating storage facilities

On the left Shirashima Floating Oil Storage Base, Japan; on the right Kamigoto Floating Oil Storage Base, Nagasaki Prefecture, Japan

Floating Emergency Bases

As floating structures are inherently isolated from earthquakes and floods, they are ideal for applications as floating emergency rescue bases in earthquake and flood prone countries. Japan has a number of such floating rescue bases parked in the Tokyo Bay, Ise Bay and Osaka Bay, see Figure 5.9.

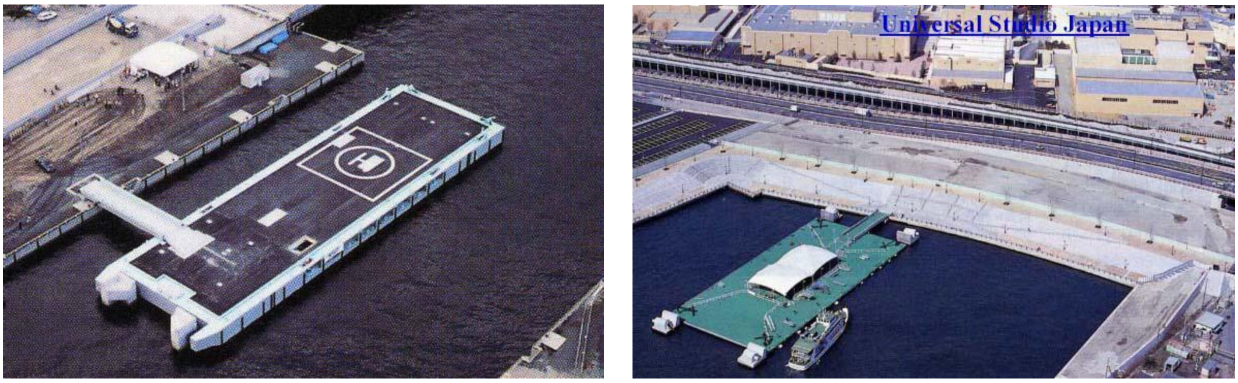


Figure 5.9 Examples of floating emergency bases

On the left Emergency Rescue Base in Tokyo Bay and on the right Emergency Rescue Base in Osaka Bay, Japan

5.3.2 Catalogue of floating and composite technology

A catalogue has been developed for bridge technology. In the catalogue, floating and composite bridge and base structures with the corresponding method of usage have been suggested for five possible situations during floods: footbridge for pedestrians, vehicular bridges and two types of composite structure (see Figure 5.10).

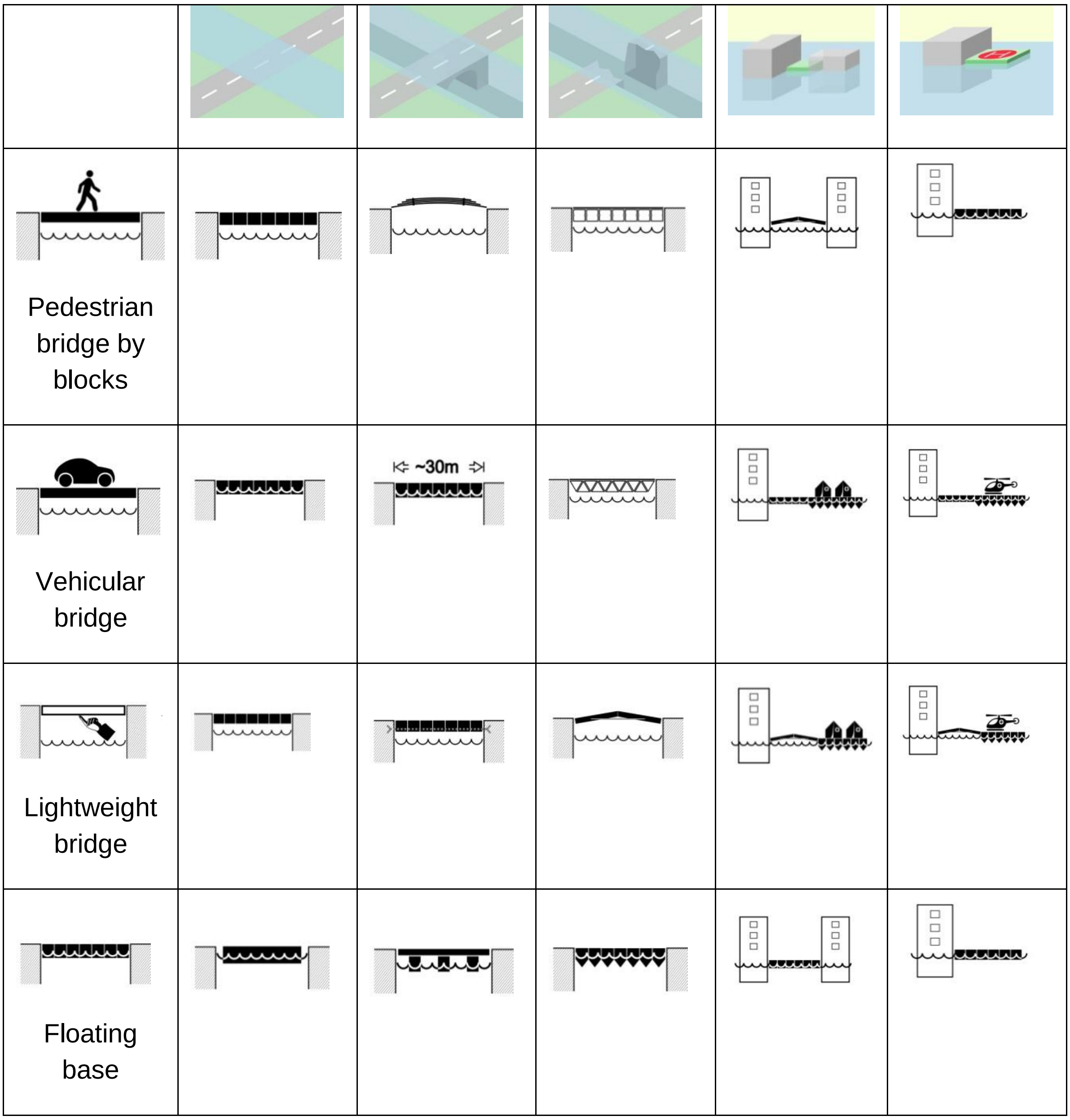


Figure 5.10 Proposed catalogue, different uses of floating and light weight technology according to the situation

The technologies described in this section aim to improve the resilience of existing critical infrastructure such as road infrastructure, emergency services and energy supply so that they remain fully operational during periods of (extreme) flooding. They should be planned and designed so that they can be readily installed and managed in such a way that the users are not at risk during the flooding. The present research has contributed to the development of guidance on the application of these temporary and demountable technologies but it is recognised that guidance is still in its infancy.

5.4 Critical buildings

5.4.1 Hotspot buildings

Urban systems contain assets of high value, complex and interdependent infrastructure networks. Hotspot buildings are defined as essential nodes in critical infrastructure on which urban areas depend for their functioning. Hotspot buildings within these networks include power stations, water treatment plants, control centres of public transport, waste water treatment plants, fire fighting stations, communication hubs, food distribution centres and hospitals. The availability and functioning of hotspot buildings is needed for crisis management, to maintain daily life as normal as possible during floods and is also required for fast and effective recovery after flood disasters. Table 5.1 tabulates requirements of critical buildings to secure functioning during floods.

Table 5.1 Requirements of critical buildings

	Ensure supplies for production	Access to site by workers	Ensure water and sanitation	Energy supply	Food supply	Ensure flood safety	Ensure waste collection	Indoor climate control	Connection to network vital to deliver critical function, inc. communications
Water treatment	✓	✓	✓	✓		✓	✓		
Sewage treatment	✓	✓	✓	✓		✓	✓		✓
Electricity substations		✓		✓		✓			✓
Energy storage	✓	✓		✓		✓			
Hospitals	✓	✓	✓	✓	✓	✓	✓	✓	
Fire stations		✓	✓	✓	✓	✓	✓		✓
Police stations		✓	✓	✓	✓	✓	✓		✓
Communications		✓		✓		✓		✓	
Food distribution	✓	✓	✓	✓	✓	✓	✓	✓	
Financial centres	✓	✓		✓		✓			
Airports	✓	✓		✓		✓			
Bus stations	✓	✓				✓			✓
Train stations		✓		✓		✓			✓
Metro stations		✓		✓		✓		✓	✓

Three tools have been developed and incorporated into an Excel model, to help designers and decision makers select and evaluate flood proofing concepts for flood proofing hotspot buildings in different stages of the urban development process. In the beginning of such a process when options are explored, a general overview is presented on the most suitable flood proofing concepts based on flood depth and flood duration. In this phase the relevance map gives an indication of the relative importance of flood proofing a particular hotspot building based on flood impacts and the service area of a particular hotspot building. Both tools require only a small amount of data and specific information. In the next phase of the urban development process, when possible measures for flood proofing are selected, the selection tool gives insight into which flood proofing concepts could be feasible based on information on location characteristics and hotspot characteristics. The selection tool requires a small amount of information, although more data should be available than in the first phase. In the decision making phase, the evaluation tool provides detailed information about the costs of several possible options for flood proofing a specific hotspot. Relatively detailed information on the hotspot, flood characteristics and location characteristics should be available for application of this tool.

Flood proofing methods

Flood proofing is a way of making buildings resilient against flooding. This can be done by avoiding contact with floodwater or by making the building cope with floodwater and minimising damage caused by floodwater; the following methods are available:

- Wet flood proofing

  Wet flood proofing or wet proof construction is a building method that allows temporary flooding of the lower parts of the building. To prevent damage, preferably building materials are applied that are water resistant. As an alternative, materials can be used that can be easily repaired or replaced (Tables 5.2 and 5.3 give indication of the resilience of some finish materials and insulating materials, respectively, based on laboratory tests).

Table 5.2 Flood resilience characteristics of finish materials

Source: CIRIA, 2006

Material	Resilience characteristics*			Overall resilience performance
	Water penetration	Drying ability	Retention of pre-flood dimensions, integrity	
Timber board				
OSB2, 11mm thick (Oriented Strand Board)	Medium	Poor	Poor	Poor
OSB3, 18mm thick (Oriented Strand Board)	Medium	Poor	Poor	Poor
Gypsum plaster board				
Gypsum Plasterboard, 9mm thick	Poor	Not assessed	Poor	Poor
Mortars				
Below DPC (Damp Proof Course) 1:3 (cement:sand)	Good	Good	Good	Good
Above DPC (Damp Proof Course) 1:6 (cement:sand)	Good	Good	Good	Good

Table 5.3 Flood resilience characteristics of insulation materials

Source: CIRIA, 2006

Material	Resilience characteristics*			Overall resilience performance
	Water penetration	Drying ability	Retention of pre-flood dimensions, integrity	
Cavity insulation				
Mineral fibre	Poor	Poor	Poor	Poor
Blown-in	Poor	Poor	Poor	Poor
Rigid PU foam	Medium	Medium	Good	Medium

*Resilience characteristics are related to the testing carried out and exclude aspects such as ability to withstand freeze/thaw cycles, cleanability and mould growth

Another important design aspect is the location of electrical lines and delivery points above the expected flood level. Construction parts have to be designed in such a way that they can easily be dried after the flood. A schematic of wet proofing a house is given in Figure 5.11.

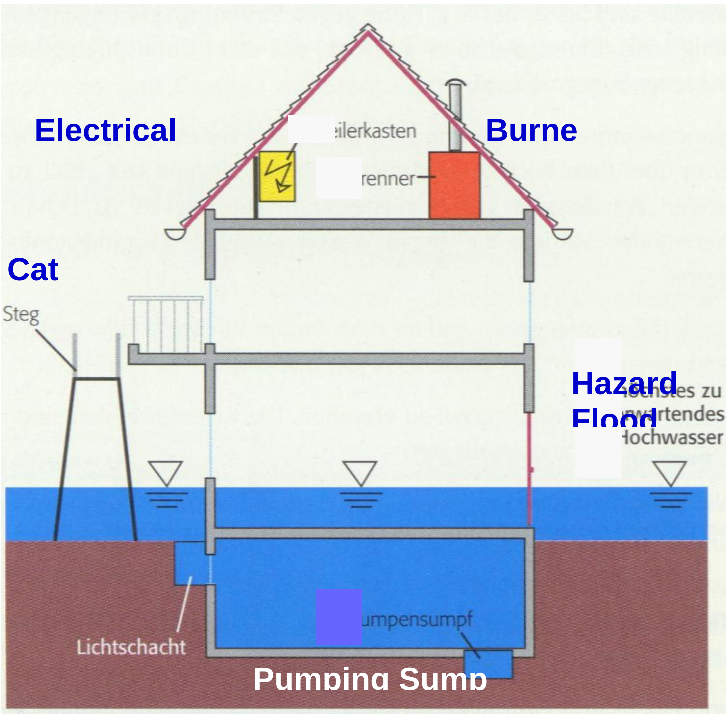


Figure 5.11 Schematic of wet proof method

Source: Pasche, 2008

- Dry flood proofing

  With dry flood proofing or dry proof construction, the water is prevented from entering the building. The building is made waterproof by treating the facades with coatings, using resistant materials or buildings with a low permeability – Figure 5.12. In addition, the building materials should have good drying ability and integrity. Openings in the facades can be closed off with flood shields, panels or doors. These can be temporarily installed or can be permanent features, but in both cases, dry proofing is an integrated part of the building. An alternative approach is to erect temporary barriers located outside and around the building in order to prevent the floodwater reaching it.

Figure 5.12 Example of dry proofing Hamburg, Germany

Source: Pasche, 2008

- Raising or moving structures

  The entire building can be raised above the expected flood level in order to prevent damage. To enable the continuing functioning of such a building, the connection to infrastructure is to be secured against flooding as well. An example is an access road that is also elevated. Two major options are:

  - Buildings on stilts, where buildings are founded on stilts that extend above the ground, they are ‘lifted’ above the ground (Figure 5.13). This type of building can be built above land as well as water. It enables multifunctional use of space; in the first case with for example parking, with the latter as water retention. With this type of construction, points of attention are the spatial quality under the building and the access during a flood.

Figure 5.13 Office building on stilts

Amsterdam, The Netherlands and Trondheim, Norway - Source: Blogspot.com, 2011

- Building on mounds

  A mound is an artificial hill. In the Netherlands this is a traditional way of building flood resilient. In the modern use of a mound, the building is raised from the ground level by an artificial hill. The benefits of this method are that gardens or surrounding grounds are also protected from the flood and that multiple buildings could be built on the mound, assuming the mound is large enough. On the down side extensive earth works are needed to build the mound (Figure 5.14).

Figure 5.14 Synagogue on mound, Sliedrecht, The Netherlands

Source: Refdag.nl, 2011

- Floating and amphibious structures

A floating building is a building that is founded on a floating structure that is permanently located in the water. The building has to be moored with mooring posts. Because of the water fluctuation, the connection with the land has to be flexible. It is possible to move the building and moor it somewhere else. It is a flexible and reversible mode of construction and therefore responds to the societal objective to increase the capacity to adapt the built environment to climate change (Figure 5.15).

Figure 5.15 Floating pavilion, Rotterdam, The Netherlands
Source: De Wit, 2010

An amphibious structure has a traditional foundation combined with a floating body. In a normal situation the building is situated on the ground. When a flood occurs the building will start to float. For that reason the building has to be fixed in a horizontal direction by mooring posts. Amphibious construction is only possible for new buildings (Figure 5.16). In particular in floodplains where floods frequently occur and in emergency water retention basins, this construction method can be applied.

Figure 5.16 Amphibious dwelling in Maasbommel, The Netherlands
Source: Waterbestendigbouwen.nl, 2011

- Active or temporary flood proofing

Temporary flood barriers are placed only if a flood is expected to damage buildings. After the flood the barrier is removed again. Temporary barriers can protect high value buildings, infrastructure nodes or hotspots. Temporary barriers are made from wood, steel, aluminium or plastics (Figure 5.17).

Figure 5.17 Temporary barriers in Prague, Czech Republic
Source: VRV company, 2007

- Passive or permanent flood proofing

Permanent flood barriers that are specifically constructed to protect one or a couple of buildings are another strategy to prevent flooding. Permanent flood barriers can either be a dike around the hotspot or an integrated flood defence in the surrounding area of the hotspot such as walls, gates or other structures (Figure 5.18).

Figure 5.18 Permanent flood gate Meppel, The Netherlands
Source: Floodbarrier.nl, 2011

Whether or not a flood proofing method is suitable for the building that has to be protected, depends upon the shape of the building, the expected flood level, the duration, the expected flooding frequency, and the predictability of the flood. By choosing a location for the building this has to be taken into account – as shown in Tables 5.4 to 5.7.

Table 5.4 Design considerations for flood proofing concepts

		Flood proofing techniques							
		Wet proof	Dry proof	Stilts	Mounds	Floating	Amphibious	Temp barrier	Perm barrier
Design considerations	Small footprint	green	grey	green	green	grey	grey	white	white
	Large space demand	red	grey	red	red	grey	grey	green	green
	Large building height	grey	grey	grey	grey	red	red	white	white
	Heavy building	grey	grey	grey	grey	grey	red	white	white
	Weight evenly distributed	grey	grey	grey	grey	green	green	grey	grey
	Permanent water	white	white	grey	white	green	red	white	white
	Important functions on ground level	red	grey	grey	grey	grey	grey	grey	grey
	Sufficient space around hotspot	white	white	white	white	white	white	green	green
	New	green	green	green	green	green	green	green	green
	Retrofit	green	green	red	red	red	red	green	green

Green = requirement, red = limitation, grey = not of influence, white = not applicable

Table 5.5 Applicability of flood proofing concepts according to flood level and flood duration

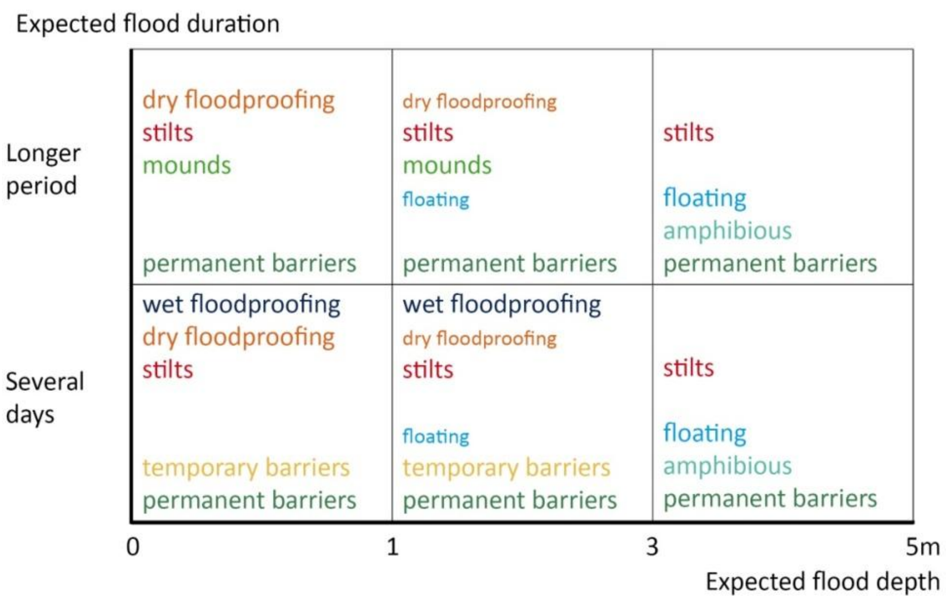
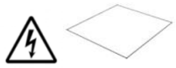
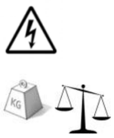
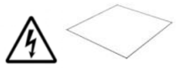
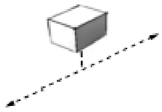
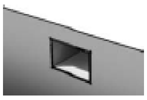
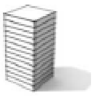
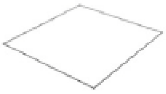


Table 5.6 Overview of flood proofing concepts for hotspots

	Limitations*	Wet proof	Dry proof	Stilts	Mound	Floating	Amphibious	Temporary Barriers	Permanent Barriers
Drinking water treatment		✗	✓R	✗	✓	✓	✓	✓R	✓R
Sewage water treatment		✗	✓R	✗	✓	✓	✓	✓R	✓R
Substations, surface		✗	✗	✓	✓	✓	✓	✓R	✓R
Substations, building		✗	✓R	✓	✓	✓	✓	✓R	✓R
Substations, underground		✗	✓R	✗	✗	✗	✗	✓R	✓R
Energy storage		✗	✓R	✗	✓	✓	✓	✓R	✓R
Hospitals		✗	✓R	✓	✓	✓	✓	✓R	✓R
Fire stations		✗	✗	✓	✓	✓	✓	✗	✓R
Police stations		✗	✗	✓	✓	✓	✓	✗	✓R
Communication centres		✓R	✓R	✓	✓	✓	✓	✓R	✓R
Food distribution		✗	✓R	✓	✓	✓	✓	✓R	✓R
Financial buildings		✗	✓R	✓	✓	✗	✗	✓R	✓R
Airports		✗	✗	✓	✓	✓	✓	✓R	✓R
Bus station		✗	✗	✓	✓	✓	✓	✗	✓R
Train station platform and tracks		✗	✗	✓	✓	✗	✗	✗	✗
Metro station underground		✗	✓R	✗	✗	✗	✗	✓R	✓R

Notes: * see Table 5.7 below for legend on Limitations; R denotes "suitable for Retrofit"

Table 5.7 Legend for Table 5.6 (Limitations)

 Underground infrastructure	Some hotspots require a connection with the underground infrastructure for their functioning. Examples: are electricity, waste water and drinking water connection. When applying **floating** or **amphibious** flood proofing this connection has to be flexible and with piles the connection should be protected.
 Vital road connection	Hotspots that are dependent of the road network to maintain their function are for instance: fire stations and police stations. Flood proofing methods that interrupt the road connection are not possible or less suitable. Examples are **wet proofing** and **dry proofing**.
 Vital track connection	Hotspots that require a rail connection to maintain their function (e.g. train station). Trains are extremely heavy vehicles and they cause an eccentric load when they move. For this reason **floating** and **amphibious** methods are not suitable. In addition, **wet** / **dry proofing**, **temporary** and **permanent barriers** are not feasible, because they interrupt access of the train to the building. Underground tracks are an exception. In this case please refer to 'subterranean'
 Subterranean	A hotspot located underground is basically protected from floods. The connection with the ground level, usually the entrance has to be protected. Because the connection with the underground hotspot is vital, methods that do not support such a connection are not suitable. Building on **stilts**, **floating** or **amphibious** are therefore not applicable. **Wet proofing** is not suitable because if the entrance is allowed to be flooded, the underground hotspot will not be protected.
 High building	High buildings need special attention for stability in case **floating** and **amphibious** structures are applied. The optimal form for high floating buildings is a pyramid because of the low centre of gravity and equal division of forces. Usually a height of 4 storeys is seen as the maximum.
 High or uneven vertical load	Buildings with high or uneven vertical load need special attention on stability when applying **floating** or **amphibious** structures
 Heavy building	Hotspot buildings with al lot of machinery or fluids are considered heavy. This has to be taken into account when calculating the buoyancy for **floating** or **amphibious** structures.
 Non-building	The hotspot does not consist of one more buildings but is an open field with objects for example a surface electricity substation. **Wet** and **dry proofing** are solutions applied directly onto buildings and therefore not applicable.
 Vital functions on ground level	Many hotspots have important functions on the ground level. Or floodwaters entering the hotspot may contaminate it or be contaminated by it. In this case **wet proofing** is not an option.
Retrofitting	When retrofitting an existing building is being protected. Flood proofing methods that are usually too costly or not suitable for retrofitting are: amphibious, floating, stilts and mounds.
New building	All of the systems can be applied on new buildings

Design tools

An interactive flood proofing design tool has been developed allowing policy makers, decision makers and designers to narrow down the range of possibilities of flood proofing methods for hotspot buildings in their projects. The tool consists of three stages: the Relevance Map, the Selection Tool and the Evaluation Tool. The Relevance Map provides a first check to evaluate the level of relevance of applying flood proofing measures. The Selection Tool is used to select the applicable flood proofing measures based on the type of hotspot and other qualitative aspects. The Evaluation Tool provides quantitative data, such as cost estimates and application ranges, and it is used to find the most optimal flood-proofing methods for a given situation.

- The Relevance Map

  In order to assess the broader local or regional relevance of flood proofing a hotspot building, two factors are of importance: the service area of the hotspot (how many people rely on this service) and the magnitude of the anticipated flood scenario (how many people will be affected by the flood).

  The amount of people that depend on the hotspot is referred to here as the 'hotspot service area'. The hotspot types have been clustered into three levels in terms of their service area: district, city and region (table below has been added for reference). Hotspots with regional or larger importance serve a significant support area and a high economic value. For example airports and food distribution centres are generally large scale facilities that serve many people. If an airport would flood, this would have a huge effect on the economy of that region. If a food distribution centre would flood, it would affect the stores in a very large area. On the other hand, the flooding of a district bus station would not affect that many people and would have less regional impact on the economy.

Table 5.8 Hotspots by importance

Service area	Hotspot
Regional or larger	Airports, Train station, Energy storage, Food distribution centre Communication building (network operations / data / telecomm.) Hospital (specialized / regional hospital) Financial centre (stock exchange, central bank)
City	Metro station, Electricity substation (transmission substation) Communication building (data centre), Drinking water treatment, Sewage treatment, Hospital (general hospital), Financial (city bank)
District	Bus station, Electricity substation (distribution/transformation) Police station, Fire station, Financial building (branch office) Hospital (clinic)

Secondly, the magnitude of the (anticipated) flood event is relevant. This can be defined as the amount of people that is affected by the flood and it is referred to as 'flood impact'. If a hotspot that only has a local importance is hit by a small scale local flood, the impact is low. People that normally rely on this hotspot can easily find similar hotspot that has not been flooded at a small distance. On the other hand, if an international airport is flooded, the impact of flood proofing on the broader economy it is high, even if the flood would only be limited to a small region. In case both the hotspot importance is high and the flood impact is high, flood proofing of the hotspot would be necessary to improve urban flood resilience. Both factors have been combined in Figure 5.19 – this gives a general idea about the relevance of flood proofing a particular type of function designated as a hotspot.

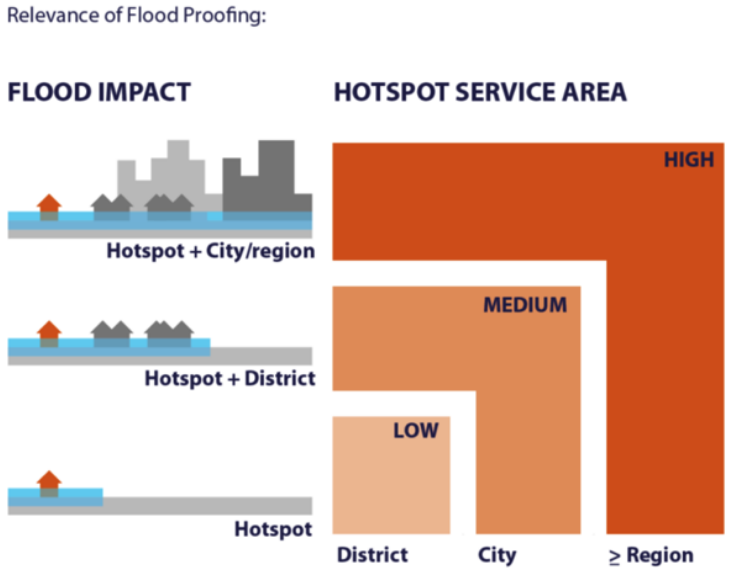


Figure 5.19 Flood proofing hotspot relevance map

- The Selection Tool

The Selection Tool narrows down the number of feasible flood proofing measures for each type of hotspot. Building-specific and location-specific limitations will exclude certain flood proofing options. For example, if there is no possibility of creating water or using existing water, floating is not an option and if a metro station is created underground, stilts or wet proofing cannot be applied. Such qualitative advantages and disadvantages, most of which have already been discussed for the individual hotspot types, have been used as a basis for the selection tool.

In the selection tool the different characteristics of hotspot typologies have been converted into a series of simple Yes or No questions (Figure 5.20).

Flood proofing selection tool

Questions:	ANSWER: 0 = no 1 = yes
Are you retrofitting an existing hotspot?	0
Does the area around hotspot needs flood protection?	0
Does the hotspot contain fluid storage with considerable weight?	0
Does the hotspot consist of installations instead of buildings?	0
Is there a possibility for or availability of permanent water?	1
Does the ground floor needs to contain vital functions?	1
Is space around the hotspot permanently available?	1
Is space around the hotspot available in case of flooding?	1
Is vehicle access vital during flood?	0
Hotspot with permanent rail connection above ground level?	0
Is the hotspot situated underground?	1

Flood proof measures to choose from:

Dry proofing, Mound, Flood wall, Dike, Temp barrier.

Dry proofing, : POA Emergency entrance has to be elevated during flood. Openings such as windows and doors are a point of attention.

Mound, : POA Ground displacement is needed, the solution needs a large perimeter because of the slope.

Flood wall, : Emergency entrance has to be elevated . The solution can be integrated with a customary fence.

Dike, : POA Ground displacement is needed, the solution needs a large perimeter because of the slope.

Temp barrier. : POA Manpower and time is needed for build-up, the hotspot needs a fence or wall for normal security; the solution is additional. Emergency entrance has to be elevated during the flood.

Figure 5.20 Overview of questions used as input for the hotspot selection tool

After answering all the questions, one or several possible flood proofing measures will appear on the screen. In addition, the most important points for attention will be shown for each flood proofing measure. This list narrows down the amount of available flood proofing methods for the decision maker or the designer. With this short list of qualitative aspects, the quantitative characteristics of the hotspot, like circumference and expected can be applied in third part of the design tool, the Evaluation Tool. The first two tools provide insight in the relevance of flood proofing a particular hotspot and the available flood proofing measures in a specific situation.

- The Evaluation Tool

  It is a complicated task to find the optimum and most cost effective flood proofing solution for a particular hotspot building. Many factors play a role in the decision making. These factors are both related to the properties of the hotspot (e.g. area, perimeter, height and service area) and to the type of flood that is to be expected (e.g. flood level, frequency, onset time and impact). The objective of the Evaluation Tool is to serve as a guide in this process. Based on the hotspot properties and the expected flood type, the available flood proofing measures for that specific situation are selected and can be compared on costs and efficiency. Contrary to the Selection Tool which has a qualitative character, the Evaluation Tool provides a quantitative comparison.

  The tool is based on a database of reference flood proofing products, which is built of data from different sources: research publications, data from governmental agencies, such as the UK Environmental Agency and the US FEMA, and data provided by the many suppliers of flood proofing products.

The most relevant components of the design tool are briefly described below.

- Area requirement

  Particular types of hotspot are often located in an urban context, where space for external flood-proofing measures is scarce. The available area around the hotspots will influence what types of measures are options. Flexible free-standing barriers, levees and sandbags are most space demanding. Several measures, such as floating or stilts, do not demand additional space.

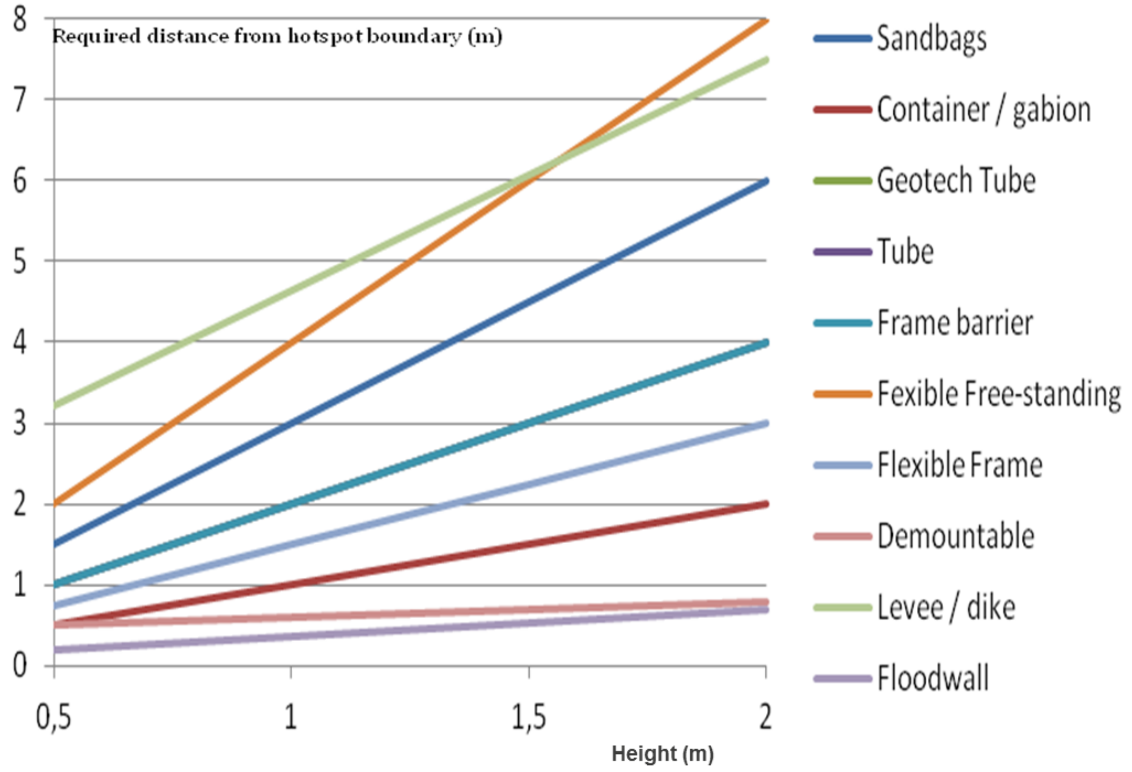


Figure 5.21 Area requirements of different flood proofing methods and heights

- Installation time

  The amount of time required to install a temporary barrier, is of great importance in relation to the prediction time of the flood. Based on various sources, the amount of time to install the systems has been estimated. Most systems are quick to set up, with flexible free-standing barriers requiring the least amount of time. Three systems may present obstacles if rapid erection is required. They are discussed below.

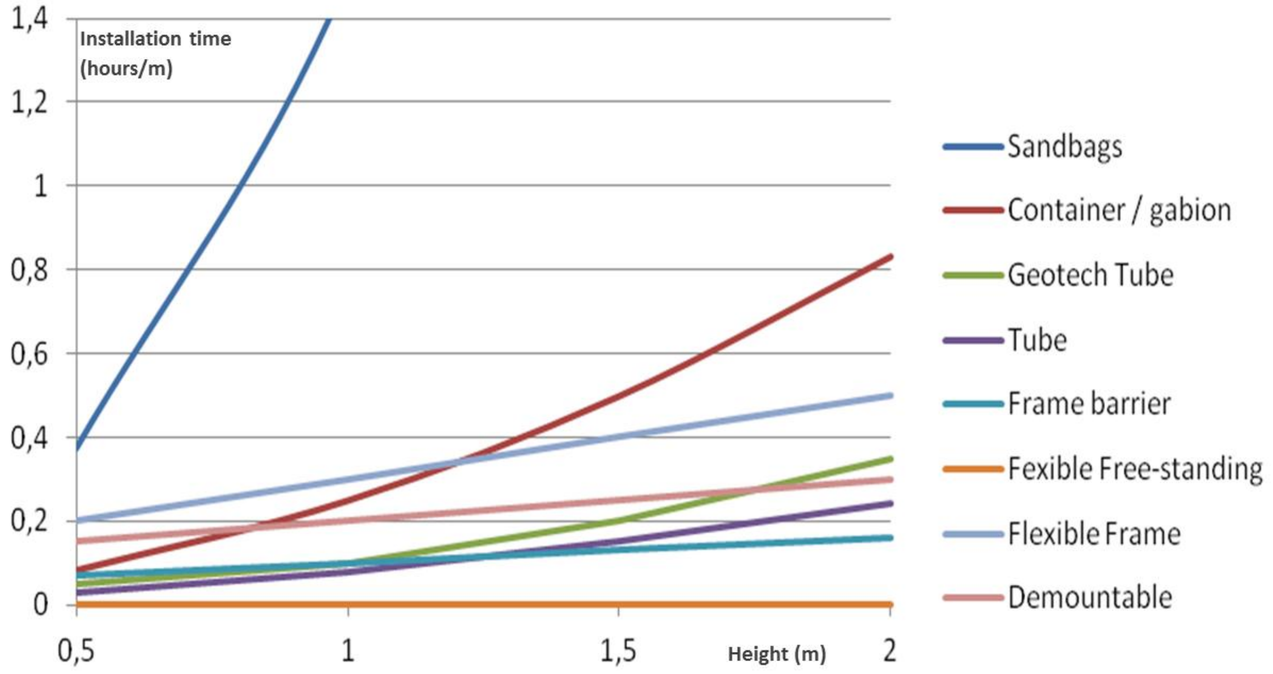


Figure 5.22 Installation time of different flood proofing methods and heights

The graph shows that **sandbags** are very labour intensive, especially at higher flood levels. **Container/gabion** systems require heavy equipment such as a front-loaders and lorries that deliver the metal gabions and sand. While the installation time is limited, installing this system is a considerable logistic challenge. **Flexible frames** are complex to install and require a relatively high level of skill. As a result, on larger projects lack of enough skilled personnel will cause longer installation times.

- Height range

  Flood proofing products have a limited height range. Most products have a maximum height between 2,5 m and 3 m. For **Flexible free-standing** barriers the maximum height is even less, up to 2 m. Generally, the permanent barriers and demountable systems have a higher maximum range.

- Cost estimation

  Costs are an essential part of the assessment of flood defense measures. Some systems are more cost effective for lower flood depths, but get very expensive as soon as they are applied for high flood depths. Both sandbags, tubes and containers are exponentially more expensive at a bigger height, because of the pyramid style stacking of the elements. Some systems only have a limited life span of one or two application cycles. Both sandbags and container/gabion systems are difficult to reuse. This will have a considerable influence on the investment over longer periods. The costs may also depend on the flood frequency, especially temporary measures that take manpower and resources to be installed.

  For each type of flood proofing measure, cost data in relation to the protection height level was gathered from a large number of sources. These two variables (costs per metre and protection height) were plotted into scatter graph and polynomial trend estimation was established for each data set. As an example, the scatter plot of the **container/gabion** data set is displayed in Figure 5.23. The formulae of each of the graphs were then inserted into the evaluation tool.

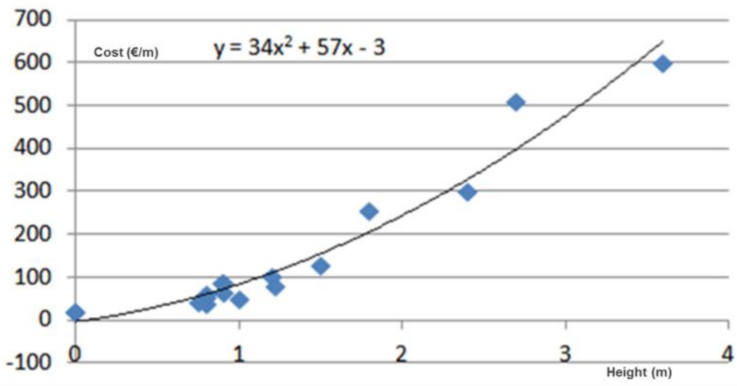


Figure 5.23 Scatter plot of container/gabion data (cost against height in metres)

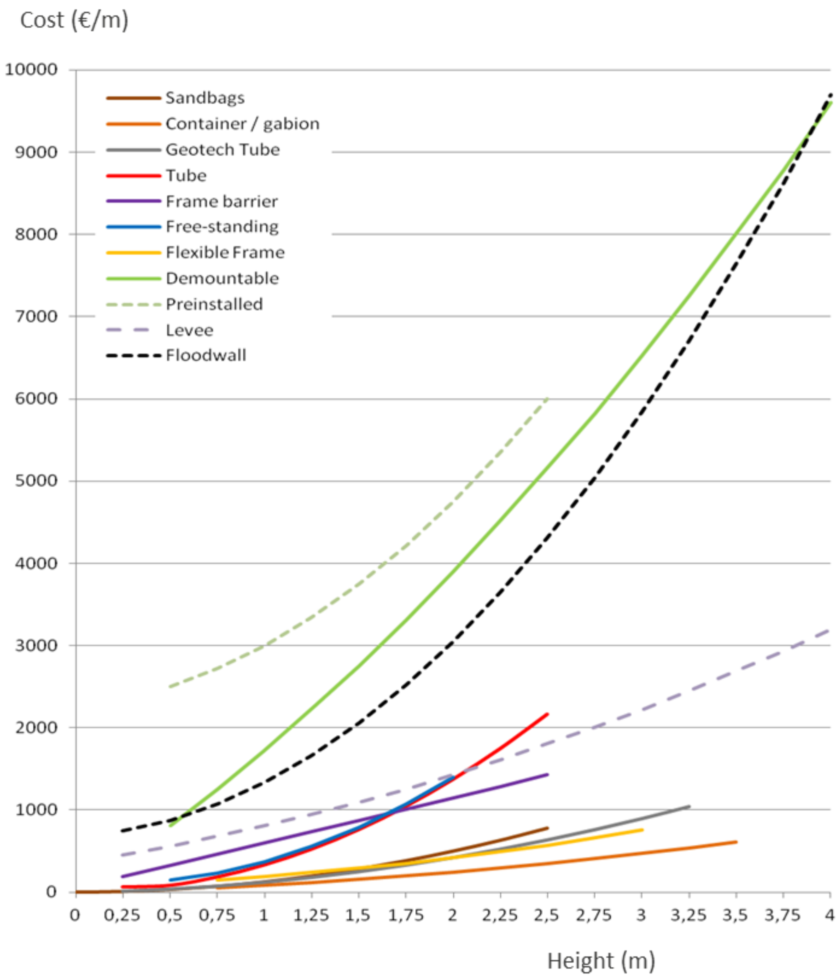


Figure 5.24 Cost estimate data (in €/m) and height ranges for barrier-type flood proofing methods

5.4.2 Smart shelters

Various and diverse mitigation plans have been implemented across the world to reduce the consequences of flooding. In addition to structural measures, emergency measures such as flood shelters are also needed immediately and urgently when flooding occurs, to provide a survival place for flood victims.

It is necessary to evacuate people when the benefits of leaving significantly outweigh the costs of ‘sheltering-in-place’. A well-progressed emergency plan for the period of inundation comprises of mass evacuation during the warning period before flood water reaches a critical level, during flooding for the people exposed and after flooding in the recovery phase. In this regard, evacuation means instructing people how to leave and where to go to leave their current dangerous or potentially dangerous location. Sheltering is one of the essential parts of the evacuation plan in addition to the other essential functions like transportation. The primary target is to evacuate the entire population at risk into areas outside the inundated region. However, there are always groups of people (elderly, sick people, disabled etc.) who have mobility issues. These should be accommodated as near to their homes as possible to increase the efficiency of the evacuation during the warning time.

Primarily, sheltering plans focus on providing a survival place for the victims during a flood and when a process of rehabilitation is underway immediately afterwards. However, shelters will often be used only for a short period of time during a flood. In order to realise economic benefits and be sustainable, shelter structures should be used synergistically for multiple purposes for the periods when there is no flood risk or inundation, which are likely to be lengthy compared with their usage during periods of flooding. In this way, the investment in constructing new flood shelters can be offset against a variety of normal use functions that will ensure the structures are continually maintained.

Practically, multi-use shelter structures can be effective through two options. Firstly, a shelter can be constructed aimed solely at flood relief with other functions added later. Secondly, any suitable existing public buildings such as schools, hospitals, and so on can be modified over time to act as shelters. This is the core idea of ‘smart shelters’ that are not only a means of mitigation but also a means of development. Smart shelters can provide facilities for a wide variety of sustainable uses such as education and health care and promote local development if they are built appropriately. Alternatively, the modification of existing buildings is a smart idea to reduce the need for large investments that may be needed for construction and maintenance of new smart shelters.

To determine the most efficient smart shelter strategy, decision makers have to decide how many shelters to build and where to build them, to be able to cover the designated area and to give shelter to all non self-reliant refugees. The spatial distribution of the land use, flood risk maps, evacuation plans and demographic data will determine the need for shelters, site selection and the number and capacity of the shelters needed. Careful planning of shelters can be cost-efficient since fewer shelters are most certainly less expensive and planning smart shelters on natural higher ground could severely reduce the costs of a shelter. Having to build and maintain one or multiple shelters has both pros and cons, but the main need will be for shelters to be accessible /

reachable within the warning time available. Both existing buildings and new construction can be used to plan the smart shelter strategy. Figures 5.25 and 5.26 illustrate two spatial concepts.

Figure 5.25 One large smart shelter covering a large area

Figure 5.26 Multiple smaller smart shelters covering several smaller areas

In order for an existing or new building to function as a smart shelter design modifications are usually necessary for coping with the hazard. The design of a building needs to be modified in such a way that all forces of flooding can be withstood. In order to plan and design a smart shelter the facility should be completely functional and operational during a flood event. Buildings will need several additional requirements to normal buildings to be able to function as a smart shelter. The smart shelter requirements can be categorized into: spatial requirements (floor area for refugees and storage for food, medicine and water) and infrastructure requirements (access, sanitation, drinking water, sewage, power supply, ventilation and communication) in order to be self-sufficient during floods. Requirements for the design of smart shelters are illustrated below:

Clarifying constraints

For the case of shelters, a main consideration prior to the development of the alternatives is to investigate if there are (inter)national standards. The constraints should include those elements that are likely to be influencing (prohibiting) factors for the number and location of shelters and the services provided. These include the specific requirements and capacities of the organisations who might be involved in an evacuation plan (emergency services), the condition of the roads for providing safe access to the shelter, the time available for evacuation, and the safety level of people settled in the shelter during flooding.

Design modifications

In order for an existing or new building to function as a smart shelter some design modifications are usually necessary for coping with the hazard. These modifications are mainly structural and made on the exterior of the building and the bearing structure. The design of a building needs to be modified in such a way that all forces of flooding can be withstood. In order to plan and design a smart shelter the facility should be completely functional and operational during a flood event. This means avoidance of the flood is the most effective way to minimise the life-safety risk to the community that relies on the shelter, as well as to minimise the potential damage to the building. A well-planned, designed, constructed and maintained smart shelter needs to be able to withstand damage and remain functional during a flood event. Other possibilities of flood proofing a building are wet proof, dry proof or even floating options which can be achieved by adding a factor of safety (i.e. freeboard, levees, or elevation). Performance evaluation of a facility affected by flooding needs to include consideration of the building response to the following load conditions:

- Lateral hydrostatics forces
- Vertical (buoyant) hydrostatic forces
- Hydrodynamic forces
- Surge forces
- Impact forces of flood-borne debris
- Breaking wave forces
- Localized scour

The parts of the building that are vulnerable to these forces will need extra protection. They may include the use of strengthened glass, water and blast proof windows, temporary flood barriers and the use of water resistant materials and insulation.

Functional requirements

Buildings will need several additional requirements to normal buildings to be able to function as a smart shelter. During normal circumstances multi-use smart shelters will provide their primary function. But in times of emergency smart shelters change their function. The smart shelter requirements can be categorised into: spatial requirements (floor area for refugees and storage for food, medicine and water) and infrastructure requirements (access, sanitation, drinking water, sewage, power supply, ventilation and communication) in order to be self-sufficient during floods.

It is necessary to define the spatial requirement per refugee in order to determine the capacity of shelters. These requirements may differ in each country. The American Red Cross recommends the following minimum floor spaces (these criteria are based on the use of the shelter both as a refuge area during the event and as a recovery centre after the event):

- 20 square feet / 1.86 m^2 per person for a short-term stay (i.e. a few days)
- 40 square feet / 3.72 m^2 per person for a long-term stay (i.e. days to weeks)

The Dutch Red Cross recommends slightly larger floor areas:

- 2.5 m^2 per person for a short-term stay (day time)
- 2 – 4 m^2 per person for a long-term stay (day and night)
- 4 m^2 = 1 bed + chair
- 3 m^2 = 1 stretcher + chair
- 2 m^2 = 1 stretcher

Note that the terms short-term and long-term may be different in different countries and that spatial requirements should be according to local law and regulation.

Additional floor space is needed for the storage of supplies in order to change the function of the building into the shelter function, i.e. beds, food and water and for additional installations that are needed to guarantee electricity, water, ventilation and sanitation. This additional space depends highly on the primary function and the spatial floor plan of the building. For instance: hotels may offer ideal floor plans to host evacuees and most likely have large parts of the food supplies reserved for guests. The additional space for this is estimated at 10% of the gross floor area of the shelter. The ICC-500 (2008 Standard for the Design and Construction of Storm Shelters) states that depending on the arrangement of the floor area of the primary function of the shelter, there are three possible calculations to define the usable floor space (Table 5.9):

- Useable floor area is 50% of the gross floor area in case of high density and fixed furnishings
- Useable floor area is 65% of the gross floor area in case of low density and unfixed furnishings
- Useable floor area is 85% of the gross floor area in case of open floor spaces with unfixed furnishings.

Table 5.9 Usable floor space (in m^2) for shelters

Smart Shelter Capacity									
Smart Shelter building type			Cinema		School		Conference Hall	
Gross Floor Area			5000	m^2	5000	m^2	5000	m^2
Spatial Requirements + 10%			500	m^2	500	m^2	500	m^2
Total Gross Floor Area			5500	m^2	5500	m^2	5500	m^2
Useable net. Area (50% / 65% / 80%)			2750	m^2	3575	m^2	4400	m^2
Capacity short-term	1,86	m^2/pers.	1478	pers.	1922	pers.	2365	pers.
Capacity long-term	3,72	m^2/pers.	739	pers.	961	pers.	1182	pers.

Emergency lighting and power, as well as a backup power source, need to be included in the design of shelters. Route marking and way finding should also be included in the shelter design. A backup power source for lighting is essential during a disaster because the main power source is often disrupted. Shelters will have different emergency (backup) power needs based upon the duration of the hazard and the use of the shelters. For short-term shelters a battery-powered system is recommended as the backup source, because it can be located, and fully protected, within the shelter. Long-term shelters may need renewable energy generators, like solar and wind power to recharge batteries if power sources continue to be disrupted during an event. Failing to provide proper illumination in a shelter may make it difficult for shelter owners/operators to minimise the agitation and stress of the shelter occupants during the event. In addition to the essential requirements that must be provided in the design of the shelter, comfort and convenience should be addressed. For smart shelters, the most critical use of emergency power is for lighting. Emergency power may also be required in order to meet the ventilation requirements, heating and to establish lines of communication.

Planning smart shelter strategies

The planning of a smart shelter strategy starts by determining the need for smart shelters. It is recommended that within the warning time of a flood event the majority of people will evacuate the area preventively and find shelter on safer grounds. However, a certain percentage of the population will stay behind, unable to leave by own means or unwilling to leave their property. Using demographic data and software tools such as the ‘evacuation calculator’ (de evacuatie calculator) of the urban area, one can determine the capacity need of the shelters in that area.

In case of a flood event the refugees will have to reach the shelter in time. This means that the shelter has to be reachable at all times and is located close enough to the victims. Planners and stakeholders will have to take into account the maximum distance to a shelter. The maximum distance (D_{max}) to a shelter can be calculated by multiplying the minimum warning time (T_{min}) by the travel speed (a) – this has been estimated at 4 km/h.

To have a complete smart shelter coverage within an area, all potential refugees will need to have access to a shelter within the maximum distance. Otherwise multiple shelters are needed.

BOX 5.1 Case Study Dordrecht

The city of Dordrecht (the Netherlands) forms the southern gateway to the urban agglomeration of Amsterdam, Utrecht, Rotterdam and The Hague and is situated in one of the lowest parts of the Netherlands (from -1 m to +3 m above sea level). It counts approximately 120,000 inhabitants and lies next to the bifurcation of the Beneden Merwede, the Oude Maas and the Noord. The city is effectively located on an island, being surrounded by the Beneden Merwerde and the Oude Maas in the north, the Dordtsche Kil in the west and the Nieuwe Merwede and Hollandsch Diep in the south (Figure 5.27).

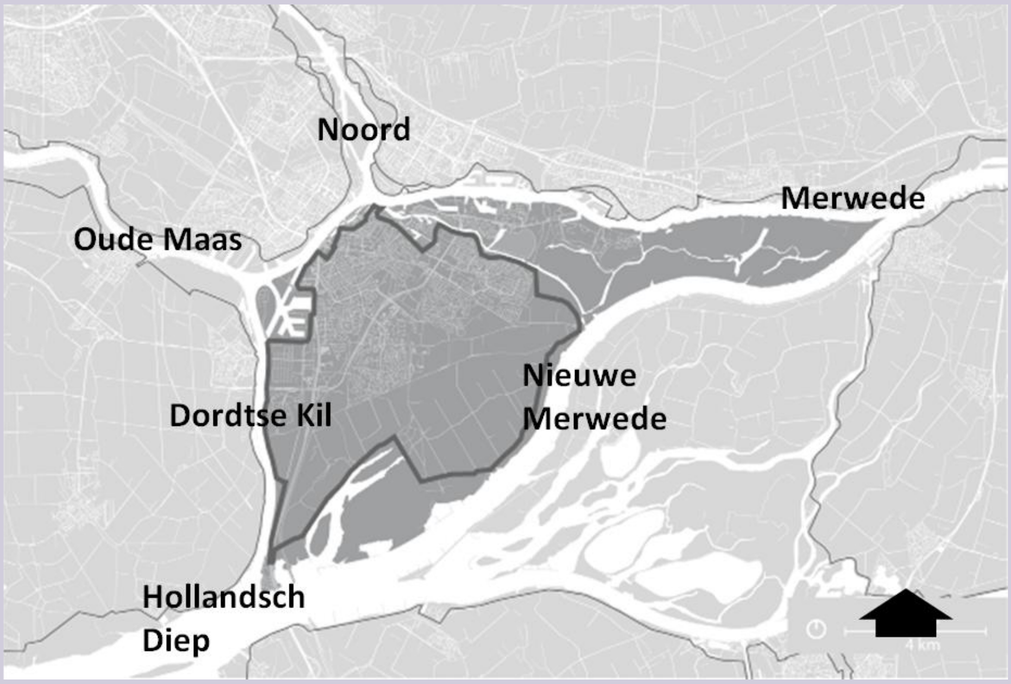


Figure 5.27 Rivers and canals surrounding the Island of Dordrecht, The Netherlands

Figure 5.28 shows the three main land use categories of the Island of Dordrecht. These categories are: residential & transport, industry & commerce, and agriculture & recreation. These categories are based on the damage categories used in the standard method to calculate damages and casualties due to floods. The figure shows that most agriculture and recreational areas lie south of the (Wieldrechtse) Zeedijk and east of the city, while the residential, industrial and commercial areas lie in the north west of the Island. Most industrial areas lie next to the rivers, outside the primary defence system.

The island is connected to the main land by only a few bridges and tunnels. The four main important connections are: the Drecht tunnel and (train and vehicles) bridge in the north east, the Merwede and Baanhoek bridges (train and vehicles) in the north, the Kil tunnel (vehicles) in the east and the Moerdijk bridge (train and vehicles) in the south west.

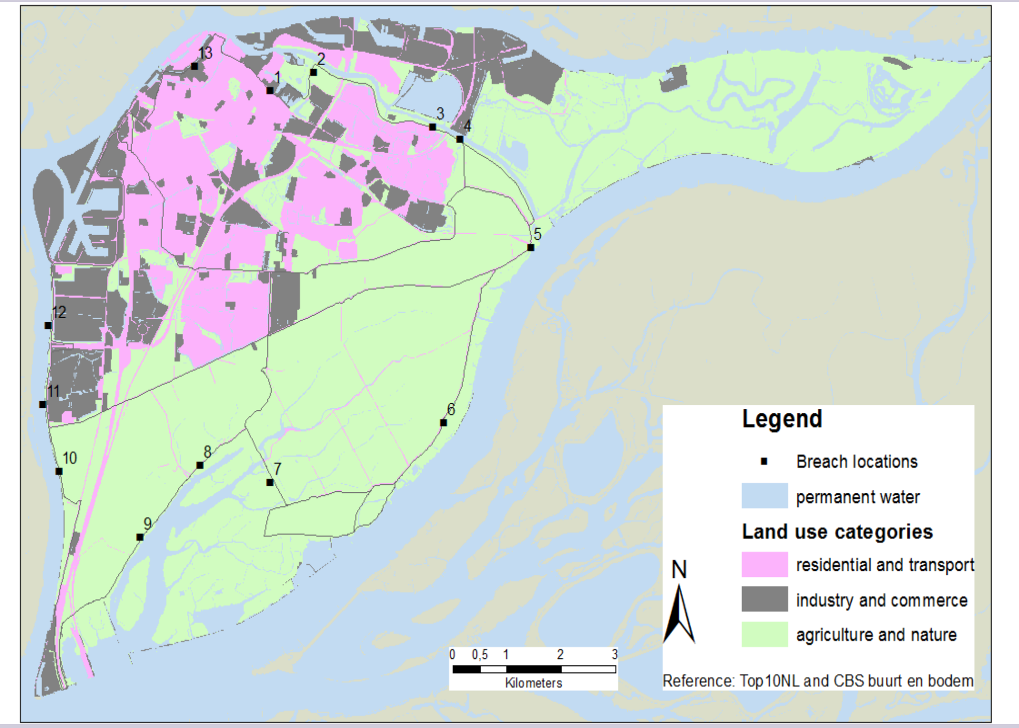


Figure 5.28 Main land use on the Island of Dordrecht

Source: Lips, 2012

System analysis

Flood probability - This parameter describes the probability that a breach occurs in the dike ring, and is built up from the probability of failure of the dike ring sections and several failure mechanisms. The dike ring of the Island of Dordrecht has a legal protection standard of 1/2,000 per year. The factor between the failure probability of a dike section and the failure probability of the dike ring is taken as approximately 4 for the mechanism overtopping / overflow. Furthermore, it has been assumed that the mechanism overtopping / overflow and the mechanisms piping and instability have an equal contribution to the failure probability. Taking into account the protection standard, the length effect and the distribution of the failure probability over the failure mechanisms, the failure probability of the dike ring has been estimated at 1/250 per year.

Flood pattern - The flood pattern describes how floodwater enters and propagates through a dike ring area. The maximum water depth and maximum water velocities through the different breaches are shown in Figures 5.29 and 5.30. These figures show that for the area north of the (Wieldrechtse) Zeedijk the maximum water depth (from different breaches) lies in between 2 and 5 metres. The maximum water depths south of the (Wieldrechtse) Zeedijk are much lower and lie in between 0.2 and 2 metres. Furthermore, these studies showed that a breach near breach location 5, Kop van het land, is the most destructive and inundates the largest area with the highest water depths compared to the other breaches. Figure 5.30 shows that the highest velocities are reached near the breach locations and small areas in between higher areas (embankments) that lie within the dike ring. The velocities can be faster than 0.5 m/s near the breaches and in between higher areas, but are less than 0.2 m/s in most areas of the island.

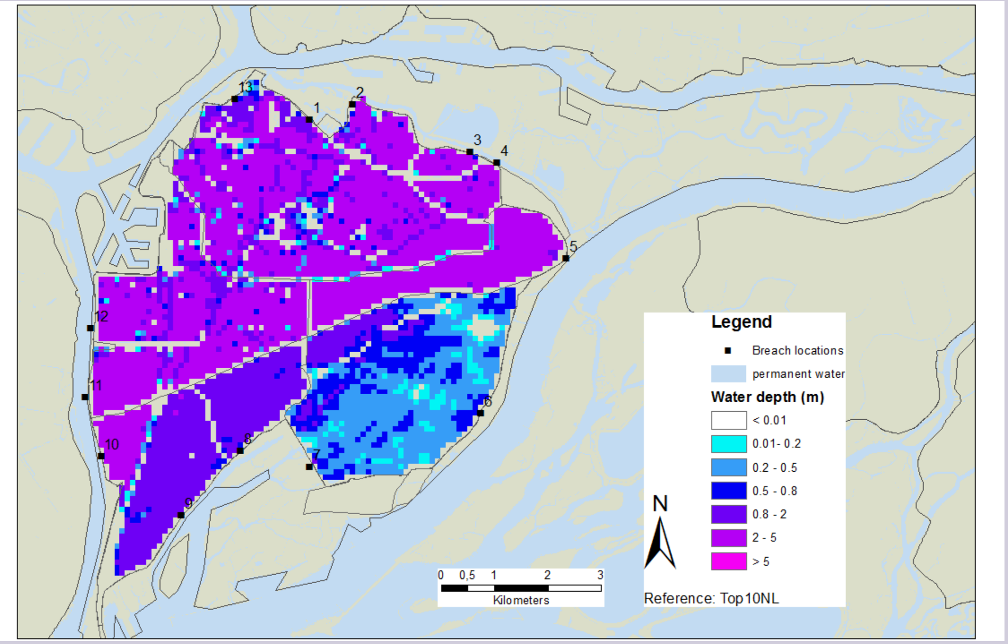


Figure 5.29 Maximum water depths for all breaches

Source: Lips, 2012

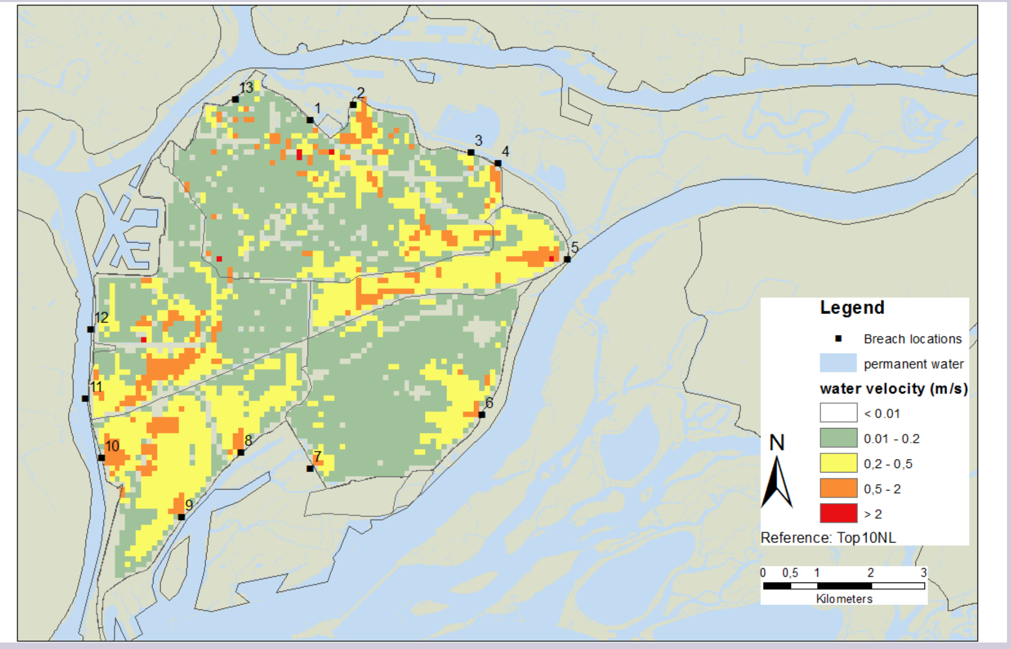


Figure 5.30 Maximum water velocities for all breaches

Source: Lips, 2012

Preventive evacuation - The preventive evacuation is the percentage of inhabitants of the dike ring area that can be evacuated before a breach occurs. In the Water Safety 21st century project, preventive evacuation has been schematized with four evacuation scenarios: 1) unexpected, no evacuation; 2) unexpected, unorganized; 3) expected, unorganized; and, 4) expected, organized. A conditional probability (which is the probability that a given evacuation scenario occurs) and an evacuation percentage have been assigned to each evacuation scenario (Table 5.10). By combining the conditional probabilities and the evacuation percentages an average evacuation percentage of 15% of the inhabitants is found for the Island of Dordrecht.

Table 5.10 Conditional probability and evacuation percentage per evacuation scenario

Preventive evacuation strategy					
Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Average
Conditional probability	0.40	0.44	0.12	0.04	
Evacuation percentage	0.00	0.03	0.59	0.76	0.15

Number of causalities - The number of causalities gives the human lives lost as a direct consequence of a flood. This can be determined using the expected mortality rate (defined as the probability that a person dies as a result of the flood characteristics occurring at a particular location) and the ability to evacuate before a breach occurs. The Flood Information System Damage and Casualty Module (HIS-SSM) contains mortality functions that calculate the probability of death at a particular location based on the flood characteristics occurring, such as the water depth, water velocity and rise rate. The number of casualties for the Island of Dordrecht was analysed with HIS-SSM for two situations. A first set of calculations has been made for the situation with a Design Water Level (1/2000 per year) and a further set of calculations has been made for a situation with a factor 100 lower probability (1/200000 per year). Table 5.11 shows the number of casualties as calculated by Hoss et al (2011). This table shows that the number of casualties is high in areas with many residential areas (e.g. dike section 5), while it is lower in areas with an industrial function (e.g. dike section 12). Furthermore, damage and casualties are higher in areas that suffer a bigger water depth. In general the areas that suffer the biggest flood impact lay at the northern side of the island, while at the southern side flood impact is less.

Table 5.11 Number of casualties per dike section

Number of casualties													
Dike section	1	2	3	4	5	6	7	8	9	10	11	12	13
Casualties with a 1/2000 per year water level	25-100	40-165	40-160	40-160	170-710	0	0	0	0	2-7	20-85	10-40	0
Casualties with a 1/200000 per year water level	55-230	90-370	140-600	115-480	285-1,200	0	0	0	1-4	5-20	40-170	25-105	15-75

Source: Hoss *et al,* 2011

The expected value of the numbers of casualties was calculated by the summation of all possible breach scenarios. Here, all breach scenarios have a contribution depending on the probability that it occurs and the number of casualties associated with it. This expected value gives the total flood risk of a dike ring with regard to casualties, expressed in expected annual number of casualties (EANC). For the Island of Dordrecht, the expected value of the numbers of casualties has been estimated at 0.42 casualties per year.

The visualization of the Local Individual Risk (LIR) - including evacuation - is given in Figure 5.31. The Individual Risk expresses the flood risk at every location in the dike ring area. It is equal to the probability of dying as a result of the flood characteristics (water depth, water velocity and rise rate) for a certain location. The IR is larger in the urbanised parts of Island of Dordrecht than in the rural parts. The industry park Dordtse Kil in the west of the island is by far the largest area with an increased LIR.

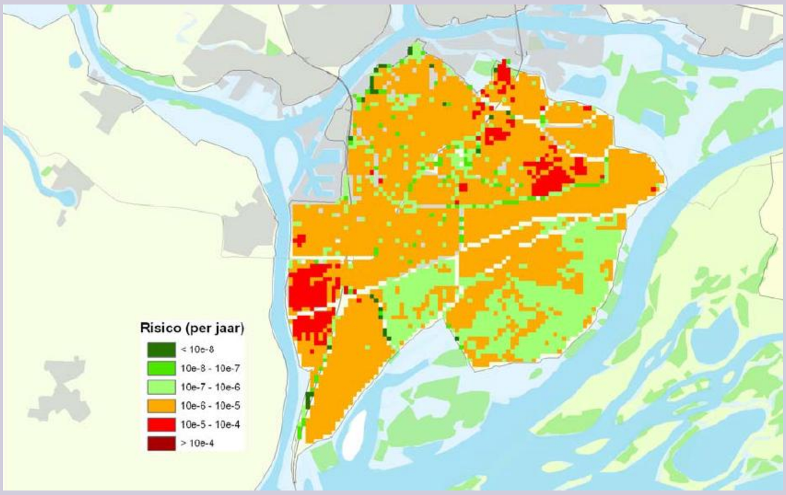


Figure 5.31 Local individual risk (including evacuation)-LIR-for the Island of Dordrecht, The Netherlands

Setting objectives

The objective set by the municipality, in close cooperation with the other stakeholders involved in flood risk management for the Island of Dordrecht, is to find practical measures on the city level that make the Island of Dordrecht safer and more attractive. An important starting point in this respect is connecting flood safety with spatial developments and water awareness.

The city of Dordrecht aims to identify synergistic opportunities where measures in one level of flood safety, such as protection, are synergetic to the effectiveness of other levels of flood safety, such as prevention or preparedness. Another important connection is that between flood safety and spatial development. Successfully connecting policy development ambitions in different sectors can speed up the implementation process for flood safety. Furthermore, new sources of funding can be addressed and/or costs can be reduced.

The area specific evacuation strategy is mainly directed toward measures in the third safety level (preparedness) and is supported by measures from the first safety level (protection) and second safety level (prevention). This strategy strives to reduce the flood risk with regard to casualties below certain target values. Target values can be predefined by the stakeholders or can be imposed by law. Different target values can be established for the different risk measures, such as the LIR and EANC. These target values can be used to assess whether a given intervention reaches the desired flood safety. One of the objectives of the Second Delta Committee is to make the Netherlands ten times safer. In this respect, the potential interventions can be ranked according to the degree by which they reduce the EANC. The actual target value for flood risk corresponding with a ten times saver situation can be calculated by dividing the EANC for the reference situation by ten. The target value for the LIR, as proposed by the Delta Programme Rhine Estuary-Drechtsteden, should be below 10-5 per year.

Potential interventions

Complete preventive evacuation for the Island of Dordrecht is not seen as feasible for the following reasons: 1) there are few main escaping routes (main highways) off the Island; 2) the amount of time for the evacuation is short (24 hours before the highest water levels occur it is impossible to evacuate anymore due to the fact that a heavy storm is blowing over the area); 3) the number of people that need to be evacuated is large (densely populated area); 4) neighbouring dike ring areas will be experiencing the same problem, so that there is no place to evacuate to. Therefore, an area specific evacuation strategy is envisioned. The proposed interventions for this strategy are to designate buildings on high places as smart shelters, to improve the self-reliance of the people, and to improve warning and crisis communication.

Shelters - Buildings on naturally existing high places on the island are to be designated as smart shelters for the non self-reliant people. For this purpose, several schools have been selected to serve as shelters to receive evacuees. This is because these buildings already have a function in accommodating large amounts of people. Their canteens will be constructed on higher floor levels once these schools are renovated or newly build.

Improving self-reliance - Through communication about potential disasters and training the self- reliance of the people will be increased. This is aimed at encouraging self-reliant people to stay in their houses or to seek shelter in high buildings in the area.

Improving communication - By an improved warning system the likelihood of an expected and organized evacuation increases. The improvement of the communication to the people during a disaster will increase the effectiveness of disaster management. This intervention will need to be implemented on several levels: local, regional and national.

Setting functional requirements

As part of the area specific evacuation strategy, about 20% of the people that remain on the island after preventive evacuation will still be evacuated to the smart shelters. The required sheltering capacity has been calculated using these factors, and it amounts to about 8000 to 14000 shelter places. The shelters should be self-sufficient, either permanently or temporarily (i.e. using emergency responses), in terms of sanitation, drinking water, sewage, power supply, ventilation and communication.

Cost effectiveness

The effect of the area specific evacuation strategy on the flood risk with regard to casualties has been assessed. The improved warning system will alter the conditional probabilities per evacuation scenario in favour of the scenarios with higher evacuation factors, whereas improved preparation will increase the evacuation factors for these scenarios (Table 5.12). This results in a higher average evacuation percentage, raising from 15 to 28%. Furthermore, the construction of smart shelters will lead to a reduction of the mortality by 50%. This means that the number of casualties is halved.

Table 5.12 Conditional probability and evacuation percentage per evacuation scenario

Area specific evacuation strategy					
Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Average
Conditional probability	0.28	0.38	0.18	0.16	
Evacuation percentage	0.00	0.07	0.71	0.79	0.28

With the area specific evacuation strategy the EANC reduces to 0.145 expected casualties per year, which amounts to 0.28 less expected casualties per year. This comes down to a reduction of the risk of 66%. Though this is a significant reduction, these interventions alone are not sufficient to make the Island of Dordrecht ten times safer in terms of casualties compared to the reference situation.

Figure 5.32 shows the LIR map for the area specific evacuation strategy. Comparing this figure with Figure 5.31 it can be seen that the LIR changes considerably. The critical spots with a LIR greater than 10^{-5} per year, like the Dordtse Kil, become much smaller. This suggests that the proposed interventions are largely effective in reducing the LIR to the target value (10^{-5} per year). Furthermore, there is little "unnecessary" risk reduction in areas that already meet the target value in the reference situation.

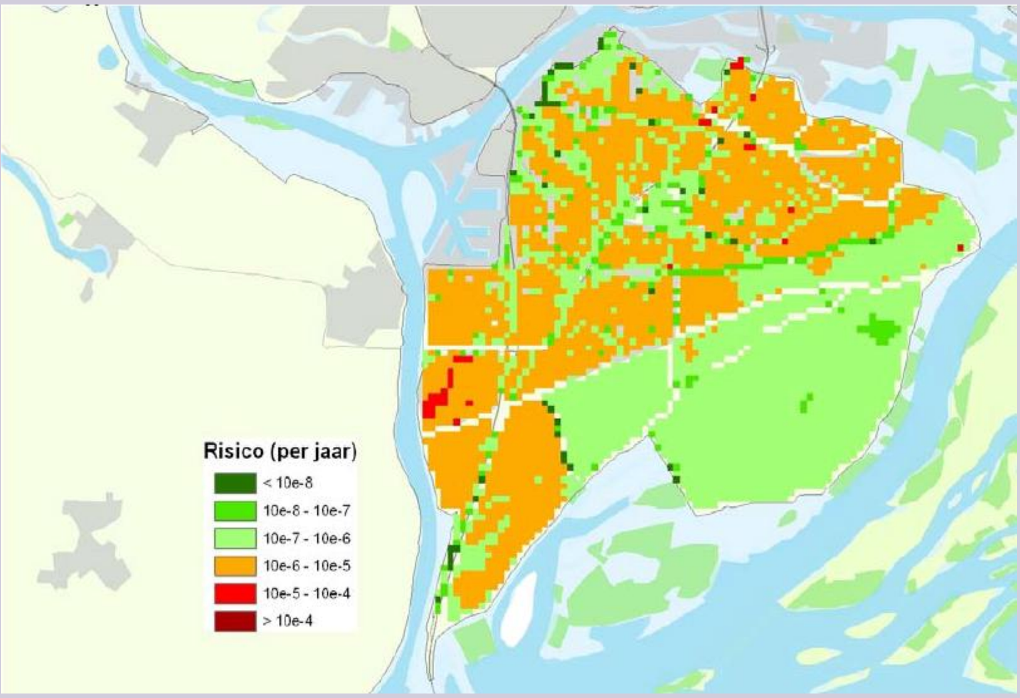


Figure 5.32 Local individual risk (including evacuation)-LIR-for the Island of Dordrecht for area specific evacuation strategy

Source: Hoss *et al*, 2011

Cost - Table 5.13 gives an overview of the cost items and cost estimates for the area specific evacuation strategy. The cost items have been classified as investment cost in the preparation phase, recurrent cost in the preparation phase, and recurrent cost in the response and recovery phase. The cost estimates give the order of magnitude of estimated cost for the cost items. These are shown as a range (minimum - maximum) for some cost items.

Table 5.13 Overview cost items and cost

Area specific evacuation strategy		
Investment cost in the preparation phase	Cost estimate	
Planning cost to determine the type, number, and size of the needed shelters	0.1	MEuro
Implementation of modification measures to improve present buildings to be a shelter	9.8 - 17.2	MEuro
Recurrent costs in the preparation phase		
Risk communication between different emergency services involved in evacuation programs and to the public	-	MEuro
Education and training of the emergency services staffs	2.5	MEuro
Recurrent cost in the response and recovery phase		
Costs of displacement of people into shelter	0.2 - 0.4	MEuro
Cost of providing immediate and urgent needs such as food, health care, etc.	10 - 35	MEuro

The modification and extension of the existing crisis management plan is required, because the area specific evacuation strategy requires different responses and capacities from the current strategy. For example, the type, number, and size of the shelters should be investigated as part of the planning process. The planning cost has been estimated from the cost incurred for the development of the Regional Basic Plan Floods. This amounted to approximately 0.1 MEuro.

The cost for adding the shelter-function to schools is estimated at 20% of the investment cost of building new schools. The average construction cost for an educational building in Dordrecht amounts to 1000 Euro per square metre of gross floor area. The costs for the addition of shelter locations are therefore equal to 200 Euro per square metre of gross floor area. Assuming a ratio of usable flood area versus gross floor area of 0.65, this amounts to € 308 Euro per square metre. The required usable floor area for sheltering one person (for the period of 1-2 weeks) is approximately 4 square metres (based on the American Red Cross recommendations). The cost for the addition of a shelter-function to schools is therefore € 1232 per shelter place. Assuming 8000-14000 shelter places, the total investment cost amount to 9.8 to 17.2 MEuro.

Risk communication between different emergency services involved in evacuation programs and with the public is an essential part of the area specific evacuation strategy. For example, people should be made aware that it is safer to find shelter on the island than to evacuate and risk getting stuck in traffic. Also, for the non self-reliant people it should be clear that they can get health care, etc. in designated shelter locations in the neighborhoods. The costs for risk communication are unknown.

The emergency services staff should be trained and the new strategy should be practiced. These costs were estimated at 2.5 MEuro per year.

It is estimated that about 100 policemen are required for the displacement of 5000 non self-reliant people into shelters. Given the short early warning period, it is assumed that the displacement into shelters has to take place within one day. The cost of a policeman per 24 hours is 1500 Euro. Assuming that 8000 to 14000 persons have to be displaced, the total cost is estimated at 0.2 to 0.4 MEuro.

The cost of providing health care has been estimated using the average care cost per day in a nursing home. This amounts to 185 Euro per person per day. These costs do not include medical supervision. Assuming 8000-14000 shelter places for 1-2 weeks, the total cost is about 10 to 35 MEuro (minimum: 1 week shelter for 8,000 people; and maximum: two weeks shelter for 14,000 people).

Cost-benefit analysis

The benefits of the area specific evacuation strategy can be calculated by expressing the casualties in terms of economic damages. In the Water Safety 21st century project a monetary value of 6.7 MEuro is assumed per casualty. The reduction in casualties with the area specific evacuation strategy has been estimated at 0.28 less expected casualties per year. This implies that the economic damage is reduced by 1.9 MEuro per year. These annual benefits should be discounted into present values terms, taking into account a discount rate of 4%. In case of an infinite time horizon, the present value of benefits comes down to 48.8 MEuro.

The costs of the area specific evacuation strategy consists of investment cost in the preparation phase, recurrent cost in the preparation phase, and recurrent cost in the response and recovery phase. The present value of costs has been calculated at 75.0 to 82.8 MEuro, by adding the discounted costs together over the time horizon.

Subtracting the benefits from the costs gives a negative NPV of 26.3 to 34.0 MEuro. This implies that the investment in smart shelters cannot be justified economically. It is of note, however, that this is mainly due to the relatively high cost of education and training of the emergency services staff.

References:

HOSS F, JONKMAN S N & MAASKANTA B (2011), *Comprehensive assessment of multilayered safety in flood risk management – the Dordrecht case study*. Floods: From Risk to Opportunity, IAHS Publ. 357, 2013.

LIPS N (2012), Application of storylines for strategy development in flood risk management. A case study on the flooding of the island of Dordrecht (The Netherlands). MSc Thesis Universiteit Utrecht, Utrecht, The Netherlands.

Chapter 6 Further information

6.1 Further information

Table 6-1 below provides signposting to different topic focussed information arising from the FloodProBE research. The main deliverable reports associated with each topic are listed, along with a link to the project website where more information (fact sheets, executive summaries, technical reports, links to associated pilot site work etc) may be found. Note that not all topic areas relate to all pilots, but some pilots include work covering multiple topics.

Web links: The web links provide a direct link to the FloodProBE website and a 'bundle' of information relating specifically to the associated topic or question or pilot. A more general search of FloodProBE outputs can be made via the documents area at http://www.floodprobe.eu/project-documents.asp

Table 6.1 Sources of information

Topics	Section in this Guide	Associated (Deliverable) Report	Web link to access more detailed Information
Applying FloodProBE Technologies within the Urban Design Process	**2**		Link
Levee Assessment:	**3**		Link
Assessing levee erosion processes: Internal erosion	3.2.1	D3.1 WP03-01-12-11	Link
Assessing levee erosion processes: Structure transitions	3.2.2	D3.1 WP03-01-12-11	Link
Assessing levee erosion processes: Performance of grass cover	3.2.3	D3.1 WP03-01-12-11	Link
Levee assessment using geophysical technologies	3.3	D3.2 WP3-01-12-20	Link
Levee assessment using remote sensing technologies (LIDAR)	3.3	D3.2 WP3-01-12-20	Link
Combining different data sources to gain insight into the levee condition.	3.4	D3.3 WP03-01-12-24	Link
Critical infrastructure assessment:	**4**		Link
Step-wise approach and tools for network assessment	4.2	D2.1 WP02-01-12-04	Link
Risk assessment for global understanding	4.2.1	D2.1 WP02-01-12-04	Link
Assessment of interdependencies of infrastructure networks	4.2.2	D2.1 WP02-01-12-04	Link
Analysing the course of a flood event on critical infrastructure through the storyline method	4.3	D2.1 WP02-01-12-04	Link
Assessment of likely level of damage to critical buildings	4.4	D2.2 WP02-01-12-05	Link

Topics	Section in this Guide	Associated (Deliverable) Report	Web link to access more detailed Information
Design and Engineering:	**5**		*Link*
Design and engineering...of flood defences	5.2		*Link*
Strengthening of earth flood defences	5.2.1	D4.1 WP04-01-12-12	*Link*
Multifunctional flood defences	5.2.2	D4.2 WP04-01-13-02	*Link*
Design and engineering...of critical networks / infrastructure	5.3		*Link*
Overview of Innovative road and bridge technologies	5.3.1	D4.3 WP04-01-13-03	*Link*
Catalogue floating and composite technologies	5.3.2	D4.3 WP04-01-13-03	*Link*
Design and engineering...of critical buildings	5.4		*Link*
Hotspot buildings (and how to make them more resilient)	5.4.1	D4.4 WP04-01-11-18 D4.3 WP04-01-12-01	*Link*
Smart shelters (concepts and constraints)	5.4.2	D4.3 WP04-01-12-15	*Link*

6.2 References

The various chapters of this guide are based upon content drawn from the project reports listed below. Each of these reports contains more detailed information on the specific issues, and includes a detailed reference list, which is not reproduced here. Each of these reports may be accessed online using the links in Table 6-1 above.

FloodProBE reports:

1. FloodProBE (2012), D2.1 'Task 2.1 Identification and analysis of most vulnerable infrastructure in respect to floods', 2012
2. FloodProBE (2012), D3.1 'Guidance on improved performance of urban flood defences', 2012
3. FloodProBE (2013), D3.2 'Rapid and cost-effective dike condition assessment methods: geophysics and remote sensing', 2013
4. FloodProBE (2013), D3.3 'Combining information for urban levee assessment', 2013).
5. FloodProBE (2013), D4.1 'Report on bio-technological strengthening on flood embankments, including the applicability based on experiments, and concepts close to industrial application', 2013
6. FloodProBE (2013), D4.2 'Design concepts of Multifunctional Flood Defence Structures', 2013
7. FloodProBE (2013), D4.3c 'Construction and Technologies for flood-proofing Buildings and Infrastructures; Concepts and Technologies for flood-proof Road Infrastructure', 2013
8. FloodProBE (2012), D4.3 'Construction Technologies for floodproof buildings and infrastructures; Technologies for flood-proofing hotspot buildings, 2012;
9. FloodProBE (2013), D4.4 'Building resilience measures; outline design guidance and roadmap for accelerated acceptance', 2013.
10. FloodProBE D5.1 – 'Report detailing integrated pilot results and lessons learned', 2013

Other references:

11. CIRIA (2006), Improving the flood resilience of buildings through improved materials, methods and details, Work package 5 – Laboratory tests, WP5C Final Report, by Escarameia M, Karanxha & Tagg A, July 2006, www.ciria.org.
12. Fauchard C & Meriaux P (2007), Geophysical and Geotechnical Methods for Diagnosing Flood Protection Dikes, Guide for Implementation and Interpretation, Editions Quae.
13. FLOODsite EU Project (www.floodsite.net)
14. Floods Directive (2007), Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks.