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Schelfhout

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THE RISK ANALYSIS OF LEVEE SYSTEMS

RÉMY TOURMENT⁽¹⁾, MICHAEL WALLIS⁽²⁾, BRUNO BEULLAC⁽¹⁾,
ANDREAS KORTENHAUS⁽³⁾, DAVID M. SCHAAF⁽⁴⁾ & HARRY SCHELFHOUT⁽⁵⁾

⁽¹⁾ Irstea, Aix en Provence, France
remy.tourment@irstea.fr, bruno.beullac@irstea.fr

⁽²⁾ HR Wallingford, Wallingford, United Kingdom
m.wallis@hrwallingford.com

⁽³⁾ Leichtweiß-Institut, Braunschweig, Germany
a.kortenhaus@tu-bs.de

⁽⁴⁾ USACE, Louisville, KY, USA
David.M.SchAAF@usace.army.mil

⁽⁵⁾ Deltares, Delft, The Netherlands
harry.schelfhout@deltares.nl

Abstract

Levees are part of systems that protect against flooding. Flood risk assessment of protected areas is particularly important to communicate flood risk, integrate it in various policies, actions and measures, and to reduce it. This paper, following recent advances from international projects, details key adaptations of the general concept of risk analysis to levees and the differences and complementarities between levee assessment and flood risk analysis. An analytical method of levee systems risk analysis integrating functional analysis and failure mode analysis is also presented.

Keywords: Flood protection; Levee systems; Risk analysis; Levee assessment; Methods

1. Introduction

Flood risk may be seen as a combination of the probability of a flood event occurring and the magnitude of economic, social, and environmental consequences that are associated with flood inundation. For a leveed area, it can be calculated by the product of the probability of the flood event and the probability of the levee system failure, and the impact of the consequences of flooding in the leveed area.

Levee system managers seek to make good investment decisions; decisions that minimise whole life costs of levees and maximise environmental gain whilst ensuring communities are appropriately protected from flooding now and in the future. Increasingly, consistent analysis techniques and decision support tools are available to support decision making at all levels. It is important that these tools and techniques provide:

- support to develop optimal investment strategies.
- an improved understanding of the role that an individual levee plays within a larger levee system,
- a better understanding of the impact of uncertainty within the estimated risk,
- the ability to progressively refine the analysis,

Recent advances are contributing to the design of a coherent and practical process of risk assessment. A risk-based approach has become the general objective, although the details of the tools and methods required to implement it are still being developed. This paper presents a synthesis of recent research in terms of the concepts related to the risk analysis of levee systems from recent international projects including the International Levee Handbook, Urban Flood and FloodProBE.

2. Particulars of levee systems risk analysis

2.1 Levee systems complexity

Levees have been built up and extended over decades or sometimes centuries. Few were originally designed or constructed to modern standards and records of their construction and historical performance rarely exist. Most levees form only part of complex flood defence systems that may also include flood walls, pumping stations, gates closure structures, natural features etc. The principle of risk analysis comes from the industrial sector where in the main, systems are relatively well known and controlled (Peyras, 2003). Because of their high complexity and structural variability however, the adaptation of risk analysis to levee systems is much more difficult.

Unlike other structures built using concrete or steel, levees can be irregular in the standard and nature of their construction and can deteriorate over time if they are not well maintained. Historically they have been constructed by placing locally won fill material onto alluvial flood plains (with all their inherent natural variability). Typically they are long linear structures - part of a chain in an overall flood defence system which is only as strong as its weakest link.

Weak links in the system may not become apparent until a storm or flood event occurs as many levees may stand for much of their lives without being loaded to their design capacity. Good design, inspection, evidence-based assessment, and effective maintenance and adaptation are therefore vital if levees are to perform adequately when they are subjected to such events.

2.2 Objectives of flood risk analysis of levee systems

In order to try to ensure the long term safety of a levee or a whole flood defence system, assessments (including risk analyses, performance assessments and visual inspections) are typically conducted on a regular, periodic basis, as well as on special occasions, such as during or immediately after loading events (floods, storms, earthquakes, etc). However, levee performance assessment and risk analysis, although closely related, are quite different activities:

- Levee or levee system assessment - the process of understanding the state, or the structural integrity, or the performance of an existing levee or levee system. A complete assessment should include a diagnosis of the actual or possible causes of failure.
- Risk analysis and risk attribution - risk analysis of a levee system estimates the overall level of risk associated to the levee system, according to the levee itself, its performance AND the stakes [receptors] in the leveed area and their vulnerability to flooding. Risk attribution identifies the risk associated with particular parts or sections of the levee system.

An assessment of a levee can help to determine what measures might need to be taken to remediate the levee (or levee system) if its likely performance does not meet flood risk reduction requirements.

The risk analysis of the flood defence system, can then help to prioritize those actions, taking into account the assets and their vulnerability in the leveed area. These actions could include for example: to initiate an emergency procedure, initiate a complete diagnosis of some part of the system in order to remediate structural problems (design and repair), make some 'routine' maintenance works, or just to maintain routine monitoring and inspection of the levee system.

A succession of analyses, alternating performance assessments and risk analyses can be undertaken at various levels of detail according to the role and objectives of the organization for whom the levee assessment or risk analysis is conducted, and also according to the point in the levee system life cycle. The approach will be different if the organization is the owner or the manager of a single levee system, or if it is in charge of the safety of a large number of systems. For instance, in the USA, the U.S. Army Corps of Engineers has about 2,500 levees in its portfolio that it has to help manage. Initially an assessment methodology and supporting analysis tools were developed to screen each of the levees and then classify them into one of four risk categories. This was done partially by a quantitative analysis method and also qualitatively with senior technical experts. The highest risk levees (those with a combination of expected poor performance under loading vs. high consequences) are then evaluated in further detail to ensure the screening assessment was accurate. The screening process uses default failure modes, whereas the detailed assessment process for high risk levees uses a potential failure modes analysis coupled with estimation of performance under varying load levels.

In this paper, sections 4 and 5 deal with deeper explanations and example methods for levee assessment and risk analysis respectively. To be efficient and well structured, both of these activities can be based on a functional analysis and a failure modes analysis. Section 3 explains the principles and methods for these.

2.3 Steps of risk analysis method

The analysis of flood risk requires the identification and examination of all the components that determine the risk of flooding in a system. The process must be able to evaluate all these components and integrate them (figure 1).

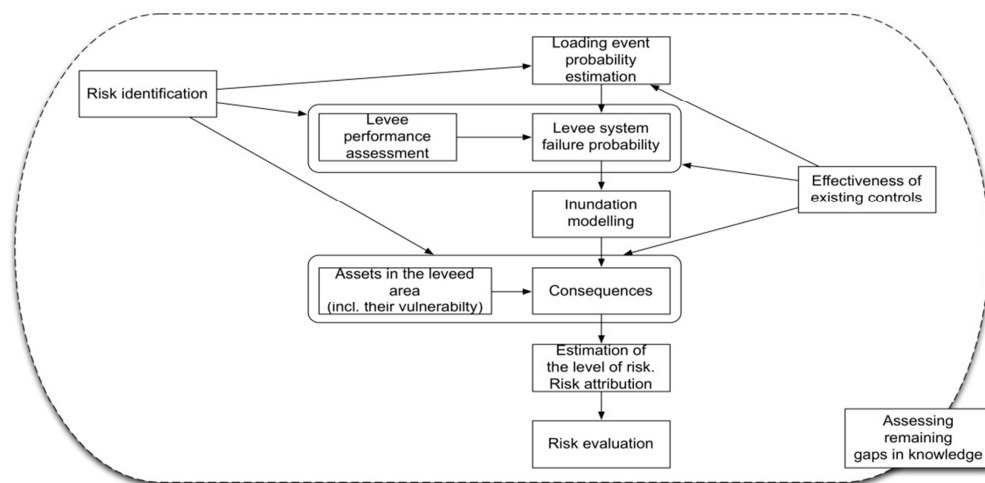


Figure 1. A framework for the analysis of different components of flood risk in a leveed area (R. Tourment & M. Wallis, International Levee Handbook, CIRIA 2013)

- **Risk identification** - In order to identify the risk, the driving factors affecting risk must first be recognised and recorded to identify what the chances are that it might happen, and what situations might arise. These factors include the sources of the hazards and their likelihood of occurrence, the 'pathways' of hazard transfer (e.g. levee failure and flood spreading), and the vulnerability of the receptors in the leveed area.
- **Event probability estimation** - Floods are episodic events. Large floods are rarer than medium sized or small floods. The probability of each size of event can be characterised as the chance that it will occur in any one year (its annual probability).
- **Analysis of levee failure** - How and where a levee system might fail is an important consideration in estimating the level of risk as this (in conjunction with the topography of the leveed area) will determine the receptors that are impacted by flood water. This is directly related to the assessment of performance of each levee in the system during a flood.
- **Inundation modelling**- In order to assess potential damage or to prepare evacuation plans, information is needed on inundation routes and flood spreading including water depths, flow velocities, and timing of inundation. Typically this information is derived from computer inundation models that simulate inundation along rivers, coasts and even urban drainage systems.
- **Consequence estimation** - A 'consequence' results when a 'receptor' – a vulnerable person or property, is actually exposed to a flood and suffers some actual harm or damage. Such consequential impacts may be a direct result of flooding (e.g. casualties, damaged buildings and/or contents), or indirect (e.g. health and social impacts, loss of business income etc). An analysis and evaluation of these potential impacts needs to be conducted in order to determine the potential magnitude and significance of the flood event.
- **Effectiveness of existing controls** - Existing control measures (structural or non-structural) put in place to limit the possibility of the occurrence of a flood, or to limit its consequences should be taken into account in the estimations of the event probability, of levee failure, and of the consequences of the inundation. Such measures may aim to control or influence either the 'Source' (e.g. via breakwaters, upstream flood management including dams, etc.), the 'Pathways' (e.g. via levee maintenance, monitoring and emergency management, etc) or the 'Receptors' (e.g. via flood warning, population evacuation, resilient buildings, etc) parts of the system.
- **Estimation of level of risk** - Flood risk is estimated by taking into account the probability of a flood event occurring and the potential consequences of that event derived from the previous steps.
- **Assessing remaining gaps in knowledge** - Risk analysis is often undertaken despite there being *gaps in knowledge* that if filled, could influence the outcome. They should be recognised in the process and known knowledge gaps identified either in the **data** or in the **methods of analysis** used for the assessment. Such variances can result in imprecision in the results which may need to be improved to reduce uncertainty in the outputs of the risk analysis.

2.4 Further use of risk analysis results

- **Risk attribution** - It is not possible to protect against all flood events - either because a flood may be greater than the level of protection provided, or because defences in the system may fail. All flood defence systems therefore leave a residual risk of flooding. Risk attribution is a method of attributing that residual risk in the leveed area to individual levee segments. This can inform the prioritisation of intervention measures to reduce the risk further.

- **Risk evaluation** - The aim of risk evaluation is to determine the significance of the flood risk to society. Communicating the evaluation to decision-makers is important to enable them to determine whether or not to proceed further with risk reduction measures. Benchmarks for the acceptability and tolerability of societal risks (including flood risk) are determined by the appropriate authorities in each country.

3. Functional analysis and failure mode analysis

The method for structural failure analysis presented in this section was formalized during the ILH project. This was based on earlier works and hydraulic failure analysis was completed later by Irstea (Tourment et al., 2013, 1 & 2). Together they can be used to conduct efficient and well-structured levee performance assessments and levee systems flood risk analyses.

The main function of levee systems is flood protection, so, levee system failure can be defined as the unintentional inundation of the leveed area. This can happen either: by inflow of water before the planned protection level¹ is reached, or, by a breach in the levee system. The first case can be referred to as "hydraulic failure" and the second one as the result of a "structural failure" scenario (figure 2). These two different cases are not necessarily unrelated as either can happen alone or lead to the other.

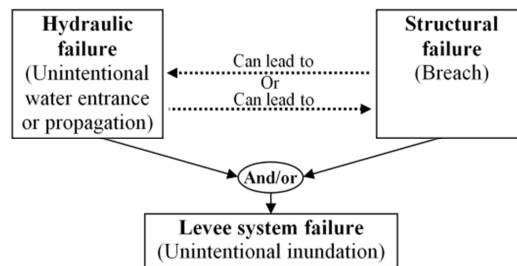


Figure 2. Levee system failure (Tourment et al, 2013, CIRIA, 2013).

Most of the activities related to levee assessment, maintenance or design are directly related to possible structural and hydraulic failures of levee systems. In this context, the analysis of failure modes is a process that is used to analyze, identify and represent failure scenarios to improve levee assessment and risk assessment, and in order to choose the most representative ones to study further. It can be based, as in this method, on a functional analysis.

3.1 Functional analysis

Functional analysis of levee systems can be undertaken at three different scales (or resolutions). Scale 1: the levee system as a whole and including its main functions and technical functions due to its environment (water environment, leveed area). Scale 2: functionally homogeneous structures that form the levee system including hydraulic functions of these subsystems (dams, spillways, gates, water storage area...). Scale 3: structural elements that form the sub-systems of cross sections of homogeneous sections of levees including the geotechnical functions of the components (protection against erosion, levee body, filter, drain, refill...). Failure is defined as the inability to achieve a defined performance threshold for a given function, in this case, the flood protection function of levee systems. Failure may affect a levee system, or a section of levee, or a component of a section of a levee.

¹ 'Protection level' is the flood level up to which the levee system prevents water entering the leveed area.

3.2 Failure modes analysis

Hydraulic failure can be studied at Scale 2 and structural failure at Scale 3. Then a failure modes analysis can be conducted at both scales by building hydraulic and structural failure scenarios. The results and the way they are used are presented in table 1.

Table 1. Results and use of failure modes analysis

Granularity	Result of failure analysis:	Primarily used in relation with:
1. Whole system	Not applicable (Always: a failure of the levee system creates a flood in the leveed area in case of flood from the water side)	Defining the levee system, the loads, the leveed area assets
2. Levee system	Flood propagation scenarios (including breaches, "simple" overtopping and other hydraulic failures i.e. failure to close a gate)	Inundation modelling of the protected area
3. Cross Section	Structural failure scenarios (Breach scenarios)	Levee safety/performance assessments

3.2.1 Hydraulic failure analysis

Hydraulic failures can result from either:

- an error in the design or construction of the levee;
- a modification in the morphologic environment of the levee system (for instance, raising of the river bed or of the foreland, or a settlement under the levee, leading to an overflow for a lower return period event than the protection level);
- another hydraulic failure;
- an operational failure (for instance a gate which is not closed during an event, by human error, or poor maintenance resulting in the impossibility of operation);
- a breach resulting from a structural failure scenario.

Inundation of a leveed area caused by a flood higher than the design protection level of the system is not a hydraulic failure, as the protection function of the levee system was fulfilled, until the design level was exceeded. A hydraulic failure scenario is a succession of events that lead to an unwanted or unplanned inundation of the leveed area.

These events include loadings from the water side (transformed by elements in the water side: groynes, weirs, other levees, beaches ...), hydraulic failure of levee subsystems and associated causes, normal hydraulic working of subsystems, hydraulic consequences of hydraulic failure or normal working of subsystems. A hydraulic failure scenario ends when no more hydraulic failure occurs and the levee system returns to a new stabilized state.

3.2.2 Structural failure analysis

A structural failure scenario leads to a breach and consists of a process (traditionally called "failure mode") which involves both physical and functional phenomena. The first mechanisms of a structural failure scenario are initiated by external loadings or actions on the levee. A mechanism can result in the deterioration or damage of one or more components. Component deterioration or damage results in the degradation or failure of one or more functions, associated to the said component(s). Degradation or failure of a function can then initiate or aggravate mechanisms, creating new elementary chains of events for the same or other components. Such a scenario can stop when the hydraulic loading (flood or storm) or other type of action (drought, animals, vegetation, human activities...) ceases.

The state of the levee is then deteriorated (which means that the functions of some of its components are degraded or failed) but not necessarily ruined (meaning that there is a breach). The scenario can then recommence when a new loading/action occurs.

3.3 Place in the risk analysis process

In order to include both hydraulic and structural aspects of failure in a flood risk analysis we propose the following process of integration. The red boxes in figure 3 denote the use of failure modes analysis.

4. Levee assessment

The objective of a levee assessment is to evaluate the performance of a levee, or even of a complete levee system (CIRIA 2013, Chapter.5). The assessment process can be described, in a very simple way, as the use of one or more methods of treating and combining data in order to obtain an evaluation of the performance of the levee system, according to its main function (to protect against flood) and its reliability (against possible modes of failure). For each or all potential failure modes in a levee, the assessment process must provide an estimation of the potential for failure during one or more different loading events.

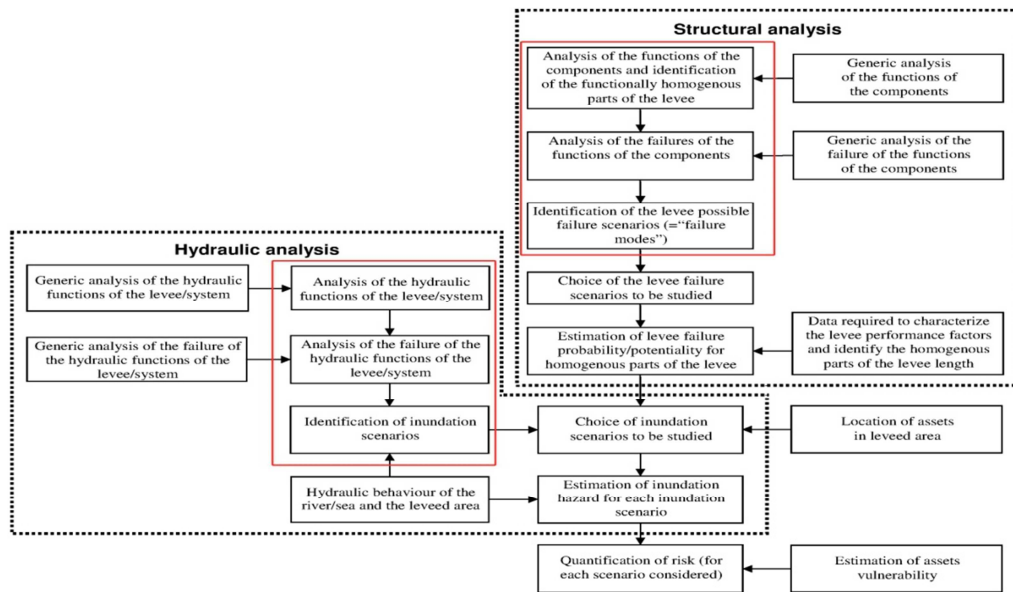


Figure 3. Hydraulic and structural failure analysis of protection systems in the levee flood risk analysis process (Tourment & al, 2013, CIRIA, 2013)

There are different assessment methods, all based on a combination of data, using expert judgment, index based methods, and mathematical models based on physical or empirical equations. There are different possible forms of result of an assessment, including:

- threshold (a limit load),
- safety factor,
- index (examples: on a 0-5 or 0-10 scale),
- qualitative (example: Very Good, Good, Fair, Poor, Very poor),

- conditional chance of failure (for a given load),
- fragility curve (conditional chance of failure given for a range of loads).

The last two forms are particularly useful, even necessary, when conducting a risk analysis. The form of the result depends largely on the method used, but also on the way it will be used thereafter. It is possible to convert one type of result to another.

Models used during an assessment can be the same as the ones used in the justification of a project. However, assessment is about the qualification of performance, so its result should be a rating of a given state at the time of the assessment, and should be related to the intended nominal state.

In the same assessment these different types of methods can be applied in combination. For example, it is to be expected that given the variability of materials and parameters in existing levees, some level of expert judgment will need to be added in the conclusions of any assessment report. Expert judgment can take into account any data (even when not used as input into any model) if it is relevant to a given failure mode.

An example of integrating additional data with a fragility curve derivation for one failure mode of one levee section is given below, combining measurements and field observations with a probabilistic model.

Take a levee section which suffers from seepage under high load conditions. The mechanism of failure might be piping, hence this process is considered in relation to other factors that might increase or reduce the risk of occurrence (Schweckendiek, T, 2013). The original fragility curve utilises base soil parameters and assumes that failure would occur if seepage occurred. According to the limit state equation for seepage through a sand core, (failure mode Ba1.5b, adopted from the FLOODsite failure modes report, Allsop *et al*, 2007), nine parameters are required to analyse this failure mode and assess levee performance. However there are a range of factors that could affect seepage and concentrated leakage erosion, such as insufficient drainage, animal burrows, cracking, external erosion etc.

These can be identified, and other parameters that affect the analysis, such as geometry, geotechnical inputs and loadings also noted. Different sources of additional data may then be considered, along with the nature of the data, the parameter that the data influences, and the nature of that influence.

For example, the analysis of geophysical data can determine the internal composition of the embankment, refine the original value used for permeability and hence change the value for seepage. Similar consideration can also be given to additional data arising from visual inspections (e.g. animal activity; grass quality), remote sensing surveys, surface geological investigations, historic records, etc.

Such additional data can be used to refine the performance assessment. For example, where animal activity is identified, the type of animal dictates the type of burrow, which in turn allows the potential reduction in seepage path length to be calculated and hence change the assessment of embankment performance. A result from such a refinement of the analysis is shown in Figure 4.

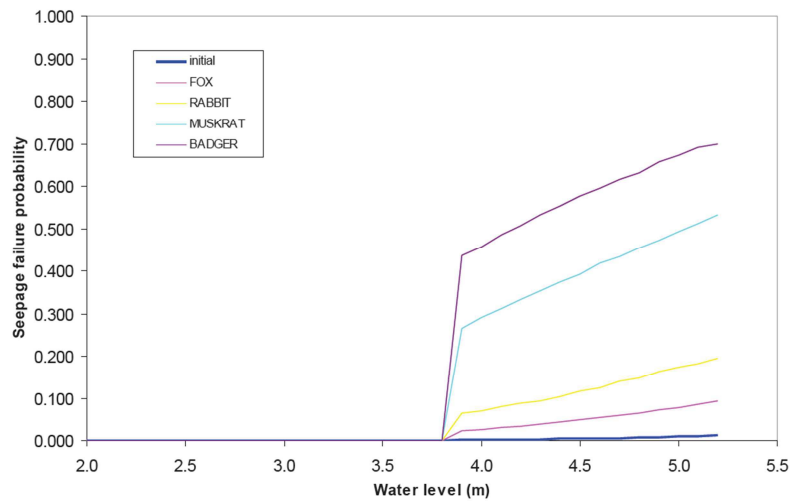


Figure 4. Example of a modified fragility curve for a levee, utilising the analysis of field observations relating to animal activity (R van Der Meij, *et. al.*, 2012).

A similar approach can be undertaken for the other factors and the combined effect on overall performance assessed. This example shows how additional data, much of which is either already collected during embankment inspections, or which may be collected from existing records or databases, may be used to improve performance assessments. The example relates to the use of data in relation to just one mechanism, for one part of the fault tree, which represents the combination of mechanisms required to result in failure. To maximise value from additional data, the relationship between available data and all of the parameters needed to assess each of the mechanisms within the fault tree should be undertaken.

5. Flood risk analysis

5.1 Scenarios

The flood risk in a leveed area depends on the performance of the levee system. Where a failure in a levee system occurs will partly (in conjunction with the topography of the leveed area) determine the receptors that are impacted by flood waters. How and where a levee system might fail is therefore an important consideration in estimating the level of risk. This activity is directly related to levee assessment; in a risk analysis the result should be expressed in probabilistic terms.

The failure of any one component of a levee system may be dependent on the performance of another component, OR, it could be completely independent, OR it could be partially dependent. These relationships are not well understood, and cannot be easily described or represented mathematically. So whatever the method used for a levee system assessment and the way in which its result is expressed, one may need to transform the result into probabilities in order to be used in a (quantitative) risk analysis.

In order to make the link between levee failure and the resulting inundation scenario to be studied/evaluated, it can be useful in a risk analysis to complement the "raw" result of an individual levee performance assessment by a characterizing the possible failure(s) ("simple" hydraulic or breach failure, location of failures).

5.2 Consequence analysis generalities

An analysis and evaluation of the likely consequences of a flood event needs to be estimated in order to determine the potential significance of a flood event. A 'consequence' results when a vulnerable person or property is actually exposed to a flood and suffers some actual harm. Consequences may be a direct result of flooding (e.g. damaged buildings and/or contents) or indirect (e.g. loss of business earnings due to recovery time) (Smith and Ward 1998, Parker *et al*, 1987, Penning-Rowsell *et al*, 2003, and Messner and Meyer, 2005).

With the recognition that it is not possible to protect from all floods, we need to find innovative ways to manage the associated risks and likely consequences. Within this context there is a growing awareness that floods are not just about damage to buildings, the environment and economy but that they are also "people problems" as well as "water problems" and that human behavior can be adapted to mitigate the negative effects that floods can bring.

To inform future investment in flood risk management options, a clear understanding is required of the likely risks and impacts of future flooding, of the potential benefits of mitigating these impacts, and of the appropriate methodologies needed to evaluate them.

The evaluation of the consequences of inundation in a leveed area results from a combination of the results of hydraulic modeling of the inundation and the estimated vulnerability of the different assets identified and located in the leveed area.

This vulnerability, which is a function characterizing its damage according to the hydraulic characteristics of the inundation (i.e. water level, flow, duration, ...), also needs to be assessed. A leveed area can contain many different types of assets, including: people, buildings, natural/undeveloped areas, agriculture, factories/business, transport, utility and communications networks, etc.

The vulnerability of these different types of assets can be approached in different ways to characterize their damages, such as: casualties or life loss (Jonkman *et al*, 2008), social, economic and environmental consequences (Tapsell, 2008) and, patrimonial loss for example. Some difficulties lie in the fact that the vulnerability of a type of asset can often be studied in several ways.

For example the consequences of an inundation for a flooded factory can be approached in terms of economic losses, but also in terms of social issues for employees or even in terms of effects on the environment.

5.3 Risk attribution

Levees work together in a system to reduce the risk of flooding. However levees do not all contribute the same level of risk reduction to the whole.

Some levees are more or less reliable than others, some may have more variable crest levels for example or may be weaker structurally than others. Failure of different parts of the levee system may lead to different inundation of the leveed area (in terms of flooded area, water levels, time, speeds V and H etc). Risk attribution is a process of attributing a level of risk to different parts of levee system, following the previous risk analysis methods.

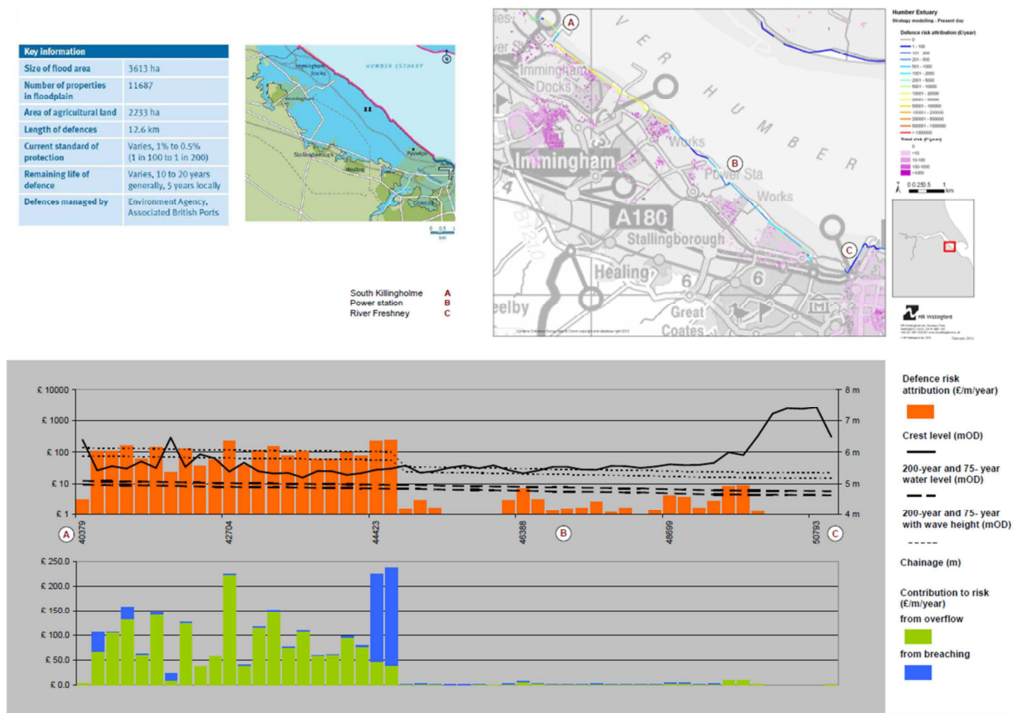


Figure 5. An example map and histogram showing risk attributed to defences on the Humber, UK (Courtesy of the Environment Agency, UK).

Risk attribution can be done (see Gouldby *et.al.* 2008) for each inundation scenario (for each part of the levee length) and lead to their relative classification according to the risk attributable to each. It also can be integrated at the whole levee area scale, and lead to the estimation of the global inundation risk attributed to the entire levee system. Figure 5 shows an example of risk attribution mapping and tabulation for a part of the Humber Shoreline, UK (a fictitious example using trial data and future climate scenarios).

6. Conclusions

Recent advances are contributing to the design of a coherent and practical process of assessment. A risk-based approach has become the general objective, rather than "simple" structural performance assessments, although the tools and methods required to implement these are still being developed.

Additional site-specific data, over and above 'typical' values used in generic assessments can be integrated into reliability assessments to improve the estimation of the probability of failure of levees and levee systems.

In a system of levees, levels of risk can be attributed to each discretised defence length and inundation scenario, providing valuable information for decision-makers and for the prioritisation of remedial measures. This paper illustrates the framework for these advances, with some examples, hoping to help future studies and methods to be developed in this framework.

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