

Combining information for urban levee assessment

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Summary

Work package 3.3 shows how to integrate gathered data and the mathematical models presented in the other sections of this FloodProBE project work package 3. It provides guidance on how to use information that is not incorporated in the traditional assessment framework. The added value of using all relevant data is made explicit for both the asset manager and the consulting engineer. This document shows how data is used to assess flood defence performance and how data might be analysed in the future to provide more reliable performance assessments. The work presents different examples of assessment methods and how performance assessment can be improved using the different approaches.

The accuracy of a traditional assessment cannot be improved after a certain point as some aspects are not taken into account inside the current frameworks. Initial assessments can be improved if measurements, observations, expert knowledge or other data is combined with the traditional assessment method. Incorporating these additional aspects is not always straightforward as our traditional assessment tools are not necessarily designed to deal with different data types. This report presents a number of data combination techniques from both a theoretical and a practical point of view and gives guidance on improving the assessment through adding additional data sources. Some improvements can be implemented directly without much effort (cost); others need some research and development in order to be ready for use in practice.

A theoretical approach to improve the assessment results is applied in several cases in this report. These cases show that it is quite possible to combine fundamentally different data types for an assessment and thereby improve the quality of the assessment.

In order for these changes to take place in practice, both engineers and asset managers need to change the way they think about data. Data needs to be gathered and maintained in a structured manner (GIS) and the assessment methods must not ignore important data because it does not suit a particular model. This report gives guidance on how to manage the data and how to improve the assessment models.

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1 An introduction to the FloodProBE Project and work package 3

1.1 The FloodProBE project

FloodProBE is a European research project with the objective of providing cost-effective solutions for flood risk reduction in urban areas. FloodProBE aims to develop technologies, methods and tools for flood risk assessment and for the practical adaptation of new and existing buildings, infrastructure and flood defences leading to a better understanding of vulnerability, flood resilience and defence performance. This research supports implementation of the Floods Directive through the development of more effective flood risk management strategies. The project utilises pilot sites across Europe, to help provide practical industry guidance and cost effective construction solutions.

More information on the FloodProBE activities can be found at www.floodprobe.eu

The FloodProBE project has been structured into six different work packages (WP's) as follows:

- WP2 addresses issues related to understanding vulnerability and assessment of the vulnerability of urban areas or systems.
- WP3 deals with failure modes and the assessment and identification of weak spots in urban flood defences.
- WP4 investigates cost-effective construction technologies and concepts for improving performance of existing and new flood defences and for increasing the flood resilience of urban systems and assets
- WP5 supports integration of the research and newly developed knowledge into existing decision support models or systems, the production of industry guidance and the interaction and integration of pilot site studies across Europe.
- WP6 addresses the dissemination and stakeholder-involvement activities whilst WP1 comprises all activities related to the management of the consortium.

1.2 FloodProBE work package 3

Over the past decade, floods in Europe and wider internationally have highlighted the vulnerability of flood defence systems composed of man-made structures (such as levees, walls, etc.) and natural structures (such as dunes, etc.). Examples of these flood events include Windstorm Xynthia (France, 2010), floods in the south of France (2002 and 2003), historical floods in Central Europe (summer 2005), and in the United-States (Hurricane Katrina, 2005) and Asia (Thailand, 2011). Understanding the performance of the flood protection system, and hence the level of protection and degree of flood risk posed is a key first action for managing the flood risk. Identifying weak points within the flood defence system where actions would be most beneficial, both in terms of flood protection and cost, is one of the most important but most difficult tasks.

Many levees are old structures, built several centuries ago, then rebuilt or repaired (after a breach), modified and heightened, sometimes with materials that do not necessarily match the original function or design of the structure. Levee foundations can also be heterogeneous and may not have been treated to improve their water-tightness or other fundamental properties required to support the function of the levee. Other factors which introduce weaknesses into a levee include: (i) trees, roots, burrows or termite nests which can modify the structure of the levee and reduce its mechanical properties; (ii) particular geological formations and their evolution which can also threaten the dike (as occurred in the city of Orléans, France, where levees have collapsed in karstic areas). In the urban context, other issues such as embedded networks, pipes and human construction (houses and walls) can threaten the integrity of the levee. With this range of factors affecting performance, levees have to be considered as heterogeneous structures. Hence, with many tens of thousands of kilometres of levee defences in Europe it is essential that there are 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.

Research under FloodProBE work package 3 relates to the assessment of earthen levee performance in the urban area. The work package is divided into three Tasks: actions under Task 3.1 deal with fundamental knowledge about the failure mechanisms or resistance of the dike; actions under Task 3.2 deal with rapid, cost-effective investigation techniques and Task 3.3 deals with the question of the assessment methodology itself.

An assessment¹ is a process that has the objective to evaluate the performance of a levee or levee system relating to one of its main functions: to protect against a given natural event and to be stable/safe. A complete assessment should include a diagnosis of the actual or possible causes of failure, in order to mitigate or prevent them.

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 or levee system, according to its main function (to protect against a flood) and/or its reliability (against 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.

Assessment makes use of a lot of data. Some data are typically available at the start of an assessment process, while other data may be needed but are unavailable; so specific data gathering may have to be made during the assessment process. This data gathering can be done during specific inspections and investigations and all data has its place within the levee manager's information system.

Task 3.1 of work package 3 deals with improving fundamental knowledge regarding possible failure modes of a levee. Specific actions include:

- mechanisms leading to the failure of an earthen levee through internal erosion (Action 3.1.1),
- structural weaknesses and associated failure modes arising from structure transitions (Action 3.1.2),
- performance of grass cover on levees against external erosion (Action 3.1.3)

¹ ASSESSMENT relates to the global process of evaluating the level of safety of the levee; DIAGNOSIS includes an assessment and specific analysis of the causes (mechanisms, failure modes) of a problem or of a risk.

Task 3.2 of work package 3 deals with rapid and cost-effective investigation techniques which provide essential data for use during an assessment. Specific actions include

- a review of geophysical methods, and particularly rapid and non intrusive methods, to complement classical geotechnical investigations (Action 3.2.1),
- a review of the use of high density LiDAR to support flood risk assessments in urban areas.

Task 3 of work package 3 investigates how data is used to assess flood defence performance and how data might be analysed in the future to provide more reliable performance assessments. The work presents different examples of assessment methods and how performance assessment can be improved using the different approaches.

1.3 Structure of this report

Chapter 2 provides an introduction to the issues, aims and objectives of the Task3.3 work. The use of different types and sources of data (to those currently used) and how these may provide added value to make more accurate performance assessments for urban flood embankments is introduced.

Chapter 3 provides a review of the data used in performance assessments and explains how additional data and data analysis techniques may be used to improve the accuracy of levee performance assessments. Chapter 4 provides a range of examples, building from the methods introduced in Chapter 3. Chapter 5 explains the role of GIS in data storage, analysis and interrogation. The role that GIS can play varies according to the data type and method of analysis being undertaken, however GIS typically underlies most asset management systems.

Chapter 6 provides a summary of the key issues, focussing upon the different data and methods that could be used and the implications for asset managers. Since the concepts and methods identified in this programme of work are looking at ways in which performance assessment could develop over the coming decade, recommendations for the next steps towards implementation are also provided.

1.4 Overview of other WP3.3 products

This report is one of a set of reports aimed at helping to improve flood risk assessment. More detailed information is available in the background report (FloodProBE Report WP03-01-13-01). This background report elaborates on data sources, data types, mathematical techniques to combine data and provides more detail about the practical examples. Two papers published in the proceedings of the FLOODRisk 2012 conference (Van der Meij 2012a) (Van der Meij 2012b) also describe the theoretical possibilities of combining data and the practical application.

2 Combining information for urban levee assessment

Levee management has changed 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 levels of the assessment. More and more information regarding levees is stored within GIS systems. 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 are combined and used to make an assessment. The aim of FloodProBE work package 3.3 was to investigate how we might incorporate and use a wider range of information into a performance assessment. The work shows levee managers and engineers that the quality of an assessment improves by enlarging the traditional assessment framework in this way.

In current practice, a levee assessment almost always involves determination of the so-called reliability of a levee for main, or all types of failure mechanism. Many reliability analysis tools exist with which the overall reliability of a levee can be determined, such as RASP in the UK (Sayers et al., 2004), SIRS-Digues and DIGSURE in France (Maurel et al., 2004, Tourment et al, 2012) and FEWS-DAM in the Netherlands (Knoeff et al., 2011); these make use of either physically based models, performance indicators, engineering judgment or a combination thereof.

A levee assessment has been traditionally based on deterministic approaches, sometimes including an assessment of uncertainty and leading to management actions that would typically include a degree of conservatism related to the uncertainty. Data may be gathered, and used in mathematical models (describing either physical or empirical laws) to assess the resistance to potential failure modes; an assessment of overall performance follows from these various model analyses. An assessment may consider only one loading condition, or a number or the full range of loading conditions possible. Equally, the assessment results may be presented in a number of different ways.

Clearly defined data is required for the analyses that underpin any assessment. Having established an assessment process, the assessor is not routinely looking for additional sources or types of data to improve the analysis approach and it would be difficult to take any such additional information into account without developing new diagnosis methods. Hence, development of new diagnosis methods does not (typically) form part of routine asset management procedures. In the situation where additional or new information is used to update or change input parameters, it is not usually done in an objective (i.e. reproducible) manner. Hence, since additional information is difficult to use directly within existing models or methods of assessment, when it is available, it is often not formally used at all.

In practice, adopting the use of a wider range of data to improve performance analysis will be a slow process as changes are required in the way data is collected, stored, processed and analysed for the assessment. Therefore, this FloodProBE work highlights how levee assessment might be improved as well as the changes needed in terms of data collection, storage and analysis to support this new approach.

This research focuses on several different aspects of the assessment process. It 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. The need to register all information within a GIS system is also considered 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.

Collating and storing a wider range of information in databases and using this data more formally for levee performance assessment also has other advantages. Inspectors and managers who work in the field will be better understood and will better understand the assessment when their inspection data is more visibly used within the assessment process. In general, the knowledge and awareness of the actors increases because the wider range of data sources are often easier to understand than the more technical data that are often used for the mathematical models. For example, observations relating to soil moisture or historic weather conditions as compared to physical measurement of the soil pore water pressure.

Application of these methods may require a different data acquisition strategy, but this is not necessarily difficult. Several examples are provided to show how wider data sources may be incorporated into each step of the assessment.

3 Data used in assessments and combination techniques

3.1 Relation between data and failure modes

3.1.1 Existing methods for analysing safety modes

Levees can fail through different series of events. Such a series of events is called a failure mode. FLOODsite Project Report “Failure Mechanisms for Flood Defence Structures” (Allsop et al, 2007) lists 75 relevant failure modes for water retaining objects like levees and structures. For a specific levee, the dominant failure modes must be identified for an assessment. For each failure mode, a method must be used to assess the safety.

The method of an assessment depends on the required detail of the assessment. Quick (and cheap) methods exist with little precision that may not be objectively reproducible. In the case of flood fighting, such methods may be most suitable. For a periodic mandatory risk assessment, a reproducible method is preferred.

These different methods can require different data types. Observations, indexes, measurements, historical and assimilated data are just some examples. Some data types are more relevant in case of a specific assessment purpose than others. Where indexes can give a grading to a levee to decide whether the quality suffices, measurements and assimilated data can directly say something about the safety of the water retaining structure. Simple models often suffice with simple data like indexes, while more complex models often need large amounts of data assimilation.

A unique way of grouping different assessment methods does not exist. In this section, the methods are listed from relatively simple (expert judgment) to very complex (mathematical models).

3.1.1.1 Expert judgment

An expert regarding flood safety has experience to assess whether a flood defence can withstand a certain water level. This is based on previous experiences without explicitly using forms or index based methods. The quality of the assessment stands with the quality of the expert; the process leading to the conclusion is not always transparent and could be questioned.

3.1.1.2 Index based methods

In such an assessment, a number of performance features are assessed to determine the safety. An example of such a method is a check on erosion of the inner slope of a levee based on several observations such as the angle of the slope and the quality of the grass. A check list with scores is used. Such a method can be relatively simple, for example the check might only assess whether the initial design criteria are met or not. Such a method can also be very complex if there is the need to combine fundamentally different types of data in order to undertake a more rigorous assessment.

3.1.1.3 Empirical models for failure modes

If there is a clear relationship between a number of parameters and the performance of a levee (for different failure modes), rules 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 model is Bligh's model for backward erosion (Bligh, 1910). It often suffices for assessing the safety, even though there is not always a sound physical and / or theoretical background for the models.

3.1.1.4 Physical and mathematical models for failure modes

An investigation of the critical situation, the limit state, is a method of determining the safety of a levee based solely 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 chance of failure as a function of the water level can be deduced. As empirical models, most physical and mathematical models can be presented in a limit state equilibrium equation.

Remark: the distinction between empirical and physical / mathematical models is not always clear. Many models describing failure modes are combinations of empirical and physical knowledge, e.g. the model of Sellmeijer describing backward erosion (see FloodProBE Report WP03-01-12-11: Guidance on improved performance of urban flood defences).

3.1.2 Data used in the assessment

Each method related to the evaluation of a levee system or element of the levee is based on data. When this data is processed by some method (human or computer analysis) it gives an outcome related to the safety or performance.

An assessment needs a wide range of data types. It may need topographic data, geotechnical data, geophysical data, hydraulic data, morphodynamic data, an inventory of the assets in the protected area, meteorological records, seismological data or the presence of external elements in the immediate environment. The existing methods for analysing safety modes rely on a pre-defined set of data for the assessment. This data set is fixed and can only be overruled by engineering judgment.

3.1.3 Potential for improvement

In every step of an assessment – from gathering data to reporting the assessment result – there is uncertainty. This uncertainty comes from the uncertainty in parameters, imperfections and omissions in the physical models and the fact that not everything is taken into account. At every step of the safety assessment, information is left out because it does not fit the traditional assessment methodology.

In geotechnical engineering, especially when it comes to safety assessment, it is not common to consider factors if they are not already in the prescribed framework. Neglecting information that does influence or inform on the safety of the embankment has several disadvantages. The uncertainty of the outcome of the assessment is unnecessarily large. On one hand, signs of deterioration or upcoming failure can be neglected, which means that the level of safety is overestimated. On the other hand, embankments with sufficient resilience may be unnecessarily strengthened due to insufficient knowledge.

By carefully incorporating all relevant information in the assessment, the quality of the assessment will improve. General input data can be tuned locally to serve as better input for the assessment model. This tuning can take place by incorporating, for example, the observations of local sand transport or the presence of animal burrowing. The model itself can become better if it contains less assumptions and simplifications and if it is ensured that all relations inside the model are correct. The output of the data can be improved if additional data types are incorporated. This improvement decreases the uncertainty at every level of the analysis. In the end, engineers and managers can take better, informed, decisions which improves the safety of the hinterland and prevents unnecessary costs for levee repair or reinforcement works.

With the increasing availability of GIS data, more opportunities arise to use it for assessment. Historically, this happened mainly through expert judgment. Several techniques exist to fully utilize all available GIS data in a more reproducible way based.

3.2 Common types of data combination techniques

The mathematics and science behind the methods of combining data goes too deeply into the theory for the scope of this document. The background report (Bligh, 1910) goes deeper into these mathematical techniques. This report groups the combination techniques into five categories as listed below:

Standard mathematical techniques:

- Averaging between different models (interpolation)
- Least squares method for finding a trend (interpolation/ extrapolation)
- Time series for extrapolation of data (extrapolation)
- Kalman filtering for improving the model
- Updating probability density functions with survived loads.

Adding additional relationships:

- Improve data based on observations
- Based on historic measurements

Advanced regression techniques:

- Artificial Neural Networks
- Fuzzy logic
- Adaptive Neuro Fuzzy Inference System (ANFIS)

Classification techniques:

- Decision Tree Learning
- Support Vector Machines
- Bayesian Learning (both naive, semi-naive and in belief nets)
- Discriminant functions
- Association rules

Design using evolutionary computation:

- Genetic algorithms
- Swarm intelligence
- Simulated annealing

3.3 The use of data combination techniques during the assessment process

As stated at the end of Section 3.1.1 and shown in section 3.2, many different techniques to combine different types of data for assessing levees exist. For the purpose of levee management, the grouping can best take place according to the point in the analysis that the data is combined. Data can be combined at three points during the analysis process:

1. **Refining the input data:** Integration can be performed at the start of any analysis in order to have the right data input or to refine or improve the input data. The performance model remains unchanged.
2. **Improving the (performance) model:** At a later stage, data can be combined to improve the precision of the model through calibration or by incorporating additional effects. Also, the speed can be enhanced by using more advanced models.
3. **Adjusting the output:** In the final stage, one or several assessment results can be updated based on additional information. The performance model and its input data remain unchanged.

The following three sections consider these three possibilities.

3.3.1 *Refining the input data*

A way of reducing the uncertainty in reliability analysis for a levee is through data assimilation. Observations of the levee behaviour or performance can be combined with the results of the prediction model. Based on these observations, certain parameters can be calibrated. For example, it is possible to predict the settlement of an embankment in time. If the settlements are measured after the prediction, there could be a change between the prediction and the actual settlements. This extra knowledge can be used to improve the quality of further predictions. Two solutions are possible to improve the quality of the model prediction. Input parameters can be modified in order to give better results, or the model itself can be modified. This section addresses updating the input data.

Many techniques already exist to perform such calibrations. The techniques vary from rather straight forward averaging and least squares analysis to more complex time series analysis and Kalman filtering techniques. The best suitable technique depends on the quantity, quality and precision of the data. When there is very little data (e.g. laboratory or field measurements), the few data points available can be used as the basis for wider predictions. On the other hand, when there is a large monitoring scheme, predictions can be improved even more. There are too many techniques available to discuss all of them in this paper. These techniques are widely used in mathematics and applied sciences, but not so commonly for safety assessment.

This section presents two examples on how to update the input data: a regression analysis and a Kalman filtering technique to show the possibilities at each end of the spectrum. A regression analysis is used for a situation with very little data and much uncertainty in the model and the Kalman filtering for improving a method with much data and a more reliable model.

Updating data in data-sparse area's can simply be performed with a regression technique. The performance of a levee decreases over time as the height of the crest decreases. Mathematical

models exist to predict the settlement of the crest of an embankment. These models are known to have a very large band of uncertainty. Data required for these models are parameters that typically follow from experience or laboratory tests. These parameters are never perfect for every location and can be improved by monitoring settlements in the field.

One proven concept to back-calculate the settlement parameters is by using a weighted least squares method, also known as a maximum posterior estimate. This method updates the values of fit parameters, by minimizing not only the difference between measurements and predictions, but also the difference between the initial value and the updated value of the fit parameters. Separate weights to each of the differences can be attached. Such a weight determines the relative importance of each difference. A large weight implies a more certain value of a measurement or parameter; a small weight implies a more uncertain value. In this case, only a few measurements are sufficient to greatly improve the quality of the prediction and therefore the chance of flooding in the future. If, for example, embankments are monitored for deformations every few years by satellite, this process can be automated.

At the other end of the spectrum is the possibility to improve the model predictions in a data-rich environment. One proven concept is the use of a Kalman filter. A Kalman filter uses measurements observed over time containing inaccuracies and produces values that tend to be closer to the true values of the measurements and their associated calculated values. The filter produces estimates of the true values of measurements and their associated calculated values by predicting a value, estimating the uncertainty of the predicted value, and computing a weighted average of the predicted value and the measured value. Most weight is given to the value with the least uncertainty. The estimates produced by the method tend to be closer to the true values than the original measurements because the weighted average has a smaller estimated uncertainty than either of the values that went into the weighted average (Kalman, 1960).

The benefits of using such updating techniques are clear. These methods assure that the best possible input data is entered into the model. The quality of an assessment cannot be any better than the quality of the data that goes into the assessment. By combining different techniques to ensure the use of the right input data, the quality of the output will increase, resulting in a more accurate assessment of the levee.

3.3.2 Improving the traditional model

Calibration of parameters will never lead to perfect results if the (performance) model describing the failure mechanism is incorrect. 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; for example, one can average the results of two different assessments to combine the aspects from both models. To do so, the outputs must be of the same data types. To determine which method is most suitable, one must know which data types need to be combined and what outcome is to be expected. If the outcome is of the same type, a weighted averaging is always an option. If the outcome is of a different type (for example a boolean and a numeric outcome) more advanced techniques are required.

A more advanced method to change the probability density function is by adding survived loads to the analysis. Observation before failure of the system can be used to update the chance of failure. Also, the chance can be updated if one event in a fault tree is observed (Van der Meij et al., 2012).

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. Fuzzy logic (FL) systems, Bayesian belief networks (BBN), artificial neural networks (ANN) and evolutionary computation are examples of methodologies based on computational intelligence. If there is sufficient data about observed failures in a GIS system, several computational intelligence techniques can be used directly for assessment. Case based reasoning, association rules and discriminant functions can be applied directly for assessment.

In the majority of cases where the data is not sufficient, for example if not many failures are registered, additional knowledge must be added to such a system. Expert knowledge is an important source to improve the quality of the assessment. With the aid of a BBN, experts can quantify risks to make an overall assessment. This risk, as quantified in a BBN by experts, can be combined with information about previous (partial) failures if this is available. This will make the model more precise as the expert knowledge can be calibrated.

Another possibility in data rich areas is the use of a neural network to simulate the behaviour of a system. In flood risk management, ANNs cannot be applied frequently for safety assessment because they are not able to extrapolate results. As safety assessment normally takes place at low probabilities, extrapolation of model results is therefore often a requirement. 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. 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. By also quantifying likelihood of (parts of) the system, an objectified method can be constructed to make classifications or even assessments of the safety of an embankment.

ANNs are not equipped to handle a safety assessment as they are not able to extrapolate results. An Adaptive Neuro-Fuzzy Inference System (ANFIS) has the same capabilities when it comes to regression, but can also contain expert knowledge like a normal fuzzy system. It has potential to capture the benefits of fuzzy logic and neural networks in a single framework. This can make the system more robust at the boundaries of its validity while also adding expert knowledge to a system which will result in better safety assessment.

This summary shows that there is a vast number of techniques available to improve assessment models. These techniques can use a wider range of data sources and types than standard assessment techniques typically used in current practice. In each specific case, research is required to decide which technique best suits the assessment method and goal.

3.3.3 Adjusting the traditional output

The final opportunity to use additional data sources is after the primary analysis. An assessment result can be adjusted based on information that has not been taken into account previously. 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 was not initially taken into account.

A comprehensive way of presenting the performance of an embankment is through fragility. A fragility curve gives the chance of failure at every water level. The probability of failure of a levee can then be calculated by multiplying this fragility curve by the probability density function of the water level.

Making use of a wider range of data sources and types gives additional information to the assessment. It thereby alters the inputs to these various approaches and therefore influences the initial fragility curve. Whilst some safety assessments may provide different outputs (not necessarily fragility curves), for the purpose of illustration, the fragility curve has been adopted here to demonstrate the influence of adjusting the output data based on wider data types.

Fragility curves can be constructed for an embankment using traditional tools. This fragility curve is said to be representative for a certain section. As time passes, more information becomes available on this levee section. Entering this newly available data into the model will shift the initial curve specifically for that area where the additional data is representative.

If additional data types can be translated into input parameters, the fragility curve can be shifted based upon the new data. For most data types, it is not difficult to find a relation between additional data and input for the model. Observation of animal burrowing can translate to a change in seepage length. Visual inspection of vegetation can inform on the reduction in seepage length due to roots and geological surveys can inform on permeability. Continuous local refinement of the assessment improves the quality locally and in time.

3.4 Guidance on when to use which technique

Combination of data is not a goal by itself. It becomes relevant only when there is a need for or value in achieving a better assessment. There are theoretically too many data types to be combined with different types of models to give an overview of which data and model can be combined with a certain mathematical technique. It is possible, though, to give guidance to choose the right integration strategy. It takes three steps to decide on the strategy:

1. Consider your uncertainty;
2. Find out what data can help to reduce the uncertainty;
3. Look for a technique that combines this data type with the existing model.

The first step in improving the quality of the assessment lies in addressing the uncertainty. If a source of uncertainty is known, then information can be identified that might reduce this uncertainty. Often, this data is already available or easy to collect, but simply not used within the current framework of analysis.

If one specific data type is chosen, it needs to be decided on which level this data is integrated in the existing framework. It can be used to calibrate the input data, improve the model or tweak the output. The best option depends upon the type of data and the type of model that needs to be combined. Once the level of integration has been decided, the best suited mathematical technique can be chosen. The best suited technique depends, once again, on the specific data type and the type of model.

Table 3.1 shows which type of technique works for the different steps. An almost infinite amount of subtypes exist. The best technique often depends on case specific detail, therefore no general guidance can be given. It is up to the Engineer to decide which technique to implement.

Table 3.1 Applicability of the mathematical technique in the assessment process

<i>Type of technique</i>	<i>Process data</i>	<i>Improve model</i>	<i>Process output</i>
Standard mathematical	yes	no	no
Additional relationships	yes	no	no
Advanced regression	yes	yes	no
Classification	yes	yes	yes
Evolutionary computation	no	yes	yes

4 Applications

This chapter presents a number of examples to demonstrate the theory given in the previous section and to show applicability of the methods. Table 4.1 gives an overview of the examples. The first column names the example; the second column shows the level at which the data is combined (data, model or output). The third column is the (mathematical) combining technique and the final column gives a short description of the example and the data types.

Table 4.1 Overview of the examples

Example	Combination level	Analysis method	Description of data combination technique and data types
4.1 Back calculating settlement parameters during construction	Input	Maximum posterior estimate	Combining field observations (measurements) with laboratory results
4.2 Index based assessment based on functional analyses.	input	Combining of indexes	Combination of information from visual inspection, geometrical, geotechnical, morphological information, information from database, etcetera.
4.3 Updating the input with observations	Input	Updating model input	Updating fragility curves on internal erosion
4.4 Improve backward erosion model based on observations	Model	Bayesian Belief Network	Combining expert knowledge, mathematical models and field observations to improve assessment of backward erosion.
4.5. Updating probability density functions for backward erosion using survived loads	Model	Bayesian updating based on survived loads	Combining field observations like uplift or sand boils with Sellmeijer model
4.6 Using a stochastic subsoil model for risk analysis	Input	Risk analysis	Combining geological knowledge with mathematical models for risk assessment.
4.7 Risk analysis	Model	Risk analysis	Combining probabilities of failure

4.1 Back calculating settlement parameters during construction

Example name	Back calculating settlement parameters during construction
Location / pilot	Dordrecht, The Netherlands
Analysis method	Maximum posterior estimate
What is combined?	Measurements are combined with a physical model
Failure mode(s)?	Settlement affecting crest elevation
Improvements	Input parameters are adjusted in order to make better predictions

Graphics

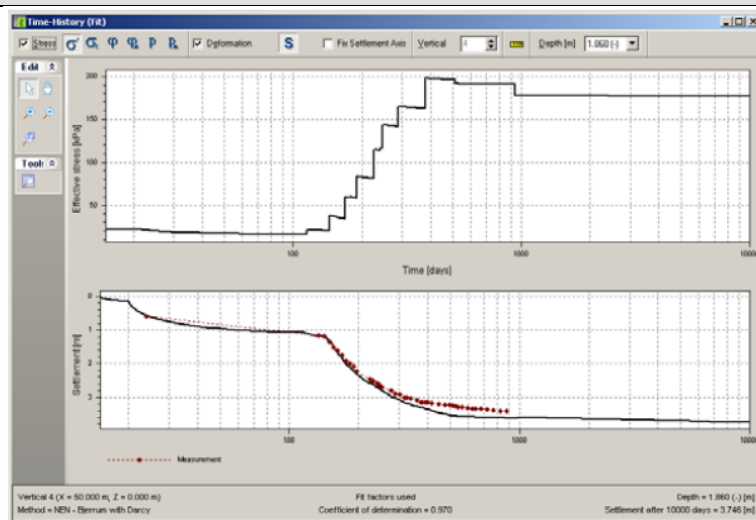


Figure 4.1.1: Prediction versus measurement before fitting

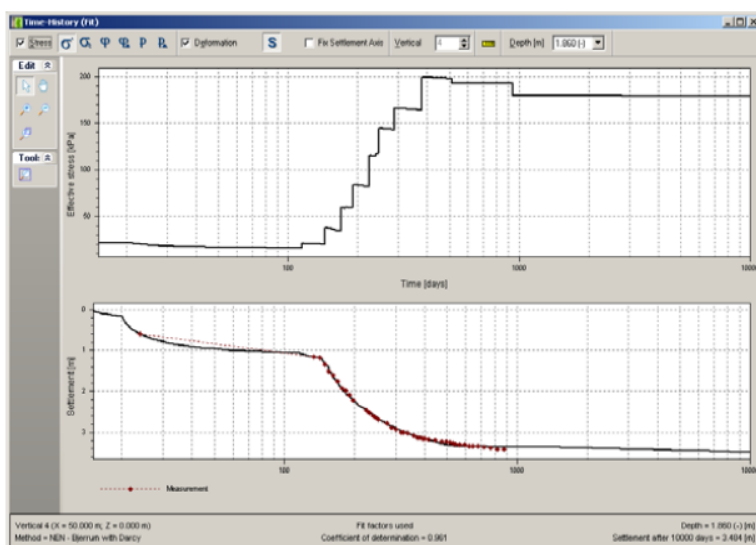


Figure 4.1.2: Prediction versus measurement after fitting

Explanation

Several physical formulas exist to predict the settlement of a soil body (i.e. a levee), accounting for consolidation and creep. These formulae require two, three or more input parameters to describe the constitutive behaviour of the soil. These parameters can be determined by testing a soil sample under laboratory conditions.

In reality, these values do not always prove to be very exact. The subsoil can be very heterogenic and therefore the applicability of the laboratory results may be limited. Reduction of the uncertainty can be achieved by increasing the number of tests, but in many cases it can be much more efficient to use actual field measurements as input data for the model. This example shows how this can be done.

At first, there must be a good initial estimate of the relevant soil parameters (e.g. based upon laboratory tests or on experience). These parameters are used to make a first estimation of the settlement in time. These parameters can be tuned using a “maximum posterior estimate”, which is a special variant of the weighted least squares method. This method updates the values of the laboratory parameters, by minimizing not only the difference between measurements and predictions, but also the difference between the initial value and the updated value of the fit parameters. Separate weights to each of the differences can be attached. Such a weight determines the relative quality of the observation and thereby also of the initial parameters. A large weight implies much confidence in the observation and a small weight implies more trust in the initial laboratory parameters.

Figures 4.1.1 and 4.1.2 show the results of such a fit. The graphs in Figure 4.1.1 show the construction of a soil body in several steps in time (top) and the prediction of the settlement during and after construction based on laboratory results only (bottom). The two graphs in Figure 4.1.2 show the prediction that is updated by field observations – the data points on the lower curve.

The precision of the predicted settlement is much higher than the precision would have been without inclusion of the observation data.

Using such a method, only a few measurements can improve the quality of the prediction significantly. If embankments are monitored for deformations every few years, e.g. by airborne interferometric radar, this process can be automated.

4.2 Index based assessment based on functional analyses.

Example name	Index based method relying on functional analysis of levee components
Location / pilot	Camargue, France
Analysis method	Combination of indexes (status indicators, function criteria, performance indicators) with the help of rules based on formalized expert knowledge
What is combined?	Information from visual inspection, geometrical, geotechnical, morphological information, information from database (encroachments structures, ...)
Failure mode(s)?	The example details the method for internal erosion, but the method also exists for overflowing, external erosion and macro stability, and the generic principles for the method are presented.
Improvements	Combining different types and nature of data (geometrical, geotechnical, hydraulic, morphodynamic, visual observations etc.) with an explicit methodology.

Graphics

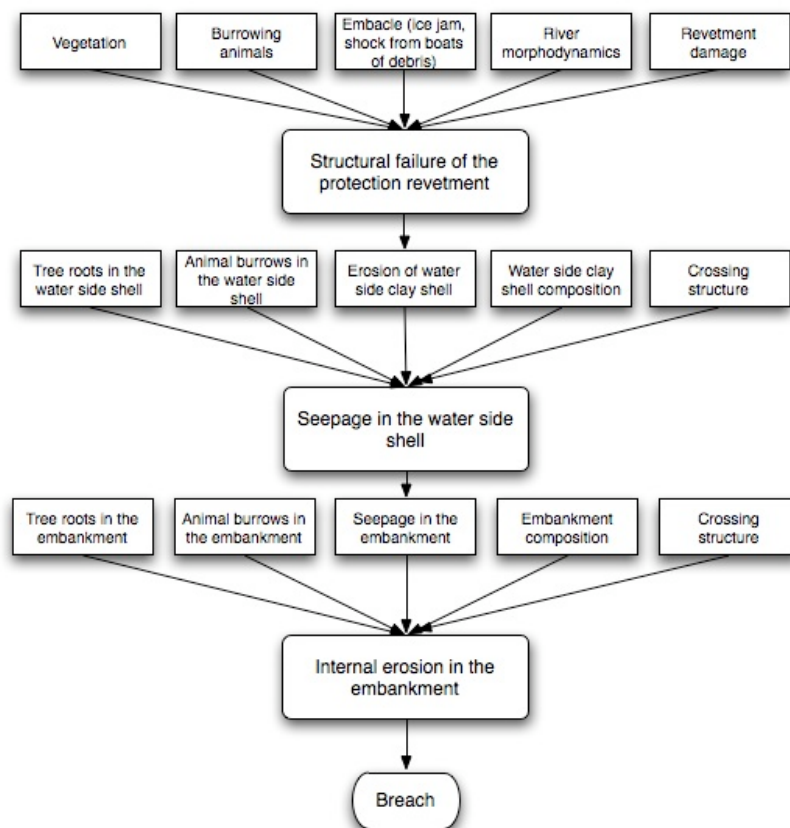


Figure 4.2.1: Example of a fault tree for internal erosion on a levee with a water side impervious shell, including relevant status indicators

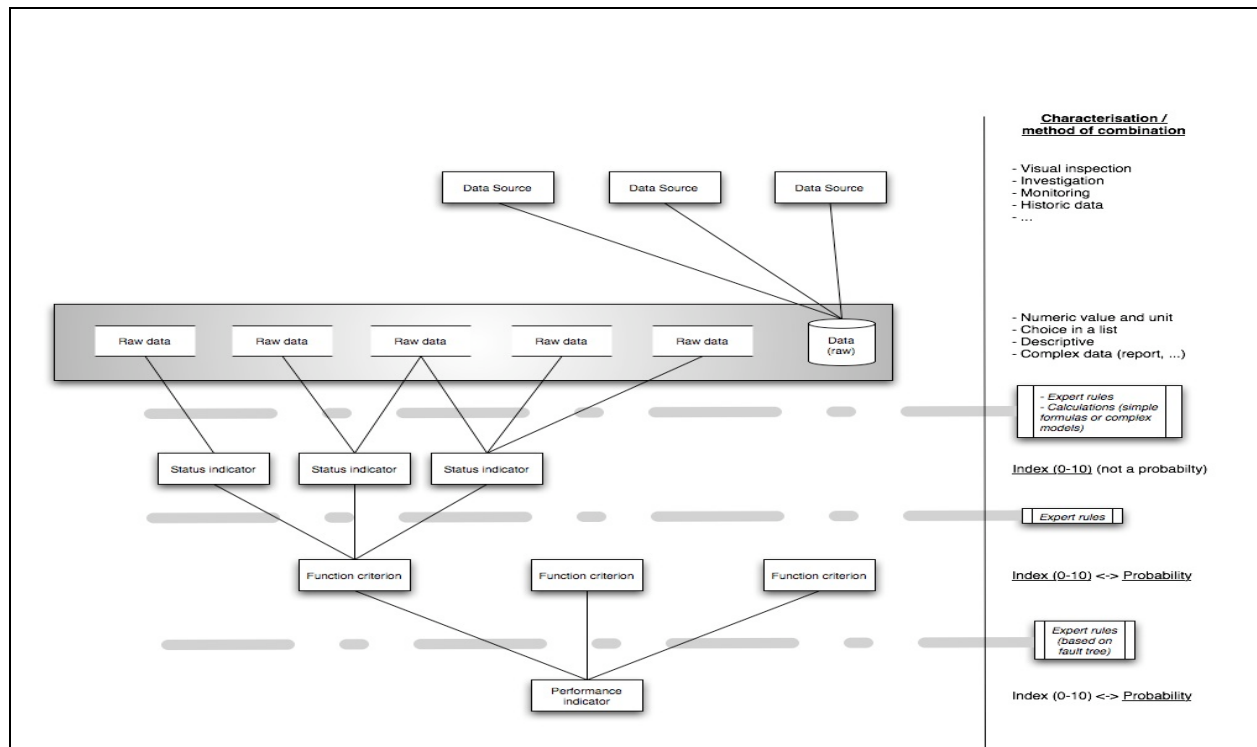


Figure 4.2.2: General assessment process using the index based method



Figure 4.2.3: Assessment process for internal erosion on a levee with a water side impervious shell

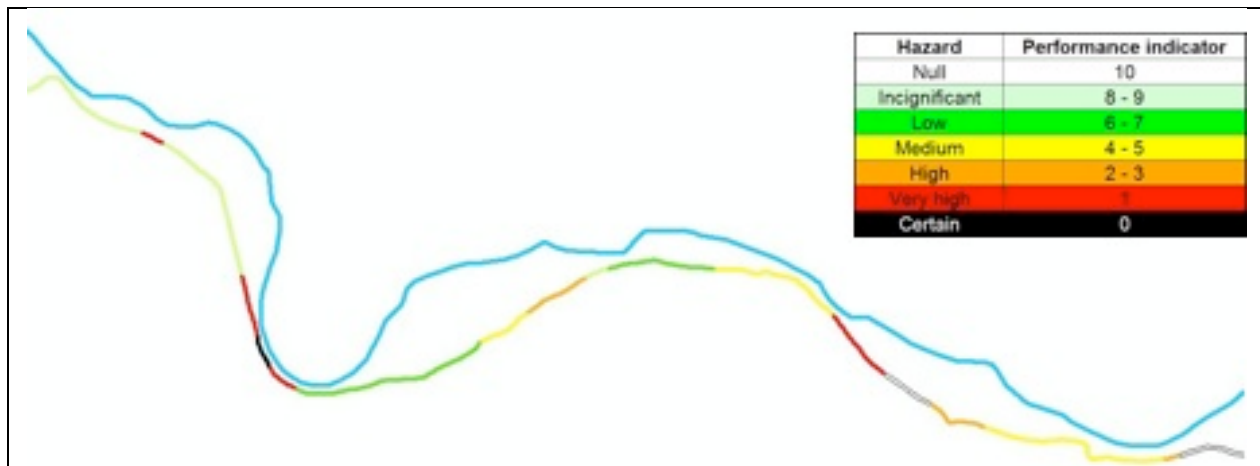


Figure 4.2.4: Example of a map showing global levee assessment results for different levee segments

Explanation

Based on a functional analysis of levee components, in each cross section, failure scenarios are identified and analysed, linking essential functions (like protection, imperviousness, stability, filtration etc.) and components. Figure 4.2.1 presents such a failure scenario.

The data are first used to establish the different status indicators. Values of these indicators result either directly from raw data or from pre-processed data or from combined data. They are relative to one function, and a single component associated with the function. Example: the nature (or state) of the protection revetment of the river side slope.

Function criterion calculation are then performed, based upon the combination of status indicator values. They are relative to one function in relation to the studied failure mode. Example: resistance of the revetment to external erosion.

Finally, as shown in Figures 4.2.2 (general) and 4.2.3 (application to internal erosion), the evaluation of performance indicators is based on a combination of function criterion. They are relative to one failure / breach scenario (or "failure mode") for a given cross section. Example: performance of the levee segment relative to the "internal erosion scenario".

The final assessment takes into account all failure modes.

Expert judgement is used, in a formalized way, to produce the aggregation rules for status indicators to function criteria, and from function criteria to performance indicators.

A GIS is used to manage all available data related to the levee, to make available each data relevant to all status indicators, to pre-process the data to produce the status indicators for those who have established by expert rules, to pre-process the combination of the status indicators and function criteria to produce the function criteria and the performance indicators, to represent the assessed performance both for global performance indicator and individual failure modes performance indicators.

4.3 Improving fragility curve representation

Example name	Improving fragility curve representation using additional data
Location / pilot	Winteringham flood embankment, Humber Estuary, UK
Analysis method	Using additional data and functions
What is combined?	Measurements and field observations combined with a physical model
Failure mode(s)?	Pipe formation through the embankment
Improvements	The fragility curve representation is updated (improved) by taking into account additional factors affecting pipe formation

Illustrations



Figure 4.3.1 Flood embankment at Winteringham, Humber Estuary, UK

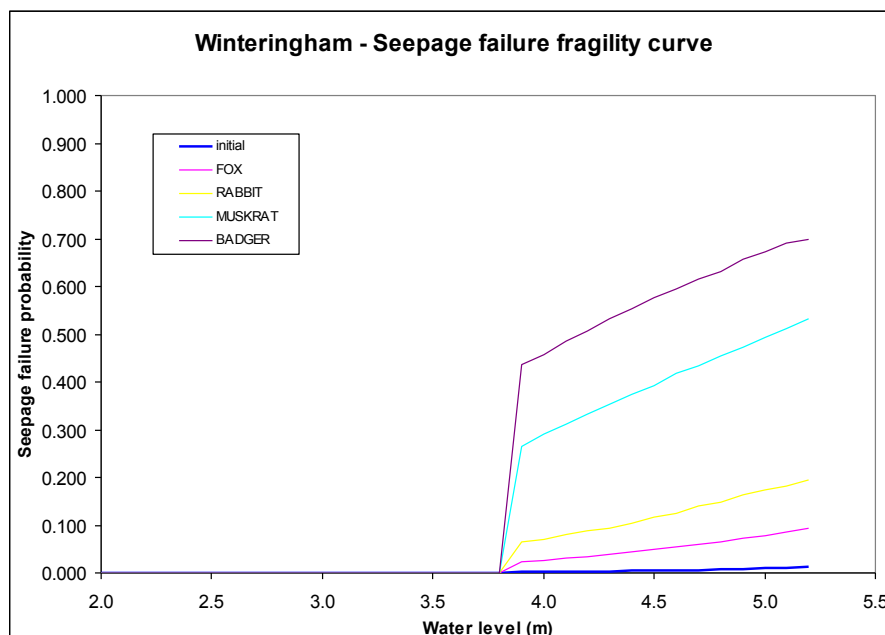


Figure 4.3.2
Example of a modified fragility curves arising from analysis of field observations relating to animal activity

Explanation

This example looks at how the performance of an embankment, in this case represented by a fragility curve, can be improved by including analysis of additional data. The flood embankment at Winteringham (UK) suffers from seepage under high load conditions. The mechanism of failure here might be piping, hence this process was considered in relation to other factors that might increase or reduce the risk of occurrence.

To create the original fragility curve, the embankment was analysed using base soil parameters and geometry and assuming that failure would occur if seepage occurred. This was a simplification of the likely processes in order to demonstrate the concept of using additional information to improve the performance analysis. Failure mode Ba1.5b (seepage through a sand core) was adopted from the FLOODsite failure modes report (Allsop et al, 2007).

Nine parameters are required to analyse this failure mode and assess embankment performance. A range of factors that could affect seepage and concentrated leakage erosion, such as insufficient drainage, animal burrows, cracking, external erosion etc. can be identified and parameters such as geometry, geotechnical inputs and loadings that affect the analysis 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, analysis of geophysics data can clarify the internal composition of the embankment, refining the value used for permeability and hence changing the analysis for seepage. Similar consideration was given to additional data arising from visual inspections (animal activity; grass quality), remote sensing, historic problems, historic river plan form, weather (rainfall) and surface geology.

By identifying or developing a relationship between the observed factor and the data parameter(s) used in the performance analysis, the additional data may be used to refine the performance assessment. For example, where animal activity was 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 the change in embankment performance. This example is shown in Figure 4.3.2. A similar approach was undertaken for the other factors and then the combined effect on overall performance may be assessed.

Hence this example shows how additional data, much of which is either already collected during embankment inspections, of which may be collected from existing records or databases, may be used to improve performance assessments. The example shows use of data in relation to one mechanism which would form part of a fault tree showing the combination of mechanisms required to result in failure. To maximise value from the 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.

More detail and examples of this approach can be seen in FloodProBE Report WP03-01-12-02: D3.1 Guidance on improved performance of urban flood defences . (See www.floodprobe.eu).

4.4 Bayesian Belief Network (BBN): Backwards erosion

Example name	BBN backwards erosion
Location / pilot	The Netherlands
Analysis method	Bayesian belief network
What is combined?	Observations and experiences
Failure mode(s)?	Backward internal erosion
Improvements	Explicitly includes expert judgment and observation in assessment

Graphics

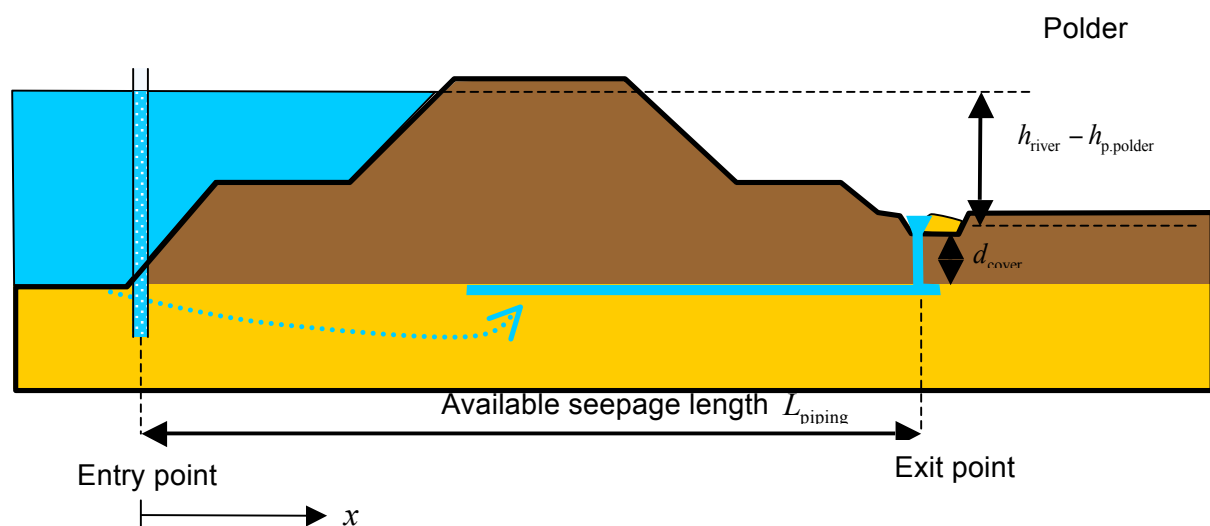


Figure 4.3.3: Process of backwards erosion

Explanation

The probability of failure of the levee by backward erosion can be calculated with a model describing the hydraulic head required for bursting of the impermeable layer on top of the aquifer in which backward erosion occurs. This probability is calculated with the mathematical model of Sellmeijer, which describes the hydraulic head required for development of a complete pipe below the levee. (Sellmeijer, 1989). The uncertainty of the calculated critical hydraulic head is caused by uncertainty in the model (e.g. time effects that are not accounted for) and in the parameters used (permeability, grain properties, length and thickness of the aquifer).

This example shows how the reliability can be significantly improved by adding local- and expert knowledge, which are not input parameters of the above mentioned mathematical

models, by means of a Bayesian Belief Network (BBN). A BBN uses probability theory to create flow charts with nodes and arrows representing parent and child nodes. The link between parent and child nodes is calculated by the rule of Bayes (Cheng et al, 1997). This flow chart (structure and nodes) is built by an expert or by a panel of experts.

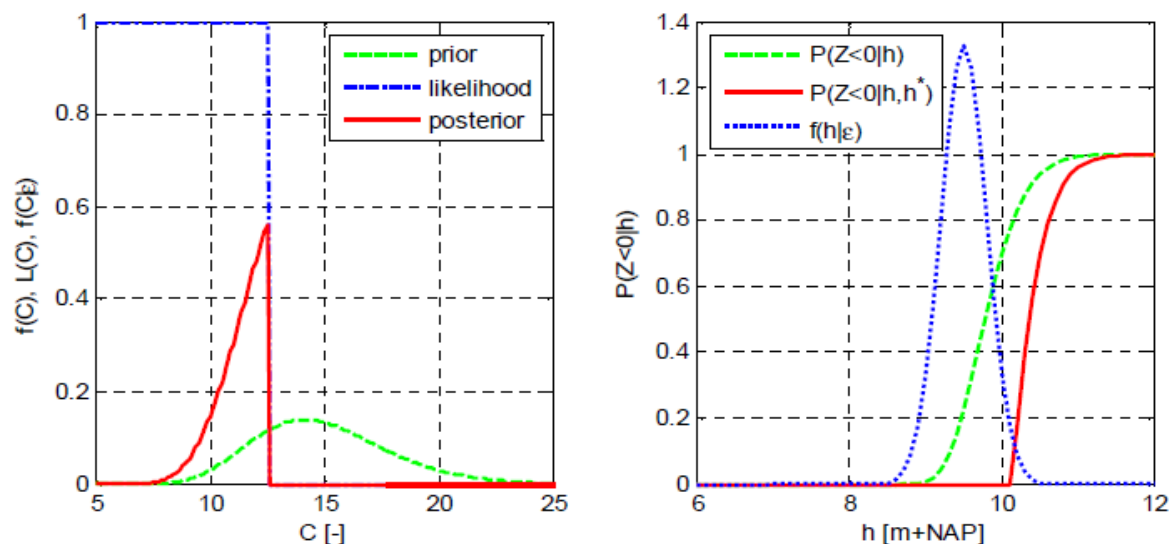
BBN nodes include both soft and hard data. Examples of soft data are events such as the observation of leakage or sand boil (now or in the past), frequency of inspection, or the (expected) increase or decrease of the water level. An example of hard data is the probability of failure by backward erosion for the actual water level according to the mathematical model.

For a large number of combinations of the pre-defined events (nodes) probability tables are filled based upon the knowledge and experience of the experts. An indication of the quality of the expert opinion can be obtained by comparing the results of different groups of experts or by comparing the results of experts with those of non-experts. Based upon these tables the BBN will produce an updated probability of failure of the levee by backward erosion.

4.5 Updating backward erosion fragility curves using survived loads

Example name	Updating fragility curves for backward erosion by using survived loads
Location / pilot	Waterboard of "Groot Salland", The Netherlands
Analysis method	Bayesian updating
What is combined?	Observations with a physical model
Failure mode(s)?	Backwards erosion
Improvements	Incorporate knowledge of historic survived loads.

Graphics



(a) Prior and posterior distribution of C (b) Prior and posterior fragility curves
Figure 4.3.4 Prior and posterior distribution (a) and failure (b). (Schweckendiek, 2010)

Explanation

The reliability of a flood defence can be described as a probability density function, in which both strength and hydraulic load are uncertain. Such a function describes the probability of failure given a certain hydraulic load (in most cases water level). This example shows that knowledge that the water defence survived water levels without failure can be used to update the probability density curve, resulting in a reduction in the calculated probability of failure (Schweckendiek, 2010).

In this example the probability on backward erosion is calculated with the well known equation of Bligh (Bligh, 1910). It is assumed that the critical hydraulic gradient according to Bligh (the reciprocal of which is called creep factor C) is the only uncertain variable. The survival of the flood embankment at a water level h^* proves that the value of C must be smaller than C^* , which in this case is determined to be 12.5. A part of the probability mass of C can be redistributed, in this case the part greater than $C^* = 12.5$. The impact of updating on the fragility curve is shown in the Figure 4.3.4. Figure 4.3.4-a the prior and (updated)

posterior distribution of C are given. Figure 4.3.4-b shows the resulting prior and posterior fragility curves (green and red line respectively). The probability of failure shifts to a higher water level. The analysis can be extended for more uncertain variables, such as model uncertainty.

4.6 Incorporating geological knowledge in risk analysis

Example name	Incorporating geological knowledge in risk analysis
Location / pilot	Waterboard "Hollands Noorderkwartier", The Netherlands
Analysis method	Risk analysis
What is combined?	Geological knowledge with deterministic safety analysis
Failure mode(s)?	Macro stability and piping
Improvements	Heterogeneity of the subsoil is taken into account through the knowledge of a geological specialist.

Graphics

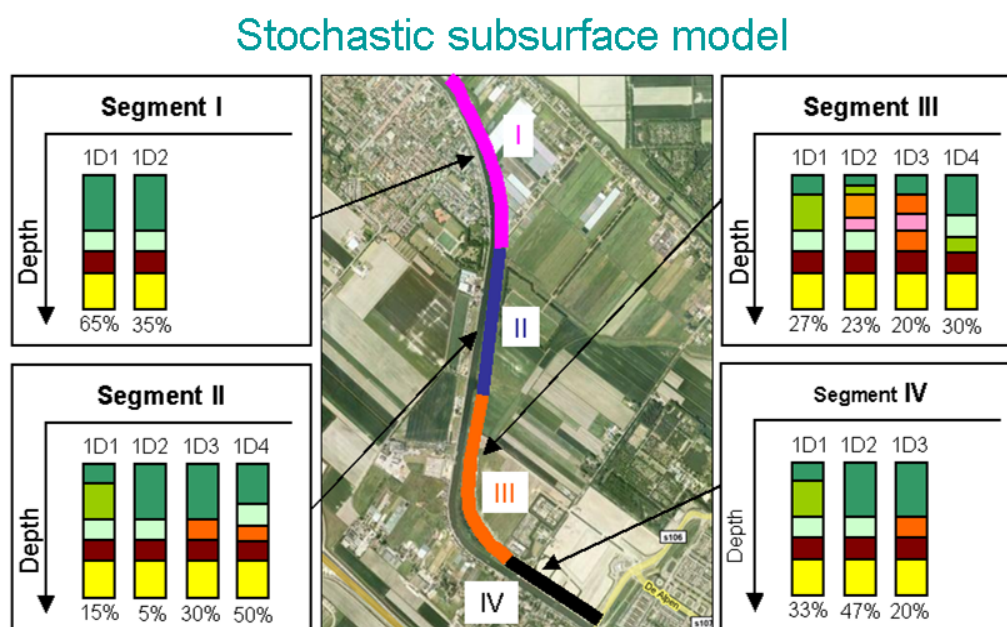


Figure 4.3.5 Stochastic subsurface information

Explanation

In both data rich and data sparse areas, the uncertainty of the subsoil usually contributes significantly to the uncertainty of the assessment result, due to local variations. Traditionally the subsurface model (i.e. the configuration of soil layers) is based on CPT's, borings or geophysical investigations in an individual point location. The soil layering between the point observations is often based on interpolation or another selection criterion such as worst average. However, by interpolation well known properties of the subsurface such as discontinuities are not accounted for properly. This leads to high uncertainties. This example shows how uncertainties can be accounted for in a quantitative way applying a so-called stochastic subsurface model.

The subsoil can be subdivided into a number of fundamentally different geological sections based on CPT's or borings in point locations and knowledge of regional geology. Within one geological section, different scenarios, or realizations, of vertical stacks of subsoil layers are defined. Depending upon the estimated length of these geological sections along a levee, for each possible soil profile a probability of occurrence is estimated. This yields for each levee section a number of scenarios with a probability of occurrence, as shown in Figure 4.3.5. The scenarios in each section represent the relevant characteristics of the subsurface, e.g. for slip failure or backward erosion.

In a traditional analysis, one section contains one representative soil layer which results in one probability of failure. When using a stochastic subsoil model, for each subsurface scenario the probability of failure is calculated. The total probability of failure is derived by combining the probabilities per scenario. Based on the stochastic subsurface model additional investigations (e.g. CPT's) can be performed from which probabilities of scenarios can be adjusted and the accuracy of the assessment increases. A stochastic subsoil model data-sparse area's will have much uncertainty and therefore result in larger probabilities of failure. As more information is gathered, the precision increases. Especially in the beginning of a project, this approach enables incorporation of "soft" information such as knowledge of the regional geology.

4.7 Assessment of a levee at Orléans

Example name	Assessment of a levee at Orléans, conducted in the frame of the regulatory hazard study in 2011-2012
Location / pilot	Orléans, France
Analysis method	Application of mathematical models on fixed lengths of levee, based on physical or empirical laws (according to the different failure modes), and adjusted according to other data
What is combined?	Geometric data, geotechnical data, hydraulic loads, results from visual inspection (examples: animal burrows, trees) and other databases (example: pipe encroachments) as well as organization (levee monitoring during floods).
Failure mode(s)?	Overflowing, internal erosion, slope sliding followed by another mechanism, external erosion followed by another mechanism, hydraulic uplift followed by regressive internal erosion.
Improvements	Evaluation of the failure probability for different hydraulic loads, taking into account levee properties, condition, for scenarios composed of one or more mechanisms, including a distinction between probability of appearance and probability of evolving into a breach. Use of both mathematical (physical and empirical based) models and expert judgment based formalized rules.

Graphics

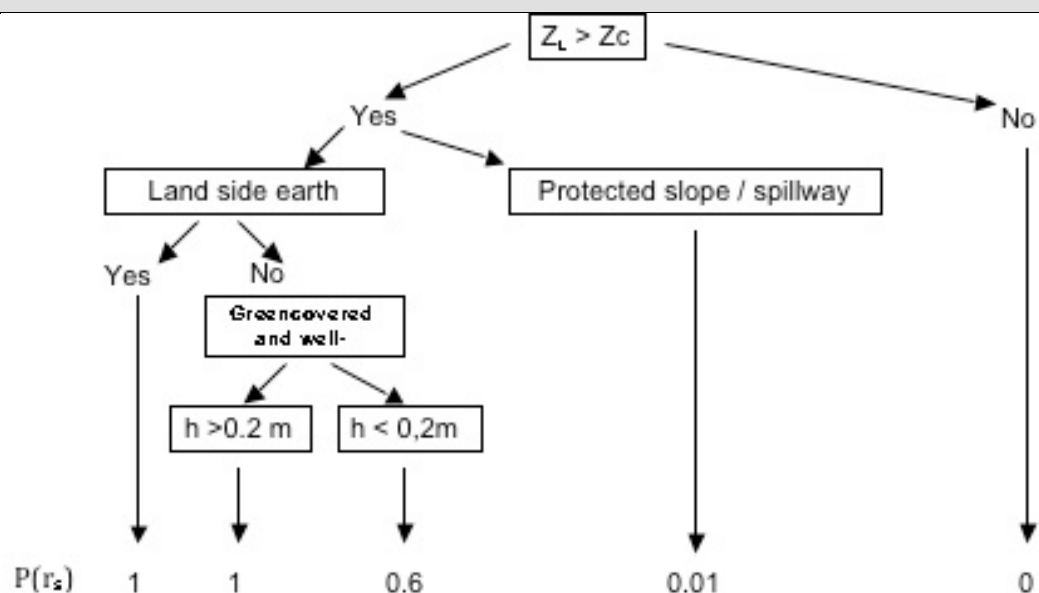


Figure 4.7.1: Probability assessment for overflowing causing breach

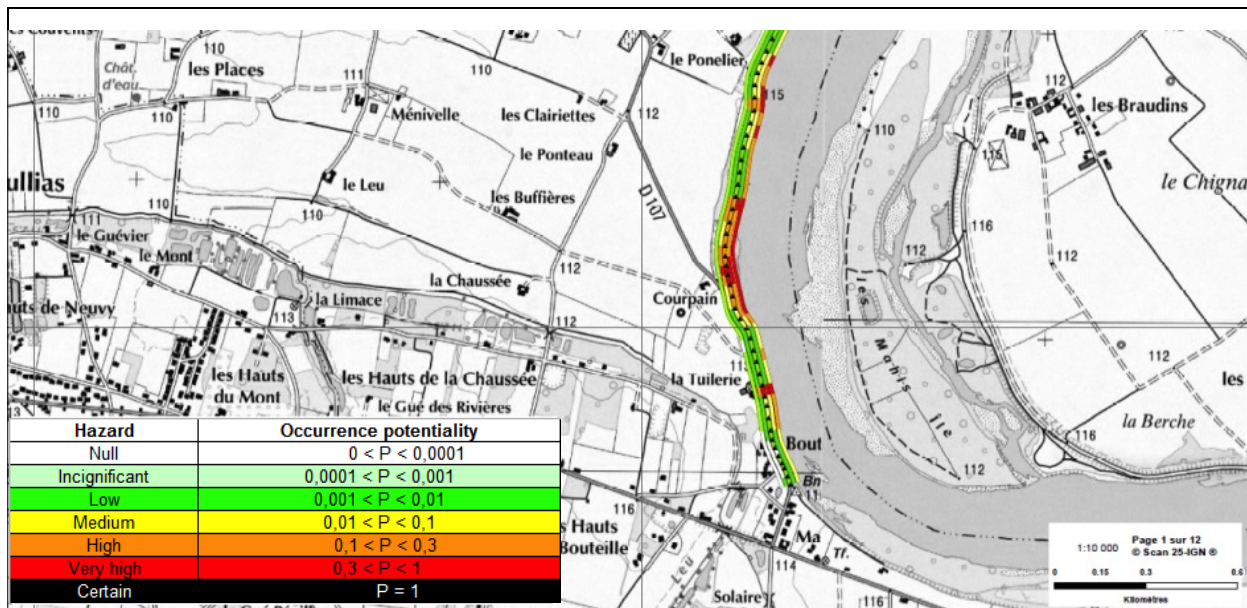


Figure 4.7.2: Global assessment results

Explanation

Five main failure modes have been identified for analysis within this assessment. These failure modes are either composed from one single mechanism (overflowing, internal erosion) or from two or three mechanisms (slope sliding followed by internal erosion, external erosion followed by internal erosion or by collapsing and then internal erosion, uplift followed by regressive internal erosion etc.).

Each of these failure modes (or breaching scenarios) has been evaluated on fixed lengths (50m) of the levee, for different floods (Q50, Q100, Q170, Q200, Q500). First the probability $P(A)$ (that the first mechanism will occur) has been determined and then the probability $P(r)$ that this event will cause the levee to breach, involving either the continuation of the first mechanism up to the breach or the involvement of other mechanism(s), for each probability flood grade $P(QT)$ of interest has been determined. The result calculates the breach probability with a specific failure mode: $P(R) = P(A). P(r). P(QT)$

Different models have been applied for each of these terms on each of the sections for each flood. These models are different for each mechanism and failure mode, taking into account either physical models (slope sliding, ...) or empirical models (Sellmeijer internal erosion for initiation of this mechanism, ...), as well as formalized expert rules (resistance to overflowing erosion see Figure 4.7.1, taking into account monitoring for countering internal erosion, etc).

Data comes from the levee manager GIS data management system (SIRS Dignes), a specific visual inspection, a search through historic information (reports) related to geotechnics and a DEM (created by a LiDAR Survey, see FloodProBE Task 3.2).

The model was developed in a spread sheet. A table for equivalence between probabilities and their qualification in terms of common language (i.e. Possible yet extremely unlikely event, Very unlikely event, Unlikely event, Likely event, Usual Event) has been developed,

helping to either produce probabilities starting from expert judgement based rules, or to express in words the probabilistic results.

Once the breach probability has been assessed for each failure mode and flood grade, these results will be used as such by the work manager or in combination for producing the following probabilities: global probabilities for each flood grade (all failure modes); global probabilities for each failure mode (all flood grades); global probabilities (for all failure modes and all flood grades). Suitable probability-based methods for producing such combinations are still to be determined.

Whatever the expected type of results, these can be graphically expressed, using a GIS, on a map displaying the levee breach hazard along the considered length of the levee (Figure 4.7.2). They can also be stored as such in a GIS data management system.

5 The role of GIS

5.1 Theory

In most circumstances of current practice systems are not equipped to incorporate a sufficiently wide range of input data. Even though there is not much experience in using the techniques described in previous chapters to combine all relevant data, it is not the science that prevents managers and engineers from improving the assessment; data is not yet structurally gathered for use in levee assessment. Consequently, simple changes in daily practice can initiate a different – improved – approach for assessment. Improving assessment through better data combination using Geographical Information Systems (GIS), eventually combined with specific assessment tools, can be achieved through the following steps (Figure 5.1.).

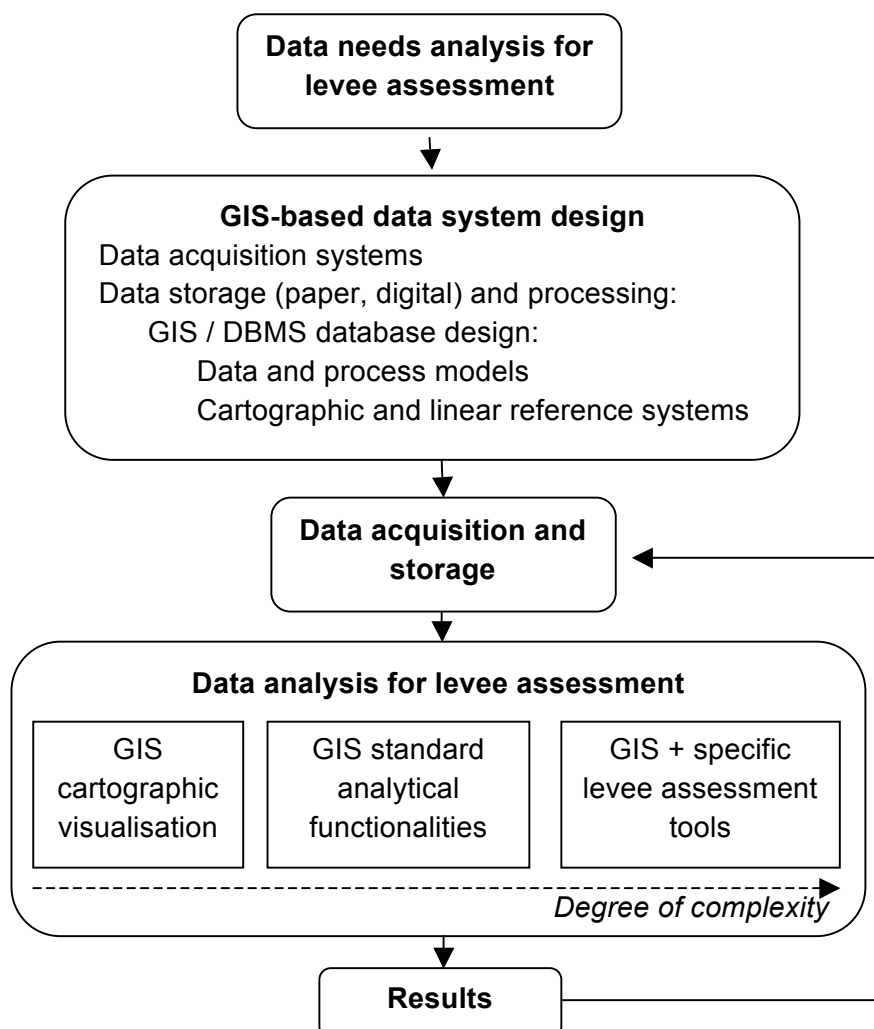


Figure 5.1: Steps for designing and implementing GIS-based levee data systems

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

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 organized 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).

Implementing such a system requires a preliminary analysis and design phase i) to understand the current organization, ii) to determine the levee manager needs in term of information system for levee assessment, iii) to build up one or several conceptual data models in order to store the digital data in a structured way and iv) to determine the most appropriate spatial reference systems (both cartographic and linear) for geocoding all of the data.

Examples of existing GIS & DBMS's are the NFCDD in the UK (Environment Agency), the IRIS in the Netherlands, and the SIRS digues in France.

GIS database modelling

GIS database modeling has to take into account both the graphical and attribute dimensions of the levee items. Several choices of (geo)graphical modelling of the levee can be made, ranging from a simple schematic representation in the form of a straight line to the full 3D representation through several levels of representation in 2D (see Figure 5.2.). The choice of a solution is a compromise between the complexity and cost of implementation and use, the levels of accuracy obtained and the visual quality of displays.

One of the challenges is to design a conceptual data model which can combine both the representation of linear items (e.g. type of surface material of the landside part of the levee) and specific point items (e.g. trees, animals burrows).

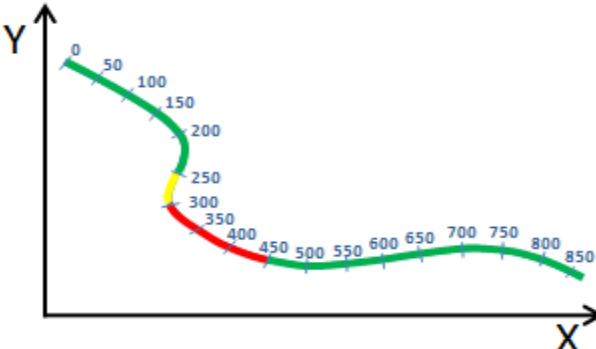
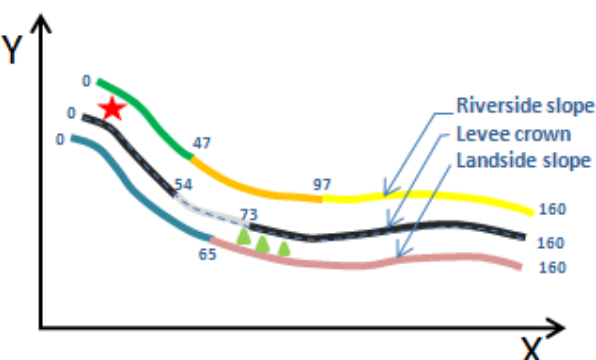
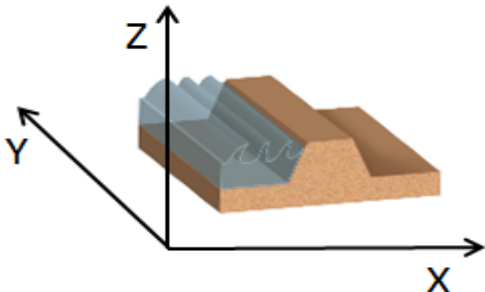
Dimension & spatial referential(s)	Examples of (carto)graphic display	Advantages / drawbacks
. 1D . Linear		+ Easy to implement - Very poor representation of the levee system
. 2D (pseudo-2D for the levee) . Cartographic . Linear: axis of the levee divided into segments of equal length		+ Rather easy to implement - Non optimized data management (data replication) - Accuracy dependent to the segment length - Punctual items poorly represented
. True 2D . Cartographic: true 2D representation of all levee items (punctual, linear and surfacic)		+ Highly accurate 2D representation of the levee system in its surroundings - Very complex and costly implementation (data capture, data updating, data processing)
. 2D (dynamic pseudo-2D for the levee) . Cartographic . Linear + dynamic segmentation + graphic display of items on either sides of the main axis according to their actual transversal location		+ Accurate pseudo-2D representation of the levee system in its surroundings + Excellent compromise between the cost of implementation and the accuracy of representations and results
. True 3D . Cartographic: true 3D representation of all levee items (punctual, linear and surface)		+ Highly accurate 3D representation of the levee system in its surroundings - Extremely complex and costly implementation (still at the research level)

Figure 5.2.: Alternatives for (geo)graphical representation of a GIS-based levee data system

Dynamic segmentation

Dynamic segmentation, available on some GIS, is a tool to maintain and manipulate data in an efficient way which is related to linear features such as levees or other types of linear infrastructure. Along a levee, start and end points of different attributes rarely coincide. The materials used to cover the top of the levee provide a good example as they do not exactly coincide with events such as nature, condition and operation. Using a standard GIS data model, linear feature representing this component of the levee would have to be broken into many segments into the GIS to accurately represent these events and then continuously be segmented as changes occur with the surface of the levee. The GIS user is therefore likely to run rapidly into storage and processing problems.

Dynamic segmentation is the process of transforming linearly referenced data (also known as events) that is stored in an event table into graphical features (punctual or linear) that are displayed, combined and analyzed on a map (see Figure 5.3.). When implementing dynamic segmentation, a route is first created to model the linear feature. Routes are associated with a linear reference system, which describe distances along the route. Attributes, or events, are related from their respective table directly to any position along the route as often as the user would like without ever affecting the original linear feature.



Event ID	Levee ID	From_M	To_M	Rating
1	L5	0	3	fair
2	L5	3	7,5	good
3	L5	7,5	10	poor

Figure 5.3 : Dynamic segmentation of a linear structure

Dynamic segmentation uses the tables in PK and can split a single line feature (e.g. a polyline representing the whole levee) into separate sections of varying length depending upon the values taken by an attribute or several attributes stored in the data base. For example, a levee can be divided into segments structurally homogeneous in terms of height, or nature of the protective coating on the river-side slope. This technique also allows to position point features on the line; features such as terriers or pipes crossing the levee. Finally, it allows the manager to choose the level of aggregation of information entered. It can have a very detailed and informative content on a part of the levee of particular interest and much less detail on another part. Another advantage of dynamic segmentation is that the encoding and topological graph of the linear feature can remain the same when an update is performed. New events can be represented without modifying the

linear feature at all and breaking it into pieces as in a classical GIS. The graphical part of the levee is described once and for all, only changing the attribute tables that store, for each attribute observed, the values taken by this attribute and the start and end for each observed value. Also, cumulated linear distance of a given attribute, such as the levee in good condition, can then be calculated directly from the routes and associated attributes.

Dynamic segmentation and data combination

Dynamic segmentation is an efficient way to combine several attributes stored in the levee GIS database, taking into account their position. It can help during the assessment by bringing together multiple attributes stored in different tables of the database, to display them in a unified cartographic display, to perform multi-criteria spatial queries (e.g. selection of all the levee segments that are both under a certain height and with burrows) and to generate statistics and maps from this multi-criteria approach.

From an assessment perspective, dynamic segmentation can also be used not only to combine raw data but various criteria, such as for instance performance indicators derived from a functional analysis of levee components (see example 5.2.1).

5.1.2 Levee assessment through visual cartographic GIS functionalities

From the simple and familiar interactive map, a GIS system can give easy and quick access to a vast array of data, bringing together data through cartographic visualization which would otherwise be stored in a range of different formats and locations and be very difficult to compare and combine in assessment models. Such accessibility to key and supplementary data can enable the levee owner / operator to gain a deeper understanding of the levee systems helping to put context to the data and facilitating the discovery of trends and relationships that may be otherwise difficult to recognize.

A GIS system can also help the levee owner / operator to communicate more visual information to local authorities and the general public.

5.1.3 Levee assessment through standard analytical GIS functionalities

In addition to improved accessibility to data and visual analysis from a wide variety of themes and sources, the GIS analytical and reporting functionalities can help with the operations of the levee manager.

Automated data reports can be made which can help the levee manager to identify gaps in knowledge that can either be used to direct data gathering programs or further research (e.g. failure mode analysis), such as identifying levees which are deteriorating faster than anticipated. All this additional information can be used with the previously mentioned techniques to improve the assessment.

Automated screening processes or multi-criteria queries can be run for instance to identify levees that might fail and to find particular reliability parameters which may contain a particular construction method which has been found to be problematic. Additionally, the GIS can be used to run spatial analyses to find levees which protect more than a given number of homes or compare neighbouring river levels against the levee crest levels.

5.1.4 Levee assessment combining GIS and specific levee assessment tool(s)

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 a 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.

Finally, the assessment results can be returned to the GIS to give the levee managers an overall view of the levee assessment. GIS cartographic and reporting functionalities can help to synthesize the information. It is crucial to have all this information at hand during, for example, a high water event, but it also aids in policy analysis.

5.2 Application

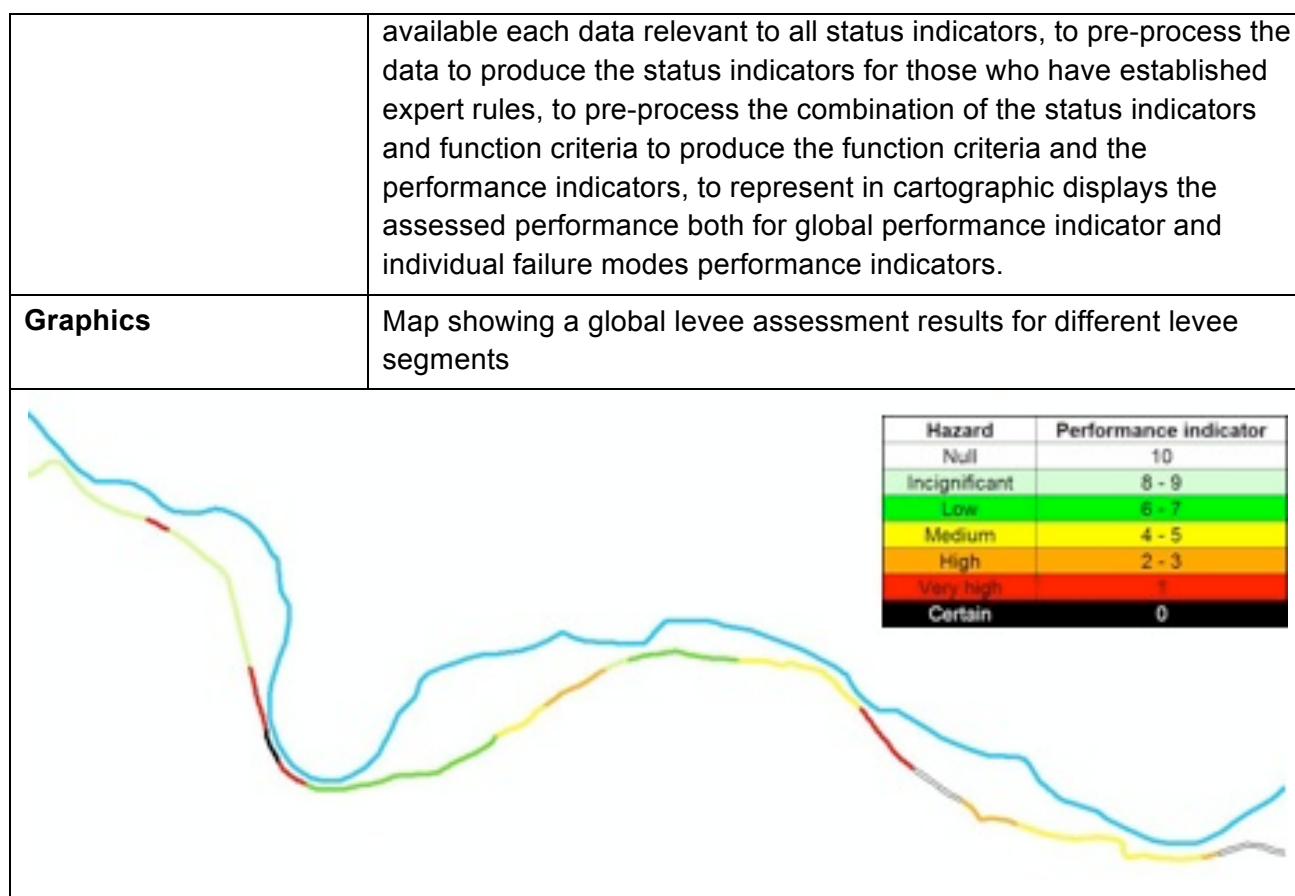
The following examples can be used to improve levee assessment through better data combination or specific GIS functionalities or connection to a specific assessment tool.

5.2.1 Example 1: Functional analysis of levee components

This example has already been presented in Section 4 (see 4.1.2) in terms of an assessment model. It is described here from a GIS perspective.

Example name	Index based method relying on functional analysis of levee components
Location / pilot	Camargue (Rhône river), France
Failure mode(s)	This example details the method for internal erosion, but the method also exists for overflowing, external erosion and slope sliding.
Analysis method	Performance indicators with a rule-based multi-criteria assignment method. GIS dynamic segmentation used to determine homogeneous levee segments in term of performance level
GIS software / application	SIRS digues: ArcGIS & Access DBMS based application
Assessment tool	Specific tool developed in Visual Basic
Level of readiness	SIRS digues: fully operational software used in real conditions Specific assessment tool: prototype demonstration tool
Level of integration	The SIRS digue and its additional module are fully integrated: same database and same GUI accessible from the SIRS digue
Reference system(s) used for geocoding data	Camargue levee linear reference system + standard national cartographic system (Lambert III)

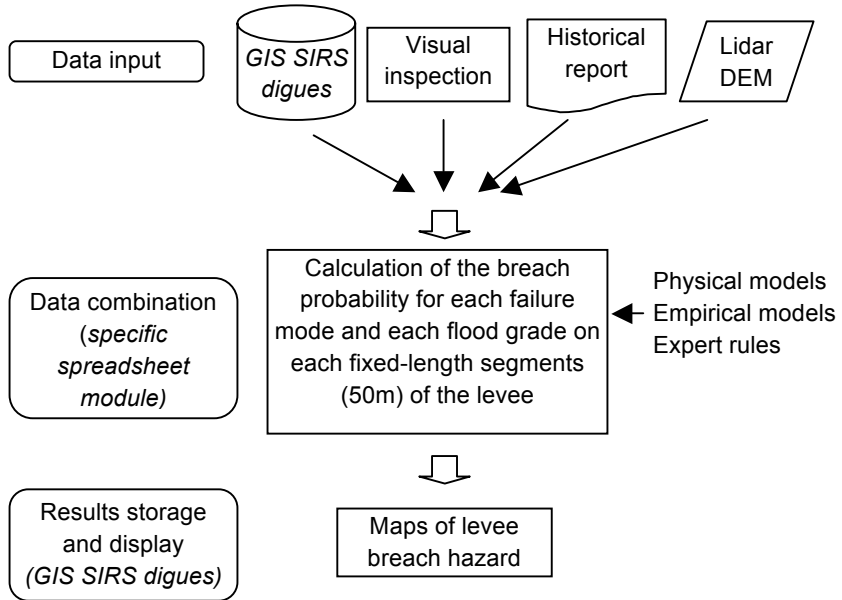
Data used for the assessment	All the data have been entered in the SIRS-digue database and geo-referenced both in the linear and the cartographic systems <table><tr><th>Source</th><th>Type</th><th>Nature</th><th>Representation</th></tr><tr><td>Visual observations</td><td>Condition inspections</td><td>Disorders (e.g. animal burrows) Vegetation (e.g. trees)</td><td>1D, 2D</td></tr><tr><td>Plans</td><td>Levee cross sections</td><td>Topographic</td><td>2D</td></tr><tr><td>Geotechnical survey</td><td>Measurements</td><td>Morpho-dynamic</td><td>2D</td></tr><tr><td>Geotechnical survey</td><td>Measurements</td><td>Geotechnic</td><td>2D</td></tr><tr><td>Survey report</td><td>Structural surveys</td><td>Structural (e.g. encroachments structures)</td><td>2D</td></tr></table>	Source	Type	Nature	Representation	Visual observations	Condition inspections	Disorders (e.g. animal burrows) Vegetation (e.g. trees)	1D, 2D	Plans	Levee cross sections	Topographic	2D	Geotechnical survey	Measurements	Morpho-dynamic	2D	Geotechnical survey	Measurements	Geotechnic	2D	Survey report	Structural surveys	Structural (e.g. encroachments structures)	2D
Source	Type	Nature	Representation																						
Visual observations	Condition inspections	Disorders (e.g. animal burrows) Vegetation (e.g. trees)	1D, 2D																						
Plans	Levee cross sections	Topographic	2D																						
Geotechnical survey	Measurements	Morpho-dynamic	2D																						
Geotechnical survey	Measurements	Geotechnic	2D																						
Survey report	Structural surveys	Structural (e.g. encroachments structures)	2D																						
Data combination	<pre>graph TD A[Data input (GIS SIRS digues)] --> C B[(Visual inspections Structural, geometrical, morphological & geotechnical data)] --> C subgraph C [] direction TB C1[Status indicators] --> C2[Function criteria] C2 --> C3[Performance indicators (for each failure mode at each cross section)] end D[Rules based of formalized expert judgment] --> C3 C3 --> E[Results storage & display (GIS SIRS digues)] C3 --> F[Dynamic segmentation] G[Levee linear reference system] --> F F --> H[Maps of performance indicators for levee segments of variable length]</pre>																								
Description	The SIRS digues GIS application and its additional calculation module is used to manage all available data related to the levee, to make																								



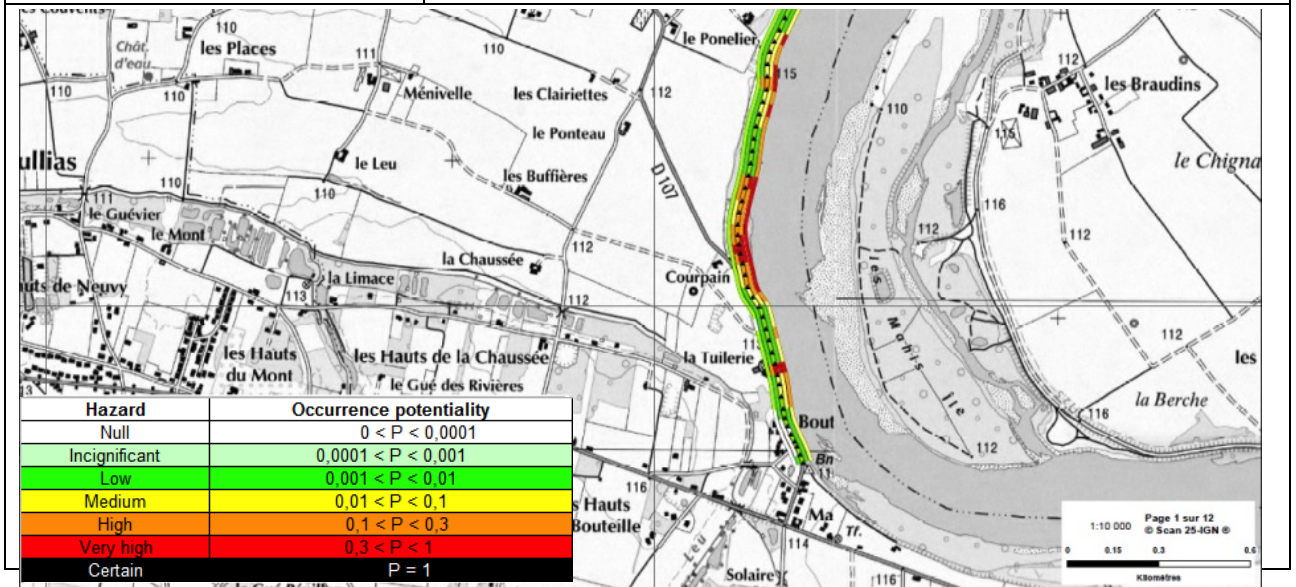
5.2.2 Example 2: Determining failure probabilities at the Orléans levee

This example has already been presented in Section 4 (see 4.1.7) in terms of an assessment model. This FloodProBE test site is described here from a GIS perspective.

Example name	Assessment of an Orléans levee based on failure probabilities, conducted in the frame of the regulatory hazard study in 2011-2012
Location / pilot	Orléans (Loire river), France
Failure mode(s)	Overflowing, internal erosion, slope sliding followed by another mechanism, external erosion followed by another mechanism, hydraulic uplift followed by regressive internal erosion.
Analysis method	Application of mathematical models on fixed lengths of levee, based on physical or empirical laws (according to the different failure mode), and adjusted according to other data
GIS software / application	SIRS digues: ArcGIS & Access DBMS based application
Assessment tool	Specific tool developed in a spreadsheet
Level of readiness	SIRS digues: fully operational software used in real conditions Specific assessment tool: prototype demonstration tool

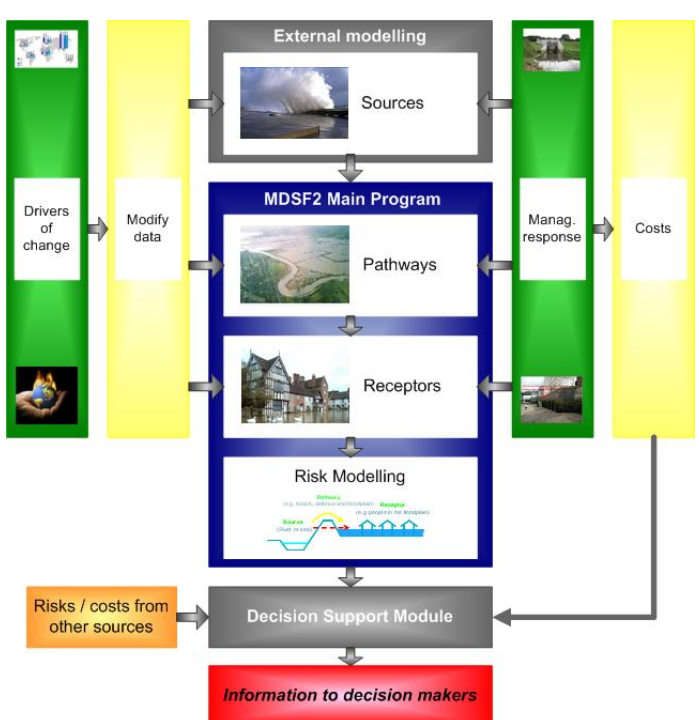
Level of integration	Low integration: separate database and GUI, simple data exchange between the SIRS digue and the assessment tool			
Reference system(s) used for geocoding data	Loire levee linear reference system + standard national cartographic system (Lambert III)			
Data used for the assessment	All the data stored in the SIRS-digue database are geo-referenced both in the linear and the cartographic systems			
	Source	Type	Nature	Representation
	Visual observations	Condition inspections	Disorders (e.g. animal burrows) Vegetation (e.g. trees) Monitoring during floods (e.g. seepage)	1D, 2D
	Hydraulic modelling	Measurements	Hydraulic (e.g. hydraulic loads)	2D
	Geotechnical survey	Measurements	Geotechnic	2D
	Historical report	Structural surveys	Structural (e.g. encroachments structures)	2D
	Remote sensing	Lidar survey	Geometric	3D
Data combination	 <pre> graph TD subgraph Data_Input [Data input] GIS_SIRS_digues[(GIS SIRS digues)] Visual_inspection[Visual inspection] Historical_report[Historical report] Lidar_DEM[/Lidar DEM/] end subgraph Data_combination [Data combination (specific spreadsheet module)] Calculation[Calculation of the breach probability for each failure mode and each flood grade on each fixed-length segments (50m) of the levee] end subgraph Results [Results storage and display (GIS SIRS digues)] Maps[Maps of levee breach hazard] end GIS_SIRS_digues --> Calculation Visual_inspection --> Calculation Historical_report --> Calculation Lidar_DEM --> Calculation Calculation --> Maps Physical_models[Physical models] --> Calculation Empirical_models[Empirical models] --> Calculation Expert_rules[Expert rules] --> Calculation </pre>			
Description	The GIS SIRS digue is first used as one of the data sources to support the spreadsheet assessment tool which allows calculation of the breach probabilities. Then, the SIRS digue is used to store the assessment results and to display them in a			

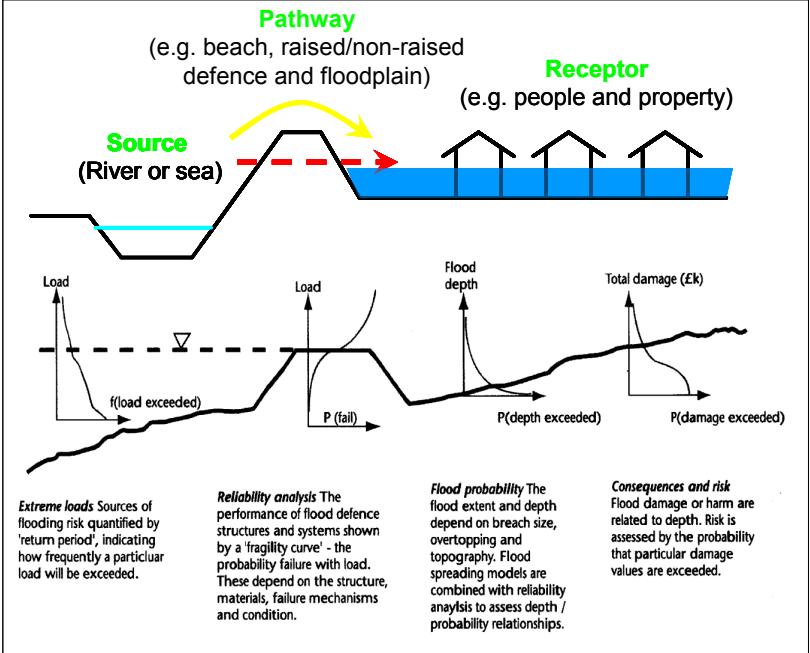
	cartographic way based on its linear reference system and a table of equivalence to represent probabilities in visual language (levels of probability expressed in words and associated with colour codes).
Graphics	Map of global breach probabilities (for all failure modes and all flood grades)

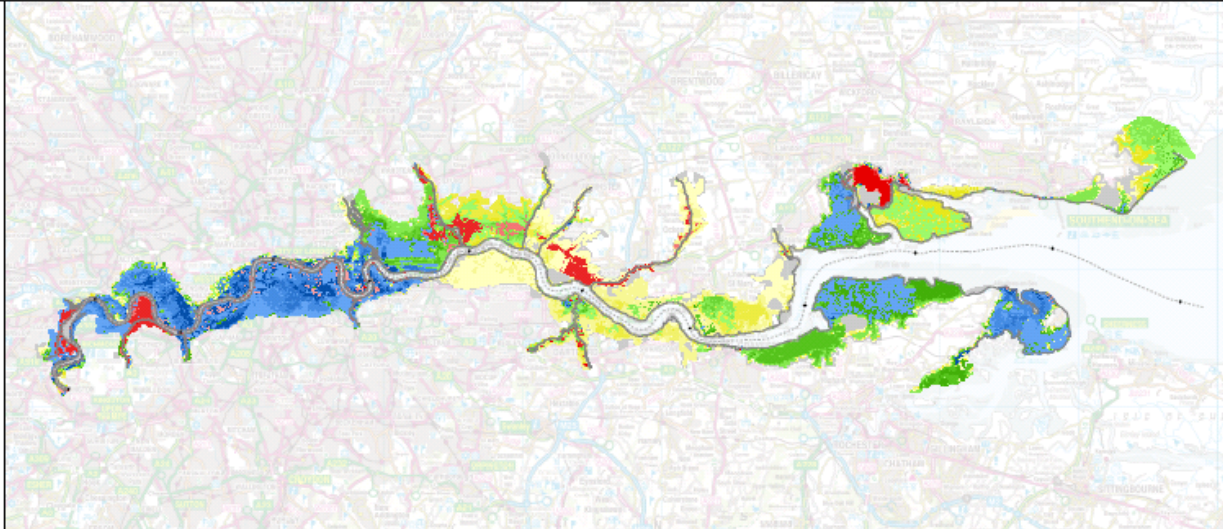
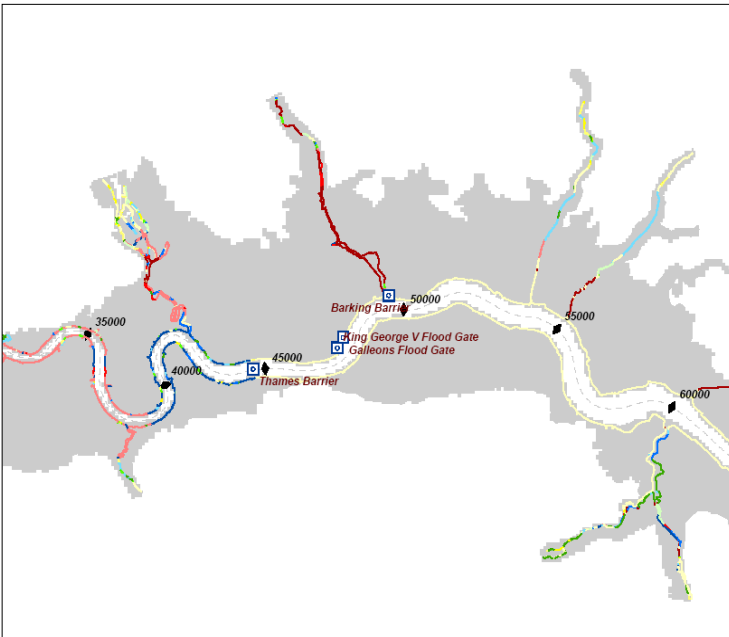


5.2.3 Example 3: System flood risk analysis in England and Wales (MDSF2 & RASP)

This example shows how system wide flood risk is analysed in England & Wales by the Environment Agency. The approach includes assessment of loads, defence response, flood inundation and impact, whilst maintaining links between impacts and their source such that the risk posed by discrete flood defence lengths can be identified, and hence management activities prioritised. This example builds from work also reported under Task 18 of the FLOODsite project (see www.floodsite.net).

Example name	Assessment of flood risk systems in England & Wales.
Location / pilot	River Thames, London
Failure mode(s)	Core flood defence failure modes (as represented through fragility curves)
Analysis method	A hierarchy of models that support analysis of source-path-receptor including analysis of hydraulic load conditions, flood defence performance, flood inundation and flood impact. 
GIS software / application / assessment tool	RASP and MSDF2 operate as a combination of discrete modelling tools, with data manipulated and integrated via GIS. More information on MDSF can be found in Environment Agency, 2011 and Environment Agency, 2012.
Level of readiness	Application within some Environment Agency regions. Ongoing programme of software development.
Level of integration	Good integration between models.
Reference system(s) used	ODN (UK) but applicable to any system

for geocoding data	
Data used for the assessment	The models draw on data covering all aspects of the system, from hydraulic load conditions, through defence condition and hence fragility (i.e. response under various load conditions) to topography for flood inundation and assets within the inundation areas in order to calculate risk. Integration of load, response, probability of inundation and consequence of inundation provides calculation of flood risk.
Data combination	 The diagram illustrates the flood risk assessment process. At the top, a cross-section shows a 'Source (River or sea)' on the left, a 'Pathway' (e.g., beach, raised/non-raised defence and floodplain) in the middle, and 'Receptor' (e.g., people and property) on the right. Below this, four graphs show the progression from 'Load' to 'Flood depth' to 'Total damage (£k)'. The first graph shows 'Load' vs 'f(load exceeded)'. The second shows 'Load' vs 'P(fail)'. The third shows 'Flood depth' vs 'P(depth exceeded)'. The fourth shows 'Total damage (£k)' vs 'P(damage exceeded)'. Below the graphs, four text boxes provide further details: Extreme loads: Sources of flooding risk quantified by 'return period', indicating how frequently a particular load will be exceeded. Reliability analysis: The performance of flood defence structures and systems shown by a 'fragility curve' - the probability failure with load. These depend on the structure, materials, failure mechanisms and condition. Flood probability: The flood extent and depth depend on breach size, overtopping and topography. Flood spreading models are combined with reliability analysis to assess depth / probability relationships. Consequences and risk: Flood damage or harm are related to depth. Risk is assessed by the probability that particular damage values are exceeded.
Description	Risk Assessment for Strategic Planning (RASP, www.rasp-project.net) provides an integrated approach for assessing risk from fluvial and coastal flooding. It can be used for: - National monitoring of risk from flooding; - Strategic prioritisation of investment in defence improvements or other flood management options (e.g. increased storage or diversion); - Targeting flood warning and emergency preparedness; - Highlighting priorities for monitoring and maintenance and justification of maintenance decisions; - Scheme design and optimisation. It describes the flood risk system in terms of source, pathway and receptor components and integrates these to provide the overall flood risk. Traditionally the sources are the in-river and coastal water levels, the pathways are the linear assets and floodplain, and the receptors are the people and property in the floodplain. However, these can be altered as appropriate to the site and the availability of external model results. The main

	embedded physics-based process is the Rapid Flood Spreading Model (RFSM), which spreads inflow volumes across the floodplain. For details of the RASP methods and RFSM, see Gouldby et al., 2008; Lhomme et al, 2008.
Graphics	Example of typical outputs from RASP analysis  Typical outputs from a system flood risk analysis using the RASP framework. Plot above shows risk of inundation (as compared to a standard inundation map). Plot to the left shows the attribution of risk to specific defences, allowing prioritisation of maintenance activities and capital works. 

6 Conclusions and recommendations

The accuracy of a traditional assessment cannot be improved after a certain point as some aspects are not taken into account within the assessment framework. Initial assessments can be improved if measurements, observations, expert knowledge or other data is combined with the traditional assessment data. Incorporating these additional aspects is not always straight-forward as our traditional assessment tools are not designed to deal with different data types. This report presents a number of data combination techniques from both a theoretical and a practical point of view. This report gives guidance on improving the assessment through adding additional data sources as combining all available information will improve performance representation. Some improvements can be implemented directly (see Section 6.1), whilst others need some development in order to be ready for use in practice (see Section 6.2).

The examples in this report show that it is not difficult to combine data, but the levee managers and engineers need to work together to make an efficient system for the assessment. The Orleans – SIRS DIGUE - example is a good balance between these approaches and provides an example of a pre prototype tool. These methods form part of an ongoing real assessment of flood risk in the city. Here it is shown once again that the assessment goals (management) cannot be considered separately from the data and the failure modes (engineering).

6.1 A practical approach for immediate application

A levee manager benefits from an improved performance representation of the levee. It prevents the manager from spending unnecessary money on safety or it prevents the manager from taking unacceptable risk. Both the manager and Engineer are aware of aspects that can be taken into account to improve the assessment. This improvement can only take place through good cooperation between the two.

The levee manager and an engineer need to go through three steps in order to improve the levee assessment process. First, the potential of data combination must be understood. This report gives an insight into the possibilities and limitations of different methods. In the second step, the process of failure must be understood. In this step, it is important to think “out of the box” because there can be indicators that are useful, but not routinely used for assessment. A broad understanding of the entire system is required.

Finally, when both the system and the potential of different data combination methods are understood, an assessment can be set up that offers an improvement upon the current system. Many possibilities exist to improve the current system. Table 3.1 gives guidance on the options for improvement, and which techniques exist to make those improvements. More insight into these techniques is given in scientific papers by Van der Meij (Van der Meij,2012a; Van der Meij 2012b.).

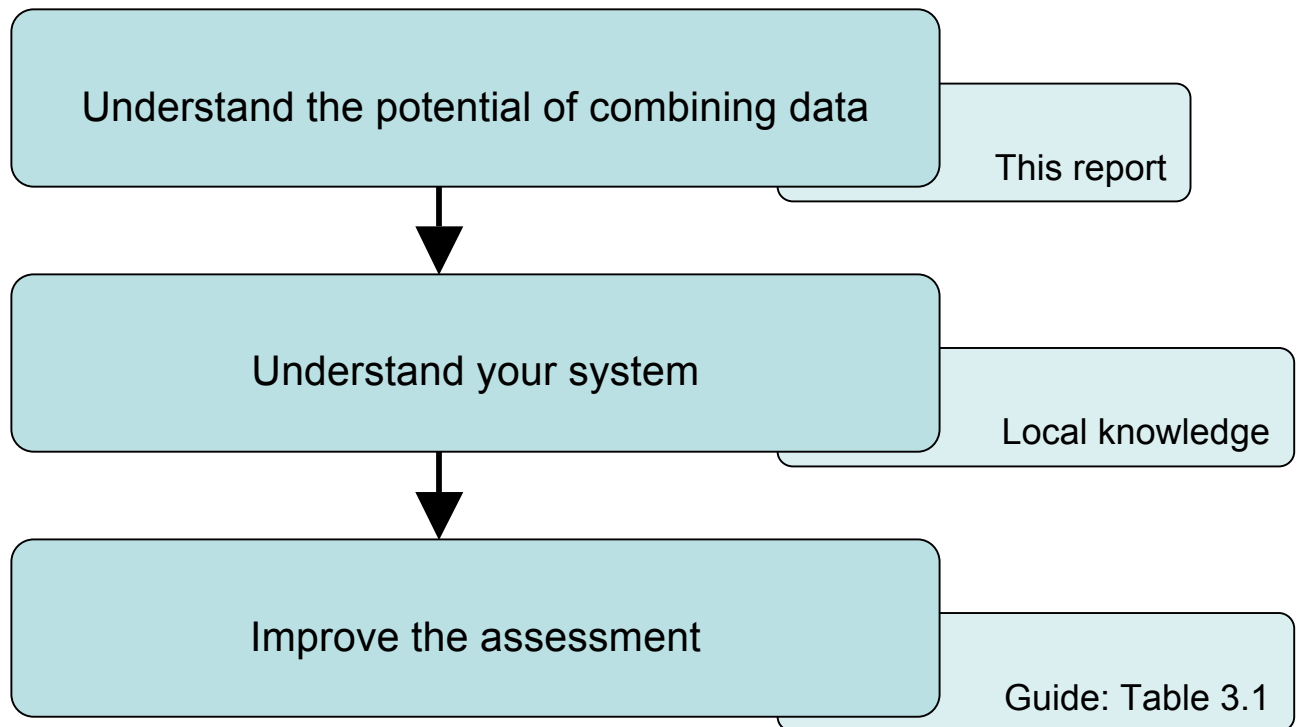


Figure 6.1 Steps toward improving the assessment.

6.2 Steps towards future implementation

A significant improvement can be made to currently available tools. On several levels, though, there are restrictions for direct implementation. By developing new, innovative ways of asset management, the right assessment can be made at the right moment in time. On top of that, research towards new knowledge, tools and method regarding levee assessment makes the flood protection management even more robust (see Figure 6.2).

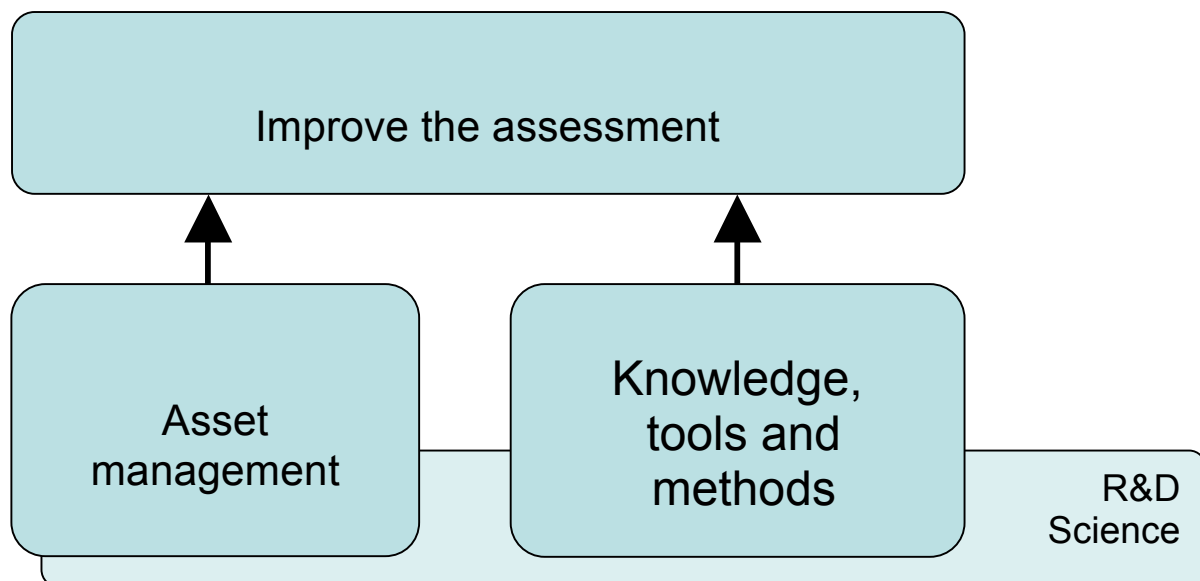


Figure 6.2 R&D steps toward improving the assessment.

6.2.1 Asset manager actions

It is difficult to draw generic conclusions about changes in behaviour asset managers need to make, as the local situation depends very much upon the legislation in each country. In general, legislation should be such that asset managers benefit from a better assessment. This is often not the case. In each country, it needs to be investigated how the asset manager can benefit from a good assessment. If the asset manager benefits from a reduced uncertainty – i.e. a better prediction of the risk – the asset manager will have an incentive to perform such an analysis.

Several programmes are going on in Europe to make the flood protections safety criteria dependant on the quality of the assessment. Streamlining these initiatives can be beneficial for all parties.

6.2.2 Development of knowledge, tools and methods

The development requirements of knowledge, tools and methods are more generic than the development of the policy related issues as they are more generically applicable. The development needs to take place on several different levels. At the bottom, more understanding is required regarding the role of data in assessments. Also, more knowledge is required regarding the exact development of the failure mechanisms. Finally, more understanding regarding the integration of the failure mechanisms and the length effect regarding these mechanisms is necessary. Table 6.1 poses a number of research questions related to these three categories.

Data	• What is the influence of uncertainty in data on the assessment? • What are the most efficient data combination techniques?
Failure mechanisms	• Failure mechanisms generally need better definition / understanding • Which assessment methods are most optimal? • How is all data related to all failure mechanisms? • What is the role of uncertainties in the development of a failure mechanism?
Integration of mechanisms and length of a levee	• Performance data needs to be generated/gained automatically for rapid assessments • What is the effect of the length of a flood defence on the performance of the defence? • What are the best techniques to combine the probabilities of failure due to different failure mechanisms? • How can observations over the length of a levee be combined? • What is the role of known and unknown uncertainties?

Table 6.1 Required R&D for improved assessment

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