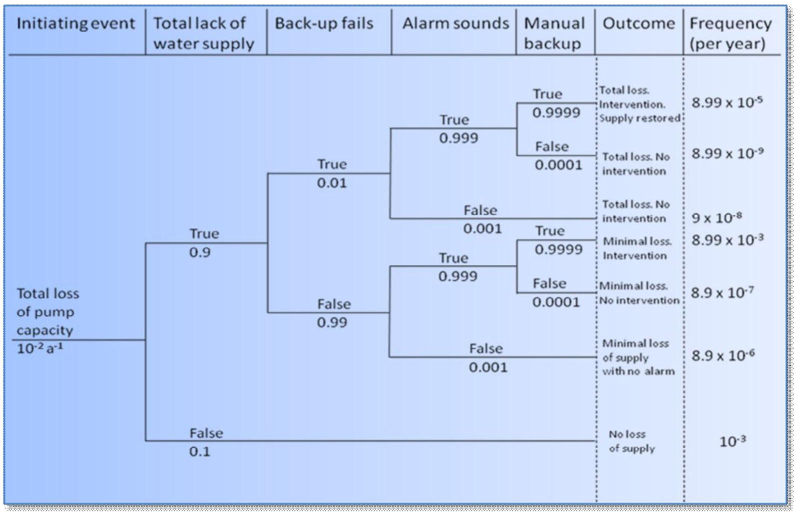
# Major risk categories and associated critical risk event trees to quantify




SEVENTH FRAMEWORK PROGRAMME

# Major risk categories and associated critical risk event trees to quantify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This report is:

**PU** = Public

# Summary

This report forms the Deliverable 2.3.1 - 'Major risk categories and associated critical event trees to quantify' - in Work Package 2.3 of the EC FP7 project PREPARED. The report focuses on defining risk and uncertainty, and details methods related to risk assessment, uncertainty analysis and propagation. 'Risk' is introduced and defined, followed by an introduction to risk assessment, with literature review details of several relevant methodologies, all of which could be used in the risk analysis of (urban) water systems. A summary of the most used methods is provided. Deterministic quantitative risk assessment (QRA) is introduced, followed by the recognition that there is always some inherent uncertainty when dealing with the key facets of determining risk - probability analysis and determination, followed by consequence analysis. Because of this, uncertainty as a concept is introduced, along with the most likely sources of uncertainty, followed by the details of suitable methods that could be used in order to propagate estimated uncertainty through a risk assessment. This leads to a discussion on stochastic QRA, which aims to account for the uncertainty using the methods described. Finally, some preliminary risk categories for water systems are outlined and these are subsequently broken down to examine some potential social, environmental and economic risks posed by the various hazards that may impact water systems in the face of a changing climate. An example event tree analysis is provided, in a generic form, i.e. not related to any PREPARED case study and/or demonstration city. The risk categories and their subsequent decomposition into specific critical event trees are very much preliminary, and must be finalised and agreed upon in collaboration with the demonstration city related to this Work Package. The outputs of a meeting between the city of Eindhoven, the demonstration city for WP2.3 and the University of Exeter (UNEXE) are discussed in the Conclusions section, and it is noted that much progress was made during this productive meeting, which in the following months is expected to lead to a specific QRA tool to be used as Decision Support Tool (DST) for flood risk assessment by the city.

# Contents

# 1 Introduction

This report forms the Deliverable 2.3.1 - 'Major risk categories and associated critical event trees to quantify' - in Work Package (WP) 2.3 of the EC FP7 project PREPARED. The aim of this WP is to develop quantitative models for the assessment of social (including health), environmental and economical type risks related to the sustainable performance of urban water systems (water supply / distribution and wastewater collection) under the changing climate conditions (and changing human activity) in the future. The specific objectives are (a) identifying the relevant risk categories for quantification, together with the associated critical risk event trees; (b) developing deterministic QRA models for these risk categories; (c) adding uncertainty, in order to develop stochastic QRA models; and (d) implementing experiences from testing in the PREPARED cities in the QRA models.

The report focuses on defining risk and uncertainty, and details methods related to risk assessment and uncertainty analysis and propagation, through a detailed literature review. Some preliminary risk categories for water systems are outlined and these are subsequently broken down to examine potential social, environmental and economic risks posed by the various hazards that may impact water systems in the face of a changing climate.

It should be noted that the detailed selection of the risk categories to analyse, and the agreement of the risks posed to each of the three sectors mentioned above (social, environmental and economic) should be undertaken in close cooperation with the demonstration city for this Work Package - in this case, Eindhoven. However, at this stage, information from the intended demonstration city for this Work Package (Eindhoven) has not been available yet (apart from an initial expression of interest and a preliminary teleconference), and as a result the risk categories and their subsequent decomposition into specific critical event trees are pretty much preliminary, and must be finalised and agreed upon in collaboration with the demonstration city related to this Work Package. Anyway, the development of a model related to a demonstration city is scheduled to start after the first year of the project (i.e., after the completion of this report), and does not affect the scope of this literature review. A meeting in April 2011 between Eindhoven, the PREPARED demonstration city for WP2.3 and the University of Exeter (UNEXE) did make significant progress, and a summary of the meeting is given in the Conclusions section. It is believed that it may lead to a successful QRA tool to be used by the city for flood risk assessment as Decision Support Tool (DST).

Given the importance of the collaboration with a PREPARED city, especially for the development of the QRA model, a preliminary short report (Vamvakeridou-Lyroudia et al, 2010) had been handed to the Eindhoven stakeholders in May 2010, in order to facilitate deliberations and decisions upon the subject. This report is essentially expanding and reviewing in detail the issues described in that preliminary report, with several additional information and details.

## 1.1 Report structure

The report is structured into four main sections (including the current section-Introduction). Section 2 introduces the concept of 'risk', and provides a simple definition, although it is stressed that in the literature there is no one single agreed definition for risk, and it can largely depend on the system under consideration. Risk is essentially split into key areas - the probability of a hazardous event occurring, and the consequences of that event.

Section 3 goes into the details of risk assessment. This Section begins with a general introduction of risk assessment, placing it within the larger framework of risk management. Risk assessment is essentially composed of risk analysis and risk evaluation. The main aim of risk analysis is to acquire and amalgamate information about the risk of concern, and it is essential that the end-user plays a key role in defining the hazards, their probabilities and the consequences. This is because it is the end-user who is the main expert in their area / of their system.

Following from this introduction, qualitative and quantitative methods for the assessment of risk are considered, and a summary is provided highlighting the methods which are most commonly used for the assessment of risks in (urban) water systems. A brief introduction to deterministic quantitative risk assessment (QRA) is included, and the essential key point of any deterministic QRA model is being pointed out, namely that given the same inputs, the same output(s) will always be calculated / produced by the model.

However, due to the inherent uncertainty in both probability estimation and even more so in consequence analysis, it is stressed that this uncertainty should be taken into account for risk assessment. This leads to the introduction of stochastic QRA, along with the concept of uncertainty and its sources. Methods of propagating stated uncertainties through a risk analysis in order to estimate the uncertainty associated with the output are discussed. These include: Monte-Carlo analysis, the Latin Hypercube technique and Fuzzy sets. The aim of accounting for and quantifying uncertainty is to provide the decision maker with better information on which to base management decisions.

Section 4 presents some general critical risk categories to analyse for water systems (both water supply and wastewater systems are considered). First, some general risk categories are presented with respect to each type of system (clean or waste water). These general categories are then broken down further in order to consider the risks posed to social, environmental and economic sectors. Because of the lack of case specific data from Eindhoven yet, these categories are still preliminary, and they need to be refined and finalised with considerable input from the specific case study. An example event tree is also provided to show the methodology that could be used as part of the QRA. However the literature review, the methods and the example provided can be considered generic enough, for urban water systems.

Finally, Section 5 concludes the report, while Section 6 lists the references cited.

# 2 The concept of risk

### 2.1 Definition of 'risk'

Risk is an extremely difficult term to define precisely because it can be applied to a wide variety of situations and systems. Indeed, it could be suggested that 'risk' cannot be fully defined until the system itself has been chosen and defined, making risk a flexible term, adaptable to the situation in which it is being used.

There is no single, universal definition for '*risk*' (Vatn, 2004). Despite this, a very broad definition for risk can be summarised as "*a combination of the probability, or frequency, of occurrence and the consequence of a specified hazardous event*", with most definitions containing elements relating to the probability and consequence of a given (usually negative or unwanted) event. If a system is influenced by more than one hazardous event, then the total risk comprises the possibility of a number (preferably 'all') of unwanted / hazardous events (Rostrum, 2008). Risk can therefore be defined as a combined / aggregated expression, as follows:

$$\text{Risk} = f\,(\text{Frequency, Consequences}) \qquad (2.1)$$

as mathematically formulated by Kaplan and Garrick (1981). In Eqn. 2.1, both the frequency and the consequences refer specifically to the particular hazardous event which is taking place. Kaplan and Garrick (1981) also brought about the 'set of triplets' idea, which asks:

- What can happen?
- How likely is it that this will happen?
- What are the consequences if it happens?

The first question can be answered in an almost infinite number of ways. The answer to the second question is usually expressed as a probability or frequency of an event occurring, while the third question can be answered as some sort of cost (e.g. monetary cost, environmental cost, human cost).

Therefore, *risk* can be effectively 'mapped' on a diagram plotting the hazard on one axis, and the probability on the other (Figure 1). As a third dimension on Figure 1, note that '*environment*', '*goods*' and '*life*' are also included on the x-axis, and the important point is made that hazards to human life pose a greater risk than those to the other two categories.

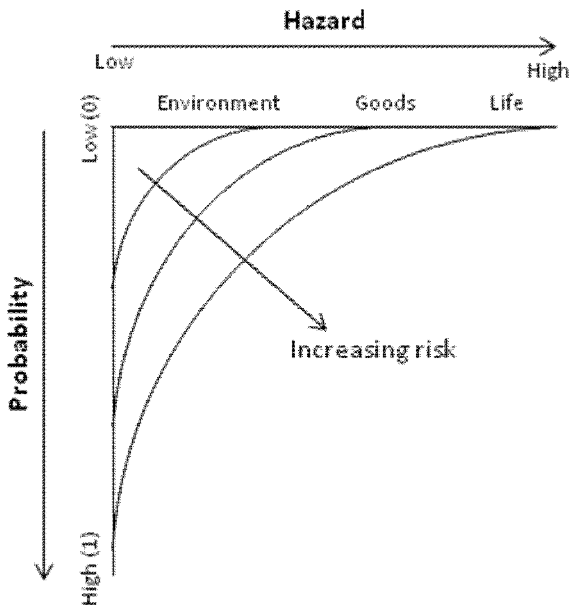


*Figure 1: Theoretical relationship between hazard, probability and risk. Note that hazards to life are rated more highly than those to economic goods or the environment (adapted from Moore, 1983). It is implicit here that the consequence of a hazardous event to life is greater than that to the natural environment for example.*

# 3 Risk assessment

### 3.1 Introduction to risk assessment

Risk assessment is generally set in the wider framework of risk management, as set out in IEC (1995) (Figure 2). Risk management comprises risk assessment and risk reduction / control. While both are important, this report focuses solely on the risk assessment side of total risk management (i.e. risk analysis and risk evaluation).

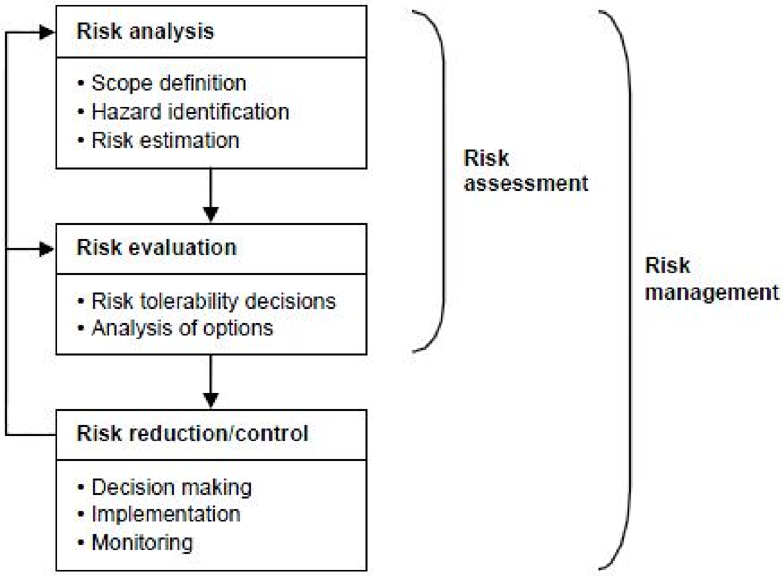


*Figure 2: The risk management process.*

As shown in Figure 2, risk assessment comprises two components:

- Risk assessment / analysis, which identifies the hazard(s) and estimates the risk to the population, and;
- Risk evaluation, in which judgements are made about the tolerability of the risk on the basis of the risk analysis.

*Risk assessment/analysis* can be broken further down into a coherent procedure, as outlined in Figure 3. Several methods / techniques exist and can be applied for each of the main "boxes" in Figure 3. *Hazard identification* or identification of the undesired event(s) is supported by e.g., use of Checklists, Preliminary hazard analysis, and use of Event data sources. The *frequency or causal* analysis is supported by e.g., fault tree analysis (FTA), reliability block diagrams (RBD), influence diagrams, and the use of reliability data sources, while the *consequence* analysis is supported by e.g., event tree analysis (ETA) or consequence models. Also for the consequence analysis it may be necessary to use specific simulation models (e.g. EPANET2 for clean water supply/distribution systems, SWMM5 for waste water systems), so as to estimate the values of hydraulic parameters that may be needed for QRA.

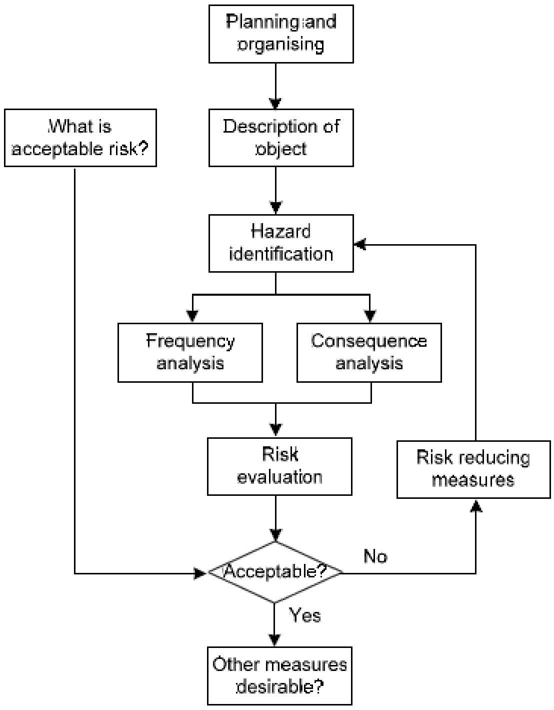


*Figure 3: Risk analysis and assessment procedure (from Rostrum, 2008).*

The main aim of risk analysis is to acquire and amalgamate information about the *risk of concern*. This information is then used to evaluate the risk and to start to define any risk reducing measures that may be required if the expected outcome is beyond a certain threshold of tolerability. How the risk analysis will be performed depends on the risk itself and it can be either *qualitative* or *quantitative*.

Recent trends in risk assessment for complex environmental systems (e.g. seismologic/earthwake risk assessment) include a third factor, besides *probability* and *consequences,* by breaking down consequences in two separate factors *vulnerability* and *loss* (Karimi et al, 2007). Thus for a complex (urban) water system, Risk Assessment, either qualitative or quantitative, may be considered as consisting of three steps:

1. Hazard assessment: Assessing the likelihood/probability of an event occurring.
2. Vulnerability analysis: Analyzing the behaviour of the system should the event occur and evaluating the damage level corresponding to it.
3. Loss analysis: Estimating the financial loss (and casualties) corresponding to each damage level of the system

Although this breakdown may, at first glance, seem similar to the previous two step (or two factor) approach, there are subtle differences in the concept, that make the three step approach more suitable for QRA of complex urban water system: The vulnerability analysis relates an event with a damage level of the system (not the damage per se), whereas the third step links a specific damage level to loss (financial, human etc). This segmentary approach enables separate and distinct aggregation models to be developed and applied at two discrete hierarchical levels. Within PREPARED, it will the methodology of choice, to be applied for QRA related to climate change in the Tasks to follow.

In the hazard identification box shown in Figure 3, it is the end-user (i.e. the stakeholders of the PREPARED demonstration city) who must identify the hazards, which will be included in any QRA modelling exercise by the PREPARED research experts. This is because it is the end-users (i.e. the stakeholders) who are the expert, and who have the most intimate knowledge of their system. They are the people who know what the most likely hazards posed to the system are, as well as the conditions that will initiate the hazardous event. Each hazard should also be accompanied with a list of potential consequences (economic, social, environmental, etc.), and an idea of the importance/relevance of that hazard. In addition, some idea of the frequency of occurrence should also be provided, even if this is only in linguistic terms (e.g. very likely, not so likely).

Therefore, the interaction between local stakeholders and QRA experts can be considered essential for the development of adequate, comprehensive and useful QRA models.

## 3.2 Qualitative methods for the assessment of risk

There are many tools and methodologies which have been developed in order to assess and analyse risk, either qualitatively or quantitatively, in a wide variety of disciplines. The specific method used ultimately depends upon the context in which the risk is placed, and upon the system under consideration. Because of the vast variety of possible methods available for the assessment of risk (including some very specific ones), this review will focus on the more popular techniques and on those more pertinent to the study of (urban) water systems, as the type of systems related to PREPARED.

### *3.2.1 Checklists*

Checklists can be considered as the oldest low technology methodology adopted for qualitative risk assessment. Checklists can be very efficient in terms of the time taken to complete them. They generally use knowledge gained from the analysis of other similar systems. Identified hazards and consequences are arranged into checklists (Marlowe, 2002). By definition, the list is never complete, and can always be added to and updated by new knowledge. Checklists can be used as input to more rigorous hazard analysis techniques.

### 3.2.2 *Hazard and Operability Analysis (HAZOP)*

This procedure involves fully describing a process and then questioning every part of it in order to determine how many deviations can arise from normal system operation, and where these deviations can arise (Wirth and Sieber, 2000). Once identified, it is determined whether a particular deviation will have a negative effect on the system. Action may then be taken if necessary. HAZOP can be very useful for identifying unforeseeable hazards that have been incorporated into a system as a result of lack of information or due to poor system design for example. Cooperation between team members/interested parties is recommended in order to make the most of the process, and to identify as many system deviations as possible. In terms of water systems, HAZOP is most suited to treatment systems and the distribution network. For further reading and greater details see Wirth and Sieber (2000).

### 3.2.3 *What-if analysis*

What-if analysis determines the system values that have the greatest impact on the results of normal system operation. Input values can be varied and the amount and sign of the change to the output is noted. Inputs can then be ranked in terms of the magnitude and sign of their effects. Critical factors within a system can be identified as part of this analysis. Further information on this type of what-if analysis can be found in Kapelan et al. (2004).

A more qualitative what-if analysis takes the form of a brain-storming exercise in which a team of experts is assembled and then asked the question '*What happens if....?*' concerning different hazardous scenarios or failure events (Nolan, 1994). In this way, the entire system and the hazards and possible consequences can be assessed. The scenarios can ask any question, and some may even be unrealistic but are useful for thinking differently about a system to ensure that all consequences are captured.

### 3.2.4 *Preliminary Hazard Analysis (PHA)*

PHA is a semi-quantitative analysis that identifies all the potential hazards that may lead to an accident. The events are then ranked according to their severity. Hazard controls and mitigating systems can then be formulated and implemented. This method is usually carried out early in the lifetime of a project, but can also be used retrospectively on an existing system in order to retrofit safety measures. For further details see Rausand (2005).

### 3.2.5 *Human Reliability Assessment (HRA)*

HRA assesses the impact of human errors upon a given system. Performance, functionality and safety are all assessed. For example, for a water system the impact on the quality of the water could be assessed in the event of human error in relation to a key component concerning the control of water quality. For further reading, see Ng et al. (2004).

### *3.2.6 Preliminary Risk Analysis*

PRA is an accident-centred risk assessment approach, where the main aim is to characterise the risk associated with various accident scenarios. A systematic examination of the main issues is conducted by experts and stakeholders. The main contributors to the accident scenarios are postulated, as are any safeguards that may mitigate either (a) the accident occurring in the first place, or (b) the risk from the accident, if it were to occur. Risk reduction and prevention methods can also be put forward during the analysis. Rasche (2001) goes into further details regarding this method.

### *3.2.7 Hazard Assessment Critical Control Points (HACCP)*

Hazard Assessment Critical Control Points (HACCP) is a methodology mostly employed in the food production and processing industry. CCPs are closely monitored to ensure that food is safe for human consumption. It seeks to identify hazards and reduce risks throughout all stages of the production process. HACCP originated from Failure Mode and Effects Analysis and was further developed by NASA for space programs to reduce the risk of astronauts consuming contaminated food in space. HACCP processes are now widely adopted in many countries. See Weingold et al. (1994) for more information.

## 3.3 Quantitative methods for the assessment of risk

### *3.3.1 Fault Tree Analysis*

Fault Tree Analysis (FTA) examines, displays and evaluates failure paths in a system. This tool is very popular, and is regularly used for safety and reliability investigations, and in some fields is required for product certification (Ericson, 1999). It may be qualitative or quantitative, and follows a logical scheme that links the top event (i.e. the failure) to the causes. In a quantitative analysis, the probability of the top event occurring can be calculated for a specific time interval.

FTA was developed in 1962 by Bell Telephone Laboratories for the U.S. Air Force. Fault tree diagrams follow a top-down structure and represent graphical pathways within a system that can lead to an undesirable loss event. Pathways connect contributing events using standard logical symbols (i.e. AND, NOT, OR). AND and OR gates are the two most commonly used in FTA. As an example, consider two input events that can lead to an output event. If the occurrence of either input can lead to the output, then the events are connected using on OR gate. However, if *both* must occur for the output event to happen, then they are connected using an AND gate. FTA uses a standardised system of graphic signs which are used for the construction of fault tree diagrams. Figure 4 shows an example of a simple fault tree diagram for a hypothetical pump station.

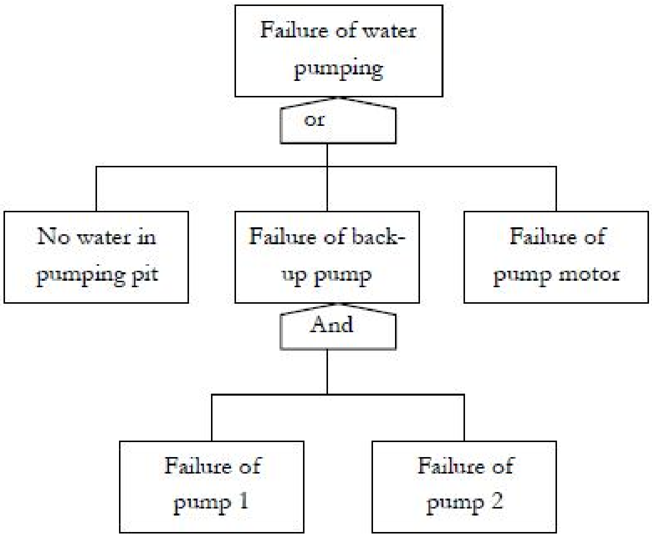


*Figure 4: A simple fault tree (from Rostrum, 2008)*

The main difference between FTA and Reliability Block Diagrams (RBD-Section 3.3.4) is that in fault trees one works in the *'failure space'*, while the opposite is true for RBDs. In addition, fault trees look at fixed probabilities while RBDs may include time-varying distributions in the probability. Generally, fault trees can easily be converted to RBDs, however the reverse is usually a lot more difficult to accomplish.

FTA is suitable for complex systems (e.g. water and environmental systems) where critical components are listed. FTA can model redundancy and fault tolerance, and is therefore commonly used to model catastrophic risk. However, FTA can be costly and time consuming, and it heavily relies on the correct identification of faults and failure mechanisms and their interactions so that system behaviour can be predicted. Thus, it is also data-demanding for which data may not necessarily be readily available (Ericson, 1999).

Ultimately, FTA provides a scientific approach which is systematic and flexible enough to allow analysis of various factors. By using a top-down approach, the causes of a specific event can be identified. The graphic representation leads to an easy understanding of the sequence of events.

### *3.3.2 Event Tree Analysis (ETA)*

Event Tree Analysis (ETA) is based on event trees. An event tree is a visual representation of all the events which can occur in a system *after* a failure has occurred, and so is the 'next step' in the path mapped out in FTA (Andrews and Dunnett, 2000). Event trees can be used in systems where the components operate side by side, or stand-alone.

The starting point, or initiating event, disrupts normal system operation. The event tree then displays the sequences of events involving success and/or failure of the system safety components and the ultimate consequences of that failure. The event sequence is influenced by safety barriers, and each event in the tree will be conditional on the occurrence of the previous event(s).

Like FTA, ETA can be qualitative or quantitative if the probabilities of certain events occurring are known. ETA is suitable for identification of events that require further analysis using FTA. Figure 5 shows an example event tree diagram. For more information on ETA, see Andrews and Dunnett (2000).

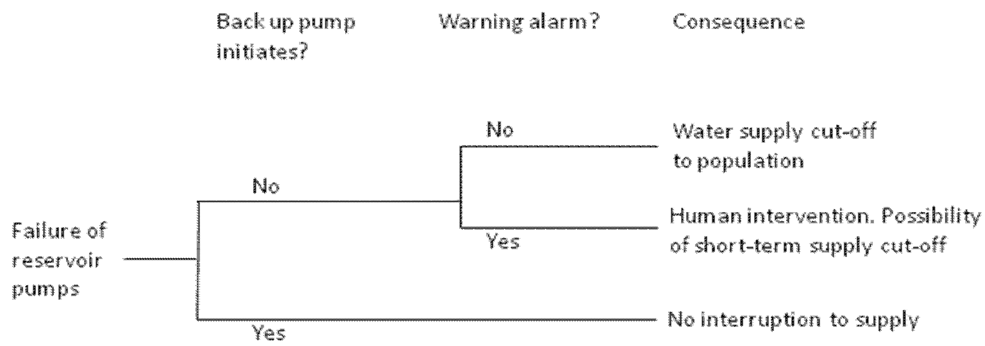


*Figure 5: An example hypothetical event tree diagram. Probabilities may be added to each event if known, or they can be estimated, making the analysis quantitative.*

### 3.3.3 *Failure Mode and Effects Analysis (FMEA)*

This technique (which is also known as potential failure modes and effects analysis-FMEA *or, (*its extension) effects and criticality analysis-FMECA), identifies potential failures in a system (Rasche, 2001). Failure again generally refers to something that is unwanted or deemed as negative. Although FMEA started in WWII as a military tool, nowadays it is most widely applied to manufacturing, so a failure here is an error or defect which may affect the customer. However FMEA can also be readily applied to urban water systems. The effects analysis deals with what the failures may cause (i.e. consequences). Because FMEA is mainly designed to eliminate/reduce failures, it can also be considered as a decision support tool, that may be used to evaluate risk management priorities. FMEA requires that:

(a) the system is divided into elements,
(b) the functional structure of the system is defined and;
(c) the failure mode is defined.

The analysis starts by selecting an element at the lowest tree level for which sufficient data are available. Failure modes at this level are tabulated. Elements are evaluated individually and in sequence, and the consequence of failure of each of the elements is considered to be the failure mode. The consequences of this failure for the next highest level in the system are then considered. Thus one moves higher through the system, identifying failure consequences at each level. The probability of failure for each element may also be estimated and risk can be assessed.

FMEA methodology also consists of indentifying a systems components and listing the consequences if each item fails. Consequences are then evaluated by three criteria and ranked.

- severity (S)
- likelihood of occurrence (O)
- inability of controls to detect it (D)

According to this, the systems components are ranked according to the Risk Priority Number (RPN), as follows:

$$RPN = S * O * D. \tag{3.1}$$

where S stands for severity, O for the likelihood of occurrence and D represents the inability for detection. The RPN, which ranges from 1 to 1000, is then used to prioritise the failures and thus to develop actions which lead to the reduction of the risk. More details about FMEA methodology can be found at http://www.asq.org/learn-about-quality/process-analysis-tools/overview/fmea.html and at the dedicated FMEA/FMECA website http://www.fmea-fmeca.com/.

The main downside with the FMEA methodology is that is it usually time consuming, expensive and does not take into account human errors (Rasche, 2001).

#### *3.3.4 Reliability block diagrams*

A reliability block diagram (RBD) is a tool developed to perform system reliability analysis for large and complex systems. RBD is based on diagrams showing network relationships (Item Software, 2007). It shows the logical connections of (functioning) components needed to fulfil a specific system function. The rational course of an RBD starts with an input node and ends at a concluding output node after flowing through a diagram consisting of a series of parallel blocks (also known as images). Each diagram should contain only one input and output node (Figure 6). Therefore, if a system has more than one component or function, then a new diagram is required for each one.

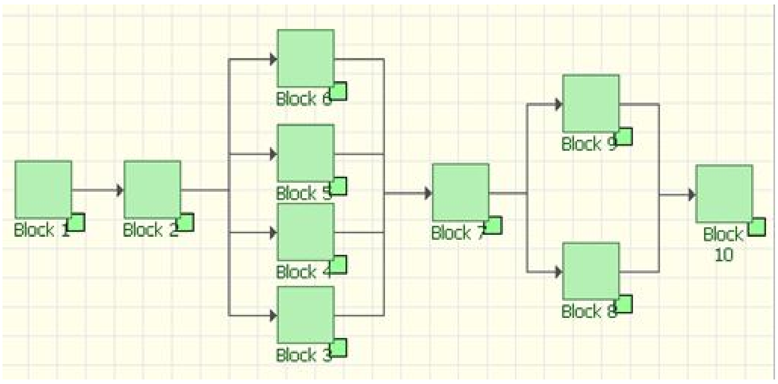


*Figure 6: Example reliability block diagram (from www.weibull.com)*

Each block should show the maximum number of components to simplify the diagram, and the function of each block should be easy to identify. Blocks should be mutually independent so that failure in one does not cause failure in the other. For each block, a failure rate is estimated and a replacement rate is given. Given these two rates, a function expressing the probability of failure conditioned to the time is constructed. The methodology is based on the principle that there must then be some trade off between failure rate and repair rate. This relationship is determined by analysing the system. A comprehensive description of this analysis is given in Item Software (2007), and more information of RBDs is given in Rausand and Hoyland (2004).

### 3.3.5 Barriers and bow-tie diagrams

Bow-tie diagrams are normally used to show the causes and consequences of failure. The logical course through the diagrams is from left to right. The unwanted event is shown in the middle, then the causes are shown to the left, with the consequences on the right. Safety barriers are also shown which on the 'causes' side reduce the occurrence of the event while on the 'consequences' side mitigate the potential impacts of the event. Figure 7 shows a generic bow-tie diagram which could be applied to any situation.

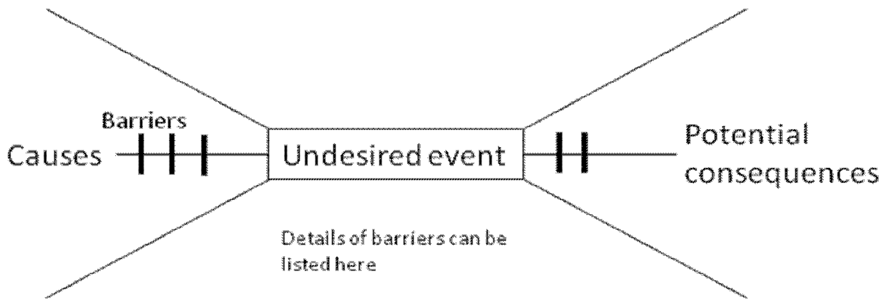


*Figure 7: An example generic bow-tie diagram.*

Safety barriers are means designed for prevention, control and / or mitigation of undesired events. Obviously, these means will differ for every system under consideration. It is usually assumed that if the barriers work well, then they have a direct and significant impact on the risks posed by the system. The effectiveness of safety barrier performance may be characterised by their functionality, reliability, response time and robustness (Sklet, 2006).

#### 3.3.6 *Summary*

Of all the methods of risk analysis described above, some are more frequently used than others in the assessment of water systems. **Error! Reference source not found.** in Appendix A summarises the most frequently used methods.

### 3.4 Deterministic Quantitative Risk Assessment

Quantitative risk assessment (QRA) combines three key ideas (Almoussawi and Christian, 2005):

- the chance of something going wrong
- the consequences if it does and;
- the context within which the situation is set.

As stated in Section 2.1, risk can be considered as an aggregated expression (mathematical/arithmetic operator) combining *probability* AND *consequence.* The most common arithmetic operator applied is *multiplication (*Moore, 1983). *Thus* the equation to estimate the level of risk can be written:

$$\text{Risk} = \text{Probability} * \text{Consequence} \qquad (3.2)$$

However, in spite of the wide use of Equation 3.2, there are serious objections to the use of a single multiplication formula for risk assessment, because of significant drawbacks, the main being that two potential hazards/events can produce the same risk level, e.g., 0.001 *1,000 = 0.1*10 = 1, although they may be quite different in nature. It would be better for it to be replaced by a trade-off curve between probability (frequency) of occurrence and consequences (Kapelan et al, 2004; Kapelan et al, 2007).

*Probability* is a measure of how frequently an event occurs. It may be simulated or calculated from historical or statistical data. It should be noted that probability will vary according to the event that is being described, the method by which it is being calculated, and the length and quality of the data series being used. Even for the most well-defined system, there is still uncertainty inherent in estimating the probability of and event, therefore in environmental systems, this uncertainty may be significant. Probabilities are usually expressed as a numerical value between 0 and 1, with 0 meaning no chance of occurrence and 1 meaning total certainty. For example, in a hydrological context, a certain discharge may have an annual probability of occurrence of 0.01 or 1% (or to rephrase this, a, expected return period of 100 years) but with an uncertainty of 10% or more.

The quantification of the *consequences* is even more difficult because the consequences may be subjective or may not be quantifiable by some time-series of data (e.g. the effect of a flood on a person's wellbeing). Some may attempt to quantify the consequences in purely economic terms, however there may be other factors which may not be so readily quantified such as loss of water quality, customer dissatisfaction or loss of human life. This is also the reason that two-level approach may be needed (i.e. separating the damage level from the loss for the consequences of a single event, as described in Section 3.1. In any way, the consequences of an event are specific to each event, but, as it happens with probability, there is significant uncertainty in quantifying them. Even in a simple example like the loss suffered by one house in a flood event, there are uncertainties as to the value of each individual item lost to the flood.

For the deterministic QRA, which will determine the risks for a given hazard scenario to an urban water system as a result of the future changing climate, the probability of the risk(s) occurring, along with a measure of the uncertainty, will be estimated in consultation with the PREPARED demonstration cities.

An example of the type of hazard scenario that may occur is flooding of water pumps due to rising sea levels. The probability of this event occurring could be estimated by considering such factors as existing or planned flood defences for the pumps, elevation of the pumps, distance from the sea, projected sea level rise, etc. To fully determine the risks associated with pump flooding, the causes, probability and potential consequences of the hazard occurring will be analysed, and some of the methods outlined in Section 3.2 will be used.

In order to analyse the consequences of certain events occurring in urban water systems, it may necessary to use specific simulation software such as EPANET2 (Rossman, 2000), for water supply and distribution systems (http://www.epa.gov/nrmrl/wswrd/dw/epanet.html) and SWMM, for sanitary and stormwater systems (Rossman, 2010) (http://www.epa.gov/ednnrmrl/models/swmm). These software tools are required in order in estimate some of the hydraulic parameters that are required for the QRA.

By definition, the resulting (numerical) risk estimated from the deterministic QRA will *always* be the same given the same numerical inputs, with no variability (i.e. the uncertainty is not really taken into account). However, as mentioned above, both the estimation of the probability of an event and the consequences of an event have inherent uncertainty. The next section deals with uncertainty, its sources, methods for the quantification of this uncertainty which, thus, leads to stochastic QRA.

### 3.5 Accounting for uncertainty and stochastic QRA

Uncertainty is inherent when estimating the probability of an event, its consequences, or it may be introduced during the modelling process as a result of numerical rounding issues relating to the computing process or due to poor model design. Uncertainty can be stated as a phenomenon that reflects incomplete knowledge about a subject. For example, floods of a certain magnitude are commonly expressed in terms of a probability of annual occurrence, such as 0.01, or 1 in a 100 years. However there are very few records with data going back 100 years, and the value for discharge corresponding to this figure is arrived upon by statistical analysis of the best available dataset and suitable extrapolation of the data. However, because there are not 100 years of data, the statistical analysis and the extrapolation are both subject to some degree of uncertainty, which must be stated.

In QRA, uncertainty may also arise due to incomplete understanding of the hazard, its probability of occurrence or its effects. Uncertainty is thus a lack of confidence. The modelling of this inherent uncertainty requires three steps (Wojtkievicz et al., 2001):

i) identify the sources of uncertainty;
ii) characterise the uncertainty;
iii) quantify the uncertainty.

#### *3.5.1 Identifying the source and characterising uncertainty*

In order to identify the uncertainty, all sources must be investigated. Uncertainty may be classified into three main groups: *data* uncertainty, *model* uncertainty and *knowledge* uncertainty (Hall, 2003).

- *Data uncertainty* may be due to measurement uncertainty (e.g. limited measurement precision, indirect data sets), incomplete or insufficient data, and unreliable or inexact data.

- *Model uncertainty* affects model inputs (e.g. total population, quantity of water available), model parameter uncertainty, particularly coefficients, uncertainty associated with the model choice and structure and model output uncertainty (which is a combination of the previous factors.

- *Knowledge uncertainty* is the uncertainty about the future or uncertainty due to ignorance or incomplete knowledge. For any natural system, or a system with natural components, this is unlikely to be well known, and can be poorly constrained even for well defined man-made systems (for example future acts of sabotage or extreme weather events are usually not known).

In uncertainty characterisation, each source of uncertainty is qualitatively or quantitatively estimated so that the uncertainty is better defined. Examples of quantitative uncertainty characterisation are: a probability density function with pre-defined parameters (Halder and Mahadevan, 2000); fuzzy-membership functions (Zadeh, 1965); an interval bounded by upper and lower values (Alefeld and Herzberger, 1983), combined probability-possibility density functions (Kamiri et al, 2007) and other methods including random sets (Hall and Anderson, 2002). More details are given below.

The failure of most processes in a system can usually be described by a probability model which represents the relative fractions with which various outcomes would be expected, given a population of identical replications if the system of concern were hypothetically to be observed a large number of times. Probability models may range from fairly simple to very complicated ones, and this largely depends on the system under consideration.

Recently the concept of *possibility* theory (Dubois and Prade 1998, Zolotukin 2002) has been increasingly applied alongside classic probability theory (or replacing it), in combination with fuzzy sets and fuzzy theory (Ross et al, 2002), leading to combined approaches for quantifying the uncertainty of occurrence of an event in QRA (Karimi et al, 2007).

As is the case for risk, there are many definitions of uncertainty. Traditionally, uncertainty can be split into two categories: natural (or *aleatory*) variability which describes the randomness observed in nature and; knowledge (or *epistemic*) uncertainty, which refers to the state of knowledge about a physical system and our ability to measure and model it. Some suggest that only knowledge uncertainty can be reduced because of inherent randomness and chaos in nature, which cannot be reduced. Indeed, even though we have a generally good understanding of the broad scale workings of nature, our knowledge is far from complete, and there are many things we just do not know (Ross, 2004).

Even in well developed theories, there are still considerable uncertainties and knowledge gaps which remain unaccounted for. In practice it is of course very difficult, and in some cases impossible, to separate out the two types of uncertainty. For example, the model may be poorly defined and built, and may not capture the physical processes well, however this poor model design may be as a consequence of a poor understanding of the physical system due primarily to aleatory uncertainty. This also affects risk management, the ultimate goal for QRA, i.e. the decisions about the measures to be taken for attenuating risk (Yager, 2002).

### *3.5.2 Quantifying uncertainty*

Quantitative uncertainty characterisation is usually done by using the probability density functions because it enables the use of well tested statistical methods. In addition, more unconventional methods such as fuzzy theory (Yager, 2002), interval mathematics and random sets may also be used to characterise the uncertainty. Additionally combined probability-possibility density functions may be used, along with fuzzy theory (Zolotukin 2002, Karimi et al 2007). The following presents some common methods used in quantifying uncertainty:

1. analytical based methods
   a. First Order Second Moment Model (Kapelan et al., 2003)
   b. Second Order Second Moment Model (Haldar and Mahadevan, 2000)
   c. First Order Reliability Model (Xu and Goulter, 1999)
   d. Mean Value and Advanced Mean Value (Wojtkievicz, et al., 2001)

2. sampling based methods
   a. Monte Carlo Sampling (MCS) techniques (Press et al., 1990)
   b. Latin Hypercube sampling techniques (Sadiq et al, 2003)
   c. Hammersley Sequence sampling technique (Kalagnanam and Diwekar, 1997)
   d. bootstrap methods (Efron, 1982)
   e. quasi-MCS sampling technique quasi-Monte Carlo methods, such as Halton, Sobol, and Faure numeric sequences (Niederretier, 1992)
   f. importance sampling technique (Engelund and Rackwitz, 1993)

3. Non-conventional methods
   a. Interval mathematics (Kutscher and Schulze, 1993).
   b. Possibility-Probability density functions (Karimi et al, 2007)

4. Optimisation methods
   a. Multiobjective optimisation (Kapelan et al, 2005)
   b. Fuzzy optimisation (Yager, 2002)

Because of the large number of different methods, only the most popular/frequently used techniques will be presented in detail in this report, together with those that are being considered for potential use in PREPARED.

#### 3.5.2.1 *Monte-Carlo sampling*

Monte-Carlo sampling (MC) (Press et al., 1990) is a simulation-based approach for the forward propagation of uncertainty. This method can be applied to any model, whose uncertain parameters are modelled as a stochastic process. This tool is particularly useful for analysing uncertainties if the uncertainty on the input parameters can be described by a probability density function.

Monte-Carlo sampling is iterative. In each iteration, an instance of the stochastic parameters is randomly created. The model is then simulated using these parameters, and the output is sampled. The technique involved randomly sampling a value from each of the input probability distributions and passing this combination of inputs through the model to obtain one realisation of the response variable (output). Many instances of sampling of the inputs generate many instances of the model output, and this allows the observation of the propagated uncertainty through the creation of a probability distribution of the output values. For example, if the input parameters are known to within a distribution, then Monte-Carlo sampling will perform say 1000 iterations of the model simulation with input values varying from samples taken from within the given range. The range of outputs (1000 in total) is then given and the probability distribution of the outputs can be derived (Kapelan et al, 2003).

#### 3.5.2.2 *Importance sampling (IS)*

Importance Sampling (IS) (Engelund and Rackwitz, 1993) is a Monte-Carlo based technique that estimates the statistics of a random variable sampled under a given probability distribution function. IS consists of a Monte-Carlo simulation where a system is simulated under a different set of parameters. The major drawback is that original reference parameters may be very difficult to obtain.

#### 3.5.2.3 *First Order Second Moment Method (FOSM)*

This error propagation equation is an analytical approach for modelling uncertainty and is very well established, with many applications (e.g. topography, water distribution network calibration etc) (Kapelan et al, 2003). This method is applicable whenever a model is given in the form of a scalar equation.

$$y = f\left(x_1, x_2, \ldots, x_n\right) \tag{3.4}$$

where $y$ is a scalar, and $x_1, \ldots, x_n$ are uncertain variables and parameters. The fundamental assumption of the error propagation equation approach, is that $x_1, \ldots, x_n$ are independent random numbers with normal distribution. If $f(\cdot)$ is linear, $y$ is normal distributed. If $f(\cdot)$ is non linear, and 1) $f(\cdot)$ is differentiable and 2) $x_1, \ldots, x_n$ have *small* variance, then $y$ is still normal and the approach can be still applied.

If *f*(.) is linear, then the model is given in the form:

$$y = a_0 + a_1 x_1 + \ldots + a_n x_n \tag{3.5}$$

The variables/parameters $a_0, a_1, \ldots, a_n$ are deterministic, whereas $x_1, \ldots, x_n$ are normally distributed:

$$x_i = \mu_i + \delta_i \quad \delta_i \sim N\left(0, \sigma_i\right) \quad i = 1, \ldots, n \tag{3.6}$$

Where $\mu_i$ represents the expected value for parameter $a_i$ and $\delta_i$ stands for a normal random variable, with expected value equal to 0 and standard deviation equal to $\sigma_i$. For convenience, the model can be rewritten as following

$$y = a_0 + a_1 x_1 + \ldots + a_n x_n = \\ = \left(a_0 + a_1\mu_1 + \ldots + a_n\mu_n\right) + a_1\delta_1 + \ldots + a_n\delta_n \tag{3.7}$$

It is well known that $y$ is also normally distributed:

$$y \sim N\left(\mu_y, \sigma_y\right) \tag{3.8}$$

The expected value $\mu_y$ and the standard deviation $\sigma_y$ are obtainable with explicit formulae:

$$\mu_y = a_0 + \sum_{i=1}^{n} a_i \mu_i \quad \sigma_y = \sqrt{\sum_{i=1}^{n} a_i^2 \sigma_i^2} \tag{3.9}$$

So, if the model is linear and the uncertainty is represented as independent normally distributed random variables, then the models output uncertainty is modelled as a random number with normal distribution, whose parameters are obtained with an explicit formulae.

If *f*(.) is non-linear, then the error propagation equations approach can still be applied, as long as two further requirements are fulfilled:

- $f(\cdot)$ must be first order differentiable.
- Standard deviations $\sigma_1, \ldots, \sigma_n$ must be *relatively small*.

This is also known as the First Order Second Moment approach (FOSM). Given the aforementioned assumptions, the input $x_1, \ldots, x_n$ are still normally distributed, and the method consists on building the first order differential

$$y = f\left(x_1, x_2, \ldots, x_n\right) \approx f\left(\mu_1, \mu_2, \ldots, \mu_n\right) + f_{x_1}\left(\mu_1, \mu_2, \ldots, \mu_n\right)\delta_1 + \ldots + f_{x_n}\left(\mu_1, \mu_2, \ldots, \mu_n\right)\delta_n \tag{3.10}$$

Where $f_{x_i}\left(\mu_1, \mu_2, \ldots, \mu_n\right)$ is the partial differential $\frac{\partial f}{\partial x_i}$ evaluated in $x_1 = \mu_i, \ldots, x_n = \mu_n$. The model is now linear again, and thus the output $y$ is also normally distributed:

$$y \sim N\left(\mu_y, \sigma_y\right) \tag{3.11}$$

The expected value $\mu_y$ and the standard deviation $\sigma_y$ are derived as:

$$\mu_y = f\left(\mu_1, \mu_2, \ldots, \mu_n\right) \quad \sigma_y = \sqrt{\sum_{i=1}^{n} \left[ f_{x_i}\left(\mu_1, \mu_2, \ldots, \mu_n\right)\right]^2 \sigma_i^2} \tag{3.12}$$

Thus it is identical to the linear case, however it is essential that $\sigma_1,\ldots,\sigma_n$ are small enough to let $\delta_1,\ldots,\delta_n$ vary within ranges such that $f(\cdot)$ is well approximated by its first order differential. If this is not the case, the application of this method would bring further uncertainty into the model.

#### 3.5.2.4 *Latin Hypercube sampling (LHS)*

Latin Hypercube Sampling (LHS) is a variation of MC sampling, providing a more efficient and stratified sampling that can be applied to multiple variables (McKay et al., 1979). The method is commonly used to reduce the number of runs necessary for a Monte-Carlo simulation to achieve a reasonably accurate random distribution. LHS is a probabilistic procedure. Briefly, each variable is broken into *nS* intervals of equal probability. One value is selected at random from each interval. The *nS* values obtained for one variable are paired randomly with the values from another. This combination continues until a set of *nS nX*-tuples are formed. This set is the LH sample.

An example, published in Helton and Davis (2003) is given by generating the LHS for **x** = [*U,V*] and nS = 5 (Figure 8). The ranges of *U* and *V* and divided into 5 intervals of equal probability. These lines (at 0.2, 0.4, 0.6 and 0.8) extend horizontally to the cumulative distribution function then drop down to the abscissa to produce the intervals. Random values are then sampled from these intervals. When the values for *U* and *V* in each interval have been identified, they are paired randomly. Because the pairing is not unique, many possible LHS can result. See Figure 8 and Helton and Davis (2003) for further information.

LHS can be incorporated into an existing Monte-Carlo model easily and will work with variables that follow any analytical probability distribution. The sampling algorithm ensures that the distribution function is evenly sampled.

The main reasons for the popularity of LHS include: conceptual simplicity, dense stratification over the range of the variables, availability of sensitivity analysis procedures and effectiveness for model validation. The results from LHS can be presented to a wide audience fairly easily, with detailed understanding of the methods not being required. It also ensures that no part of the variables probability distribution is missed. A comprehensive overview of the LHS method is described by Helton and Davis (2002, 2003).

Generally LHS methods improve over MC sampling procedures, since they guarantee more even sampling of the parameter space. However, there is the disadvantage that they may not adequately sample the high probability density region of parameter space (Blasone et al, 2008). They have been used for risk assessment in some types of water/ecology systems, often in combination with other MC techniques (Sadiq et al, 2003).

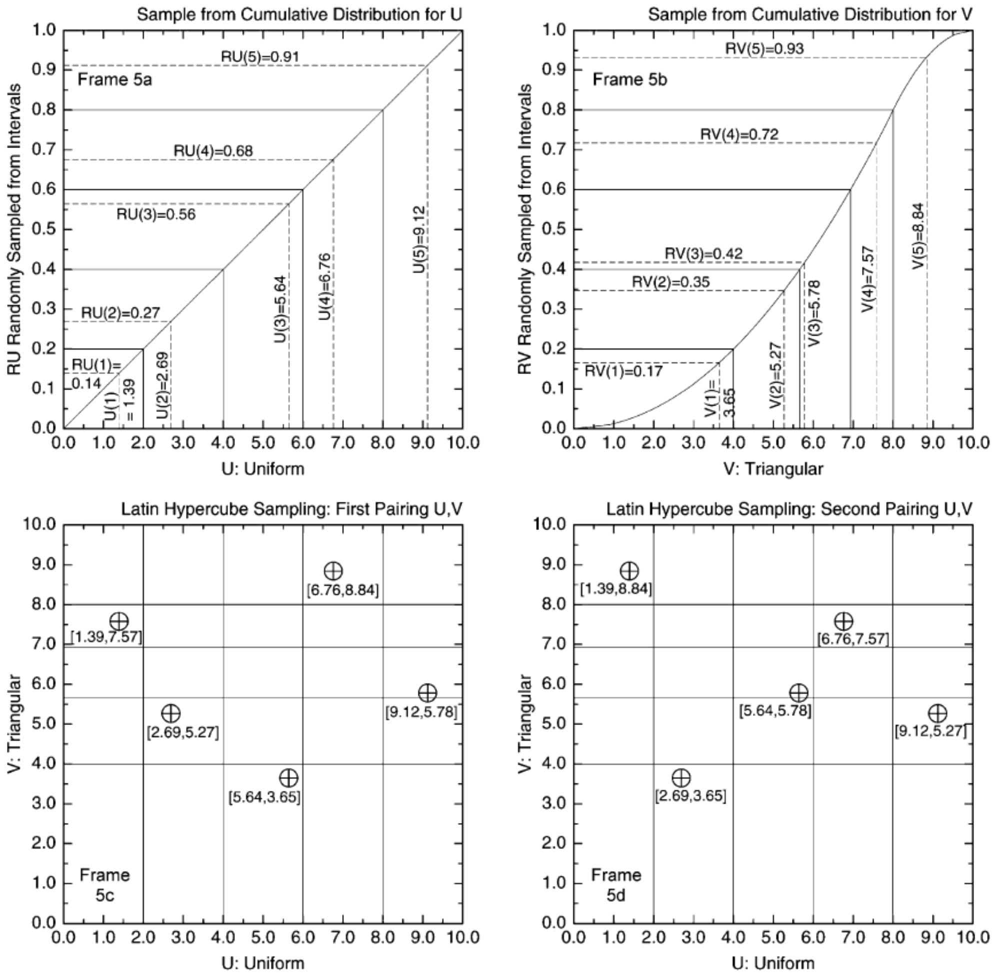


*Figure 8: Example of LH sampling to generate a sample of nS = 5 from **x** = [U,V]. From Helton and Davis (2003).*

#### *3.5.2.5 Interval mathematics*

Interval mathematics addresses uncertainty that arises due to (Kutscher and Schulze, 1993):

i. imprecise measurements
ii. the existence of several different methods, techniques or theories to estimate model parameters.

In many cases it is not possible to estimate the probabilities of different values of imprecision in data - in some cases only error bounds can be reported. This is especially true for conflicting theories for the estimation of model parameters. In these cases, interval mathematics can be used for uncertainty estimation as this method does not require information about the type of uncertainty in the parameters.

The main aim of interval analysis is to estimate the bounds on various model outputs based on the bounds of the inputs and parameters. Uncertain parameters are assumed to be unknown but bounded by upper and lower limits. If, for example, a parameter x is known to be between x+n and x-n, then the interval representation is given as [x-n, x+n]. Model estimates would belong to another interval. For some models, uncertainty can be propagated. For example, if two uncertain variables *a* and *b* are represented by the following intervals [$a_i$, $a_u$] and [$b_i$, $b_u$], then arithmetic operations are given:

$$a+b=\left[a_l+b_l,a_u+b_u\right]$$
$$a-b=\left[a_l-b_u,a_u-b_l\right]$$
$$a\cdot b=\left[\min\left\{a_l\cdot b_l,a_l\cdot b_u,a_u\cdot b_l,a_u\cdot b_u\right\},\max\left\{a_l\cdot b_l,a_l\cdot b_u,a_u\cdot b_l,a_u\cdot b_u\right\}\right]$$
$$\frac{a}{b}=\left[a_l,a_u\right]\cdot\left[\frac{1}{b_u},\frac{1}{b_l}\right]$$

(3.13-3.16)

The main advantage of interval mathematics is that it can address problems of uncertainty analysis that cannot be studied through probabilistic analysis. Thus, it is useful for cases in which a probability distribution is not known. However, this method is not ideal for the estimation of output uncertainty, as the uncertainties are forced into one interval (Kutscher and Schulze, 1993). If the probability structure of input parameters is known, interval mathematics is not recommended.

#### 3.5.2.6 *Fuzzy sets*

Fuzzy theory handles the sources of uncertainty that arise from vagueness or 'fuzziness' rather than from randomness. Fuzzy logic extends conventional logic by introducing the concept of partial truth - truth values between completely true and completely false. Fuzzy logic was introduced by Zadeh (1965) as a means of modelling the uncertainty of the natural language. Fuzzy theory uses 'fuzzification' to generalise any specific theory from a discrete to a continuous (fuzzy) form. In recent years fuzzy theory has been increasingly applied for a great number of engineering applications (Ross, 2004).

In standard set theory, each member of an element is defined in a discrete way - it is either a member, or it is not. However, in some systems, there are variables which cannot be so easily described. In such cases, uncertainty arises out of the vagueness involved in defining the attribute (e.g. 'tall' people) (Klir and Smith, 2001). Another instance, where fuzzy sets are useful is the inclusion of linguistic descriptions/definitions to set theory (e.g. the set of “good” solutions to a problem) (Ross, 2004). While classical set theory allows for one value *or* another, fuzzy theory allows for a gradual degree of membership, expressed as a membership function. This can be illustrated using an example from Isukapalli (1999).

In classical theory, the truth value of a statement can be given by the membership function $\mu_A(x)$ as:

$$\mu_A(x) = \begin{cases} 1 & iff \quad x \in A \\ 0 & iff \quad x \notin A \end{cases} \tag{3.17}$$

For example, a classically defined set may include 'all pipes whose failure probability is 0.1'. Therefore, all those elements that have a failure probability of 0.1 have a value of 1, while all those whose failure probability is not 0.1 have a value of 0.

On the other hand, fuzzy theory allows for a continuous value of $u_A(x)$ between 0 and 1:

$$\mu_A(x) = \begin{cases} 1 & iff \quad x \in A \\ 0 & iff \quad x \notin A \\ (0,1) & if \quad x \text{ partially belongs to } A \end{cases} \tag{3.18}$$

Here, the boundaries are not precisely defined, and fuzzy sets use a range or a set of probabilistic values to represent the probability, *p*. Associated with each probability in the range or set, a membership function is defined to express the grade, between 0 and 1, with which an analyst believes that the likelihood of the hazard is *p*. The difference between membership of a classical (crisp) set and a fuzzy set is shown graphically in Figure 9, where it can be seen that for the classical set, a number is either in the set (value = 1) or it is not (value = 0) if the value lies outside of the membership range.

In fuzzy sets, a value has a degree of membership, and the function to define this degree of membership can take many forms including monotonic and symmetric (shown in Figure 9). The difference illustrated in Figure 9, that crisp sets have a unique membership function value while fuzzy sets do not (i.e., it is a continuous function), is a key difference between these theories.

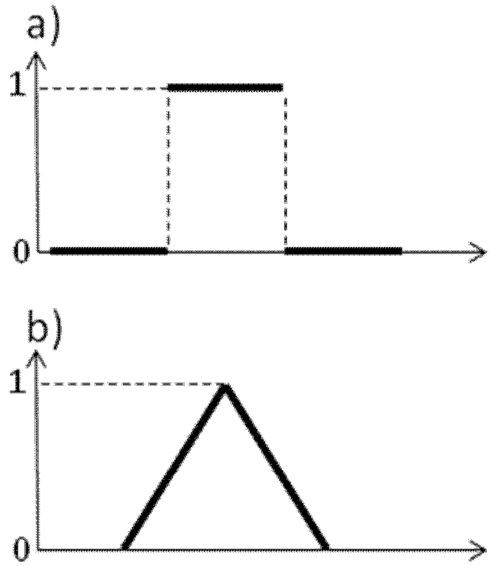


*Figure 9: Membership functions for a) a classical set and b) a fuzzy set (Adapted from Ross, 2004)*

As an example, a fuzzy set *A* can be defined as 'the set of pipes whose failure probabilities are about 0.1'. Because the condition is no longer strict as in the classical sense, it can be defined by a membership function $\mu_A(x)$ as in the example given above. Pipes with a failure probability of 0.1 will be given the highest grade, i.e. 1, while as the failure probability goes further from 0.1, the membership grade will decrease away from 1 according to the form of the function.

In fuzzy theory, statements have a range. Fuzzy sets can also be paired to the probabilistic approach by handling the situation where probabilities are not precisely known, which in practice is almost universal. At a first glance, fuzzy theory appears to be more suitable for qualitative reasoning and the classification of elements into fuzzy sets, rather than for quantitative estimation of uncertainty. It can also lead to quantitative risk assessment, especially through fuzzy inference theory leading to fuzzy aggregation, used in a combined approach with other multicriteria methods, such as Analytic Hierarchy Preference (AHP) method, so as to encapture and model linguistic preferences by the user (Sadiq and Husain, 2005).

Recently, however, fuzzy sets and fuzzy theory have been increasingly used for the development of the possibility theory (Dubois and Prade, 1998) and its mathematic expressions (Klir and Smith, 2001). Possibility and probability theory can be combined (Ross et al, 2002), leading to combined methodologies, i.e., fuzzy probability (Karimi and Hüllermeier 2007).

The latter has been applied successfully for the risk assessment of natural hazards, like earthquake damage (Karimi et al, 2007). It is a methodology suitable for assessing the risk of natural disasters, particularly under highly uncertain conditions, i.e. where neither the statistical data nor the physical knowledge required for a purely probabilistic risk analysis are sufficient. The theoretical foundation of the method is based on employing fuzzy set theory to complement the probability theory with an additional dimension of uncertainty, i.e. expressing likelihood by fuzzy probability (possibility-probability density functions) (Karimi and Hüllermeier 2007).

### 3.5.3 *Stochastic QRA - an introduction*

While deterministic QRA will yield the same output risk for any given set of inputs, stochastic QRA attempts to take into account the inherent uncertainty in the risk analysis process using the methods above. By using one or more of the methods described above, the uncertainty of each element in the risk analysis will be quantified. Thus, each model input will have either a range of values which represents the uncertainty as a probability distribution, or may take a mean value with a specified standard deviation or error (Babayan et al., 2005, 2006).

These uncertainties will be then taken into account during the stochastic QRA procedure, with the stochastic element being propagated through the risk assessment, so that for each model input, a range of outputs (most likely in some form of distribution) will be derived given the initial uncertainty. As a result, error or uncertainty can be quantified or at least reduced when it comes to the final calculation of total risk.

For Monte-Carlo-type methods, which are the most commonly used due to their flexibility and simplicity and have been often used in the literature for stochastic risk assessment in many different fields (Ma, 2002; Li et al., 2007; Sari et al., 2007; Chen et al., 2010), simulations are run many times for slightly varied input parameters, yielding variations on the original outputs (Sun et al., 2010; Behzadian et al., 2009). The alteration of the input parameters can either be based on statistical data if available, or an artificial range of values of can specified if inadequate data are available. The range of values to choose within usually follows a prescribed probability distribution (e.g. uniform, normal). Values will be chosen within this range to use as input to the MCS. A range of model outputs is thus given, and may be formulated into some probability function or the output can be stated as a mean with an estimation of the error or standard deviation (Cutore et al., 2008). In addition, some studies link the stochastic element captured in Monte-Carlo sampling to a fuzzy-based analysis, creating a powerful tool that can be applied to a more integrated risk analysis (e.g. Li et al., 2007; Chen et al., 2010). Such a methods may be very usefully applied for the Eindhoven case study in the PREPARED project.

Another model to introduce a stochastic element into risk assessment is the first order reliability model (FORM, Hamed, 2000). Because this method is used to address problems where the probability of failure and sensitivity information are sought it is not considered in detail here. In addition, a stochastic element is not directly modelled, rather a value for stochastic sensitivity is derived, which is a measure of the change in a value when a random variable is perturbed. Details of the FORM method are given in Hamed (2000).

In doing this uncertainty analysis as part of the stochastic QRA, a better understanding of the risk posed to urban water systems from climate change and the uncertainty surrounding future predictions will be gained (Kapelan et al., 2005b; Dorini et al., 2010). It will give policy makers a better idea of how best to mitigate the future issues that will arise as a result of climate and can help to decide where best to spend available resources so that the final mitigation options are the most cost-efficient possible while also providing the most robust future water network possible (Kapelan et al., 2006; De Marinis et al., 2009). In addition, uncertainty can be taken into account to some degree, and thus enhanced resilience built into the system under consideration, which in this case is the urban water system comprising the water distribution network and the waste water network (Kapelan et al., 2007; Woodward et al., 2010).

Within PREPARED, the models and methodologies selected for QRA for the specific case study related to the demonstration city (Eindhoven) will be implemented first as deterministic QRA models and consequently expanded to stochastic QRA models. The methodologies selected for application largely depend on the specific case study, the risks involved, the availability of statistical data, as well as the level of knowledge, system and data uncertainty.

# 4 Risk categories and risk event trees for water systems infrastructure

### 4.1 General risk categories for water systems with an emphasis on climate-change related risk

There are two main risk areas to consider when dealing with a public water system: water *quality* and water *quantity*. Both these aspects are important for the two main 'streams' (types) within urban water systems, namely the water supply and distribution networks (clean water systems) and the wastewater or stormwater networks (sewage systems).

Considering these streams separately, some potential generic risk categories related to urban water systems for analysis in this Work Package are outlined in Table 1. This list is probably not exhaustive, and indeed some of the effects of climate change on urban water systems are probably as yet unforeseen.

*Table 1: Outline of generic risk categories potentially affecting urban water systems*

| | **Urban water system 'stream'** | |
|---|---|---|
| | **Water supply and distribution** | **Wastewater and stormwater** |
| **Risk category** | Surface water (rivers, springs, lakes) | Storm water network (age, capacity) |
| | Groundwater (aquifer volume, quality) | Storm / flood protection system (capacity, condition) |
| | Water intake and transport (pipes, valves) | Sanitary network (age, capacity) or channels (capacity) |
| | Water treatment (plants, technology) | Pumps (back-ups, robustness) |
| | Reservoirs (operations, quality, volume, safety) | Retention basins (operations, robustness) |
| | Pipe network (age, capacity) | Waste water treatment plants (operation, location) |
| | Consumer points (taps) | Discharge pipes (location, age) |

Obviously, each element in the list above can be broken down further. For example, the pipe network can be broken down into individual components including pipes, valves, filters, etc. There is risk associated with each element.

For PREPARED, the main aim in Work Package 2.3 is to '*assess the social, environmental and economic type risks related to the sustainable performance of water supply/distribution and wastewater collection systems under the changing climate conditions*'. The sustainable performance of water supply/distribution systems and waste- and storm-water networks is explicitly made reference to. Table 1 outlines some general risk areas associated with these two systems. It is also in line with the latest trends in risk analysis for human settlements (UN-HABITAT, 2011).

The contents of Table 1 are further disaggregated so that the detailed impacts of climate change to each system are considered, and so that some of the potential risks to social, environmental and economic infrastructure are analysed. The results are outlined in Table 2 and Table 3. It should be pointed out that for all major risk categories, potential risks have been listed in three groups:

(a) Social risks, referring to the protection of public health and public safety
(b) Environmental risks, referring to the protection of the environment
(c) Economic risks

The first two categories are in accordance to the hazard lists in other Work Packages, i.e. WP2.1 and WP2.2 and the Water Cycle Safety Plan Framework. Economic risks are not mentioned there, but they need to be examined and taken into account for QRA (WP2.3) and WP2.4 (Risk Reduction), according also to the Description of Work. This classification has been the subject of extensive discussion among the leaders and participants of the work packages involved, in order to avoid misunderstandings and confusion. There may be further additions/modifications to this list as PREPARED progresses, while the lists are further examined with the help and cooperation of PREPARED cities.

*Table 2: Potential impacts posed by climate change on water supply and distribution systems. For each major risk category, social, environmental and economic type risks are considered.*

| **Water supply and distribution systems** | |
|---|---|
| **Major risk category** | **Potential risks posed by changing climate** |
| Surface water supply (e.g lakes, reservoirs, rivers) | *Social risks, referring to the protection of public health and public safety*<br>-potential of less water available leading to restrictions<br>-lowering of water quality<br>-health risks (increased occurrence of disease)<br>-price per unit of water may increase<br><br>*Environmental risks, referring to the protection of the environment*<br>-alteration of critical habitat<br>-degradation of the water supply<br>-lower or changed biodiversity<br>-alteration of the hydrological regime of catchments<br>-quality impacts to surface water<br><br>*Economic risks*<br>-increase in the cost of filtering / treating lower quality surface water<br>-more water may have to be imported to relieve potential shortages<br>-costs to infrastructure upgrades<br>-cost associated if a supply fails (for example, lost man-hours, compensation, clean-up efforts, insurance, etc) |
| Groundwater supply (e.g aquifer volume, water quality) | *Social risks Social risks, referring to the protection of public health and public safety*<br>-climate change may lead to more pumping of aquifers which may mean less overall supply<br>-less water in aquifers could lead to water quality issues<br>-the price per unit may increase<br><br>*Environmental risks, referring to the protection of the environment*<br>-the quality of aquifers may be affected |

| Water supply and distribution systems | |
|---|---|
| **Major risk category** | **Potential risks posed by changing climate** |
| | by climate change, for example by salination due to sea level rise / aquifer drawdown<br>-overexploitation of aquifers will have catchment-wide environmental effects<br><br>*Economic risks*<br>-the cost to recover groundwater could increase<br>-the cost to treat water could increase<br>- there is a cost associated if a supply fails (for example, lost man-hours, compensation, clean-up efforts, etc) |
| Water intake and transport (valves, pipes) | *Social risks, referring to the protection of public health and public safety*<br>-the price per unit may increase as improvements are required<br>-water supply may become less reliable<br><br>*Environmental risks, referring to the protection of the environment*<br>-more standing water could result in the proliferation of bacteria<br>-an increased frequency of extremes and any associated flooding may lead to environmental damage<br><br>*Economic risks*<br>-cost implications if the infrastructure needs upgrading |
| Supply water treatment plants | *Social risks, referring to the protection of public health and public safety*<br>-supply may falter in a warmer climate as a result of shortages<br>-bacterial / microbial growth may result in lower water quality<br><br>*Environmental risks, , referring to the protection of the environment*<br>-more intense storms may affect plant operation and water quality<br>- climate changes may impose changes to available water volumes altering habitats |

| **Water supply and distribution systems** | |
|---|---|
| **Major risk category** | **Potential risks posed by changing climate** |
| | *Economic risks*<br>-there are costs to upgrade and refurbish plants<br>-there may be risks to cost if utilities fail to meet demand quantity / quality |
| Reservoirs (operation, volume, quality) | *Social risks, referring to the protection of public health and public safety*<br>-less water in reservoirs may result in lower quality water<br>-less water or fewer reservoirs will mean fewer outdoor amenities<br>-lower water quantities may be available under a changing climate<br>-the unit price may be increased<br><br>*Environmental risks, , referring to the protection of the environment*<br>-changes to reservoir water quality will impact on local environment<br>-implications for reservoir fauna<br>-reservoir siltation may increase<br>-climate change will affect the hydrology of the water supply<br><br>*Economic*<br>-increased cost associated with reservoir upkeep<br>-climate change may mean that silts need cleaning more often by emptying the reservoir of, in some cases, flushing |
| Pipe network (age, condition) | *Social risks, referring to the protection of public health and public safety*<br>-climate change and increased frequency of intense storms may lead to increased pipe leak frequency and a less reliable supply<br>-if climate change alters pipe condition there may be quality issues<br><br>*Environmental risks, , referring to the protection of the environment*<br>-climate change may result in alterations to the chemistry of the water |

| Water supply and distribution systems | |
|---|---|
| **Major risk category** | **Potential risks posed by changing climate** |
| | -in drought periods, there will be less water in pipes which could lead to more siltation<br>-increased storm intensity may lead to more overflowing and flooding<br><br>*Economic risks*<br>-as a result of climate change, there may be an increased cost of refurbishment / improvement<br>- there is a cost associated if a supply fails (for example, lost man-hours, compensation, clean-up efforts, etc) |

*Table 3: Potential impacts posed by climate change on wastewater and stormwater networks. For each major risk category, social, environmental and economic type risks are considered.*

| Wastewater and stormwater networks | |
|---|---|
| **Major risk category** | **Potential risks posed by changing climate** |
| Storm water network (age, capacity, condition) | *Social risks, referring to the protection of public health and public safety*<br>-increased temperatures could lead to anaerobic conditions in pipes and the proliferation of bacteria with health impacts<br>-more intense storms could lead to increased frequency of overflow with corresponding flood impacts of foul water<br><br>*Environmental risks, , referring to the protection of the environment*<br>-pollution due to overflowing and due to microbial / bacterial growth<br>-changes to habitats due to microbial growth<br><br>*Economic risks*<br>-increased costs to improve capacity / lifespan of the network<br>-increased costs to maintain cleanliness<br>- cost associated if a service fails (for |

| Wastewater and stormwater networks | |
|---|---|
| **Major risk category** | **Potential risks posed by changing climate** |
| | example, lost man-hours, compensation, clean-up efforts, etc) |
| Storm/flood protection systems (capacity, condition) | *Social risks, referring to the protection of public health and public safety*<br>-sea level rise and more intense storms could lead to increased frequency of floods as barriers are overtopped<br><br>*Environmental, , referring to the protection of the environment*<br>-ever greater engineering efforts could impact local environment<br>-increased frequency of flooding may lead to habitat alterations<br><br>*Economic*<br>-increased costs to continually maintain and upgrade defence works<br>-the costs of clean-up efforts after floods/failure may increase and be more frequent |
| Sanitary network (age, capacity, condition) | *Social risks, referring to the protection of public health and public safety*<br><br>-sea level rise and increased frequency of intense storms could lead to overflow of this network leading to health issues<br>-changing personal habits may be enforced<br><br>*Environmental risks, , referring to the protection of the environment*<br>-climate chage may impact the local environment if this network was to overflow<br>-bacterial growth could proliferate<br><br>*Economic risks*<br>-there may be icnreased costs to upgrade pipes/filters/defence mechanisms<br>-costs of clean-up efforts after floods/failure may increase and be |

| Wastewater and stormwater networks | |
|---|---|
| **Major risk category** | **Potential risks posed by changing climate** |
| | more frequent |
| Pumps (back-ups, robustness) | *Social risks, referring to the protection of public health and public safety*<br>-failure of pumps (due to flooding, pollution) could result in sub-standard waste water removal / disposal = health impacts<br><br>*Environmental risks, , referring to the protection of the environment*<br>-if pumps fail, there is the potential for overflow and impacts to local environment<br><br>*Economic risks*<br>-the cost to replace and maintain pumps may increase<br>-the upgrade cost to ensure resilience may increase |
| Retention basins (operation, robustness, design criteria) | *Social risks, referring to the protection of public health and public safety*<br>-the increased frequency of storms may cause more floods / outbursts leading to health impacts<br>-lifestyles may need to change if basins get full<br><br>*Environmental risks, , referring to the protection of the environment*<br>-increased temperatures would encourage bacterial / microbial growth which would have ecosystem impacts<br><br>*Economic risks*<br>-increased cost for maintenance and to improve resilience<br>-costs to build new basins |
| Waste water treatment plants (location, defences, age) | *Social risks, referring to the protection of public health and public safety*<br>-there are high risks if these plants stop working or if fail to cope with increasing storm intensity etc.<br>-people may need to alter habits rather |

| Wastewater and stormwater networks | |
|---|---|
| **Major risk category** | **Potential risks posed by changing climate** |
| | than keep building capacity<br><br>*Environmental risks, , referring to the protection of the environment*<br>-if temperatures rise this may impact on the effectiveness of the plants to treat the water to a high standard<br><br>*Economic risks*<br>-increased costs required to improve and maintain plants<br>-increased or new costs to improve flood defences of WWTW<br>-cost associated with the need to increase resilience against increased pollutants / volume fluxes<br>- there is a cost associated if a supply fails (for example, lost man-hours, compensation, clean-up efforts, etc) |
| Discharge pipes (age, locations) | *Social risks, referring to the protection of public health and public safety*<br>-climate change, which may alter effluent quality and quantity may have knock-on effects on leisure activities if discharge pipes are located near beaches / rivers<br><br>*Environmental risks, , referring to the protection of the environment*<br>-pollution may increase if there are increased concentrations of bacteria / microbes / pollutants washed in to the system<br>-in times of drought, there is a risk that pipes may no longer be submerged<br><br>*Economic risks*<br>-an increased cost for maintenance<br>-cost of clean-up operations<br>-cost associated with monitoring outflows: there may be fines if laws not adhered to |

Failure of part of each system/element can now be considered, and a resulting ETA diagram (together with probabilities) can be drawn up. Some of the typical hazards which can impact water quality in a catchment (some may also affect quantity) are listed below (list adapted from Rosen et al., 2007):

*Catchment:*

- Farming
- Human activity
- Flushing of pollutants
- Nitrates/phosphates
- Oil spills
- Dam collapse
- Accident
- Sabotage

*Water treatment:*

- Power failure
- Inadequate microbial barrier
- Internal contamination

*Distribution:*

- Contamination (e.g. due to pipe breakage)
- Pipe breakage leading to supply shortage
- Sabotage

### 4.2 An example event tree for the risk to an urban water system

In this section, an example event tree analysis is undertaken. This is a completely hypothetical example, and has no relation to any real-world scenario. It has not been designed to illustrate an example from Eindhoven, but is used here for detailed illustration of the method. Hypothetical probabilities have been associated with each event in the tree, and the total probability of each outcome has been calculated. Thus, this is an example of a quantitative event tree analysis. This is also deterministic in the sense that for the initial event and subsequent sequence of events that occur, the exact same final probability is derived. There is no uncertainty associated with any element in the tree, although it could be included. Then, a range of final probabilities would be arrived at, with the actual probability lying somewhere within that range of uncertainty.

The hypothetical example presented (Figure 10) examines the events that may occur if *all* the clean-water supply pumps for a given region failed. A likely sequence of events is proposed, with probabilities assigned to each. The diagram is 'read' from left to right. The initiating event is total loss of all the supply pumps in a given region. This may then lead to a total lack of water supply. If supply fails, the first failsafe is the initiation of a back-up pump to restore supply. These pumps may or may not work, leading to the next barrier - the activation of an alarm system to alert manual workers who can then restore supply. Finally, the manual back-up may or may not work, either for safety, operational or logistical reasons. All these combinations lead to a series of different outcomes, each with its own probability (Figure 10). In the following paragraph detailing the scenarios and their final probabilities, all the probabilities are given as the frequency of the expected outcome per year. It is beyond the scope of this report to analyse ways for estimating probabilities. They are case specific and should be estimated prior to QRA. For instance, for a rainfall event, probability of occurrence may be estimated as the inverse of the return period T (in years), i.e., 1/T.

Firstly, the failure of the pumps may, for some reason, not lead to failure of the water supply, so there is minimal loss in service. The expected annual probability of this scenario is $10^{-3}$. Next, if there is loss of supply, and the back-up pumps fail, but if the alarm sounds and the manual intervention works, then there is some supply loss, but it is quickly restored by the intervention (probability $8.99 * 10^{-5}$). The next scenario is the same as the previous one except that manual intervention does not work for whatever reason ($8.99 * 10^{-9}$). The next scenario states that the back-up pumps fail, as does the alarm system. Here, there is total loss of supply with no intervention of any kind ($9 * 10^{-8}$). The next scenario assumes that the back-up pump works, and that the alarm works and that there is manual intervention, leading to minimal supply loss ($8.99 * 10^{-3}$). If the last scenario occurs but without the intervention, the probability is $8.9 * 10^{-7}$. Finally, if the back-up pumps work, but the alarm fails, then there is no intervention but a limited loss of service. The probability is $8.9 * 10^{-6}$.

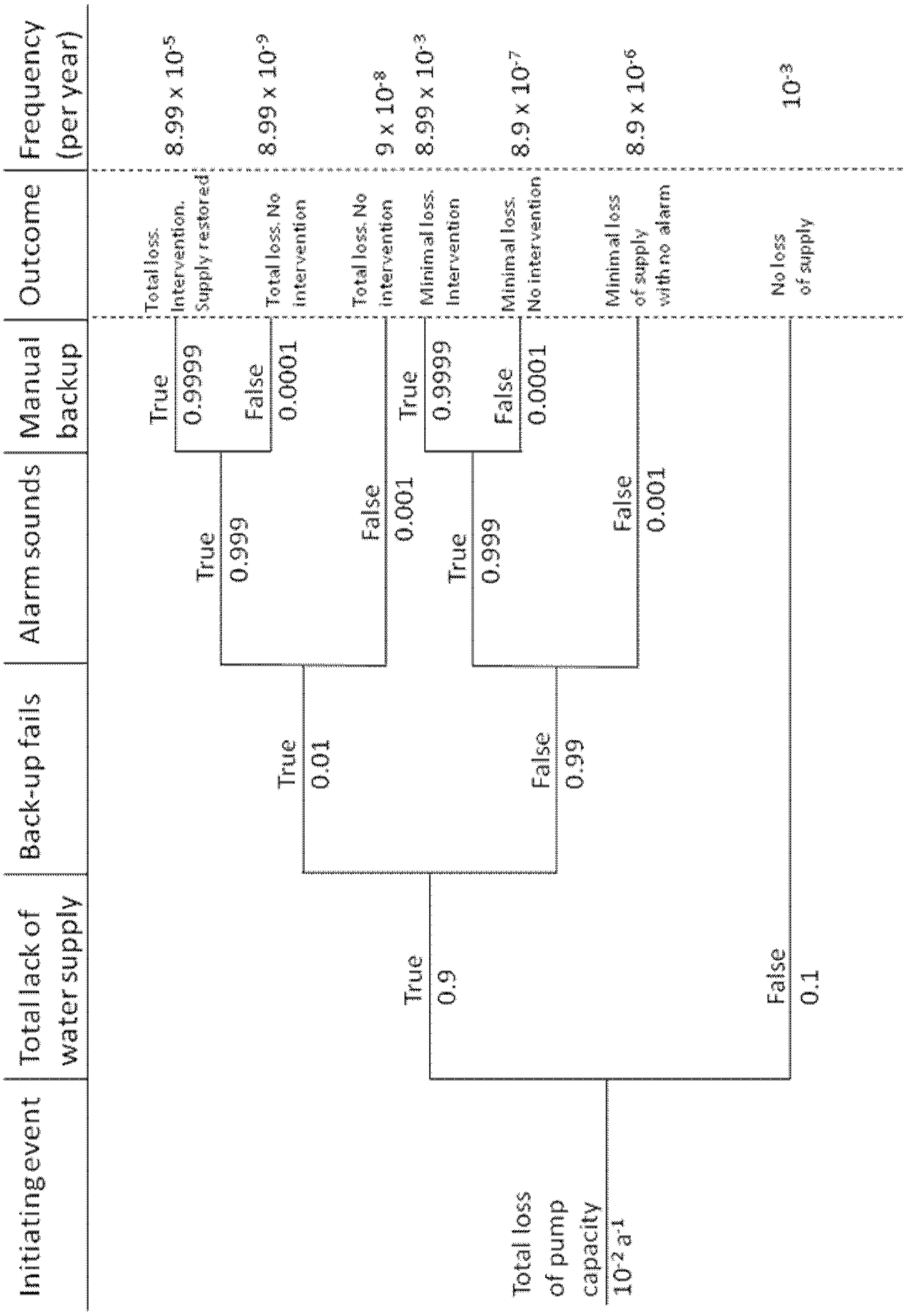


*Figure 10: Hypothetical event tree analysis diagram under the scenario of all the pumps for a water-supply system failing. A number of subsequent events with their probabilities are analysed, and final event probabilites are calculated.*

# 5 Conclusions

The area of risk assessment for water distribution systems is fraught with uncertainty. When this risk assessment involves considering the risks associated with the potential impacts of future climate change, the uncertainties are even greater. This is because there is considerable uncertainty in climate change estimates, whether this is in the prediction of temperature changes, or prediction in the probability in the amount of sea-level rise that a region may experience. In addition to these uncertainties are the uncertainties related to the water system. For example, the average or expected failure rate of certain components will be known, but there is of course uncertainty around these estimates. This may arise for example due to poor manufacturing of one particular component, extreme weather events shortening a components lifespan, human intervention, etc.

Risk is usually defined as a function (aggregation) of probability and consequences. Therefore the risk assessment must also take into account potential consequences posed by a hazardous event occurring. This arguably introduces even greater uncertainty than the estimation of the probability of occurrence of certain events. This is because some consequences are very difficult to quantify, while others may be impossible to quantify. For example, how can the impact to a person's wellbeing and health due to prolonged flooding or lack of access to clean water be quantified? Any metric developed attempting to quantify such values will be highly subjective and prone to serious uncertainty. Another example is the monetary quantification of the losses caused by certain hazardous events. The total loss in this sense is usually quite poorly known, and the estimated total is uncertain.

The aim of Work Package 2.3 in PREPARED is to develop quantitative ways to determine the risks posed to the functioning of urban water systems, in terms of social, environmental and economic type risks, by future changes to climatic conditions. The demonstration city for the Work Package will be Eindhoven, Netherlands, and so all the methods developed will be applied to Eindhoven as a demonstration city, with the aim that they can be extended to other PREPARED demonstration cities and then to any other city. Initially, this will be carried out through quantitative risk analysis (QRA) measures which will give as an output, single values of total risk, which will always be the same for the same inputs. Section 3.2 considered some of the most popular risk assessment methods. The most common used in water-systems analysis are:

- event tree analysis
- failure modes and effects analysis
- fault tree analysis
- hazard and operability analysis
- human reliability analysis
- preliminary hazard analysis

However, as mentioned above, there is considerable uncertainty when undertaking a risk assessment and therefore presenting a single fixed value for total risk is not sufficient in most cases. Therefore, the next stage will be to develop stochastic methods for QRA which will take to uncertainty associated with the inputs (i.e. that from both the estimation of the hazard probability and that associated with the estimation of the consequences) and propagate this through the QRA procedure such that the output values reflect the input uncertainty. This may be given by stating a range of total risk values, or by displaying total risk as a probability distribution, or by some other method.

The report has also introduced some potential general risk categories for examination in the context of urban water systems, and has broken these general categories down to analysis some potential risks posed by future climate change to social, environmental and economic sectors. For example a general risk category posed to water supply systems might be the risks posed to surface water features with are used to draw water for drinking. Breaking this category down, climate change may affect the volume or quality of this water, which may pose risks to the social (less water), environmental (habitat alteration) and economic (increased cost of filtration) sectors.

Eventually, the exact risks to the analysed in this Work Package will be developed in close cooperation with Eindhoven to ensure that the analysis focuses on the most pressing issues. As stated above however, the aim is to make the method extendable, so that it could be implemented in any PREPARED city. An example event tree analysis is presented as an example of what will be required for every hazard identified in the Eindhoven water system.

At the moment, the details of the critical risk categories to analyse, along with information regarding probabilities and consequences has not been defined from Eindhoven. It is anticipated that over the coming months, the necessary information will become available so that the Work Package can be completed in close relationship to a real case study provided by a PREPARED city. The exact major risk categories need to be fully defined by Eindhoven (who obviously have the expertise with regard to their water network, and who know what the major risks posed to their system are). Then, and also in cooperation with Eindhoven, the probabilities of different events occurring, along with the consequences of those events need to be quantified and the uncertainty clearly stated. From this, a full QRA can be accomplished for Eindhoven, which should ultimately be transferable to other PREPARED cities.

While this report was being finalised, a meeting was carried out between Eindhoven and UNEXE in April 2011. The aim was to discuss the collaboration between the partners and to initiate work. The meeting was successful, and significant progress was made. To summarise, Eindhoven will provide output water levels from an in-house hydrodynamic model and will specify precisely the risks to quantify. Two main areas of study were defined.

The first refers to impacts from rainfall events, with four different rainfall types being specified: (i) rain event with return period = 2 years; (ii) rain event with return period T = 100years; (iii) long duration events and ; (iv) an average event when considering the annual cycle. The impacts resulting from system malfunction (mechanical or constructional) were also considered important to analyse. The impacts of climate change will be assessed according to Dutch government climate projections as given in KNMI 2006. The main impact areas of concern were defined as economic, environmental, health and safety. It is hoped that UNEXE will receive further communication from Eindhoven, possibly with the delivery of the surface water levels by the end of May 2011, and work will proceed for the specific QRA model, which is due in a year's time.

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# 7 Appendix A

*Table 4: The most frequently used techniques for the risk analysis of water systems*

| Method | Summary | Comment |
|---|---|---|
| Event tree analysis (ETA) | A logical diagram which displays possible event sequences following an undesired event in the system | Commonly used in water systems analysis. Can be quantitative. |
| Failure modes and effects analysis | Technique of hazard identification and frequency analysis, analysing all kinds of failure modes of the (relevant part of the) system with respect to their effects on other parts of the system | Quite commonly used in water systems analysis. Can be quantitative. |
| Fault tree analysis (FTA) | Logic diagram that displays the relationship between an unwanted event in the system and the reasons for the event | Commonly used in water systems analysis. Can be quantitative. |
| Hazard and operability analysis (HAZOP) | Technique of hazard identification, systematically evaluating every part of the system in order to show how deviations from the intended operation may occur and whether these deviations will cause problems | Commonly used in water systems analysis, particularly treatment systems. Mainly qualitative. |
| Human reliability analysis | Technique of frequency analysis dealing with the human effect on the performance of the system | Not often used for water systems. Mainly qualitative. |
| Preliminary hazard analysis | Technique to identify hazards and frequency analysis that can be applied at an early stage of designing in order to identify hazards and assess their criticality | Not often used for water systems. Mainly qualitative, though a quantitative element could be added. |
| Checklists | List all possible effects of failure. Lists are never complete | Not often used for water systems. Qualitative. |
| What-if analysis | Asks what happens if certain (unwanted) actions affect a system. Potential measures are proposed to limit event occurrence | Not often used for water systems. Qualitative. |

| | | |
|---|---|---|
| Reliability block diagrams | Indicate relationship between failure rate and repair rate in a system through the use of a graphical compartment-style flow diagram | Could be used for water systems, and can be quantitative. |
| Hazard assessment and critical control points | Hazards, usually in a production line, are assessed. Control points (locations) are then identified with the aim of reducing the hazard | Not often used for water systems, more common in food processing lines. |
| Barriers and bow-tie diagrams | Links the unwanted event with both the causes and effects, but makes explicit reference to measures that may be put in place in order to prevent the cause leading to the event, or to ameliorate the effects of the event should it take place | Could be used for water systems. These are mainly qualitative. |
| Preliminary risk analysis | PRA is an accident-centred risk assessment approach, where the main aim is to characterise the risk associated with various accident scenarios. A systematic examination of the main issues is conducted by experts and stakeholders. Measures to reduce risk are proposed | Could be used for water systems. These are mainly qualitative. |