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Sustainable Water Management in the City of the Future

Integrated Project
Global Change and Ecosystems

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RE	Restricted to a group specified by the consortium (including the Commission	
CO	Confidential, only for members of the consortium (including the Commission Services)	

SWITCH DELIVERABLE: PhD THESIS

RISK AND UNCERTAINTY ANALYSIS FOR SUSTAINABLE URBAN WATER SYSTEMS
Audience This document presents a summary of PhD research undertaken on the above title. It provides brief information about the research work and contribution made for developing sustainable urban water systems for a city of the future. The final version of the thesis will be public after completion of necessary examination process from UNESCO-IHE and TU Delft, Netherlands in the near future. Consortium members and external audience will be invited to take this into account while doing the thematic research, and to give further feedback in the future.
Purpose This document informs about a summary of the contribution made on risk and uncertainty analysis for developing sustainable urban water systems. The main contribution of this research are i) identification of major global change pressures (e.g. climate change, population growth, urbanisation etc.) and their impact on urban water systems; ii) development of a new risk assessment framework, iii) a hybrid technique for the risk and uncertainty analysis and iv) computing tools that can be applied to analyze the integrated risk in urban water systems and to incorporate sustainability in the future urban water systems. Those contributions have been demonstrated by applying in a case of urban water systems in Birmingham UK.
Background This document builds on Deliverable 1.1.3(a, b & c) and more. The research outcome will be a step towards the development of the overall SWITCH approach.
Potential Impact This research focuses on how complexities and uncertainties associated in integrated urban water systems can be analysed. It provides a new framework of risk assessment that can analyse the risk of a component or sub-system or entire systems as per a need. It emphasises on identification and assessment of the future change pressures and a system approach of analysis for interconnected and interdependent urban water systems.
Issues Complete research document will be available after the PhD exam.
Recommendations Presently, this document provides an overview of the research work. It presents a brief summary, table of contents, future plan to complete the rest of work, and publication lists.

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1.0 Research Proposal (as approved by AB)

Please, see a separate attached file for the research proposal approved by academic board of UNESCO-IHE.

2.0 Draft Thesis

3.1 Summary of the thesis

Since the Brundtlands Commissions' report on our common future (WECD, 1987), awareness of sustainability has increased significantly among government, industry and the general public. Policymakers worldwide have sought to incorporate sustainability considerations in every aspect of the development program including urban water systems. It is widely accepted that any conception on sustainability must account for the interconnection of environmental, economic, and social factors, considers both local and global resources base, and attentive to the need of future generations. It is, therefore, important that knowledge of future dynamic change pressures (both internal and external), their impacts in UWS, system resilience relative to foreseen and unforeseen stressors, inherent risks and associated uncertainties will be helpful for the decision-making process while developing appropriate strategies for the sustainable UWS. The framework, techniques and tools developed to meet these objectives will enhance to analyse and incorporate sustainability in the existing systems as well as the possible alternative systems.

The subject of this research is risk and uncertainty analysis for the sustainable urban water systems. This research does neither focus on defining sustainability nor developing the measure for sustainability. However, it hypothesized that if any system fails to meet a minimum level of services or set performances requirement either for the present or in the future then the system will not be sustainable. The aim of this research is to develop a framework, techniques and tools for modelling risk and uncertainty that can be applied for developing the sustainable urban water systems. The outcomes of this research can be summarised as follows:

1. Review of risk and uncertainty assessment techniques and modelling theories that are suitable to integrated UWS;
2. Development of a hybrid hierarchical integrated risk assessment (H-HIRA) framework that can incorporates future change drivers, analyse uncertainties, computes integrated risk assessment of a complex and dynamic systems in different levels, and analyse a better strategy for coping the identified risk;
3. Identification of possible major future change drivers and sources of risk and uncertainties in UWS;
4. Development of a hybrid technique for uncertainty modelling based on evidence theory that allows to transform probability to possibility distribution;
5. Identification of multiple risk criterion and development of a fuzzy set based multi-criteria analysis technique to identify a better strategy during decision making under the risk;
6. Development of info-gap theory based decision making technique that can be applied to analyse a robust strategy during severe uncertainties and data limited cases;

7. Demonstration of the developed framework, techniques and tools for analysing the risk and uncertainty in different components of UWS.

This research defines risk as a combination of the likelihood of an undesirable event (e.g., drought, flood) occurring and its consequences (e.g., water scarcity, flood damage). Risk of interest in this research is strategic and technical risk in UWS due to the impacts of global change pressures. It will be described as a set of scenarios of hazards, likelihood of hazards, and severity for a specific time in a particular system. It assesses both hazards as well as vulnerability aspect of the risk.

A risk-based approach in the case of UWS involves analysing the likely impacts of future change pressures under a very wide range of future conditions. A basic goal of risk-based decision is to identify a strategy that is “a least regrettable” or “no regrettable” while meeting the other overall goals of a system. Risk assessment is a technical and scientific process by which the risks of given situations for a system are modelled and quantified. It includes risk analysis and risk evaluation. Risk analysis establishes, organizes and analyzes scientific knowledge and information for potentially hazardous events, activities, or substances that might pose risks under specified circumstances. It should inform about the exposures and vulnerabilities. Risk evaluation assess if the risk is acceptable or not. Based on the risk evaluation results, further strategies are developed to reduce the frequency of adverse events and to mitigate the consequences given their occurrence for the risk control/management.

Risk assessment methods are categorized according to whether a risk is determined by quantitative or qualitative analysis. Basically, qualitative risk analysis uses expert opinion to identify and evaluate the probability and consequence of a hazard. Commonly used qualitative techniques are safety review or audits, checklists, “what if” analysis, preliminary hazard analysis, and hazard and operability study. Quantitative analysis relies on statistical methods and databases to analyse the risk. Probabilistic risk analysis, failure modes and effects analysis, fault tree, and event tree are generally considered quantitative risk assessment techniques. Other methods such as diagraph/fault graph, Markov modelling, dynamic event log analytical methodology are advanced quantitative technique though applied for a specific operational failure and risk analysis. The selection of any method depends upon the availability of data for evaluating hazards and the vulnerabilities.

The UWS are interconnected, interdependent, large-scale and complex systems. A fundamental aspect of a complex system is their heterogeneous nature, hierarchical non-commensurable objectives, multiple decision makers, multiple transcending aspects, and elements of risk and uncertainty. Complex infrastructure systems are typically exposed to varieties of hazard sources and have a large number of possible failure modes, which often exhibit spatially and temporally variable consequences. Both qualitative and quantitative data are available and require for its analysis. For the further analysis, decision maker requires information of components, sub-systems and whole systems. To address this issue, a risk assessment framework has been developed based on a hybrid approach that allows to analyse the risk due to future change pressures, capture the associated uncertainties, address the complexities of UWS system by decomposing it into a hierarchical order of sub-system and components, and identify a robust strategy to cope the risk. Both probability and fuzzy set theory has been applied to process the data available for the risk assessment.

Uncertainty is the main issues of strategic risk analysis. Uncertainties arise from different sources and have different types. Uncertainty may result from imprecise knowledge, where the probabilities and extent of either the hazards and/or their associated consequences are unpredictable. Even when there is definite knowledge of these components, there will be still uncertainty because outcomes are determined probabilistically and it is still unknown if and when they will occur. The literature review on uncertainty suggests that probability theory and fuzzy set theory are the two most widely used theories for uncertainty representation in risk assessment. Probability theory assumes uncertainty mainly due to randomness, whereas fuzzy set theory assumes it due to vagueness (or fuzziness) and imprecision. In this research the Monte Carlo method and the Latin hypercube sampling are used as the standard techniques for uncertainty propagation in the probabilistic approach and alpha-cut for the fuzzy approach. This research employs the evidence based theory to transfer one from of the uncertainty information into the other (i.e., probability distribution into the fuzzy number or vice versa). The hybrid approach of uncertainty analysis will be flexible to capture the information available in a complex system like UWS.

The thesis investigates several global change drivers (internal and external) that can potentially impact to sustainable management of future UWS. Global change is related to changes in human life and environment due to impact of global dynamics. The global change addresses the geophysical, biological, chemical and ecological components, and categorise into social, economic and ecological dimensions. The review identifies nine major drivers of change including climate change, population growth and urbanisation, deterioration of infrastructure systems and more. However, the major change drivers considered in this research are climate change, population growth and urbanisation, and deterioration of infrastructure systems. DPSIR framework has been employed to analyse the sources of risks, uncertainties and risk control measures. It is a simple, broadly applied in other multidisciplinary research. It is a transparent framework that can be applied to complex systems, specifically to analyse the types of drivers, pressures, states, and impacts. It facilitates the analysis of socio-environmental systems in terms cause-effect links, their consequences for the UWS, and decisions to be taken to cope with them. The outcome of the DPSIR scoping analysis identifies the major sources of future drivers, sources of risk and uncertainties, and appropriate responses (adaption and mitigation) in different components of UWS that will be useful for the decision maker specially during the future planning.

This research develops the different approaches of decision making under risks and uncertainties. It argue that the decision making under the risks is the situation when there is sufficient information for the analysis and the uncertainties can be captured by the probability distribution function or fuzzy number. To determine the potential coping option for a specific types of risk, a fuzzy set theory based multi-criteria analysis is proposed. The multi-criteria used for the analysis are risk criterion that includes reliability, resiliency, vulnerability, and system costs. These criteria are represented by the fuzzy numbers and composite index is computed using fuzzy synthetic evaluation technique. The relative importance of available options or alternatives for adaptation or mitigation of the risks will be judged based on the composite index value.

This research develops an info-gap theory based technique for robust decision making during uncertainty. The decision making under the uncertainties is a condition where either the information for analysis is insufficient (data scarce situation) or the uncertainties cannot be described by probability and fuzzy set theory (presence of ignorance or severe uncertainties). This approach aims satisficing (always performing above a specified benchmark) the objectives which is measured by info-gap robustness function. The info-gap robustness function will evaluate on how wrong the decision can be without violating the requirement of acceptable performance. The option/strategy which ensures the maximum robustness value under uncertainties will be chosen for the decision. This technique can be helpful for the decision maker for robust decision making against the uncertainties associated to the complex dynamic system and uncertain future.

Three application examples are undertaken for the analysis. The first application is the risk of water availability in Birmingham in year 2050.It demonstrated the developed risk assessment framework for this application. The future demand of water is analysed considering the climate change, population growth, socioeconomic change, and water losses from the system. All the input parameters have been described either by probability and fuzzy number. For the propagation of the probability distribution function Monte Carlo and Latin hypercube sampling has been undertaken. The risk of future demand is analysed considering the existing water resources and future scenarios. The second application is for risk analysis of a water supply system. Due to unavailability of failure data, the illustration example only demonstrates the risk assessment framework on how it can be applied in a real case. The description of uncertainties and propagation is also demonstrated using water distribution network and assessing the performance in the future. The third application is related to decision making under severe uncertainties for pipe failures due to deterioration/ageing. It uses the pipe failures data of Birmingham, UK. The approach can sufficiently demonstrates on how a robust decision can be made during severe uncertainties.

This research has demonstrated that risk based decision making is one of the best approach for the sustainability. Knowledge on sources of future change drivers, analysis on impacts, risk and uncertainties can help to develop alternative strategies for the sustainable development. We conclude that the new H-HIRA framework of risk assessment and modelling can handle the major shortcoming of current risk assessment framework while dealing with complexities, multiple sources of hazards, different types/sources of uncertainties, recognition of system dynamism, and exploration the possible options for coping (adaptation and mitigation) for the identified risks in UWS. The multiple risk criteria analysis for decision making under the risk will be helpful for selecting the best alternative for the adaptation and sustainable development of UWS. The info-gap robustness analysis will search for the robust strategy that meets the minimum requirement set for a system. The results will be useful for decision making without regret or with least regret. The research also presents recommendations for future research and further development of risk assessment and modelling to improve the credibility of risk based decision making for sustainable UWS.

3.2 Table of contents and structure of thesis

Final thesis will be produced covering the following contents and structure.

3.2.1 Table of contents

(Size of thesis 200 -220 pages)

SUMMARY
List of figures
List of Tables
List of symbols

1 INTRODUCTION
1.1 Risk and Uncertainty Analysis in UWS
1.2 The Need for Risk and Uncertainty Analysis for Sustainable Urban Water Systems
1.3 Present State of Knowledge
1.4 Research Definition
1.4.1 Aim and objectives of the present research
1.4.2 Application examples
1.5 Outlines of the Thesis

2 REVIEWS ON RISK AND UNCERTAINTY ANALYSIS
2.1 Introduction
2.2 Risk and Uncertainty Analysis
2.2.1 Risk assessment, Risk perception and Risk Aversion
2.2.2 Risk, Reliability, Resiliency and Vulnerability
2.2.3 Risk and Uncertainty
2.3 Risk Assessment Methods
2.3.1 Qualitative techniques
2.3.2 Quantitative techniques
2.3.3 Hybrid techniques
2.4 Types and Sources of Uncertainties
2.4.1 Types of uncertainties in urban water systems
2.4.2 Sources of uncertainties in urban water systems
2.5 Theories of Uncertainty Representation
2.5.1 Probability theory based method
2.5.2 Fuzzy set theory based method
2.5.3 Possibility theory and Evidence theory
2.6 Decision Making Under Risk and Uncertainty
2.6.1 Multi-criteria analysis
2.6.2 Info-gap theory
2.7 Risk Assessment Framework
2.7.1 Basic concepts
2.7.2 Dealing with the complexities
2.7.3 Dealing with the uncertainties
2.7.4 Dealing with dynamic systems
2.7.5 A hybrid hierarchical integrated risk assessment (H-HIRA)
2.8 Summary

3 GLOBAL CHANGE PRESSURES AND SOURCES OF RISK AND UNCERTAINTIES IN UWS
3.1 Introduction

3.2 Major Global Change Pressures in UWS
3.3 Sources of Risk and Uncertainty in UWS Using DPSIR framework
3.3.1 Climate change
3.3.2 Population growth and urbanisation
3.3.3 Socio-economic changes
3.3.4 Deterioration of infrastructure systems
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4 RISKS AND UNCERTAINTY MODELLING FOR URBAN WATER SYSTEMS
4.1 Introduction
4.2 Quantitative Risk Modelling Techniques
4.2.1 Hierarchical Risk modelling
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4.3 Mathematical Modelling for Uncertainty Analysis
4.3.1 Scenario planning
4.3.2 Probability theory based methods
4.3.3 Monte Carlo simulation & Latin hypercube
4.3.4 Fuzzy set theory-based methods
4.5 Hybrid Technique of Uncertainty Modelling
4.5.1Operations on random and fuzzy variables
4.5.2 Probability–fuzzy transformations
4.5.3 Probability–fuzzy transformations using Evidence theory
4.6 Summary

5 DECISION MAKING UNDER RISK AND UNCERTAINTY
5.1 Introduction
5.2 Decision Making Under Risk
5.2.1 Reliability, Resiliency, and Vulnerability
5.2.2 Multi-criteria Analysis technique
5.2.3 Modelling of multi-criteria analysis for risk management
5.3 Decision Making Under Uncertainty
5.3.1 Info-gap theory of uncertainty analysis
5.3.2 Modelling of Info-gap theory for decision making under uncertainty
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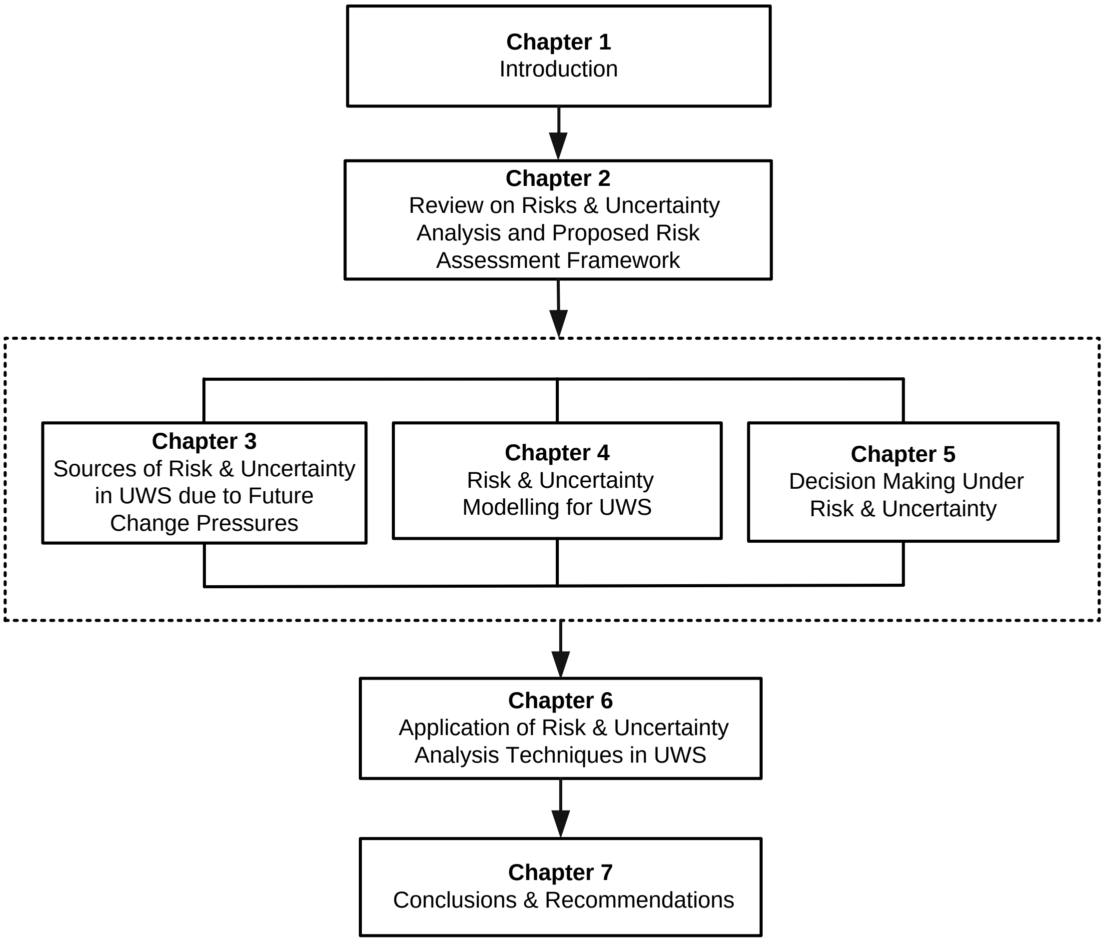
6 APPLICATIONS OF RISK AND UNCERTAINTY ANALYSIS IN URBAN WATER SYSTEM
6.1 Introduction
6.2 Application of H-HIRA for Water Demand Situation in Birmingham

6.3 Application of H-HIRA for a Water Supply System
6.4 Application of Info-gap Theory for Water Pipes Failures
6.5 Discussions and Conclusions

7 CONCLUSIONS AND RECCOMENDATIONS
7.1 Conclusions
- 7.1.1 Major global change pressures
- 7.1.2 Risk assessment framework
- 7.1.3 Risk assessment Technique
- 7.1.4 Uncertainty analysis
- 7.1.5 Decision making under risk and uncertainty

7.2 Recommendations

3.2.2 Structure of the thesis chapters



3.0 Planning for finalisation of thesis

SNo.	Activities	Date	Remarks
1	To finalise the final thesis (internal)	By the end of April 2010	The manuscript for the three journal papers are under the process
2	To finalise the final thesis (external)	By the end of May 2011	
3	Submission /examination process : (Formation of examination committee, taking exam date from the TU Delft, and exam/graduation program)	(May 2011 to September 2011)	

There is not any major deviation on research work from the early proposal.

4.0 List of publication

A) <u>Journal Paper</u>

- Khatri, K., Vairavamoorthy, K., and Akinyemi, E. (2010). A Framework for Computing a Performance Index of Urban Infrastructure Systems Using a Fuzzy Logic Approach. *ASCE Journal of infrastructure systems (In press).*

B) <u>Conferences and Proceedings</u>

- Khatri, K., and Vairavamoorthy, K (2010). A new approach of risk analysis for complex systems under future uncertainties: a case of urban water system. Accepted for international conference on vulnerability and risk analysis and management (ICVRAM) and ISUMA 2011 fifth international symposium on uncertainty modelling and analysis by ASCE, 2011 April (11-13), Maryland, USA.

- Khatri, K., and Vairavamoorthy, K (2010). A new approach of decision making under risk and uncertainty while selecting a robust strategy. Accepted for international conference on vulnerability and risk analysis and management (ICVRAM) and ISUMA 2011 fifth international symposium on uncertainty modelling and analysis by ASCE, 2011 April (11-13), Maryland, USA.

- Khatri, K., and Vairavamoorthy, K (2010). A hybrid approach of uncertainty analysis for performance measurement of water distribution system. Accepted for international conference on vulnerability and risk analysis and management (ICVRAM) and ISUMA 2011 fifth international symposium on uncertainty modelling and analysis by ASCE, 2011 April (11-13), Maryland, USA.

- Khatri, K., and Vairavamoorthy, K (2009). Water Demand Forecasting for the City of the Future against the Uncertainties and the Global Change Pressure: Case of Birmingham. Pro. EWRI/ASCE 2009 May (17-21), Kansas, USA.
- Vairavamoorthy, K., and Khatri, K., (2007). Risk Assessment for Sustainable Urban Water Management. UNESCO-IHP, (8-10-2007), UNESCO, Paris.
- Khatri, K., and Vairavamoorthy, K. (2007). Challenges for Urban Water Supply and Sanitation in the Developing Countries. Symposium 13-15 Jun, 50th Anniversary UNESCO-IHE, Delft.

C) <u>Book chapter</u>

- Khatri, K., Vairavamoorthy, K., and Porto, M. (2007) Challenges for Urban Water Supply and Sanitation in the Developing Countries. In G.J. Alaerts & Dickinson N.L. (Eds.), Water for Changing World, Developing Local Knowledge and Capacity. Delft, Netherlands.

D) <u>Briefing Note</u>

- Khatri, K., Van der Steen, P. and Vairavamoorthy, K. (2007). Climate Change: Accra-Ghana. Briefing paper, SWITCH, UNESCO-IHE, Delft.
- Khatri, K., Van der Steen, P. and Vairavamoorthy, K. (2007). Climate Change: Alexandria-Egypt. Briefing paper, SWITCH, UNESCO-IHE, Delft.
- Khatri, K., Vairavamoorthy, K. and Pathirana, P., (2007). Inventory of Important Global Change Pressures on Urban Water Systems in the City of the Future, White paper, 6th Framework, EU, SWITCH, UNESCO-IHE, Delft.

5.0 Approval by supervisors (signatures, comments)

The presented structure of the thesis and deadlines has been approved by promoter and supervisor of this research Professor Kalanithy Vairavamoorthy.

<u>Submitted by</u>

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