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Integrating Risk Management into the Water Planning and Management Industry


Keywords: Risk management framework, risk assessment, risk causes, risk controls, design of controls, and integrated risk modelling

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Executive Summary

This report presents a risk management framework for water planning and management. The framework is divided into four parts.

The first, overarching principle of the framework is the participation of all stakeholders in the risk management activities, including defining the boundaries, objectives, measurements, possible problems (system defects) and the expected values of the performance of the system at hand.

The second part is the risk assessment process, in which the hazards (events) and their associated vulnerabilities (impacts) for the whole system are identified. Understanding of the risks is further enhanced by identifying the causes of these hazards. The sequence of cause $\rightarrow$ hazard $\rightarrow$ vulnerability forms an impact chain. For each impact chain, technical methods such as event/fault/decision trees can be used to determine the magnitude of hazards and vulnerabilities and their likelihoods, and thus give the risk team a measurement of risk. Stakeholders contribute to the identification of the risk causes, hazards, vulnerabilities (which might be impacts to their physical assets, as well as to the environment, the economy and society). As the result of multiple impacts, multi-objective analysis is used to evaluate the overall risk. All stakeholders participate in the multi-objective evaluation, and are committed to the agreed outcomes.

The third part is the design of controls (processes, policy, devices, interventions etc.) that act to minimize negative risks or enhance positive opportunities. Controls are arranged in a coherent manner to form risk prevention or mitigation options. Controls in various options affect the evaluations of the impact chains differently, and thus offer a natural risk ranking method that extends beyond the base case evaluation established in the previous part. Stakeholders continue to contribute to harmonise the evaluation criteria and establish possible risk treatment options.

The fourth part is the iteration of and adjustments for parts 2 and 3 for the selection of an optimal solution using some form of multi-objective analysis.

The framework is described at two levels of detail. The coarse level presents the overall relationship between elemental components of the framework. For ease of reference, we adopt a set of mathematical notations to discuss the framework at this level of detail. The basic risk concepts and terms, such as hazard, vulnerability, cause, risk, impact chain, etc., are introduced.

The finer level presents the methodological steps for each stage of the framework. Where possible, relevant domain knowledge from water planning and management practice, and its related tools, are added to provide relevancy to the steps. It also addresses the use of computer domain models, if any, for the simulation and evaluation of risk.

Currently the risk management framework is generic. It depends heavily on domain knowledge and related frameworks, such as Integrated Water Resource Management.
(IWRM), Integrated Urban Water Management (IUWM), Water Sensitive Urban Design (WSUD), etc. to contribute to risk identification and design of controls. This paper lists an early attempt to collect and categorise patterns for the design of controls for risk mitigation.

In hindsight, the framework can be improved if the abstraction level is lowered to the domain of water planning and management. This refinement will help to specify the principles, steps and system considerations that are specific to water planning and management. This new approach is now under conceptualisation.

At the end of the report, this framework is compared with relevant risk frameworks to give the reader a perspective of where the ideas originate from.
# Table of Contents

Integrating Risk Management into the Water Planning and Management Industry......... 2  
Authors: .......................................................................................................................... 2  
Keywords: ................................................................................................................... 2  
Executive Summary .................................................................................................... 3  
1. Introduction ............................................................................................................ 6  
2. What is risk management? .................................................................................... 8  
3. When and where is risk management needed in water planning and management industry? .............................................................................................................. 10  
4. Elements in the integrated risk management framework ..................................... 11  
   4.1 Stage 1 - Risk Analysis .................................................................................... 11  
   4.2 Stage 2 - Formulating risk prevention, mitigation and preparedness measures . 14  
   4.3 Stage 3 - Comparing and adjusting risk prevention/mitigation measures and proposing a solution ........................................................................................................... 17  
5. Instruments for integrating risk management with water enterprise/community planning and management .......................................................... 17  
   5.1 Instruments and approaches in risk analysis (Stage 1) ...................................... 18  
   5.2 Computer modelling and simulation of risks ................................................... 19  
   5.3 Instruments and approaches in formulating risk prevention and mitigation scenarios (Stage 2) ............................................................................................................. 20  
   5.4 Instruments and approaches in comparing and adjusting scenarios for risk prevention and mitigation (Stage 3) ................................................................................. 25  
6. Control patterns for facilitating the development of risk management scenarios .... 26  
7. Comparison with other work ................................................................................ 27  
8. Summary ................................................................................................................ 29  
References.................................................................................................................... 31  
Appendix 1: Context categories for risk analysis and management ....................... 33  
Appendix 2: Sample causes (controls/factors), sorted by their objectives and context.34  
Appendix 3 Comparison of frameworks.................................................................. 35
1. Introduction

Managing risks in the water planning and management industry is fraught with difficulties. The process has three stages: first we must identify and assess the risks; then we propose plans to prevent or reduce the risks; and finally we have to implement the most acceptable plan to treat risks (AS/NZS 4360). Ideally, the process of risk assessment and planning leads to implementation. In reality, the chain of assess-plan-treat risks is often broken into two parts: the part of risk assessment and planning is carried out by consultants (expert process); and then decisions on implementation are determined by key stakeholders (a decision making process). There are many studies that assess risks, and many risk mitigation plan proposals. But during the necessary political process leading to implementation, many of these proposed plans will be shelved. Those that are not shelved are often modified and reduced before reaching the implementation stage. More often than not, due to the inability of parties with opposing interests to reach agreement, the final acceptable risk plan is reduced to a “business as usual” approach.

The Commonwealth Scientific Industrial Research Organisation (CSIRO) has identified six key issues impacting on risks to one of the country’s major river systems, the Murray Darling Basin. These issues are climate change, farm dams, ground water extractions, afforestation, bushfire and irrigation (van Dijk et al. 2006). All these issues have physical, social and economic dimensions; all interact, and all impact on the risk of supply failure. In dealing with such a complex and difficult picture there is an urgent need to re-examine the whole process of risk management. There is nothing wrong with current expert evaluation processes, which are based on scientific investigation. And there is nothing wrong with the political process of compromise, which is based on democratic and market principles. However, we need to make sure that both expert and political processes are well integrated so that: (1) the expert process considers the full implications to all stakeholders; and (2) the stakeholders involved in decision making have a holistic and well-informed picture of the risk issues that are facing them and do not lock into parochial positions (read “business as usual”).
Yum et al. 2007

Integrating Risk Management into the Water Planning and Management Industry

This paper presents a holistic framework of risk management for the water planning and management industry. The framework is generic in the sense that it is independent of any particular risk models, and is characterised by the following emphases:

1. Unified understanding of risks and commitment to risk mitigation: involving stakeholders throughout the process of risk assessment, planning and decision making so that all stakeholders understand the issues and become involved in the solutions.
2. Covering all significant risk causes emanating from various levels of operatives, including physical, social and economic influences.
3. Quantifiable assessment of risks: assessing risks in terms of probabilities of occurrence and measurements of impact (i.e. risk = \( \Sigma \) probability \( \times \) impact).
4. Integrating preventive controls\(^1\) or management measures into the enterprise routine and the community planning/development process.
5. Quantifiable assessment of risk mitigation plans: assessing scenarios of controls deployed to treat risks (i.e. scenario assessment = \( \Sigma \) probability \( \times \) impact).
6. Decision making on unified enterprise and community goals of risk management.

The conceptual framework of risk management presented in this paper is based on two separate risk frameworks. Stage one is risk analysis, which is derived from disaster risk management (Kolher et al. 2004). From the perspective of risk mitigation, the water planning and management industry in Australia shares a lot of common concerns with the natural disaster management industry, e.g. drought, flood, water quality, equity, resilience, biodiversity, etc. Both industries serve and protect their community from the perspective of public good while respecting established interests. Both share a future orientation, and are proactive rather than reactive. A lot of experience and practice in integrated disaster risk management can be adapted into the water planning and management industry.

Stage two is the formulation of alternative scenarios for risk prevention/mitigation, which is derived from the work of Blackmore (2005).

The current paper consists of 8 sections.

Section 2 introduces the concept of risk management, emphasising that the risk concept is related to damaging events that have not yet happened.

Section 3 identifies where and when risks are considered in today’s risk management practice. This section provides the groundwork of integrating risk management into water / community planning and management.

Section 4 presents the conceptual framework that is the core of this paper.

\(^1\) Control is an existing process, policy, device, practice or other action that acts to minimize negative risk or enhance positive opportunities. It may be also refer to a process designed to provide reasonable assurance regarding the achievement of objectives (AS 4360). Community perception, or "outrage", is itself a control, since it influences the performance of the system by interacting with other controls and it can be changed by experience, education and knowledge.
The gist of integration is that, during the risk assessment stage, two complementary evaluation tasks are performed together: (1) evaluating hazards and their impacts on vulnerable people or assets, given nothing has been modified; and (2) identifying and evaluating the deployment of controls to (re-) design the structural or non-structural systems/components in water planning and management so as to prevent or reduce hazards and vulnerabilities. See Section 5.

Studying and arranging controls to prevent or reduce risks is a key method of the framework. The quality of risk management can be further enhanced if the essential controls can be categorised and presented to the planners or operators of the industry as tools of various water planning and management frameworks (see Section 6.)

Section 7 compares the current framework with other related approaches. Finally Section 8 summarises present and future work derived from the current study.

2. What is risk management?

The terms risk and risk management have diverse meanings in various contexts. This paper adopts the following definitions:

Risk management is a process in which the tuple of elements \( (A, X, H, V, C, R, S, \mu_H, \mu_V, \mu_R) \), are identified, determined and evaluated in steps, where

- \( A \) (Area) is a non-empty set of locations \((x, y)\) in which the study takes place;
- \( X \) (Extent) is a set of one or more extents (levels of detail) within which the study is conducted (individual building scale, allotment scale, cluster scale, urban scale, catchment scale, regional scale);\(^2\)
- \( H \) is the set of all hazards/events considered in all scenarios \( S \) (see below);
- \( V \) is the set of all vulnerabilities in all scenarios \( S \);
- \( C \) is the set of all causes of hazards/events and vulnerabilities in all scenarios \( S \);
- \( S \) is the set of all scenarios identified in the risk management process; \( \mu_H \) is a hazard measure function from \( H \) to \([0, 1]\), which maps each hazard \( h \) to the probability of its occurrence at location \((x, y)\); \( \mu_V \) is a vulnerability measure function from \( H \) to \((\infty, \infty)\), which provides the measure of vulnerability \( v \) susceptible to the hazard \( h \) at location \((x, y)\).

\(^2\) From now on every consideration of locations, hazards, vulnerabilities and their measures is implicitly based on an appropriate extent \( x \) at the early part of RA. For the sake of simplicity, the reference to an extent \( x \) is no longer mentioned, but it is always there.
\(\mu_s\) is a measure function from \(S\) \(A\) to \((-\infty, \infty)\), which provides the expected damage of all hazards and vulnerabilities at location \((x, y)\) \(A\) for all scenarios \(S\).

- **Risk** is the chance of something happening that will have an impact upon objectives (AS 4360:2004). Risk is often specified in terms of events and consequences that may flow from them. Risk is measured as a combination of consequences and their likelihood (see the next dot point).

- A risk event has two components, i.e. hazard and vulnerability. Hazard is measured by the probability of the (risk) event at location \((x, y)\) \(A\), i.e., \(\mu_H : H \ A \ \mathbb{R}^+ \ [0, 1]\).\(^3\) Vulnerability is measured by the function \(\mu_V : H \ V \ A \ \mathbb{R}^+ \ [0, \infty)\), which offers the value of damage to the vulnerable \(v\) \(V\) if the hazard \(h\) \(H\) occurs at \((x, y)\) \(A\).\(^4\) Damage is mainly measured along four dimensions: physical, environmental, social and economic. Analytically risk is the sum of the product of probability of occurrence and magnitude of damage:

\[
\text{Risk} = \text{hazard} \times \text{vulnerability at any single location (Kohler et al. 2004),}
\]

or, when a risk scenario is disaggregated to an area \{(x, y) \(A)\}:

\[
\mu_S (S, x, y) = \sum_{h} \mu_H (h, x, y) \times \mu_V (h, v, x, y),
\]

where the summation of \(h\) and \(v\) are over all hazards and vulnerability elements in the scenario \(S\).\(^5\)

Figure 1 shows the containment relationship between risk management and the rest of the world. This document focuses on preventative risk management before the occurrence of a hazardous event.

Essentially **risk management** is a management process that is taken **before** the occurrence of the (risk) event. The result of risk management is a collection of recommendations for a risk prevention/mitigation plan, and, preferably, an associated implementation of the plan. In this paper, emergency responses and reconstruction/recovery are outside the scope of risk management as they are activities after the occurrence of the (risk) event.

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\(^3\) When there is no quantitative measure of probability of the hazard, the values of the measure function \(\mu_H\) can become discrete, e.g. \(\mu_H : H \ A \mathbb{R}^+ \ {1(very\ low), 2(low), 3(medium), 4(high), 5(very\ high)}\). In this case expert opinions are relied on to provide the measurement.

\(^4\) When there is no quantitative measure of vulnerability, the values of the measure function \(\mu_V\) can become discrete, e.g. \(\mu_V : H \ V \ A \mathbb{R}^+ \ {1(very\ low), 2(low), 3(medium), 4(high), 5(very\ high)}\). In this case expert opinions are relied on to provide the measurement.

\(^5\) If measures \(\mu_H (h, x, y) \times \mu_V (h, v, x, y)\), where \(h\) \(H\) and \(v\) \(V\), are in non-compatible measure units and cannot be added together (e.g. one is in \$ and the other is in ML), multiple evaluations will be carried out across various scenarios \(S\).

The vulnerability of the exposed population might also contribute to the frequency of occurrence of the consequence – their vulnerability might be cyclic, for example.
3. When and where is risk management needed in water planning and management industry?

There are two types of risk management: (1) managing risks during project development, and (2) managing risks during the lifetime of a product, a process, or infrastructure long after its development. This paper focuses on the second type of risk management for the water planning and management industry. “Water system” is a socio-technical system that cannot be restricted to any project in any enterprise.

In disaster risk management there is a shift of emphasis from crisis response to factoring risk prevention / mitigation mechanisms into development planning (Cardona, et al. 2003, Godschalk et al. 1998.) The authors of this paper believe that a similar shift should happen in the “water system”. In the water planning and management industry, risk management considerations should be integrated into (i.e. designed and built into) their products, processes and services. This makes risk management directly relevant to two whole of enterprise /community considerations: (1) strategic planning and management,
Yum et al. 2007
Integrating Risk Management into the Water Planning and Management Industry

(2) operational planning and management. Generally speaking, enterprise development considerations are of a shorter time frame (1-5 years), whereas community considerations will focus on long life impacts (tens of years to hundreds of years). As a result, sustainability is a “must” consideration in community planning and management.

4. Elements in the integrated risk management framework

The following figure shows the proposed risk management framework used in this paper. The framework consists of the following stages:

Figure 2: Key stages in the integrated risk management framework. Dash arrows represent contextual influences. Continuous arrows represent information flow. The diagram shows that risk management (light blue) is considered under the context of water/community planning and management (deeper blue).

4.1 Stage 1 - Risk Analysis

Risk analysis (RA) is the basic stage of risk management which is used to study the causes and measurement of risks and provide the basis of planning and implementing measures to prevent or reduce risks (Kohler et al. 2004, pp. 23-28).

Before RA analysis is performed, the context of the problem must be established: What are the objectives of the RA (water supply, demand, storage, quality, etc.)? What is the scope of the study? Who are the key stakeholders (household, industry, farm, water

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6 For private companies, risk management is integrated with enterprise planning and management. For the government and local communities, risk management is integrated with community planning and management. For public or independent water authorities, risk management has been aligned with both communal and enterprise planning/management.

7 We always assume that there are feedback and/or feed forward links between these stages.
licensee, state/territory government, Federal government)? At which geospatial level should the issues be tackled (allotment, precinct, reach, catchment, region)? Appendix 1 lists some context categories for easy reference. Each category is associated with some likely water management frameworks (e.g. IWRM, IUWM and WSUD) and related control components. RA is only related to column 1 of the table in Appendix 1. Column 2 of the table lists management issues (e.g. see Lawrence 2001). The management issues will be considered later in Stage 2 of this framework.

After establishing the context, RA can be carried out in two steps: Hazard analysis and vulnerability analysis. See also Section 5.1 for details.

Hazard analysis describes and assesses the following aspects of hazards: (1) Analysis of spatial location and extent (location A, extent X), (2) temporal analysis (frequency, duration and probability of occurrence), and (3) dimensional analysis (scale, intensity).

Vulnerability analysis studies damage (consequence) to populations and systems/elements when the hazard event occurs. It provides the following results: (1) identification of populations and systems/elements that are potentially at risk, (2) identification of causes of vulnerability \(^8\) \((H_R \text{ and } C_R)\), (3) analysis of the resilience of the vulnerable population \(^9\), and (4) assessment of potential damage/loss.

A key concept in RA is the impact chain that helps to identify hazards, vulnerabilities, their causes and relationships. Both hazard and vulnerability must be simultaneously present at the same location to give rise to risk scenarios. Both hazard and vulnerability have causes and they must be identified. The causes of hazard and vulnerability set off an impact chain. Figure 3 shows the impact chain of the risk of inadequate (and adequate) supply of river water to farmers. Different hazards have impact chains of various lengths.

Describing the risk in terms of impact chains (causes \(\leadsto\) hazards \(\leadsto\) vulnerability) offers the risk team (including stakeholders) a causal network of dependencies. Technical methodologies such as event/fault/decision trees can be used to determine the magnitude of hazards and vulnerabilities and thus give the risk team a measurement of risk.

The totality of causes, hazards, vulnerabilities and their dependency relationship (impact chain) forms the base scenario of our risk management framework. Formally, the risk (base) scenario \(R\) is represented by the tuple:

\[ R = (C_R, H_R, V_R, >_R, \mu_{HR}, \mu_{VR}, \mu_R) \]

- \(C_R\) is the set of all causes identified in scenario \(R\);
- \(H_R\) is the set of all hazards in scenario \(R\); and

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\(^8\) Causes of vulnerability are the causes that influence the vulnerability of people, systems/elements under consideration. There are four basic types of causes of vulnerability: physical, economic, social and environmental. As with causes of events, there is an associated frequency of occurrence.

\(^9\) This is a separate area of study that is not yet specifically included in most risk assessments. Detailed consideration of evaluation of resilience is being considered by the eWater Risk and Resilience Team, but is outside the scope of this paper.
Integrating Risk Management into the Water Planning and Management Industry

$V_R$ is the set of all vulnerabilities in scenario $R$; and

$\succ_R (C, H, V)$ is a partial order relation that represents the impact chains from causes to hazards and vulnerabilities;

$\mu_{HR}$ is the measure function on the hazards in scenario $R$ from $H_R$ to $[0, 1]$ such that $\mu_{HR}(h, x, y) = \text{probability}(h \mid (x, y) \in A)$ for all $h \in H_R$;

$\mu_{VR}$ is the measure function on the vulnerability in scenario $R$ from $H_R V_R A$ to $(-\infty, \infty)$ such that $\mu_{VR}(h, v, x, y) = \text{damage to vulnerability } v \in V_R \text{ susceptible to hazard } h \in H_R \text{ at location } (x, y)$;

$\mu_R(R, x, y)$ is the measure function from $S$ to $(-\infty, \infty)$, which measures the expected damage over all possible hazards and associated vulnerabilities at location $(x, y)$ for the base scenario $R$.

Section 5 will show the stages of developing the risk (base) scenario and when to fill in the missing items/values for the tuple $(C_R, H_R, V_R, \succ_R, \mu_{HR}, \mu_{VR}, \mu_R)$.

The bulk of work in Stage 1 is to identify hazards and their vulnerability (downward impacts). As a point of divergence from the conventional risk analysis approach, the framework also considers the causes of hazards and vulnerabilities, thus preparing the groundwork for developing strategies and measures of risk prevention and mitigation (Section 4.2.)

Figure 3: Impact chain identifying direct physical hazards, their impacts on the vulnerable and the causes of risk (Stages 1 & 2). Thick (red) arrows indicate the impact chain. Dashed thin (black) arrows indicate influences. Boxes with shadow represent the integrated risk management considerations of risk management (light blue) and enterprise/community planning and management (deeper blue).

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1 Here, in $\mu_R(R, x, y)$, $R$ (representing the base scenario) is not a running variable in $S$. It is a constant.
4.2 Stage 2 - Formulating risk prevention, mitigation and preparedness measures

The primary method of formulating risk prevention and mitigation measures in this framework is to examine the causes of hazards and vulnerabilities, and organise or design an alternative set of controls that will have impacts on the causes and thus prevent or reduce the hazards/vulnerabilities. From this perspective, Stage 2 is a synthesis process (design/management planning), while Stage 1 is an analysis process (decomposing risk into components: causes, hazards, vulnerabilities and their dependency relationships.) The design, planning and selection of controls are guided by a set of objectives, which include objectives of risk prevention and mitigation, plus relevant enterprise/community objectives such as IWRM, IUWM, WSUD, etc. (see Subsection 5.3 below.) The process of design of controls can be facilitated if related tool boxes are made available to help the
Yum et al. 2007
Integrating Risk Management into the Water Planning and Management Industry

designer/planner/operators to select the controls to meet the objectives. Column 2 of Appendix 1 lists some controls that can be considered under the associated contexts.

In risk management, the concepts of risk cause and control are related but should be distinguished. Risk causes are causal factors that give rise to respective hazards/vulnerabilities. Controls are processes or physical devices designed to reduce or remove the causes and impacts of risk. For example, in a supply-demand water balance model, “inefficient use of clean water” is a cause of the hazard “higher than necessary demand of clean water”. Installation of a rainwater tank then is a control that is designed to reduce or remove the cause “inefficient use of clean water”. Emergency response and recovery are also controls that reduce impact.

The relationship between controls and their associated risk causes and impacts is a complex one. There are usually more controls than causes, meaning that controls can work together to reduce the chance and impact of occurrence of risks. For example, the controls “rainwater use” and “community education” can work together to offer an alternative water source for gardening and toilet flushing and thus reduce the hazard “higher than necessary demand of clean water” and its impact on households (e.g. DSE 2007).

There are risk causes that cannot be controlled or manipulated by humans (e.g. rainfall, temperature, river, hill side slope, etc.) The main game of risk mitigation is to deploy layers of overlapping controls to reduce the causal factors of risk.

In hazard reduction (reducing the occurrence of hazard events), depending on the level of consideration, the controls include: spatial planning (to protect against landslide), land use planning (arrangement of dry land, forest, agriculture, urban development in catchments), settlement planning (to avoid flood, drought, etc.), sustainable resource management (e.g. Integrated Water Resource Management (IWRM), Integrated Urban Water Management (IUWM), Water Sensitive Urban Design (WSUD)), drainage, dams, afforestation, (to manage storm water and reduce land/mud slides), riparian buffers (to reduce pollutant inputs to streams), codes and regulations (to reduce incidences of failure, thus reduce hazards), and etc.

In vulnerability reduction (reducing the impacts), measures include: spatial and settlement planning (to reduce damage to settlers), sustainable agriculture (to conserve water), training, integrating risk management into the community, building codes, regional development policy and planning, water rights, community participation, and etc.

Controls affect risk causes and the causes affect hazards (probabilities of occurrence) and vulnerabilities (impacts on physical assets, populations, the economy and the environment). Therefore the appropriateness of control deployment can be measured in terms of their effects on hazards and vulnerabilities that are identified in the risk assessment stage. Different sets of controls may produce different results. For example, the council may like to know which is the most cost effective way of saving water out of the following sets of controls:
Yum et al. 2007
Integrating Risk Management into the Water Planning and Management Industry

- Business as usual
- Rain water tanks (RWT) for gardening and toilet flushing only
- RWT together with reticulation of recycled grey water,

And how much rebate should the council consider for householders willing to install these systems?

A self-consistent set of controls which are able to produce effects on hazards and vulnerabilities is called a scenario.

Stage 2 results in a collection $S$ of scenarios, in which the previously examined risk (base) scenario $R$ is a member. All scenarios are represented similarly, i.e. each scenario $S$ $S$ is represented by the tuple:

$$S = (C_S, H_S, V_S, \succ_S, \mu_{HS}, \mu_{VS}, \mu_S)$$

where

- $C_S$ is the set of all causes identified in scenario $S$;
- $H_S$ is the set of all hazards in scenario $S$; and
- $V_S$ is the set of all vulnerabilities in scenario $S$; and
- $\succ_S (C_H V) (H V)$ is a partial order relation that represents the impact chains from causes to hazards and vulnerabilities in scenario $S$;

- $\mu_{HS}$ is the measure function on the hazards in scenario $S$ from $H_R$ to $[0, 1]$ such that $\mu_{HS} (h, x, y) = \text{probability} (h | (x, y) A)$ for all $h$ $H_S$;

- $\mu_{VS}$ is the function on the vulnerability in scenario $R$ from $H_S V_S A$ to $(-\infty, \infty)$ such that $\mu_{VS} (h, v, x, y) = \text{damage to vulnerability} v V_S$ susceptible to hazard $h H_S$ at location $(x, y)$;

- $\mu_S (S, x, y) = \text{expected damage over all possible hazards and associated vulnerabilities} = \sum_h \sum_v \mu_{HS} (h, x, y) \mu_{VS} (h, v, x, y)$ where the summation is over every hazard $h H_S$ and every vulnerability $v V_S$ in the risk scenario $S$.

Stage 2 (formulating risk prevention and mitigation measures) is a complex process, which is at least as complex as the risk analysis (RA) stage. Section 5 below will provide a set of relevant instruments that integrate both the RA stage and the stage of formulating risk prevention/mitigation measures. Iteratively stepping through these instruments will produce a set of scenarios, which will be passed to Stage 3 for comprehensive comparisons and suitable adjustments.

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11 The set $C$ of all causes considered in Steps 1 and 2 should at least cover all causes included in $C_S$ for all scenarios $S$ $S$, possibly with much more choices that have not included in any of $C_S$. This is also true for the sets $H$ and $V$. 

P.16
4.3 Stage 3 - Comparing and adjusting risk prevention/mitigation measures and proposing a solution

This stage involves: (1) comparisons of scenarios, (2) adjusting controls to improve risk prevention/mitigation scenarios, and (3) finalising a satisficing\textsuperscript{12} solution. Since the base scenario and the alternative scenarios are developed and examined at different times, there may be a need to repeat the scenario establishment stages several times. The following (auditing) identities help to verify the consistency of the concepts:

\[ \bigcup_{S} H_{S} \; H, \text{ where } S \text{ runs over all scenarios } S \; S. \]
\[ \bigcup_{S} V_{S} \; V, \text{ where } S \text{ runs over all scenarios } S \; S. \]
\[ \bigcup_{S} C_{S} \; C, \text{ where } S \text{ runs over all scenarios } S \; S. \]
\[ \mu_{H}(h, x, y) = \mu_{HS}(h, x, y), \text{ for any } h \in H_{S} \text{ for some scenario } S \; S. \]
\[ \mu_{V}(h, v, x, y) = \mu_{VS}(h, v, x, y), \text{ for any } h \in H_{S}, \text{ any } v \in V_{S} \text{ for some scenario } S \; S. \]
\[ \mu_{S}(S, x, y) = \mu_{S}(S, x, y) \text{ for some scenario } S \; S. \]

5. Instruments for integrating risk management with water enterprise/community planning and management

Before moving on to discuss the instruments that help flesh out the details in the risk management tuple \((A, X, H, V, C, R, S, \mu_{H}, \mu_{V}, \mu_{R})\), we summarise the goals of the main framework stages as follows.

The aim of RA (Stage 1) is to establish the risk scenario, in which the impact chain of hazards and vulnerabilities is identified and the risks are preliminarily assessed, i.e., to identify and fill in elements in the risk (base) scenario in Subsection 4.1:

\[ R = (C_{R}, H_{R}, V_{R}, >_{R}, \mu_{HR}, \mu_{VR}, \mu_{R}) \]

The aim of Stage 2 is to establish alternative scenarios that are claimed to prevent/reduce risks, i.e., to identify and fill in elements in all established scenarios in Subsection 4.2 (including the base scenario):

\[ S = (C_{S}, H_{S}, V_{S}, >_{S}, \mu_{HS}, \mu_{VS}, \mu_{S}) \text{ where } S \; S. \]

Stage 3 is to compare the measures \(\mu_{S}\) across all scenarios \(S \; S\). If needed, adjustments to scenarios via controls are carried out to improve the risk prevention/mitigation scenarios. As noted in Footnote 4, if measures of hazards and vulnerabilities are coming from different domains, for each \(S \; S\), \(\mu_{S}\) is broken into multi-disciplinary measure

\textsuperscript{12} Satisficing, a term coined by Herbert Simon, is a cross between “satisfying” and “sufficing.” It refers to the fact that when human are presented with numerous choices, we usually select the first reasonable option, rather than the best one available (which may not exist.)
functions. Multiple objective evaluations are needed to compare the performance of scenarios.

5.1 Instruments and approaches in risk analysis (Stage 1)

Before risk analysis can be started, the objective of the risk management must be clearly established – ie what failure in system performance are we trying to avoid? Once the measure of system performances is determined, risk analysis can be carried out.

The first stage in risk analysis is to identify the hazard type. There are ways to classify hazard types in the water planning and management industry, e.g.

- Meteorological causes (e.g. flood, drought, lack of water for distribution and use, fire which may cause pollution to waterways and catchments, storms which may cause flood, etc.)
- Geological causes (e.g. land/water/snow movements due to large slope angles.)
- Developmental causes (e.g. human developments which cause undesirable effects on environments and bio-diversity.)
- Health considerations (e.g. water quality, pollution to bays and waterways, epidemics, etc.)
- Others (e.g., human and industry wastes, animal and plant diseases, pests, overgrows, etc.)

After identifying the hazard type, risk analysis (RA) is broken down into hazard analysis (HA) and vulnerability analysis (VA) steps. The following set of questions is adopted from Kohler et al. (2004) to facilitate the process of risk analysis:

1. [HA1] Which locations and areas are threatened by the hazard? (Spatial analysis – Location, extent of hazards, e.g. individual building scale, allotment scale, cluster scale, urban scale, catchment scale, regional scale.)
   - Identify Area $A=\{(x,y) \mid \ldots\}$.
   - Identify Extent $X = \{\text{individual building scale, allotment scale, cluster scale, urban scale, catchment scale, regional scale}\}$.
   - Study the context: landscape, landform, watershed, water network, urban network and space, past and current features.

2. [VA1] Are there vulnerable people and bases of life? Who and what are affected and threatened? Which are the important bases of life? What is produced? What does the local population make its living from? (Identifying vulnerable people and elements.)
   - List all hazards ($H_R$) in the risk (base) scenario $R$.
   - List all vulnerabilities ($V_R$) that are susceptible to the hazards in $H_R$.

3. [HA2] Identification and analysis of the cause of hazards. What are the scales of hazards? When and how often are future hazards to be expected? What is the probability of occurrence? (Temporal and dimensional analysis)
   - Identify the causes of hazards.
   - Identify the scales of hazards.
Yum et al. 2007

Integrating Risk Management into the Water Planning and Management Industry

• Analyse and estimate the measure of hazards \( \mu_{HR} (h, x, y) \) for all \( h \in H_R \) and all \( (x, y) \in A \).

5. [HA3] Optional: How can the assessment of hazards be visualized? (Hazard map)
   • Present hazard measures \( \mu_{HR} (h, x, y) \) as maps.

6. [VA2] Identification and analysis of the cause of vulnerabilities. Four types of vulnerability factors can be identified: physical factors (e.g., buildings, infrastructure), environmental factors (e.g., land use, water, flora, fauna), economic factors (e.g., agriculture, production, income, distribution) and social factors (e.g., education, organization, population, health). (Impact chain)
   • Identify the causes of vulnerabilities and thus identify all causes \( C_R \) in \( R \).
   • Analyse and develop the impact chain \( \triangleright_R \).

7. [VA3] How are vulnerabilities assessed? Identifying (multiple) methods for quantifying damage to physical, environmental, economic and social vulnerabilities.
   • Estimate the measure of hazards \( \mu_{VR} (h, v, x, y) \) for all \( h \in H_R \), \( v \in V_R \) and all \( (x, y) \in A \).

8. [RA1] How are risks assessed? (Risk map)
   • \( \mu_R (R, x, y) = \sum_h \sum_v \mu_{HR} (h, x, y) \times \mu_{VR} (h, v, x, y) \) where the summation is over every hazard \( h \in H_R \) and every vulnerability \( v \in V_R \) in \( R \).
   • Optional: Present risk measures \( \mu_R (R, x, y) \) as maps.

9. [RA2] Who should be involved? What can be changed? (See Section 5.4 for detail)
   • This is expanded as Stage 2 of the framework proposed in this paper. See also subsection 5.3.

5.2 Computer modelling and simulation of risks

The use of computer-based models to simulate risk scenarios is becoming increasingly important. Hydrological simulation models have been developed to provide quantitative assessment of water runoff at various levels of detail, e.g. MUSIC for urban stormwater (MUSIC Development Team 2005) and E2 for models of catchments.

Figure 4 shows how this proposed risk framework leads to computer modelling and simulation. In the case of analysing drought risks, “shortage of clean water” is a hazard, which impacts on the vulnerabilities (water balance, crops and livestock). Rainfall and various flow controls and wetlands are causes which have impacts on the hazard and vulnerabilities. The measures of hazards and vulnerabilities are various at different locations and different extents. An appropriate precipitation-runoff model can help evaluate the local water balance and thus offers an evaluation of the impact of “shortage
of clean water” (hazard) on water balance (vulnerability). The dependency relationship among causes, hazards and vulnerabilities help identify the inputs, parameters and outputs of the associated computer model. Once necessary input and parameter data are available, the model simulation can be run at any time.

The evaluation of risk has to be carried out between multiple disciplines. Generally hazards have impacts on four vulnerability types: (1) physical vulnerability, (2) environmental vulnerability, (3) economic vulnerability, and (4) social vulnerability. As a result, various models from different disciplines should be used to evaluate the hazards/impacts.

Figure 5 shows the deployment of various (plausible) evaluation models for the impacts on the vulnerabilities susceptible to the drought hazards.

5.3 Instruments and approaches in formulating risk prevention and mitigation scenarios (Stage 2)

Traditionally risk analysis often fails to effectively evaluate interactions across the borderline of disciplines and stakeholder jurisdictions, and thus has the limitation of not being able to cope adequately with unexpected events. In order to encourage thinking outside the box, Blackmore (2005) and Blackmore & Diaper (2006) suggested that controls should be considered holistically to cover all possible domains when considering risk prevention and mitigation.

Figure 4: Use of models and simulations in Risk analysis. Dashed arrows represent influences. Thick arrows represent impact chain connections.

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13 All this is measured in ML, which is the measure selected to show achievement of the objective “shortage of clean water”. This is why we need objective setting in our framework, see the first paragraph of Section 5.1.

14 If there is no appropriate computer models suitable for use, expert opinions will be sought.

15 All domains include: (1) technical system domain, (2) technical operational domain, (3) behaviour cultural domain, (4) natural environment, (5) socio-economic domain, (6) political domain, and (7) international domain.
Advancement in knowledge is needed to improve the effectiveness of controls. For example, at the international/national/catchment level of water planning and management, the consideration of controls should fall in line with the holistic Integrated Water Resource Management (IWRM 2006) framework for integrating sectors, scales, disciplines and stakeholders to deal with uncertainty in operations and climate change impacts.
At the urban water management level, the Integrated Urban Water Management (IUWM) framework offers tool sets (which can be counted as controls as well) for integrating four approaches together for a more sustainable approach of urban water usage: (1) water conservation, (2) stormwater use, (3) grey water and wastewater reuse, and (4) ground water use. Mitchell (2004) identified a set of tools (controls too) needed for IUWM developments at various level of design:

- **Home** – water efficient fixtures, appliances & practices such as AAA taps and shower heads, efficient garden water practices, composting toilets, etc.
- **Allotment scale** – On-site infiltration, minimise impervious surfaces, vegetation retention, roof gardens; non-structural approaches such as instant information on the internet, regulation, organic backyards, trading waste agreements with price for wastewater treatment, etc.
- **Street scale** – harvesting stormwater, diverting storm water into swales, bio-retention system, dissipation, absorption and infiltration to ground water; water sensitive stormwater management (grass swales, bio-retention systems, wetlands, gross pollutant traps, groundwater infiltration basins, etc.)
- **Precinct scale** – master planning stage, land use relationships, movement networks, development density, open space configuration, etc.
- **Allotment to regional scales** – stormwater non-structure approach such as car washing on pervious ground only, agreements on chemical and building materials used by householders/industries, improved litter management; efficient reticulation: peak levelling of water supply and wastewater, pressure management of supply, vacuum wastewater systems, etc.
- **All scales** – non-traditional water sources: rainwater tank, stormwater ponds, aquifer storage and recovery, treated wastewater, etc; wastewater treatment: onsite wastewater treatment to suburban scale, greywater/blackwater schedule flows, urine separation, composting toilets, reed beds; biosolids management: vermiculture, fertiliser, etc.

Water Sensitive Urban Design (WSUD) evolves from its former stormwater management perspective to provide another set of water technologies (controls) integrating sustainable management of water resources with urban design (Lloyd *et al.* 2002). Types of technology include (Melbourne Water 2006):

- **Grassed or vegetated swales** – primary treatment with conveyance function; can provide secondary treatment.
- **Filtration trenches** – primary treatment with conveyance and detention functions; can provide secondary treatment.
- **Bio-retention systems** – secondary treatment, conveyance, detention and retention functions; can provide tertiary treatment.

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17 Structural approaches involve excavating for pipelines and ditches, building canals, dams and structures and installing storages and treatment plants to prevent or reduce risks. Non-structural approaches involve other measures such as education, community responsibility, water charge, water use rights and water allocation, selection of crops with high water efficiency, irrigation scheduling, etc.

18 Detention: short term storage of stormwater. The purpose of a detention device is to slow down the rainwater runoff to reduce the impact of stormwater.
Yum et al. 2007
Integrating Risk Management into the Water Planning and Management Industry

• Wetlands – tertiary treatment systems; storage, detention, possible reuse options.
• Rainwater tank – enabling the use of stormwater as a resource – for drinking, watering gardens, toilet flushing, etc.
• Greywater reuse – collecting from households, primary treatment on site, reuse for external irrigation or internal toilet flushing.
• Rain gardens, rooftop gardening, urban forests.

The paragraphs above address structural tools, but non-structural tools, such as regulations, restrictions, education and financial incentives, play an equally important role in water management. Further, non-structural controls can be more readily adjusted and provide a potential fast-track lever for enhancing sustainability.

Other effective methods from other industries can be adopted in the implementation of both structural and non-structural controls. For example, strategic planning and system selection, operational management best practice, Total Quality Management (TQM), performance correction model, performance improvement model, due diligence, regulation, etc. (Emde et al. 2006)

Selecting controls is a goal driven activity aimed at achieving certain objectives (Subsection 4.2.) In an integrated risk management situation, selected controls can be complementary, reinforcing, contradictory or mutually opposed to each other. As a result, Stage 2 ends up with a few combined selections of consistent and coherent controls ($C_S$ where $S$ is the base scenario $R$ established in Stage 1 is a natural member of the set $S$ of all established scenarios).

Blackmore (2005) suggested a sequence of systems design activities, leading from contextual identification to scenario generation for risk prevention and mitigation. This has been adapted (and modified) as a guideline for formulating (designing) alternative scenarios for risk prevention and mitigation (Stage 2):

1. Establish the context of risk prevention and mitigation:
   • Specify the objectives of risk prevention/mitigation in the study.
   • Define system context in terms of enterprise/community management objectives as well as systems integration objectives of IWRM, IUWM, WSUD, etc. Both structural approaches and non-structural approaches are considered.
   • Reconfirm the extent of study (already established in Stage 1), to decide the geospatial area of the issues and their appropriate extents of consideration (See also Section 6.)
   • Reconfirm and study the context: landscape, landform, watershed, water network, urban network and space, their past, current features and future changes.

2. Identify controls and factors that have impacts on each of the hazards and vulnerabilities.

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18 Retention: long term storage of stormwater.
19 The base scenario $R$ established in Stage 1 is a natural member of the set $S$ of all established scenarios.
Yum et al. 2007

Integrating Risk Management into the Water Planning and Management Industry

• Study and identify the controls in $C$ that can be used to achieve the objectives within the context of enterprise/community planning/management.

4. Specify alternative scenarios that are believed to have improved effects on hazard/vulnerability prevention/mitigation.
   • Select a set $C_{S1}$ (where $S1$ is an index label, $C_{S1} \neq C_R$) of coherent, complementary and reinforcing controls which is believed to produce favourable impacts on risk prevention/mitigation.
   • Select other sets $C_{Si}$ (where $Si$ is an index label, $C_{Si} \neq C_R$, $i = 2, \ldots, n-1$, and $n$ becomes the total number of scenarios) of coherent, complementary and reinforcing controls each of which is believed to produce favourable impacts on risk prevention/mitigation.

5. Estimate the measures of hazards and vulnerabilities for each control set $C_{Si}$.
   • For each of $C_{Si}$, where $i = 1,\ldots,n-1$:
     • Establish the corresponding hazards ($H_{Si}$), vulnerabilities ($V_{Si}$), impact chain relation ($>_{Si}$) as in Steps [VA1] and [VA2] of Stage 1.
     • Establish the hazard measure function and its values $\mu_{HSi}$ as in [HA2] of Stage 1.
     • Establish the vulnerability measure function and its values $\mu_{VSi}$ as in [VA3] of Stage 1.

6. Calculate the expected damage over all possible hazards and associated vulnerabilities for each control set $C_{Si}$.
   • For each of $C_{Si}$, where $i = 1,\ldots,n-1$:
     • Establish the measure function and its values $\mu_{Si}$ ($Si$, $x$, $y$) as in [R1] of Stage 1.
     • Formally replace the index $Si$ labels by the tuple $(C_{Si}, H_{Si}, V_{Si}, >_{Si}, \mu_{HSi}, \mu_{VSi}, H_{Si})$.
   • $S = \{Si \mid i = 0, \ldots, n-1, \text{and } S0 = R \text{ is the base scenario}\}$

7. Improve controls and re-evaluate risk
   • Pass $S$ to Stage 3 of this framework.

Figure 6 demonstrates the process of considering the alternative scenarios of risk, leading to a similar set of computer models and simulations as in RA. The difference is that causal controls are selected and put together to form possible alternative solutions (scenarios) to meet both the risk prevention/mitigation objectives as well as the planning/management objectives of the enterprise/community. Among other controls, the key controls of “water use” and “water supply” are manipulated to prevent/mitigate the hazard of “shortage of clean water”. The impacts of the control set on water balance (and other measures) are determined by appropriate rain runoff models. This example shows the integrated considerations of both structural (storage, wetland, etc.) and non-structural (water use and water supply.)

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20 For the sake of easy counting, we assign the index $S0 = R \ S$.  

P.24
5.4 Instruments and approaches in comparing and adjusting scenarios for risk prevention and mitigation (Stage 3)

Stage 3 involves the process of comparing and adjusting the scenarios, and finalising a satisfying solution. There are some special instruments for the support of this stage:

- Participatory approaches to scenario development.
- Integrated water planning and management frameworks.
- Toolboxes facilitating the adjustment of controls in scenarios.
- Various supportive models that relate controls (C_S), factors to measures (μ_H, μ_V, μ_S) for some S_S.
- Multi-objective evaluation methods for a satisfying solution.

Stage 3 is the most important stage of the framework, in terms of scoping and coverage of risk assessment and risk management. This stage enables the stakeholders to consider all relevant domains by breaking down the barrier of disciplines and organisations, devising and evaluating integrated solutions that meet the two types of objectives: (a) risk prevention/mitigation, and (b) integrated water planning and management frameworks.

Since the scenario evaluations are from various disciplines and their values cannot be suitably added, multi-objective evaluations are needed to compare these scenarios (Figure 7.)

Figure 6: Use of models and simulations in analysing and assessing alternative scenarios of risk prevention/mitigation. Dashed arrows represent influences. Thick arrows represent impact chain connections.
6. Control patterns for facilitating the development of risk management scenarios

The selection of causes (controls and factors) in Stages 1 and 2 of the framework is a non-trivial process of design. It is built on the synergy of the following three major contexts (Lawrence 2001; see also footnote 12):

• technical context in the realm of integrated water resource management (e.g. IWRM, IUWM, WSUD, ESD, etc.), which includes the following dimensions:
  o physical causes,
  o environmental causes,
  o economic causes, and
  o social causes
• local landscape and bio-geochemical context, and
• administrative and management context (policy, compliance), which includes:
  o planning policies of the authorities (e.g. Sydney’s SEPP 59),
  o coordination of national, regional and local development plans,
  o negotiation and co-operation among stakeholders,
  o coordinated planning and/or management goals of the enterprise/community.

Figure 7: Multi-criteria evaluation of scenarios.
For the ease of use and evaluation in the framework steps, the causes can be categorised by their contexts and presented to the user of the framework as prompts by a computer program (Yum et al. forthcoming). The description of the computer program’s design is outside the scope of this paper; but at this stage, the cause is preliminarily characterised by the following property fields:

- Name (name/type of control)
- Objective (for what purpose)
- Context (technical context, local context, or administrative context)
- Extent (allotment level, precinct level, river/catchment level, or regional level)
- Indicator (what to measure)
- Related models (if any)

Appendix 2 shows a table of sample controls sorted by their objectives and contexts.

7. **Comparison with other work**

AS/NZS 4360:2004 is the latest edition of the Australian risk management standard. HB203:2006 is Standards Australia’s handbook on environment risk management, which
is close to the expert area of the water planning and management industry. Both booklets use the risk management process shown in Figure 2. After taking out the omnipresent input and feedback steps of “communicate and consult” and “monitor and review”, the standard framework consists of the key steps of (1) establish the context, (2) identify risks, (3) analyse risks, (4) evaluate risks, and (5) treat risks.

Figure 8: risk management process as in AS/NZS 4360:2004

A literature survey on risk management in water planning and management shows several "trends.

(1) There is no consensus on how terms like risk, hazard and vulnerability are used. (2) There are trends of unification of thought: risk should not only focus on scientific evaluation of probability and physical damage, but also need to address social suffering, environmental impacts and economic costs (e.g. Cardona, et al. 2003). (3) Risks considered by governments require strategic integrative considerations (e.g. AGO 2005); while risks considered by enterprises are more focused and often of an operational nature. (e.g. Emde et al. 2006) (4) Risk management in Integrated Water Resource Management (IWRM) is frequently associated with disaster risk management. (5) There is a need to bridge the integrated frameworks like IWRM, IUWM, and WSUD with institution- wide risk management to force the issues into the open and to better serve the consumers and the society.

The conceptual framework of risk management presented in this paper is based on two separate risk frameworks. Stage one (risk analysis) adopts the framework of Kolher et al. (2004) without no major modification. The work of Kolher et al. offered a consistent foundation of terms and definitions, which forms the basis of this work.

Stage two of the framework (formulation of alternative scenarios for risk prevention/mitigation) is derived from the work of Blackmore (2005). The main difference is three fold: (1) Blackmore separated controls from systems/elements on
Yum et al. 2007

Integrating Risk Management into the Water Planning and Management Industry

which the controls have impacts, (2) when evaluating the probability of risk, Blackmore included also the probability of control failure, (3) the impact of controls on risk is the sum of the impact of all controls, i.e. \[ \sum_x \sum_y \sum_h \sum_v \text{probability(failure of c o n e)} \times \mu_h (h_{ce}, x, y) \times \mu_v (h_{ce}, v_{ce}, x, y) \]

where the subscripts c (control) and e (affected element/system) run over all controls a la Blackmore and their affected systems/elements.

This work considers causal controls as (management) measures designed for risk prevention/mitigation. What is considered as a control in this work is the combination of the control a la Blackmore (2005) plus the affected systems/elements. Only the combined effect of all controls on hazards/vulnerabilities within individual (risk) scenarios is evaluated and compared. The main reason for the difference is mainly for easy use of causal patterns (Section 6). In the framework, the users think of putting together causal patterns for risk prevention/mitigation, and then they start evaluating their effects on hazards and vulnerabilities \[ \mu_R (R, x, y) = \sum_h \sum_v \mu_{HR} (h, x, y) \times \mu_{VR} (h, v, x, y) \]. The consideration of systems failure can be absorbed into the development of scenarios.

Appendix 3 shows a table of comparison of the work with 3 related frameworks.

8. Summary

This paper presents a framework for integrating risk assessment and risk mitigation planning for the water planning and management industry. The emphasis is to involve stakeholders into an open process to understand the risks that confront them, to carry out planning that offers solutions, and finally to commit to implementations that best suit them.

The framework proposes a causal impact chain approach to help stakeholders understand risk and quantify its measurement: The event/fault/decision tree methodologies determine how causes affect hazards (probability of events) and vulnerabilities (impacts on physical assets, people, environment and economy).

After risk analysis, the same group of stakeholders work together to monitor system performance and design integrative preventive controls that will alleviate the risks. Alternative sets of controls become scenarios that are different from the “business as usual” base case. Each alternative scenario determines how much its associated controls affect risk causes and thus the same event/fault/decision tree methodologies determine how much hazards and vulnerabilities can be alleviated.

The above stages will be iterated until the stakeholders agree on some tradeoffs to reach agreement on implementations.

The merit of using controls as a platform for the design of risk mitigation plans has a number of merits: (1) it allows layers of additive controls that are working simultaneously

P.29
Yum et al. 2007
Integrating Risk Management into the Water Planning and Management Industry

with each other (e.g. rainwater tank use together with education effort at the state/territory level, in conjunction with any national approach of water savings;) (2) it supports long term planning (in terms of tens of years) by integrating controls into planning regulations or industry’s best practice.

The work presented has just finished the stage of conceptualisation. Currently under planning are two applications to demonstrate use of the framework: one in the river operation / risk management context and one in the urban water risk management context.
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Yum et al. 2007
Integrating Risk Management into the Water Planning and Management Industry

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### Appendix 1: Context categories for risk analysis and management

<table>
<thead>
<tr>
<th>Context</th>
<th>Likely management context and controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building and landscape level</td>
<td>Management context: IWRM; IUWM WSUD</td>
</tr>
<tr>
<td>• Risk context: Stormwater volume and quality, use, and supply of water at allotment scale in all (drought and flood) seasons.</td>
<td></td>
</tr>
<tr>
<td>• <em>Key stakeholders:</em> House/building owner, building operator, neighbourhood, and city council.</td>
<td>Controls: Potable water supply, storm water, waste water (with recycling option), chemical or industrial waste in site, water conservation (mulching, RWTs), grey water (with recycling option), ground water, swales, ornamental ponds, setbacks from pavements, etc.</td>
</tr>
<tr>
<td>Urban cluster level (blocks, buildings, streetscape and precinct)</td>
<td>Management context: IWRM; IUWM WSUD</td>
</tr>
<tr>
<td>• Risk context: Stormwater volume and quality, use, and supply of water at urban cluster scale in all seasons.</td>
<td></td>
</tr>
<tr>
<td>• <em>Key stakeholders:</em> Precinct owner / operator, city council.</td>
<td>Controls: Storm-water run-off, buffer strips, traps, infiltration trenches wetlands, porous pavement, sand filters, swales, water conservation (mulching, water efficient irrigation systems), etc.</td>
</tr>
<tr>
<td>Urban waterway and corridor in a whole catchment context</td>
<td>Management context: IWRM</td>
</tr>
<tr>
<td>• Risk context: Use, storage and supply of water in a whole catchment area in all seasons.</td>
<td></td>
</tr>
<tr>
<td>• <em>Key stakeholders:</em> Catchment authority, city council, irrigator (farming), water licence holder, mining/industry water user, state government.</td>
<td>Controls: Erosion and sediment controls, sediment traps, screens, booms, detention basins, vegetated waterways, wetlands, pollution control ponds, lakes, waste water recycling options, overflow management options, ground water recharge, etc.</td>
</tr>
<tr>
<td>Whole regional waterways, catchments and floodplains</td>
<td>Management context: IWRM</td>
</tr>
<tr>
<td>• Risk context: Use, storage and supply of water in a whole regional area in all seasons.</td>
<td></td>
</tr>
<tr>
<td>• <em>Key stakeholders:</em> Catchment authority, state/territory governments, irrigator (farming), water licence holder, mining/industry water user, Federal Government.</td>
<td>Controls: Stablised banks, fencing, inlet sedimentation forebays, protection riparian and floodplain vegetation, buffer zones, setback of land use from water edge, wastewater recycling and treatment options, water rights, regional water use/supply, etc.</td>
</tr>
</tbody>
</table>
Appendix 2: Sample causes (controls/factors), sorted by their objectives and context.

<table>
<thead>
<tr>
<th>Causes</th>
<th>Objectives/impacts</th>
<th>Context</th>
<th>Extent</th>
<th>Indicator</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potable water supply, storm water, waste water (with recycling option), grey water (with recycling option), ground water</td>
<td>Sustainable water resource conservation</td>
<td>technical context – IWRM, IUWM</td>
<td>Allotment, precinct, catchment, region</td>
<td>Water volume</td>
<td>Integrated water supply and use models</td>
</tr>
<tr>
<td>RWT, vegetated buffer strip</td>
<td>Reduce run-off, minimise pollutant load</td>
<td>technical context – IWRM, IUWM, WSUD</td>
<td>Allotment, precinct, catchment, region</td>
<td>Water volume, Pollutant loads</td>
<td>Evaporative rainfall runoff models</td>
</tr>
<tr>
<td>Information/education on water conservation practice for household (Factors) slope, soils, areas</td>
<td>Household uptake of water conservation technologies</td>
<td>Administrative/com munal context</td>
<td>Allotment, precinct, catchment, region</td>
<td>Number of uptakes of technology</td>
<td>Cost benefit model</td>
</tr>
<tr>
<td>Ripple zones, ponds, wetland, aquatic and riparian vegetation</td>
<td>Land use capability</td>
<td>Local context</td>
<td>Allotment, precinct, catchment, region</td>
<td>Various overlay maps</td>
<td>Hydrological models</td>
</tr>
<tr>
<td>Gross pollutant traps, water quality control ponds</td>
<td>Minimising pollutant load from developed areas to discharging points</td>
<td>technical context – IUWM, WSUD</td>
<td>precinct, catchment, region</td>
<td>Pollutant loads</td>
<td>Stormwater runoff models</td>
</tr>
<tr>
<td>Detention time/flow, turbidity, SS (nutrient sorption), pH</td>
<td>Reducing nuisance plant growth (e.g. algae)</td>
<td>technical context – water quality</td>
<td>catchment, region</td>
<td>TP, TN, BOD, TSS</td>
<td>e.g. Pond model (Holt et al. 2005)</td>
</tr>
<tr>
<td>Land use, easement, setback</td>
<td>Governmental, regional priorities</td>
<td>Administrative or communal context</td>
<td>Allotment, precinct, catchment, region</td>
<td>compliance</td>
<td>NA</td>
</tr>
</tbody>
</table>
Appendix 3 Comparison of frameworks.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Stage 1 Risk analysis</strong></td>
<td></td>
<td><strong>(Merged into steps below)</strong></td>
<td></td>
</tr>
<tr>
<td>0. Identify hazard type</td>
<td>0. Identify hazard type</td>
<td></td>
<td>Identify risks</td>
</tr>
<tr>
<td>1. [HA1]</td>
<td>1. [HA1] Which locations and areas are threatened by the hazard?</td>
<td></td>
<td>Analyse risks (determine likelihood &amp; consequence)</td>
</tr>
<tr>
<td>• Identify Area A.</td>
<td>(Spatial analysis)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Identify Extent X.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Study the context.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. [VA1]</td>
<td>[VA1] Are there vulnerable people and bases of life? Who and what are affected and threatened? Which are the important bases of life? What is produced? What does the local population make its living from?</td>
<td></td>
<td></td>
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<tr>
<td>• List all hazards (HR) in the risk (base) scenario R.</td>
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<tr>
<td>• List all vulnerabilities (VR) that are susceptible to the hazards in HR.</td>
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<tr>
<td>3. [HA2]</td>
<td>[HA2] Identification and analysis of the cause of hazards. What are the scales of hazards? When and how often are future hazards to be expected? What is the probability of occurrence? (Temporal and dimensional analysis)</td>
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<tr>
<td>• Identify the causes of hazards.</td>
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<td>• Identify the scales of hazards.</td>
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<tr>
<td>• Analyse and estimate the measure of hazards μHR (h, x, y) for all h HR and all (x, y) A.</td>
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<tr>
<td>4. [HA3] Optional</td>
<td>[HA3] How can the assessment of hazards be visualized? (Hazard map)</td>
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<tr>
<td>• Present hazard measures μHR (h, x, y) as maps.</td>
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</table>
5. [VA2]  
- Identify the causes of vulnerabilities and thus identify all causes $C_R$ in $R$.  
- Analyse and develop the impact chain $I_R$.

<table>
<thead>
<tr>
<th>[VA2] Identification and analysis of the cause of vulnerabilities</th>
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</table>

6. [VA3]  
- Estimate the measure of hazards $\mu_{VR}(h, v, x, y)$ for all $h \in H_R$, $v \in V_R$ and all $(x, y) \in A$.

<table>
<thead>
<tr>
<th>[VA3] How are vulnerabilities assessed? Identifying (multiple) methods for quantifying damages to physical, environmental, economic and social vulnerabilities.</th>
</tr>
</thead>
</table>

7. [RA1]  
- Compute $\mu_R(R, x, y) = \sum_{h} \sum_{v} \mu_{HR}(h, x, y) \times \mu_{VR}(h, v, x, y)$  
- Optional: Present risk measures $\mu_R(R, x, y)$ as maps.

<table>
<thead>
<tr>
<th>[RA1] How risks are assessed? (Risk map)</th>
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<tr>
<th>Stage 2 formulating risk prevention and mitigation scenarios</th>
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<tr>
<th>[RA2] What should be changed? What can be changed?</th>
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<tr>
<th>Treat risks</th>
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<p>| 1. Establish the context of risk prevention/mitigation |
| 2. Identify hazards and controls |
| 3. Specify scenarios and select characteristic and extreme examples |</p>
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula</th>
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</thead>
<tbody>
<tr>
<td>4.</td>
<td>Estimate the measures of hazards and vulnerabilities for each control set</td>
<td>4. Estimate consequence and likelihoods</td>
</tr>
<tr>
<td>5.</td>
<td>Calculate the expected damage over all possible hazards and associated vulnerabilities for each control set</td>
<td>5. Calculate scenario risk, and rank The risk is [ \sum \sum \sum \sum \text{probability}(\text{failure of } \text{c on e}) \times \mu_{H}(\text{h}<em>{ce}, x, y) \times \mu</em>{V}(\text{h}<em>{ce}, v</em>{ce}, x, y), ] where the subscripts c (control) and e (affected element/system) run over all controls \textit{a la} Blackmore and their affected systems/elements.</td>
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<tr>
<td>Stage 3</td>
<td>Comparing and adjusting scenarios</td>
<td>6. Improve controls&lt;br&gt;7. Re-evaluate risks&lt;br&gt;8. Repeat steps 4 and 5</td>
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