

RISK ASSESSMENT AND RISK MANAGEMENT IN WATER SUPPLY SYSTEMS: STATE-OF-THE-ART AND CASE STUDIES IN SOUTHERN AFRICA

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ABSTRACT

Water suppliers have a responsibility to provide water that is safe and acceptable to the persons utilizing the water. Of main concern is public health of the water supply, and the water supplier should be aware of any risks involved in supplying safe drinking water, and have risk management strategies in place. Apart from public health, it is also necessary for water suppliers to be aware of the risks of not complying with legal requirements for drinking water quality and water treatment operations.

Water utilities are currently drawing up Water Safety and Security Plans (WSSPs) and other risk management strategies using state-of-the-art procedures and systems. TECHNEAU, a European Commission funded project, is one of the largest EC projects developing both new technologies and strategies to ensure safe and healthy drinking water. A generic framework for integrated risk management from catchment to consumer (source-to-tap) in WSSPs has been developed. In the project, specific tools and training seminars for risk assessment and risk management are also being developed, including a hazard database (THDB) and a database on risk reduction options (TRRDB).

Several case studies are carried out to test and evaluate the applicability of the different risk analysis methods, and to test and update the THDB and TRRDB tools. In Southern Africa, case studies were performed at Upper Mnyameni Village in the Eastern Cape and at the Windhoek New Goreangab Water Reclamation Plant (NGWRP).

The paper presents an overview of the generic framework and risk tools that were developed in TECHNEAU, and the case studies that were performed at Upper Mnyameni and Windhoek.

1. INTRODUCTION: NEED FOR RISK MANAGEMENT IN DRINKING WATER SUPPLY

Water suppliers have a responsibility to provide water that is safe and acceptable to the persons utilizing the water. Of main concern is public health of the water supply, and the water supplier should be aware of any risks involved in supplying safe drinking water, and have risk management strategies in place. Apart from public health, it is also necessary for water suppliers to be aware of the risks of not complying with legal requirements for drinking water quality and water treatment operations.

Water utilities are currently drawing up Water Safety and Security Plans (WSSPs) and other risk management strategies using state-of-the-art procedures and systems.

2. STATUS OF RISK MANAGEMENT AND RISK ASSESSMENT INTERNATIONALLY

In the 3rd edition of the Guidelines for Drinking-water Quality, the World Health Organisation (1) emphasises the preparation of risk-based Water Safety Plans (WSPs) (in South Africa, it is referred to as Water Safety and Security Plans (WSSPs) to manage risks to drinking water consumers. The WHO, among others, emphasises that the entire supply system, from source to tap, should be considered when managing risks. The WSSP framework facilitates a much needed increase in awareness and understanding of risk issues for providing safe drinking water. However, an analysis of the WSSP framework indicates that there are opportunities for further development, primarily regarding risks to water quantity and methods for hazard identification, risk estimation and risk evaluation. The Bonn Charter strategy (2) also promotes an integrated approach and further specifies the use of WSSPs in drinking water management.

The WHO provides general descriptions of hazard identification and a method for qualitative (or semi-quantitative) classification of risks (1)(3). The method provides a useful structure for risk assessment and facilitates a ranking of risks as a basis to prioritise the undesired events. This enables the development of risk reduction measures (“safety measures”) to be performed on a prioritised basis. The results of the risk prioritisation that is done in the risk evaluation stage are often presented as a risk matrix. A major drawback of risk ranking methods is that it is difficult to properly model complex systems with interactions between components.

MacGillivray *et al* (4) describe in a state-of-the-art review article a variety of risk analysis methods and tools for water utilities, including strategic (new technology), programme (asset management) and operational (plant performance) risk analysis. However, there is a need for water utilities to develop their own risk analysis strategy for specific situations, which formed the basis for the risk assessment and risk management work that was performed in the TECHNEAU project.

3. DEVELOPMENTS IN THE TECHNEAU PROJECT

The Integrated Project TECHNEAU “Technology Enabled Universal Access to Safe Water” is financed by the European Union to stimulate the development and application of innovative and cost effective European strategies and technologies for safe drinking water supply. The project is financed within the scope of the EU 6th Framework Programme and is conducted by a consortium of 30 universities, research institutes and technology suppliers from Europe and developing countries. South Africa also participates in the project with local partners being the Water Research Commission and Chris Swartz Water Utilization Engineers. A large number of water utilities are also committed to the project. TECHNEAU commenced in January 2006 and the project duration is 5 years.

The main objective of the risk assessment and risk management work area of the TECHNEAU project is to integrate risk assessments of the separate parts of a water supply system into a comprehensive decision support framework for cost-efficient risk management in safe and sustainable drinking water supply. A generic framework for this integrated risk management has been developed. Specific tools for risk assessment and risk management were also developed, including the TECHNEAU Hazard Database, the TECHNEAU Risk Reduction Options Database and methods for Decision Support in risk management. A specific focus of the project was also the development and testing of the

Fault Tree Analysis methodology for risk assessment based on modeling of complex water supply systems.

4.1 A Generic Framework for Risk Assessment and Risk Management

The generic framework is aimed at providing a comprehensive structure for integrated risk management (5). The framework involves the complete water supply cycle, *i.e.* from catchment to consumer (“source-to-tap”). It considers both water quality and water quantity at different levels of complexity. The framework formed the basis for further development of risk management procedures and methods in the TECHNEAU project. The main components of the suggested framework are shown in Figure 1. To provide the necessary basis for integrated risk management for both basic and complex systems on the operational as well as strategic levels, the framework includes all major steps in the risk management process.

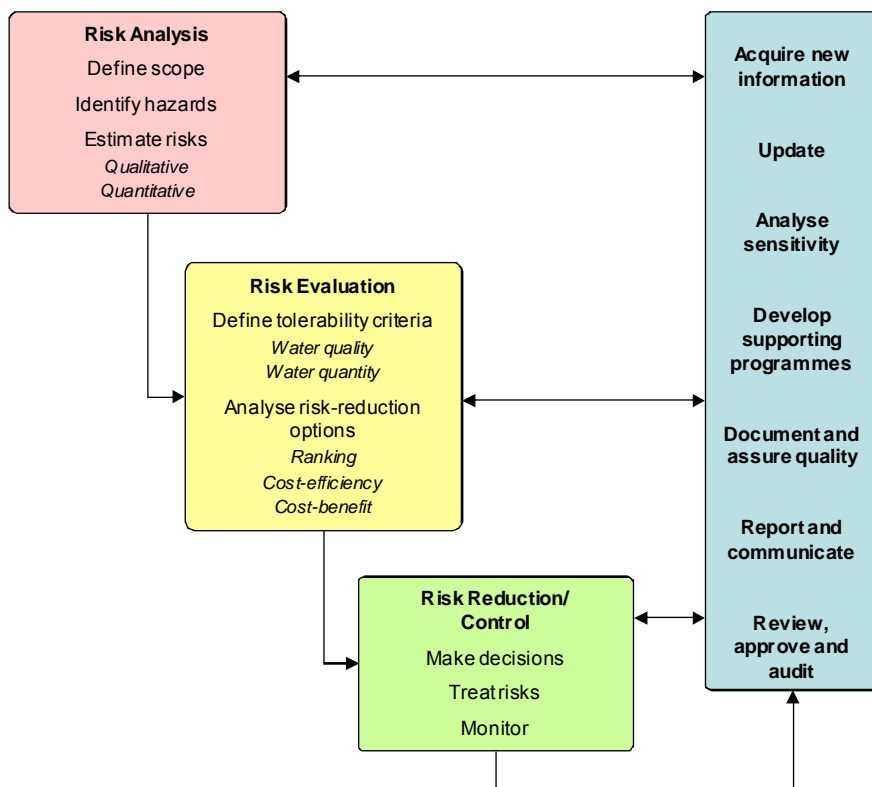


Figure 1 The main components of the TECHNEAU generic framework for integrated risk management in a WSSP (after 5).

To be efficient and functional, the framework must also include a set of reliable and well-established tools, adapted to specific decisions to be made and considering type of water supply system, level of complexity, and level of decisions, *i.e.* operational or strategic. Principal levels of sophistication of risk assessment tools are:

- Qualitative, *e.g.* based on checklists and classification of risk levels, providing relative ranking of lists and identification of critical points for risk reduction.
- Quantitative, *e.g.* based on models for combining and structuring events and chains of events, and estimations of quantitative risk levels. This level of sophistication facilitates quantitative comparison of estimated risk levels with established risk tolerability levels.

- Quantitative including decision analysis methods, facilitating strategic analysis of risk reduction measures, e.g. estimations of the risk reduction – investment trade-offs in prioritisation of risk reduction options.

The suggested framework cannot provide one single risk management method applicable to all types of water utilities for decisions at both strategic and operational levels. Instead, the framework provides:

- Principles for good risk management practice
- The relevant set of tools necessary for performing risk assessment and management
- Description of these tools, e.g.:
 - TECHNEAU Hazard database, THDB
 - Risk assessment methods description
 - TECHNEAU Risk reduction options database, TRRDB
 - Decision support tool
- Clear examples of risk assessment applications and testing of these

4.2 The TECHNEAU Hazard Database

One of the first aspects that need to be addressed in risk management is the identification and description of potential hazards. Traditionally, hazard identifications are performed for separate parts of the water supply system. Within the TECHNEAU project the water supply system is regarded as a whole and the identification of hazards is done from source to tap (also called “catchment to consumer”). The consequences of hazards are related to all the stages of the water supply and the chain of cause and consequences is evaluated through the process. Applying this holistic view helps water companies in preventing sub-optimization of risk management when focusing on specific aspects of water supply.

The objective of this database is to help end-users working in water supply systems with the identification of relevant hazards by providing a catalogue with potential hazards of technical, geographical or human origin for the whole part of the system. The database has a generic set-up. It does not cover all possible specific operational hazards, but should be regarded as a checklist to assess possible risks of the supply system.

One crucial aspect in setting-up a hazard identification database is the required level of detail. The database has to be generic for ease of use and at the same time complete for providing sufficient information. The database presented in this study aims to cover both aspects.

The water supply system is subdivided into 12 sub-systems, of which 10 are physical sub-systems representing the installations, one is a non-physical subsystem representing organizational aspects and one is a sub-system representing future hazards (6).

4.3 The TECHNEAU Risk Reduction Options Database (TRRDB)

The objective of the TRRDB is to help water utilities and water services providers to identify relevant risk reduction measures in their water supply systems. In the methodology for performing risk assessments, the next step after identifying and estimating the hazards within the system, is to analyse existing or identify new risk reduction options to mitigate the probability and consequences of the critical hazards, i.e. those with the highest risk level. All the options are divided into the same 12 subsystems as the THDB, and are therefore used in parallel with using the THDB spreadsheets. The risk reduction options in

the TRRDB are provided in a catalogue containing three different types of risk reduction options, viz. control (C), education and information (E), and physical barrier (B). The TRRDB is in the process of being finalised and will be available early in 2010.

4.4 The Fault Tree Analysis

A method for integrated and quantitative risk analysis of entire drinking water supplies, from source to tap, has been developed within TECHNEAU (7). The method is based on fault tree technique but has been developed to account for specific interactions between components and events common in water supplies.

A fault tree is basically a logic diagram modelling failure events that may occur in a system and the interactions between these events (Figure 2a). The top event represents a failure in delivering the required quantity and/or quality of drinking water. The top event failure is broken down into intermediate and basic events, i.e. to the lowest practical level of failure in the system.

The risk of a top event failure is calculated as the product of its probability and consequence. Accordingly, probability data for each basic event are needed to calculate the aggregated probability of the top event failure. Typical data needed are time between successive failures and the duration of a failure (i.e. time the system component is unavailable), as presented in Figure 2b. Estimates of these data may be based on statistical information, e.g. from regular performance monitoring, or on expert judgements by water utility personnel.

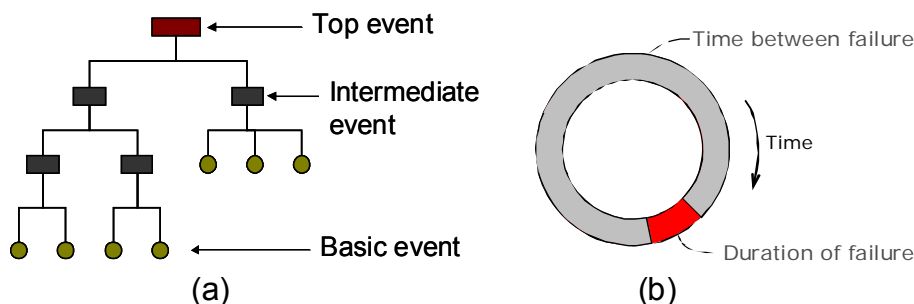


Figure 2 (a) Fault-tree schematic showing links between the top event (ultimate failure) and the intermediate and basic events; (b) Probability data needed are time-to-failure and duration

This new FTA risk assessment tool was developed and first tested in a case study on delivery disruption, i.e. quantity failure, of a water supply system in the city of Göteborg, Sweden. The tool will be demonstrated at Windhoek where there is a risk of quality failure with possible health consequences due to the nature of the raw water source and potential for high pathogen concentrations.

A comprehensive description of the fault tree method is presented by Lindhe *et al.* (7) and Norberg *et al.* (8).

5. TECHNEAU RISK ASSESSMENT CASE STUDIES: AIMS AND OVERVIEW

Within Work Area 4 (WA4) *Risk Assessment and Risk Management*, in the TECHNEAU project, six risk assessment case studies were carried out at different drinking water systems during 2007-2008. The aim of the case studies was to apply and evaluate the applicability of different methods for risk analysis (i.e. hazard identification and risk

estimation) and to some extent risk evaluation of drinking water supplies (5). The case studies provide a number of different examples on how risks in drinking water systems can be analysed and evaluated. The following six drinking water supplies constitute the case study sites where risk assessments were performed in WA4: Göteborg (Sweden), Bergen (Norway), Amsterdam (the Netherlands), Freiburg-Ebnet (Germany), Březnice (Czech Republic) and Upper Mnyameni, Eastern Cape (South Africa).

6. CASE STUDIES IN SOUTHERN AFRICA

6.1 Upper Mnyameni

Upper and Lower Mnyameni are two rural villages in the Eastern Cape province, about 80 kilometers from the south east coast. The villages are supplied with drinking water by a water treatment plant that takes its water from the Mnyameni dam. Altogether the water treatment plant supplies approximately 2 500 people with water. These communities are very rural and no major industries or other commercial activities are supplied with water from the Upper Mnyameni water treatment plant.

Raw Water Source

The raw water source is the Mnyameni Dam which is situated approximately 1 kilometer from the Upper Mnyameni village. The outflow from this dam is the source of the Keiskamma River. The dam is surrounded by precipitous mountains and the incoming water comes from rain and snow melting, but also from groundwater flow into the dam. The fact that the dam is partly supplied by groundwater makes the supply of raw water stable for long periods with dry weather. The flow of water into the dam is much higher than the demand from two water treatment plants.

The objectives of this case study were to identify hazards in the drinking water supply system (from “source-to-tap”), estimate and evaluate the risks to humans and the development of the society, and evaluate the risk assessment methods that were used. Two types of risk analysis were performed. The first risk analysis was performed by risk ranking of likelihood and consequences and presentation of risks with risk matrices. The second risk analysis was performed by using South African Risk Evaluation Guidelines. The TECHNEAU Hazard Data Base (THDB) was used to facilitate hazard identification for both methods.

Hazard Identification

The following eleven hazardous events were identified from the brainstorming session and by using the TECHNEAU Hazard Database:

1. High turbidity causing ineffective chlorination.
2. Contaminated taps due to animals leaning/scratching against them.
3. Inadequate hygiene due to low water availability at homes.
4. Contaminated groundwater leaking into pipes.
5. Poor storage of water.
6. Lack of treated water leading to use untreated water.
7. High turbidity when the WTP is unmanned causing high bacterial amount.
8. Ineffective mixing of chlorine leading to high bacterial amount.
9. Sabotage at any part of the system.
10. Incorrect actions due to lack of enough operational skills.
11. Pump failure when the plant is unmanned.

The eleven possible hazards that can affect the drinking water were rated by experts at Amatola Water. The hazards were rated by likelihood and consequence of occurrence. There were two consequence ratings, one focused on human health and one on number of people affected.

Risk estimation and presentation of risks with risk matrices

Both the probability (likelihood) that the different hazards will occur, and the consequence of the events, were ranked on a scale from one to five. The consequences of the events were ranked with respect to health consequences (first matrix) and number of people affected (second risk matrix). The two risk matrices were weighed and merged to provide a total risk matrix. The total risk matrix is shown in Figure 3. The green field shows risks that are considered to be acceptable and the red field indicates that the risks are unacceptable and could not be tolerated, i.e. must be reduced immediately. The yellow field indicates the ALARP (As Low As Reasonably Practicable) region. That means that the risk can be accepted if it is economically and technically unreasonable to reduce it. The scenarios that already falls under the green field does not need any measures.

Risk reduction options

Risk reduction options were identified for the different risks (hazards) that were listed. These are the measures that can be taken to decrease the risk of the different scenarios. Figure 3 shows how the risks move in the matrix when measures are taken.

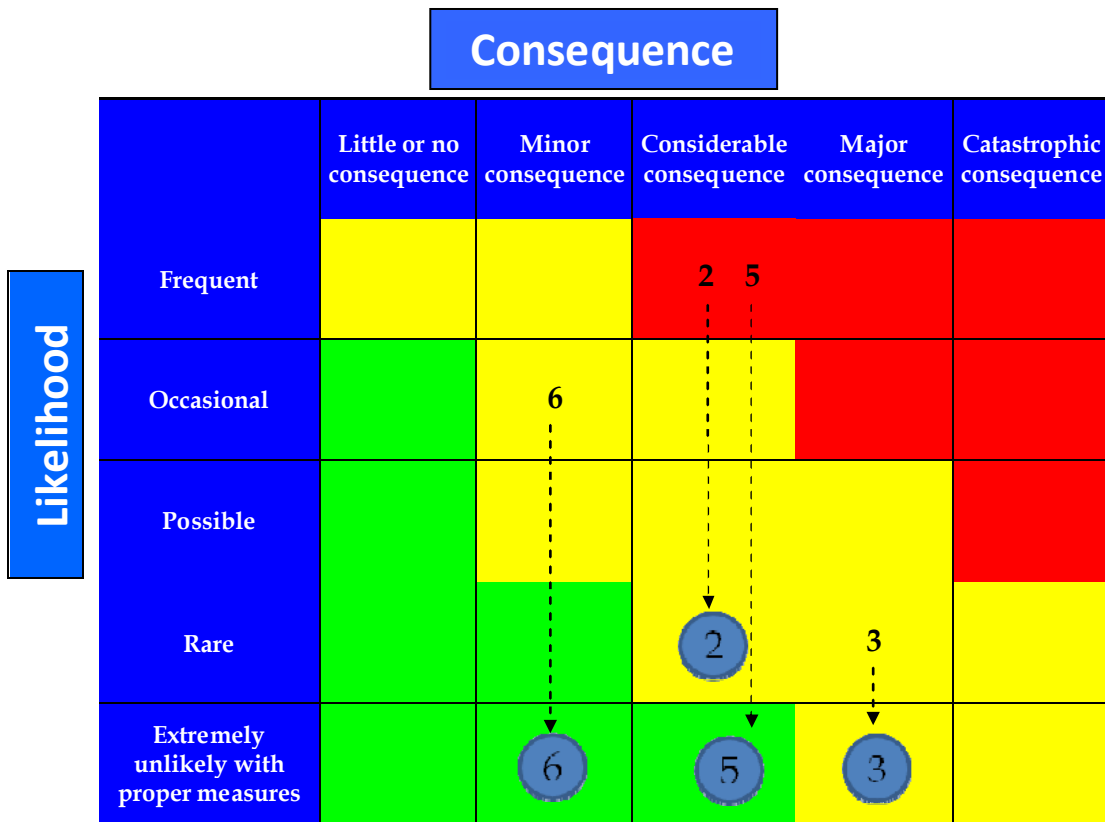


Figure 3 Risk matrix that shows how the hazardous events move after risk reduction measures have taken place (9).

Conclusions

Risk estimation with risk matrices is a useful and efficient tool. It is easy to understand and present data. When choosing what consequences are of importance it is vital to think it through thoroughly. For the Upper Mnyameni case it was chosen to use *health* and *number of people affected* by a certain hazardous event as consequence factors.

Suggested risk reduction options were found to reduce the risks significantly.

6.2 Windhoek

The multi-barrier approach to reclamation and treatment of wastewater to produce drinking water at Windhoek, Namibia, was investigated in the first WA7 large-scale case study in TECHNEAU. The New Goreangab Water Reclamation Plant (NGWRP) was commissioned in 2002 with a capacity of 21 000 m³/d. Raw water to the NGWRP is a blend of water from the Goreangab Dam and domestic treated effluent from the Gammams Wastewater Treatment Plant (GWWTP). Drinking water supplied to the inhabitants of Windhoek contains about 35% water produced at the NGWRP.

Water utilities considering the use of reclaimed water will need to establish robust and comprehensive risk assessment and risk management procedures.

A risk assessment carried out at NGWRP by WINGOC and TECHNEAU partners Chalmers and Swartz identified weaknesses at the plant in terms of microbiological and chemical monitoring. These weaknesses are being addressed in surveys investigating process performance, the removal of specific contaminants and the demonstration of various monitoring and analytical techniques.

In addition to the surveys, the initial risk assessment is being extended to develop and demonstrate the new risk assessment tool incorporating Fault Tree Analysis (FTA). The FTA risk assessment tool will provide water utilities with a practicable, easy-to-use means to help assess the reliability of analysed parts of the system.

In accordance with the WHO's Water Safety Plan (WSP) risk assessment procedure, a 'risk team' comprising personnel from WINGOC, City of Windhoek and TECHNEAU (Swartz and Chalmers) was assembled for a two-day workshop in December 2008 to review the system and hazards. It was decided that the first step of the risk assessment would cover only the chemical treatment processes: flocculation, dissolved air flotation and sand filtration (Figure 4).

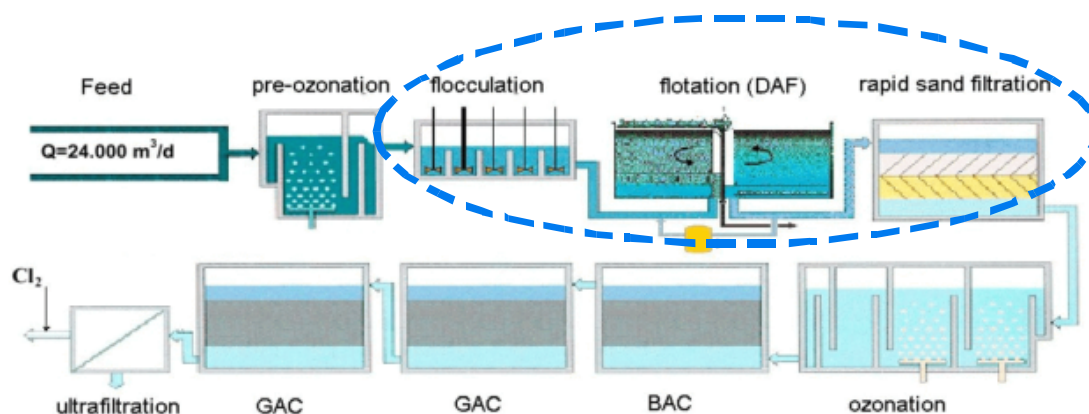


Figure 4 NGWRP schematic showing the three chemical treatment processes included in the FTA.

The hazard identification exercise resulted in identification of 44 basic hazardous events to be included in the fault tree representing the three chemical treatment processes (see Figure 5 for the basic lay-out of the fault tree).

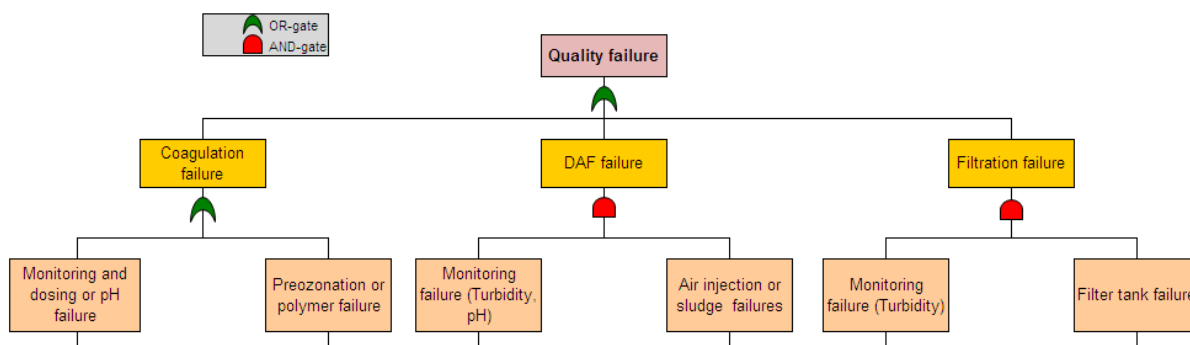


Figure 4 Fault tree showing the top three levels of failure events.

Appropriate time between failure and duration data for each of the basic events are being collated by NGWRP personnel. Once this task is completed, Monte-Carlo simulations will be performed to calculate probability distributions for system failures for a range of scenarios, including best and worst cases and various combinations of process failures.

Following calculation of the probabilities, the final step will be the calculation of risks of people being sick due to consumption of water subject to quality failures, calculated using appropriate consequence models. For the present case study, the Failure Modes and Effects Analysis (FMEA) model developed in WA 4 will be assessed as a simple, easy-to-use consequence analysis method. Other in-depth tools such as Quantitative Microbial Risk Assessment (QMRA) models are available, if required, that could be used to further quantify the impact on peoples' health (number of people being infected by pathogens, e.g. viruses, bacteria and parasites) as a result of process failures at the plant.

7. WATER SAFETY AND SECURITY PLANS IN SOUTH AFRICA: STATUS

In its strive towards continuous improvement of drinking water management practices, the Department of Water and Environmental Affairs (DWA) Drinking Water Quality Regulation Unit is applying increasingly comprehensive criteria for Water Services Authorities to meet during the biannual assessment of water supply systems (catchment to consumer). At the top of the list of these criteria is the drawing up of a Water Safety and Security Plan to ensure the practising of comprehensive, preventative drinking water quality management for municipalities. This is a requirement to meet the criteria for Blue Drop Certification.

The recommended steps that are being taken in compiling the WSSPs for municipalities are described briefly below:

Assemble a team to develop the water safety and security plan

A multidisciplinary team of experts with a thorough understanding of drinking water systems are assembled. This includes engineers, scientists, catchment and water managers, water quality specialists, environmental or public health professionals, operational staff and representatives of consumers.

Document and describe the water treatment system

A comprehensive understanding of the water supply system (source-to-tap) is obtained, and all existing processes and infrastructure are considered to determine whether and how potential risks can be managed.

Assess the existing/proposed system (description of the process and a flow diagram)

Overview descriptions of the drinking water system are drawn up, and include characterization of the source, identification of potential pollution sources in the catchment, measures of resource and source protection, treatment processes and storage and distribution infrastructure.

Undertake a hazard assessment and a risk characterization

A hazard assessment is performed and those areas of great risk are identified (*i.e.* hazard events are listed). The TECHNEAU Hazard Database is used to assist with the identification of these actual or potential risks in the water supply system. The identified hazards are then prioritized through a scoring system for likelihood (probability) that the hazardous event will take place, and the consequence when the event actually takes place. The prioritised hazards are subsequently presented in a matrix containing the risk ratings.

Identify control measures

The next step is to identify control measures that can be applied to eliminate the hazards. The assessment and planning of control measures ensure that health-based targets will be met, as the identification and implementation of control measures are based on multi-barrier principles.

Define monitoring of control measures

Each control measure is monitored to enable effective system management and to ensure that health-based targets are achieved.

Verification that the Water Safety and Security Plan is working

Verification is necessary to ensure that the system as a whole is operating safely.

Prepare management procedures for normal and incident conditions

Management procedures are drawn up for normal and incident situations and conditions.

Develop supporting programmes

Supporting programmes are developed as part of the Water Safety and Security Plans, e.g. verification protocols for the use of chemicals and materials in the drinking water supply.

Establish documentation and communication procedures

All the relevant information regarding the water supply systems are well-documented, and entails description and assessment of drinking water system (including programmes to upgrade existing water delivery), plans for operational monitoring and verification of drinking water systems, water and safety management procedures for normal operation incidents and emergency situations.

The WSSPs that are drawn up for South African municipalities will be reviewed every three years.

8. NEW DEVELOPMENTS AND TRENDS IN RISK MANAGEMENT

Water Safety Plans have been implemented in several countries and will most likely be further applied in both developed and developing countries in the future. Most likely the concept of WSP will be incorporated into the future editions of the European Drinking Water Directive. According to e.g. Pollard *et al.* (10) the drinking water sector is formalizing and making explicit approaches to risk management and decision-making that were formerly implicit. To facilitate risk management of drinking water systems, including preparation of WSPs, suitable methods and tools for analysing systems and comparing risk-reduction measures are necessary. Since drinking water systems are very diverse and exhibit different types of risks, one single method or tool cannot be used in all cases. Instead, a set of methods and tools is necessary and the methods and tools developed within TECHNEAU is one important contribution.

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