Process Approach to Drinking Water Quality Risk Assessment Using Bowtie Analysis

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The continuous supply of safe clean drinking water requires a comprehensive understanding of the hazards and risks of the complex systems and processes involved all the way from a catchment to tap. The multibarrier approach is widely considered as best practice risk management for drinking water supply, which recognizes that each individual barrier may not completely removal all contamination. Additionally, there is not reliance on a single barrier, as barriers can and do at times fail. Drinking hazards may occur or be introduced at any point in the drinking water supply system, therefore water quality is not only influenced from the performance of the previous barrier but can also be impacted by the unique hazards innate to each barrier. Bowtie analysis is widely used in high risk processes, due to the ability to take a barrier approach to risk analysis. There is no consensus formed on the best method for hazard analysis of drinking water risks using Bowtie diagrams. In practice, commonly one or more barriers are included in a single Bowtie diagram, which has the potential to miss the hazards associated from the performance of individual barriers on corresponding downstream barriers. Furthermore, a single diagram limits the ability to understand the evolution of the risk from drinking water quality barrier to barrier. The case study presented uses a series of linked bowtie risk assessments which reflect the evolution of risk along the drinking water process from source to tap. This process approach provides a good visual representation of how the performance and reliability of single process barrier can influence final process outcomes.

Introduction

The continuous supply of safe clean drinking water requires a comprehensive understanding of the hazards and risks of the complex systems and processes involved from a catchment to tap perspective. The multibarrier approach is widely adopted as best practice risk management for drinking water supply. Within a safety critical system, barriers are an effective method for preventing against unwanted events and the corresponding consequences (Hollnagel 2008). The multibarrier approach to risk management recognizes that each individual barrier may not completely removal all contamination with targeted barriers for specific risks. Additionally, there is not reliance on a single barrier as barriers can and do at times fail. Barriers are often considered solely in terms of treatment technologies used, however drinking water barriers can extend well beyond treatment. Critical barriers to the safe supply of water also include source protection, distribution security, water quality monitoring and response capabilities. A compromise in the performance or effectiveness of any barrier in place should be a call to action for operators involved in the supply of drinking water (Hrudey 2006). According to (NHMRC, NRMMC 2011) common preventive measures in the catchment to tap approach are incorporated as or within several barriers, including:

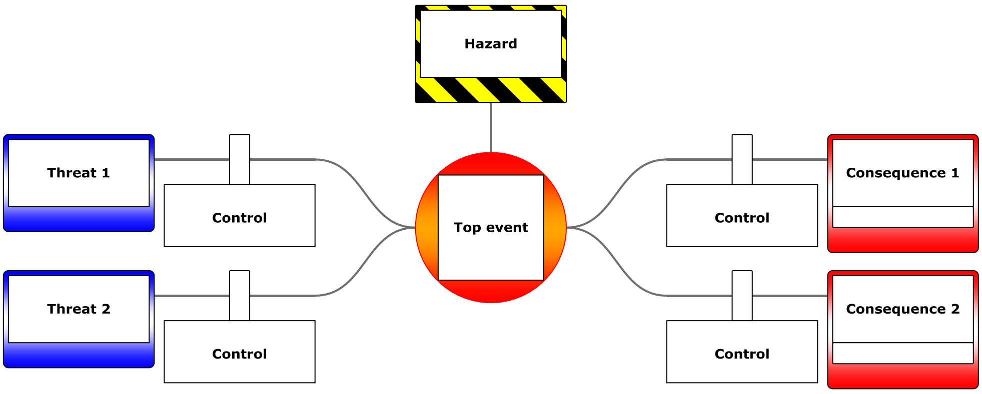
- catchment management and source protection;
- detention in protected reservoirs or storages;
- extraction management;
- Water treatment processes such as coagulation, flocculation, sedimentation and filtration;
- disinfection;
- protection and maintenance of the distribution system.

This paper proposes a catchment to tap process approach to hazard analysis for municipal drinking water systems using a series of connected Bowtie diagrams, where each diagram represents the risk management in an individual water quality barrier. Drinking water hazards or threats may occur or be introduced at any point in the drinking water supply system, therefore water quality is not only influenced from the performance of the previous water quality barrier but can also be impacted by the unique hazards innate to each water quality barrier. While drinking water may become contaminated at any stage of the water supply process the risk of unsafe water is not realised until the consumer drinks the contaminated water. Therefore, the hazard assessment of a drinking water supply should investigate safety from a catchment to tap perspective.

While with any drinking water supply there are many hazards which can result in harm to consumers, in this paper the focus is primarily on the risk of public illness due to contamination with pathogenic organisms. Of all potential drinking water contaminants, pathogens present one of the greatest risks to public health due to the low does required to cause illness and the potential for rapid variations in concentration over a short period of time. Furthermore, the population may be exposed to waterborne pathogens before any testing has been completed. Therefore, frequent sampling of final product alone is not a reliable sole strategy for verifying the safety of water supplied (World Health Organisation 2017). To ensure water safety, management focus should be placed on the performance of the entire system including protection of water sources, appropriate treatment, disinfection and distribution management. There has been a long history of using risk-based approaches in the supply of drinking water systems. A catchment to consumer approach to risk management that includes all steps in the drinking water supply process is advocated by the World Health Organisation in Bartram et al. (2009). Effective capture of risks in a drinking-water supply requires detailed hazard assessment which is comprehensively documented to capture factors such as system performance, controls in place, assumptions made, data used etc. Furthermore, documentation should provide a description of operations are undertaken and the procedures that guide them (World Health Organisation 2017). Documenting such an approach is generally captured in water safety plans, catchment management strategies and other operational management plans.

The Bowtie diagram are used throughout many high-risk industries and get their name from the close resemblance to a gentleman's bowtie. In a common Bowtie diagram shown in Figure 2, the left-hand side diagram represents a simplified Fault Tree Analysis (FTA), which represents possible causes of a loss of control over a hazard. The FTA is developed through repeatedly asking what probable adverse actions could occur and what are the related causal factors. The right-hand side of a Bowtie diagram takes the form of an event tree analysis (ETA) diagram which describes how a loss of control over a hazard can lead to various unwanted outcomes and consequences (de Ruijter and Guldenmund 2016), which in this study is public illness due to infectious pathogen contamination.

Figure 1: Generic Bowtie diagram format used for each barrier in the drinking water supply



Bowtie Diagrams are suitable for capturing drinking water hazards and controls, due to the ability to take a barrier approach to risk analysis and communication. The barrier approach to safety is well-known from the Swiss Cheese analogy provided by Reason, (2000). In the swiss cheese model, the holes in cheese represent deficiencies in barriers, absence of suitable barriers or scenarios where barriers fail to halt the progression of the risk event. The barriers represented are risk treatments or controls that can include processes, policies, practices, equipment, or other actions, all of which modify risk. Displaying hazard analysis outcomes using Bowtie diagrams is commonly used in Australia and Europe in a wide range of high-risk operations where an organisation has identified significant risks to business objectives. This is due to the ability to visually demonstrate major hazards are identified and controlled (Saud et al., 2013). For risk management in drinking water schemes, Bowtie diagrams can highlight both the possible causes and consequences of hazardous events and the controls required to prevent hazardous events or reduce the severity (Hokstad et al., 2009).

There is no consensus on the correct method for creating Bowtie diagrams for hazard analysis and risk assessment in drinking water supplies. In practice, often one or more drinking water quality barriers such as water treatment and source protection are included in a single bowtie diagram (Hokstad et al 2009), this approach has the potential to miss the hazards associated from the performance of individual barriers on downstream barriers. Furthermore, a single diagram limits the ability understand and display the evolution of the risk associated with each drinking water quality barrier.

To illustrate the concept this study presents a case study based of theoretical municipal water supply system. For the case study presented a bowtie diagram is developed for each of the drinking water barriers and the resulting bowties are stitched together to present a complete assessment of drinking water risk management from catchment to tap. In the stitching process the consequence for the upstream barrier becomes the top event for the downstream barrier. In addition, each barrier has additional threats unique to the barrier functions which are included in the bowtie analysis.

Drinking Water System Case Study

For the case study a theoretical drinking water supply is used to illustrate the structure of a process approach to drinking water safety. The drinking water system selected is based on a typical municipal surface water source for a municipal potable supply.

System Description

The theoretical water supply system is constructed to represent a typical licenced public drinking water supply network with significant potential for contamination through pathogens both from the source water and throughout the supply system. The following is the description of the system considered.

Water Service Provider: a single water utility managing supply from source to tap

Surface water catchment: multiple land uses and management from multiple agencies

Storage reservoir: Large storage (>2gigalitres) with multiple offtake levels

Water Treatment: Sand Filtration with coagulation and flocculation

Disinfection: Chlorination and UV

Distribution to customers house: through a municipal reticulation network

Bowtie Methodology

Bowtie diagrams on their own do not provide the initial analysis to identify the hazards of the system or process of interest. In this study Bowtie method is the term used to refer to a combined use of hazard analysis to capture relevant system hazards and hazardous events, threats and consequences, and a Bowtie diagram to visually represent relevant barriers to prevent unacceptable losses. In this study, at the stage of hazard identification and analysis, a basic tabular Hazard Identification (HAZID) process based on a combination of the Hazard Analysis Critical Control Points (HACCP) method and informal brain storming was used to identify the threats typically associated with the consequence of supply of unsafe water and eventually loss of control over the hazard of each drinking water barrier. The HACCP process originally developed for the food industry is commonly used in drinking water safety, the process involves systematically moving through each stage of the water supply system to identify drinking water hazard and controls. Following the hazard analysis is the identification, monitoring and reporting of Critical Control Points (CCP) which are process step at which action is needed to prevent risk or reduce risk to an acceptable level. The violation of the CCP limits can indicate immediately that water quality is compromised and potentially no longer safe to drink. This HACCP analysis information can be beneficial in informing the potential threats, controls barriers and indicators of safety in the bowtie diagram.

In a typical Bowtie diagram the control barriers between the threats and the top event are the preventative barriers, responsible for avoiding the realisation of the top event. The control barriers to the right of the top event are the recovery barriers intended to prevent the top event progressing to the consequence or reducing the impact of the consequence. The Bowtie structure means either quantitative, semiquantitative or qualitative assessments can be used. In the FTA and ETA elements of Bowtie Analysis a Quantitative assessment approaches use the probability of occurrence of critical and outcome events, however, this data can be difficult to obtain (Ferdous, et al. 2012). Semiqualitative assessments like those used in drinking water assessment commonly include the traditional risk matrices. Semiqualitative risk assessment using a matrix provides the analysist a method for assessing risk in the absence quantified probabilistic data (Jacinto and Silva 2010). The risk matrix combines consequence and likelihood to define the level of risk is usually defined by the water supplier. The use of risk matrices is widely practiced in drinking water risk assessment and are recommended in formal drinking water guidelines such as the Australian Drinking Water Guidelines (NHMRC, NRMMC, 2011). In each case the inherent risk is assessed before controls are placed, then once the control barriers have been defined and effectiveness assessed a final residual risk can be provided. In this study the focus is on the systematic identification of process hazards and controls therefore a qualitative approach is considered suitable to illustrate the process approach using bowtie analysis. However, in a real-world scenario a risk assessment can be provided for each of the hazards in the process would have an individual risk assessment.

The qualitative Bowtie analysis process in this study uses eight key steps in a Bowtie risk assessment procedure adapted from CGE Risk (2017):

Step 1: Identify Hazard –an activity that has the potential to cause harm such as sickness, injury or death to people,

Step 2: Identify top event –the realisation of the hazard and unintended departure from normal situation or point of loss of control in which some degree of harm is caused.

Step 3: Identify Threats –the means by which a hazard may be introduced into the system.

Step 4: Evaluate Consequences –the result that follows the realisation of the top event or degree of harm caused by an accident.

Step 5: Identify preventative barriers – barriers on the left side of the diagram from the top event, if effective these barriers will prevent the threats from causing the top event

Step 6: Identify recovery barriers - barriers to the right of the top event, these barriers prevent the top event from causing a loss

Step 7: Identify escalation factors – situations where specific barriers are not effective in achieving safety control requirements

Step 8: Identify escalation factor barriers – barriers to prevent escalation factors from impacting on the effectiveness of either preventative or recovery barriers

Steps 1 through 4 were supported through the HAZID process, as the case study is a theoretical system a review of literature and the authors' knowledge and experience was used to inform the HAZID. After the initial HAZID process the series of bowties are drawn without the control barriers. Then systematically control barriers were included in each Bowtie diagram based on common industry practices for the scenario developed. Control barriers considered included any process, practice, policy, device, or other planned operations intended to modify risks associated with the water quality barrier.

Process Indicators of safety and measuring system performance

Within the drinking water safety system like other safety systems, the two principle hazard response types being prevention and detection both of which require targeted barriers (Hollnagel 2008). For a drinking water system being able to measure and monitor the performance of control barriers to prevent or respond to drinking water threats, as well as the water quality is critical for verifying that each customer is receiving safe drinking water. Through using Bowtie diagrams developing leading and lagging indicators can be easily identified. In each diagram the measure of performance of the control barriers to the left of the top event are considered leading indicators. The measure of performance of control barriers to the right side are lagging indicators (Swuste, et al. 2016). At steps 6 and 7 as part of identifying the control barriers in the bowtie diagram, consideration was given to potential measures for the performance of the required function in the system.

Results and Discussion

Form the initial HAZID process a total of bowtie five hazards were selected, one for each of the water quality barriers. In developing the bowtie diagrams the role in ensuring the water safety for each water quality barrier was considered. The details of each water quality barrier role and related hazard and top event are shown in table 1.

Table 1: description of each water quality barriers and the corresponding Bowtie diagram hazard and Bowtie Diagram top event

Water Quality Barrier	**Role**	**Bowtie Diagram Hazard**	**Bowtie Diagram Top Event**
Source Protection	Protect the water at the source from contamination	Manage Drinking Water Source	Supply unsafe water (catchment)
Reservoir Storage	Attenuation of pathogens and control of extraction for best quality water	Manage Reservoir Storage	Supply unsafe water (Reservoir)
Water Treatment	Remove pathogens from water	Drinking Water Treatment	Supply unsafe water (Treatment)
Disinfection	Kill remaining pathogens not removed during treatment Provide a residual for continued downstream protection	Drinking Water Disinfection	Supply unsafe water (disinfection)
Distribution to customer's tap	Ensure water remains free of pathogen contamination	Drinking water distribution	Supply unsafe water (distribution)

For the final set of high-level bowtie diagrams together as a chain in a relationship model for the top events is presented in figure 2. The chain illustrates the progression and control of risk from the catchment through to the consumer's tap where the consequence from the upstream barrier becomes a threat of the downstream barrier.

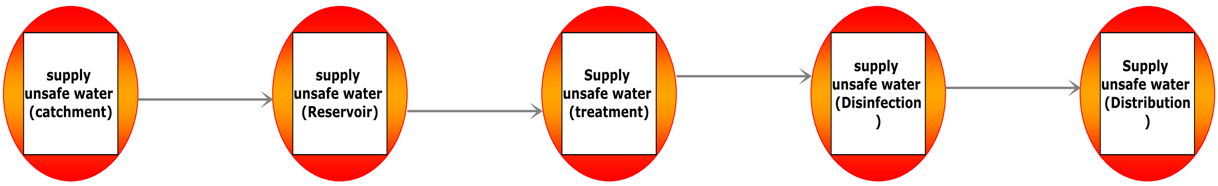


Figure 2: the chain of top events for the progression of unsafe water in the drinking water system

Threats and Consequences

Focusing on the loss of public illness due to the pathogen contamination, defining the threats that can result in the top event being realised requires having a good understanding the role and functions of the water quality barrier. There are several threats common to the majority of surface water supplies like the one described in this case study. In a real-world case, there may be more or less threats identified depending on the characteristics of the system of interest. The unique characteristics and functions of each water quality barrier means that while operating in the same environment the threats for each water quality barrier are often limited to the specific barrier. However, in the bowtie chaining approach the consequence of '*supply of unsafe water*' is common to all water quality barriers. The exception to this is the final water quality barrier hazard of '*Drinking Water Distribution*', where the customer comes in to contact with the potentially contaminated water. In the final stage where the risk of contaminated water is realised in addition to public illness other consequences such as loss of reputation and loss of continuity of supply are considered. The resulting bowtie diagrams with threats and consequences are presented in Figures 3a to 3e. For the threats in each Bowtie diagram a description is provided of the threats and consequences. Information captured on the threat include a description, an assessment of contribution to the top event. For consequences there is also a description and a level of concern is also provided based on the potential for contribution to the overall loss of public sickness. In this case study presented the concern level is major for the supply of unsafe water.

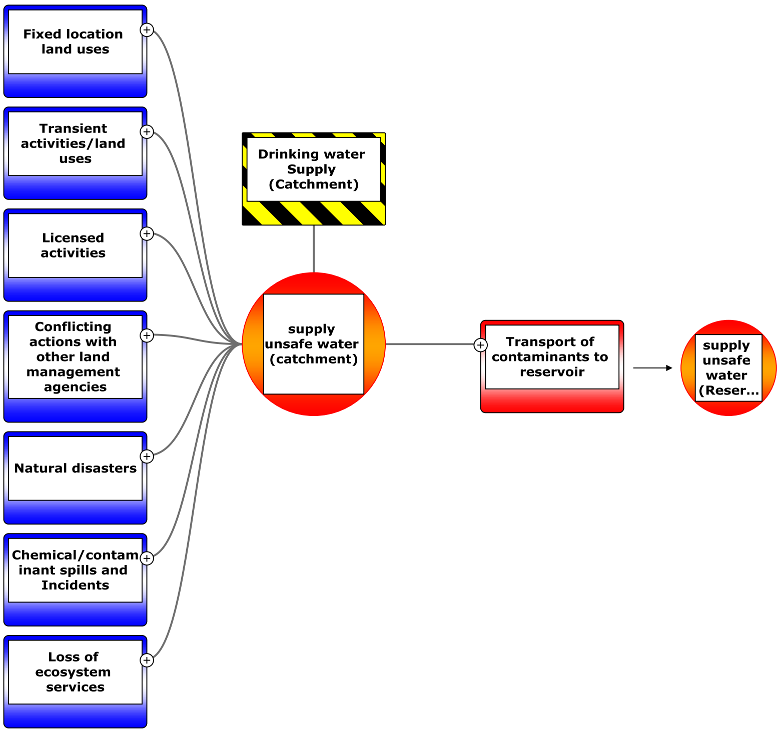


Figure 3a: Bowtie diagram showing threats and consequences for the top event of Supply unsafe water (catchment)

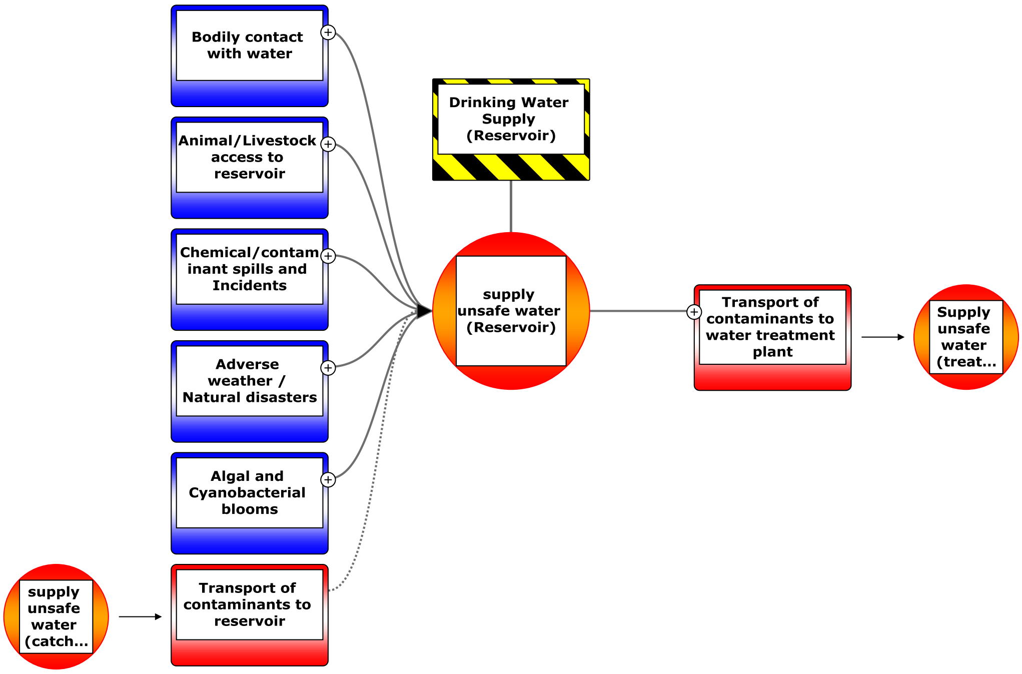


Figure 3b: Bowtie diagram showing (blue bordered boxes) and consequences (red bordered boxes) for the top event of Supply unsafe water (reservoir): Note: control barriers not shown

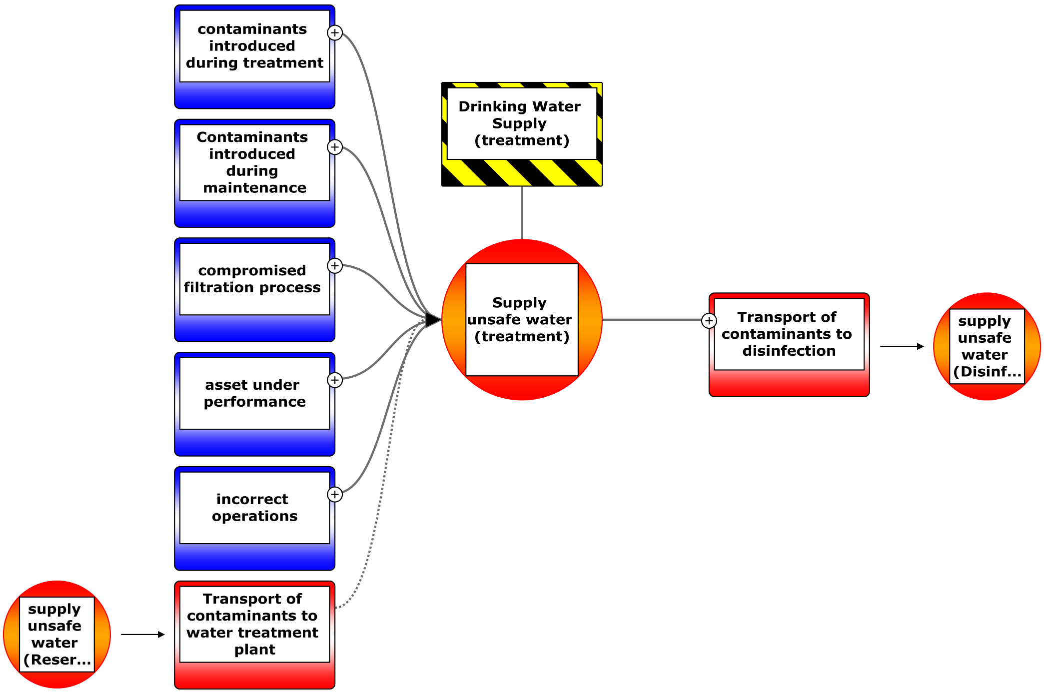


Figure 3c: Bowtie diagram showing (blue bordered boxes) and consequences (red bordered boxes) for the top event of Supply unsafe water (treatment). Note: control barriers not shown

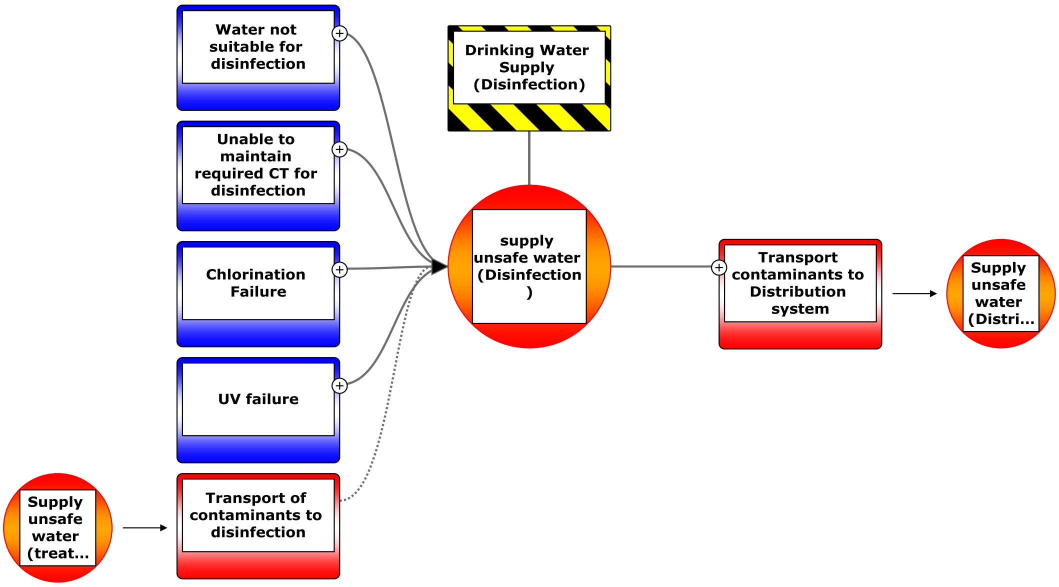


Figure 3d: Bowtie diagram showing (blue bordered boxes) and consequences (red bordered boxes) for the top event of Supply unsafe water (disinfection). Note: control barriers not shown

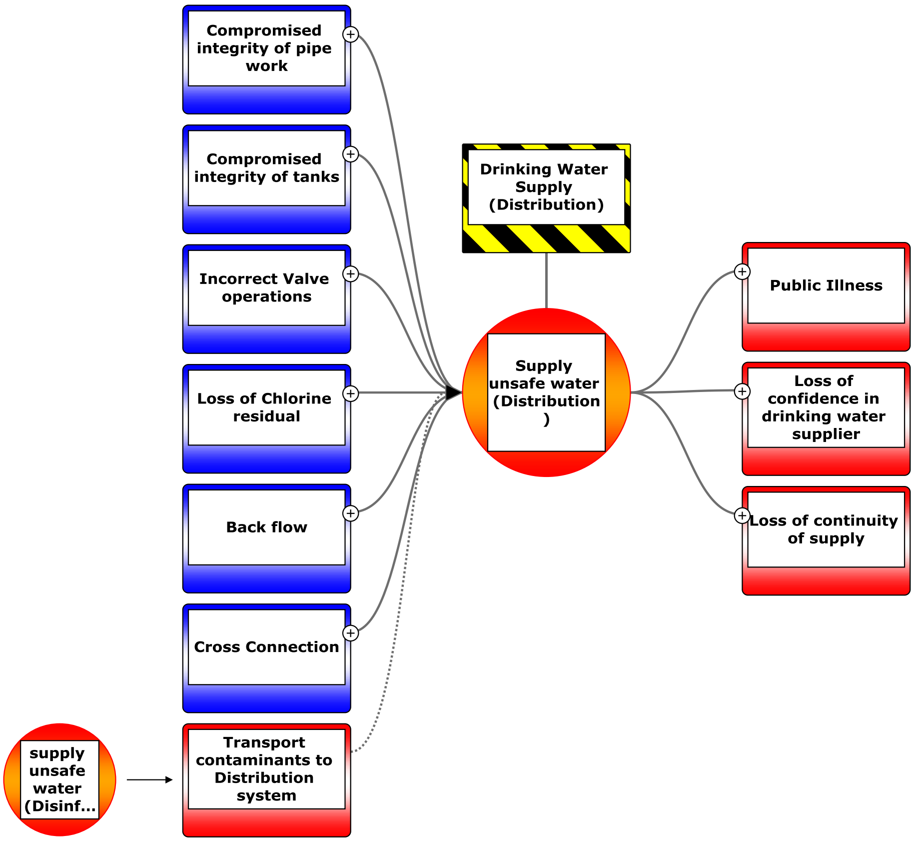


Figure 3e: Bowtie diagram showing threats (blue bordered boxes) and consequences (red bordered boxes) for the top event of Supply unsafe water (distribution). Note: control barriers not shown

Bowtie Diagram Control Barriers

Selecting control barriers for each of the bowtie diagrams was undertaken once the initial threats and consequences are identified in the in HAZID process. The barriers are taken in part from HAZID stage and prompting using the Bowtie diagram. Prior to control barriers being included in the final bowtie diagram each of the controls need to be assessed as effective at eliminating or reducing the progression of the risk of unsafe water. To ensure effectiveness the actions must not only control the risk progression but be readily implemented with the resources and technical skills available to the water quality barrier.

To understand the intended roles and function of the control barriers in the Bowtie Diagram, each control barrier was reviewed in detail and the follow items are included in description of each barrier in the system to articulate the barrier performance requirements;

- Safety Requirement: system safety requirements to be enforced by the application of the barrier to the safety system
- Assets and resources: the key assets that are included in the barrier and/or resources required to perform the function of the barrier
- Procedure/process: the formal organisational procedures and processes that support the implementation of the barrier
- Activities and Tasks: the key activities and tasks by personnel required to support the implementation of the safety requirements as well as the agency or agencies responsible
- leading safety indicators (for preventative barriers only): indicators that measure performance of the preventative barriers and provide indication of the overall performance on the water quality barrier
- lagging safety indicators (for recovery barriers only): indicators that measure performance of the recovery barriers and provide indication of the overall safety performance on the water quality barrier and potential threats to downstream barriers

In some cases, not all categories will apply to each control barrier, but the details provide the required information to be able to both understand the scope of function and performance expectations. This type of information can feed directly into risk assessments and required action plans for ensuring ongoing safety of drinking water supply.

In this case study, a total of 105 control barriers were identified across the entire system based on analysts' experience and common risk management measures used in drinking water systems. Of the 105 control barriers identified 22 are reactive and consist primarily of detection of out of spec water quality and water quality incident response protocols for the respective water quality barrier and the entire system. The 83 preventative barriers identified the focus was on detecting and responding to conditions which could contribute to a decline in performance of the water quality barrier or could present a challenge greater than the water quality barrier can safely manage.

Indicators of safety

Once the water quality barriers for the system have been identified and the control barriers included in the Bowtie diagram indicators of the safety performance can be developed. Each barrier has its own challenges in setting process safety indicators in that some the control barrier functions are challenging to provide metrics on. Some examples of leading and lagging indicators of safety for a drinking water system include;

Leading indicators

- detection of faulty assets through asset inspection to confirm performance is as expected
- Measuring preventative barrier performance through the Preventative maintenance completed as planned

Lagging indicators

- Water sampling for pathogens is a good example of typical lag safety indicators for a detection barrier in that the results are received after the water has already been supplied to customers
- Count of Incident responses to out off spec water quality as an effective recovery barrier for when then top event has been realised

A complete example of details provided for control barriers using the preventative barrier of *'catchment surveillance'* under the threat of "*transient activities and land uses*" in the Bowtie Diagram for the top event of '*supply unsafe water (catchment)'* is as follows.

- Safety Requirement: Ensure that the catchment condition matches the expected condition
- Assets and resources: Catchment Area, Field operators
- Procedure/process: Catchment surveillance procedure, and procedure for responding to out of specification catchment conditions
- Activities and Tasks: inspect all high-risk areas and temporarily approved fixed location activities
- leading safety indicators: % of surveillance completed to required plans, number of high-risk activities observed, and actions created to remedy potential risks to water quality

An example of details provided for control barriers using the recovery barrier of '*water quality incident protocols'* to prevent of reduce the impact of the consequence of "*public illness*" in the Bowtie Diagram for the top event of *'supply unsafe water (distribution)'* is as follows.

- Safety Requirement: all incidents with potential to result in public illness must be responded to negate or reduce public health impacts
- Assets and resources: dependent upon the type of incident experienced
- Procedure/process: Incident protocols for specific incident types
- Activities and Tasks: investigate potential causes and respond as required
- lagging safety indicators (for recovery barriers only): Number of incidents responded to in a given time period and effectiveness of response protocols in restoring normal conditions

Conclusion

A multi-barrier approach is widely considered good practice for the supply of safe drinking water. Such an approach has the ability to reduce both the probability and consequence of potential hazardous events in drinking water systems as well as provide a greater resilience to abnormal events. Being able to effectively capture the hazards of drinking water supply unique to each water quality barrier supports the holistic approach to the overall safety of the water supply system. For drinking water supplies the ultimate loss of public illness is not realised until the consumption of the water which is the very last step in the process, however the cause may be the failures of one or more upstream water quality barriers. This paper illustrates how a process approach based on the Bowtie method can support a catchment to tap approach to hazard analysis and risk assessment for the complete drinking water supply system. The case study presented uses a series of linked bowtie risk assessments which reflect the evolution of risk along the drinking water process from source to tap. This process approach provides a good visual representation of how the performance and reliability of single process barrier can influence final process outcomes. The use of control barriers in the Bowtie diagrams allows the analyst to plan for the safety of the system and develop plans for improving overall water safety.

The Bowtie diagram can further support the monitoring of overall system risk management performance through leading and lagging process safety measures. Reporting against these measures allows the relevant organisational groups understand the overall performance of the system and identify when there is potential for the supply of unsafe water. Overall the information gathered in this type of hazard analysis process can assist water service providers in better understanding the risk from a catchment to consumer perspective. Information and findings from a process risk approach can feed into other processes such as water safety planning, asset management strategies, stakeholder engagement etc.

Building on the use of risk matrixes, the Bowtie approach can support the drinking water supplier to further expand into more advanced analysis of hazard and risk. Taking the lead from other high-risk industries bowtie diagrams can be used to support quantitative analysis of system risk and through further advanced analytical methods such fuzzy logic to support uncertainty analysis.

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