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WiCE rapport

Water Wise - A decision support system for safe water use and reuse

KWR

Bridging Science to Practice

Water Wise
A decision support system for safe water use and reuse

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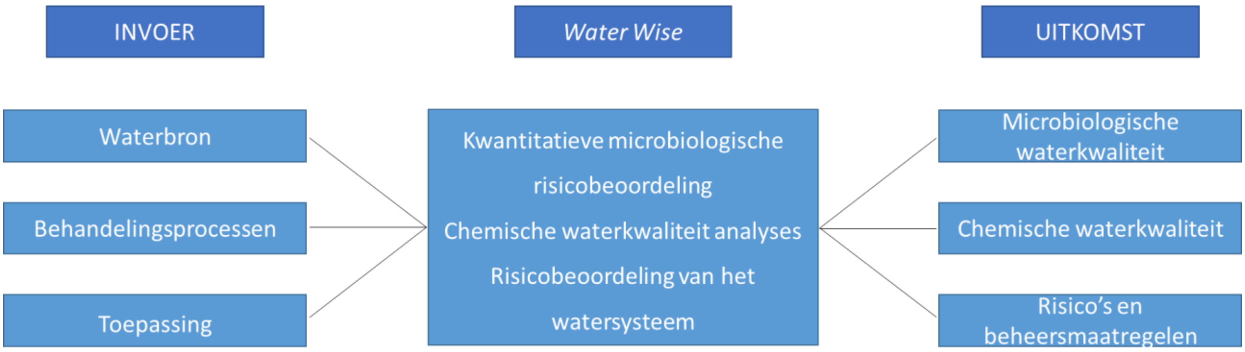
BTO Managementsamenvatting

Water Wise*: een beslissingsondersteunende tool voor veilig water(her)gebruik in nieuwe waterketens*

Auteur(s) Alex Hockin MSc, Astrid Reus MSc, dr.ir. Anthony Verschoor

Dit onderzoek heeft met *Water Wise* een tool ontwikkeld waarmee het mogelijk is om voor nieuwe waterketens de microbiologische en chemische waterkwaliteit te onderzoeken, vergelijkingen te maken met relevante (inter)nationale richtlijnen en gebruikers te begeleiden in het uitvoeren van een basis risico-inschatting. *Water Wise* is een conceptueel ontwerp, gebaseerd op bestaande methodieken en kennis van KWR. Met de ontwikkelingen van de circulaire economie bestaat bij drinkwaterbedrijven een grote behoefte aan een gebruiksvriendelijke, transparante en consistente tool waarmee gezondheidsrisico's van het (her)gebruik van alternatieve bronnen voor drinkwater, zoals afvalwater en regenwater, kunnen worden beoordeeld. Ziekten en giftige stoffen kunnen zich hierdoor echter gemakkelijker door de waterketen bewegen en dergelijke risicoverspreiding moet worden beperkt. Er zijn veel voorbeelden van water(her)gebruik waarbij gezondheidsrisico's minder goed zijn gereguleerd dan voor drinkwater. Het doel van *Water Wise* is om gebruikers te begeleiden om veilige en slimme keuzes te maken voor hun waterketens om de optimale water(her)gebruik oplossing te vinden.



Invoermogelijkheden en uitkomsten voor Water Wise*, een beslissingsondersteunende tool voor veilig water(her)gebruik.*

Belang: behoefte aan gebruiksvriendelijke tool voor evaluatie van water(her)gebruikketens

De circulaire economie leidt tot veranderingen in watergebruik en maakt nieuwe waterketens noodzakelijk. De drinkwatersector is verantwoordelijk om in die transitie een actieve rol te spelen. Zij staat garant voor de levering van veilig en betrouwbaar drinkwater aan consumenten. Bestaande tools houden echter slechts rekening met een beperkt aantal aspecten van de waterkwaliteit en nemen niet de hele waterketen in ogenschouw. Voor nieuwe, vaak gedecentraliseerde waterketens is daarom behoefte aan een gebruiksvriendelijke, transparante en consistente tool waarmee de waterkwaliteit en risico's voor de volksgezondheid kunnen worden geëvalueerd.

Aanpak: beoordeling bestaande tools en ontwerp van *Water Wise*

Relevante modellen, tools en kaders van KWR en literatuur zijn beoordeeld op toepasbaarheid in het uiteindelijk beslissingsondersteunende systeem.

Voor de tool *Water Wise* is een storyboard ontworpen, inclusief tools voor waterkwaliteit (microbiologie, chemie), een database van (inter)nationale richtlijnen en van gevaren en beheersmaatregelen voor watersystemen. Het storyboard is gepresenteerd aan verschillende eindgebruikers binnen en buiten de watersector (o.a. drinkwaterbedrijf, bierproducent en ziekenhuis). In een terugkoppeling is inzicht verkregen in de behoeften van eindgebruikers, specifieke waterketens en bijbehorende risico's.

Resultaten: beslissingsondersteunende tool voor veiligere en slimmere waterketens

Het conceptuele ontwerp van *Water Wise* helpt in het selecteren van mogelijke waterbronnen, behandelingsprocessen en vormen van eindgebruik. Gebruikers kiezen eerst uit een lijst hun specifieke waterbron, gebaseerd op een onderliggende database met microbiologische en chemische waterkwaliteitsgegevens. Vervolgens berekent de tool hoe efficiënt de geselecteerde parameters worden verwijderd. De geschatte waterkwaliteit na behandeling wordt vergeleken met (inter)nationale richtlijnen om de beoogde toepassing te toetsen. Tot slot krijgen gebruikers met het Water Safety Planning concept (Bartram et al., 2009) inzicht in een voorlopige risicobeoordeling. Zo nodig kan op grond van de toetsing het systeem worden aangepast of met andere systemen worden vergeleken. Dit biedt zicht op de bijdrage van verschillende bronnen, behandelingsprocessen en toepassingen aan de veiligheid van waterketens.

Een evaluatie van twee voorbeelden heeft aangetoond hoe de tool licht kan werpen op verschillende hergebruikscenario's. Hieruit blijkt dat bij hergebruik van effluent uit een rioolwaterzuiveringsinstallatie (RWZI) voor de agrarische sector, ondergrondse bevloeiing (Bartholomeus et al., 2017) veiliger is dan oppervlakteberegening (Beard et al., 2019). Daarnaast biedt direct gebruik van RWZI effluent een grotere zekerheid in de watervoorziening dan oppervlaktewater. Dit onderzoek is complementair aan andere WiCE projecten, waaronder De Waterfabriek. Hierin wordt maatwerk geleverd op het gebied van waterkwaliteit door 'fit-for-purpose' behandelingsprocessen. Het directe waterhergebruik van RWZI effluent verwezenlijkt de behoefte van de eindgebruiker én draagt bij aan een robuustere waterketen.

Toepassing: vergelijken en evalueren van water(her)gebruikscenario's met *Water Wise*

Verantwoord (her)gebruik van water in een circulaire economie betekent een balans tussen waterkwaliteit, gezondheid en veiligheid van verschillende combinaties van waterbronnen, behandelingsprocessen en toepassingen, en het evalueren hiervan. *Water Wise* biedt een gebruiksvriendelijke tool om voor verschillende waterketens de beoogde waterkwaliteit en risico's transparant en consistent te kunnen inschatten. De tool integreert niet alleen *state-of-the-art* kennis van waterkwaliteit, behandelingsprocessen en verwijderingsefficiënties, maar ook bedreigingen voor het system en mogelijke beheersmaatregelen. Daarmee bewijst het zijn waarde niet alleen in de mogelijkheid om waterketens te evalueren, maar ook als manier om van elk element de data centraal te beheren, bijvoorbeeld van microbiologische en chemische waterkwaliteitsgegevens voor verschillende bronnen en van (inter)nationale richtlijnen voor waterhergebruik hiervan.

Dit onderzoek is een eerste stap in de richting van een tool voor kwantitatieve risicobeoordeling voor nieuwe waterketens. Het geeft inzicht hoe vooraf eindgebruikers risico's kunnen verminderen. Met meer onderzoek en input van experts op het gebied van nieuwe waterketens kan de tool nog completer worden gemaakt.

Rapport

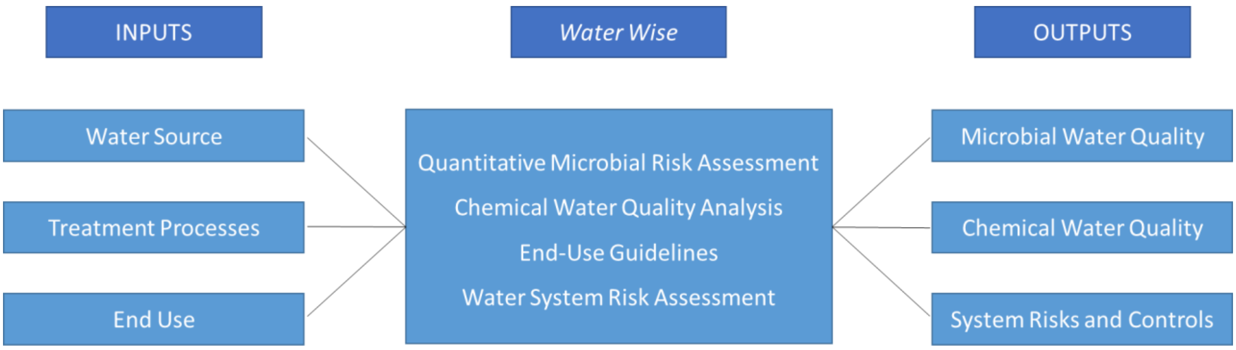
Dit onderzoek is beschreven in het rapport *Water Wise: A decision support system for safe water (re)use* (BTO 2020.033).

BTO Management summary

Water wise: *Decision support system for safe water use and reuse*

Author(s) Alex Hockin MSc, Astrid Reus MSc, dr. ir. Anthony Verschoor

A circular economy opens new and transformed ways of dealing with water. Alternative sources, such as wastewater and rainwater, will be increasingly used and reused in applications where drinking water is currently employed. However, there are many instances of water use and reuse in which the associated health risks are less well controlled than they are for drinking water. This means that toxicity and disease might be transmitted more easily through the water cycle – and this 'risk cycling' must be carefully managed. *Water Wise* has been conceptually designed, building on existing tools and KWR knowledge, to address the need for an easy-to-use, transparent and consistent tool to assess new water (re)use cycles. The tool evaluates the microbial and chemical water quality, compares it to relevant national and international guidelines, and provides users with a basic risk assessment process. The purpose of *Water Wise* is to guide users in making safer and smarter decisions regarding their water cycles, with the aim of identifying optimal water use and reuse solutions.



Inputs and outputs for Water Wise*, a decision support system for safe and smart water use and reuse cycles.*

Importance: User-friendly tool for evaluating water use and reuse cycles

The circular economy means changing the linear way we use our water and finding new water cycles. There is however no easy way to assess the risks associated with new, often decentralised, water cycles. Several tools exist to assess water quality or risk, but they typically only address a few aspects of water quality without considering the cycle as a whole.

Since the drinking water sector has the necessary experience in provide safe, reliable water quality to its customers, it should take an active and leading role in the circular economy. There is a need for an easy-to-use, transparent and consistent tool to assess new water cycles in order to ensure public safety.

Method: Review of existing tools and creation of tool framework for end-user feedback

Relevant models, tools and frameworks from both within KWR and from literature were reviewed for inclusion in the final decision support system (DSS). A storyboard for a tool, *Water Wise*, was created, incorporating microbial and chemical water quality tools, a database of national and international guidelines, and a database of water system hazards and control measures. The storyboard was presented to end-users from different water use sectors (drinking water, food and beverages, healthcare) to get feedback and insight into end-user needs and typical water cycles and associated risks.

Results: *Water Wise* – a decision support tool for safer and smarter water cycles

A tool framework was created which guides users through the selection of possible water sources, treatment processes and end-uses. To begin with, users select their choice of source water from a list. The tool has a database on the microbial and chemical water quality of these sources. The tool then evaluates the removal efficiency for the microbial and chemical parameters selected, and presents the estimated water quality following treatment. This water quality is compared with the relevant national and international guidelines, to determine whether the water is likely to meet the standards for its intended use. Lastly, users are guided through the steps in making a basic risk assessment of the specified water system, as a way of introducing users to the concepts of Water Safety Planning (Bartram et al., 2009). Users can then export the results of the assessment, go back and modify the selected system, or compare different systems to gain insight into how different sources, treatment processes and end-uses contribute to water cycle safety.

Two cases were evaluated and compared to demonstrate the insights that the tool can provide in different reuse scenarios. The first case involved the 'de facto' reuse of wastewater treatment plant (WWTP) effluent for surface irrigation (Beard et al., 2019), and the second the direct reuse of WWTP effluent in subsurface irrigation (Bartholomeus et al., 2017). The comparison showed that subsurface irrigation provided a higher degree of safety. An assessment of the system hazards also highlighted the security of supply of irrigation water in the case of the direct reuse of WWTP effluent compared to the use of surface water for spray irrigation. This research complements other WiCE research. For example, the use of 'Water Factories' to provide customized water quality through fit-for-purpose treatment processes. The direct reuse of WWTP effluent fulfils the needs of the end-user, while also contributing to more a robust water cycle.

Implementation: Comparing and evaluating water use and reuse scenarios using *Water Wise*

The responsible use of water in a circular economy means evaluating and balancing the water quality and health and safety of different water sources, treatment options and end-use combinations. *Water Wise* provides an easy-to-use tool to transparently and consistently evaluate the expected water quality and risks involved in different water use cycles. The tool integrates state-of-the-art knowledge on water quality, treatment processes and removal efficiencies, as well as system hazards and possible control measures. The tool provides value not only in the ability to evaluate water cycles, but also as a way to centrally store the data for each of the tool elements. For example, a central storage of microbial and chemical water quality data for a variety of sources, and national and international guideline values for water reuse for these same sources.

This research is a first step towards creating a tool to quantitatively evaluate the risks inherent in new water cycles and better understand how end-users can mitigate these risks beforehand. To complete the tool, more research and expert opinions on new water cycle risks are needed.

Report

This research is reported in *Water Wise: A decision support system for safe water use and reuse* (BTO 2020.033).

Summary

Circular economy provides a changing way of dealing with water. In place of drinking water, wastewater and rainwater will be used more often and discharged less frequently. In addition to the water itself, elements present in the water cycle can be recovered for new applications. As a result, changes in the current water infrastructure will occur. Instead of central production and disposal there will be a shift toward more decentralized, local water reuse and water cycles.

Toxicity and disease can be transmitted through the water cycle. When increasing reuse of water or raw materials from water, the risks can also be circulated (Grundmann et al., 2013; Lieder et al., 2016). Such 'risk cycling ' must be prevented to avoid adverse human health effects and controlled in order to achieve the goal of making the Netherlands fully circular by 2050 (Wassenaar et al., 2017). There are many examples of water (re)use where the health risks are less well controlled than for drinking water, for example reuse of water in agriculture, horticulture or industry. There is also often a lack of clear safety and water quality guidelines for these applications.

With changing water cycles, the responsibility to provide safe water remains with providers, but also involves new stakeholders, water sources, treatment technologies and end-uses. In particular, there is the desire to explore alternatives to high quality drinking water for uses which do not require such expensive and resource intensive water treatment. These new water cycles would benefit from an easy-to-use tool that can evaluate the chemical and microbial water quality and perform basic risk assessments in a consistent and transparent manner.

In this research we propose a decision support system, *Water Wise,* which fills the niche identified for a user-friendly tool which can provide basic water quality information for a variety of source waters, predict the chemical and microbial quality for different water sources and removal efficiency for a variety of treatment processes, compare the quality to relevant guidelines and perform a preliminary risk assessment of the water system.

Water Wise has been conceptually designed, building on existing tools and knowledge at KWR. Tools included are the AquaNES QMRA (for quantitative microbial risk assessment) and a tool for quantitative chemical risk assessment, a working database of water quality guidelines and a working database of risks for water systems. A major advantage of the proposed tool is the incorporation and alignment of multiple tools into one, such that water quality can be evaluated consistently for chemical and microbial parameters, and also for the systems risk assessment.

Two cases were evaluated to showcase the insights that the tool can give on different reuse scenarios. The cases, comparing the 'de facto' reuse of WWTP effluent for spray irrigation (Beard et al., 2019) and the direct reuse of wastewater treatment plant (WWTP) effluent in subsurface irrigation (Bartholomeus et al., 2017), demonstrate the increased safety that subsurface irrigation provides. An assessment of the system hazards also highlighted the security of supply provided by the direct reuse of WWTP as compared to surface waters. This research compliments other WiCE research. For example the use of 'Water Factories' to provide customized water quality through fit-for-purpose treatment processes. The direct reuse of WWTP effluent fulfils the need of the end user, while also contributing to more a robust water cycle.

The concept of the tool has been presented to a variety of end-users in different industries (drinking water, health care, food and beverage). Feedback from end-users has been incorporated into the framework and storyboard for the tool. Future work on the tool is proposed to take place in a follow-up project.

Contents

1 Introduction

1.1 Water use and the circular economy

Circular economy provides a changing way of dealing with water. In place of drinking water, wastewater and rainwater will be used more often and discharged less frequently. In addition to the water itself, elements present in the water cycle can be recovered for new applications. As a result, changes in the current water infrastructure will occur. Instead of central production and disposal a shift is taking place towards more decentralized, local water reuse and water cycles.

Similar developments have occurred in, for example, the energy sector, where more and more decentralized production is taking place in addition to centralized power plants. Though there are many clear parallels with the energy sector (e.g. matching supply and demand, buffering shortages and surpluses), there are also unique challenges in the water sector, above all the security of the supply of high quality water.

Toxicity and disease can be transmitted through the water cycle. With increasing reuse of water or raw materials from water, the associated risks can also be circulated (Grundmann et al., 2013; Lieder et al., 2016). Such 'risk cycling ' must be prevented to avoid adverse human health effects and controlled in order to achieve the goal of making the Netherlands fully circular by 2050 (Wassenaar et al., 2017). There are many examples of water (re)use where the health risks are less well controlled than for drinking water, for example reuse of water in agriculture/horticulture and industry. Often there is also a lack of guidelines for water quality for these specific applications or clear safety guidelines. For example, only six EU member states have water reuse standards (*i.e.* Cyprus, France, Greece, Italy, Portugal and Spain) (BIO by Deloitte, 2015), despite widespread interest and investment in water reuse projects within Europe and abroad.

Microbiological and chemical risks in the circular economy depend on the type and concentration in the source water, technology used for reuse (treatment processes) and the use of the water (end-use). Characterization and quantification of these aspects will help to design safe and healthy reuse cycles. Furthermore, hazards in the water cycle need to be recognized in advance to prevent chemical, microbial or aesthetic issues from occurring, in addition to the security of supply (e.g. preventing interruptions in supply). Risks databases exist (e.g. PREPARED, TECHNEAU) although these databases are almost exclusively based on the end-use for drinking water.

1.2 Role of the drinking water sector

Changing water cycles means the involvement of new stakeholders, water sources, technologies and end-uses. Drinking water utilities may wish to expand or diversify their sources for drinking water, while waterboards have the opportunity to turn wastewater discharges into new sources of fit-for-purpose water supplies, for example through the use of water factories. There are many drivers which encourage more responsible use, and reuse, of water, including increasing water stress and water scarcity, as a result of drought or overuse of limited freshwater resources. This is a trend worldwide, and the Netherlands has the opportunity to take a leading role.

The drinking water sector and KWR researchers are actively involved in many water (re)use projects including *SUPERLOCAL, TANQIA, TKI Sluiten Watercyclus Noord-Holland,* as well as in the Water in the Circular Economy (WiCE) programme as a whole. Drinking water utilities must also evaluate alternative and supplemental drinking water sources with changing climate and water use patterns to ensure the security of supply in case of drought, pollution or other unforeseen events. Finally, the drinking water sector also plays an important quality assurance role in implementing and auditing water safety plans when evaluating new, private or decentralized water systems. All of these applications would benefit from an easy to use system to evaluate the chemical and microbial water quality and perform basic risk assessments in a consistent and transparent manner.

1.3 Research objectives

This research aimed to develop a conceptual tool to evaluate the chemical and microbial quality of water (re)use cycles, to model the risks quantitatively and, where possible, identify measures to manage the risks to achieve safe and responsible reuse. The tool is envisioned as a user-friendly, decision support system (DSS), where the optimal (re)use cycle can be designed for each end-user. The tool has been developed conceptually (through a storyboard) and presented to possible end-users from different sectors (drinking water, healthcare, food and beverage industry and academic research) for feedback. Finally, the developed methodology was evaluated for two case studies to demonstrate the possible outputs, to identify gaps in knowledge and to indicate where more research is needed.

2 *Water Wise*: A Decision Support System for Safe Water (Re)Use

2.1 Models for assessing risk in water (re)use

. Several tools have been developed for the water and wastewater sector to aid in the selection and design of water and wastewater treatment trains (for examples see Hamouda et al. (2009) and Oertlé et al. (2019)). However, these tools other available models are often focused on individual aspects of water use (e.g. optimizing disinfection) or address only one type of risk (e.g. chemical *or* microbial).. Within KWR, several discrete tools have been developed to assess the effectiveness of different water treatment processes or process trains. Some of these models also assess the risk of exposure (e.g. QMRA). Relevant models, tools and frameworks from both within KWR and the literature have been summarized in Appendix I Table with a description of possible integration within *Water Wise* and limitations of the individual tools.

2.2 Vision for *Water Wise*

Based on the review of the available tools, there is an opportunity for a user-friendly tool which can provide basic water quality information for a variety of source waters, predict the chemical and microbial quality for different water sources and removal efficiency for a variety of treatment processes and compare to relevant guidelines, perform a preliminary risk assessment and guide users through the water safety plan (WSP) approach (Figure 1).

A storyboard is a representation of the user interface of the tool without the actual background functionality. The storyboard shows what the tool could look like and demonstrates step-by-step how the tool could be used by end-users. The goal of the storyboard is to make discussions with end-users more concrete and thus lead to a tool that fulfils the needs and expectations of end-users. It raises enthusiasm and stimulates the thinking process of end-users, identifying new useful functionalities and prioritizing them. A storyboard for *Water Wise* was created and used in discussions with end-users from a variety of industries.

The goal of *Water Wise* is to help guide end-users to make safe and smart decisions regarding their water cycles so that the optimal (re)use solution can be found. Water cycles in *Water Wise* are not particularly limited to water reuse, as primary water sources including surface water, rainwater and groundwater are also considered.

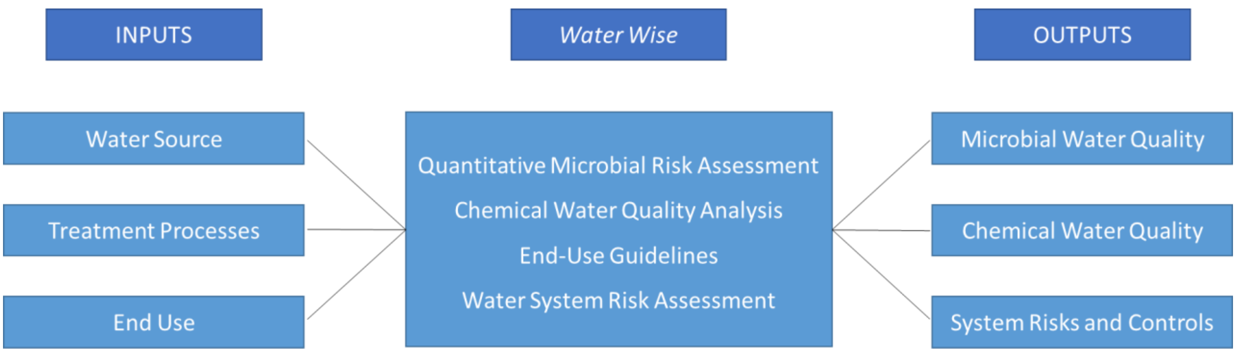
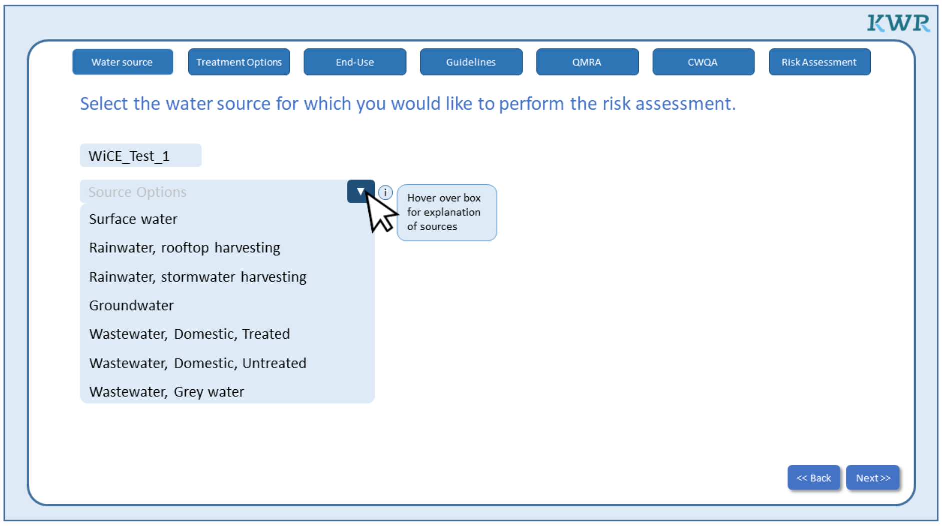


Figure 1 Inputs and outputs for Water Wise*. Based on the user's choice of source water, treatment processes and end-use of the water, the water quality is assessed against the appropriate guideline to determine compliance. In addition, a risk assessment is performed for the chemical, microbial and operational risks in the water cycle.*

The following figures present the storyboard for *Water Wise*. The storyboard incorporates feedback from various end-users (see section 3) and functionality of existing tools at KWR, but also expands on those tools which still require additional research, expansion of current databases or creation of new databases. The full storyboard can be found here.

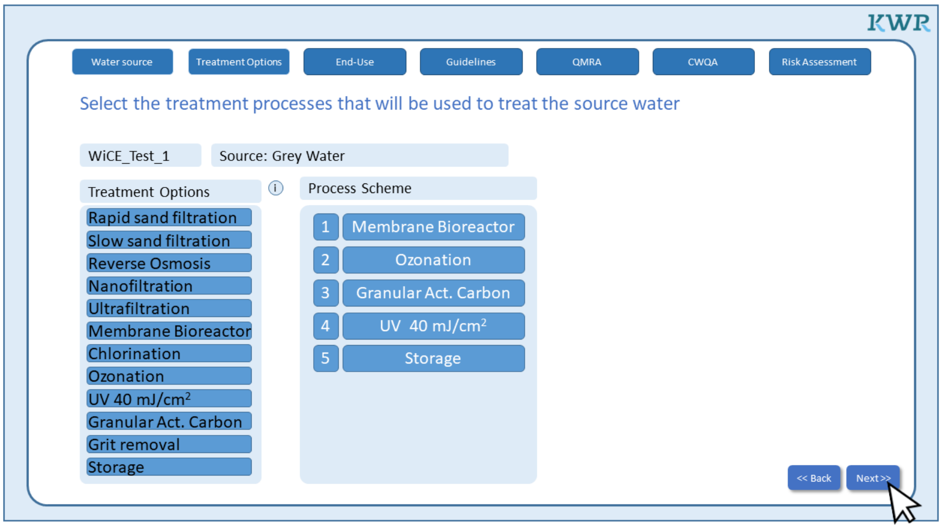
Storyboard: Webtool Interface	Explanation



The user signs in and gives a name for his or her water cycle. This allows users to come back and edit or re-evaluate the cycle later.

The user first selects a source water from the dropdown list.

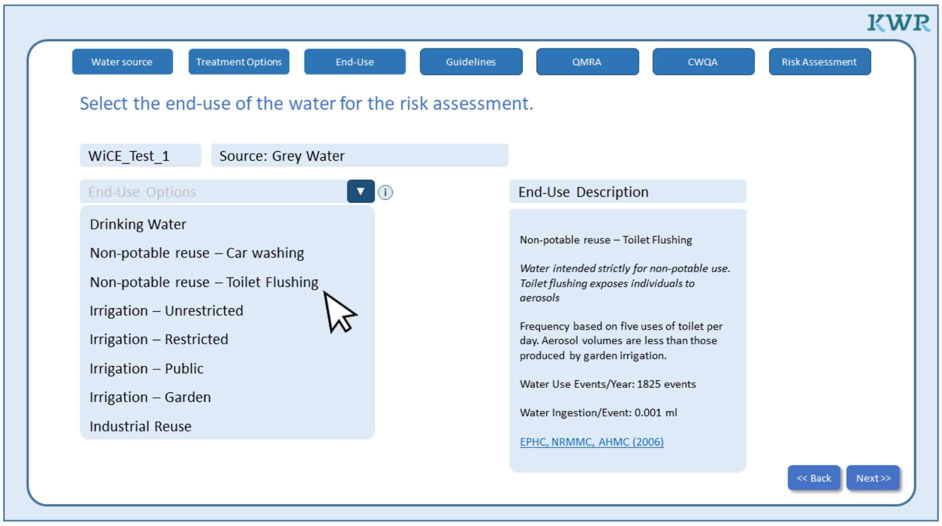
A short explanation is given by hovering over the different water sources.



The user then creates a treatment train by dragging and dropping treatment processes.

The hover over box gives further details on the different treatments.

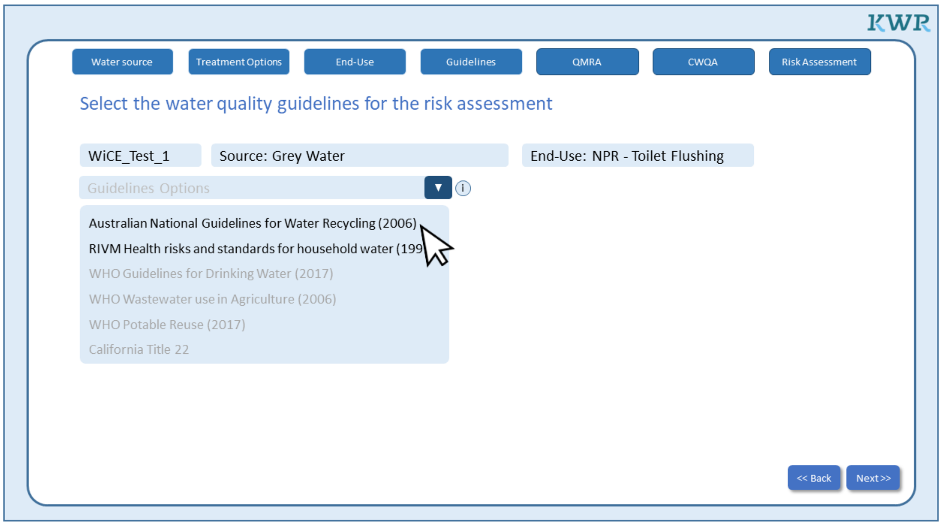
There is also the option to add pre-existing treatment trains (e.g. conventional WWTP treatment trains).



The user selects the end-use of the water.

For each end-use, a short description is given for the type of use and the frequency of use.

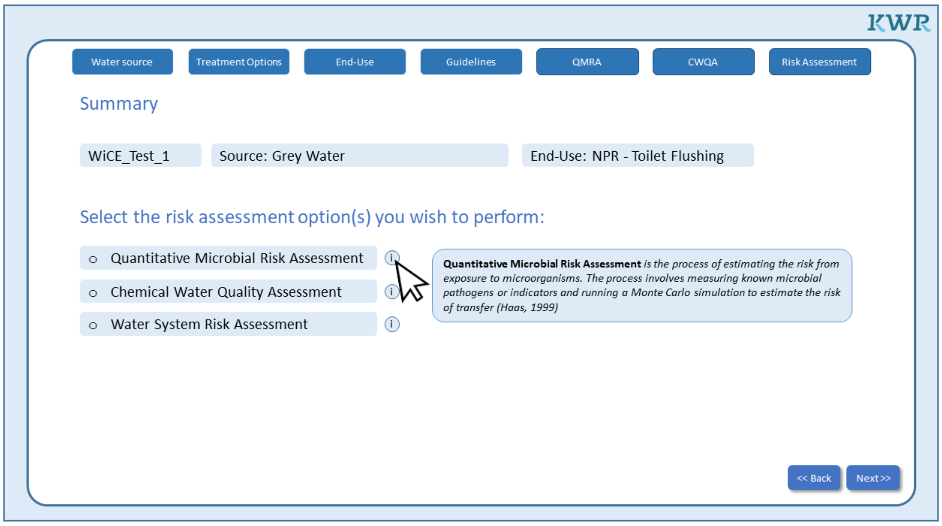
Later exposure calculations use numbers of water use events per year and the water ingestion per event.



The user has a choice of guidelines to compare to their estimated water quality.

Guidelines in grey indicate end-uses which do not match the chosen end-use.

Users can select the guideline which best suits their needs.

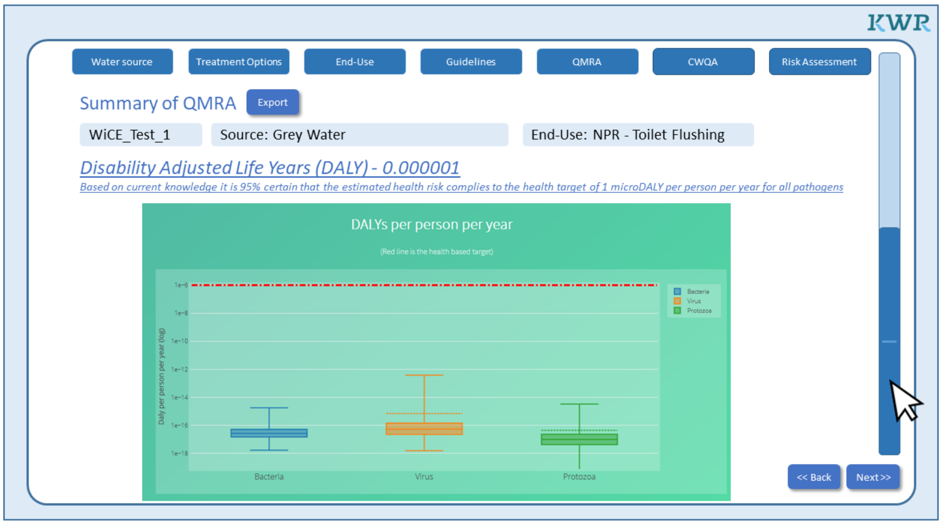


The user can select which of the three water quality analyses to perform.

A hover over box gives a short explanation of each of the risk assessments.

QMRA gives a summary of the minimum and maximum range of pathogens in the chosen water type with reference to the corresponding literature.

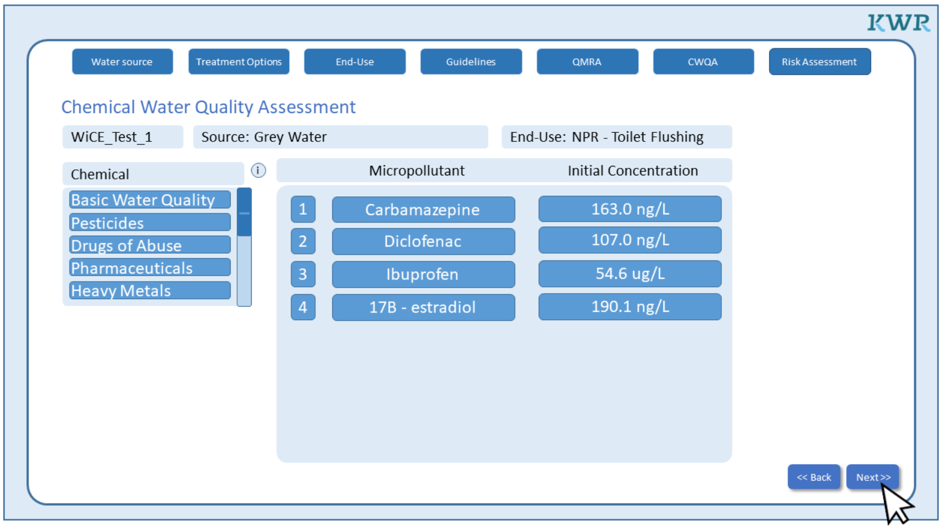
The user also has the option to modify the given table or to upload their own data for use in the calculations.



The risk of the water cycle is then compared with two health based targets: the annual risk of infection and Disability Adjusted Life Years (DALY).

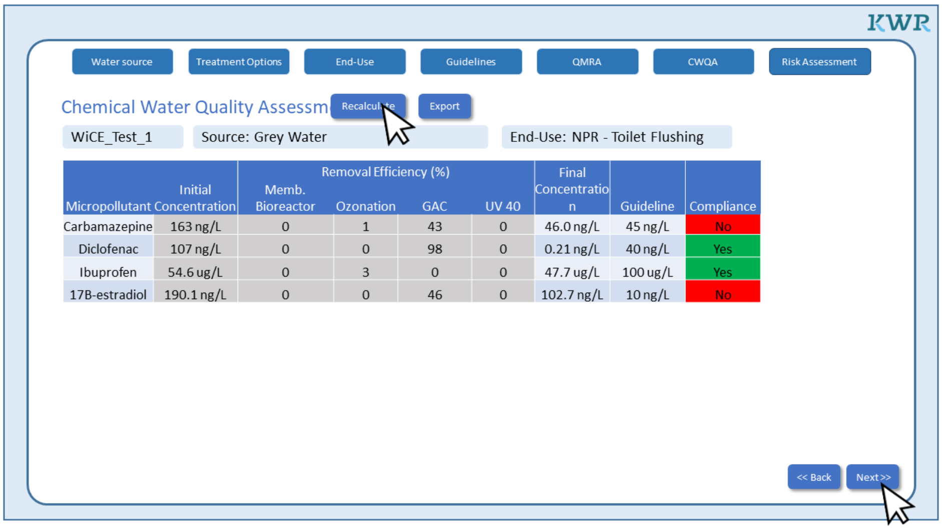
The results are presented in box plots and tables (table not shown, see Appendix III Case Study Additional Data).

The user can also export the QMRA results to a spreadsheet or a PDF.



The chemical water quality assessment allows users to select chemicals to evaluate in the chosen water source.

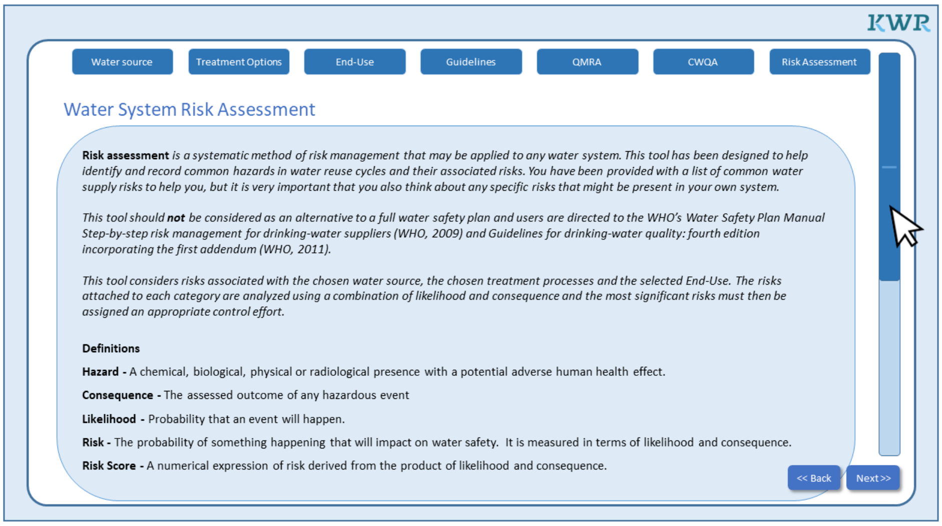
Chemicals are grouped based on use, but the user can also select to evaluate all chemicals for the given water source. Typical concentrations for these chemical are given for the selected water source.



A summary of the typical concentrations of the chosen chemicals in the water source and removal efficiencies of the selected treatment processes are given based on a database collected from literature.

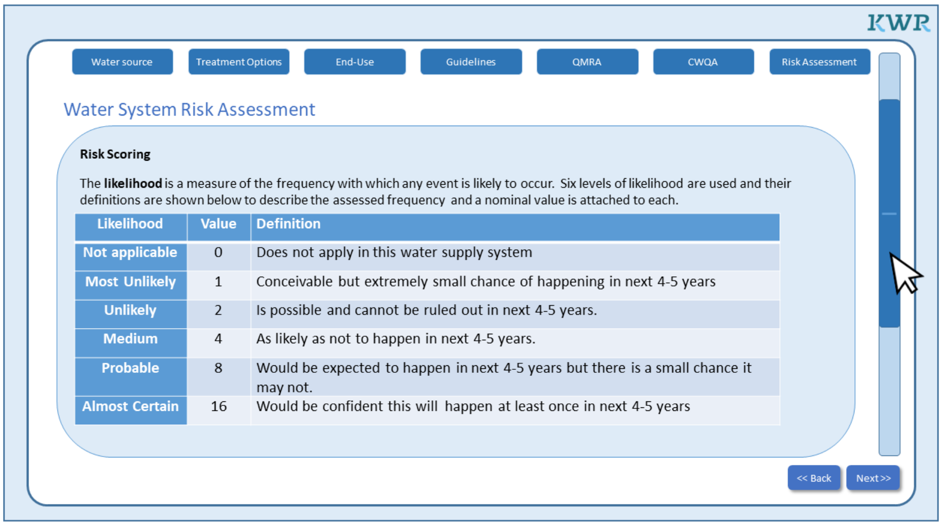
The user can also modify the given initial concentrations and removal efficiencies if desired.

The user can also export the chemical water quality assessment.



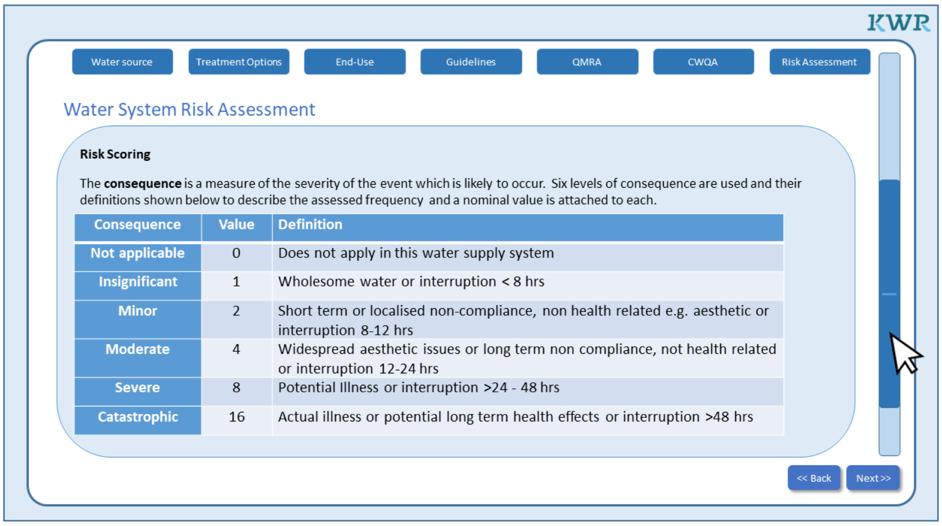
The water system risk assessment is explained, based on the WSP from the WHO (Bartram et al., 2009).

The user is advised that *Water Wise* is not a substitute for a WSP.



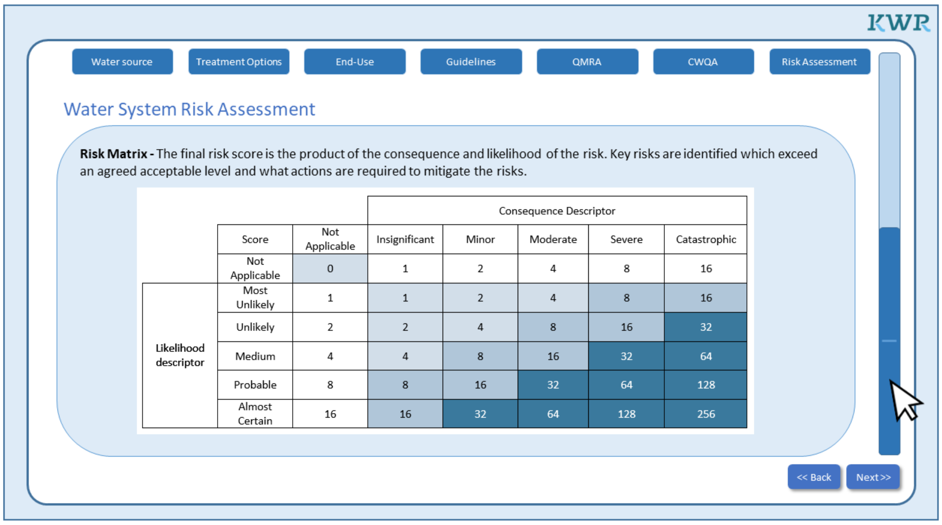
The basics for scoring the likelihood of the hazard occurring are explained (Bartram et al., 2009).

The score ranges from 0 (not applicable) to 16 (e.g. very likely to happen in the next 4-5 years).



Scoring for the consequence of the hazard occurring is explained (Bartram et al., 2009).

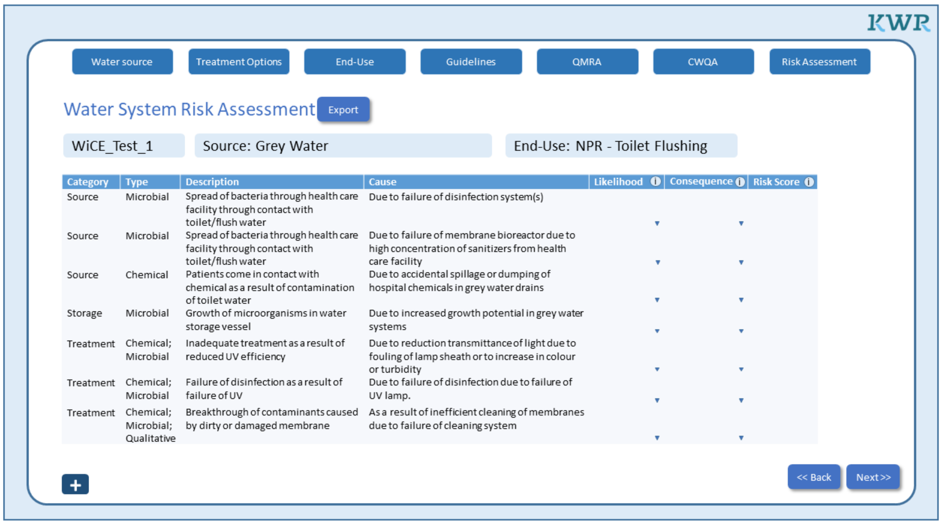
The score ranges from 0 (not applicable) to 16 (e.g. acute illness).



The scores for likelihood and consequence are then multiplied to calculate a risk score.

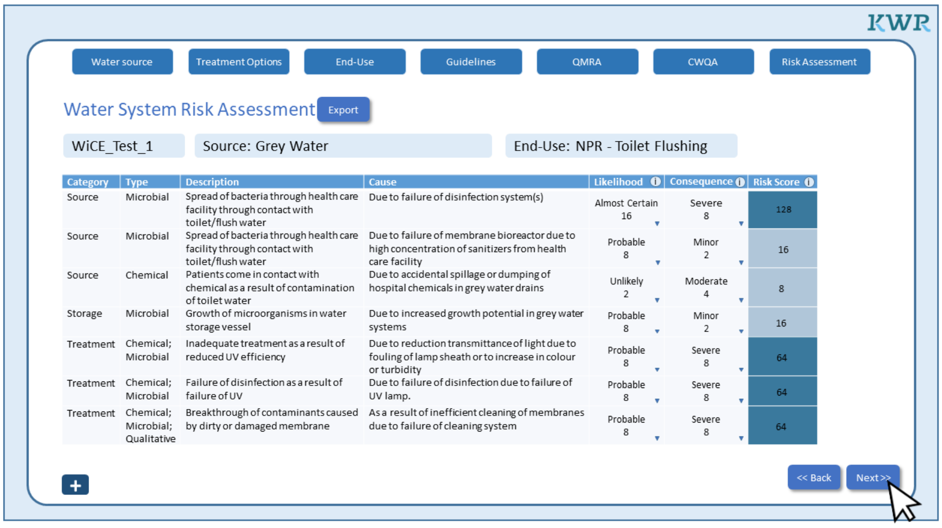
Risk scores above 32 are considered key risks (Government of Alberta, 2012).

Key risks must be addressed with appropriate control measures.



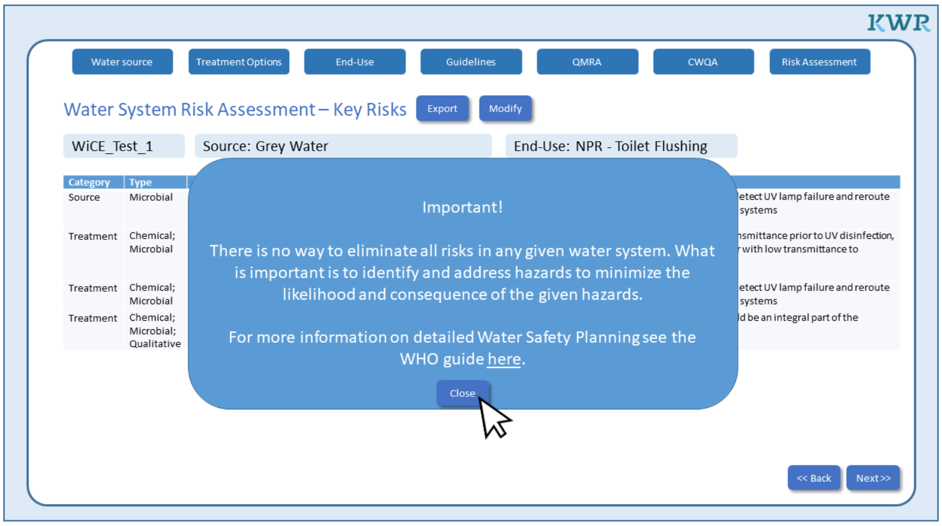
Based on the chosen water source, treatment processes and end-use, a list of hazards for the water system is given.

The user then scores the likelihood and consequence of the hazards with the previously shown rubric.

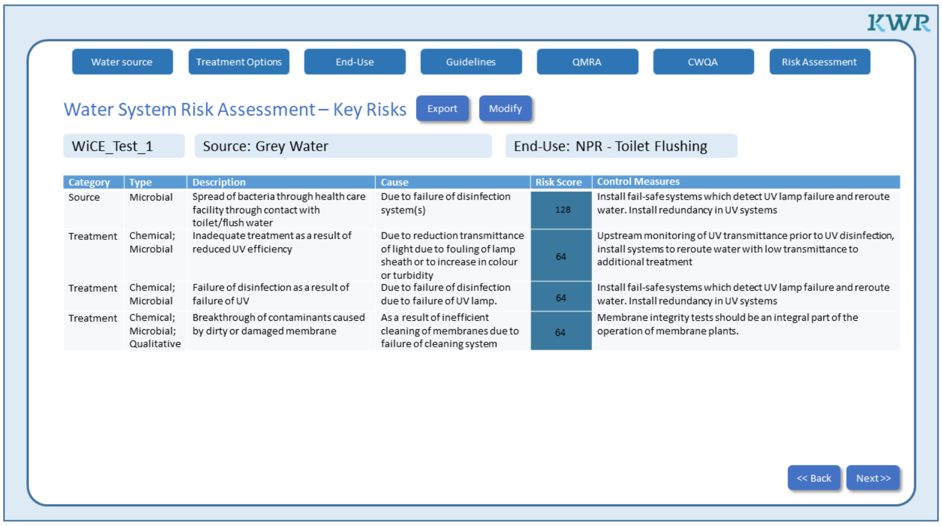


Based on the scoring completed by the user, a risk score is calculated for each hazard.

Key risks (>32, in red) are identified by the tool.



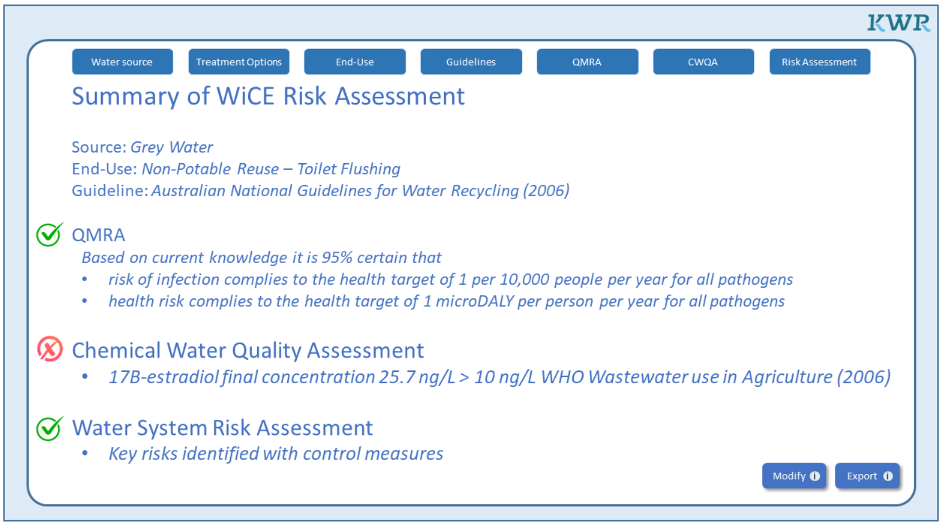
Based on user feedback, we have added a pop-up window which explains that all water systems have hazards and it should not be interpreted that because hazards are found in the user's system that the system is by definition unsuitable for the given end-use.



The key risks identified are summarized with suggested control measures from the risk databases.

The user can edit the given control measures, add additional hazards or change scores.

The user can also export the risk assessment to a spreadsheet or PDF.



At the end of the tool a summary of the three assessments is given.

Green checkmarks indicate the chosen guidelines and/or health targets are met. Red crosses indicate one or more health targets or guidelines have not been met.

The user can export the results of the assessments from this page to PDF or excel. The user can also modify the assessment, by clicking on the appropriate icon at the top (e.g. water source, treatments etc.).

2.3 Quantitative Microbial Risk Assessment

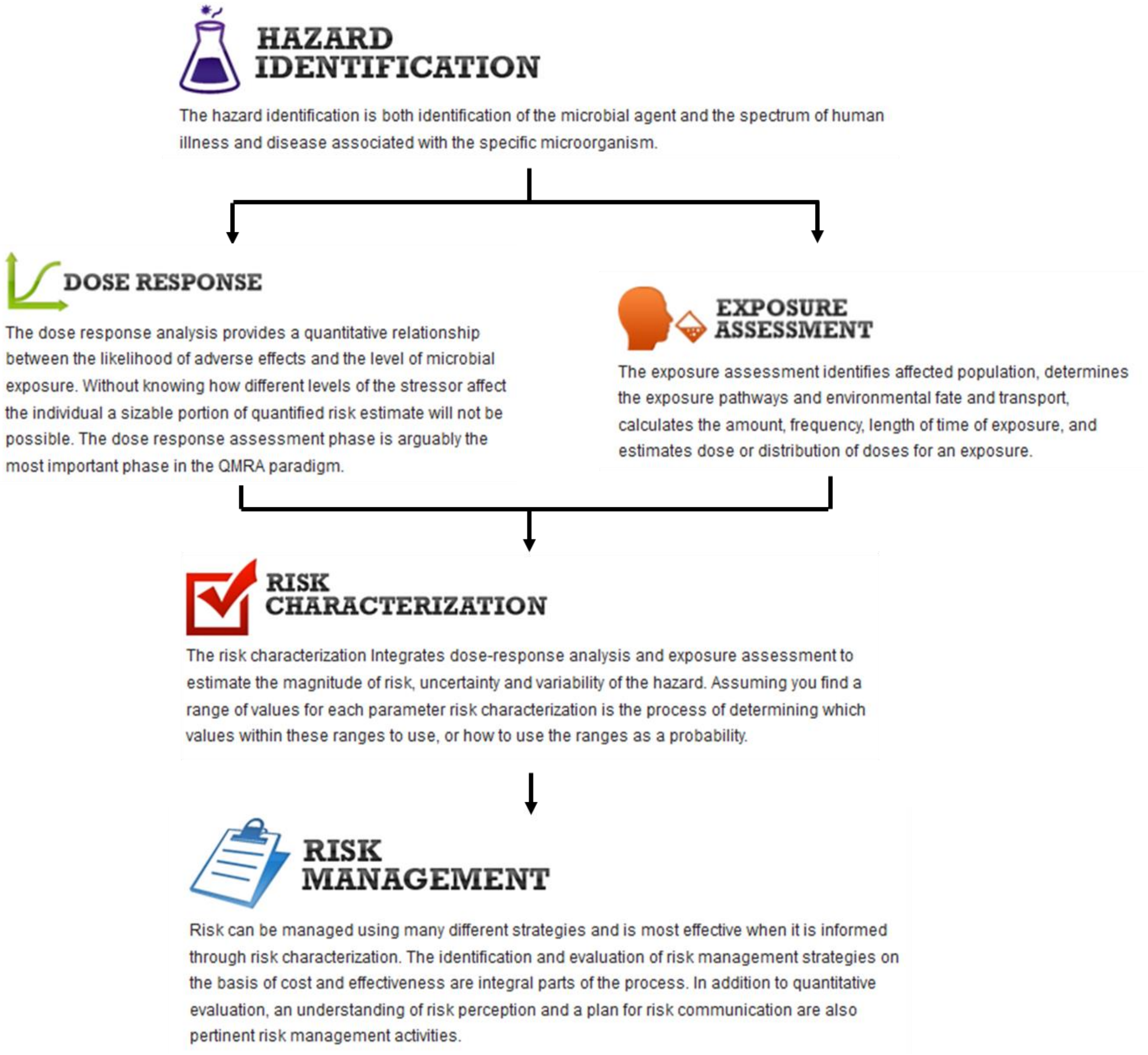


Figure 2 QMRA Framework from QMRA Wiki.

QMRA is a framework to assess the spread of pathogens through environmental exposure and the risk of adverse outcomes (QMRA Wiki, Figure 2). The process of QMRA involves identification of hazards, assessment of the dose response of pathogens and relationship with adverse effects, assessment of the exposure of the identified population, characterization of risk incorporating the dose response and exposure data and risk management planning to address the risks characterized.

The AquaNES QMRA tool was developed jointly by KWR and KWB (Kompetenzzentrum Wasser Berlin) within the EU Horizon 2020 project AquaNES. The QMRA tool in *Water Wise* is based on the AquaNES QMRA tool. The tool uses state of the art knowledge on pathogen concentration in a variety of source waters, removal efficiencies for treatment technologies, dose response models and exposure data. The goal of the tool is to make QMRA more accessible and transparent to improve the safety of water (re)use systems. The tool also incorporates international health based targets and presents the data used and results of the calculations in a transparent way. As users become more familiar with the tool, more advanced risk assessments can be performed, by using custom data sets for source water concentrations and removal efficiencies. To perform a basic risk assessment the user needs only to choose from a list of provided source waters, assemble a treatment train and choose an end-use. The tool then performs a Monte Carlo simulation and the risk of the input water cycle is compared to two commonly applied health based targets, the annual risk of infection and Disability Adjusted Life Years (DALY) (WHO, 2017).

2.4 Chemical Water Quality Assessment

A tool for chemical risk assessment was developed within the EU Horizon 2020 project AquaNES. The tool has a database of micropollutant concentrations and removal efficiencies reported in literature for different source waters and treatment processes. However, performing a risk assessment for organic micropollutants is not a simple task, as the risk from micropollutants is not determined by individual chemicals and health based threshold values are not necessarily available for all chemicals in all use categories (ter Laak, 2019). The existing tool allows users choose the source water and treatment train and the tool gives the estimated concentration in the source water, removal efficiencies and final concentration in the treated water. Until now, the risk assessment portion of the tool has only been investigated in combination with the AquaPriori tool (See Box 2.4.1 below).

In addition to the database of organic micropollutants, *Water Wise* is envisioned to also supplies basic water quality information, such as turbidity, total suspended solids, total dissolved solids, total organic carbon, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen, total phosphorous, conductivity and nitrate. This information is not yet in a database, but could be assembled from the literature, including concentrations in source waters and removal efficiencies for the same treatment processes in the QMRA tool. The end result of the chemical water quality assessment would be the comparison of the chemical water quality against guideline values for the specified end-use.

2.4.1 AquaPriori – Quantitative Chemical Risk Assessment

In a project parallel to this WiCE project, the AquaPriori tool was used to predict the activated carbon performance towards contaminants of emerging concern (CECs) in drinking water. The tool, that now is able to import a single value for each input, was adapted to analyse distributions of inputs. This was useful to model how the uncertainties of the input parameters affect the estimated CECs breakthrough profile and the resulting treated water quality. Moreover, the adapted AquaPriori tool was able to provide probabilistic estimation of the maximum CECs concentrations in treated water that, coupled with toxicological analyses, was used to develop a Quantitative Chemical Risk Assessment (QCRA) procedure. The developed QCRA procedure, comparing to the traditional chemical risk assessment, is able to consider the high uncertainties related to CECs achieved treatment removals and toxicity to assess the human health risk in a probabilistic way that has been demonstrated to be more precautionary. In particular, the tool was adopted to assess the probabilistic risk for several case studies differing for source water quality and GAC treatment operating conditions. Finally, the tool was useful to simulate intervention scenarios and to optimize the design of GAC treatment systems, their upgrade and management minimizing the generated probabilistic human health risk. This tool could be adapted, for example, to simulate GAC treatment performance in other water matrices to evaluate the probabilistic risk in situations of direct potable reuse or to select the best drinking water source.

2.5 Water Quality Guidelines

Water Wise will contain a database of water quality guidelines for different end-uses, including drinking water, non-potable reuse (e.g. car washing, toilet flushing), irrigation (e.g. restricted, unrestricted, public, garden) and various industrial uses (e.g. process water, food sector). The tool will then be suitable for comparison of the estimated microbial and chemical water quality to the guideline values, and can assess whether the given treatment train is likely to meet the required guidelines. The tool is meant to be interactive, and therefore if the required end-use water quality guidelines are not met, the user can go back and modify treatments and observe how modifications in the treatment train affect the ability to meet the guidelines. Within the tool, when an end-use is selected, the tool will filter the choices of guidelines so that only the guidelines relevant to the specified end-use are displayed

A basic database of guidelines has been assembled and an overview of additional guidelines which could be included in the future have been assembled.

2.6 Water System Risk Assessment

The WHO recommends the use of WSP to ensure the safety of drinking water systems. WSP is a systematic method of risk assessment and risk management approaches, which encompasses the whole drinking water cycle, from source to tap. The same safety principles, though, can be applied to different water (re)use cycles (Hochstrat et al., 2017). Importantly, within the tool, the water system risk assessment is *not* meant to be a replacement for a full WSP. The goal of the risk assessment portion of *Water Wise* is to familiarize users with the concepts of WSP and guide users through a portion of the WSP framework (module 3 and 4 in Figure 3). The tool provides a list of hazards from a database, linked to the specific water source, treatment processes and end-uses chosen by the user.

For full details on WSP, users are directed to the WHO's *Water Safety Plan Manual Step-by-step risk management for drinking-water suppliers* (Bartram et al., 2009) and *Guidelines for drinking-water quality: fourth edition incorporating the first addendum* (WHO, 2017), and the WHO website on sanitation safety planning.

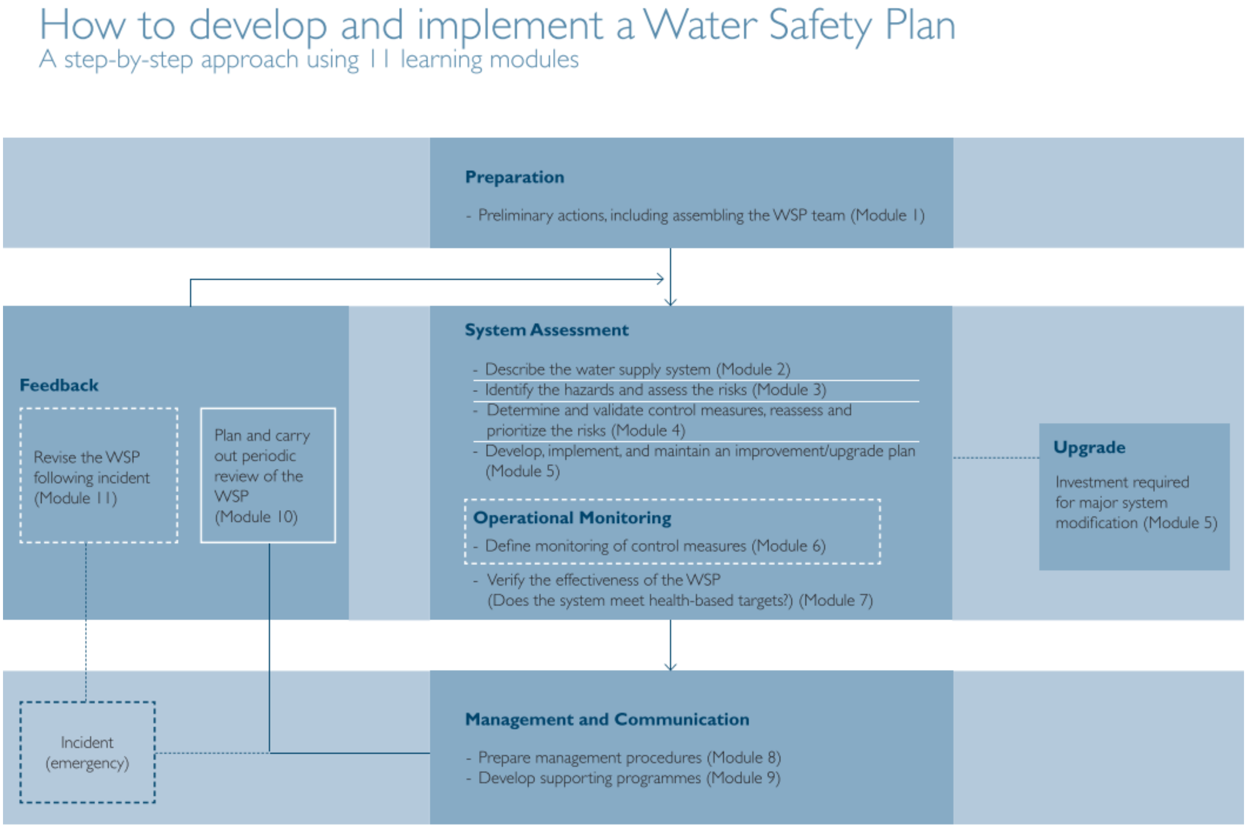


Figure 3 Water Safety Planning Framework from (Bartram et al., 2009)

Water Wise risk assessment consists of three components; 1. Hazard Identification, 2. Risk Scoring, 3. Hazard Controls.

Hazards Identification

Based on the choice of water source, treatment processes and end-use, associated hazards from a database are displayed to the user. Currently, a hazard database has been assembled from three existing databases: WSP Alberta (Government of Alberta, 2012), TECHNEAU and PREPARED (EU projects, (EU, 2010a, 2010b)). A limitation of the current databases is their focus on drinking water systems only. While similar hazards can be identified for non-drinking water uses, additional hazards should be collected focused on non-potable use and on reuse cycles. Examples of adaptations for reuse cycles are given in the case study (Section 4). Not all hazard types and categories have been tagged and the database must be cross-referenced for each of the source, treatment and end-use options during the programming of tool. The current database contains 659 hazards and hazard events collected from the three databases and additional hazards added from the case study review.

Risk Scoring

The user must score the given hazards based on the likelihood and consequence for the given system. The tool will *not* suggest risks scores, as it is important to engage the user in thinking through how likely it is a particular event will occur and what the consequences of the event will be. To help guide the user, the hazards will be tagged based on whether the hazard has an effect on health (e.g. microbial, chemical contamination), aesthetics (e.g. taste, odour) or affects the security of supply (e.g. loss of pressure in network). The hazard category will also be classified, indicating which part of the water cycle the hazard originates in (e.g. water source, treatment process, transport & storage or end-use). The tool uses a combination of the WHO semi-quantitative risk assessment (Bartram et al., 2009) and the WSP of Alberta (Government of Alberta, 2012) ranking for likelihood, consequence and overall risk scoring (Table I, Table II and Figure 4).

Table I Risk scoring and explanation for likelihood of a particular hazard. The likelihood is a measure of the frequency with which any event is likely to occur. Six levels of likelihood are used and their definitions are shown below to describe the assessed frequency and a nominal value is attached to each.

Likelihood	Value	Definition
Not applicable	0	Does not apply in this water supply system.
Most Unlikely	1	Once every 5 years
Unlikely	2	Once a year
Moderate	3	Once a month
Likely	4	Once a week
Almost Certain	5	Once a day

Table II Risk scoring and explanation for the consequence of a particular hazard. The consequence is a measure of the severity of the event which is likely to occur. Six levels of consequence are used and their definitions shown below to describe the assessed frequency and a nominal value is attached to each.

Consequence	Value	Definition
Not applicable	0	Does not apply in this water supply system.
Insignificant	1	No impact or insignificant impact on water quality
Minor	2	Short term, minor or localised non-compliance, non-health related e.g. aesthetic
Moderate	3	Moderate aesthetic issues or long term non-compliance
Severe	4	Major regulatory impact, illness or interruption >24 - 48 hours.
Catastrophic	5	Public health impact, acute illness or potential long term health effects

			Consequence Descriptor				
	Score	Not Applicable	Insignificant	Minor	Moderate	Severe	Catastrophic
	Not Applicable	0	1	2	3	4	5
Likelihood descriptor	Most Unlikely	1	1	2	3	4	5
	Unlikely	2	2	4	6	8	10
	Moderate	3	3	6	9	12	15
	Likely	4	4	8	12	16	20
	Almost Certain	5	5	10	15	20	25

Figure 4 The final risk score is the product of the consequence and likelihood of the risk. Key risks are identified which exceed an agreed acceptable level, in this case risk scores above 32 (Government of Alberta, 2012)

Hazard Controls

Finally, the tool has a complementary database of possible control measures to mitigate key risks identified. The PREPARED database already contains possible control measures, while controls for the remaining hazards should be added in future work. The user also has the option at this stage to customize the control measures to the specifics of their system. The current database contains 98 control measures linked to 76 hazards (more than one control can be applicable to a hazard and vice versa).

3 End-user consultation

The tool storyboard was presented to possible end-users in different water use sectors to get feedback, learn what different end-user needs were, how they would use the tool and for what purpose and to improve the design of the tool. . Each end-user was already involved in one or more water (re)use cycles and the real-life examples of the cycles were used wherever possible. The tables below describe the end-users' sector, for what purpose they might use the tool and their feedback on the tool.

3.1 Drinking Water Sector

End-User	Drinking water company (NL)
Tool Use	Alternative/supplementary drinking water source
Description	Supplementary drinking water sources were evaluated at a drinking water company to supplement the current drinking water sources. The search for a supplementary water source was spurred by climate change and the wish to have redundancy and back-ups available in the drinking water system. A multi-criteria analysis had been performed previously for several supplementary drinking water sources and we wished to evaluate how the *Water Wise* tool could complement or add to their evaluation already performed.
Feedback	• Assessment of drinking water sources should include quality, quantity, public perception, security of supply, quality of source, CO_2 footprint/sustainability of system and transport/distribution requirements. • The tool mainly assesses quality, and therefore is too simple for the complete evaluation of sources. • Specific feedback on the sources was given and incorporated into the tool (e.g. further divide industrial water into food/non-food sector, cooling waters etc.). • For chemical parameters, it would be sufficient to report compliance with guidelines and evaluation of micropollutants not necessary at this time. • Thought possible end-users for *Water Wise* could include (domestic) rainwater users, international clients (e.g. water utilities in developing countries), and industrial clients.

End-User	Drinking water company (B)
Tool Use	Evaluation of water reuse systems
Description	This drinking water company assesses various water reuse systems for the production of drinking water or other water supplies. To ensure the drinking water safety, they use the WSP approach to evaluate reuse systems and has their own hazards database system which they use and maintain. The hazards database is updated yearly in consultation with other water authorities who perform similar evaluations to capture new or emerging issues in reuse systems.
Feedback	• As the drinking water company already has their own database/system for risk assessment the tool is too simple to be used for that aspect. Much can be learned from their experiences in the evaluation and risk assessment of small scale or reuse systems in this respect. • However, positive feedback was given for the ability for inexperienced users to perform a risk assessment with little to no data and for the ability to adjust standard values (e.g. microbial concentrations or removal efficiencies) if own data were available. • For the chemicals present in different sources, a point was made that it would be better to group chemicals based on structure or class which would be more appealing to end-users. The long list of chemicals is likely to be overwhelming of confusing. • Treatment processes are currently based on large-scale drinking water plants, however, small scale installations may have different processes and it should be checked whether small installations also have similar removal efficiencies. • A point was made about the differences between chemical and microbial standards. Guideline values may not be health-based but based on the limit of detection for different measurement techniques. • Pay attention to include treatment processes not common in the Netherlands, for example chlorine should be an option for drinking water treatment processes to support global use of the tool.

End-User	KWR Researchers and WiCE Kerngroep
Tool Use	Various types of water reuse
Description	Presentation of the tool to researchers working within the WiCE programme
Feedback	• Add a pop-up window with the contact information of researchers at KWR for support or a more detailed system assessment. • The key is to balance the specificity of the client's system against the generality inherent in any easy to use tool.

	• A key area of development will be the chemical 'risk' assessment, as there is a lot of work on-going and still needed to properly evaluate the health risks for different groups and mixture effects of chemicals. • Suggestions to couple the tool with other WiCE projects to evaluate similar case studies for which the water quantity has been evaluated. • The WiCE Kerngroep was triggered by the lack of regulations for reuse of wastewater in healthcare facilities. • Agreed the tool should be open source and is a good promotion of the type of work KWR is able to provide to clients. • The end-users should be further clarified. • Finally, including the cost of the water system is wanted as many end-users will also be concerned with the balance of cost and water quality. However, as the scope of this project was to evaluate the risks in water reuse.

3.2 Health Care Sector

End-User	Hospital (NL)
Tool Use	Wastewater reuse for toilet flushing
Description	A water reuse system was installed in the hospital to separately supply, collect and treat toilet flushing water. The treatment system was specifically designed to remove pharmaceutical and other chemical components. Treatments consisted of membrane bioreactor, ozonation, granular activated carbon, UV-disinfection and a storage facility. The client referred to the reuse system as a 'grey water' reuse system, however, after consultation it was found that the system was in fact a black water reuse system (sewage). After installation the client had problems with microbial growth in the system . The client was interested to know what information the tool could provide.
Feedback	• The most interesting point for the client was the lack of regulation in hospital water reuse within the EU and worldwide. Inclusion of guidelines within the tool revealed to the users that there were no guidelines within the Netherlands for health care facility reuse, while there was a specific prohibition of reuse of water in Spain in health care facilities (and other high-risk environments for human health or the environment such as food industry, cooling towers etc.). • Otherwise the concern from the client was that the tool might be too generic for their purposes. • Were positive about the idea of the tool, found it user friendly and easy to understand and liked the explanation around water safety planning and hazard identification

3.3 Food and Beverage Sector

End-User	Brewery
Tool Use	Rainwater for beer production
Description	Rainwater is collected from rooftops, filtered and used for beer production in local breweries. Possible issues with the system are occasionally high nitrogen content of the rainwater. Interest in what treatments are possible or could be highlighted in the tool to help removing the nitrogen.
Feedback	• A lot of specific feedback about rainwater and rainwater harvesting, which highlights the need when developing the tool to consult experts for each different type of water use, not only experts in different water use sectors. • The type of rooftop is very important in harvesting rainwater for consumption as the taste is affected. Need to specify different roof types (e.g. zinc/copper, bitumen, greenroof) and add possible effects of different rainwater receiving materials on water quality. • There is no regulation for using rainwater in the Netherlands. • There is little published about rainwater quality in general and specifically in the Netherlands about how rainwater quality differs by location. This makes it difficult to evaluate if ‘standard’ values for rainwater are valid for the Dutch context. • Treatment techniques should be explained better, especially for users unfamiliar with the technical language. Further explanation in the categories for membrane filtration needed (range of pore sizes). Also suggested to have the choice of example treatment train for each end-use to help inexperienced users. • More and clearer explanations are needed for each step and choice in the tool (e.g. QMRA, chemical removal, risk assessment). • Suggested to group the chemical parameters (e.g. naturally occurring, industrial, medical or agricultural sources etc). • Important to distinguish in the removal efficiency calculations where the removal is known to be zero or where the tool has no information. For the chemical removal further explanation is desired on how the calculations are done. • Change colour when final water concentrations close to the guideline limits (currently only coloured when exceed the limit). • Inexperienced users need more explanation on risk assessment to explain the general concept of hazards: all systems have hazards and good management is identifying and addressing these hazards. • For example, users should not be deterred from using a particular source because the tool suggests hazards associated with that source. The goal of the tool is to make an inventory of the hazards and to identify any hazards which may not have appropriate controls already present. • Addition of the costs of system would also be very helpful, especially for inexperienced users to know an order of magnitude cost difference between different treatment options. Addition of benefits/opportunities to offset the costs is also desirable.

3.4 Lessons from end-user feedback

- Different users have different needs and expectations of such a tool. For example, a drinking water utility might require much more detail from a risk assessment than an end-user who is doing a simple or initial feasibility study on water reuse in their facility. The tool will not be able to meet all user's exact requirements and a balance must be found between the level of detail and the complexity of the tool. A link

- There is a need for clearer, and in some cases more extensive explanations. A balance has to be made however, between too much and too little information. A possibility could be to include a 'beginner-user' option, where users are guided through the tool with more explanation and an 'experienced-user', where explanations are limited.

- Cost estimation is desired. The scale will be the major determinant of cost, rather than type of treatment. In addition, the price of drinking water includes a range of costs: production, transport, monitoring, client service, taxes, and nature conservation.
- Additional colour categories for risk levels in order to convey the right message. For example, red has a negative connotation and it would be prudent to avoid red where is does not imply non-compliance. Colouring categories should be included when values are also close to exceedance or just above exceedance.

- Example treatment trains would be helpful, especially to inexperienced users. Example treatment trains should take into account the variety of water cycles possible within the tool.

- Some water utilities already have risk assessment databases and it would be very nice to link their database with *Water Wise*

- Group chemicals within the chemical water quality assessment. What categories should be explored further, or perhaps can be tailored to the specific end-use in mind, so as to reflect the guidelines which the chemicals will eventually be compared to.

- Additional treatments including small scale treatments should be included to appeal to small-scale reuse cycles.

- Include sustainability and social aspects in order to make balanced and informed decisions regarding different choices of water sources, treatment options and end-uses.

4 Case study evaluation

To evaluate *Water Wise* tool, two case studies were completed in partnership with on-going research at KWR on water reuse (Bartholomeus et al., 2017, Pronk et al., 2020). Water reuse is concerned with both the quantity and quality of water to be reused. *Water Wise* evaluates the quality and safety of the water cycle while the partner projects also consider the flow of water (quantity). We used their cases to see what contribution *Water Wise* could add, in particular to the evaluation of water quality and also the safety of the water cycle. Furthermore, the case studies also highlight important information missing in the tool, what aspects of the tool are the most valuable for end-users and what aspects of the tool can be improved upon.

Pronk et al. (2020) demonstrated how water reuse could reduce the pressure placed on the water system due to changes in economy, population growth and climate change. The ability of water reuse to contribute to a more robust water cycle was modelled with Sankey diagrams. The current water system in the Netherlands is presented in Figure 5 and a scenario using WWTP effluent for agricultural irrigation is presented in Figure 6. The models took into account water quality based on five categories (drinking water, groundwater, surface water, treated wastewater and wastewater). For details about the scenarios and assumptions of the models see (Pronk et al., 2020).

Two cases based on using WWTP effluent for agricultural irrigation were evaluated. The first case involves 'de facto' WWTP effluent reuse for spray irrigation. The first case is the current situation, as many farmers use surface waters for irrigation and WWTP effluent is discharged to surface waters, resulting in 'de facto' use of WWTP effluent for irrigation (Beard et al., 2019). The second is the case of local reuse of WWTP effluent from the Haaksbergen WWTP for subsurface irrigation.

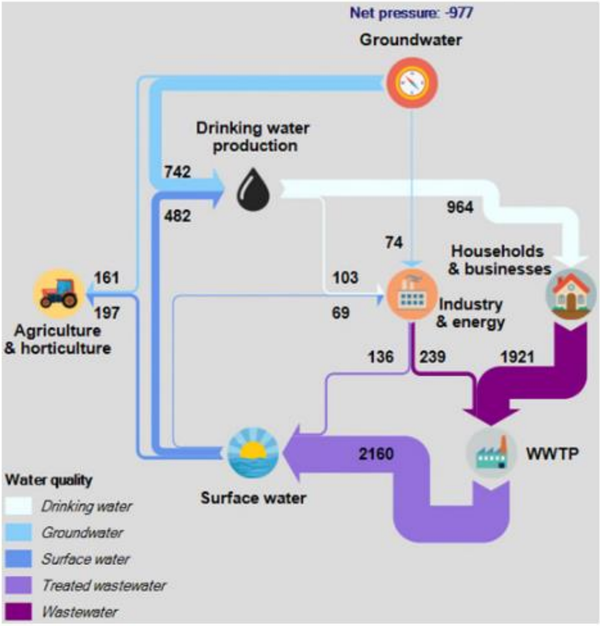


Figure 5 Current water flows in the Netherlands. The colours of the arrows indicate the water quality while the size of the arrows give the magnitude of water flows in Mm³ per year. The net pressure on groundwater reserves (top in the figure) is calculated as the anthropogenic groundwater replenishment minus the anthropogenic groundwater abstractions (Pronk et al., 2020)

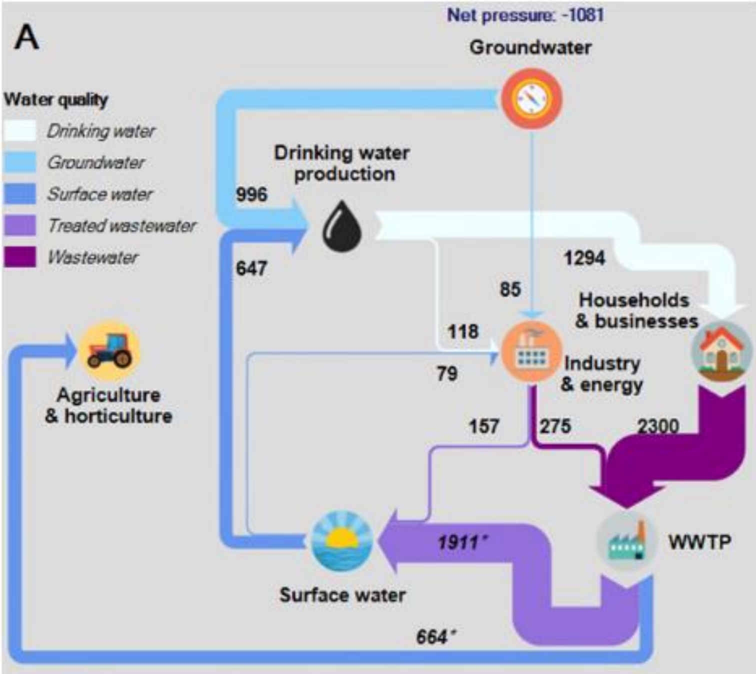


Figure 6 Calculated water flows in the Netherlands assuming WWTP effluent can meet all the demands for irrigation water. The colours of the arrows indicate the water quality while the size of the arrows give the magnitude of water flows in Mm³ per year. The net pressure on groundwater reserves (top in the figure) is calculated as the anthropogenic groundwater replenishment minus the anthropogenic groundwater abstractions (Pronk et al., 2020).

4.1 Case Descriptions

4.1.1 Case 1: 'De facto' WWTP Effluent used in sprinkler irrigation

Beard et al., (2019) described how small streams in the Netherlands contain high percentages (90-100%) of treated wastewater and many surface water bodies are dominated by treated wastewater flows. The research found that de facto reuse is likely during drought periods, when irrigation demand is higher and treated wastewater dilution in surface waters reduced. The risk to water quality depends on the type of irrigation used. This case evaluates the water quality and risks for spray irrigation (unrestricted) to contrast and compare the results to Case 2, i.e. of direct WWTP effluent reuse in subsurface irrigation.

In the tool, the water source was chosen as contaminated surface water. While no treatment processes are present in the actual case, the current QMRA tool requires at least one treatment process be input to calculate the health risk. Therefore primary treatment was used. WHO Wastewater use in Agriculture (2006) guideline was chosen. For the chemical risk assessment, the current database of micropollutants was used, however, within the guidelines no micropollutants are considered so the chemical risk assessment is limited.

4.1.2 Case 2: Haaksbergen WWTP effluent for subsurface irrigation

Underground irrigation systems can be used to increase and regulate the groundwater level and moisture content of soils, acting as a buffer against drought and crop damage. Climate change is expected to increase the occurrence of droughts and increase the pressure on available (ground) water resources. Using treated effluent for irrigation offers an efficient solution to deal with water shortages for both water boards and farmers. In this case study, effluent from the Haaksbergen WWTP (Vechtstromen Water Board) was used in a Climate Adaptive Drainage (KAD) system for subsurface irrigation of an agricultural field (corn). The case study is described in (Bartholomeus et al., 2017) (BTO 2016.050) and the water flows in (Pronk et al., 2020).

The water source used for this case was raw wastewater and the treatment processes were chosen to reflect typical wastewater treatment in the Netherlands (no disinfection of effluent). Bank filtration was chosen to mimic soil passage (as no soil passage option was available in the current QMRA tool). However, the travel distance in the soil would be shorter than for bank filtration, so this should be kept in mind when considering the removal efficiency and final results. Chemical water quality for micropollutants was taken from the micropollutant database with removal efficiencies. These results were compared with measured concentrations from the WWTP and in the Tool inputs

	Case 1: 'De facto' WWTP Effluent Reuse	Case 2: 'Haaksbergen'
Source	Surface Water	Raw Wastewater
	Contaminated	Raw Sewage
	Rivers, lakes, ponds that are prone to discharges of treated or untreated wastewater or other sources of fecal contamination (e.g. cattle accessing the water, runoff from agricultural land)	Municipal sewage that has not received any treatment or only minimal treatment e.g. sedimentation.
Treatment Train	*QMRA* 1. Primary Treatment*	*QMRA* 1. Primary Treatment, 2. Secondary Treatment, 3. Conventional clarification, 4. Bank Filtration
	Chemical Water Quality Assessment Full Conventional WWTP	*Chemical Water Quality Assessment* Full Conventional WWTP
End-Use	Unrestricted irrigation	Restricted irrigation
Description	100 g of lettuce leaves hold 10.8 mL water and cucumbers 0.4 mL at worst case (immediately post watering). A serve of lettuce (40 g) might hold 5 mL of recycled water and other produce might hold up to 1 mL per serve. Calculated frequencies are based on Australian Bureau of Statistics (ABS) data Water Use events per Year equal to 70 (events) Water ingestion amount per Event equal to 0.005 (liter) Source: EPHC, NRMMC, AHMC (2006)	Based on unrestricted irrigation, but far less frequent exposure due to restricted access Water Use events per Year equal to 1 (events) Water Use per Event equal to 0.005 (liter) Source: EPHC, NRMMC, AHMC (2006)
Guideline	WHO Wastewater use in Agriculture (2006)	WHO Wastewater use in Agriculture (2006)

* The current QMRA tool requires at least one treatment process to be input.

Table III Summary of influent concentrations for each contaminated surface water and raw wastewater for the three pathogens. All pathogens are log10 normally distributed

Pathogen	**Unit**	**Influent Concentration**			
		Contaminated Surface Water[1]		**Raw Wastewater[2]**	
		Min	**Max**	**Min**	**Max**
Bacteria	CFU/L	90	2,500	100	1,000,000
Viruses	PFU/L	2	480	50	5,000
Protozoa	(oo)cysts/L	30	60	1	10,000

[1] WHO (2004), [2]WHO (2011): Drinking water guideline, Table 7.7

Table IV Summary of log treatment removal efficiencies.

Pathogen	Unit	Treatment Log Removal							
		Primary[1,2,3]		Secondary[1,2,3]		Conventional clarficiation[4]		Bank Filtration[4]	
		Min	Max	Min	Max	Min	Max	Min	Max
Bacteria	CFU/L	0.2	2	1	3	0	0.5	2	6
Viruses	PFU/L	0.1	3.4	0.5	2	0	0.1	2.1	8.3
Protozoa	(oo)cysts/ L	1	2	0.5	1.5	0	1	1	2
[1] WHO. (2006), [2]DEMEAUWARE Deliverable 3.1 (p.18-19), [3]NRMMC-EPHC-AHMC (2006), [4]WHO (2011): Drinking water guideline, Table 7.7									

4.2 Results

Need to add somewhere the log removal values for the specified who guidelines

QMRA

For Case 1, the use of 'de facto' wastewater effluent for irrigation, the calculations were performed first for unrestricted irrigation and then restricted irrigation. In both cases the health targets of 1 in 10,000 infections per year and 1 microDALY per person per year were not met for any of the pathogens (Figure 7 A-D).

For Case 2, with treated wastewater effluent and restricted irrigation, the estimated risk of infection complies to the health target of 1 per 10,000 people per year for all pathogens, though there is some uncertainty for protozoa as the 95% confidence interval was slightly exceeded (Figure 7 E). Based on current knowledge it is 95% certain that the estimated health risk complies with the health target of 1 microDALY per person per year for all pathogens (Figure 7 F).

The goal of the QMRA tool is to bring insight into how different treatment processes contribute to the overall safety of the system. The contribution of bank filtration (soil passage) is clearly seen in TableIV, as the log removal values of bank filtration are the highest compared to the WWTP processes. Bank filtration was added to observe the contribution of soil passage, from the underground infiltration of the irrigated water, to the overall safety of the system in Case 2. Overall, the results show that subsurface irrigation of treated effluent is a safer option compared to spray irrigation of contaminated surface waters.

Additional calculations from the QMRA tool on the dose response model and the health risk calculations and a summary of the Monte Carlo simulation results are found in Table IX, Table X and Table XI, Appendix II.

Chemical Water Quality Assessment

The chemical assessment gives the concentration of micropollutants in the influent and the removal efficiencies for the different micropollutants for the specified treatment train. The effluent concentrations are calculated for the given influent concentrations and removal efficiencies. The WHO (2006) irrigation guidelines do not specify any reference values for the concentration of micropollutants in effluent water.

The results of the chemical water quality assessment for Case 1 are given in Table XII, Appendix II. As the source water is assumed not be treated before irrigation, no final concentrations have been calculated.

The results for Case 2 were compared to the 24-hour effluent samples from the Haaksbergen WWTP (Bartholomeus et al., 2017). Sixty one micropollutants were measured in the 24-hour samples, of which 12 of those micropollutants were also included in the calculated effluent concentrations and an additional 4 were in the tool database, but no values for wastewater concentrations were available (Table V).

Thirty-one additional micropollutant concentrations were calculated for the effluent not included in the 24-hour sample assessment (Table XIII, Appendix II). The calculated concentrations were in the same order of magnitude as the measured concentrations for 8 of the 12 micropollutants, with the tool overestimating the concentrations of Atenolol and Naproxen and underestimating the concentrations for Metoprolol and Trimethoprim (Table V).

Risks
Risks were assembled from the risk database based on the type of source water, the treatment trains, transport and storage and the end-use for the two cases. The risks were scored based on their likelihood and consequence. Controls for each hazard have not been added, as this requires more context into the specifics of the systems than was possible than in these basic case evaluations.

In Case 1 a total of 52 risks were identified, of which 17 were classified as key risks (Table VI). Themes for the key risks included effects of climate change on quality and supply of surface waters, security of supply of surface waters in general, quality of surface waters due to WWTP and combined sewer overflow (CSOs) and effects of water quality on the soil and underlying aquifer of irrigated fields.

In Case 2 a total of 45 hazards were identified, of which 13 were classified as key risks (Table VI). Themes for key hazards for Case 2 were microbial growth in the distribution system, potential for contamination of the underlying aquifer (chemical or microbial) and clogging due to biofilm formation. The remaining risks that did not score as key risks can be found in Table XIV and Table XV (Appendix III).

From the risk assessment, more risks around security of supply and quality of water were identified for surface waters for Case 1. In Case 2 there is a direct supply of treated wastewater from the WWTP, while in Case 1 the supply from surface water is under the influence of WWTP effluent, where the supply is subject to more outside forces (e.g. runoff from other industry, environmental impacts on water quality, different uses of surface waters (shipping, recreational, foresty, etc)).

4.3 Lessons Learned from Case Studies

- Specific treatments must still be added to existing tools (e.g. QMRA, chemical water quality assessment) to evaluate more water cycles. For example, subsurface irrigation needs a soil passage component, which is shorter than bank filtration.

- The WHO Wastewater use in Agriculture (2006) specifies the log-removal necessary for safe reuse, however, the tool as it is now does not calculate this. This should be included and other guidelines checked if they have other, non-concentration guidelines which should be incorporated.

- When evaluating the health targets, the targets were for human health, however, in both the case studies the crops irrigated were not meant for human consumption. The current tools should also reflect this distinction when assessing risk

- The hazards database should be streamlined. As it is an amalgamation of three databases, some hazards are repeated and those duplicates should be removed.

- The hazards database, is for the most part, focused on drinking water. Many hazards are broadly applicable though and were altered to better reflect the end use of irrigation instead of drinking water. More hazards specific to the different end-uses should be added to the database.

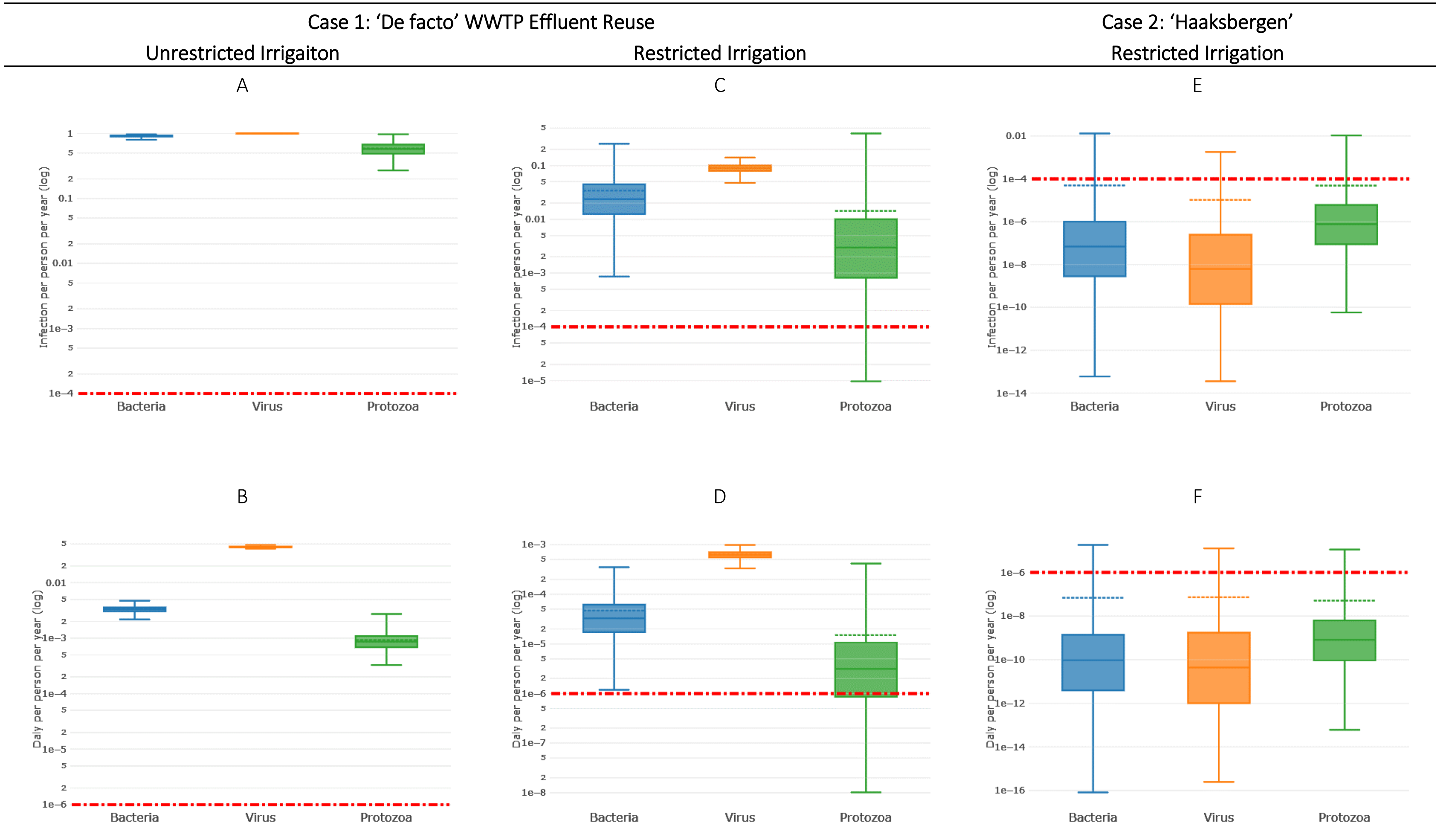


Figure 7 Results of the Monte-Carlo simulation from the QMRA tool for Case 1 (Unrestricted A, B; Restricted C, D) and for Case 2 (E, F). The red, dashed line indicates the health targets of 1 in 10,000 risk of infection per person per year (A, C, E) and 1 microDALY per person per year (B,D, F). The boxes give the upper and lower quartiles, the solid line the median value and the dashed line the mean value. The whiskers show the minimum and maximum values.

Table V Influent, removal efficiency and calculated effluent concentration from chemical water quality assessment tool (under development).The measured 24- hour effluent sample from Haaksbergen case WWTP (Bartholomeus et al., 2017). Red text indicates the calculated effluent concentration not in the same order of magnitude as the 24-hour effluent sample from Haaksbergen. Blank cells indicate no values in the database.

Chemical	**Influent Concentration (µg/L)**	**Average Removal Efficiency (%)**	**Effluent Concentration (µg/L)**	**24-hr Effluent (µg/L)**
Atenolol	4.02	63	1.50	0.23
Bezafibrate	0.0008			< 0.01
Carbamazepine	0.18	11	0.16	0.47
Clofibric acid	0.03	94	0.00	< 0.01
Diclofenac	0.68	46	0.37	0.25
Erythromycin				0.13
Fluoxetine				< 0.01
Gemfibrozil	0.22	92	0.02	0.02
Ketoprofen	0.04	66	0.01	< 0.01
Metoprolol	0.15	20	0.12	2.3
Naproxen	0.53	64	0.19	0.05
Pentoxifylline				< 0.01
Propranolol	0.03	33	0.02	0.05
Sotalol	0.34	23	0.26	0.94
Sulfamethoxazole	1.35	52	0.65	0.15
Trimethoprim	0.18	69	0.06	0.11

Table VI Key risks identified for Case 1 with scoring with the likelihood (Like.), consequence (Cons.) and the total risk score (Score).

Type	Category	Hazard	Hazard event	Like.	Cons.	Score
Source	Supply	Climate changes	New precipitation and evaporation patterns	4	16	64
Source	Chemical, Microbial, Supply, Aesthetic	Climate changes	The climate changes' effects on water quality (changed surface runoff and material transport affecting water quality)	4	16	64
Source	Chemical, Microbial, Supply, Aesthetic	Contamination and / or unavailability of water	Water shortage or contamination leading to (partly) closing of intake, insufficient alternative raw water source	4	16	64
Source	Supply	Extended periods without supply	Due to unavailability of surface water due to drought, affecting public health and causing disturbances in services and activities	4	16	64
Source	Chemical, Microbial, Supply, Aesthetic	Extended periods without supply	Due to unavailability of surface water due to increased evaporation causing quality problems, affecting public health and causing disturbances in services and activities	4	16	64
Source	Supply	Extended periods without supply	Due to unavailability of surface water due to increased evaporation causing quantity problems, affecting public health and causing disturbances in services and activities	4	16	64
Source	Microbial, Supply	Microbiological contamination of raw water	Due to wildlife dying or defecating in watershed.	8	8	64
Transport & Storage	Microbial	Microbial growth	The growth of bacteria and/or biofilm, due to a warm temperatures in pipelines	8	8	64
Transport & Storage	Supply	Blockages in screening sleeves	Floods, algal bloom or vandalism	2	16	32
Source	Supply	Shortage of water	Drought, blockage of water upstream or abstraction	4	8	32
Transport & Storage	Microbial	Microbial growth	Too long residence times of water in the network	4	8	32
Treatment	Chemical	Contamination of water supplied	Introduction of contaminants by improper use of material or operational errors in WWTP	4	8	32
Treatment	Chemical	Discharge of heavy metals and other chemicals in the water cycle or soil	Due to untreated WW discharge from wastewater system due to failure in WWTP caused by; insufficient treatment plant capacity for peak load; flooding etc. causing environmental problems	4	8	32
Treatment	Chemical, Microbial	Discharge of nutrients (P/N) in the water cycle or soil	Due to untreated WW discharge from wastewater system due to failure in WWTP caused by; insufficient treatment plant capacity for peak load; flooding etc. causing environmental problems	4	8	32
Treatment	Chemical, Microbial	Discharge of organics in the water cycle or soil	Due to untreated WW discharge from wastewater system due to failure in WWTP caused by; insufficient treatment plant capacity for peak load; flooding etc. causing environmental problems	4	8	32
Treatment	Chemical	Emerging contaminants	Presence of emerging contaminants able to overcome existing WWTP processes	4	8	32
End-use	Chemical, Microbial	Public concern	Reports on detection of chemicals or pathogens of very low tolerability	16	2	32

Table VII Key risks identified for Case 2 with scoring with the likelihood (Like.), consequence (Cons.) and the total risk score (Score).

Type	Category	Hazard	Hazard Event	Like.	Cons.	Score
End-use	Chemical, Microbial	Contamination of aquifer	Runoff from agriculture and urban green areas containing fertilizers, sludge, herbicides, etc.	8	8	64
End-use	Chemical, Microbial	Contamination of aquifer	Infiltration of wastewater to aquifer	8	8	64
End-use	Chemical, Microbial	Public concern	Reports on detection of chemicals or pathogens of very low tolerability	16	2	32
Transport & Storage	Microbial	Microbial growth	The growth of bacteria and/or biofilm, due to a warm temperatures in pipelines	8	8	64
Transport & Storage	Microbial	Clogging of distribution pipes and pumps	Clogging of infiltration pipes due to growth of biofilm	16	2	32
Transport & Storage	Chemical, Microbial	Microbial growth	The growth of bacteria and/or biofilm formation due to high concentrations of nutrients in the supplied water	16	2	32
Transport & Storage	Microbial	Microbial growth	Too long residence times of water in the network	4	8	32
Transport & Storage	Microbial, Supply	No/insufficient water supply to consumers	Fouling of water meter due to sediments or biofilm	8	4	32
Treatment	Chemical	Contamination of water supplied	Introduction of contaminants by improper use of material or operational errors in WWTP	4	8	32
Treatment	Chemical	Discharge of heavy metals and other chemicals in the water cycle or soil	Due to untreated WW discharge from wastewater system due to failure in WWTP caused by; insufficient treatment plant capacity for peak load; flooding etc. causing environmental problems	4	8	32
Treatment	Chemical, Microbial	Discharge of nutrients (P/N) in the water cycle or soil	Due to untreated WW discharge from wastewater system due to failure in WWTP caused by; insufficient treatment plant capacity for peak load; flooding etc. causing environmental problems	4	8	32
Treatment	Chemical, Microbial	Discharge of organics in the water cycle or soil	Due to untreated WW discharge from wastewater system due to failure in WWTP caused by; insufficient treatment plant capacity for peak load; flooding etc. causing environmental problems	4	8	32
Treatment	Chemical	Emerging contaminants	Presence of emerging contaminants able to overcome existing WWTP processes	4	8	32

5 Conclusions and recommendations for future work

5.1 Conclusions

Within this research a conceptual decision support tool, *Water Wise* was developed which can:

- Provide basic water quality information for a variety of source waters,
- Predict the chemical and microbial quality for different water sources and removal efficiencies for a variety of treatment processes, and
- Compare to relevant guidelines, perform a preliminary risk assessment and guide users through the WSP approach.

Water Wise has been conceptually designed, building on existing tools and knowledge at KWR. Tools included are the AquaNES QMRA and tool for quantitative chemical risk assessment, a current database of water quality guidelines and a working database of risks for water systems. Anadvantage of the proposed tool is the incorporation and alignment of multiple tools into one, so that water quality can be evaluated consistently for chemical and microbial parameters, and also for the systems risk assessment. This will help both researchers and end-users alike.

Two cases were evaluated to demonstrate the insights that the tool can give on different reuse scenarios. The cases, comparing the direct reuse of WWTP effluent in subsurface irrigation and the 'de facto' reuse of WWTP effluent for spray irrigation demonstrate the increase in safety that subsurface irrigation provides. Systems risk assessment also highlighted the security of supply provided by the direct reuse of WWTP compared to surface waters. This research compliments other WiCE research, for example the use of 'Water Factories' to provide customized water quality through fit-for-purpose treatment processes to fulfil the need of the end-use, while also contributing to a more robust water cycle. From these cases we determined that the current tools should be expanded to include treatment processes specific for different end-uses (e.g. irrigation and soil passage), that the end-points in different guidelines should also be included (concentration based guideline values versus log-removal credit requirements), that the hazards database must be further streamlined to remove duplicates and to provide more hazards specific for non-drinking water end-uses.

In addition, through end-user engagement with the storyboard, it was apparent that end-users have very diverse needs and expectations. It might not be feasible to combine all needs in the same tool. Furthermore, a balance must sought between the level of detail required for new users to use the tool and the complexity of the tool to make it appealing for experienced users. One option would be to include different levels of detail in the tool by allowing users to select a 'beginner' or 'experienced' option at the beginning to access or suppress more detailed explanations.

Future work on the tool is proposed to take place in a follow-up project. The feedback from end-user consultations was used to prioritize activities for future work, summarized below.

5.2 Recommendations for follow-up activities

The following recommended follow-up activities have been splits into three categories, 1. The minimum requirements to turn the storyboard into a reality, 2. Requirements to make the storyboard an effective first version of the tool, and finally, 3. Things which could be added in the future, but are not required or feasible within a first version for the tool ('wish-list').

1. Working version of the tool

- Alignment of the options for sources, treatment process and end-uses between the QMRA and chemical water quality assessment tools.

- Complete the risk database cross-referencing for risk types (source, transport & storage, treatment and end-use) and categories (chemical, microbial, aesthetic and supply) for all hazards/hazard events.

- Programming of the interface as a web- or downloaded tool.

2. Effective first version

- Collect additional chemical water quality data (basic water quality) for the chemical database and the corresponding removal efficiencies from literature.

- Add additional treatment removal data based on new and currently in development tools at KWR e.g. AquaPriori (Textbox Section 2.4.1)

- Expand with additional guidelines for water quality from the guidelines overview documents and align with the options for end-use. Where guidelines do not exist for a particular end-use, collect state of the art knowledge and expert opinions on water quality targets.

- Complete the hazard controls database for hazard events based on case study, expert opinion and literature.

- Expand the risks database to include more non-drinking water hazards, based on case studies, expert opinions and literature.

3. Future wish-list

- Expand end-uses to include other sectors, for example energy (e.g. geothermal) and additional industrial, food processing and urban reuse options could be considered.

- Add a cost estimate calculator to the tool, a popular suggestion from end-user feedback, though outside of the scope of the current project. For example, the RH DHV cost calculator or building on small-scale cost estimator begun at KWR (Stofberg et al., 2019).

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I Overview of Reviewed Tools

Table VIII Tools available within and outside of KWR for possible use within Water Wise

Tool	Source	Description	Possible Application within *Water Wise*	Limitations
AquaNES QMRA	KWR/EU Horizon 2020	An interactive webtool that performs quantitative microbial risk assessment (QMRA) based on user input of source water type, treatment processes and desired end-use. The tool reports the exposure and risk of the chosen water cycle as disability adjusted life years (DALY's) per person per year and the risk of infection per person per year.	Used to quantify the microbial risk for different water supply, treatment and end-use combinations. The tool already has initial concentrations for many source water choices and removal efficiencies for different treatments from high-level documents (e.g. WHO, Australian Guidelines for Water Recyling, etc.) and guidelines for different end-uses.	Data on initial microbial concentrations and removal efficiency is limited to what is reported in the high-level documents and does not encompass all water sources and treatment techniques. Issue of how to combine different data sources within the tool.
AquaNES QC(R)A	KWR/EU Horizon 2020	An interactive webtool that calculates the concentration of micropollutants after treatment for a chosen water source and treatment train. The tool has the choice for only four water sources and the database of initial concentrations in the sources is limited. In principle only the removal efficiency is calculated and there is no real quantitative chemical (risk) assessment (QC®A) performed.	Used to calculate the chemical removal for different micropollutants for different water supply, treatment and end-use combinations. The tool already has initial concentrations for some water sources but is limited.	Only the removal efficiency is calculated and there is no quantitative risk assessment performed in the latest version of the tool. Guidelines for chemical concentrations have not yet been included. The tool is still under development.
AMVD Reference Document	KWR	A reference document (webtool/database) which brings together knowledge about the effectiveness of different treatment technologies for the removal or inactivation of pathogenic microorganisms. The tool	The tool could provide the single removal efficiency value for different technologies from high-level documents or show the spread/distribution of removal which the values are based on from the AMVD	Limited to four treatment technologies and only for microbial parameters.

Tool	Source	Description	Possible Application within *Water Wise*	Limitations
		summarizes the current status of four treatment technologies (UV, ozone, soil passage and ozone) based on data from literature.	(assessment microbial safety drinking water) reference document. Showing this distribution would also help to inform (inexperienced) users about the inherent uncertainty in water treatment technologies.	
AquaPriori	KWR	AquaPriori is a tool that statistically predicts the removal efficiency for non-tested, priority substances in water treatment processes based on quantitative structural property relationships (QSPR). The tool is currently being developed for two processes, activated carbon and reverse osmosis (Vries et al., 2017).	Generic process conditions can be used to calculate the removal efficiency for previously untested micropollutants. Links to the specific tool, or eventual integration of the tool itself, could provide advanced options to calculate removal efficiencies for micropollutants whose removal efficiency is not known in advance.	The tool is still under development and limited to activated carbon, reverse osmosis and a database for soil passage. The AquaPriori tool was used within a Masters thesis to predict the activated carbon performance for contaminants of emerging concern (CECs) in drinking water. The tool was adapted to provide probabilistic estimation of the maximum CECs concentrations in treated water coupled with toxicological analyses.
Hazards Databases	KWR/Various EU Projects	Previous EU projects TECHNEAU and PREPARED compiled databases of hazards in drinking water systems. In addition, an Excel-based Water Safety Planning template developed by the Government of Alberta also has a database of possible hazards. The databases cover a range of hazard types (e.g. biological, chemical, operational and aesthetic) and hazards arising from different stages of the system (e.g. hazards from the type of source, type of treatment technology etc.). In the PREPARED database,	The databases form the starting point for creating a larger, broader database of hazards for water use which encompasses a range of different source-treatment-end-use combinations. This sort of database would be unique as other hazard databases in the literature are focused on single use applications, mainly for drinking water.	The databases are intended for drinking water production and, while some hazards are transferable, there is a lack of hazards for other types of water (re)use. Additional hazards for different uses will need to be added to the databases, taking into account different hazards for treatment processes used for different applications. This knowledge is available within KWR.

Tool	Source	Description	Possible Application within *Water Wise*	Limitations
		hazards also have one or more control measures listed to mitigate the hazard.		
Water Safety Planning (WSP)	WHO	WSP are an approach for planning and implementing safe and reliable drinking water supply (Bartram et al., 2009). The WSP process guides water suppliers through risk assessment of all steps in the water supply from catchment to consumer. WSPs can be adapted to different types and sizes of water supplies and elements of the WSP approach can be incorporated into non-drinking water systems	The risk assessment portion of the WSP approach can be incorporated into *Water Wise*. Hazard identification and assessment and determination of control measures (modules 3 and 4 from Bartram et al., 2009) are particularly applicable. These modules involve identifying hazardous events which may compromise the water supply and ranking the likelihood and consequence for each hazardous event. In this manner, hazardous events with a high risk score (likelihood x consequence) can have controls identified.	It should be noted that each water system should have its own unique WSP and a generic tool cannot replace the expertise and knowledge required for a full WSP, however by combining concepts from the WSP framework, a tool can help to guide operators through the planning process and provide insight into risk management within their own water system. Specifically, the system assessment portion of the WSP (Bartram et al., 2009) is incorporated and adapted within *Water Wise* tool. The WSP approach is also focused on drinking water systems and associated tools/models/frameworks may need further adaptation to be suitable for other types of water supplies.
Poseidon	Oertlé et al., 2019	*Poseidon* is an Excel-based DSS for prefeasibility studies for water reuse systems. The tool has a database of removal efficiencies for 37 treatment processes for 12 water quality parameters and can also lifecycle costs. *Poseidon* was the only tool found from a limited literature review of available, open-source reuse models.	The tool serves as a first example what sort of water reuse tools are available.	The tool is focused on 12 indicator parameters; microbial indicators: faecal coliforms, total coliforms, and viruses; chemical indicators: nitrate, BOD, COD, total nitrogen, total phosphorous, nitrate, total organic carbon; and aesthetic/physical indicators: turbidity, total suspended solids and total dissolved solids. The tool lacks indicators for protozoa, which is present in the QMRA tool and the *Poseidon* does not perform a risk assessment for exposure, only

Tool	Source	Description	Possible Application within *Water Wise*	Limitations
				compliance to standards. The chemical indicators are simple and do not have any micropollutants or emerging contaminants included, nor a way to assess new or emerging components. The tool is Excel based and therefore new versions must be downloaded manually and quickly becomes out of date. User-friendliness and transparency of excel based tools is generally low.

II Additional Data – Case Study 1 & 2

Unrestricted Irrigation QMRA simulation

Table IX Summary of dose response model and health risk results from QMRA

Pathogen	Model Pathogen	Dose Response Model[1]				Health Risk[2]	
		Distribution	K	Alpha	N50	Infection to Illness	DALY per Case
Bacteria	Campylobacter jejuni	Beta-Poisson		0.144	890	0.3	0.0046
Viruses	Rotavirus	Beta-Poisson		0.253	6.17	0.5	0.014
Protozoa	*C. parvum and C. hominis*	Exponential	0.0572			0.7	0.0015

[1]Bacteria: Black et al 1988, Viruses: Ward et al, 1986, Protozoa: Messner et al. 2001, [2]WHO (2011): Drinking water guideline, Table 7.4

Table X Summary of QMRA Results for Case 1: Restricted irrigation. Red text indicates exceedance of the specified health target.

Data	Unit	Mean	5%	50%	95%
Bacteria risk assessment					
Source Concentration	N/l	782.95	86.19	462.56	2515.59
Primary treatment	log10	1.1	0.29	1.1	1.91
Secondary treatment	log10	2	1.1	2	2.9
Conventional clarification	log10	0.25	0.025	0.25	0.475
Total Treatment	log10	3.35	2.07	3.32	4.65
DALY per Year	/person/year	1.90E-07	9.85E-10	2.88E-08	8.15E-07
Exposure per Year	number/person/year	0.00701	3.61E-05	0.00105	0.0299
Infection Risk per Year	/person/year	1.38E-04	7.14E-07	2.08E-05	5.90E-04
Source Concentration	N/l	782.95	86.19	462.56	2515.59
Virus risk assessment					
Source Concentration	N/l	43.29	29.91	42.36	59.63
Primary treatment	log10	1.75	0.265	1.75	3.24
Secondary treatment	log10	1.25	0.575	1.25	1.93
Conventional clarification	log10	0.05	0.005	0.05	0.095
Total Treatment	log10	3.11	1.39	3.15	4.78
DALY per Year	/person/year	6.82E-06	1.51E-08	6.08E-07	3.81E-05
Exposure per Year	number/person/year	0.00167	3.63E-06	1.46E-04	0.0093
Infection Risk per Year	/person/year	9.74E-04	2.15E-06	8.68E-05	0.00545
Source Concentration	N/l	43.29	29.91	42.36	59.63
Protozoa risk assessment					
Source Concentration	N/l	101.18	2.21	30.62	450.73
Primary treatment	log10	1.5	1.05	1.5	1.95
Secondary treatment	log10	1	0.55	1	1.45
Conventional clarification	log10	0.5	0.05	0.5	0.95
Total Treatment	log10	2.98	2.16	2.98	3.79
DALY per Year	/person/year	5.61E-08	3.58E-10	1.04E-08	2.53E-07
Exposure per Year	number/person/year	9.35E-04	5.96E-06	1.74E-04	0.00422
Infection Risk per Year	/person/year	5.35E-05	3.41E-07	9.94E-06	2.41E-04
Source Concentration	N/l	101.18	2.21	30.62	450.73

Table XI Summary of QMRA Results for Case 2: Restricted irrigation. Red text indicates exceedance of the specified health target.

Data	Unit	Mean	5%	50%	95%
Bacteria Risk Assessment					
Source Concentration	N/l	279914.6	146.38	10697.85	1174678
Primary treatment	log10	1.1	0.29	1.1	1.91
Secondary treatment	log10	2	1.1	2	2.9
Conventional clarification	log10	0.25	0.025	0.25	0.475
Bank filtration	log10	4	2.2	4	5.8
Total Treatment	log10	7.3	5.03	7.27	9.62
DALY per Year	/person/year	6.84E-08	7.19E-14	9.52E-11	1.09E-07
Exposure per Year	number/person/year	0.00258	2.64E-09	3.49E-06	0.00399
Infection Risk per Year	/person/year	4.95E-05	5.21E-11	6.90E-08	7.89E-05
Virus risk assessment					
Source Concentration	N/l	1268.11	53.34	546.37	4208.33
Primary treatment	log10	1.75	0.265	1.75	3.24
Secondary treatment	log10	1.25	0.575	1.25	1.93
Conventional clarification	log10	0.05	0.005	0.05	0.095
Bank filtration	log10	5.2	2.41	5.2	7.99
Total Treatment	log10	8.38	4.83	8.34	11.7
DALY per Year	/person/year	7.30E-08	1.75E-14	4.36E-11	1.34E-07
Exposure per Year	number/person/year	1.76E-05	4.21E-12	1.05E-08	3.22E-05
Infection Risk per Year	/person/year	1.04E-05	2.50E-12	6.23E-09	1.91E-05
Protozoa risk assessment					
Source Concentration	N/l	2881.96	1.06	89.82	6620.9
Primary treatment	log10	1.5	1.05	1.5	1.95
Secondary treatment	log10	1	0.55	1	1.45
Conventional clarification	log10	0.5	0.05	0.5	0.95
Bank filtration	log10	1.5	1.05	1.5	1.95
Total Treatment	log10	4.52	3.56	4.5	5.46
DALY per Year	/person/year	5.11E-08	5.51E-12	8.10E-10	1.26E-07
Exposure per Year	number/person/year	8.52E-04	9.18E-08	1.35E-05	0.00209
Infection Risk per Year	/person/year	4.86E-05	5.25E-09	7.71E-07	1.20E-04

Chemical water quality assessment

Table XIICase 1 - Chemical water quality assessment for surface water

Chemical	Concentration (µg/L)
17 β-estradiol	0.21
17α-ethinyl estradiol	0.21
Acetaminophen	0.10
Androstenedione	0.20
Atrazine	0.18
Benzopyrene	0.08
Caffeine	0.22
Carbamazepine	0.12
DDT	0.12
DEET	0.11
Diazepam	0.15
Diclofenac	0.07
Dilantin	0.16
Erythromycin	0.20
Estriol	0.26
Estrone	0.23
Fluorene	0.31
Fluoxetine	0.19
Galaxolide	0.13
Gemfibrozil	0.17
Hydrocodone	0.17
Ibuprofen	0.16
Iopromide	0.20
Ketone	0.24
Lindane	0.22
Meprobamate	0.19
Metolachlor	0.31
Naproxen	0.12
Oxybenzone	0.08
Pentoxifylline	0.17
Progesterone	0.14
Sulfamethoxazole	0.01
TCEP	0.16
Testosterone	0.25
Triclosan	0.16
Trimethoprim	0.22

Table XIII Influent concentration, average removal efficiency and effluent concentration for Case 2

Chemical	**Influent Concentration (µg/L)**	**Average Removal Efficiency (%)**	**Effluent Concentration (µg/L)**
17 β-estradiol	0.01	100	0.00
17α-ethinyl estradiol	0.08	0	0.08
4-tert-butylphenol	0.78	93	0.05
Acetaminophen	26.05	100	0.03
Ampa	1.40	0	1.40
Atrazine	0.03	14	0.02
Benzotriazole	0.01		
Bisphenol a	0.50	60	0.20
Caffeine	16.85	67	5.49
Carbendazim	0.11	36	0.07
Chlorpyrifos	0.08	50	0.04
Decabromodiphenylether	0.30	68	0.10
Desethylatrazine	0.04	17	0.03
Diazinon	0.06	48	0.03
Dichloromethane	1.00	88	0.12
Diuron	0.18	0	0.18
Estriol	0.44	100	0.00
Estrone	0.05	87	0.01
Fluoranthene	0.20	80	0.04
Glyphosate	0.73	0	0.73
Ibuprofen	0.61	87	0.08
Iomeprol	0.01		
Irgarol 1051	0.01	52	0.00
Isoproturon	0.06	32	0.04
Mecoprop	0.01		
Nonylphenol	4.94	0	4.94
Pentabromodiphenylether	0.39	98	0.01
Primidone	0.0006		
Roxithromycine	0.08	39	0.05
Simazine	0.03	0	0.03
Sulfamethazine	0.13	13	0.11
Tetrabromodiphenylether	0.92	100	0.00
Tetrachloroethylene	1.50	93	0.11
Tribromodiphenylether	2.60	100	0.00
Trichlorobenzene	0.09	0	0.09
Trichloromethane	5.00	1	4.96
Triclosan	25.39	89	2.72

Table XIV Case 1 Risks identified for Case 1 with scoring with the likelihood (Like.), consequence (Cons.) and the total risk score (Score)

Type	Category	Hazard	Hazard Event	Like.	Cons.	Score
Transport & Storage	Supply	Water infrastructure collapses or bursts	Due to extreme storms, causing injuries to public	1	16	16
Treatment, Transport & Storage	Chemical, Microbial, Supply, Aesthetic	Sabotage, Vandalism	Intentional contamination of the network water (terrorism, sabotage, vandalism, arson) or physical damage	1	16	16
Source	Microbial, Chemical	Contamination of raw water resulting from algal blooms	Due to algal blooms due to increased nutrient levels or changing weather patterns.	2	8	16
Source, End-Use	Microbial, Supply	Presence of microbial pathogens in water used for irrigation	Due to use of water from sources contaminated by untreated CSO discharges due to excessive flow in sewer system caused by excessive runoff resulting from high intensity rainfall, causing damages to public health	2	8	16
Source, End-Use	Microbial, Supply	Presence of microbial pathogens in water used for irrigation	Due to use of water from sources contaminated by untreated CSO discharges due to sewer system equipment failure caused by flooding in the installation	2	8	16
Source, End-Use	Microbial, Supply	Presence of microbial pathogens in water used for irrigation	Due to use of water from sources contaminated by untreated CSO discharges due to sewer system flow constriction caused by high river or sea level, causing damages to public health	2	8	16
Source, End-Use	Microbial, Supply	Presence of microbial pathogens in water used for irrigation	Due to use of water from sources contaminated by WW discharge resulting from failure in WWTP caused by insufficient plant capacity during peak load causing damages to public health	2	8	16
Source, End-Use	Microbial, Supply	Presence of microbial pathogens in water used for irrigation	Due to use of water from sources contaminated due to discharge of untreated WW due to failure in WWTP caused by caused by flooding in the plant	2	8	16
End-use, Treatment	Chemical, Microbial	Contamination of water supplied	As a result of contamination of wastewater by industrial operations (including continuous discharge as well as installations, construction work and other)	2	8	16
Source	Chemical	Contamination of catchment zone	Toxic chemicals from air deposits or air pollution	2	8	16
Transport & Storage	Supply	Failure of the maintenance	Inappropriate maintenance scheme	2	8	16
Transport & Storage, End-use	Chemical, Microbial	Direct contamination of infiltration boreholes and surroundings (bank)	Due to improper borehole installation near irrigation lines	2	8	16

Table XIV continued

Type	Category	Hazard	Hazard Event	Like.	Cons.	Score
Transport & Storage, End-use	Supply	Extended periods without supply	Due to failure in the transport system causing disturbances in supply	2	8	16
Treatment	Microbial	Emerging pathogens	Prescence of emerging pathogens able to overcome existing WWTP processes	2	8	16
Treatment	Chemical, Microbial, Aesthetic	Inadequate treatment	As a result of as a result of raw water bypassing all or part of the treatment process caused by; insufficient treatment plant capacity for peak load; flooding etc	2	8	16
Treatment	Chemical	Presence of chemical contaminants in supply water	Due to distribution of chemically contaminated water caused by failure in timely detection and control of contamination in WWTP	2	8	16
Treatment	Chemical	Presence of microbial pathogens in water used for irrigation	Resulting from failure in WWTP caused by insufficient plant capacity during peak flow, peak load or flooding of the WWTP	2	8	16
Transport & Storage	Microbial, Supply	No/insufficient water supply to consumers	Fouling of water meter due to sediments or biofilm	4	4	16
Source	Chemical	Deterioration of raw water quality caused by shallow water body and wind effects	Resulting from shallow water body and wind induced turbulence	4	4	16
Source	Microbial, Chemical	Direct contamination of water source area	Bloom of toxic blue algae	4	4	16
Transport & Storage	Chemical, Microbial	Microbial growth	The growth of bacteria and/or biofilm formation due to high concentrations of nutrients in the supplied water	8	2	16
Transport & Storage	Chemical, Microbial	Contamination of water supplied	As a result of the use of non-approved or inappropriate materials in the network	1	8	8
Transport & Storage	Chemical, Microbial	Contamination of water supplied	Contamination due to cross-connection with water from other systems (e.g., waste, fire protection, garden watering and irrigation)	1	8	8
Transport & Storage	Chemical	Oil contaminating water due to use of unacceptable pump lubricants	Due to non-food grade leaking into wet well	1	8	8

Table XIV continued

Type	Category	Hazard	Hazard Event	Like.	Cons.	Score
Treatment	Chemical	Contamination of recreational water bodies in surrounding environment	Due to run-off, leaching or flow from irrigated fields to nearby water bodies	1	8	8
Transport & Storage	Microbial	Microbial growth	Microbial growth due to exposure of the water to light	2	4	8
Transport & Storage	Supply	Failure of pumps due to flooding	Due to inadequate drainage or poor siting of pump house	1	4	4
Transport & Storage	Supply	Failure of pumps due to power surge at pump station.	Due to pump failure due to electrical fault caused by power surge	1	4	4
Transport & Storage	Supply	Failure to meet demand as a result of loss of power supply	Due to power failure and no standby generator	1	4	4
Transport & Storage	Supply	Failure to meet demand as a result of breaks caused by age-related deterioration.	Resulting from break due to deterioration of pipe condition due to age	1	4	4
Transport & Storage	Supply	Failure to meet demand as a result of failure to mend break in a reasonable time	As a result of poor access	1	4	4
Transport & Storage	Supply	Failure to meet demand due to insufficient pumping capacity	Due to pumps operating below rating or inadequately sized.	1	4	4
Transport & Storage	Chemical	Clogging of distribution pipes and pumps	Due to chemical composition of the supply water	2	2	4
Transport & Storage	Supply	Failure of pumps and resulting loss in supply	Due to power loss, breakdown, poor maintenance etc.	2	2	4
End-use	Chemical, Microbial, Supply, Aesthetic	Failure of monitoring system	Accident, defect, power failure, operational failure, management failure, human error, damaged monitoring devices	2	1	2

Table XV Case 2 Risks identified for Case 1 with scoring with the likelihood (Like.), consequence (cons.) and the total risk score (score).

Type	Category	Hazard	Hazard Event	Like.	Cons.	Score
End-use, Treatment	Chemical, Microbial	Contamination of aquifer	As a result of contamination of wastewater by industrial operations (including continuous discharge as well as installations, construction work and other)	2	8	16
End-use, Treatment	Chemical, Microbial	Contamination of water supplied	As a result of contamination of wastewater by industrial operations (including continuous discharge as well as installations, construction work and other)	2	8	16
Transport & Storage, End-use	Chemical, Microbial	Direct contamination of infiltration boreholes and surroundings (bank)	Due to improper borehole installation near irrigation lines	2	8	16
Treatment	Microbial	Emerging pathogens	Presence of emerging pathogens able to overcome existing WWTP processes	2	8	16
Treatment	Chemical	Presence of chemical contaminants in supply water	Due to distribution of chemically contaminated water caused by failure in timely detection and control of contamination in WWTP	2	8	16
Treatment	Chemical	Presence of microbial pathogens in water used for irrigation	Resulting from failure in WWTP caused by insufficient plant capacity during peak flow, peak load or flooding of the WWTP	2	8	16
Transport & Storage	Supply	Water infrastructure collapses or bursts	Due to extreme storms, causing injuries to public	1	16	16
Transport & Storage, End-use	Chemical, Microbial	Contamination of aquifer	Geophysical incidents resulting in leaking infrastructure (e.g. extreme hydraulic events such as torrential rain, floods, erosion, landslides, karstic land surface with open flowlines; etc.)	1	16	16
Treatment, Transport & Storage	Chemical, Microbial, Supply, Aesthetic	Sabotage, Vandalism	Intentional contamination of the network water (terrorism, sabotage, vandalism, arson) or physical damage	1	16	16
Transport & Storage	Microbial	Microbial growth	Microbial growth due to exposure of the water to light	2	8	16
Transport & Storage	Microbial	Microbial growth	Sediment accumulation and microbial growth in water stagnated at dead-end branches	2	8	16
Transport & Storage	Supply	Failure of the maintenance	Inappropriate maintenance scheme	2	8	16
Transport & Storage, End-use	Supply	Extended periods without supply	Due to failure in the transport system causing disturbances in supply	2	8	16

Table XV continued

Type	Category	Hazard	Hazard Event	Like.	Cons.	Score
Treatment	Chemical, Microbial, Aesthetic	Inadequate treatment	As a result of as a result of raw water bypassing all or part of the treatment process caused by; insufficient treatment plant capacity for peak load; flooding etc.	2	8	16
Transport & Storage	Chemical, Microbial	Contamination of water supplied	As a result of the use of non-approved or inappropriate materials in the network	1	8	8
Transport & Storage	Chemical, Microbial	Contamination of water supplied	Contamination due to cross-connection with water from other systems (e.g., waste, fire protection, garden watering and irrigation)	1	8	8
Transport & Storage	Chemical	Oil contaminating water due to use of unacceptable pump lubricants.	Due to non-food grade leaking into wet well	1	8	8
Treatment	Chemical	Contamination of recreational water bodies in surrounding environment	Due to run-off, leaching or flow from irrigated fields to nearby water bodies	1	8	8
Transport & Storage	Supply	Leakage of supplied water	Trees, roots, cracks in concrete (e.g. in chamber walls) or pipelines	2	4	8
Transport & Storage	Microbial	Network water contamination	Poor hygiene during pipes installation/repair	2	4	8
Transport & Storage	Supply	No/insufficient water supply to consumers	Freezing of water within meters and/or external pipes exposed to extremely low temperatures	2	4	8
Transport & Storage	Chemical	Clogging of distribution pipes and pumps	Due to chemical composition of the supply water	2	2	4
Transport & Storage	Chemical, Microbial	Contamination of water supplied	As a result of unsatisfactory or damaged new connections caused by inadequate installation procedures and/or failure to follow a suitable code of practice	1	4	4
Transport & Storage	Supply	Failure of pumps due to flooding	Due to inadequate drainage or poor siting of pump house	1	4	4
Transport & Storage	Supply	Failure of pumps due to power surge at pump station.	Due to pump failure due to electrical fault caused by power surge	1	4	4
Transport & Storage	Supply	Failure to meet demand as a result of loss of power supply	Due to power failure and no standby generator	1	4	4

Table XV continued

Type	Category	Hazard	Hazard Event	Like.	Cons.	Score
Transport & Storage	Supply	Failure to meet demand as a result of breaks caused by age-related deterioration	Resulting from break due to deterioration of pipe condition due to age	1	4	4
Transport & Storage	Supply	Failure to meet demand as a result of failure to mend break in a reasonable time	As a result of poor access	1	4	4
Transport & Storage	Supply	Failure to meet demand due to insufficient pumping capacity	Due to pumps operating below rating or inadequately sized	1	4	4
Transport & Storage	Supply	Failure of pumps and resulting loss in supply	Due to power loss, breakdown, poor maintenance etc.	2	2	4
End-use	Chemical, Microbial, Supply, Aesthetic	Failure of monitoring system	Accident, defect, power failure, operational failure, management failure, human error, damaged monitoring devices	2	1	2
Transport & Storage	Supply	Loss of pressure as a result of leakage	Due to leakage due to inadequate leakage control/poor maintenance	1	1	1