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Applying the water safety plan to water reuse: towards a conceptual risk management framework

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The Water Safety Plan (WSP) is receiving increasing attention as a recommended risk management approach for water reuse through a range of research programmes, guidelines and standards. Numerous conceptual modifications of the approach – including the Sanitation Safety Plan, the Water Cycle Safety Plan, and even a dedicated Water Reuse Safety Plan – have been put forward for this purpose. However, these approaches have yet to encapsulate the full spectrum of possible water reuse applications, and evidence of their application to reuse remains limited. Through reviewing the existing evidence base, this paper investigates the potential for adapting the WSP into an approach for water reuse. The findings highlight a need for the management of risk to reflect on, and facilitate the inclusion of, broader contexts and objectives for water reuse schemes. We conclude that this could be addressed through a more integrated approach to risk management, encapsulated within an overarching risk management framework (adapted from the WHO's Framework for safe drinking water) and operationalised through the Water Reuse Safety Plan (WRSP). We also propose that the WRSP should be based on modifications to the existing WSP approach, including an increased emphasis on supporting communication and engagement, and improvements in decision support mechanisms to better account for uncertainty, risk interactions and risk prioritisation.

Water impact

This paper advances our understanding of how the Water Safety Plan risk management approach can be applied to water reuse schemes, in the form of a Water Reuse Safety Plan (WRSP). While a WRSP has been proposed previously, this paper helps further operationalise the approach by proposing specific risk requirements for it, based on existing evidence. This paper also presents guidance for an overarching management framework to help guide the implementation of a WRSP approach.

Introduction

The management of risk is a significant challenge for the development and operation of water reuse schemes. Risks in water reuse schemes arise from a variety of hazards, which can lead to a wide range of consequences. Understanding of risk has led to the development and use of a number of risk-based management approaches and governing frameworks. The resulting view is that, for water reuse schemes, system wide risk-based management can be more effective than reliance on end product compliance alone.[1,2]

Experience has been gained through applying a number of risk management approaches to water reuse schemes, at both scheme appraisal and operational stages. The principle examples involve derivations of the Australian Guidelines for Water Recycling (AGWR), the Hazard Analysis and Critical Control Point (HACCP), the Water Safety Plan (WSP) and ISO guidelines.[3–12] Documented evidence of using these approaches illustrate the benefits of risk management processes (*e.g.* to minimise the chance of failure through mistakes or omissions) and illuminate specific water reuse risk management needs. That said, risk management approaches are not immune to challenges, particularly from institutional arrangements, public engagement and broader uncertainties associated with risk identification and assessment.

An increasing number of water reuse standards, guidelines and projects are promoting the Water Safety Plan (WSP) risk management approach. For example, the latest edition of the US EPA Guidelines for Water Reuse[13] promotes the use of a risk management system such as the WSP. Despite this

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growing interest, only a limited number of schemes have documented the application of a WSP-based approach to water reuse schemes.[12,14–16] These limited and context specific examples are currently not sufficient to fully understand the broader suitability of this risk management process for water reuse.

In Australia, a significant number of water reuse risk management plans have been developed, through the application of the Australian Guidelines for Water Recycling (AGWR). While they don't implement the WSP approach *per se*, the AGWR present an overarching risk management framework that (like the WSP) is based on HACCP principles. Some of the plans that have emerged from the AGWR framework have been referred to as safety plans.[17,18] Outcomes from applying the AGWR suggest that the development of country specific guidance is desirable, obtainable and advantageous.[9,19] However, a number of limitations have also been documented, including a lack of consistency in the validation of technology and the scope of the risk management framework being too narrow.[10,20] Nonetheless, experience from Australia provides valuable insight for examining how a risk management approach can be extended to water reuse.

The WSP approach operationalises the World Health Organisation's (WHO) overarching risk management framework – the *Framework for Safe Drinking Water* (FSDW). This framework is applied system-wide from catchment to tap and is designed primarily to meet health-based targets.[21] For non-potable water reuse, the WHO's *Guidelines for the Safe Use of Wastewater, Excreta and Greywater*[22] apply to wastewater and greywater reuse in aquaculture and agriculture. The WHO has developed a modification of the WSP – the Sanitation Safety Plan (SSP) approach – to implement these guidelines, albeit for a limited number of source water and end use options.[23] The availability of both WSP and SSP manuals helps promote their application and ensure consistency and confidence in the process.[23,24] Both of these existing guidelines establish a foundation framework for applying a WSP-based approach to water reuse, but are also limited in their scope.

Other WSP-based approaches have also emerged, such as the Water-Cycle Safety Plan and the Urban Drainage Safety Plan, which highlight the WSP's appeal and broad international applicability.[25,26] What is currently lacking is a better understanding of how a WSP-based approach can be comprehensively applied to water reuse schemes, and what specific modifications might be required for this. Whilst water reuse is incorporated to some extent in existing WSP-based approaches, none address the full scope of reuse schemes, nor do they appear to have engaged meaningfully with the specific literature base, associated best practice guidance, and industry experience associated with reuse. Other studies[27] have proposed a Water Reuse Safety Plan (WRSP) as a WSP-based approach that is applicable to a range of water reuse systems and incorporates risks to the environment. However, the relative lack of documented examples of applying such a WSP-based approach to reuse, along with evolving water reuse risk management requirements, suggests that further investigation is required.

This paper aims to help develop and operationalise a WRSP approach applicable across urban, industrial, agricultural, environmental and potable reuse applications. In doing so, this paper examines how the WSP could be adapted most effectively for water reuse. The paper also explicitly considers the need to develop an overarching risk management framework, alongside (and adapted from) the FSDW, in which to situate a WRSP approach. To achieve these aims, we will first examine the nature of the FSDW and the WSP and consider what gaps exist in its ability to address water reuse. Next, we draw from a review of the water reuse literature and identify some key risks that warrant particular consideration for water reuse schemes. We then examine how these key risk considerations might be addressed with the WSP approach, and within its overarching framework (the FSDW). This provides the basis for discussing how the WSP and its framework might be adapted into a comprehensive risk management approach for water reuse – namely a WRSP approach situated within a broader management framework.

Steering the water safety plan towards reuse

Emerging from the principles of the *Stockholm Framework*, the WHO's *Guidelines for Drinking Water Quality* (GDWQ)[21] take an integrated approach to risk assessment and risk management to control water-related disease. The GDWQ is a preventative management approach described by the *Framework for Safe Drinking Water* (FSDW) that consists of three components: 1) establishment of health-based targets, 2) Water Safety Plans; and 3) a system of independent surveillance

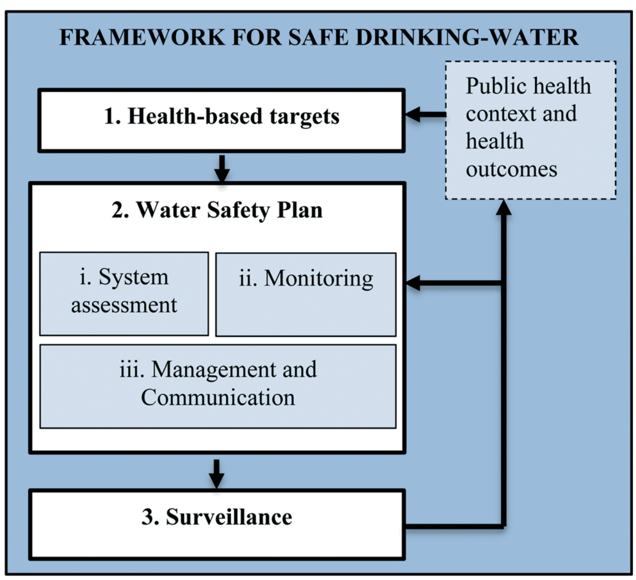

Fig. 1 WHO's Framework for Safe Drinking-Water (adapted from WHO 2011 ref. 21).

(Fig. 1).[21] The FSDW is the risk management framework and the WSP is the applied risk management process. The WSP is essential to operationalising the risk management framework in a consistent and transparent way. Within the WSP component are three elements. These are: i) System assessment, ii) monitoring, and iii) management and communication.

The WSP and its three elements are further divided into eleven modules designed to assist with the development and implementation of risk management. The eleven modules and their relationship to the three WSP elements are shown in Fig. 2. These modules should be followed to make preparations for normal operating and emergency situations. The system assessment is conducted by a WSP team who describe the catchment to tap system by identifying hazards, characterising the risks, determining controls and developing an improvement plan.

The basis of the WSP is the Hazard Analysis and Critical Control Point (HACCP) method. HACCP was developed by the food industry to provide a systematic analysis of hazard within a process to "*ensure food is safe and suitable for human consumption*".[28] Through a process of hazard analysis; critical control points identification; establishment of critical limits; monitoring; taking corrective actions; recordkeeping; and verification, risk managers can understand the relationship between hazard and process and thus take preventative action against threats. This approach has been adopted by

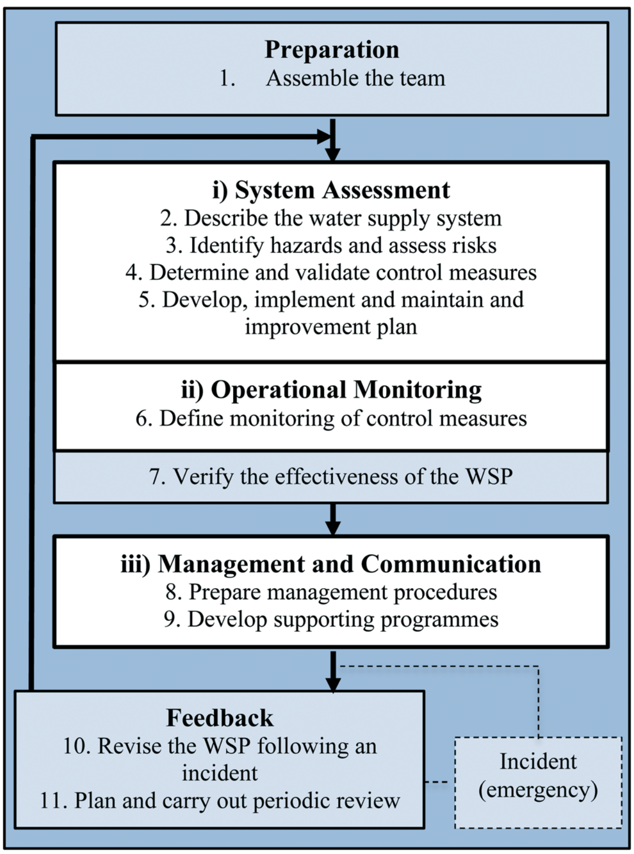

Fig. 2 How to Develop and Implement a WSP (11 modules) (adapted from Bartram *et al.*[24]).

the water industry and modified to accommodate elements such as risk assessment, community involvement, non-critical control points, multiple barriers and Disability Adjusted Life Years.[3–6,29] Such a risk management process provides a structured system to identify, prioritise and control risk and to minimise the chance of failure through error, oversight or lapse of management.[30] The WHO's WSP is an internationally recognised, well-established and trusted method for managing potable water supply schemes and is a regulatory requirement in a number of countries.[31] Such an approach is now often considered necessary for managing water reuse schemes.[1]

The WSP can be adapted to specific contexts for different drinking water supplies. Such examples include assessing risks associated with supply security, water pressure and aesthetics (*e.g.* taste, colour).[25,32,33] Still, there is a recognised need for more research and capacity building to implement the WSP, particularly for small water supplies.[34,35] There is also a recognised need to integrate better risk management tools and to address some non-technical operational and human factors.[36–38] One attempt to achieve these aims is the Water Cycle Safety Plan (WCSP) approach that extends the WSP to the urban water cycle. The WCSP extends the scope of the WSP beyond public health hazards to consider public safety (flooding) and protection of the environment.[25] The WCSP framework was developed as part of the PREPARED project,[39] and was designed to include all aspects of the urban water cycle, including water reuse (*e.g.* greywater reuse and rainwater harvesting[40]). Other adaptions of the WSP include the Water and Sanitation Safety Plan, the Urban Drainage Safety Plan and the Building Water Safety Plan.[26,41–43]

Water reuse guidelines, standards and research programmes are increasingly referring to and promoting the use of the WSP or a Water Reuse Safety Plan (WRSP) for both potable and non-potable water reuse schemes. This is particularly the case in North America[13,44–48] and Europe.[1,16,27,49–53] To date, however, there are relatively few documented examples of the application of a WSP-based approach (based on the WHO guidelines) to water reuse. One example, by Dominguez-Chicas & Scrimshaw,[12] evaluated the first three WSP modules (1. Assemble the team; 2. Describe the water supply system; and 3. Identify hazards and assess risks) for a pilot scale IPR scheme. They describe these initial steps of the process as being essential and capable of prioritising hazards. However, they also found that high levels of uncertainty and precaution resulted in an over estimation of high-risk parameters. Other applications of the WSP to reuse focus on benefits of risk communication and stakeholder engagement.[14,15,54–56]

The review has highlighted that the WSP approach is focused primarily on hazards that could impact human health. Though this focus might consider the role of unplanned, indirect potable reuse (IPR), agricultural non-potable reuse of greywater and wastewater, it is not effective for addressing hazards non-specific to human health (*e.g.* diffuse nutrients). The literature pertaining to risk management for water reuse, best practice guidance and industry experience is extensive. However, the authors are not aware of examples that integrate principles from this body of work into existing WSP-based concepts. This is developed further in the following sections.

Risk considerations for water reuse

This section draws from an extensive review of water reuse literature. This review identified a number of key risk considerations for water reuse: 1) risk characterisation and decision support tools to interpret uncertainty, 2) integration and prioritisation of risks, risk controls and operational monitoring 3) understanding technological performance and the capabilities of water professionals 4) communication and engagements with regulators, stakeholders and the public.

Risk characterisation

The probabilistic nature of risk assessment introduces uncertainty to the process, which can limit the capacity of risk risk managers to identify hazards.[11,57] Factors that can contribute to uncertainty include: lack of available information on catchment hazards (including a lack of understanding on what hazards to include in the assessment, lack of information on the quality of source or receiving waters, and variability in the technical and operational data for treatment systems.[11,12,58,59] Hazard identification for water reuse can be aided through the identification of common hazards across different projects (*e.g.* twelve common hazards are identified in the AGWR for managed aquifer recharge[60]).

Uncertainty will also exists within risk control and operational monitoring and the understanding of public support and stakeholder expectations.[60–63] In addition, scheme- or technology-specific hazardous events need to be considered. For example, van den Akker *et al.*[64] discuss public health hazards that could be introduced to a systems *via* membrane cleaning. Water treatment can generate hazardous by-products, such as disinfection by-products (*e.g.* THMs, NDMA) or greenhouse gases.[60,65,66]

There is perhaps a tendency to overestimate risks though the assumptions required during both qualitative and quantitative risk characterisations.[63,67] For example, conservative margins of safety can be used which may result in overestimating the significance or magnitude of risks.[12,68,69] This can be true for Quantitative Microbial Risk Assessment (QMRA).[70] However, even with limited available data, the benefit of QMRA and other quantitative risk assessment techniques is that they can serve to interpret uncertainty, assess treatment options and highlight the need for risk controls.[63,70] The water reuse literature outlines a number of potential improvements that could support decision making during hazard identification and risk characterisation. However, as Salgot & Priestley[3] note, despite advances in the tools available, simplifications are often required for practical application.

Risk integration and prioritisation

Integrated risk management processes should consider a wide range of risks across the entire scope of water reuse.[20] Water reuse risk management plans typically relate to microbial and chemical hazards and their potential consequences for human health and environmental end points.[11,27] These hazards can be interdependent and the realisation of a single event might trigger a cascade of secondary or tertiary consequences that will have far ranging effects (refer to Fig. 3),[71] specifically within an operational context.[72] Thus, initial consequences could escalate to threaten commercial, contractual, reputational or broader water resource planning and policy objectives.[9,11,13,20,73–77]

A more integrated risk assessment process would extend beyond consideration of health and environmental effects to include other aspects like technology and process performance impacts,[78,79] which might, for example, impact operating costs, supply pressure or availability.[80] How hazards, risks or technologies are perceived might also impact on the acceptability of a supply and thus the objective of building public support and confidence.[81,82] Other factors to consider include system scale and complexity. Smaller schemes with well understood catchments and low risk end users could use simplified risk management processes.[8,55] Risk management schemes need not be overly complicated,[11] however, failure to integrate all elements of a system can diminish the effectiveness of scheme performance.[75]

Risk-based decision making requires that hazards and consequences are prioritized and that a broad range of issues are assessed and compared alongside one another. For example, health risks must be considered alongside availability of supply and, depending upon the objective of the decision maker, compromise between water quantity and quality may be considered.[83] Individual hazards may relate to a number of consequences and therefore certain outcomes and water quality targets may need to be prioritised. However, the prioritization process will be affected by uncertainty. For example, the impact of endocrine disrupting compounds in fish has been documented, yet the implications for human health remains inconclusive,[84] so the relative priority of the hazard is difficult to establish.

Technological performance & water sector experience

The performance of the system can affect the quality of the product water.[85] Multi-barrier systems are recommended for reuse to address the fact that individual process elements and barriers can fail.[86] The water reuse system comprises different treatment technologies and performance of these technologies may decrease over time or can also introduce additional risk to the system.[83] For example, nitrosamines are shown to increase after ozonation and chloramination.[87,88] Validation of treatment process log reductions is another important consideration.[21] Indicative log reduction and actual validated system performance reductions are recommended considerations for the risk management process for reuse.[10,11,13,89]

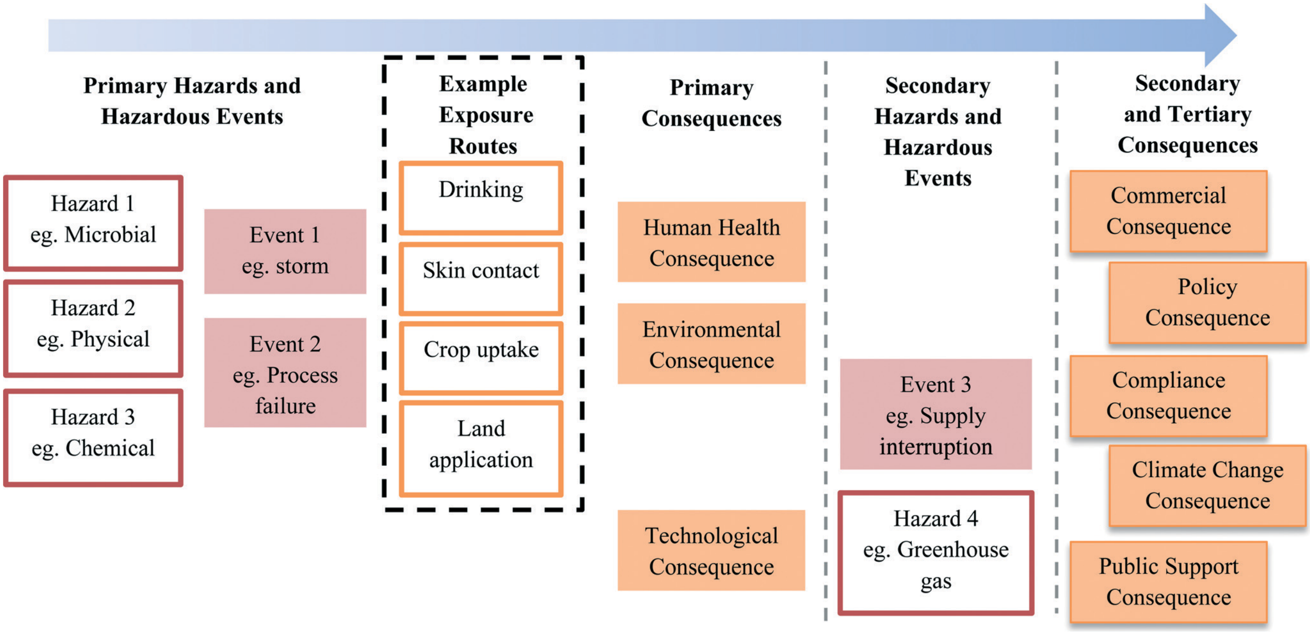

Fig. 3 An illustrative example of possible risk interactions for water reuse with primary, secondary and tertiary consequences.

The performance of water treatment technologies, and the potential for them to introduce risk to the system, can be monitored *via* performance targets.[89] This approach may be beneficial for systems where experience with water reuse schemes is low.[79,90] Example performance targets can include: reliability (*e.g.*, pressure), operational running costs, energy consumption, and customer satisfaction.[24,32,60,91] Operator capabilities are another important consideration, particularly in the absence of industry experience.[11] Individual human errors or broader system faults can lead to hazardous events occurring.[92] For indirect potable reuse schemes, environmental buffers may be utilised "to provide 'time to respond' to treatment malfunctions or unacceptable water quality".[93] There is a potential for a lack of organisational experience with water reuse schemes to increase the perceived burden of management and documentation requirements and this may impact on investment in water reuse.[94,95]

Communication and engagement

Risk communication is susceptible to issues of ambiguity that are often due to perceived difficulties in communicating scientific concepts.[96–98] Often these problems are due to differences in social values or how individuals perceive risk.[99] Effective communication is therefore valuable to reduce uncertainty and build public support and this can be achieved by improving awareness through constructive and continual engagement with water reuse stakeholders.[58,100–102] One way of achieving this may be to involve members of an effected community more closely in the risk management process.[103]

When communicating risk, it is important to understand that risks might affect stakeholders throughout the system (*e.g.* catchment, treatment plant).[25,32] Understanding stakeholder attitudes across the system can be helpful for reducing uncertainty and improving risk characterisation, particularly around potable reuse.[73,104] Poor understanding of both stakeholder and public attitudes can also have a negative impact on how governing administrations promote water reuse.[105] Uncertainty in both attitudes and governance may also influence water practitioner's perceptions of risks, their assessment of risk and decisions around the role of water reuse in water resource planning.[101,106,107]

Mapping risk considerations onto the WSP

This section maps the key considerations from the water reuse literature review onto the WSP's three main structural elements: system assessment, operational monitoring, and management and communication. This is done to evaluate how the WSP addresses these risk considerations, and identity how these it might be best adapted into a risk management approach for reuse.

System assessment

The WSP acknowledges uncertainty in risk assessment but it does not provide specific guidance or tools to help address it. As identified in the literature, challenges to system assessment might include: a lack of knowledge and guidance on the hazards to consider, the conditions that might trigger a hazardous event, and the variance inherent in probabilities and consequences. Both qualitative and quantitative assessment methods can be used to characterise risk. A typical technique is the semi-quantitative matrix that can be used to prioritise risks and vulnerabilities.[21] Comparing different risks presents a challenge due to subjectivity, for example, Hrudey *et al.*[108] describe the challenges in comparing health risks from inadequate disinfection with possible risks of cancer or adverse reproductive outcomes arising from disinfection by-products.

Water reuse risk assessment requires guidance on how to make better decisions in the presence of uncertainty. Whilst WSP documentation identifies the need to account for variability and uncertainty, little advice is provided for the practitioner. In the WSP manual, Bartram *et al.*[24] suggests using "significant" and "not-significant" as a simplified approach where risks are difficult to characterise. Similarly, whilst QMRA is recommend by the WHO, is it suggested that the strength of the approach (and other quantitative assessments) lies in the interpretation of model uncertainties in decision making.[67,109–111] Other tools identified in the WSP literature, such as multi-criteria decision analysis (MCDA), can enable uncertainty modelling to prioritise safety measures and this may bring benefits to WRSP guidance.[36]

A number of recommendations arise in the water reuse literature for dealing with variability and knowledge uncertainty. Chen *et al.*[63] suggests fuzzy sets or hybrid fuzzy-stochastic modelling and Khan[93] recommends Monte Carlo based probabilistic assessments for optimising multiple process treatment performance. These approaches can help to reduce the propagation of conservative assumptions in deterministic approaches. However, such approaches may have limited appeal to water reuse scheme assessors or operators who may not have time or resources to undertake detailed modelling. Therefore, more research and guidance on such analyses is needed before they can be used routinely in place of simpler deterministic analyses.[11]

"The WSP approach should be considered as a risk management strategy or umbrella which will influence a water utility's whole way of working towards the continuing supply of safe water."[24] For this reason, any water reuse risk management guidance may need to consider potential risk interactions and the related risk controls, particularly for schemes with multiple and mixed end user requirements (potable and non-potable). Though suggested, no guidance for how to accommodate more complex and system wide risk interactions is provided.

Failure Mode and Effects Analysis (FMEA) can be used to analyse water systems, including those incorporating reuse systems.[112,113] Dominguez-Chicas & Scrimshaw[12] identify a number of indicators that could be used to determine failure modes and the potential effects for IPR. Although this may be advantageous to the management of a system as part of a WSP, such an initial and conceptual model currently has little practical application. Further development of FMEA would be beneficial to water reuse risk management as part of a WSP based approach. Other techniques such as fault tree and event tree analysis may be advantageous to water reuse, particularly for understanding and assessing relationships between events and consequences.[72]

These findings highlight a need for risk assessment to consider cumulative effects arising from the interaction of multiple hazards or exposure pathways.[114,115] As with risk assessment, risk controls will also need to consider risk interactions. Heterogeneous risk controls may be required for some schemes with multiple end uses and this is not an explicit consideration of the WSP pro-forma. Additionally, technology may be relied on to treat the water to a certain quality, however, risks can also be controlled through non-technical barriers such as restricting exposure or behaviour change, particularly for non-potable reuse.[116] Thus the benefits of non-technical barriers would supplement a WSP for water reuse.

Operational monitoring

Operational monitoring is the definition and validation of control measures, the establishment of procedures to demonstrate that the controls are working and corrective actions.[24] Operational monitored is challenged by regulation requirements, cost, levels of detectability and scientific knowledge in new and emerging chemicals (what to monitor).[62] Cost-benefit analysis can be introduced to the WSP framework to help decision makers prioritise monitoring needs. Operational monitoring typically includes measurement of parameters at control points across the system.[21] However, observational monitoring techniques can also be beneficial to water reuse, particularly where suitable analytical capabilities are unavailable. Qualitative techniques can include audits of signage and visual inspection of irrigation systems and vegetation health for non-potable reuse.[11] Qualitative monitoring can also enable operators to become more familiar with operational and risk management processes through regular and critical interaction with them.

WSP documentation provides guidance on the use of faecal indicator organisms such as *E. coli* in providing safe drinking water. The benefit of using surrogate indicators is identified by Godfrey *et al.*,[55] again, particularly where there are limited analytical facilities or where the detectability of particular hazards is challenging or expensive. Other surrogates may be useful for reuse, for example, dissolved oxygen can be used to monitor for trade waste discharge, however, this requires careful management to avoid false alarms.[117] The use of surrogates and qualitative monitoring for water reuse is covered in some detail in the AGWR, however, a comprehensive summary is not provided in the WSP based guidance or emerging concepts such as the WCSP.

Management and communication

Management and communication is the third WSP element and includes supporting programmes. WSP supporting programmes are described as actions that are important to ensuring water safety but are not control measures and do not directly affect water quality treatment.[21] Supporting programmes include training, research and quality assurance such as process validation. What is highlighted in the literature is that the documentation needs to be efficient and actually contribute to improving risk management without being overly bureaucratic. This is not so much a question for the structure of the WSP and relates more to the effectiveness of implementation guidelines and organisational capabilities, culture and support.[118] The benefit of adapting the WSP to water reuse is that support can be derived from resources such as the WSP and SSP manuals, templates, case studies, networks and a substantial body of literature.

Communication is a suggested supporting programme for the WSP. The WSP team should therefore set out to promote a continual dialogue with stakeholders and the public. Although the WSP contains a communication element, more emphasis on this can be required for water reuse. The AGWR and ISO 31000 are examples of a more encompassing approach to communication within the risk management process. Bringing engagement into the system assessment would allow for external concerns of risks to be more suitably addressed and this may lead to improvements in public support and scheme design efficiencies.

Broader framework considerations

The WSP does not stand alone and is situated within its broader risk management framework – the Framework for Safe Drinking Water. The FSDW was developed from the WHO's harmonised risk framework. This is an iterative process that links the assessment of risk with risk management using the definition of health targets and the assessment of health outcomes.[119] This section of the paper evaluates how the FSDW addresses the key risk considerations for reuse identified previously. The focus of this section is on components 1 and 3 of the FSDW – as we have addressed component 2, the WSP in the previous section (see Fig. 1). This section also considers the context of acceptable risk which helps establish the targets (health-based) for the FSDW. This provides the basis for examining how the FSDW might be adapted into a complementary risk management framework for water reuse, within which a WRSP could be situated.

Acceptable risk context

The acceptability of water reuse risks will depend upon the end use of the water and the diversity of the stakeholder.[25,63,76,120,121] Acceptability may also vary where vulnerabilities exist within communities such as with immunocompromised groups, this is particularly the case for non-potable reuse.[122]As a result, how risks are measured will need to vary with the context.[123,124] The DALY, used to measure disease burden, is used in the WSP and AGWR frameworks, however, this might not be flexible enough to account for the different contexts in which water reuse is applied. In addition, this measure does not account for environmental risks (*e.g.* land salinity or eutrophication of a receiving water), nor does it address concerns about odour, colour, taste or supply reliability.[82,125]

Broader consideration needs to be given to the selection of technology and the design of water reuse schemes. This can be hampered by a lack of available performance data or a limited understanding as to how certain technology will perform within a given cultural or organizational context. The local context and experience may favour certain technology. For example, dual membrane process trains incorporating reverse osmosis are essentially default for many indirect potable and non-potable urban reuse schemes (particularly in Australia and California). However, this may not be the most cost effective or sustainable solution to provide safe water.[10] The views of the public and their attitudes to risk may also differ to water industry practitioners.[126,127] Negative public attitudes can be enough to render a scheme unviable, particular for potable reuse.[128] Non-potable reuse is also subject to negative attitudes and views on acceptable levels of risk. Negative experiences with cross-contamination in the Netherlands led to the Dutch government discouraging large scale non-potable schemes.[129] Such attitudes and concerns need to be taken seriously in the given context and cannot be overlooked when defining what is acceptable, the water supply targets and for developing water reuse risk management framework requirements.

Targets

For the FSDW the targets are health-based, but the risk context for reuse shows that targets may need to be broader. Internationally, water quality requirements for identical water reuse applications can vary in both the number of parameters used to assess risk and the target values.[130] These differences can be explained by the availability (or lack) of data (*e.g.* toxicological), views on acceptability, and the extent to which the precautionary principle is applied.[124] Depending on the scheme, targets will also vary depending on the characteristics and sensitivity of the receiving environment and intended end use.[11,13,131] This will be a reflection of the acceptable risk context.

Targets for microbiological quality remains paramount yet there remains some epistemic uncertainty around the range of chemicals that may be present in reclaimed water, particular for potable but also for a number of non-potable reuse applications.[58] Guideline water quality targets for water reuse may differ from standard potable water targets, particularly through the consideration of environmental guideline values and contaminants of emerging concern (CEC).[11,93] CEC targets may be considered for potable reuse. However, this is more an issue of public and regulator perception when advanced treatment is used.[107] Such contaminants are being given increasing attention in non-potable reuse application, particularly for agricultural and environmental uses. In some cases, the level of advanced treatment may be minimal and there exist various knowledge gaps around the impact of a number of chemicals.[132,133]

Review and surveillance

Review of the WSP is essential and should be carried out periodically or following any incident, while surveillance is required to "continuously and vigilantly assess and review the safety and acceptability of water supplies".[21,24] Surveillance will include monitoring potential changes to the system such as the possibility of cross-connections being introduced when non-potable networks are modified.[129,134,135] The responsibility for such auditing will need to be clarified when stakeholders commit to a scheme. As would auditing methods, where dye testing and fluorescence analysis are suggested.[69,134]

Observable outcomes may not always be immediately apparent at an individual project level. A review of international IPR schemes by Rodriguez *et al.*[83] suggests that despite variations in scheme design, no health impacts in the communities served have been observed. Sinclair *et al.*[135] make a similar finding for dual reticulated neighbourhoods. Although the sensitivity of such studies has been questioned, they do provide benefits such as the confirmation that there is no substantial problem.[93] The broader implication of this is that methods need to be considered in the framework that can assess a scheme's effectiveness against outcomes. Key knowledge gaps include developing a better understanding of the health effects of some long term exposures (particularly to low chemical concentrations) and the mixture effects of chemical (for which cell based bioassays can be employed).[11,136]

Using surrogate indicators may be a way to assess outcomes and this can be supported by the observation of changes in institutions, operations, investment or policy.[137,138] Critical success factors may be employed to validate outcomes against objectives by identifying activities that support the defined goals.[139,140] As with any surrogate indicator, it needs to be clear how their measurement correlates with the parameter of interest.[141] Review is required to monitor for newly detected chemicals, changes in legislation, advancements in technological capabilities and changes in social attitudes.[83,89,104,142] A key challenge to a risk management framework for water reuse is to facilitate social learning and to find new ways to discuss risk and uncertainty.[143]

Towards a WRSP and a risk management framework for reuse

The sections above have highlighted the potential for the WSP, and its overarching risk management framework, to be modified to more effectively address key risk considerations for water reuse. These modifications will help further develop the Water Reuse Safety Plan (WRSP) approach as an effective tool for all applications of water reuse. A WRSP is not a new proposal. What this paper proposes is how to further operationalise the WRSP based on modifications to the existing WSP, and also suggests conceptual requirements for a governing risk management framework for a WRSP.

Previous work on WRSPs illustrates the need to address both human and environmental health risks,[27,46] however, this paper suggests a need to engage with broader dimensions of risk. Sanz & Gawlik[27] propose WRSP modules, however, these do not include supporting programme, stakeholder engagement or communication requirements, despite evidence showing the benefits of these elements for water reuse.[54,55] Secondly, this current proposal does not attempt to situate the WRSP within a governing framework and therefore does not facilitate an integrated approach to the understanding of acceptable risk or risk responsibilities. Finally, through emphasising a need for reliable data to undertake risk assessment, this proposal does not engage with aspects of variability and knowledge uncertainty. We suggest that interpreting aspects of uncertainty is important for water reuse risk management to aid decision making and to reduce the propagation of conservative assumptions that may result in an over estimation risk.[12,63]

One of the WSP's strengths is that it provides a structured, standardised approach that can be applied across project stages from feasibility to implementation. This is supported by the WSP manual, numerous case studies, templates and empirical evidence. The WSP benefits from adoption within the water sector for drinking water supply in a number of countries and regions. Therefore applied methodologies and organisational capabilities already exist in many water industries. This adoption is extended to a regulatory requirement in some countries, such as the UK. Conversely, other settings may have alternative preferences for risk management – or no formal approach at all. A WRSP framework could be seen as competing with other established approaches in some instances.

HACCP (from which the WSP evolved as an application specifically for the water industry) is still promoted in the water reuse literature.[3,107] This continued use of HACCP may be because it provides a generic and familiar approach to the systemic assessment of risk. HAACP can also be accredited for water supply and water reuse.[10] The AGWR is another risk management framework that is becoming influential beyond Australia and has been tested on recognised international schemes like Windhoek's DPR scheme.[10,144] We do not propose that a WRSP-based risk management framework should replace these existing approaches, but rather that it can serve as a complementary framework that could prove particularly suitable for those areas where the WSP is already widely used.

An overarching water reuse risk management framework (derived from the FSDW) should promote an integrated systems approach to risk, operationalised through the WRSP (Fig. 4). A WRSP would build on existing WSP modules to help: 1) characterise risks and provide decision support tools to interpret uncertainty; 2) integrate and prioritise risks, risk controls and operational monitoring; 3) progress the understanding of technological performance and improve the capabilities of water professionals; and 4) support engagement and communication with regulators, stakeholders and the

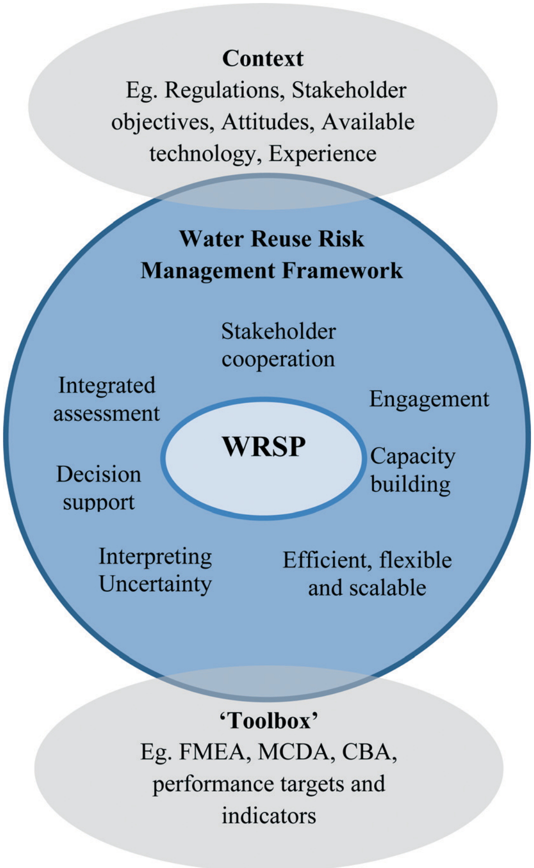

Fig. 4 A conceptual Water Reuse Risk Management Framework, operationalised through a WRSP approach.

public. A broader systems approach to the risk management framework will help planners and practitioners anticipate potential threats and opportunities for water reuse schemes. The aim would be to facilitate decisions that address longer-term risks and costs.[9] Inclusion of performance targets for both processes (validation of log reductions) and services (customer satisfaction) would help integrate water reuse risk analysis across multiple objectives.

Human dimensions of water reuse risk management are diverse. This includes understanding the needs and expectations of multiple stakeholders and satisfying the concerns and needs of reclaimed water users (including the public). Human factors can trigger hazardous events through design and operational decisions. The findings of this review suggest that better understanding and integration of stakeholder and public attitudes would help to improve confidence in water reuse decisions and the overall risk management. The use of conservative margins of safety and interpretations of public perception may, in some cases, lead to over engineered systems. Thus, a more integrated approach to risk management may assist in optimising context specific scheme design and operation.

In keeping with other studies and guidelines, this review finds that guidance on developing and implementing a WRSP should include emphasis on gaining regulatory commitment.[11,25,54] Regulatory engagement is necessary to define roles and responsibilities for managing risk. Regulatory cooperation will help achieve clarity on water reuse requirements, particularly around developing targets, operational monitoring and reporting requirements. An overarching risk management framework for reuse requires a level of flexibility in order to be able to consider a range of schemes, regional and national policies, legislation and standards. Maintaining water safety often requires inputs from multiple organisations. To address this complexity, an open audit system could be made available to all relevant agencies.[109] Such an aspiration is consistent with other research that demonstrates water reuse technology should be joined with institutional arrangements that involve the public and provide more transparent governance.[145]

Risk assessment processes must consider the effect that different technologies can have on a system. The use of performance targets could encourage the integration of a WRSP with other business areas and could create benefits from the mobilisation of existing operational and technical experience. A current limitation to the Australian approach is a lack of consistency in the validation of technology.[10] A key benefit to a WRSP approach would therefore be the inclusion of indicative log reduction values to assist with multi-barrier design. This would also include standardised requirements for validating technology. Inclusion of other performance targets such as reliability, operating costs, energy consumption (per quantity supplied) and customer satisfaction would help to link system performance with other business areas and across different stakeholder objectives. Broadening the use of performance indicators could also help to facilitate the realisation of other water reuse benefits such as nutrient and energy recovery.

Water reuse also requires improved engagement and communication. Communication needs to go beyond the provision of information, and include understanding of community attitudes, and expectations.[73,104] Attempts to understand attitudes should also extend to stakeholders and water practitioners whose perspectives on certain risks and uncertainties will vary.[101,106] A WRSP approach can look to other risk management processes such as the AGWR and ISO 31000 to help integrate communication improvements that aim to facilitate equitable deliberation and social learning.[97,101] Integrating stakeholders and affected communities in the risk assessment, control and management may prove to be advantageous. This would require minor restructuring of the WSP pro forma and supporting programmes. This may bring improvements to scheme design, particularly as it is recognised that decisions are often made to mitigate perceived public perceptions.[93] A contribution of this review is to suggest the need to integrate socio-technical considerations and human factors into the risk management framework.

The findings of this study highlight a need to consider multi-dimensional risk interactions involved with water reuse schemes. This is particularly the case for non-potable and indirect reuse where a range of risk pathways and receptors becomes possible. DPR scheme management may in fact be somewhat simpler without the need to consider intermediate environmental risks, for example. Whilst the challenges of risk interactions are not unique to water reuse, any WRSP guidance would benefit from drawing on research and developments in these areas. Aspects to consider might include hazard interactions, triggers, and cascades of hazardous events with multiple primary and secondary consequences. Although the safety plan may benefit from restricting the scope of operational risk management (particularly to human health and environmental impacts), the overarching risk management framework should consider a broader systems approach (to integrate commercial and regulatory risks, for example). This in turn reflects on the requirements for integrating risk controls and operational monitoring. This integrated approach to risk should also address best practice advice on interpreting uncertainty to enable decision making.

Integrating decision support tools such as cost-benefit analysis, MCDA and FMEA into the WRSP approach would prove advantageous. This is to assist with risk prioritisation and optimisation at various stages of the process. Project feasibility can include identifying the scope of risk assessment required. Simplified assessments are recommended for domestic scale, low risk schemes and detailed assessments for more complex schemes.[8,60] The scope of the targets and risks will depend on the nature and complexity of the catchment to tap system. As a result, the overarching risk management framework needs to facilitate flexibility in its scope and application with an aspiration that the WRSP risk management process can improve efficiency and outcomes. Current risk management processes are demonstrated to be flexible. This is shown in the literature with HACCP, the WSP and the AGWR all being adapted and modified to meet the particular needs of both decision makers and end users.

The FSDW incorporates the WSP and is a risk management framework designed for drinking water supplies. Although the WSP may in some respects be suitable to operationalise aspects of water reuse risk management, the requirements for a governing framework are less clear. While we have proposed the development of a standalone risk management framework for water reuse, it is important not to overlook the AGWR and the WCSP as existing risk management frameworks capable of fulfilling this role. The AGWR are applicable to a range of water reuse configurations and for this reason they are seen as a significant risk management framework with potential for international implementation.[10,19,27,79] However, the AGWR are tailored to the Australian regulatory system, and may therefore present a less coherent approach in other international settings. This is particularly the case for scheme approval and operational management where jurisdictions in Australia have alternative documentation and risk management requirements.[7,8] Whilst experience from Australia provides valuable insight for water reuse risk management learnings, the loss of the ‘safety plan’ identity may not leverage the necessary organisational and stakeholder buy-in in some international contexts. The AGWR are also limited in their consideration of broader system risk interactions.

Specific requirements for water reuse schemes currently fall between existing WHO guidelines on drinking water and wastewater management. A WRSP approach would complement and extend the SSP and provide a stand-alone risk management process for all variants of non-potable water reuse. Such an approach could also be applied to potable reuse, either as a standalone process for a particular scheme (from catchment to tap) or as a complement to existing drinking WSPs, where they are presently adopted. A more integrated approach to assessing potable and non-potable water supplies is particularly required for schemes involving dual-reticulation, where some aspects of risk assessments may be duplicated for each distribution network – particularly around matters of cross contamination. Similarly, for indirect potable reuse (IPR) schemes, there may be overlaps in how catchment risks are considered where a WRSP supplements existing drinking water risk management processes. Careful integration between the two processes would help avert unnecessary duplication.

The Water Cycle Safety Plan (WCSP) approach may account for these overlaps by including all aspects of an urban water cycle. However the WCSP concept does not currently account for many of the key risk considerations for water reuse. Future work should examine the potential for harmonising the WCSP approach with the WRSP approach to better facilitate water reuse within the urban water cycle. Further work will also be needed to ensure harmonisation of WRSPs with existing WSPs or alternative risk management processes currently used for potable reuse.

Conclusions

This paper has highlighted a number of key risk considerations for further developing the WRSP approach. Proposed modifications to the existing WSP approach and its overarching risk management framework, in order to adapt them for water reuse, include aspects such as supporting communication and engagement with the public, stakeholders and governing bodies, and improving decision support mechanisms to better account for uncertainty, risk interactions and risk prioritisation. These aspects are not unique to water reuse, but require a greater degree of attention than what is currently afforded in existing WSP guidance. Other modifications of the WSP (such as the WCSP), as well as the AGWR, are currently limited in their ability to address all applications of water reuse across multiple contexts. However, they do provide valuable insights which can inform the further development of the WRSP approach.

As with the WSP, a WRSP approach should be encompassed within a broader risk management framework. This will help establish risk management principles and ensure objectives are suitable for the context. Like the WHO's Framework for Safe Drinking Water, the risk management framework for reuse would guide scheme managers in setting targets and routinely assessing management performance. The AGWR, the WCSP approach and ISO 31000 are important references for broader framework requirements. For water reuse, important risk considerations extend beyond public health outcomes, and an overarching risk management framework must therefore reflect and facilitate broader contexts and objectives for water reuse schemes. The findings of this study highlight that a more integrated systems approach to risk management for water reuse, encapsulated within a risk management framework and operationalised through the WRSP, would help scheme managers to better anticipate potential risks and opportunities.

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