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Stakeholder evaluations of risk interventions for non-potable recycled water schemes: a case study

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Abstract

Non-potable recycled water schemes can benefit sustainable urban water management through reducing demand for drinking water and mitigating environmental loadings through the provision of advanced wastewater treatment. However, scheme feasibility can be diminished by high capital and operating costs which can be elevated by perceptions of health risks and subsequently overly cautious risk reduction measures. Conversely, a failure to anticipate the risk management expectations of stakeholders can undermine scheme feasibility through insufficient demand for recycled water. The aim of this study was to explore how stakeholders' perceptions and preferences for risk management and recycled water end-uses might influence scheme design. Using a case study scheme in London, four risk management intervention scenarios and six alternative end uses were evaluated using a stochastic PROMETHEE-based method that incorporated quantitative microbial risk assessment and stakeholder criteria weights together with an attitudinal survey of stakeholders' risk perceptions. Through pair-wise criteria judgements, results showed that stakeholders prioritised health risk reductions which led to the more conservative management intervention of adding water treatment processes being ranked the highest. In contrast, responses to the attitudinal survey indicated that the stakeholders favoured maintaining the case study's existing levels of risk control but with more stakeholder engagement. The findings highlighted potential benefits of understanding risk perceptions associated with different design options and contrasting these with multi-criteria model results. Extrapolating from these findings, future research could explore potential challenges and benefits of providing flexibility in scheme designs to appeal to a wider range of stakeholder needs as well as being more adaptable to future social, environmental or economic challenges. The study concludes that contemporary risk management guidance would benefit from more explicitly outlining constructive ways to engage stakeholders in scheme evaluation.

Keywords: multi-criteria evaluation, stakeholder engagement, risk management, non-potable recycled water

1. Introduction

It is argued that non-potable recycled water schemes, often implemented at discrete and geographically focused scales, have significant potential in contributing to sustainable urban water management (Marlow et al., 2013) by (often cumulatively) delivering reductions in potable water demand and associated abstractions from natural water bodies as well as reducing environmental loads through advanced wastewater treatment (Muston, 2012). Competing with the benefits are challenges, such as achieving suitable water quality, the need for additional infrastructure investment (Leverenz et al., 2011) and unanticipated operating costs (e.g. through sub-optimal membrane performance) that can detract from longer-term sustainability (West et al., 2016). In often multifaceted, multi-agency scheme designs (Chen et al., 2012a; West et al., 2016), there remain uncertainties over stakeholders' risk appetites and risk management expectations for a variety of recycled water end uses (Pickering, 2013). These uncertainties pose challenges in evaluating what water treatment technologies, risk management procedures and scheme configurations are necessary to protect public health (Turner et al., 2016). Due to the scope of these challenges, decision makers and designers may tend towards evaluation methods like cost-benefit analysis, which can overlook social or environmental benefits (a challenge discussed by Chen and Wang, 2009) and the broader interests of a range of stakeholders (Farrelly and Brown, 2011). The result can be scheme designs that, whilst fit for purpose, may be less easily adapted to changing, social, economic or environmental conditions (Pahl-Wostl et al., 2007)

Scholars have developed methods that attempt to integrate assessments of social, environmental, economic and technical factors (Hernández et al., 2006; Urkiaga et al., 2008) as well as to evaluate the range of strengths, weaknesses, opportunities and threats for different scheme design options (Mainali et al., 2011). Multi-criteria evaluations have been demonstrated as beneficial for evaluating water reuse scheme designs, for example, for selecting disinfection techniques (Gomez-Lopez et al., 2009) and membrane-based treatments (Sadr et al., 2016). Moreover, multi-criteria methods can support the evaluation of prospective recycled water uses as well as the extent of uncertainties in the analysis (Chen et al., 2014; Gomez-Lopez et al., 2009). Many studies include stakeholder acceptability as an independent evaluation criterion (e.g. Sa-nguanduan and Nititvattananon, 2011), however, few have considered the suitability of more direct participation of stakeholders to explore how their perceptions might influence scheme design or risk management preferences (Woltersdorf et al., 2017).

Stakeholder preferences for different risk management interventions can impact the selection of new recycled water uses and scheme designs (Chen et al., 2014, 2013; Qadir et al., 2010). Risk management interventions can include source control, selection of water treatment technology, monitoring (critical control points, water quality compliance), regulatory audits or exposure reductions (Chen et al., 2013; Goodwin et al., 2015). Quantitative microbial risk assessment

(QMRA) is increasingly relevant to the evaluation of risks from recycled water uses (Barker et al., 2013; Lim et al., 2015) and associated risk management options (Beaudequin et al., 2016). Quantitative health risk assessments can be included within multi-criteria assessments (Linkov et al., 2006; Topuz et al., 2011) and help evaluate potential trade-offs between factors such as population risk, individual risk and the costs of risk controls (Khadam and Kaluarachchi, 2003; Westrell et al., 2004). Probabilistic-based methods are recommended to help account for and explore the implications of the uncertainty in such analyses (Alvarez-Guerra et al., 2010; Khadam and Kaluarachchi, 2003; Moglia et al., 2012).

There is a need to develop new approaches that can accommodate uncertainty and help to understand how a mix of stakeholders (that range in their knowledge and involvement with a particular scheme) would contribute to the evaluation of risk management options for recycled water scheme designs (Farrelly and Brown, 2011; Turner et al., 2016). Multi-criteria methods are reported as beneficial for assessing new recycled water uses and prioritising management options (Chen et al., 2014). Moreover, the efficacy of specific methodological approaches has been demonstrated for evaluating risk management options for specific recycled water end-uses, for example, connecting washing machines in a residential development (Chen et al., 2012). To date, however, an approach has not been appraised that considers how the evaluation of risk management interventions might accommodate preferences for scheme design and management given a broader range of stakeholders with the potential for diverse recycled water uses with differing risk profiles. Furthermore, there remain gaps in the understanding of the implications of incorporating probabilistic-based QMRA into multi-criteria evaluations (Bichai et al., 2015; Khadam and Kaluarachchi, 2003; Topuz et al., 2011), specifically for evaluating risk management options for recycled water uses. Finally, whilst there may be benefits to simulating synthetic criteria weights in multi-criteria methods (for example, if decision-makers lack confidence - Chen et al., 2014), there are also benefits to understanding how stakeholders think about problems (Bouchard et al., 2010) and carry out decision-making in practice (Stefanopoulos et al., 2014).

Through a case study of an operational water reuse facility, this contribution's main aim is to explore how stakeholders' perceptions and preferences for risk management and recycled water end-uses might influence scheme design. This aim is pursued through the use of a stakeholder questionnaire and a stakeholder-informed multi-criteria approach that incorporates probabilistic inputs and quantitative health risk assessment. The study's objectives are to understand: (i) stakeholders' self-reported attitudes towards a range of recycled water uses and risk management options; (ii) the extent to which the importance stakeholders assign to evaluation criteria might influence the approach to risk management; (iii) the extent to which the synthesis of stakeholders' self-reported attitudes towards risk management options and results from a multi-criteria evaluation method might help inform scheme design; and (iv) implications for involving stakeholders in risk-based evaluations of recycled water schemes and as part of a 'decision making framework'.

2. Methods

2.1 Case study details

Certain geographic regions are known for their development of non-potable recycled water schemes, and many of these have been documented in literature – from residential housing development schemes in Australia, to agricultural irrigation projects in Mexico or on-site reclamation in individual buildings in Japan (Lazarova et al., 2013). Moreover, there has been growing interest in the development of water recycling schemes in a European context, particularly for non-potable (mainly agricultural and industrial) purposes (WRE 2018). This study considered the Old Ford Water Recycling Plant (OFWRP) and the supply of non-potable recycled water to existing and potential future customers at the Queen Elizabeth Olympic Park (QEOP) in east London (Figure 1). This scheme is the only known occurrence of a sewer mining scheme in the UK, where wastewater is drawn from a large strategic sewer and, following advanced treatment, is then used in the public realm. Although non-potable recycled water is not widely used in the UK, a number of opportunities for such schemes have been identified in recent water resource management plans produced by the water companies identify, in strategic reviews of household water demand in the UK (Lawson et al., 2018) and in strategic development planning for the greater London area (Shouler et al., 2017).

The OFWRP abstracts raw sewage from a strategic sewer in east London, treats it through a membrane bio-reactor (MBR) process (ultrafiltration) followed by granular activated carbon (GAC) and disinfection before distributing non-potable recycled water to a range of customers via a dedicated pipe network. A number of publications can be referred to for more details of the recycled water scheme, including Goodwin et al. (2017a), Hills and James (2015) and Smith et al. (2014). The study area is relevant to the broader urban water management challenge as the east of London is experiencing a period of population growth with an extra 600,000 people projected to be living in areas surrounding the case study location (within approximately 10 km) by 2040 (Greater London Authority, 2015). Planned development within the vicinity of the case study area includes residential housing, office space, retail space, schools, university campuses, a museum, a technology hub and potentially other industries such as concrete manufacturing (LLDC, 2015). As such, there are a number of water supply and management challenges as well as opportunities for new recycled water customers.

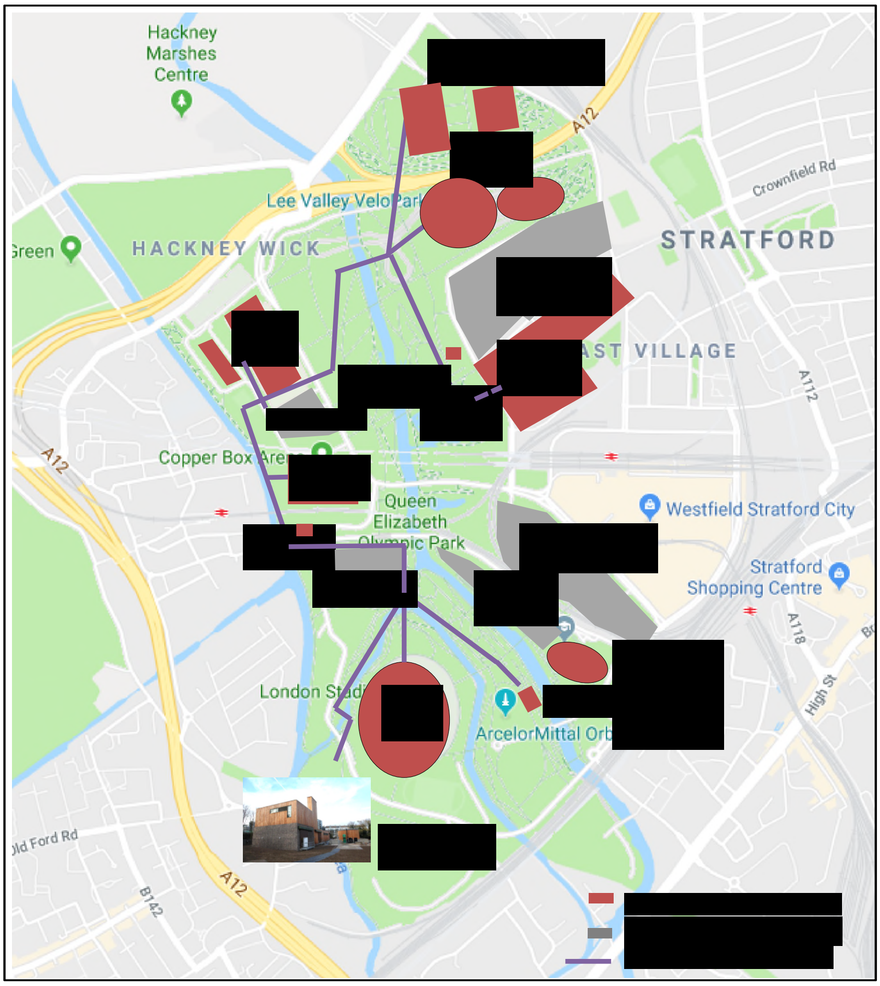

Figure 1 Layout of the non-potable recycled water network in east London at the QEOP (Figure adapted from Google Maps (n.d.) Stratford, London, ©2019 Google. Retrieved April 2, 2019, https://goo.gl/maps/4myDga7QVts, screenshot by author)

2.2 Stakeholder questionnaire

A questionnaire was designed to elicit stakeholder responses and used Likert-type questions, pair-wise criteria judgements and qualitative feedback questions.

2.2.1 Participant recruitment

Following ethical approval, a purposive sample of participants was recruited with the aim of reflecting the breadth of stakeholders involved with the case study, either directly or indirectly (those on the fringe or outside the ‘local network’ of the case study, Turner et al., 2016). The sampling aimed to recruit such ‘fringe’ stakeholders due to the recognition that they may hold knowledge and perspectives that help anticipate potential problems or innovative management opportunities (Reed et al., 2009). As such, the sample would include a range of perspectives to approximate the real-world water management challenge delineated by the case study.

Individuals were invited to participate via e-mail and through relevant, specialist social media forums. Individuals that were contacted included staff from the water company, the local planning authority, and waterway charities. They also included environmental and sustainability consultants working on similar projects in south-east England, landscape designers, gardeners, irrigation consultants, technical managers and utility coordinators for commercial housing developers, sustainability managers working in localised construction projects, civil servants from local and national government, water industry regulators, and existing customers at the QEOP.

Of 192 invitations, 58 surveys (30.2%) were started (i.e. individuals consented to participate) and 40 surveys (20.8%) were validly completed during the surveying period, which lasted from mid-June to mid-August 2017. Incomplete responses were not included in the analysis. For the completed responses, the median completion time was 20 minutes and all responses were completed in the minimum time expected (8 minutes was the fastest completion rate). Recruited stakeholders completing the survey were classified into a number of pre-defined sub-groups: water company representatives (n=13); water resource practitioners involved in water resource management in London (n=12); recycled water customers and users (n=8); and, local government planners and environmental regulators (n=7). Half of the participants were classified as within the ‘local network’ of the case study, and the other half were classed as ‘fringe’ stakeholders, based on their survey responses (see section 2.2.2). The participants included (but were not limited to) risk analysts, water quality experts, process engineers, water regulation inspectors, landscape gardeners, town planners and sustainability managers. The rate of attrition was 31% overall. Attrition was highest in the local government planners and environmental regulators group (50% not completing) and lowest in the water company representatives group (23% not completing). Given the small, purposive sample, the results were not intended to be generalizable beyond the case study, however, a heterogeneous approach to sampling aimed to recruit a diverse mix of perspective that would be representative, to an extent, of a broad range of views and, feasibly, of similar multi-stakeholder processes. Thus, implications drawn from the results were limited by the temporality of the data collection and the sample of participants.

2.2.2 Questionnaire design

The Likert-type questions used a six-point scale (1 = completely disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = completely agree, 6 = no opinion). The questionnaire began by asking participants to: (1) provide details of their knowledge of and prior involvement with the case study; (2) select the most relevant stakeholder group from a pre-defined list (with the option to enter their own definition); and (3) provide details of their roles and responsibilities in relation to the QEOP and its water management. Pre-defined stakeholder groupings were used based on those used in related water reuse studies (Baggett et al., 2006) and multi-criteria water governance studies (Salgado et al., 2009). Following these initial questions, overview information was provided on the water recycling system, the recycled water quality and current risk management practices. Next, participants were asked to state how much they agreed or disagreed with statements describing: (1) the recycled water being used for the six alternative non-potable water uses; and

(2) the salient attributes of four risk management scenarios (see Figure 2). Participants were asked to provide qualitative feedback on whether they had other preferences for recycled water uses and what factors their preferences might depend on (e.g. water quality) as well as perspectives on risk management requirements and the sharing of risk management responsibilities between different organisations. The responses were recorded anonymously, although participants had the opportunity to provide their contact details to receive updates on the research.

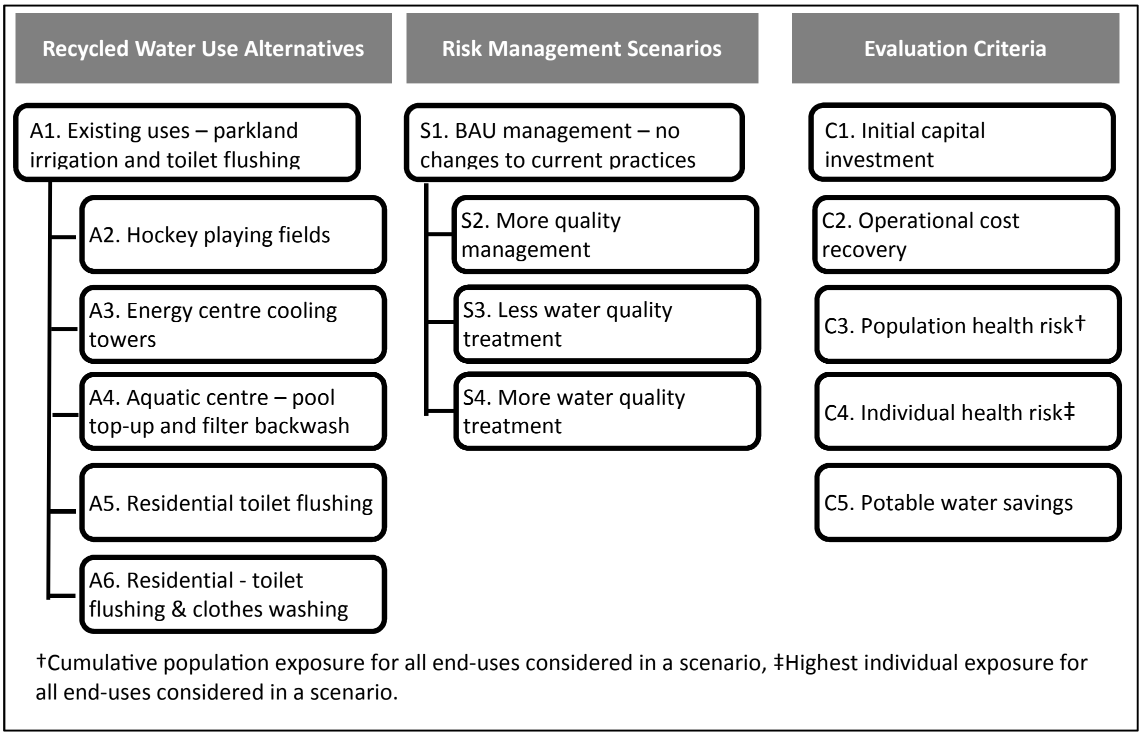

Figure 2 Summary of alternative recycled water uses, risk management scenarios, and evaluation criteria used in the case study

For the second part of the questionnaire, participants were presented with a brief narrative describing five evaluation criteria (Figure 2) before being asked to indicate subjective weights for each of the five criteria on a pair-wise basis using the Analytic Hierarchy Process (AHP) methodology (1 = the criteria are about the same importance, 3 = slightly more important, 5 = moderately more important, 7 = much more important, 9 = extremely more important (Saaty, 1980). Finally, the participants were asked for qualitative feedback on the criteria comparisons, including whether they thought important criteria were missing.

2.3 Multi-criteria method

The development of the multi-criteria process followed the stages outlined by (Hajkowicz and Collins, 2007). To develop the input data for a multi-criteria model, a number of alternative recycled water end-uses, risk management scenarios, and evaluation criteria were selected (based on previously stakeholder research for the case study) – these are summarised in Figure 2 and detailed further in the sub-sections below.

The "preference ranking organization method for enrichment of evaluations" (PROMETHEE) method formed the basis of the multi-criteria evaluation. PROMETHEE was selected as the method as it is considered appropriate for stakeholder-based evaluations due to being described (by a number of scholars) as having transparent procedures and for its relative simplicity (Kodikara et al., 2010; Lai et al., 2016). Moreover, the method was selected so that the results could be considered in the context of a previously proposed "framework for the assessment of new end uses in recycled water schemes" (Chen et al., 2014). Through a literature survey of multi-criteria methods used for water reuse studies, PROMETHEE is shown to be suitable in this context as confirmed by a number of studies (e.g. Sadr et al., 2016; Sapkota et al., 2016). A deterministic multi-criteria model for the case study was developed using Visual-PROMETHEE v1.4.

A second multi-criteria method was used to help test the sensitivity of the PROMETHEE model and thus help explore the robustness of results based on the input assumptions (Hajkowicz and Collins, 2007). The sensitivity analysis was performed using the "technique for order performance by similarity to ideal solution" (TOPSIS) method - also used in a number of water reuse studies (e.g. Gomez-Lopez et al., 2009). Where PROMETHEE uses preference functions when comparing alternatives, TOPSIS is based on comparing each alternative with an ideal (best on each criteria) and an unideal alternative (worst on each criteria) (Huang et al., 2011). The comparison identified that the outputs from the PROMETHEE model were sensitive to the definition of the preference functions, and particularly the indifference and strict preferences thresholds for the two risk criteria (population and individual health risks). Incrementing the PROMETHEE preference function thresholds and comparing the results with the TOPSIS model led to linear preference functions being selected for the two risk criteria. The other criteria used V-shape preference functions. The selection of these preference functions was supported by literature (Chen et al., 2012b; Kodikara et al., 2010). A Mann-Whitney U-test showed the distributions of the mean ranks for the risk management scenarios did not differ significantly (($z = 0.19$, $p = 0.985$) between the two methods (PROMETHEE and TOPSIS).

Next, the probabilistic model was developed. Probability distributions were included in Microsoft Excel versions of PROMETHEE (Hyde, 2006; Klauer et al., 2006) and, for 'sense checking', TOPSIS (Kolios et al., 2016). Prior to running stochastic simulations, the outputs (Phi preference flows) from the PROMETHEE Excel model (and preference functions) were checked against the Visual-PROMETHEE v1.4 model to ensure consistency. The multi-criteria method facilitated stochastic analysis of: (1) the input data for the evaluations of alternative end-uses for each of the risk management scenarios, and (2) criteria weights - follows the concept of stochastic multi-criteria acceptability analysis (Alvarez-Guerra et al., 2010). The input data for the end-use alternatives used triangular distributions (Alvarez-Guerra et al., 2010), whilst the criteria weights for stakeholder groupings were simulated using triangular (skewed where necessary) or uniform distributions. The stochastic inputs were facilitated through Palisade @Risk software version 7.5 with 10,000 iterations (Alvarez-Guerra et al., 2010).

2.3.1 Recycled water end-use alternatives

Six recycled water use alternatives were considered in the multi-criteria model to realistically represent diverse end uses with diverse risk, cost and water demand profiles (Figure 2). The first, Alternative 1, was the case study's existing recycled water customers (parkland irrigation and toilet flushing at QEOP venues). Next, five potential new customer connections were considered (as additional recycled water demand added to the BAU scenario). More details of the alternatives are discussed in Goodwin et al. (2017b). The rationale for considering these alternatives was based on realistic options for the case study that were also supported by examples in literature and were representative of a diverse mix of risk profiles. There are documented examples of recycled stormwater being used for irrigating hockey fields (Adams, 2007), cooling towers are not unusual users of recycled water (Miller, 2006; Storey et al., 2004), recycled water is feasible for swimming pools (Chen et al., 2014; Crook et al., 2005; Huxedurp et al., 2014; Marks and Zadoroznyj, 2005), and recycled water is use in residential developments for flushing toilets and washing clothes (Chen et al., 2012; Mainali et al., 2011).

2.3.2 Risk management scenarios

Four risk management scenarios were evaluated (Figure 2) that related to feasible options identified through previous stakeholder research for the case study (Goodwin et al., 2017a): Scenario 1 – Business as usual (no changes to current risk management practices); Scenario 2 - improving quality (risk) management (this scenario assumed enhancements to: signage and information, water network sampling and flushing, water regulation auditing, dye testing for cross-connections, and human exposure reductions); Scenario 3 – lower-treatment (this included removing existing GAC and poly-aluminium chloride dosing processes); and Scenario 4 - higher-treatment intervention (this scenario added reverse osmosis to the existing treatment process). More details of derivation of data for the improved quality management and the higher-treatment interventions can be found in Goodwin et al. (2017b). For the lower-treatment Scenario C, there were operational cost savings (less energy demand and chemicals along with lower estimates than BAU for labour and water quality analysis costs). The health risk results for the lower-treatment intervention were assumed equivalent to BAU as it was assumed that the removal of GAC and poly-aluminium chloride dosing from the treatment process did not alter the health risk (quantified for norovirus) (Chaudhry et al., 2015; Matsushita et al., 2013; Purnell et al., 2016).

2.3.3 Evaluation criteria

Five criteria were selected to represent the potential trade-offs between costs, environmental benefits and health risk impacts (Figure 2). These criteria were: (C1) initial capital investment; (C2) operational cost recovery (including income generated from selling non-potable water to customers alongside the income from providing a wastewater treatment service, weighed against the costs for energy, chemicals, sludge removal, staff, water analysis and maintenance); (C3) population health risk (exposure to norovirus); (C4) individual health risk (exposure to norovirus); and (C5) potable water savings. Environmental benefits were implicit in the energy and chemical costs for operating the treatment plant and the potential potable water savings. Whilst it would be possible to add more criteria, such as reductions in environmental loadings or carbon emissions, fewer criteria were selected to reduce the cognitive burden on participants making pair-wise comparisons. Details of the data used for the comparison of the criteria are summarised in Table 1, showing triangle distributions for minimum, most probable and maximum estimated values.

Quantitative Microbial Risk Assessments (QMRA) and Disability Adjusted Life Year (DALY) calculation methods for norovirus were used to assess health risks. A DALY is equivalent to the loss of one year of full health and the health-based target of $1x10^{-6}$ (µDALY) is referred to in this study. Norovirus was selected as it makes a significant contribution to the disease burden and healthcare costs in the UK (Tam and O'Brien, 2016), due to its use in related studies (Beaudequin et al., 2016; Lim et al., 2015) and due to its relevance to all the recycled water uses considered in this study (Westrell et al., 2004). Moreover, log reduction values for norovirus removal had recently been quantified for this particular case study (Purnell et al., 2016). To investigate potential risk-based trade-offs, the analysis was undertaken for DALY per person per year (pppy) and DALY per total population exposed (Goodwin et al., 2017b; Westrell et al., 2004). Due to the magnitude of differences between the DALY per total population, the multi-criteria model used logarithmically transformed values for this criterion.

Table 1 Summary of data used in the multi-criteria evaluation (triangular distributions)

Criteria	Objective	PROMETHEE preference function‡	Risk Scenario	Alternative 1 Existing uses	Alternative 2 Hockey fields	Alternative 3 Energy centre	Alternative 4 Aquatic centre	Alternative 5 Residential (WCs)	Alternative 6 Residential (WCs & WMs)
C1. ('000 £)	Maximise (costs are negative)	V-shaped p = 500	A	-330; -300; -270	-440; -400;-360	-440; -400;-360	-550; 500; -450	-2500; -2000; -1500	-2500; -2000; -1500
			B	-330; -300; -270	-440; -400;-360	-440; -400;-360	-550; 500; -450	-2500; -2000; -1500	-2500; -2000; -1500
			C	-330; -300; -270	-440; -400;-360	-440; -400;-360	-550; 500; -450	-2500; -2000; -1500	-2500; -2000; -1500
			D	-430; -400; -370	-540; 500; -460	-540; 500; -460	-650;-600; -550	-2600; -2100; -1600	-2600; -2100; -1600
C2. ('000 £.year^{-1})	Maximise benefits	V-shaped p = 100	A	-57; -50; -47	13; 15; 17	50; 85; 120	-22; -20; -18	40; 100; 160	60; 130; 200
			B	-73; -68; -60	-5; 0; 5	78; 87; 96	-38; -34.5; -31	60; 66; 73	94; 104; 115
			C	-17; 15.5; -14	46; 52; 56	124; 138; 152	12; 13.5; 15	108; 120; 132	144; 160; 176
			D	-75; -68; 61	-6; -2.5; 1	72; 80; 88	-42; -38; -34	**53; 59; 65**	**85; 95; 105**
C3. (log10[µDALY.year^{-1}])	Minimise	Linear q = 1.3 p = 5.0	A	1.81;1.99;2.14	4.29; 4.46; 4.63	1.81; 2.00; 2.15	4.96; 5.15; 5.34	3.18; 3.38; 3.53	3.18; 3.38; 3.54
			B	1.91; 1.96; 2.00	4.29; 4.46; 4.63	1.92; 1.96; 2.00	4.96; 5.15; 5.34	2.89; 2.94; 2.98	2.91; 2.95; 2.99
			C	1.81; 1.99; 2.14	4.29; 4.46; 4.63	1.81; 2.00; 2.15	4.96; 5.15; 5.34	3.18; 3.38; 3.53	3.18; 3.38; 3.54

Criteria	Objective	PROMETHEE preference function‡	Risk Scenario	Alternative 1 Existing uses	Alternative 2 Hockey fields	Alternative 3 Energy centre	Alternative 4 Aquatic centre	Alternative 5 Residential (WCs)	Alternative 6 Residential (WCs & WMs)
			D	1.15; 1.19; 1.23	3.33; 3.38; 3.42	1.15; 1.19; 1.23	4.19; 4.24; 4.28	2.51; 2.55; 2.59	2.51; 2.56; 2.60
C4. (μDALY.pppy^{-1})	Minimise	Linear q = 0.3 p = 1.0	A	0.26; 0.39; 0.60	0.74; 1.10; 1.60	0.45; 0.67; 1.00]	1.0; 1.6; 2.5	0.43; 0.63; 1.00	0.43; 0.65; 1.00
			B	0.13; 0.15; 0.17	0.74; 1.10; 1.60	0.24; 0.26; 0.29	1.0; 1.6; 2.5	0.30; 0.33; 0.37	0.30; 0.34; 0.37
			C	0.26; 0.39; 0.60	0.74; 1.10; 1.60	0.45; 0.67; 1.00]	1.0; 1.6; 2.5	0.43; 0.63; 1.00	0.43; 0.65; 1.00
			D	0.05; 0.055; 0.060	0.11; 0.12; 0.14	0.07; 0.08; 0.09	0.21; 0.23; 0.25	0.085; 0.095; 0.10	0.086; 0.095; 0.11
C5. (ML.year^{-1})	Maximise	V-shaped p = 60	A	60; 70; 84	84;90;96	123;135; 150	72; 75; 80	114; 147; 180	140; 190; 240
			B	60; 70; 84	84;90;96	123;135; 150	72; 75; 80	114; 147; 180	140; 190; 240
			C	60; 70; 84	84;90;96	123;135; 150	72; 75; 80	114; 147; 180	140; 190; 240
			D	60; 70; 84	84;90;96	123;135; 150	72; 75; 80	114; 147; 180	140; 190; 240

‡Strict preference threshold (p), indifference threshold (q). See Goodwin et al. (2017b) for details of calculations.

2.4 Analysis

Agreement statements from the questionnaire were evaluated for all completed responses (n=40). The Pearson Chi-squared test was used to compare the relative frequency of the response categories to explore any differences between stakeholder sub-groupings. Statistical analysis was undertaken using IBM SPSS Statistics version 22.0.

For the multi-criteria evaluation, the analysis was first carried out using equal weighting of the five criteria (Alvarez-Guerra et al., 2010) and using stochastic inputs for each criteria. The six alternatives and four scenarios meant there was a possibility of being ranked between 1 (best) and 24 (worst). The outputs were a range of ranks (reported for each five-percentile interval from the 5^{th} percentile to the 95^{th} percentile, thus 19 data points) for each of the six alternative recycled water uses (Alternative 1 – 6) under the four risk management scenarios (Scenario 1 – 4).

Next, the stakeholder weights elicited through the questionnaire were input into the multi-criteria model as data ranges. Of the completed surveys, the results of eleven were excluded from the multi-criteria assessment based on the AHP method consistency ratio criteria. For this study, a threshold consistency ratio (CR) of ≤ 0.20 was used for individual evaluations (Moreno-Jiménez et al., 2008), to account for the range of stakeholders invited (including 'non-experts'), the cognitive challenge of the task (Derak and Cortina, 2014) and due to a single data collection iteration being used. A CR of ≤ 0.10 was used for the overall group average with the principal aim of the process being to contrast a sufficient range of stakeholder perspectives rather than derive a single 'correct' answer (Huang et al., 2011). Whilst a CR for the AHP methods of 0.10 is typically recommended, values up to 0.25 have been used for multi-stakeholder studies (Knoeri et al., 2011). For this study it was conceived as valuable to include some less consistent individual responses (i.e. $0.10 \leq CR \leq 0.20$) in order to represent stakeholder diversity.

The range of weights elicited from the stakeholders for each criteria were fit to a distribution - aided by 'Akaike information criteria' rankings in Palisade @Risk. C1, C2, C4 & C5 used triangular distributions whilst C3 used a uniform distribution. To compare the four risk management scenarios, a frequency distribution of ranks was computed for each scenario that consisted of the range of probabilistic ranks generated for the six alternatives. The impact of adding the stakeholder weights to the multi-criteria model was evaluated by subtracting the results for the stakeholder weight model from the equal weight model to create a frequency distribution of *the change in ranks* for each risk management scenario. In all cases, the frequency of ranks was non-normally distributed (Shapiro-Wilk, $p < 0.05$ for all four risk management scenarios) and, thus, the risk management scenarios (for equal weights, stakeholder weights and the change in ranks) were compared using the independent samples Kruskal Wallis H-test with post-hoc tests (χ^2 significance level of 0.05 for three degrees of freedom was $\chi^2_{0.05}[3] = 7.815$).

Finally, the results for the two methods of data collection and analysis (attitudinal survey and multi-criteria model) were tabulated using a matrices approach (Miles et al., 2014) was employed to help structure the findings and facilitate an interpretive synthesis (Dixon-Woods et al., 2005). This synthesis also drew from qualitative responses to the questionnaire to help to understand the extent to which the stakeholders' attitudes towards the risk management options were similar or different to the results from the multi-criteria evaluation method.

3. Results

3.1 Questionnaire responses - stakeholder risk management preferences

In terms of the level of stakeholder support for the different recycled water uses, across all responses (n=40), the highest level of agreement was with the statement describing the use of recycled water in Alternative 3 ‘the energy centre (cooling towers)’ (Figure 3). Next, the existing uses of toilet flushing in venues and irrigation (A1) received near-unanimous positive responses and the statement describing the alternative of using recycled water for flushing toilets in a residential development (A5) had high levels of agreement. The statements that received the highest levels of disagreement were those describing proposed recycled water uses in the aquatic centre (A4 - almost half of respondents disagreed with the statement), in residential washing machines (A6 - one third of respondents disagreed) and for the irrigation of hockey fields (A2 - over one quarter of respondents disagreed). There were no significant differences between any of the stakeholder sub-groupings for their levels of agreement with the various recycled water uses - evidenced by comparing the relative frequency of the response categories using Pearson Chi-squared tests.

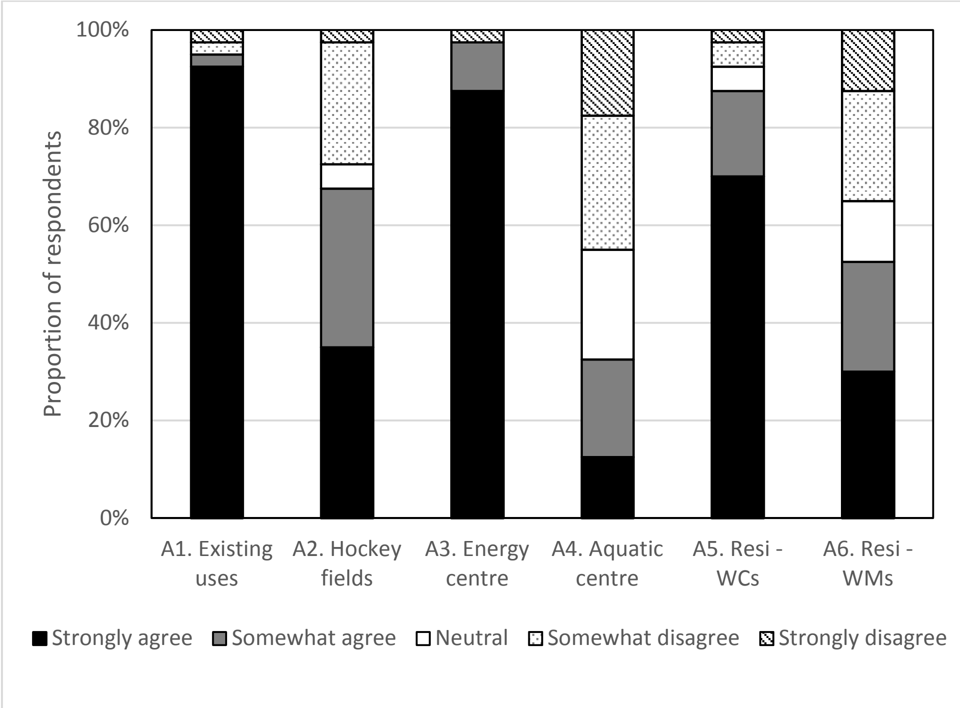

Figure 3 Stakeholder responses to statements describing the use of recycled water for the six alternative uses

Regarding risk management preferences, the statements receiving the highest levels of overall agreement (Figure 4) were that existing risk management is sufficient (S1 - nearly three quarters of respondents agreed) and that there should be more stakeholder involvement (half of the respondents). The statements relating to improving quality management (S3) and adding water treatment steps (S4) both had largely neutral responses (neither agreeing nor disagreeing). The strongest level of disagreement was to the question of removing some water treatment steps (S2) where nearly three quarters of the respondents disagreed with this statement.

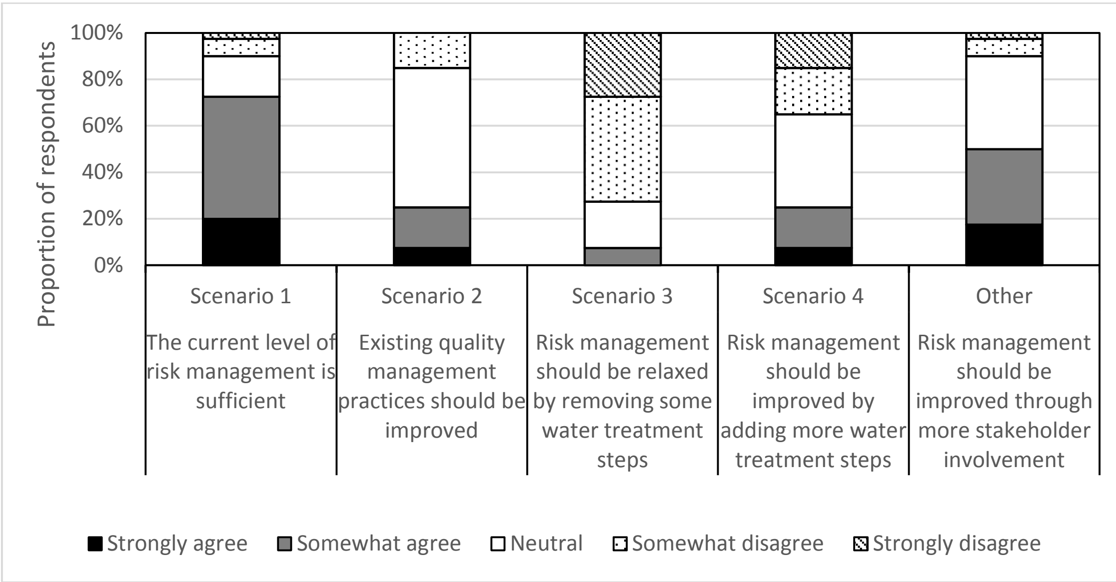

Figure 4 Stakeholder responses to risk management scenario statements

3.2 Multi-criteria evaluation - the impact of stakeholder weights

The results of the stakeholder pair-wise comparison of the five criteria showed that minimising individual risks (C4) was the most important. The more conservative risk management option, S4 (that assumed additional water treatment processes in addition to BAU), was the best ranked management scenario – both with and without stakeholder weights. Adding stakeholder weights to the multi-criteria model had the effect of improving the distribution of ranks for the two risk reduction management scenarios - Scenario 2 & 4. Conversely, adding the stakeholder weights had a negative impact on the BAU risk management scenario (S1) and less water quality treatment scenario (S3).

The stochastic PROMETHEE-based multi-criteria model was first simulated with equal criteria weights. Comparing the combined rankings for the six alternative end uses (Figure 5) showed a significant statistical difference between distribution of ranks for the four risk management scenarios (χ^2 = 10.635, p = 0.014). The post-hoc tests (with adjusted significance) showed that, statistically, Scenario 4 (additional treatment) had significantly better overall ranks than existing risk management Scenario 1 (p = 0.032) but not compared to the two other scenarios (S2 and S3). Across the four risk management scenarios, Alternative 3 was the best performing recycled water use in terms of its mean rank across all four risk management scenarios (M_{rank} = 2.6). Alternative 4, the aquatic centre, had the lowest mean rank across the four scenarios (M_{rank} = 22.3).

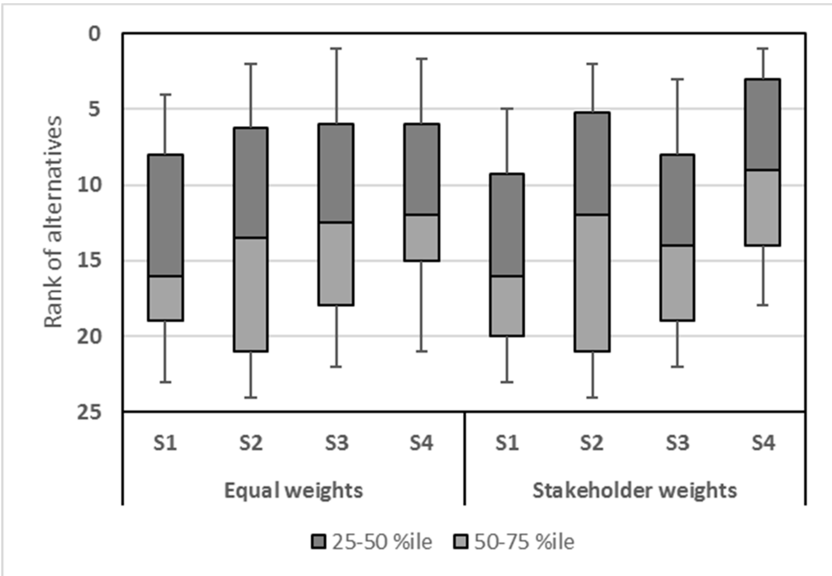

Figure 5 Distribution of ranks for the six recycled water alternatives across the four management scenarios with equal and stakeholder weighting

Risk Management Scenarios: 1 = existing risk management (BAU), 2 = enhanced risk management, 3 = lower technology, 4 = higher technology (RO). Error bars show 5th and 95th percentiles.

Following the pair-wise comparison of criteria using the AHP method, the stakeholder weighting results showed that minimising individual risks (C4) was the most important evaluation criterion. Across all valid stakeholder responses (n = 29), the preference order for the criteria was: C4 (M = 35.3%, SD = 12.2%) > C3 (M = 25.1%, SD = 11.2%) > C5 (M = 19.1%, SD = 12.4%) > C2 (M =

10.9%, SD = 6.5%) > C1 (M = 9.5%, SD = 6.8%). This preference order was largely consistent across stakeholder sub-groups, although there were some small differences. For example, 'planners and regulators' ordered both C5 (potable water savings) and C4 as equally the most important. The range of stakeholder weights were simulated in the PROMETHEE-based model after fitting them to statistical distributions. Comparing the four risk management scenarios (Figure 5) showed statistically significant differences between their distributions of ranks (χ^2 = 40.719, p = 0.001). The post-hoc tests with adjusted significance showed that Scenario 4 was ranked better (in terms of the comparative distribution of ranks) than Scenario 1 (p = 0.001), Scenario 2 (p = 0.001) and Scenario 3 (p = 0.001). In terms of the rank of the recycled water alternatives, as with equal weights, Alternative 3 had the best mean rank across the four management scenarios (M_{rank} = 4.7) and Alternative 4 had the worst mean rank (M_{rank} = 21.7).

Comparing the change in rank from the equal weight to the stakeholder weight model, the Kruskal Wallis Test gave a statistically significant result that the distributions of the four risk management scenarios were different (χ^2 = 169.302, p = 0.001). Pairwise (and adjusted with Bonferroni corrections for the multiple test comparisons), the change in ranks by adding stakeholder weights to the multi-criteria model was positive for Scenario 4 (more quality treatment through an assumed added reverse osmosis treatment step). The positive improvement in ranks was statistically significant (p<0.001) compared with the other three risk management scenarios. Scenario 2 (more quality management) also had a positive change (improvement) in ranks and this was statistically significant (p<0.001) compared with both Scenario 1 and Scenario 3. Both Scenario 1 and Scenario 3 had a negative change in ranks after the stakeholder weights were added to the model.

3.3 Interpretive synthesis of multi-criteria and attitudinal results

For the last stage of analysis, the results of the multi-criteria model and attitudinal survey were tabulated to facilitate a qualitative synthesis and interpretation (Table 2). In terms of recycled water uses, the energy centre (Alternative 3) was favoured across both the multi-criteria model and the attitudinal results from the questionnaire. There was more contrast between the results from the two methods relating to Alternative 6 (residential developments with WCs and washing machines). Whilst the multi-criteria approach ranked this end-use second (including with stakeholder weights), the attitudinal results showed only half of the respondents supported the idea of adding this end-use at the case study location. For the residential end-use with toilet flushing only (Alternative 5), there was relatively high support shown in the responses to the questionnaire from the mix of stakeholders (over three quarters of respondents agreed with the statement describing this alterative recycled water use). However, this alternative did not rank highly in the multi-criteria evaluation, particularly due to relatively worse cost recovery (C2) and lower potable water savings (C5) when compared with Alternative 6 (connecting toilets and washing machines in the hypothetical residential development). The end-use alternatives of the aquatic centre and hockey fields scored low using both data analysis methods. However, hockey fields achieved more favourable responses in the questionnaire compared with the rankings from the multi-criteria approach.

Table 2 Interpretive synthesis of multi-criteria model and attitudinal survey results – scheme design implications of stakeholders' risk perceptions

Alternative	Survey % Agree	Mean rank (1-24)	Scheme Design Implications
Alternative 1 (Existing uses)	**96%**	**14.2**	The continuation of existing uses (flushing toilets and irrigation) was highly supported by the stakeholders, yet, taking account the stakeholder's criteria preference order, the mean rank of this alternative across the four management scenarios was low.
Alternative 2 (Hockey fields)	**68%**	**18.0**	On its own, adding this water demand to BAU did not receive high support nor did the multi-criteria model show benefits to adding this use. The use could still be explored as part of a mix of new reycled water uses.
Alternative 3 (Energy centre)	**98%**	**4.7**	Both the attitudinal and the multi-criteria results idicated benefits to adding this water demand to BAU. A case for this could be suported through further exploring risk management enhancement scenarios.
Alternative 4 (Aquatic centre)	**33%**	**21.7**	There was scant evident to suport adding this end use at the existing case study. However, the inclusion of this alternative was useful for understanding how the stakeholder responded to this more unconvential proposal and thus helped calibrate the evaluative methods.
Alternative 5 (Residential WCs)	**88%**	**10.6**	Adding a connection to a hypothetical residential development produced mixed results. Whilst stakeholders indicated they were much more supportive of only having the toilets connected, the multi-critieria model showed the benefits of having additional

6 (Residential WCs & WMs)	**53%**	**5.7**	recycled water demand from clothes washing (taking into account the relative additional risks and costs). Further exploration of risk management enhancement scenarios would help support adding these recycled water end-uses to the case study scheme.			
Multi-criteria evaluation (Stakeholder weights)			Fourth in terms of 50th percentile rank. Negative change in ranks after adding stakeholder weights.	Second best 50th percentile rank. Positive change in ranks that was statistically significant compared with Scenario 1 and 3.	Third in terms of 50th percentile rank. Negative change in ranks after adding stakeholder weights.	Best ranking management scenario. Positive change in ranks that was statistically significant compared with Scenario 1, 2 and 3.
Questionnaire – attitudinal responses			73% agreed that existing risk management was sufficient.	25% agreed with adding more quality treatment, 60% were neutral.	73% disagreed that water treatment steps should be removed.	25% agreed with adding more water treatment steps, 40% were neutral.
			Scenario 1 (existing RM)	**Scenario 2 (more quality management)**	**Scenario 3 (less water quality treatment)**	**Scenario 4 (more water quality treatment)**

For the risk management scenarios, the multi-criteria method ranked the technology intervention highest (Scenario 4). This contrast somewhat with the attitude results where there was little agreement with the need for more water treatment processes (one quarter agreed) - although a high proportion of responses were neutral. There was a stronger response to the prospect of having less water quality treatment steps, to which a high proportion of respondents, approximately two-thirds, disagreed. This result, to some extent, was consistent with the multi-criteria approach as when the stakeholder weights were added into the model, they reduced the favourability (worsened the ranking) of Scenario 3 (less water quality treatment). For the business as usual management scenario (Scenario 1), the majority of stakeholders agreed existing management was sufficient – however, this feedback didn't necessarily preclude making changes or enhancements to risk management practices. Across the mix of alternative end uses, the business as usual management scenario had the worst percentile rank which indicated that 'doing something' would be preferred. Improving quality management practices (Scenario 2) had the second best 50^{th} percentile rank after Scenario 4 – thus also highlighting stakeholder support for taking steps to improve risk management. Half of the stakeholders responding to the survey also agreed that risk management should be improved through more stakeholder involvement.

The qualitative feedback provided by respondents helped to provide some explanation of some of the challenges to balancing risk management priorities. For example, some respondents described the potential trade-off between quality management procedures and water treatment processes for example, *"I think risk management should be higher if water treatment stages were removed."* (Respondent 5 – water company). Regarding the pair-wise criteria comparisons, some respondents indicated that they found the task difficult (which was supported by the consistency ratio results). Moreover, other respondents indicated that other criteria could be included, for example, benefits to upstream potable water networks, whole-life costing or regulatory certainty. Three quarters of the respondents were consistent in their pair-wise comparisons of the criteria, indicating some cognitive challenge to the task. Thus, given the challenges of interpreting the criteria and make pair-wise comparisons, the attitudinal responses allowed stakeholders to state their perceptions of the different options more directly, and indicated a benefit to utilising the two methods and triangulating the results. It is likely that more iterations of the criteria evaluation task, feasibly through a more deliberative process, could have helped to improve the data quality and to give the respondents the *"chance to think and be involved"* (Respondent 17 – water management consultant).

4. Discussion

Through a stakeholder questionnaire and a stakeholder-informed multi-criteria approach, this study explored how perceptions and preferences for risk management and recycled water end-uses might influence a water reuse scheme's design. An interpretive synthesis of results indicated that involving diverse stakeholders was likely to influence the approach to risk management for a scheme design but also that the method of engagement might capture different perspectives or priorities. As an example, the multi-criteria method ranked the technology intervention highest (Scenario 4), which contrasts somewhat with the attitude results where there was little agreement with the need for adding more water treatment processes at the case study site as a means of reducing risk. Bringing together the results of the evaluative methods highlighted some challenges in capturing stakeholder data, the delicate nature of balancing trade-offs across a range of perspectives, and how preferences for recycled water uses and risk management could impact on a scheme design. For example, the multi-criteria method favourably ranked connecting to a residential development for flushing toilets and washing clothes, however, the attitudinal results showed low support for washing clothes with recycled water. This finding was consistent with research showing that health risks through exposure to recycled water used for washing clothes can be low (Page et al., 2013) but that some stakeholders can be averse to perceived risks of this type of use (Hurlimann and Dolnicar, 2016). The mixed-method approach implied benefits to multi-faceted stakeholder engagement where triangulation of findings may help focus further stakeholder deliberation on particular aspects of a scheme design.

An objective of this study was to explore the extent to which the importance stakeholders assign to evaluation criteria might influence the approach taken to risk management. The results of pair-wise criteria comparisons showed that stakeholders prioritised risk reduction over capital and operating costs and potable water savings. Modelling the distribution of quantitative criteria evaluation data and stakeholder criteria weights (to account for uncertainty using probability distributions and Monte Carlo simulations) resulted in the two risk management enhancement scenarios being promoted (i.e. they were ranked more favourably with stakeholder weights than with equal criteria weights). The multi-criteria results indicated a perceived need for an addition water treatment step, although this was not corroborated by the stakeholders' questionnaire responses. The results also highlighted a known challenge to utilising QMRA, that is, it can lead to prioritising water quality treatment that is not necessarily needed for safe use (Bichai and Ashbolt, 2017). The inclusion of criteria for both population and individual risk, whilst useful for evaluating risk trade-offs (Khadam and Kaluarachchi, 2003; Westrell et al., 2004), also contributed to emphasising risk mitigation measures in the multi-criteria model. Moreover, the outputs from the PROMETHEE-based model were shown to be sensitive to inputs, specifically for the risk criteria's indifference and strict preference thresholds, thus highlighting the importance of scrutinising the levels of certainty (and data ranges) for model inputs and assumptions. The multi-criteria results pointed towards more cautious risk management but also suggested that the subsequent potential for increasing costs through added water treatment steps (Turner et al., 2016) could be counteracted through improved operating cost-benefits in the longer-term (if there was higher demand for recycled water driven by higher stakeholder acceptance of a more robust risk management approach). The results show how a range of inputs can help evaluate alternative recycled water uses and help guide the selection of risk control configurations (Alvarez-Guerra et al., 2010) as part of scheme design. Moreover, the evaluation method could be used to help stakeholders explore the extent of uncertainty and the impact this has on the analysis.

A further objective of this present study was to consider implications for involving stakeholders in risk-based evaluations of recycled water schemes and as part of a 'decision making framework'. Multiple criteria approaches have been shown to be helpful in identifying viable recycled water end-uses and assessing and prioritising risk controls and management options (Chen et al., 2014). Findings from this study, whilst limited by the use of a single round of stakeholder input, indicate benefits to using this type of process to help stakeholders unpick how they think about problems (Bouchard et al., 2010). For example, stakeholders provided qualitative feedback on how they had thought about potential trade-offs between the different criteria as well as suggesting other criteria they thought could have been included. Future applications could look at extending the number of criteria used in the model, depending on stakeholders' perceptions of criteria importance. The findings indicated that engaging a diverse group of interested stakeholders can bring insight to the evaluative task by putting forward different points of view (Farrelly and Brown, 2011; Turner et al., 2016) - albeit subject to the cognitive challenges of the task, the time stakeholders have available and their willingness to take part. Moreover, the results highlight how such evaluative tasks can be time-limited and can only provide a snap-shot of a selected range of stakeholder views (which may be liable to change over time or with a different sample of participants). Therefore, ongoing and facilitated stakeholder engagement is recommended. An implication for a risk-based decision-making framework is that iterative and deliberative stakeholder involvement may bring benefits to the process, to help understand objectives and risk management preferences and how they change over time. Furthermore, such multi-stakeholder decision-making processes could help bring together the often fragmented, and sometimes contradictory, policy frameworks that shape the practical implementation and operation of water recycling in many countries (Šteflov et al., 2018).

Accounting for the limitations of using a single case study and for potential methodological (e.g. the choice of multi-criteria method) or sampling biases (a high proportion of water utility practitioners took part who may perceive higher risks for water reuse schemes - Dobbie and Brown, 2014), the probabilistic multi-criteria approach, incorporating data from QMRA, was able to evaluate risk management interventions with consequences for a range of stakeholders and diverse recycled water end-uses. Through reviewing the results of such evaluative processes, scheme designers and decision-makers may be able to better account for a wider range of expectations in the design and configuration of a scheme. Thus, the findings support the benefits of using multi-criteria evaluation to aid stakeholders with water reuse scheme design (Gomez-Lopez et al., 2009; Sadr et al., 2016) through the evaluation and selection of risk reduction measures. This study has demonstrated an original approach for assessing recycled water schemes that draws on statistical inference and triangulation with attitudinal responses to survey questions. The results provide insight into stakeholder preferences, methodological choices and methods for evaluating and managing recycled water schemes. This study puts forwards evidence of the benefits that may be realised from encouraging stakeholder diversity as part of a 'framework for decision making in new end-use management' (Chen et al., 2014). Previous studies from different international contexts have identified that existing risk management processes around water recycling are limited in their ability to capture broader risks and engage a range of stakeholders (e.g. Campbell and Scott, 2011; Huxedurp et al., 2014), and this study highlights a mechanism to help address that limitation. Furthermore, the findings, whilst limited to a single case study, are relevant to the trajectory of contemporary policy and regulatory frameworks for water recycling, across numerous international regions (e.g. Australia, U.S., Europe), which are seeking ways to integrate risk-based approaches and stakeholder engagement.

5. Conclusions

This study aimed to explore how stakeholders' perceptions and preferences for risk management and recycled water end-uses might influence scheme design. Results of a multi-criteria evaluation indicated that stakeholders prioritised a higher level of water quality treatment for adapting an existing water reuse scheme to accommodate new recycled water end-uses. Contrastingly, questionnaire responses showed that stakeholders favoured existing risk management practices and more stakeholder engagement but were mostly neutral to other design and management changes. One notable finding was that the use of recycled water for flushing toilets and washing clothes in a residential development was ranked favourably through the multi-criteria method, in contrast with low support for this alternative elicited through the attitudinal survey questions. As such, the findings indicated analytical advantages to using and synthesising results from multiple evaluative methods.

Stakeholders prioritised health risk reduction, and as such, the inclusion of quantitative health risk information in the multi-criteria assessment will likely favour more conservative risk control interventions (such as adding additional water treatment steps). However, although the enhanced risk reduction scenarios had capital and operational cost implications, these could also be offset by longer-term economic benefits through securing more recycled water customers (if there was increased acceptance of and uptake of a recycled water service). A conclusion of this study is that probabilistic multi-criteria evaluation may encourage stakeholders to unpack the reasoning behind their preferences through considering the importance of difference criteria within the constraints of imperfect information. The findings showed benefits to encouraging the inclusion of stakeholder input in risk-based decision making and risk management frameworks. Contemporary policy and regulatory frameworks around water recycling, which broadly seek to integrate risk management and stakeholder engagement, could benefit from more practical ways to engage stakeholders in scheme evaluation. Future research should look at extending this study to consider more deliberative methods that can help stakeholders further unpack their reasoning and perspectives around risk mitigation preferences. Future research could also explore potential challenges and benefits of providing flexibility in scheme designs to appeal to a wider range of stakeholder needs as well as being more adaptable to future social, environmental or economic challenges.

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