Kunz, N. C., Fischer, M., Ingold, K., & Hering, J. G. (2015). Why do some water utilities recycle more than others? A qualitative comparative analysis in New South Wales, Australia. Environmental Science and Technology, 49(14), 8287-8296. http://doi.org/10.1021/acs.est.5b01827

Why do some water utilities recycle more than others? A Qualitative Comparative Analysis in New South Wales, Australia

AUTHOR NAMES

Nadja C. Kunz[1*]

Manuel Fischer[1,2]

Karin Ingold[2,1]

Janet G. Hering[1, 3, 4]

AUTHOR ADDRESS

1. Swiss Federal Institute for Aquatic Science and Technology (Eawag), Überlandstrasse 133, CH-8600 Dübendorf, Switzerland
2. The University of Berne, Switzerland
3. IBP, Swiss Federal Institute of Technology (ETH) Zürich, CH-8092 Zürich, Switzerland
4. ENAC, Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland

ABSTRACT

Although the recycling of municipal wastewater can play an important role in water supply security and ecosystem protection, the percentage of wastewater recycled is generally low and strikingly variable. Previous research has employed detailed case studies to examine the factors that contribute to recycling success, but usually lacks a comparative perspective across cases. In this study, 25 water utilities in New South Wales, Australia, were compared using fuzzy-set Qualitative Comparative Analysis (fsQCA). This research method applies binary logic and set theory to identify the minimal combinations of conditions that are necessary and/or sufficient for an outcome to occur within the set of cases analyzed. The influence of six factors (rainfall, population density, coastal or inland location, proximity to users; cost recovery and revenue for water supply services) was examined for two outcomes, agricultural use and "heavy" (i.e. commercial/municipal/industrial) use. Each outcome was explained by two different pathways, illustrating that different combinations of conditions are associated with the same outcome. Generally, while economic factors are crucial for heavy use, factors relating to water stress and geographical proximity matter most for agricultural reuse. These results suggest that policies to promote wastewater reuse may be most effective if they target uses that are most feasible for utilities and correspond to the local context. This work also makes a methodological contribution through illustrating the potential utility of fsQCA for understanding the complex drivers of performance in water recycling.

INTRODUCTION

The recycling of municipal wastewater encompasses the reclamation of effluent, including treatment and reuse for productive purposes. Wastewater recycling offers several benefits for improving urban water management outcomes including: augmenting water supplies through the reclamation of otherwise “lost” water; minimizing the energy used in water provision; protecting aquatic ecosystems through avoiding nutrient release into waterways; and recovering nutrients for productive purposes such as agriculture.[1-4] Despite these potential benefits, the percentage of wastewater recycled (hereafter referred to as recycling performance) is generally low, and there are striking disparities across utilities, cities, regions, and countries.[5-7] The objective of this article is to investigate how combinations of factors interact to yield observed differences in recycling performance between water utilities within an Australian context, with a focus on New South Wales. Understanding the reasons for these differences is important for reaching politically defined recycling targets, such as the federal government’s target to recycle 30% of Australia’s wastewater by 2015.[8]

Different factors have been found to influence wastewater recycling depending on the specific case. Survey research with program managers in California[9] has found that, despite state and federal efforts to promote recycling projects, implementation success depends on many factors including wastewater discharge requirements, water supply needs, financial/economic incentives, institutional control, economics, and influential stakeholders. The 2011/12 National Performance Report[10] for Australia discusses a different set of factors that may influence the overall volume and percentage of water recycled: rainfall, potable water availability, the size of the utility, its proximity to potential customers, and government policy. Other studies have identified factors relating to water stress[11], policy objectives[12] and public acceptance[2], among others.

A limitation of previous research is that it has primarily studied single or only a small number of cases.[13-17] Detailed case studies are important for understanding the many and diverse drivers of performance in specific contexts, but results have limited generalizability. This could be overcome by using a statistical approach to identify performance drivers across large number of cases. However such a research design is not well suited to understanding causal complexity, whereby there may be several explanations for the same observed outcome,[18, 19] which has been found to be true of wastewater recycling.[9, 20, 21] In the current analysis, Qualitative Comparative Analysis (QCA) was selected as a research approach based on its ability to accommodate causal complexity and its suitability for an intermediate number of cases. Unlike regression which uses linear algebra to quantify the average influence of individual factors on an outcome of interest, QCA applies binary logic and set theory to identify the minimal combinations of conditions that are necessary and/or sufficient for an outcome to occur within the set of cases analyzed.[22, 23] QCA has been widely applied in the social sciences [24, 25] but only recently to natural resource management.[26, 27] To our knowledge, this is the first application of QCA to water reuse/recycling.

The study focuses on Australia, where municipal wastewater recycling has been promoted as a policy response to concerns about water supply security.[28] The National Water Initiative (which was signed in 2004 by almost all Australian States and territories) highlighted wastewater recycling as one of several objectives within urban water reform.[7] In 2007, the federal government set a national target to recycle 30% of Australia's wastewater by 2015,[8] but performance is expected to be only about 20%, well below the target.[29] The heavy rainfall experienced across the Eastern states in 2010, which replenished reservoir levels in most urban areas and relieved pressure on water supply sources, is cited as one explanation for the poor performance.[29] However a closer analysis of recycling performance across water utilities suggests that other contextual factors have also limited progress towards this policy goal. For example, in 2009/10 the recycling performance in capital cities (15.2%) was notably lower than that attained across the rest of Australia (21.7%).[29] Data at the utility level (Table 1) also show disparities – some utilities recycle no water at all, while others recycle all of their treated effluent. Taking several factors at the utility level into account is thus an appropriate strategy to understand differences in recycling performance.

This analysis compares 25 water utilities in the state of New South Wales, NSW (Table 1). Internationally, there are few (if any) studies that compare recycling performance in a systematic way at the utility level; previous literature has focused on projects,[30] programs,[9] cities,[12] or countries.[11] This is also true of literature in the Australian context, with studies tending to fall into one of two categories: (1) those that discuss trends or challenges towards recycling at the national scale[7, 28, 31, 32] or (2) detailed case studies exploring the reasons for success or failure of specific wastewater recycling projects or strategies.[33-35] However it is important to understand the drivers of performance at a utility level because this is the level at which most policies within urban water management and regulation are taken, and is furthermore of interest for benchmarking. The utility level is also preferred over country-wide analyses because many of the hypothesized drivers towards recycling – including rainfall and costs – manifest at local levels, not state or national ones.

<INSERT TABLE 1 NEAR HERE>

METHODS

Research design. The starting point for a QCA is a sample of cases, an outcome of interest and a selection of factors that are expected to explain differences in performance between the cases.[36] In this study, the cases were 25 NSW water utilities (with boundaries as described in the Supporting Information, Table S1). Two performance outcomes were analyzed (for categories of recycled water use, see Table S2): a high percentage of water recycled for agricultural use (*REC_AGR*, hereafter referred to as high agricultural recycling) and a high percentage of water recycled for commercial, municipal or industrial use ("heavy") (*REC_HEAVY*, hereafter referred to as high heavy recycling). These types of use were selected because they represent the two most common uses of recycled water across the 25 case study utilities. Both the level and variation of the other types of uses (e.g. environmental, on-site or residential use, Table 1) are low and thus difficult to study with a comparative design. The "agriculture" and "heavy" outcomes were considered separately because utilities which recycled more than 30% of their effluent achieved this target via one (but rarely both) of these uses (Table 1). Data were analyzed for the 2011/12 reporting year because this was the most recent dataset available at the time the analysis was conducted and was the most reliable.

The most important explanatory factors were selected based on a review of academic literature and government reports; discussions with experts (researchers, government and industry representatives) familiar with the Australian context; and in-depth knowledge of the selected case studies. From the literature review and discussions with experts during the 2013 IWA Water Efficiency conference in Paris, a broad range of potential factors were identified. These factors were classified into two types – utility-level factors and governance-level factors – the former inspired from an industrial ecology perspective,[37] and the latter inspired by a multi-level governance perspective.[38] It was reasoned that governance-level factors (e.g. government targets/mandates; public vs. private ownership; scope of accountability) would be less influential for explaining differences between the 25 chosen case study utilities because all are located within the same state (NSW) and are thus subject to the same jurisdictional arrangement.[10] This assumption would not have been valid if utilities were being compared across states/territories due to substantive differences in regulation and governance.[10] The analysis in this paper includes six factors which are hypothesized to explain differences in recycling performance across the 25 case study utilities.

To begin with, previous studies suggest that wastewater recycling is more likely to occur in water stressed regions because it offers a means to augment existing water supplies.[2, 9, 11] Two associated factors – *Rainfall (RAINFALL) and Population density (POP)* – reflect water stress and have previously been identified as drivers towards wastewater recycling in both the Australian[39] and European[40] context. First, the demand for recycled water is expected to be lower during periods of – or in regions with – high rainfall due to access to a wider range of alternative water supply options. Second, population density is hypothesized to be a driver of water stress over a longer timescale – i.e. regions with higher population densities would tend to promote recycling due to increased demand for water and pressure on local water resources.

Two additional factors relate to the geographical location of utilities. First, inland utilities *(LOCATION)* are more likely to implement wastewater recycling for two reasons. Since wastewater treatment plants in inland regions are located far from ocean outfalls, the discharge of concentrated wastewater with high nutrient content can impact the ecological health of receiving streams.[41] In Australia, a higher level of treatment is generally required for discharge to inland rivers and streams, making recycling more cost effective.[10] Alternative water sources such as seawater desalination are also less viable in inland regions.[6] Second, utilities that are *proximate to agricultural (PROX_AGR), or heavy (PROX_HEAVY)* users are also hypothesized to recycle more because it is more economically viable due to lower conveyance and distribution costs.

The final two factors relate directly to economics, which is a crucial driver of water supply choices.[3, 42] First, it is expected that utilities will recycle the most if they are operating in an economically efficient manner and are able to fully recover their operational costs. In Australia, many utilities are government-owned enterprises and have historically underpriced water due to political pressures.[43] This historical underpricing has resulted in some utilities being unable to generate sufficient revenue to invest in new systems. Recycling is thus expected to prosper for those utilities which achieve full cost recovery of their water supply and sewerage assets through appropriate water pricing *(COST_REC)*. The second economic factor acknowledges that recycled water is an expensive water source, and is therefore only expected to prosper when utilities have the potential to earn high *Revenue for water supply services* (REVENUE). This would indicate that utilities have an economic incentive to invest in recycling because they can either charge a high price for water (due to strong demand from potential users) and/or are able to keep their costs low.

It is expected that utilities with high agricultural or heavy recycling will be located in regions with low rainfall, high population density, inland, be in close proximity to agricultural or heavy users, achieve full cost recovery, and receive high revenues from water supply. These expectations can be expressed using standard set theory notation,[44] in which ~ represents the Boolean NOT.

REC_AGR = f (~RAINFALL; POP; LOCATION; PROX_AGR; COST_REC; REVENUE)

REC_HEAVY = f (~RAINFALL; POP; LOCATION; PROX_HEAVY; COST_REC; REVENUE)

Table 2 presents the input dataset used for QCA analysis. This information was derived from publically available datasets and reports published by the Australian Government[10, 45, 46] and rainfall data purchased from the Australian Bureau of Meteorology. Table S3 details the approach used to quantify each factor.

<INSERT TABLE 2 NEAR HERE>

QCA analysis and input. Qualitative Comparative Analysis (QCA) is a set-theoretic method that strikes a balance between qualitative and quantitative analysis and is well suited to an intermediate number (N = 5-50) of cases.[47, 48] Within the set of cases analyzed, QCA aims at identifying conditions that are *necessary* (i.e. they must be always be present when the outcome is present, but can also occur when the outcome is not present) and/or *sufficient* (i.e. they always occur when the outcome is present, but other conditions are also associated with the outcome). Each case is represented as a configuration, i.e. "a specific combination of factors that produces a given outcome of interest".[49] Configurations of factors are compared across cases, which allows for the elimination of redundant factors and the identification of pathways that lead to an outcome.[26] The underlying assumptions[50] of QCA are well suited to studying the drivers of recycling performance. The assumption of *conjunctural causation* recognizes that single factors may not result in an outcome on their own but rather in combination with other factors. Second, the assumption of *equifinality* states that the same outcome can be explained by different combinations of conditions.

Fuzzy-set QCA (fsQCA) was used for the analysis because both outcomes and five of the factors (RAINFALL; POP; REVENUE; PROX_AGR; and PROX_HEAVY) are continuous datasets. fsQCA is the preferred method in this circumstance because it maintains the precision of the underlying data, unlike crisp-set QCA which involves categorizing all datasets on a binary scale.[18] Prior to performing an fsQCA analysis, each outcome and factor must be scaled to range between 0 and 1. For the five factors derived from continuous datasets, this was achieved by following the standard QCA procedure which requires three choices: threshold for full non-membership (fuzzy set value of 0); cross-over point (fuzzy set value of 0.5); and threshold for full membership (fuzzy set value of 1). The cross-over point indicates the point of maximum ambiguity whereby it is unclear whether a case is more "in" (fuzzy set value between 0.5 and 1) or "out" (fuzzy set value between 0 and 0.5) of a given set.[51] A logistic function was used to scale the variables between these three thresholds. The remaining two factors (LOCATION and COST_REC) were coded as binary (for LOCATION, 1= inland; 0 = coastal; for COST_REC, 1= achieved full cost recovery in 2011/12; 0 = did not achieve full cost recovery in 2011/12).

Table 3 summarizes the approach used to select thresholds for each outcome and factor. For the outcomes (REC_AGR and REC_HEAVY) a threshold of 0% was used for full non-membership corresponding to no recycling at all, which is both the minimum of the dataset and the minimum possible. A threshold of 30% was used for full membership to indicate that the utility had met the federal government's recycling goal. The mean of non-zero values (21.2% for REC_AGR and 7.7% for REC_HEAVY) was used as the cross-over point. The remaining explanatory factors (RAINFALL; POP; REVENUE; PROX_AGR; PROX_HEAVY) were scaled by selecting the

25% and 75% quantiles for full non-membership and full membership, respectively. This approach reduced the sensitivity of the fuzzy-set values to extremes in the respective data. For each factor, a value slightly below the median (median – 0.0001) was used as the crossover point in order to have a roughly equal number of cases as members and non-members of each set,[52] but with no cases representing exactly the 0.5 threshold, which represents perfect ambiguity between set membership and non-membership. The sensitivity of the results to threshold selection and the choice of scaling function was tested (Tables S6-S9), and is discussed in the Study Limitations.

<INSERT TABLE 3 NEAR HERE>

QCA output: Necessary conditions. Necessary conditions were identified using the in-built routine in the R package, which searches first for individual necessary conditions (e.g. ~RAINFALL) and then necessary conjunctions of conditions (e.g. ~RAINFALL*LOCATION). Conjunctions (*) correspond to Boolean AND conditions and disjunctions (+) to OR conditions.

The quality of a solution was assessed based on its consistency and coverage measures.[18, 53] *Necessity consistency* (Eq. 1) indicates how often a condition is present when the outcome occurs, relative to the overall presence of the outcome. A threshold of 0.8 was used. *Necessity coverage* (Eq. 2) evaluates the relevance of the condition (a trivial condition is almost always present, regardless of whether the outcome occurs). A threshold of 0.3 was used.[54] The negation of the outcome was tested to avoid paradoxical results whereby evidence that a condition is necessary for an outcome to be present and to be absent are equally strong.[55]

Equation 1. Formula for quantifying *necessity consistency* and *sufficiency coverage*

$$Outcome\ (Y)\ as\ a\ subset\ of Condition\ (X) = \frac{\sum_{i=1}^{I} \min\,(X_i, Y_i)}{\sum_{i=1}^{I} Yi}$$

Equation 2. Formula for quantifying *necessity coverage and sufficiency consistency*

$$Condition\ (X)\ as\ a\ subset\ of Outcome\ (Y) = \frac{\sum_{i=1}^{I} \min\,(X_i, Y_i)}{\sum_{i=1}^{I} Xi}$$

QCA output: Sufficient Conditions. The starting point for a sufficiency analysis is a truth table (see Table S4/S5) which displays a separate row for each configuration of factors that are empirically observed in the dataset, with each case belonging to one configuration. *Sufficiency consistency* (Eq. 2) indicates the extent to which given configurations of factors are consistently sufficient for the outcome. *Sufficiency coverage* (Eq. 1) expresses the empirical importance of condition X for explaining outcome Y. The QCA package in R[56] was used to simplify the truth table to identify sufficient conditions leading to an outcome. All configurations which are consistently sufficient for the outcome are included in the minimization procedure. The threshold for sufficiency consistency was defined as 0.8, which included all four utilities that recycled more than 30% of their treated effluent for agricultural uses (Albury; Dubbo; Tamworth; Goulburn) and the one utility that recycled more than 30% of its treated effluent for heavy uses (Orange).

RESULTS AND DISCUSSION

Necessary conditions. Within the 25 cases analyzed, inland location and low rainfall were both necessary for high agricultural recycling (Table 4), a finding that follows the argument laid out in the Methods section. Inland utilities are located far from ocean outfalls and are generally subject to more stringent legislation for discharging to inland rivers and streams. Furthermore, alternative water sources such as seawater desalination are less viable for inland utilities; unlike coastal utilities such as Sydney WC which used desalination to augment water supplies following an extended drought.[43] Low rainfall was also a necessary factor, which may be reflective of the fact that agricultural users are particularly reliant on rainfall as a water source. Regions with low rainfall would therefore have a higher demand for recycled water by agricultural users.

High revenue is the only necessary condition for high heavy recycling. This result is different from that for agricultural recycling, suggesting that heavy recycling prospers under different contexts. Agriculture represents the dominant use of recycled water across the world,[2] and also within Australia, suggesting that it is the easiest way to recycle wastewater. However agricultural users typically have a lower willingness to pay for water resources than capital-intensive heavy users. Therefore, it seems feasible that the only scenario under which utilities would preferentially recycle water to heavy users (rather than agricultural users) is if they are able to receive high revenue for water supply.

<INSERT TABLE 4 ABOUT HERE>

Sufficient conditions. Within the set of analyzed cases, two alternative pathways explain high agricultural recycling at an overall solution consistency of 0.93 (Table 5). Inland location and low rainfall – the necessary conditions – are not sufficient on their own but are part of the solution term for both pathways. Besides inland location and low rainfall, the pathway with the highest coverage score (that explains Goulburn, Dubbo and Tamworth) also includes low population density, high revenue and achieves cost recovery. All of these factors are consistent with the arguments described in the Methods section, except for low population density.

Contrary to our findings, it had been hypothesized that regions with higher population densities would tend to promote recycling due to increased pressure on local water resources. An explanation for this surprising finding may be that utilities with lower population densities also tend to receive less effluent, thus making it easier to recycle a higher percentage. For example, Tamworth recycles most of its treated effluent to a single farm, an approach that is not possible for large utilities such as SydneyWC (which receives effluent volumes over 100 times greater than Tamworth).

The second pathway explains the case of Albury, which also achieved high agricultural recycling but was driven by a different combination of factors (i.e., low rainfall, inland location, high population density, low revenue and close proximity to agricultural users). Of the 25 case studies, Albury had the highest proximity to agricultural users (Table 2) which may explain why the utility pursued agricultural recycling despite having a low revenue, high population density, and an inability to recover costs (in contrast to Goulburn, Dubbo and Tamworth).

<INSERT TABLE 5 ABOUT HERE>

Two pathways explain high heavy recycling at a consistency of 0.99 (Table 6). The case of the utility that recycled the highest percentage of water for heavy uses (Orange) is explained by a pathway consistent with all of the hypotheses posed in the Methods section (i.e. low rainfall, high population density, high revenue, achieves cost recovery, inland location, and proximate to heavy users). However Bega is explained by a different pathway, which – with the exception of high revenue and achieving cost recovery – contradicts all of the hypotheses in the Methods section. This result is surprising and may indicate that the two economic factors are more important for high heavy recycling than factors relating to water stress and geographical location. However these conclusions should be given modest weight on account of the low overall solution coverage score (0.35). Future research should seek to investigate whether the same solution pathways are observed when analyzing a different sample of cases.

<INSERT TABLE 6 ABOUT HERE>

A key finding from this analysis is that within the 25 cases analyzed, different combinations of conditions explained high recycling performance depending on the type of use. Inland location and low rainfall are necessary for high agricultural recycling, while high revenue is necessary for high heavy recycling. This suggests that policies to promote wastewater reuse would be most effective if they target uses that are feasible for utilities given attributes such as location, climatic factors, and potential revenue from water sales. However these necessary factors were not sufficient by themselves but only in combination with other factors. There are hence many pathways for achieving the same outcome, confirming that wastewater recycling satisfies the underlying assumptions of QCA[50] regarding *equifinality* (where the same outcome can be explained by different conditions) and *conjunctural causation* (single factors must occur in combination with other factors).

STUDY LIMITATIONS

In this study, QCA was selected as a research approach because it is suitable for analyzing an intermediate number of cases and for understanding causal complexity, whereby different combinations of factors can lead to the same result.[18, 19] While QCA has been widely applied within the social sciences,[24, 25] it has only recently been applied within the field of natural resource management.[26, 27] Given that many water resources management problems are characteristic of causal complexity, QCA may offer a promising method for conducting further cross-case comparisons, especially in the area of wastewater recycling. However potential users of QCA should also be mindful of the method's limitations.

In particular, the approach used to scale the outcome and factors can influence the results of an fsQCA analysis, but sensitivity analyses have not been widely applied in the QCA community.[57] In this study, we examined four scenarios to investigate the sensitivity of results to choices about threshold selection and the function used to scale continuous variables between the specified thresholds (Tables S6-S9). Figure 1 illustrates how these choices influenced the scaling for the factor *RAINFALL*. In the Baseline, the threshold for full membership was set at the maximum of the dataset; full non-membership at the minimum; the crossover point at the mean, and a linear function was used to scale variables between these thresholds. Scenario 1 used the same settings except that the crossover point was set at the median. Scenario 2 used the same settings as Scenario 1 except that the effects of extreme values were reduced (Fig. 1B) by setting full membership at the upper quartile and full non-membership at the lowest quartile to avoid putting a disproportionate weight on the utility with the lowest rainfall (Essential). The Final Scenario used the same settings as Scenario 2 except that a logistic (rather than linear) function was used to scale continuous variables between the specified thresholds. Overall, results were most sensitive to changes in the threshold location (Scenario 2) rather than the choice of scaling function (Final Scenario). Nonetheless, it is strongly recommended that future QCA studies should give due consideration to both of these aspects and that sensitivity analyses should be prerequisites within all fsQCA applications.

<INSERT FIGURE 1 NEAR HERE>

Within a QCA study, it is also important to have a strong justification about the choice of factors and their measurement. In this study, quantification of some factors was limited by available data at the utility scale. For example, proximity to nearby users was quantified as the percentage of land occupied by respective users – however consumptive water use intensity[11] or the distance of pipelines between WWTPs and potential users might be better measures. Similarly, rather than comparing the revenue received for water supply services, it might have been preferable to compare the pricing policies between utilities (e.g. the prices and costs of supplying recycled water relative to alternatives). These represent promising directions for future research if the required data are available.

Finally, it should be recognized that the results of this QCA analysis are specific to the 25 cases that were examined in this project and should be further generalized with caution. While the analysis represents an improvement over single or small-N research designs that are very case-specific, the research design was nonetheless constrained to the same jurisdictional arrangement (all utilities belonged within the state of NSW). There is hence an opportunity to test the generalizability of the conclusions from this study by repeating the same analysis using a different sample of case studies. Future comparative research designs should also consider alternative levels of analysis for different types of use and performance outcomes (Figure 2) in order to further disentangle the factors that promote or hinder water recycling across contexts. Analysis of trends in water recycling over time would also allow investigation about how changes in rainfall and population growth influence recycling performance.

<INSERT FIGURE 2 NEAR HERE>

POLICY IMPLICATIONS

It was significant to conclude that the drivers towards wastewater recycling differ depending on the type of use. Few, if any, previous studies have performed such a comparison, focusing instead on the drivers towards water recycling generally,[9, 11] or investigating only one type of use.[14, 16] However this finding has important policy implications because it suggests that efforts to promote recycling should be preferentially directed to target uses that are most feasible for utilities and that correspond to the local context.

Unfortunately, this finding also results in a dilemma for implementing recycling projects in major Australian cities which collect the largest volumes of wastewater and thus represent promising candidates for maximizing the overall percentage of wastewater recycled nationally (e.g. to meet the federal government's target to recycle 30% of Australia's wastewater by 2015[8]). An issue arises because Australian cities do not have attributes (e.g. low rainfall, inland location) that are well suited to maximizing water recycling for agricultural use, which represents the dominant (and therefore easiest) use of recycled water globally.[2] This may explain why several Australian cities have considered potable wastewater recycling schemes despite their political and community unpopularity.[31, 58-60]

An alternative use of recycled water in such locations could be irrigation of parks, golf courses and decorative landscaping adjacent to major roads. Although such uses are practiced and accounted for in the Australian context (see Table S2), there are compelling reasons to consider expanding non-potable schemes in urban areas. Politically, they are more attractive than potable reuse options, because empirical research has found that public acceptance of recycled water use is considerably higher for end uses that are furthest from human contact.[60-62]

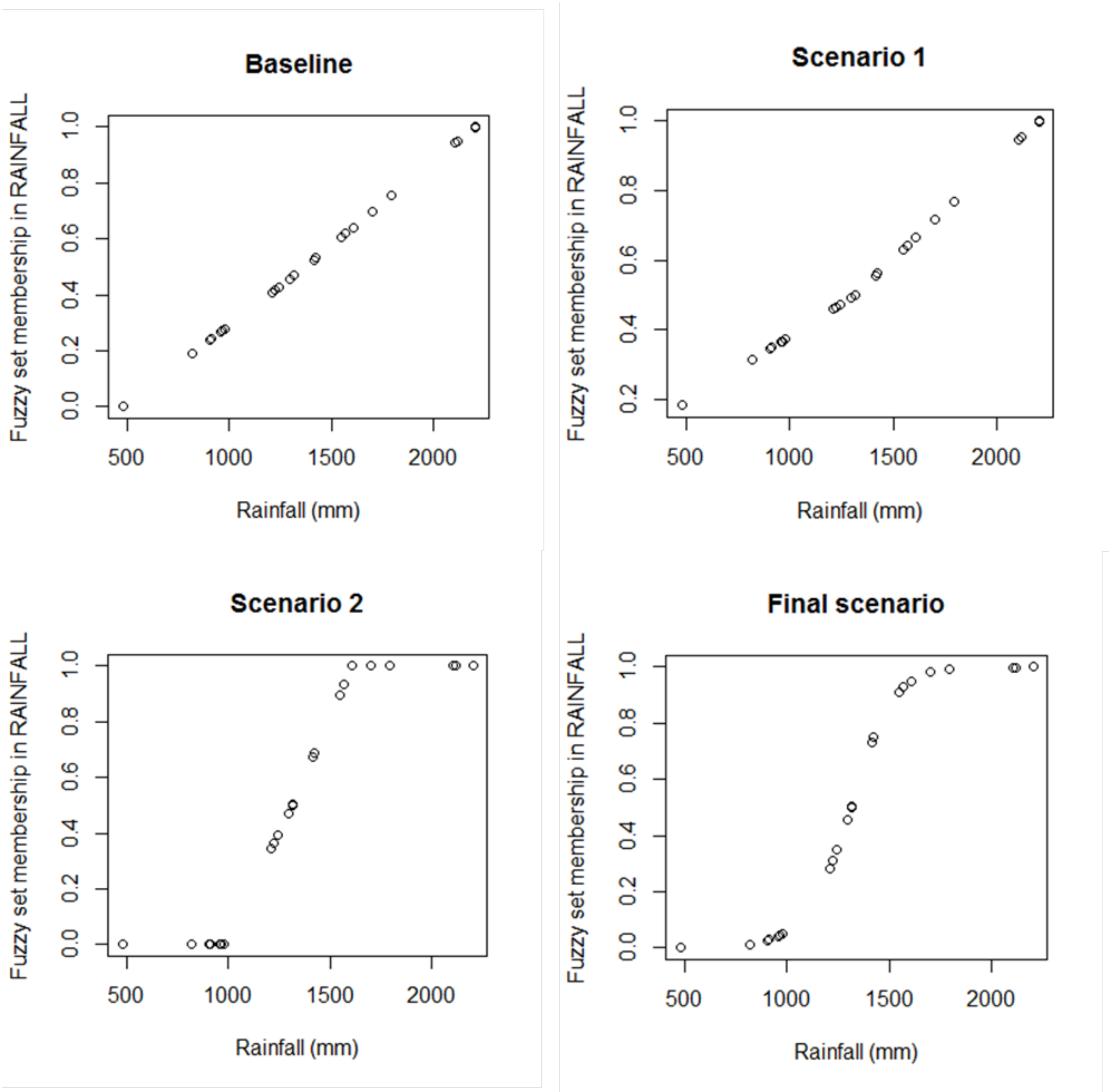


Figure 1. Four scenarios were used to investigate the sensitivity of results to choices about threshold selection and scaling function. This figure illustrates these differences for the variable “Rainfall”

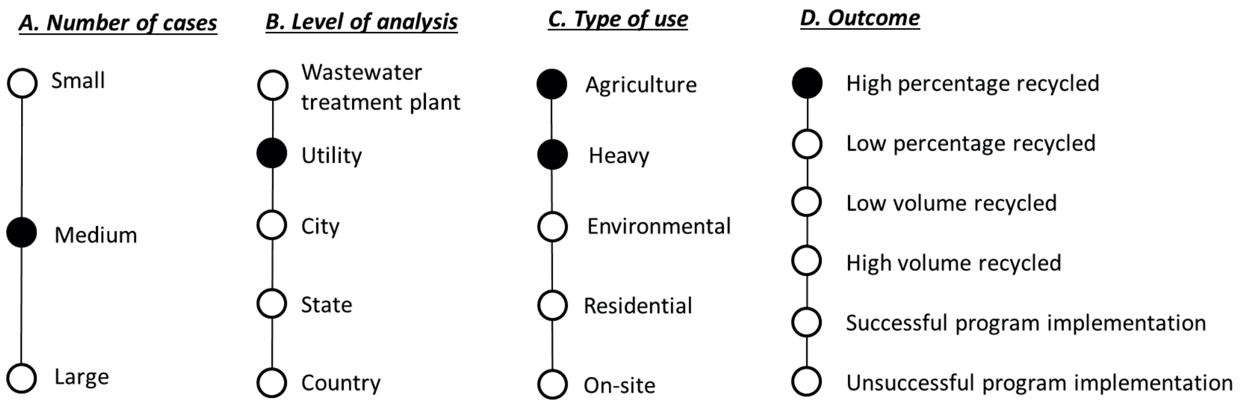


Figure 2. Factors and outcomes emphasized in this study are shown by filled circles. Open circles indicate alternatives for (A) the number of cases, (B) the level of analysis, (C) types of use and (D) outcomes that could be addressed in future research. The style of formatting of the figure uses a similar layout to that of Cash et al.[63]

Table 1. Percentage of treated effluent recycled for different uses in 2011/12 across the 25 case study utilities included in this study.[a] Utilities are ordered based on the total percentage of treated effluent recycled.

	Residential *(%)*	**Heavy** *(%)*	**Agricultural** *(%)*	**Environment** *(%)*	**On-site** *(%)*	***Total percentage recycled (%)***	***Total volume recycled (ML)***
Bathurst[b]	-	-	-	100.00	3.00	103.00	4'324
Albury	-	-	50.84	47.87	-	98.71	5'287
Goulburn	-	6.88	82.87	-	-	89.74	1'540
Tamworth	-	-	66.11	-	-	66.11	3'622
Orange	-	49.34	-	-	-	49.34	2'218
Dubbo	-	-	45.05	-	3.14	48.19	1'396
Essential	-	25.63	-	-	-	25.63	416
Bega	-	17.67	3.33	-	-	21.00	485
Byron	-	11.48	4.21	-	-	15.69	511
Shoalhaven	-	0.45	7.87	-	0.41	8.73	744
SydneyWC	0.32	1.68	0.90	2.32	2.74	7.97	45'928
Coffs	-	1.15	4.86	-	1.91	7.92	489
Hunter	-	2.03	3.50	-	0.24	5.77	4'664
Tweed	-	3.91	0.56	-	0.02	4.50	386
Midcoast	-	-	3.61	-	-	3.61	282
Clarence	-	3.27	-	-	-	3.27	109
Portmac	-	0.97	2.07	-	-	3.04	294
Wyong	0.68	1.85	-	-	0.11	2.64	465
Eurobodalla	-	2.34	-	-	0.27	2.62	86
Ballina	-	2.19	-	-	-	2.19	104
Gosford	-	0.08	-	-	1.55	1.63	271
Wingecarribee	-	0.72	-	-	-	0.72	35
Kempsey	-	-	-	-	-	-	-
Lismore	-	-	-	-	-	-	-
Queanbeyan	-	-	-	-	-	-	-
TOTAL volume	*1'993ML*	*16'064ML*	*18'798ML*	*20'124ML*	*16'678ML*		*73'656 ML*
TOTAL percentage	*0.25%*	*2.03%*	*2.38%*	*2.54%*	*2.11%*	*9.31%*	

[a] Data accessed from the National Performance Report.[10] The report also included a category for "Other", which was excluded from the table because it was zero for all utilities. [b] The total percentage recycled by Bathurst is above 100%, which would indicate more effluent was recycled than received. Discussion with the data auditors suggested that onsite reuse included a recirculating flow of water.

Table 2. Input dataset used for the QCA analysis. Utilities are ordered first by REC_AGR and second by REC_HEAVY.

	REC_AGR	REC_HEAVY	RAINFALL	POP	REVENUE	COST_REC	LOCATION	PROX_AGR	PROX_HEAVY
Description	*Percentage of treated effluent recycled for agricultural use*	*Percentage of treated effluent recycled for heavy use*	*Average rainfall within the utility boundary*	*Average population density within the utility boundary*	*Revenue per property for water supply services*	*Full cost recovery of water supply and sewerage assets?*	*Does any of the utility boundary intersect with the coastline?*	*Percentage of the utility operating region occupied by irrigated agriculture*	*Percentage of the utility operating region occupied by heavy industry*
Units	*% recycled*	*% recycled*	*mm/year*	*people/km*^{2}	*$/property*			*% land use*	*% land use*
Goulburn	82.87	6.88	914	7	777	Yes	inland	0.42	0.98
Tamworth	66.11	-	977	4	891	Yes	inland	0.74	0.21
Albury	50.84	-	904	174	438	No	inland	2.03	5.23
Dubbo	45.05	-	821	10	740	Yes	inland	1.48	0.78
Shoalhaven	7.87	0.45	1317	21	447	Yes	coastal	1.23	1.62
Coffs	4.86	1.15	2109	58	718	Yes	coastal	0.53	1.60
Byron	4.21	11.48	2206	52	678	Yes	coastal	0.35	1.87
Midcoast	3.61	-	1423	8	644	No	coastal	0.16	0.27
Hunter	3.50	2.03	1294	86	490	Yes	coastal	1.54	3.03
Bega	3.33	17.67	1243	5	738	Yes	coastal	1.04	0.36
Portmac	2.07	0.97	1703	22	711	Yes	coastal	0.23	0.42
SydneyWC	0.90	1.68	1315	401	657	Yes	coastal	1.49	8.33
Tweed	0.56	3.91	2206	60	673	Yes	coastal	1.17	1.93
Orange	-	49.34	976	141	761	Yes	inland	1.62	6.13
Essential	-	25.63	477	110	1325	No	inland	0.19	10.09
Clarence	-	3.27	1415	4	554	No	coastal	0.09	0.34
Eurobodalla	-	2.34	1208	11	629	Yes	coastal	0.43	0.53
Ballina	-	2.19	2121	76	626	No	coastal	0.48	3.00
Wyong	-	1.85	1606	197	660	No	coastal	0.62	5.01
Wingecarribee	-	0.72	1224	15	544	Yes	inland	1.06	0.81
Gosford	-	0.08	1570	174	486	No	coastal	0.47	2.79
Bathurst	-	-	963	9	651	Yes	inland	0.55	0.39
Kempsey	-	-	1546	7	645	No	coastal	0.27	0.32
Lismore	-	-	1796	23	639	No	inland	1.12	0.90
Queanbeyan	-	-	956	205	808	No	inland	-	4.48

Table 3. Thresholds used to scale the input data into fuzzy-sets prior to fsQCA analysis. Values in this table are rounded to 2 decimal places. *A value slightly below the median (median – 0.0001) was used as the crossover point.

	Threshold for full non-membership (fuzzy set value of 0)	*Cross-over point (fuzzy set value of 0.5)*	*Threshold for full membership (fuzzy set value of 1)*
REC_AGR	0% recycled	Mean of all non-zero values (21.21%)	30% recycled
REC_HEAVY	0% recycled	Mean of all non-zero values (7.74%)	30% recycled
RAINFALL	25% Quantile of the dataset (975.90 mm/year)	Median* of all values (1314.95 mm/year)	75% Quantile of the dataset (1606.38 mm/year)
POP	25% Quantile of the dataset (8.67 people/km^2)	Median* of all values (23.30 people/km^2)	75% Quantile of the dataset (110.39 people/km^2)
PROX_AGR	25% Quantile of the dataset (0.35%)	Median* of all values (0.54%)	75% Quantile of the dataset (1.1%)
PROX_HEAVY	25% Quantile of the dataset (0.42%)	Median* of all values (1.60%)	75% Quantile of the dataset (3.00%)
REVENUE	25% Quantile of the dataset (626.00 \$/property)	Median* of all values (657.00 \$/property)	75% Quantile of the dataset (738.00 \$/property)
COST_REC	Full cost recovery *not* achieved in 2011/12 for both water supply and sewerage		Full cost recovery achieved in 2011/12 for both water supply and sewerage
LOCATION	Inland		Coastal

Table 4. Necessary conditions meeting the specified consistency (0.8) and coverage (0.3) thresholds for the presence of agricultural recycling (REC_AGR) and the presence of heavy recycling (REC_HEAVY).

Outcome	***Necessary condition***	***Consistency***	***Coverage***
REC_AGR	~RAINFALL LOCATION	0.908 0.807	0.400 0.430
REC_HEAVY	REVENUE	0.886	0.389

Table 5. Sufficient conditions leading to the presence of agricultural recycling (REC_AGR). Solution consistency (/coverage) indicates the combined consistency (/coverage) of the two alternative configurations.

	Consistency	**Coverage**	**Cases covered**
~RAINFALL*~POP*REVENUE*COST_REC*LOCATION	0.904	0.548	Goulburn; Dubbo; Tamworth
~RAINFALL*POP*~REVENUE*~COST_REC*LOCATION *PROX_AGR	1.000	0.184	Albury
Solution consistency 0.926 Solution coverage 0.732			

Table 6. Sufficient conditions leading to the presence of heavy recycling (REC_HEAVY). Solution consistency (/coverage) indicates the combined consistency (/coverage) of the two alternative configurations.

	Consistency	**Coverage**	**Cases covered**
~RAINFALL*POP*REVENUE*COST_REC*LOCATION *PROX_HEAVY	0.988	0.208	Orange
~RAINFALL*~POP*REVENUE*COST_REC*~LOCATION* ~PROX_HEAVY	1.000	0.139	Bega
Solution consistency 0.993 Solution coverage 0.346			

ASSOCIATED CONTENT

Supporting Information. Table S1: Assumptions made in identifying the operating regions of the case study utilities; Table S2: Categories of recycled water use; Table S3: Quantification of factors; Table S4: Truth table for the outcome percentage of water recycled for agricultural use (REC_AGR); Table S5: Truth table for the outcome percentage of water recycled for heavy use (REC_HEAVY); Table S6: Conditions used to test the sensitivity of the outcome percentage of water recycled for agricultural use (REC_AGR) to thresholds and scaling function; Table S7: Conditions used to test the sensitivity of the outcome percentage of water recycled for heavy use (REC_HEAVY) to thresholds and scaling function; Table S8: Results of sensitivity analysis for REC_AGR; Table S9: Results of sensitivity analysis for REC_HEAVY.

AUTHOR INFORMATION

Corresponding Author

* Phone: +41 58 765 6855; email: nadja.kunz@eawag.ch

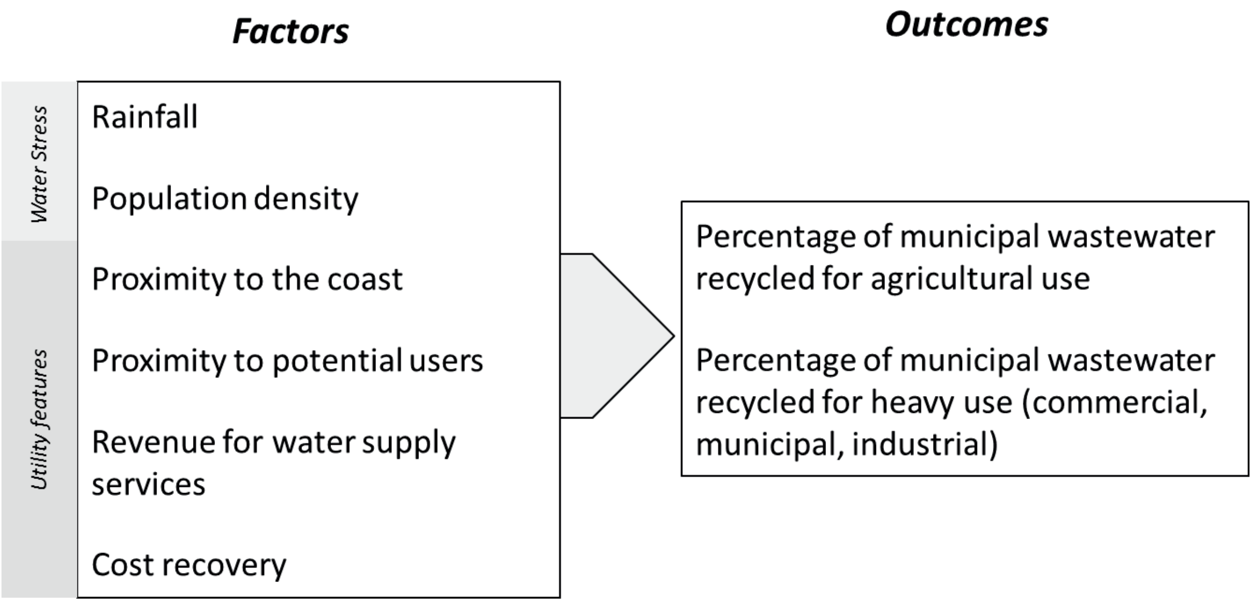
Funding Sources

This work was supported by internal project funding from Eawag.

ACKNOWLEDGMENT

We are grateful to the many individuals who shared their expert insights and thoughtful feedback during this research project. In particular, we thank John Radcliffe, Steve Kenway, and Heather Bischel for their feedback on the theoretical framework which guided the analysis. We also acknowledge the anonymous reviewers for their valuable comments on an earlier version of this manuscript.

TABLE OF CONTENTS GRAPHIC AND SYNOPSIS



REFERENCES

1. Perrone, D.; Murphy, J.; Hornberger, G. M., Gaining perspective on the water-energy nexus at the community scale. *Environmental science & technology* **2011,** *45*, (10), 4228-34.

2. Asano, T., Urban water recycling. *Water science and technology : a journal of the International Association on Water Pollution Research* **2005,** *51*, (8), 83-9.

3. Asano, T.; Bahri, A. In *Global challenges to wastewater reclamation and reuse*, On the Water Front: Selections from the 2010 World Water Week in Stockholm, Stockholm, 2010; Lundqvist, J., Ed. Stockholm International Water Institute (SIWI): Stockholm, 2010.

4. Mo, W.; Zhang, Q., Energy-nutrients-water nexus: Integrated resource recovery in municipal wastewater treatment plants. *Journal of environmental management* **2013,** *127*, 255-67.

5. Hochstrat, R.; Wintgens, T.; Kazner, C.; Melin, T.; Gebel, J., Options for water scarcity and drought management-the role of desalination. *Desalination and Water Treatment* **2010,** *18*, (1-3), 96-102.

6. Yüce, S.; Kazner, C.; Hochstrat, R.; Wintgens, T.; Melin, T., Water reuse versus seawater desalination - evaluation of the economic and environmental viability. In *Water-Energy Interactions of Water Reuse*, Lazarova, V.; Choo, K.; Cornel, P., Eds. IWA Publishing: 2012; pp 243-256.

7. Radcliffe, J. C., Evolution of water recycling in Australian cities since 2003. *Water Science and Technology* **2010,** *62*, (4), 792-802.

8. Marsden Jacob Associates *National snapshot of current and planned water recycling and reuse rates*; Final Report prepared for the Department of the Environment, Water, Heritage and the Arts: Melbourne, 2008.

9. Bischel, H. N.; Simon, G. L.; Frisby, T. M.; Luthy, R. G., Management Experiences and Trends for Water Reuse Implementation in Northern California. *Environmental Science & Technology* **2012,** *46*, (1), 180-188.

10. NWC WSAA and the NWI parties *National performance report 2011-12: Urban water utilities*; The National Water Commission the Water Services Association of Australia and the NWI parties,: Canberra, 2013.

11. Hochstrat, R.; Wintgens, T.; Melin, T.; Jeffrey, P., Assessing the European wastewater reclamation and reuse potential — a scenario analysis. *Desalination* **2006,** *188*, (1–3), 1-8.

12. Chang, D.; Ma, Z.; Wang, X., Framework of wastewater reclamation and reuse policies (WRRPs) in China: Comparative analysis across levels and areas. *Environmental Science & Policy* **2013,** *33*, (0), 41-52.

13. Arbon, M.; Ireland, M., Water recycling: a major new initiative for Melbourne - crucial for a sustainable future. *Water Science and Technology* **2003,** *47*, (7-8), 57-63.

14. Barbagallo, S.; Cirelli, G. L.; Indelicato, S., Wastewater reuse in Italy. *Water science and technology : a journal of the International Association on Water Pollution Research* **2001,** *43*, (10), 43-50.

15. Chanan, A.; Vigneswaran, S.; Kandasamy, J., Valuing stormwater, rainwater and wastewater in the soft path for water management: Australian case studies. *Water Science and Technology* **2010,** *62*, (12), 2854-2861.

16. Giurco, D.; Bossilkov, A.; Patterson, J.; Kazaglis, A., Developing industrial water reuse synergies in Port Melbourne: cost effectiveness, barriers and opportunities. *Journal of Cleaner Production* **2011,** *19*, (8), 867-876.

17. Hermanowicz, S. W.; Diaz, E. S.; Coe, J., Prospects, problems and pitfalls of urban water reuse: a case study. *Water Science and Technology* **2001,** *43*, (10), 9-16.

18. Schneider, C. Q.; Wagemann, C., *Set-Theoretic Methods for the Social Sciences*. Cambridge University Press: United Kingdom, 2012.

19. Fiss, P. C., A set-theoretic approach to organizational configurations. *Academy of Management Review* **2007,** *32*, (4), 1180-1198.

20. Institute for Sustainable Futures *Policy settings, regulatory frameworks and recycled water schemes*; Prepared by the Institute for Sustaianble Futures, University of Technology, Sydney for the Australian Water Recycling Centre of Excellence: 2013.

21. Lazarova, V.; Cirelli, G.; Jeffrey, P.; Salgot, M.; Icekson, N.; Brissaud, F., Enhancement of integrated water management and water reuse in Europe and the Middle East. *Water Science and Technology* **2000,** *42*, (1-2), 193-202.

22. Vis, B., The Comparative Advantages of fsQCA and Regression Analysis for Moderately Large-N Analyses. *Sociological Methods & Research* **2012,** *41*, (1), 168-198.

23. Thiem, A.; Baumgartner, M.; Bol, D., Still Lost in Translation! A Correction of Three Misunderstandings Between Configurational Comparativists and Regressional Analysts. *Comparative Political Studies* **2015**, 1-33.

24. Rihoux, B.; Álamos-Concha, P.; Bol, D.; Marx, A.; Rezsöhazy, I., From niche to mainstream method? A comprehensive mapping of QCA applications in journal articles from 1984 to 2011. *Political Research Quarterly* **2013,** *66*, (1), 175-184.

25. Fischer, M., Institutions and coalitions in policy processes: a cross-sectoral comparison. *Journal of Public Policy* **2014,** *FirstView*, 1-24.

26. Basurto, X., Linking multi-level governance to local common-pool resource theory using fuzzy-set qualitative comparative analysis: Insights from twenty years of biodiversity conservation in Costa Rica. *Global Environmental Change* **2013,** *23*, (3), 573-587.

27. Srinivasan, V.; Lambin, E. F.; Gorelick, S. M.; Thompson, B. H.; Rozelle, S., The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. *Water Resources Research* **2012,** *48*.

28. Radcliffe, J. C., Future directions for water recycling in Australia. *Desalination* **2006,** *187*, (1-3), 77-87.

29. Marsden Jacob Associates *Progress against the national target of 30% of Australia's wastewater being recycled by 2015*; Department of Sustainability, Environment, Water, Population and Communities,: Canberra, Australia, 2012.

30. Bixio, D.; Thoeye, C.; De Koning, J.; Joksimovic, D.; Savic, D.; Wintgens, T.; Melin, T., Wastewater reuse in Europe. *Desalination* **2006,** *187*, (1–3), 89-101.

31. Apostolidis, N.; Hertle, C.; Young, R., Water Recycling in Australia. *Water* **2011,** *3*, (3), 869-881.

32. Anderson, J. M., The potential for water recycling in Australia — expanding our horizons. *Desalination* **1996,** *106*, (1–3), 151-156.

33. Arbon, M.; Ireland, M., Water recycling: a major new initiative for Melbourne--crucial for a sustainable future. *Water science and technology : a journal of the International Association on Water Pollution Research* **2003,** *47*, (7-8), 57-63.

34. Ferguson, B. C.; Brown, R. R.; Frantzeskaki, N.; de Haan, F. J.; Deletic, A., The enabling institutional context for integrated water management: Lessons from Melbourne. *Water Research* **2013,** *47*, (20), 7300-7314.

35. Institute for Sustainable Futures *Wagga Wagga Case Study; Building Industry Capability to Make Recycled Water Investment Decisions*; Prepared by the Institute for Sustainable Futures, University of Technology, Sydney for the Australian Water Recycling Centre of Excellence: 2013.

36. Berg-Schlosser, D.; De Meur, G., Comparative research design: Case and variable selection. In *Configurational comparative methods: Qualitative comparative analysis (QCA) and related techniques*, Rihoux, B.; Ragin, C. C., Eds. Sage Publications, Inc.: United States of America, 2009.

37. Boons, F.; Spekkink, W.; Mouzakitis, Y., The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review. *Journal of Cleaner Production* **2011,** *19*, (9–10), 905-911.

38. Benz, A., Two types of multi-level governance: Intergovernmental relations in german and EU regional policy. *Regional & Federal Studies* **2009,** *10*, (3), 21-44.

39. Dillon, P. J., Water reuse in Australia: Current Status, Projections and Research. In *Water Recycling Australia 2000*, Adelaide, 2000; pp 99-104.

40. Hochstrat, R.; Wintgens, T.; Melin, T., Development of integrated water reuse strategies. *Desalination* **2008,** *218*, (1–3), 208-217.

41. Wakelin, S. A.; Colloff, M. J.; Kookana, R. S., Effect of Wastewater Treatment Plant Effluent on Microbial Function and Community Structure in the Sediment of a Freshwater Stream with Variable Seasonal Flow. *Applied and Environmental Microbiology* **2008,** *74*, (9), 2659-2668.

42. Khan, S. J.; Shaefer, A.; Sherman, P., Impediments to municipal water recycling in Australia. *Water* **2004**, 114-124.

43. Chong, J., Climate-readiness, competition and sustainability: An analysis of the legal and regulatory frameworks for providing water services in Sydney. *Water Policy* **2013,** *16*, 1-18.

44. Kaminsky, J. A.; Javernick-Will, A. N., The Internal Social Sustainability of Sanitation Infrastructure. *Environmental Science & Technology* **2014,** *48*, (17), 10028-10035.

45. Australian Bureau of Statistics, 1259.0.30.001 - Australian Standard Geographical Classification (ASGC) Digital Boundaries, Australia, July 2011. In Australian Bureau of Statistics, Ed. 2011.

46. ABARES, Catchment scale land use of Australia - Update March 2014. In Department of Agriculture Australian Government, Ed. Canberra,, 2014.

47. Rihoux, B., Qualitative comparative analysis (QCA) and related systematic comparative methods - Recent advances and remaining challenges for social science research. *International Sociology* **2006,** *21*, (5), 679-706.

48. Fischer, M., Social Network Analysis and Qualitative Comparative Analysis: Their mutual benefit for the explanation of policy network structures. *Methodological Innovations Online* **2011,** *6*, (2), 27-51.

49. Rihoux, B.; Ragin, C. C., *Configurational comparative methods: Qualitative comparative analysis (QCA) and related techniques*. Sage Publications, Inc.: United States of America, 2009.

50. Berg-Schlosser, D.; De Meur, G.; Rihoux, B.; Ragin, C. C., Qualitative comparative analysis (QCA) as an approach. In *Configurational comparative methods: Qualitative comparative analysis (QCA) and related techniques*, Rihoux, B.; Ragin, C. C., Eds. Sage Publications, Inc.: United States of America, 2009.

51. Ragin, C. C., Qualitative comparative analysis using fuzzy sets (fsQCA). In *Configurational comparative methods: Qualitative comparative analysis (QCA) and related techniques*, Rihoux, B.; Ragin, C. C., Eds. Sage Publications, Inc.: United States of America, 2009.

52. Scouvart, M.; Adams, R. T.; Caldas, M.; Dale, V.; Mertens, B.; Nedelec, V.; Pacheco, P.; Rihoux, B.; Lambin, E. F., Causes of deforestation in the Brazilian Amazon: a qualitative comparative analysis. *Journal of Land Use Science* **2008,** *2*, (4), 257-282.

53. Ragin, C. C., *Redesigning social inquiry: Fuzzy sets and beyond*. The University of Chicago: Chicago, 2008.

54. Bol, D.; Luppi, F., Confronting Theories Based on Necessary Relations: Making the Best of QCA Possibilities. *Political Research Quarterly* **2013,** *66*, (1), 205-210.

55. Thiem, A.; Dusa, A., *Qualitative Comparative Analysis with R: A User's Guide*. Springer: New York, Heidelberg, Dordrecht, London, 2013.

56. Dusa, A.; Thiem, A. *QCA: A Package for Qualitative Comparative Analysis*, 2014.

57. Thiem, A., Membership Function Sensitivity of Descriptive Statistics in Fuzzy-Set Relations. *International Journal of Social Research Methodology* **2014,** *17*, (6), 625-42.

58. Traves, W. H.; Gardner, E. A.; Dennien, B.; Spiller, D., Towards indirect potable reuse in South East Queensland. *Water Science and Technology* **2008,** *58*, (1), 153-161.

59. Hurlimann, A.; Dolnicar, S., When public opposition defeats alternative water projects - The case of Toowoomba Australia. *Water Research* **2010,** *44*, (1), 287-297.

60. Hurlimann, A., Is recycled water use risky? An Urban Australian community's perspective. *Environmentalist* **2007,** *27*, (1), 83-94.

61. Dolnicar, S.; Schäfer, A. I., Desalinated versus recycled water: Public perceptions and profiles of the accepters. *Journal of Environmental Management* **2009,** *90*, (2), 888-900.

62. Marks, J. S., Taking the public seriously: the case of potable and non potable reuse. *Desalination* **2006,** *187*, (1–3), 137-147.

63. Cash, D. W.; Adger, W.; Berkes, F.; Garden, P.; Lebel, L.; Olsson, P.; Pritchard, L.; Young, O., Scale and cross-scale dynamics: governance and information in a multilevel world. *Ecology and Society* **2006,** *11*, (2), 8.