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Assessing Decentralised Water Solutions: Towards a Framework for Adaptive Learning

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Abstract This paper reports on the use of qualitative analysis to inform a risk analysis framework for decentralised water systems. To realise the benefits from these technologies, a methodology is applied to learn from previous difficulties in implementing and managing them. A workshop process was used to capture stories from industry professionals on difficulties they have encountered in planning and implementation. Qualitative analysis of story narratives revealed stages where there was some type of development process failure; as well as failure modes and factors influencing the difficulties encountered. The analysis also generated insights: difficulties in one part of the development process tends to propagate to subsequent stages; system difficulties most often occurred in the policy stage of development due to institutional inertia and lack of adaptive governance; and the best indicator of problems with a decentralised system was complaints of poor water quality. Furthermore, this paper also provides a method to learn from past difficulties by identifying what data needs to be collected in order to populate a risk model which can be used for improving risk assessment of the development process for decentralised systems. This can provide a basis for better decision making, policy and guidelines; an important factor in mainstream acceptance.

Keywords Risk analysis · Qualitative research · Decentralised water systems · Integrated urban water management · Greenfield developments

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1 Introduction

Decentralised water systems are emerging as an important complement to centralised water services in Australian cities (Tjandraatmadja et al. 2005). Benefits of decentralised systems include: "reduced costs and resource use; improved service security and reduced risk of failure; strengthening of local economies and community wellbeing; regenerating and protecting the natural environment" (Biggs et al. 2009). In Australia, there is evidence that decentralised systems, such as greywater reuse, can help cities to reduce reliance on traditional water sources, which are under stress (Zhang et al. 2009). Decentralised systems are also responding to community expectations to consider social and environmental impacts in the choice of water servicing options (Sharma et al. 2009). There is a range of social dimensions involved in providing these types of systems (Moglia and Sharma 2009)

For this paper, the use of the term decentralised systems refers to systems that provide for water, wastewater and stormwater recycling at the local scale. The scale of the decentralised systems can range from individual lots to systems servicing a cluster of dwelling or a whole suburb. Alternative local water sources—such as rainwater, stormwater and recycled wastewater—are used in decentralised systems on a fit for purpose basis where the quality of potential water source is matched to the quality requirements of an application. Decentralised systems can operate as standalone systems, or as a satellite system that integrates with centralised services (Gikas and Tchobanoglous 2009).

Failure of these systems, for the purposes of this paper, is defined as *a situation where the used system does not perform to an adequate standard*. The definition is vague because there are many different aspects that determine whether a system performs adequately. Those various aspects concern partial performance goals, and failure to reach partial performance goals are referred to as partial failures, or failure modes. As such failure can be partial (some performance goals not reached) or complete (no performance goals reached). The partial failure modes (relating to partial performance goals) are determined in this study.

Decision-makers are faced with a range of knowledge gaps in planning and implementing decentralised water systems. Mitchell et al. (2008) identifies the critical determinants for the success or failure of decentralised systems. The critical determinants relate to the institutional arrangements—including the formal and informal processes, policies, regulations and industry norms that govern decentralised systems planning and implementation. In the case of conventional centralised water systems these institutional arrangements are founded on more than a century of practice, which means that guidelines are mature and protocols well established. Conventional urban water systems represent a large stable area of practice and expertise that requires significant impetus to change (Brown and Farrelly 2009a).

Decentralised water systems are relatively untried in cities compared to centralised systems with limited understanding of ongoing management requirements and operation under dispersed accountabilities (Brown et al. 2009a). The lack of knowledge around the long term performance of decentralised systems relates to issues such as: long term reliability, operation and maintenance costs, interactions with centralised systems, appropriate costing, and adequate governance and guidelines. These knowledge gaps impede mainstream acceptance of decentralised systems. Acceptance is required to overcome the institutional and social inertia to change the standard frameworks and practices for managing urban water systems (Brown and Farrelly 2009b; Brown et al. 2009b).

Knowledge gaps regarding decentralised systems are in some cases not so much a lack of fundamental understanding but that knowledge can be esoteric and not broadly disseminated in the urban water sector. Major actors in the urban water sector include—developers, water utilities, local councils and private consultants (Mitchell et al. 2008). Major actors, in many cases, lack experience in decentralised water services (Burkhard et al. 2000). A lack of practical experience within institutions may retard the uptake of decentralised approaches (Livingston et al. 2006). Actors are likely to be averse to change in water services if they do not understand the likelihood and consequences of failure and difficulties in the development process. The broad dissemination of historical insights on issues confronted in implementing and operating these decentralised systems can assist in informing risk analysis (Hurlimann and Dolnicar 2009).

It appears that the risks involved with these new systems are relatively poorly understood, and there is a real need for better incorporating these into policy, guidelines, decision making and planning. The risks associated with decentralised systems are entwined with the site specific context of each system. The design and planning of decentralised systems responds to the opportunities and limitations presented by the locality meaning that care needs to be undertaken in generalising understanding drawn from a single example. This highlights the need to expend effort in investigating a multitude of developments and contexts in developing a risk analysis framework for decentralised systems.

Qualitative analysis has been widely used in informing the development of risk analysis tools, as it can help in understanding and managing the complexity associated with risk assessment and analysis. Reid (1999) highlights some of the benefits of qualitative approaches to risk analysis and risk communication compared to more quantitative approaches. These include helping to breakdown the differences in understanding and experience between experts and non-experts, and allowing for intuitive perceptions of risk that consider the socio-political context (Reid 1999). Lyons and Skitmore (2004) used surveys to understand perceptions of risk management in the construction industry whilst Carr and Tah (2001) defined risk descriptions using descriptive linguistic variables, and applied fuzzy logic to define the relationships between risk factors and their consequences.

This paper presents and applies a methodology for undertaking qualitative risk analysis of the development process for decentralised water systems. A better understanding of risk associated with the development process for decentralised systems will inform the development of improved frameworks and guidelines for decentralised systems planning and operation. Learning from past experiences can avoid reoccurrence of similar difficulties. Broader dissemination of decentralised systems knowledge and experience can engender greater confidence in the urban water sector for their planning and implementation.

The study that is described in this paper is staged, in that it first draws on a workshop involving experts in the field and thus generating qualitative data representing the mental models of these experts; secondly applies qualitative analysis of this data in order to define a structure of cause and effect within a risk model; thirdly evaluates a set of case studies against this risk model; and fourthly evaluates statistically whether the cause and effect links can be statistically verified. Finally, the paper provides a discussion about how this work can be taken forward via more structured and rigorous data collection on case studies; which will allow for the formulation of a quantitative risk analysis model. This in turn ought to help policy makers, decision makers and planners to better take the risks of decentralised systems into consideration. In other words, this paper provides a foundation for learning about systemic risk in decentralised water systems.

2 Methodology

The methodology seeks to learn from the past by understanding the specific context of a decentralised system and type of complications encountered in their implementation and planning. Tacit knowledge of difficulties in decentralised system development process, held by experienced water professionals, is elicited through qualitative processes. Particular focus is on difficulties or failures in the development process of these innovative technologies.

Interviews and workshops were used to elicit expert knowledge needed to inform the risk analysis. The information obtained from these processes, in the form of narratives or stories, was revealed by qualitative analysis software—Qualrus (Idea Works 2009). Inspiration for the analysis and the choice of software is from a study which applies a similar approach to specify ontologies representing the collective elicited mental models of stakeholders, in order to design an Agent based model (Dray et al. 2006). Qualrus uses strategies founded upon case-based reasoning, natural language generation, semantic networks and production rules to assist researchers when analysing and coding qualitative texts.

The qualitative analysis in this paper has been structured in order to allow for quantitative analysis in the future. The aim of the analysis was to define the structure of a Bayesian Network model similar to that described by Moglia et al. (2009). This involves identifying the process failure modes (partial failures relating to specific performance goals) and risk factors as well as the causal links between these, but omits consideration of feedback loops. A grounded theory approach is taken in the sense that transcripts are coded, generating qualitative data, and from this concepts are extracted, marked and classified in an iterative fashion as the theory sharpens (Glaser and Strauss 1967; Kelle 2005). In line with this approach, we have also followed a sequence of steps as follows: collect and analyse data; develop theory or hypotheses on the basis of coding and categorising; and finally read literature and consult wider professional community to explain findings. This is contrary to the conventional approach that follows the process of reviewing literature, formulating hypotheses, collecting data, and testing hypotheses with data. The specific steps applied in the methodology were:

1. Water sector professionals were invited to a workshop to share stories of difficulties and failures in the development process, which were recorded;
2. Transcripts were derived from the elicited stories;
3. Qualitative analysis was used in order to identify the:
    a. Stages of the process
    b. Failure modes and factors that contribute to the potential for difficulties

4. Case study mapping:
   a. A number of case studies were mapped against the identified process failure modes to allow for further analysis
5. Statistical evaluation of cause-and effect linkages: a
   a. An analysis of the frequencies, correlations and patterns of process failures and difficulties in the case study data was undertaken.
   b. A statistical analysis was applied, by setting up hypothesis tests, to evaluate the presence and strength of causal links; allowing for the formulation of a model.

3 Results

The next few sections will describe the application of this methodology, with related discussion. This includes a description of the initial knowledge elicitation from a workshop setting; as well as the qualitative analysis of this data. It also includes a mapping of a number of case studies against the model that is identified on the basis of this qualitative analysis.

3.1 Initial Knowledge Elicitation

Nine individuals were invited to a workshop to explore the social dimension of decentralised water systems and share stories relating to the failure in the development process of decentralised water systems. These individuals were engineers, planners, social scientists and systems analysts with experience in the area. In the session for eliciting stories of failed developments, the facilitator asked the participants to share stories within a group setting on the topic of 'failure stories around decentralised water systems' relating to Greenfield developments. Specifically it was said that stories would be used to identify the failures and difficulties that occur in these developments—where failure, as above, was defined as a situation where at least one key actor is unhappy with the system. Further instructions were to tell the stories in a way that identifies the type of actors involved, as well as the key events and decisions—with less focus on personal judgments. Whilst each story was initiated and told by one person at a time, other participants also contributed with their views and observations—providing sense-checking. Fourteen stories were elicited relating to a range of circumstances, technologies and difficulties with decentralised systems. The session was recorded for subsequent analysis and Table 1 describes the main features of decentralised systems referred to in the stories; including a synopsis of the narrative.

3.2 Qualitative Analysis: Stages of the Process

After going through the narratives that were provided in the workshop, it was clear that perceived failures are diverse in nature. These perceived failures also relate to very different steps in the delivery of the water system. As such, there is a need to further break down the delivery of a water system into discrete steps, to allow for

Table 1 Decentralised system case narratives: an overview

Story title	Development type	Decentralised system/s employed	Narrative synopsis
The world according to a social scientist	Stormwater harvesting	Rainwater harvesting (RH) and greywater recycling (GR)	Difficulties in development of policy due to institutional inertia etc.
What do we do with this pricing model?	Redevelopment of townhouses	RH, GR and Local treatment (LT)	Inappropriate pricing from the user perspective due to water utility one-fits-all pricing models
The developer's perspective	Peri-urban house water supply	RH and stormwater harvesting (SH)	Maintenance related difficulties in transferring solution to new owner
Financial hardship	Greenfield development	RH, GR, LT and SH	Development company failing because of poor marketing
A concept ahead of its time	Multi-unit development	RH, LT and SH	Poor consideration of operators when choosing technology leaving operators feeling hard-done-by
Industry capacity for change	Multi-unit development	RH, GT, Water Sensitive Urban Design (WSUD)	Contractors resistant to the implementation of designs that they are not used to
Barriers to change	University re-development	GT, LT	Resistance towards solutions from several actors threatening the decision to implement
Smelly Patio	Eco-villages	GT	Poor choice of technology for urine separation creating smell and disturbance
The enthusiastic handyman	Urban water conservation	RH, GT	Illegal and dangerous plumbing for recycling of greywater
Bureaucracy stifles innovation	Greenfield development	Third pipe system	Water utility so departmentalised that it has difficulties coping with cross-cutting solutions
Bend	Eco-villages	RH	Fire fighting requirements difficult to fulfil with fully decentralised solutions
Scary social survey	Greenfield development	RH, GR	Users unhappy with developers due to poor performance and maintenance issues
Train the user	Commercial user re-development	LT	User publicly and obviously not following basic health and safety procedures
Poor maintenance	Town household-development	LT	Urban myths leading to poor maintenance and health and safety breaches

further categorisation. On the basis of grounded theory methodology (Glaser and Strauss 1967; Kelle 2005), the model is generated from the data on the basis of the researchers' interpretations of the data. In line with this approach, concepts or events (Implicit markers in Table 2) were extracted from the texts and grouped into similar categories (Explicitly mentioned stages in Table 2) on the basis of those categories of sequences of events that were already mentioned by participants. On the basis of this analysis, the delivery process for decentralised systems has been disaggregated to the following stages: policy, decision, planning, implementation, operation and maintenance, and transfer of ownership. These stages relate to critical temporal and process elements in the development of a decentralised system.

Analysis and coding of the story transcripts was undertaken to identify the stages of the process where failure in the development process of decentralised system occurred. For many transcripts, the development stages were not explicitly mentioned, but were implicit in the language being used; i.e. relating to processes. Table 2 shows the explicit temporal stages of the development process mentioned, as well as words that imply a certain stage in the process; and the titles of stories that relate to them. Unfortunately transcripts for the stories cannot be reproduced due to confidentiality limitations. It can be noted in Table 2 that the stories in the third column often appear at multiple stages of the development process. This

Table 2 Stages in the development of decentralised water systems

Explicitly mentioned stages	Implicit markers	Stories relating to this stage
Policy	Business decision	The world according to a social scientist
	White paper	What do we do with this pricing model?
	International review	Bureaucracy stifles innovation
	Pricing model	
Decision	Choice of technology	A concept ahead of its time
	Decision making	Smelly patio
	Reasons	Bend
	Incentives	Industry capacity for change
	Costs	Barriers to change
	Promotion	
Planning	Standards	A concept ahead of its time
	Requirements	Bend
	Solution	Industry capacity for change
	Design	Bureaucracy stifles innovation
		Barriers to change
Implementation	Install	The enthusiastic handyman
	Develop land	Train the user
	Project	Financial hardship
	Training of user	Industry capacity for change
	Setting up	Barriers to change
	Putting systems on line	
Operation and maintenance	Ownership	A concept ahead of its time
	Using water	Poor maintenance
	Monitor	The enthusiastic handyman
	Pumping	Train the user
		Scary social survey
Transfer of operator	Selling property	Developers perspective

is due to the complexity of the process to implement decentralised systems, and interdependencies between different stages.

3.3 Qualitative Analysis: Process Failure Modes

For each stage of the development process, shown in Table 2, there are a number of modes in which failures or difficulties can occur within the development process. To identify process failure modes occurrences of negative language were extracted from the story transcript (Table 3). This step is more subjective, and therefore there is inherent uncertainty that the elicited data captures the full range of failure modes as are perceived by the expert who provided the narrative.

Based on the extracted process failure modes, and knowledge of the actual stories, a number of categories of failure/difficulty types were derived, as shown in Table 4. In this table, each failure mode (partial failures) was linked to the process stage that it related to in the case study narratives. There are interactions between the various stages; with failure in a previous stage often leading to difficulties in a subsequent stage. For example, lack of consideration of operators in the decision, or planning stages tends to lead to difficulties in the O&M stage. The process failure modes are further described in the sections below.

Some of these modes (partial failures) require some further explanation:

- *Bureaucracy barriers* are where the regulatory and institutional framework, designed to support conventional approaches, impedes decentralised approaches. For example, the fragmented nature of policies and organisations dealing with different sections of the urban water cycle can act as a barrier to integrated approaches, such as wastewater recycling
- *Perverse incentives* promote behaviours and choices that have unexpected and undesirable impacts on the system (against the interest of the incentive makers). For example, these incentives may price out decentralised systems when in fact they reduce the cost for the water utility. Similarly, setting the price of water below its true value may act to encourage inefficient water use;
- *Lack of adaptive governance* refers to where guidelines and regulations fail to change to meet emerging needs and opportunities and the inadequate translation of lessons learnt from demonstration projects and previous experiences into functional policies and guidelines. The regulatory framework can, in many cases, lag behind current best practice in urban water management;
- *Design adherence* failure mode refers to situations where the contractor or subcontractor fails to implement the design to specifications;
- *Communication and training* refers to the fact that these technologies are relatively novel in the contexts and hence the management of these systems is, at least not currently, part of mainstream knowledge and practice. Therefore, in many cases the communication and training strategies required to implement decentralised approaches successfully are lacking;
- *Unhappy operators* refers to situations where systems are functional but their operators (which may be for example home owners, water company or contractor) are, for various reasons, unhappy having been assigned the role that has

Table 3 Negative language extracted from stories of process failure

Story title	Negative language extracted from narratives
The world according to a social scientist	Institutional failure
	Squabbles between local government, state and utilities
	Petty power struggles
	Nothing ever happened after; nothing has ever happened since
	There has still been no reform
What do we do with this pricing model?	We just didn't know how to price/bill them
	Its been damned hard for the organisation
	High level strategic decisions that has implications for the business if not the industry
The developer's perspective	Did not appreciate the wonderful design
	Pump has burnt out
	Legally responsible for the repair costs
	Small-claims court
Financial hardship	Marketing was not done so well
	Development company actually went broke
	Systems have not yet been all put on line
A concept ahead of its time	There just isn't buy-in from the people that have the ownership at the moment
	They feel hard-done-by because it was passed on to them
	It wasn't their decision making
	It costs too much
	Had to spend heaps of money in terms of upgrading the treatment facilities
Industry capacity for change	Developer baulked at the costs involved and backed away
	That's not the way you do these buildings
	Constant history of these things not happening in the way they were supposed to
	Contractors didn't come to grips with the fact that this was different
Barriers to change	Opposition came from the plumbers and the engineers who said it was really stupid
	Council objected to the fact that it might be spillage and pollution
	Said it was going to be expensive
Smelly Patio	Wrong material had been chosen
	Wrong choice of technology for that solution
	Odour problems
The enthusiastic handyman	That is illegal and also potentially quite dangerous
	Odour problems with the neighbours
Bureaucracy stifles innovation	There was nowhere in the box for him to fill out
	Problem just didn't go away
	A business decision that we haven't got no choice
Bend	The city said no you can't do that
	A solution forced on them by the bureaucracy
Scary social survey	Rainwater is yellow [ed. note: due to leaf litter in rainwater tank]
	Abusing the developer
Train the user	No one died but it was just an interesting example of user error
Poor maintenance	Maintenance failure
	Health and safety concerns

Table 4 Process failure modes of each process stage

Policy	Decision	Planning	Implementing	O&M	Transfer
Bureaucracy barriers	Inappropriate technology	Inappropriate requirements	Design adherence	Unhappy operator	Unhappy operator
Perverse incentives	Institutional acceptance	Consideration of operators	Financial hardship	Health and Safety incidents	Health and Safety incidents
Lack of adaptation	Community acceptance	Consideration of context	Communication/ training	Technology breakdown	Technology breakdown
				Water quality concerns: odour, taste, colour	Water quality concerns: odour, taste, colour
				Pollution	Pollution
					Litigation

been given to them; either because of cost-implications, operational problems, or because it is outside their usual modus operandi;

- *Pollution* refers to waterborne contaminants getting into the surrounding environment;
- *Water quality concerns: odour, taste, colour* refers to concerns being raised about the water supplied to users in terms of its intended uses;
- *Risk of litigation* refers to when things go wrong and the new operator blames the original developer of the decentralised system for not providing sufficient guidance and information.

3.4 Qualitative Analysis: Influencing Factors

Factors influencing the failure in the development process of decentralised systems were extracted from the story transcripts. A range of factors influencing risk of difficulties were identified, as shown for each of the development stages in Table 5. The qualitative data generated at the workshop serves as a starting point for defining the cause and effect relationships in the risk model. Influencing factors will be further explored, sense-checked as our method is developed and applied.

Influencing factors that require further explanation for clarity are discussed below:

- *Institutional inertia* relates to entrenched behaviours, expertise, values and leadership which create inertia in the uptake of appropriate solutions;
- *Reputation of technology* may at times precede rational and evidence based reasoning;
- *Contractor and implementer experience* is critical because it influences the chances of whether the system is implemented adequately and as planned;
- *Operator and user related:*
  - *User errors* are common as most of the problems at the O&M stage can be classified as such.. The risk of operator/user errors is greatly enhanced by having users/operators with little experience or understanding;
  - *Unhappy operators* is another relatively common failure mode and encapsulates feelings of being hard-done-by, unhappiness about costs or the effort involved (as it is relatively higher than for other solutions), or a general unhappiness about non-involvement in the original decision making or design. This is encapsulated broadly as the user/operator motivation;
- *Implementation of solutions*:
  - *Project management* is required during implementation and failure in this respect may lead to financial hardship;
  - *Preparing operators*: embedded into the implementation stage is also the transfer of the solution to the operator/user who will need to have a good grasp of roles and responsibilities as well as the operation of the system. To ensure that this happens efficiently, the communication strategy is critical;
- *Transfer of solution to a new operator*: for the single narrative that related to transfer to a new operator, two influencing factors were explicitly mentioned; i.e. firstly
  - *Efficient communication* with the new owner about roles and responsibilities and ensuring adequate understanding of the system; and secondly a
  - *Formal transfer* of roles and responsibilities to minimise the risk of litigation.

Table 5 Influencing factors contributing to the risk of failure in the development process

Stages	Influencing factors				
Policy	Institutional inertia	Institutional power struggles			
Decision	Bureaucratic barriers	Reputation of technology	Knowledge of operators/users	Knowledge of context	
Planning	Engagement style	Knowledge of operators/users	Knowledge of industry standards		
Implementation	Communication strategy	Project management	Contractor/Implementer Experience	Contractor/Implementer Understanding	Contractor/Implementer Motivation
O&M	Roles and responsibilities	Operator Experience	Operator Understanding	Operator Motivation	
Transfer	Communication with New Owner	Transfer of Roles and Responsibilities			

3.5 Case Study Mapping

We would now like to explore and show the type of analysis that can be carried out if there were adequate access to data. For this purpose, a number of case studies were explored on the basis of surveys to professionals. Specifically, these were designed to explore process failure modes and influencing factors in more detail. Nine case studies were analysed from two key sources: (1) The National Water Commission project reviewed a number of developments that contained the first Australian examples of: recycled wastewater for non-potable uses, stormwater harvesting, onsite greywater treatment and reuse, and integrated urban water management (Tjandraatmadja et al. 2009). The data for seven of these case studies was generated, by filling in a survey, by one of the researchers in that project. (2) Data for two additional case studies was provided by two water professionals by means of filling in a survey. These professionals had been closely involved in a range of aspects of the case studies.

Basic information about the case studies is shown in Table 6. There is no overlap between these new case studies and the case studies previously identified in the initial knowledge elicitation.

3.6 Case Study Analysis

Table 7 shows for the nine case study sites the development stage where difficulties occurred, as judged by professionals. Process failures, in this table, have been scored, via the use of survey forms, as one of the following: (1) historical failure/difficulty—a failure or difficulty in prior stages of decentralised system that has been addressed and resolved; (2) surmountable failure/difficulty—a partial failure (failure mode) that is judged to be expected to be, or has been, overcome; and (3) intractable failure—decentralised system does not provide adequate level of service required and needs major reengineering to address problems. It is acknowledged that there is a level of subjectivity in this scoring approach and that a planned sampling procedure needs to be used to find the judgments of all representative stakeholders.

The scoring exercise was carried out by allowing selected professionals to fill in survey forms that were designed as simple tables to fill in with scores relating to the identified process steps, failure modes and influencing factors. The case studies that

Table 6 Case study information

Case study #	Development style	Technology	Difficult stages
1	Greenfield development	LT; WSUD	I, II, III, IV
2	Urban renewal	LT; RH; SH; WSUD	II, III, IV
3	Multi-unit development	GR	I, II, III, V
4	Greenfield development	LT; SH; WSUD	All
5	Multi-unit development	GR; LT; RH; WSUD	I, II, III, IV, V
6	Greenfield development	SH; WSUD	II, III, IV, V, VI
7	Greenfield development	GR; RH; WSUD	All
8	Greenfield development	LT; RH; SH; WSUD	I, II, III, IV, VI
9	Greenfield development	LT; RH; WSUD	All

The stages referred to in the last column relate to the stage numbering as per the first column in Table 2. Difficulties here mean that the stage was problematic, and this can range from temporary and relatively minor problems, up to persistent and critical difficulties

Table 7 Mapping of process failure modes for case studies

		#1	#2	#3	#4	#5	#6	#7	#8	#9	%	C
Policy	Bureaucracy barriers	3	3				3	3	3	2	67	0.25
	Appropriateness of recommendations			2							11	**0.43**
	Clarity			2							11	**0.43**
Decision	Technology appropriateness			2	3	1	1				44	0.06
	Institutional acceptance	3									11	−0.25
	Community acceptance		3					3	3		33	**0.41**
Planning	Requirements specification	3		2	3			3		3	56	−0.46
	Consideration of operators		2	3	3	2	2			1	67	0.15
	Consideration of context	3	3	1	2	2	2	2	2	1	100	0.09
Implementation	Design adherence			3	3			2	2		44	0.32
	Financial hardship						3				11	**0.43**
	Communication	2	2			3	3	2	2		67	0.26
O&M	Unhappy key actors									3	11	−0.63
	Health and Safety			2					2		22	**0.50**
	Technology breakdown			2		2	2				33	0.34
	Water quality concerns		3	1			3				33	**0.62**
	Pollution			1					3		22	0.37
Transfer	Unhappy key actors							3			11	0.14
	Health and Safety								2		11	0.23
	Technology breakdown					1					11	−0.34
	Water quality concerns		3			2	2				33	0.24
	Pollution										0	N/A
	Litigation										0	N/A
	Sum	14	19	21	14	13	21	18	19	10	N/A	

The last column describes the statistical correlation coefficient (standard definition) between the difficulty score and the sum of the difficulty scores. A correlation rate ranges from −1 to 1, and indicate the strength of a potential linear relationship between the two variables; with 1 indicating a perfect linear relationship, and 0 indicating no relationship at all

were linked to above mentioned National Water Commission project were scored by a researcher who had a key role in this study. The two additional case studies were scored by respective water professionals who had been intimately involved in each one of them (in engineering, quality control and project management). There was no overlap between the case studies here and the decentralised system case narratives that were described in the previous steps.

This exercise of using a survey with professionals provided an example data set, to show the potential of the approach, with difficulty scores assigned to each case study, and indications of presence of failure modes and influencing factors. The last row in the table indicates the sum of the difficulty scores in each stage for each case study; the second last column indicates what percentage of the case studies that the process failure mode was present in; and the last column of the table shows the correlation coefficient between the difficulty score and the sum of the difficulty scores. This last column shows a rough indicator of how much a particular factor contributes to overall difficulty in a case study. A correlation rate ranges from −1 to 1, and indicate the strength of a potential linear relationship between the two variables; with 1 indicating a perfect linear relationship, and 0 indicating no relationship at all.

The most common process failure modes identified in the case studies were: (1) lack of consideration of context in the planning stage (all cases); (2) lack of consideration of operators during the planning stage as well as bureaucracy barriers in the policy stage (67% of cases); (3) inadequate specification of requirements in the planning stage (56% of cases). Poor choice of technology in the decision stage (44% of cases) and poor adherence to design in the implementation stage (44% of cases) were also major contributing factors to problems. Overall, planning appears to be the most critical contributing process step; in terms of difficulties and risk of development failure. Furthermore, whilst in the final stages of operation and maintenance/transfer to a new operator; the major concerns relate to odour, taste and colour (33% of cases) as well as to technology breakdown (33% of cases).

It is noted that process failure and difficulties tend to propagate from one stage to another; however sometimes skipping stage IV (Implementation). This indicates that earlier stages are more critical for shaping the success of decentralised systems. To indicate the overall level of difficulty in each development, we have summed the numbers in each of the case study columns to arrive at the numbers in the last row. Here we can see that case study #3 and #6 (score of 21) and the case studies #2 and #9 (score of 19) relate to very different types of development (see Table 6); indicating that difficulties occur regardless of development style. It is also notable that failure in policy, relating to clarity and appropriateness, shows a relatively high level of correlation (0.43) with difficulties in development. The strongest indicator of difficulties, in terms of what is physically observable, is the failure mode relating to odour, taste and colour in the O&M stage; with a correlation with overall difficulty of 0.62.

Factors influencing decentralised system process failure were analysed to determine the way in which they contribute to failure in each stage. This analysis will inform the development of an influence diagram, i.e. identifying factors contributing to high rates of difficulties; that will be applied in a quantitative analysis via Bayesian Networks. It is also noted that these factors often contribute to different modes of failure within a particular stage. For example the communication strategy factor in the implementation stage obviously impacts mainly on the communication failure mode; whilst the contractor motivation factor mainly impacts on the design adherence failure mode in this stage. For each of the case studies, the factors (as per previous section) have been estimated as *High*, *Medium* or *Low* in terms of their perceived contribution to development process failures (Table 8).

To understand links between risk factors and failure modes and the strength of the links, a hypothesis test was carried out. This evaluated whether each conditional probability is different to its unconditional counterpart; and to evaluate if this difference is statistically significant, the conditional probabilities of level of difficulty j in stage i due to factor k being of strength l are explored:

$$P(X_i = j|Y_k = l) = p_{ijkl} \tag{1}$$

Where j is the level of difficulty (i.e. 1, 2 or 3), i is the stage (i.e. Policy, Decision, Planning, Implementation, Operation & Maintenance or Transfer); and k is the factor (i.e. Institutional inertia etc); and l is the strength (i.e. Low, Medium or High). In other words, the X_i refers to the level of difficulty, j, in stage i; and Y_k refers to the strength level l of factor k. According to probability theory in the case that

Table 8 Mapping of contributing factors for case studies

		#1	#2	#3	#4	#5	#6	#7	#8	#9
Policy	Institutional inertia	H	M	H	L	L	M	H	M	L
	Institutional power struggles	L	L	L	L	L	L	L	L	M
	Adaptive governance	M	L	M	L	L	L	L	L	L
Decision	Bureaucratic barriers	H	M	L	L	L	M	H	M	M
	Reputation of technology	M	M	L	H	M	M	L	H	L
	Knowledge of operators	H	H	H	H	H	H	H	H	L
	Knowledge of context	H	M	H	H	H	M	H	M	H
Planning	Engagement style	L	H	H	L	H	M	M	H	M
	Knowledge of industry standards	H	M	H	H	M	H	H	H	L
	Knowledge of operators	M	H	H	H	H	H	H	M	L
Implementation	Communication strategy	H	H	L	L	H	H	M	H	L
	Project management	L	L	L	H	L	L	H	M	L
	Contractor motivation	M	M	L	L	M	M	L	L	L
	Contractor understanding	M	M	H	H	H	M	H	H	L
	Contractor experience	M	L	H	H	M	L	H	H	L
O&M	Roles and responsibilities	L	M	H	H	M	M	H	H	L
	Operator experience	L	H	H	M	H	H	M	H	L
	Operator understanding	L	M	H	H	L	H	H	H	L
	Operator motivation	L	M	L	L	L	M	L	L	H
Transfer	Communication with new owner	L	H	L	H	H	H	L	H	L
	Transfer of roles and responsibilities	L	M	L	H	H	M	M	M	L

a factor has no influence the conditional probability is equal to the non-conditional probability.

For example, let us estimate and evaluate the conditional probability of *Policy* level failure (level 3) where the strength of *Institutional inertia* is deemed as 'High'. The unconditional probability of high level difficulties is empirically estimated on the basis of all case study mappings as the percentage of the case studies experiencing a high level of *Policy* difficulties, i.e. five out of nine cases (56%). However, when estimating the conditional probability of when there are high levels of *Institutional inertia* (i.e. case study #1, #3 and #8), two of these case studies (case studies #1 and #3) represent a high level of *Policy* difficulty meaning that the estimate of the conditional probability is equal to 2/3 (67%).

With a null hypothesis that the factor has no influence, the number of high level *Policy* difficulties given the high level of *Institutional inertia* can be described using a Binomial distribution, with parameters n (number of cases of high level institutional inertia) and probability p equal to the non-conditional estimated probability of high level difficulties in the policy stage (i.e. 56%). To test whether to reject the null hypothesis we calculate the probability of receiving the results we have, assuming the null hypothesis, and if they are highly unlikely (i.e. less than 5% chance) then we can assume that there is an effect from this particular factor. In this case, the hypothesis test is inconclusive because of not enough data (i.e. even if all three cases of high level of institutional inertia were linked to high levels of policy difficulties, null hypothesis is still not rejected).

The analysis is repeated for the combinations of stages and factors; identifying the potential causal links shown in Table 9. It is also noted that because of our limited data set, there is currently not sufficient data in order to rule out causal links

Table 9 Statistically somehow significant causal links between factors and process failure modes

Factor	Failure mode	*P* value
Policy stage		
Institutional inertia	Bureaucracy barriers	0.17
Appropriateness of recommendations	Adaptive governance	0.22
Decision stage		
Bureaucratic barriers	Technology appropriateness	0.04
Bureaucratic barriers	Institutional acceptance	0.20
Planning stage		
Knowledge of operators	Consideration of operators	0.34
Requirements specification	Knowledge of context (Decision)	0.17
Implementation stage		
Contractor experience	Design adherence	0.22
Contractor understanding	Design adherence	0.12
Contractor motivation	Design adherence	0.12
Project management	Design adherence	0.08
Communication strategy	Communication	0.13
O&M stage		
Operator experience	Water quality concerns	0.20
Operator motivation	Water quality concerns	0.25
Roles and responsibilities	Health and Safety	0.20
Operator experience	Technology breakdown	0.20
Roles and responsibilities	Pollution	0.20
Operator motivation	Unhappy key actors	0.11

The last column of this table refers to the p-value in the hypothesis test, on the basis of Binomial distribution, where a lower value indicates a higher level of significance. As can be seen we are currently unable to achieve great levels of significance (with p values up to 0.34), but it is thought that this is due to the insufficient data rather than due to lack of causal relationships. We also note that in one of the causal relationships, a factor relating to the Decision stage (Knowledge of context) actually has an impact on a failure mode in the Planning stage (Requirements specification). Such possible links have been explored when it has been deemed that there is a reasonable connection between the topics

not identified here. We simply say that it seems plausible that the links in Table 7 represent real causal links.

With the process stages, failure modes and risk factors having been identified; in combination with tentative indications about causal links, we are now ready to specify an influence diagram of what contributes to risk in the development of decentralised water systems; and this is shown in Fig. 1. It is noted that there are no feedback loops in the diagram; and therefore this influence diagram, i.e. a basic model that can be used for qualitative risk assessment, also serves as a starting point for a Bayesian Network model which allows for holistic quantification of risk in the delivery of decentralised water systems.

This exercise shows that it is possible using this method to identify causal links between contributing factors and failure modes in various process stages. Furthermore, we can say something about which contributing factors that are the strongest (i.e. with a lower p-value). However, it is slightly premature to get into that discussion already, because more data is needed to fully make justice to this debate. The next step is to conduct a large scale survey which will allow for understanding these causal links more thoroughly.

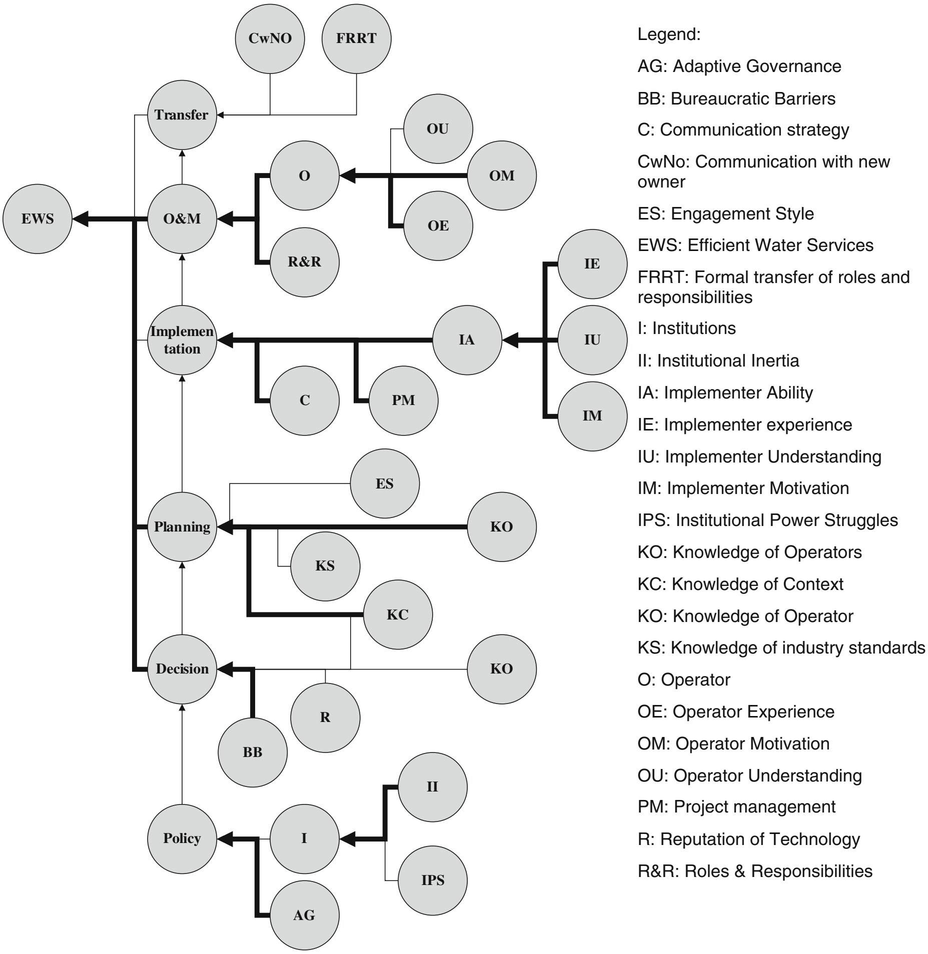

Fig. 1 Cause and effects diagram relating to risk in the provision of decentralised water systems. In this figure, the links that have been shown to be statistically significant are indicated by *thick lines*, whilst those causal links that are only gleaned via qualitative analysis are shown using *thinner lines*

4 Towards Quantitative Risk Assessment

It is noted that with the data used in this study, some causal links are not shown to be statistically significant, but the focus of this paper is on qualitative data, providing a starting point for further data collection and risk analysis. Hence, we believe that this does not necessarily indicate there is no causal link, but instead may be indicative of the limited data available. This paper has established a framework for the collection of data to inform risk assessment of decentralised water systems, with Tables 5 and 6 indicative of the format that data needs to be collected in. This data will allow a user to establish statistically significant causal links between risk factors and process failure modes for decentralised water systems. It will also, perhaps more importantly, establish conditional probabilities that will feed into Bayesian Network modelling, and enable quantitative risk assessment. The steps recommended in taking qualitative information to inform quantitative risk assessment of decentralised water systems are:

1. Formulate surveys of a range of types of stakeholders which will provide information similar to that in Tables 5 and 6;
2. Undertake survey of professionals with a high level of experience and knowledge of case studies using the survey structure specified in step 1;
3. Analyse the information provided by such surveys in order to specify conditional probabilities;
4. Utilise the conditional probabilities and knowledge about the causal links between risk factors and failure modes in order to specify a Bayesian Network model;
5. Use Bayesian Network model to quantitatively assess risk of scenarios, options and strategies, and to formulate policy and guidelines.

Whilst the model that has been developed is based on the mental models of a range of water professionals it is also important, to ensure validity and that models represent a sufficient range of perspectives, that there is on-going interaction with the professional community to ensure a dialogue about the key factors impacting on the chances of successful or failed developments. However, this is an activity which is largely outside of the more academic roles of the authors, and hence future activities would aim to transfer methods and approaches to key stakeholders and to promote this type of dialogue.

5 Innovation Learning and Adaptation

After having developed this methodology, it is clear that the approach can support industry learning by mobilising both the tacit and the formulated knowledge of stakeholders and experts on the basis of their learning-by-doing activities. In this way, a Bayesian Network model for rigorous risk analysis may provide a critical tool within adaptive governance and for accelerated learning on the basis of demonstration projects and action-based learning.

However, it is also acknowledged that the model that has emerged from the data (on the basis of discourse analysis) is linear with a number of subsequent process steps, and hence is a simplification of reality in that it does not describe some of the complexities and learning processes that occur in real life. For example, an innovation perspective, such as the multi-level perspective (Geels 2002, 2010), will provide additional insights. For example, one of the reviewers has pointed out an example where the current model would not adequately describe reality and what would be described in the model as a failure has in fact been an example of learning:

> One can thinks of a case where an insufficient knowledge of the context, would lead of some kind of requirements specifications during the “decision process”, that would be “corrected” during the implementation phase by a contractor with better knowledge of the context, leading to “design adherence failure” with possible other consequence (negative or positive) for other actors and the functioning of the system etc.

Taking the innovation perspective, the introduction of these novel technologies into new niches (Greenfield developments, eco-villages etc) can be seen as a process of innovation. In line with the thinking of Geels (2010) these are in fact '*green*' innovations in niche developments justified within a larger agenda of 'sustainability'. Characteristically, the introduction of innovative technologies into new niches is not just an engineering task, but also requires consideration of a range of socio-cultural aspects, including institutional and cultural change as well as skills development, in order for these systems to fit within their new niches (Kemp 1994). In fact, Geels (2002) has identified seven dimensions of a socio-technical regime: technology, user practices and markets, symbolic meaning of technology, infrastructure, industry structure, policy and techno-scientific knowledge. These dimensions are linked and co-evolve but each dimension has internal dynamics. Transition from a niche technology to a mainstream technology involves a dynamic interplay between all these dimensions.

In order for these technologies to move past their current niches, it is critical that dynamic scale and learning effects are realised in order to reduce costs per unit output and to improve performance (Kemp 1994). Therefore, to effectively go through this process of technological transition it is important to embed learning processes within industry, and these include experimentation, learning processes, adjustments and reconfigurations (Geels 2002). This furthermore involves a collective cognitive learning process which is a cyclic and involves intermittent (Geels 2010): (1) interpretations, cognitions and beliefs, (2) actions, (3) outcomes and experiences, and finally (4) reflection and sense-making. The methodology provided in this paper can support this type of collective learning process.

6 Conclusions

This paper has provided a foundation for learning about systemic risk in decentralised water systems; and has identified its related process stages, failure modes and risk factors. This is critical as decentralised water systems are based on technologies that are relatively untried in the local socio-economic contexts, and require new roles, guidelines and procedures to ensure high performance and reliability. This paper is a step in the direction towards quantitative risk assessment of decentralised water systems; using qualitative data and results. Furthermore, this paper outlines a pathway for a structured collection of qualitative data which will allow for the specification of Bayesian Network model. This is achieved via the surveying of water professionals for their judgments on existing cases and that will allow for hypothesis testing causal links and the specification of conditional probabilities.

Furthermore, throughout the process of developing this model we have made a number of observations on decentralised water systems and their propensity for failure and difficulties in the development process:

- Failure in one stage of the process tends to propagate to the next stage;
- Failure in the policy stage has the greatest correlation with overall difficulty in a development—with institutional inertia and adaptive governance having the greatest influence on the ability to provide efficient policy;
- On the output side, the best indicator of overall difficulty in a development is concerns about odour, taste and/or colour of the water; and with a correlation

of 0.62, a basic survey of community satisfaction with quality may serve as an indicator of difficulties in the development process.

Qualitative analysis has allowed us to elicit the tacit knowledge of decentralised water system experts to understand factors that can influence process failure and identify failure modes. Decentralised water systems are increasingly being embedded into society and rapidly changing, in comparison to conventional water systems that are founded on more than a century of practice and research. This means that experience and knowledge of decentralised systems is held by a limited number of experts. In order to improve risk assessment of decentralised water systems there is the need to draw on the experiences of process failures and difficulties. Understanding how these failures start, where in the development cycle they occur and how they propagate through the lifecycle of a decentralised water system is critical for supporting risk assessment that gives greater confidence in these systems in the broad urban development industry. The qualitative analysis methods applied allowed us to consider the experience, understanding and motivations of different perspectives, such as those planning and designing the systems compared to the operators and contractors who deal directly with the decentralised water system. These different perspectives have been important in understanding process failure as often there is disconnect between those planning the system and those implementing that can result in problems.

Further learning occurs as more data becomes available to populate the framework, allowing for identification of leverage points that could then be used to minimise risk. The potential users of the framework are:

- Policy makers trying to identify control points and better policy;
- Decision makers needing guidance about riskiness of technology options; and
- Planners attempting to improve their consideration of context, operators and necessary processes.

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