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Small town water governance in developing countries: the uncertainty curse

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1. ABSTRACT
Despite well meaning intentions, many aid interventions fail for one reason or another. The reasons are varied: lack of consideration of local circumstances and process requirements, and in particular inadequate involvement of affected stakeholders as well as inadequate cross-sectorial coordination. This is not surprising given poor organizational memory combined with decisions being made under time pressure and strict deadlines combined with little adaptive capacity. Additionally, information about the importance of process requirements and engagement is qualitative and as such is unfortunately often given secondary importance.

To address this, we suggest a Risk assessment component as part of the project design phase based on Bayesian Networks (BNs) utilizing expert and local knowledge. This not only improves organizational memory and transparency but also provides a direct link for assessing cost benefits and minimizing the risk of failure. Most importantly this prioritizes engagement, processes and an understanding of the local context. This paper describes how BNs have been developed and tested on water supply interventions in the town of Tarawa, Kiribati. Models have been populated using data from interviews and literature to evaluate water supply options, i.e. rainwater harvesting, desalination and reserve extensions; this paper reports only on the model relating to reserves extension, i.e. new reserves for protection of groundwater extracted for water distribution purposes.

Keywords: *Bayesian Networks (BNs), Risk assessment, Water aid development*

2. INTRODUCTION
In this paper, we explore the application of BN analysis to a water-related development intervention; exemplified by a case study in a small atoll town in the small Pacific island nation of Kiribati. This method is complementary to methods such as Lifecycle Assessment (LCA), Triple Bottom Line Assessment (TBL) and Multi-Criteria Assessment (MCA) for evaluating water supply options.

2.1. The Case Study context
Tarawa is located in the country of Kiribati which is an island nation in the Pacific Ocean which stretches across the equator, and borders the international dateline. Kiribati is culturally and geographically located in the Pacific region of Micronesia and consists of 33 islands, of which 32 are either coral atolls or coral reef islands. Tarawa lies within the Gilbert Group and geologically it is an atoll island chain, i.e. a string of closely connected sandy islands on a base of coral, with a lagoon in the centre (Jones 1997). Tarawa, the capital of Kiribati, has a population around 46,000 which represents about half of the national population (Kiribati National Statistics Office 2006). Tarawa is administratively divided into South Tarawa and North Tarawa. Whilst the islands of North Tarawa are essentially rural, the islands of South Tarawa are urbanized and because of their small total land area of approximately 15 square kilometers the island group has a population density of at 2,558 persons per square kilometer (Kiribati National Statistics Office 2006). This is on par with urban population densities in the developed world, and well above population densities in most Australian cities. In Betio, the most densely populated island of Tarawa, the population density is at least 8,500 people per square kilometer; which puts considerable pressures on natural resources such as land and water. Kiribati is classified by the United Nations (2008a, 2008b) as both a Small Island Developing State and as a Least Developed Country but also as a Small Town (Pilgrim et al 2004). From an urban water management perspective, this means, that Tarawa has considerable human and financial resources constraints, small size and lack of economies of scale, remoteness, economic vulnerability, unpredictable growth and high levels of resource uncertainty. Additionally, the unemployment rate in Tarawa is extremely high; with a majority of the resident workforce being engaged in subsistence type activities (Asian Development Bank 2002). Tarawa relies mainly on groundwater for reticulated water supply but many households do not have access to such supply (Falkland 2003). Unfortunately access to good quality groundwater is restricted by over-population and a shortage of land; for these reasons

alternative water sources are used, i.e. rainwater harvesting at a household level and desalination feeding into the supply system as well as at one hospital and one hotel (Falkland 2003). Groundwater for the reticulated water supply is extracted via infiltration galleries on the islands of Bonriki and Buota (Metutera 2003). In addition, most households rely, either fully or partially, on extracting groundwater from domestic shallow wells (Asian Development Bank 2000). Despite these alternative sources, reticulated water remains the main supply for many households, but this supply is intermittent and often fails to meet demand (White et al 1999). For example, there is no 24-hour supply as this is thought to lead to excessive demand and leakage (Metutera 2002).

2.2. Ongoing failures to consider complexity

Over the past 30 years, considerable funding has been spent on aid to the water and sanitation sectors in Kiribati, but with few a exceptions, these have had a less than adequate impact (White et al 2008). Projects have been characterized by narrow short-term focus, and some have been driven by international agendas rather than consideration of local needs, priorities and context (White et al 2008). The difficulties of considering the social complexity in development interventions are highlighted by the failed attempts at creating new water reserves in Tarawa. There have been efforts to resolve this problem through the application of a Companion Modelling approach (Perez et al 2003; Dray et al 2006 & 2007) aiming at *"providing the relevant information to the local actors, including institutional and local community representatives, to facilitate dialogue and devise together sustainable and equitable water management practices"* (Dray et al 2006, pp.1-2). The outcome of this process was a co-management framework as a pathway forward, but unfortunately key stakeholders did not take ownership of the negotiated outcomes and political conflicts and rivalries caused a stalemate situation. This experience has highlighted the need to 1) increase the ability of international and local agencies to consider local customs, culture and context within planning processes; 2) improve the ability of local agencies to manage their system despite resource deficiencies; and 3) improve the adaptive and coordination capacity, and embed negotiation abilities within institutional structures.

2.3. Entering the learning cycle

This paper describes a component which is part of a larger study, as described by Moglia and Perez (2007). Additionally, the study builds on previous research and experiences in Tarawa, such as the large scale SAPHE project funded by the Asian Development Bank (2008), the AtollGame and AtollScape experiences, but also the work of researchers such as Paul Jones, Ian White and Tony Falkland (Jones 1997; White et al. 1999; Falkland et al. 1999; Falkland 2003; White et al. 2003; White et al. 2008).

2.4. Rationale

In the given complex and dynamic context, this paper describes how BNs can be used to temporarily move to a situation where cause and effect relationships are discoverable. It is acknowledged that many project implementations have failed for diverse reasons. The reasons may have been obvious for some stakeholders, but for other stakeholders they were surprising. This shows that there is a need for incorporating local and expert knowledge into the planning process. Fundamentally, this is because each location and context has a unique profile of issues, constraints and boundary conditions that need to be considered. Using judgments and evaluations from past experiences, and by researchers, experts and local stakeholders, we map the factors that have previously impacted on the chances of success. Whilst the type of analysis has been applied to a number of potential interventions in the Tarawa water system, the current paper describes the situation surrounding the extension of water reserves. This intervention is perceived by a number of stakeholders as the only feasible option for providing sufficient water supply volumes to a growing population.

3. BAYESIAN NETWORK ANALYSIS

BNs provide a methodology to include inductive, abductive and deductive reasoning and BN's are particularly suitable for handling uncertainties, and supporting adaptive management (Boulanger and Brechet 2005). They are also particularly suitable for combining qualitative and quantitative information into integrated assessments (Castelletti and Soncini-Sessa 2007). For the particular case of water development interventions in Tarawa, a number of issues were considered in specifying the modeling requirements: 1) In the narratives about success or failure of interventions we often encounter conflicting information, and we therefore need the ability to handle multiple and conflicting hypothesis; and 2) the reliability of information is variable; for example statements in official reports by reputable experts as opposed to statements made over lunch by a government official; and so we need to allow for taking this diversity in information reliability into account. We also note that BNs do not support feedback loops, as only acyclic cause and effect networks can be modeled. The design of a BN has three components; its 1) *Ontological component*, which is the definition of terminology; 2) *Qualitative component,* which is the definition of causal relationships; and 3) *Quantitative component*, which consists of judgments of the state of topic domains. Validity of the BNs has been evaluated informally by comparing with the risks of historical projects, and to evaluate the consistency with observations.

3.1. Ontological component

The factors, i.e. topic domains impacting on the success or failure of reserves extension as shown, in Table 1 were identified to influence the chances of successful reserves extension. These topic domains were identified via semi-structured interview results, as well as key documents that mention reserves extensions in Tarawa.

Table 1: Descriptions of topic domains impacting on successful water reserves extension

Topic domain / Node	Description
DR: Declaration of reserves	Formal declaration of reserves, including a strategy for dealing with landowners, and legal arrangements to support this
CA: Community agreement	Overall agreement from landowners with a stake in the reserves
RM: Reserves management	Management of the reserves, in terms of ensuring no unsuitable land use or pollution occurs, and ideally that vegetation is cleared
SE: Sustainable extraction	Extraction of less or equal to the sustainable extraction rate, which depends on the rainfall conditions, i.e. droughts, and knowing the sustainable extraction rates.
LA: Legal arrangements	The legal arrangements that will allow the declaration of the reserves, and which ought to define the status and rights of landowners
EP: Engagement process	The process by which relevant stakeholders, i.e. landowners, are engaged. In particular whether it has allowed for the traditional pattern of Maneaba decision making
TO: Traditional sense of ownership	Referring to whether the landowners feel ownership and pride over their land, and whether they feel an obligation to protect it from harm and intrusion
IC: Institutional commitment and strength	The extent by which the key institutions are committed and strong enough to manage the water reserves; and whether they support or undermine the process.
CV: Clearing of vegetation	Whether vegetation is being cleared on the reserves in order to increase sustainable extraction rates, and to make transparent inappropriate land use
GI: Groundwater investigations	Investigations of the thickness and width of the freshwater lens in order to establish a sustainable extraction rate
M: Monitoring	Monitoring the salinity of the freshwater lens, to evaluate whether over-extraction is occurring. This also may involve monitoring of water quality.
SP: Sustainable pumping	Ensuring that pumping supports sustainable extraction
CM: Co-management of reserve	Co-management of water reserves including landowners and the relevant Government departments and the PUB, as suggested in the AtollGame project

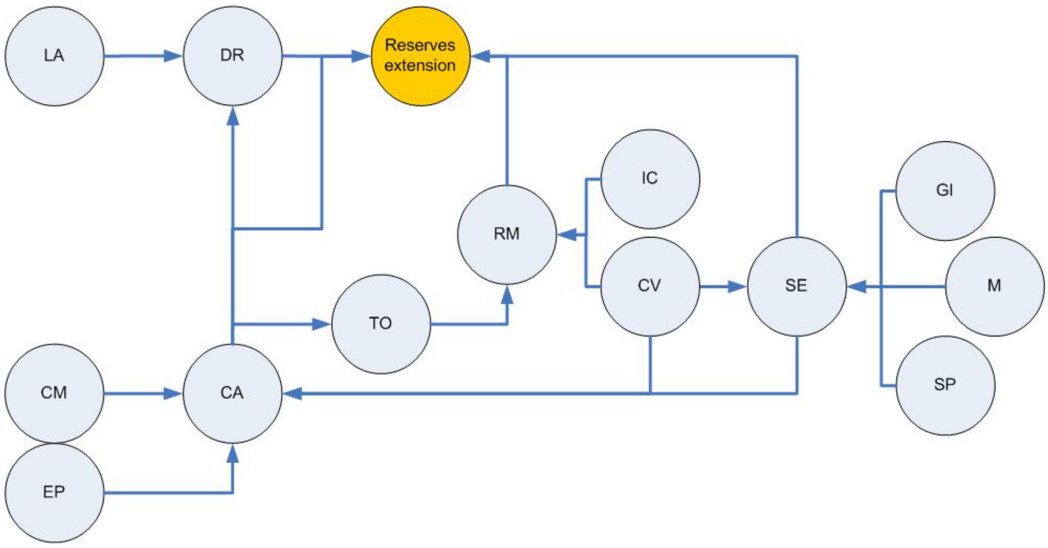

Figure 1: Bayesian Network diagram showing factors influencing successful reserves extension

Note: DR = Declaration of Reserves; CA = Community Agreement; RM = Reserves Management; SE = Sustainable Extraction; LA = Legal Arrangements; CoM = Co-Management; EP = Engagement Process; TO = Traditional Sense of Ownership; ICS = Institutional Commitment and Strength; CV = Clearing of Vegetation; GI = Groundwater Investigations; M = Monitoring; SP = Sustainable Pumping.

3.2. Qualitative component

The causal links between the items detailed in Table 1 have been identified based on qualitative statements in reports and in interviews. As per Figure 1, successful reserves extension depends on *Reserves management*, *Declaration of reserves*, and *Sustainable extraction*, and 1) chances of successful *Declaration of reserves* are improved by *Community agreement* and *Adequate Legal arrangements*; while 2) chances of successful *Reserves management* are improved by *Institutional commitment and strength*, *Clearing of vegetation*, and a *Traditional* *sense of ownership over land*; and 3) chances of successful *Sustainable extraction* is improved by *Groundwater investigations*, *Monitoring*, *Sustainable pumping* and the *Clearing of Vegetation*. Similarly the chances of 1) *Community agreement* are influenced by the implementation of a *Co-management framework*, an *Appropriate and Culturally Sensitive Engagement processes*, and *Clearing of vegetation*; which 2) in turn impacts on the chances of a *Traditional sense of ownership* which will allow for better *Enforcement of protection of the land*. We note that successful reserves extension is defined as 1) having a declaration of reserves which is respected, 2) community agreement and cooperation in the management of reserves; 3) efficient reserves management, including adequate protection of reserves, as well as 4) sustainable extraction of freshwater resources. This is of course a matter of definition, and such criteria should ideally be specified together with relevant stakeholders.

3.3. Quantitative component

In quantifying the links, a number of assumptions were made, as shown in Table 2 and 3. These probabilities all refer to Bayes formula and, if we use the details from the first row in Table 3, we get the "*The probability that we have successful declaration of reserves in the event of community agreement, is equal to 80%*". In order to apply the model, we also need to specify the conditions, i.e. the state of the topic domains for each scenario.

Table 2: Data sources for 'Reserves extensions' status quo scenario

Data source	Topic domain	State	Estimated probability	Certainty
Sectoral Strategy and Action Program (Falkland 2004)	Conflicts	Conflicts regarding the reserves	90%	80%
	Engagement process	Culturally sensitive process	10%	80%
	Legal arrangements	Legal arrangements in place	75%	80%
	Pressure for increasing lease payments	Pressure for increasing lease payments	90%	80%
Local official #1	Community agrees	Community agrees	10%	70%
	Institutional commitment and strength	Institutions are not committed and/or weak	80%	70%
Local official #2	Monitoring	Adequate monitoring	80%	70%
	Sustainable pumping	Sustainable pumping	80%	70%
Local official #3	Settlements on reserves	New settlements on reserves	99%	80%
White et al 2009	Co-management	Co-management	5%	95%
White et al 1999, Crennan 1998	Conflicts	Conflicts regarding the reserves	90%	95%
	Legal arrangements	No legal arrangements in place	90%	95%
	Traditional sense of ownership	Land owners do not feel a traditional sense of ownership	90%	95%
Expert #1	Clearing of vegetation	Clearing of vegetation	10%	80%
	Enforcement of protection	Inefficient enforcement	90%	80%
	Groundwater investigations	Adequate investigations	90%	85%
	Monitoring	Adequate monitoring	75%	85%
	Removal of fences	Fences are illegally removed	95%	80%
	Sustainable extraction	Non-sustainable extraction	75%	85%
AtollGame researchers (Pascal Perez and Anne Dray personal communication)	Conflicts	Conflicts regarding the reserves	90%	80%
	Enforcement of protection	Inefficient enforcement	90%	80%
	Engagement process	Technocratic process	90%	80%
	Pressure for increasing lease payments	Pressure for increasing lease payments	90%	80%
	Traditional sense of ownership	Land owners do not feel a traditional sense of ownership	90%	80%
Personal observations (Moglia)	Illegal activities	Illegal activities occur on reserves	100%	95%
	Settlements on reserves	New settlements on reserves	100%	95%
	Vandalism	Vandalism occurs	90%	80%

Table 3: Data sources for 'Reserves extensions' what-if co-management scenario

Data source	Topic domain	State	Estimated probability	Certainty
AtollGame negotiations (Pascal Perez and Anne Dray)	Clearing of vegetation	Clearing of vegetation	90%	80%
	Co-management	Co-management	90%	80%
	Community agreement	Community agrees	90%	80%
	Institutional commitment and strength	Institutions are strong and committed	90%	80%
	Legal arrangements	Legal arrangements in place	99%	95%
	Sustainable pumping	Sustainable pumping	90%	80%
	Traditional sense of ownership	Land owners keep a traditional sense of ownership	90%	80%

Notes: The certainty column refers to the extent by which each opinion can be trusted, and rather than assessing the reliability of each opinion on its own we have simply applied blanket rules; i.e. Experts' opinions within their domain expertise, and stated in a publicly available report or publication, is considered 95% reliable; Experts' opinions outside their domain expertise, but stated in a publicly available report or publication, is considered 80% reliable; Government officials' opinions within their domain expertise, and stated in a publicly available report or publication, is considered 85% reliable; Government officials' opinions outside their domain expertise, and stated in a publicly available report or publication, is considered 70% reliable; Direct observation are considered 95% reliable, and deductions of 15% are made if observations have been made by persons other than the analyst; and If opinions instead have been stated verbally, or in a non-formal manner, 15% certainty is being deduced from the above scores.

3.4. Software environment

Sheba is a software application for performing predictive analysis under conditions of uncertainty; providing a framework to structure and analyze categorical reasoning problems. It applies *Analysis of Competing Hypotheses using Subjective Logic* (Pope and Jøsang 2005) to reason about the effect on the projected outcomes dependent on categories of information, even when data is sparse. Techniques are used to calculate the effect of out-of-date information, and unreliable sources and observations (Pope et al 2006). This enables for creating assessments that reflect data availability; highlighting the uncertainty created by lack of relevant or reliable data.

4. RESULTS

In this paper, two scenarios relating to reserves extensions are explored 1) The *Status quo-scenario*, i.e. describing the state of topic domains in the reserves extension and management efforts so far; and 2) a *Co-management scenario* based on the recommendations from a Companion Modelling exercise, i.e. the AtollGame experience where stakeholders were involved in a role-playing game and thereby identified a management framework (Dray et al 2006 & 2007). The results of the BN analysis are shown in Table 4 where the estimated chances of successful outcomes "Opinions" and the 'Certainty' of this estimate are shown for the various topic domains. In traditional statistics terms this would represent the width of the confidence interval (or significance level if a hypothesis test is applied) for the model parameter that describes the probability of success. The reason for the wording of the term 'opinion' instead of 'estimated probability' is to indicate that this typically has been estimated on the basis of (more or less well informed) opinions and evaluations by stakeholders and experts.

Table 4: Results of scenarios

	Status quo scenario		**Co-management scenario**	
Topic domain & State	**Opinion**	**Certainty**	**Opinion**	**Certainty**
Chance of Successful Community agreement	9%	86%	77%	76%
Chance of successful Declaration of reserves	17%	70%	69%	59%
Chance of efficient Enforcement of protection	4%	93%	83%	67%
Chance of Sustainable extraction	78%	70%	81%	74%
Efficient reserves extension	***9%***	***84%***	***63%***	***65%***

We note that the chance of success using the *Status quo-scenario* is small at 9%, and that *Enforcement of protection* of the water reserves would be close to impossible (4% chance); whilst with a *Co-management scenario,* there would be an 83% chance of successful *Enforcement of protection*, and 63% chance of successful *Reserves extension*. This shows the futility of previous efforts during the SAPHE project to establish water reserves under the current institutional arrangements; whilst the framework that had been developed in a participatory and collegiate mode with stakeholders and traditional land-owners is one way forward. We also get an idea about what contributes the most to the chances of success by exploring which of the contributing factors has the greatest influence. This is calculated in the *Sheba* software, by setting 100% chance of success for combinations of 100% opinion and certainty in *Topic domains*, but with assessment of the influence of the other *Topic domains*. This type of sensitivity analysis provides the results shown in the bar chart of *Figure 2*, where each bar represents the chance of overall success given a particular combination of completely certain success of factors (abbreviated as per Figure 1). We see that *Community agreement* (CA) is of critical importance, which outperforms even a three factor combination of *Institutional Commitment and Strength* (ICS), *Monitoring* (M), and *Employing a culturally and sensitive process for engagement* (CS).

We note that this three-factor approach from only a water quality point of view would be give chances of successful enforcement of protection at 87%, and chances of community agreement at 92%, however, the overall probability of sustainable extraction is a mere 65%. Adding sustainable pumping and appropriate groundwater investigations to the mixture brings the chances of success to 73%, and this means that there is now also sustainable extraction. The reason for the low value of 73% remaining means that there would most likely remain some conflict surrounding the reserves. Thus, while from an equity point of view not ideal; from an engineering and health perspective this solution would with be adequate with a high likelihood of success.

5. DISCUSSION

A process for incorporating diverse knowledge and information into the assessment of water supply options has been developed based on BNs. By incorporating diverse knowledge and information into framework acknowledging uncertainty, it recognizes that providing urban water supply options often needs to take into account very specific local conditions and complex adaptive systems features, as well as social issues that often relate to organizational capability and community attitudes. Because of resource and funding constraints, perfect scientific understanding is not available, and even if such understanding and knowledge becomes available, the situations are so dynamic that once we fully understand it the system has changed and therefore, perfect scientific understanding may be of limited value. The best option is to enable a scientific dialectic process (which is in its essence Hegelian as it is iteration between thesis and antithesis thus enabling synthesis) down to the level of stakeholders and experts on the ground. The described BNs allow for embedding the assumptions and conceptual models into a formal model; and as such it is suitable for supporting collective learning via iterative model building, evaluation against empirical evidence and stakeholder deliberation.

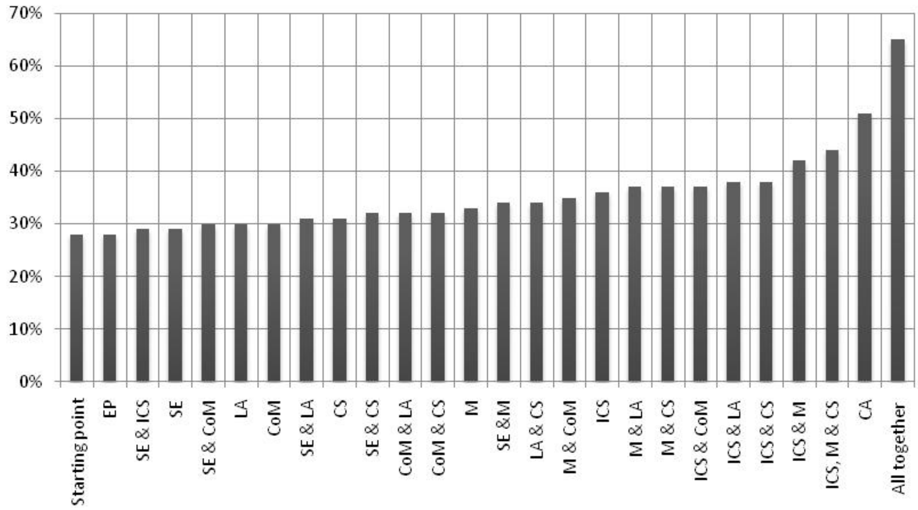

Figure 2: Contribution of factors, or combinations of factors, towards success of reserves extension

In this way, BNs provide an alternative and complementary method to other approaches such as LCA, TBL and MCA, for assessing water supply options. However, LCA only really considers the physical system, and primarily focuses on environmental impacts. The TBL approach includes the quantified value of various configurations, albeit from three perspectives and typically does not include risk assessment or implementation processes and is relatively poor at considering qualitative information. MCA formalizes the decision making and can be used in a deliberative process and can capture qualitative information, but suffers from many of the same limitations as TBL; and provides little guidance about implementation and context dependency. We believe that in addition to their obvious benefits in risk analysis, BNs are better at representing the cognitive reasoning, based on the types of causality that people employ for decision making. BNs are also better at including wider types of knowledge and information that is uncertain and where there is conflicting information. This means that also information which is controversial and uncertain can be incorporated, with appropriate acknowledgement of levels of certainty, and without having to wait for a perfect understanding of all relationships.

From a validity point of view, we note that the conclusions of the model described in this paper are very similar to what was arrived at using a *Companion Modelling* process (i.e. the *AtollGame* experience). This raises a questions relating to 1) the extent to which the formulation of the model described in this paper has been influenced by interactions with the researchers involved in *AtollGame*; and 2) whether BN modeling is in fact an alternative to *Companion Modelling* in terms of incorporating local and expert knowledge into the formulation of solutions to complex resource problems. What is clear is that knowledge from the AtollGame experience has been used in the formulation of this BN model. The next step, in order to answer the second question, would be to develop a BN model in isolation to the *AtollGame* in order to find out whether the modeling outcomes differ. Another key issue which has not been discussed in this paper is that BNs can help in identifying key information gaps; by finding those topic domains that impact critically on the outcome of the model, and evaluating what the impact of better information would be in terms of increasing the certainty in estimates. The model in this paper will feed into feasibility assessment of water supply options, and will help in formulating risk assessments and cost-benefit analysis of management options in a risk-sense, as per Australian New Zealand Standard for risk management. Importantly, the model allows for quantifying the cost-benefit of a culturally and contextually sensitive engagement approach. This means that project managers and financial officers can evaluate project designs and intervention strategies; and formally assess the riskiness of water aid. *We believe that Bayesian Network analysis, based on an understanding of history, may help facilitate better management practices in the development sector.*

6. CONCLUSIONS

This paper has shown that BN models can be applied in a framework to understand the complicated web of factors that influence and impact on the chance of success of an aid development strategy in a socially complex and highly resource constrained environment. Such situations are not unusual but rather typical in the development sector; particularly in the sphere of small town water systems which have been identified as lacking adequate management frameworks. The results also show that for the particular intervention that we have explored, considering the social and cultural context; and adhering to inclusive and appropriate engagement processes is critical in order to achieve success. Whilst that is in fact a common finding in the context area; what is novel is that this framework allows quantification of the risk of choosing a particular project design and engagement procedure. This means that such issues are not neglected when projects are conceived and designed by bureaucrats and engineers as it seems to have been common practice. The vision for the future of this methodology is to incorporate this type of risk analysis as part of the project design in the development sector. We believe that this would better bridge the gap between policy makers, engineers and local stakeholders and would drastically increase the success rate in overseas aid. Additionally, this approach addresses all the recommendations coming out of the *AtollGame* and *AtollScape* experiences.

7. ACKNOWLEDGMENTS

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