RESEARCH ARTICLE

Sustainable urban water futures in developing countries: the centralised, decentralised or hybrid dilemma

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This paper explores whether a mixture of centralised and decentralised urban water systems is preferable for sustainable urban water management. This is of importance for developing countries where there is continued demand for expanding urban water infrastructure. Processes for determining the combination of centralised and decentralised urban water solutions remain largely ad hoc. Using the South West Pacific as a case study, a multi criteria decision analysis (MCDA) methodology drawing on expert elicitation was employed to assess the technical, economic, environmental and resilience performance of urban water infrastructure alternatives; assessing water supply, sewage and stormwater systems. The MCDA analysis was then systematically contrasted with both a series of recommended infrastructural investment plans and the desires of local technocrats in Port Vila, Vanuatu. Results demonstrate a high level of agreement between the MCDA outcomes and local stakeholders, favouring hybrid infrastructure. Conversely, international consultants’ infrastructure recommendations continue to reflect traditional engineering paradigms.

Keywords: sustainable urban water management; developing countries; infrastructure; centralised; decentralised; hybrid systems

1. Introduction

The traditional, centralised approach to water servicing provides clean drinking water, sanitation and protection from urban flooding with very little apparent risk of failure (Lienert et al. 2006). However, literature suggests that this approach may be failing to adequately address the complexities of urban water management, human liveability and ecological health (Balkema et al. 2002, Daigger 2009, Bieker et al. 2010).

Currently, due to rapid changes in urbanisation patterns, there is increasing pressure on governments to provide improved and expanded urban water services in both developing and developed countries. Increasingly, literature suggests that traditional approaches to urban water service delivery may not be best suited for this rapid change, especially in a developing country context. It highlights possible benefits of implementing a range of distributed approaches (e.g. Newman 2001, Sobsey et al. 2008, Makropoulos and Butler 2010, Libralato et al. 2012), thus suggesting that a departure from conventional approaches is required (e.g. Gleick 2003, Huang et al. 2007, Mara and Alabaster 2008, Libralato et al. 2012).

In the developing world, changing priorities in water infrastructure planning are reflected in the recent water and wastewater policies of international development organisations, such as the Asian Development Bank (ADB) (ADB 2003, 2012). The need for more sustainable approaches to urban water management in developing contexts is further demonstrated by projects such as the SWITCH Urban Water research program, which endeavoured to direct urban water development toward increasingly sustainable infrastructure alternatives (Duffy and Jefferies 2010).

However in practice, centralised water supply, wastewater and stormwater systems continue to be promoted and constructed through the developing world, mimicking the traditional systems of the industrialised world (ADB 1998, 2005, 2009, 2010). While some examples of decentralised or mixed systems exist in industrialised nations (Wong et al. 2011), there continues to be no widespread shift from large technical solutions despite changes in policy. For example, the response to the recent water crises in Australian cities pertained to a construction of expansive inter-catchment pipelines and desalination plants, rather than decentralised water recycling or stormwater harvesting (Werbeloff and Brown 2011).

Thus, there remain two contrasting approaches to urban water management; a conventional paradigm based...
on traditional centralised engineering approaches (common in practice); and an emerging paradigm around decentralised or hybrid infrastructure (increasingly advocated in theory and literature (Huang et al. 2007, Montaner et al. 2007, Larsen et al. 2009, Makropoulos and Butler 2010, Libralato et al. 2012)). Contributing to this dichotomy is the fact that to date the dialogue regarding the perceived benefits of fully centralised or decentralised approaches to urban water service provision has been discussed predominately on a theoretical and ideological basis (Libralato et al. 2012), with literature only beginning to present assessment frameworks (Weber et al. 2007, Sapkota et al. 2013) and empirically based evidence (Graddon et al. 2011).

Previously literature has posed the question as to whether ‘a mixture of decentralised and centralised treatment can combine the advantages of both systems?’ (Balkema et al. 2002, p. 153). Infrastructure selection continues to be a priority question within the urban water sector (Brown et al. 2010). This question of what is the most appropriate mix of centralised and decentralised servicing approaches for urban water management is only beginning to be answered from a structured empirical or modelling approach (e.g. Coombes 2011, Sapkota et al. 2013). There is a need for robust methodologies for assessing the performance of all systems: decentralised, hybrid and centralised. This is of particular importance for urban centres in the developing world, where significant investments will be undertaken, as governments strive to provide improved urban water services for rapidly growing urban populations.

The objectives of this paper are three fold: (1) to present a multi-criteria decision analysis (MCDA) methodology utilising expert elicitation to guide infrastructure policy of urban water alternatives in developing contexts, where access to reliable data is limited; (2) to use the South West Pacific region as a case study to demonstrate the MCDA methodology and analysis; and (3) to use Port Vila as a city scale case study to systematically contrast the MCDA outcomes against both international consultants’ recommended infrastructure investment proposals and local urban water stakeholders’ desires for urban water infrastructure.

2. Case study

2.1 Regional case study: South West Pacific

To demonstrate the methodology developed in this paper, a regional scale case study in the South West Pacific region is applied, with the inclusion of Timor Leste (Timor Leste is regularly grouped with South West Pacific states as its demographic, cultural and political landscape more closely reflects those of the South West Pacific than its much larger and more heavily populated Asian neighbours). This region is characterised by (i) small but fast growing urban centres (Table 1); (ii) a lack of - or failing - infrastructure, with very limited if any stormwater or wastewater infrastructure, and water supply systems that are spatially and temporally inconsistent (ISF-UTS 2011a, 2011b, 2011c, 2011d); and (iii) degradation of urban waterways with negative impacts on public health, tourism and economic growth.

This region was selected based on numerous common features (biophysical and social), which enable generic policy guidelines to be developed. The islands of the region are geographically similar (volcanic and raised reef limestone origins), with tropical climatic and rainfall patterns, resulting in reliable quantities of groundwater, albeit of varying quality. Economically, the region is experiencing a period of economic growth, predominantly based on tourism development. Environmentally, urban centres in the region are coastal with proximate vulnerable coral reefs. Growing tourism and industrial sectors are placing greater pressures on natural resources, while increasing pollution loads. The urban centres throughout the region display adequate commonality that policy recommendations can be made for the region, however, the physical manifestation and implementation of these policies will remain specific to context.

2.2 City case study: Port Vila, Vanuatu

From within this regional case study, application of the results into a city scale case study enables the validation of results and refinement of policy recommendations. Within the South West Pacific region, the rapidly growing urban centre of Port Vila, Vanuatu, is of particular interest. It has

| Country           | Urban centre | Population (year) | Urban growth (% pa) |
|-------------------|--------------|-------------------|---------------------|
| Papua New Guinea  | Port Moresby | 307,000 (2009)    | 4.1                 |
| Timor Leste       | Dili         | 193,000 (2010)    | 5.0                 |
| Fiji              | Suva         | 175,000 (2009)    | 2.6                 |
| Solomon Islands   | Honiara      | 78,000 (2009)     | 3.7                 |
| Vanuatu           | Port Vila    | 66,000 (2009)     | 4.3                 |
| Fiji              | Nadi         | 42,000 (2011)     | 2.6                 |
| Tonga             | Nuku’alofa   | 24,000 (2010)     | 0.8                 |
| Samoa             | Apia         | 37,000 (2006)     | 2.0                 |
a functioning water supply system but relies on septic systems and lacks drainage capacity. Over the past 20 years there have been four technical recommendations produced by international consultants, suggesting urban water infrastructure investments (ADB 1994, 1996, 1998, 2010). Despite no infrastructural advancement to date, an agreement between the ADB, AusAID and the Government of Vanuatu will lead to an extensive urban water and road infrastructure investment in the next 5 years.

Over a 15 month period, stakeholders from Port Vila’s urban water sector participated in a Transitions Management process to develop an understanding of current context and challenges, develop a vision for future urban water outcomes, and identify possible strategic actions and steps for implementation (Poustit et al. 2013). This included six urban water management workshops with local and national Government officials, local and international consultants and aid agencies stakeholders. The fifth of these workshops invited local engineering and planning staff to identify desired infrastructure developments, as outlined further in the Methods section.

In this context with minimal existing infrastructure, all possible technological alternatives for water supply, wastewater and stormwater can be considered for implementation. Therefore, Port Vila presents an opportunity to compare and contrast the outcomes of the MCDA assessment against both infrastructure recommendations made for the ADB, and the desired infrastructure of local planning and engineering professionals within the Government of Vanuatu.

3. Multi-criteria decision analysis

Several empirical and analytical approaches can be employed to provide an integrated assessment of urban water system performance. Life-cycle analysis, triple bottom line assessment, cost-benefit analysis, contingent valuation, and various multi-criteria assessment methodologies, all provide insight into future systems’ performance (Balkema et al. 2002, Lai et al. 2009, Sparrevik et al. 2011). Of these no single approach can claim to be a superior method of assessment; different methodologies will be suited to different contexts (Mutikanga et al. 2011).

Traditionally, integrated assessment studies have presented an ‘either/or’ approach, assessing one technology against another for a number of alternative systems. For example, Abrishamchi et al. (2005) analysed eight systems, while Lennartsson et al. (2009) evaluated four alternatives, these methodologies exclude options for partial contributions from multiple alternatives. Therefore, while highly beneficial, these studies do not yet offer a comprehensive methodology for assessing the full range of technological alternatives available when a city-wide strategic infrastructure plan is being developed for a city with considerably limited existing infrastructure. The closest methodology for comprehensive assessment of hybrid infrastructure to date is presented by Sapkota et al. (2013). However, this methodology has yet to be empirically demonstrated and continues to be theoretical.

Of the various integrated assessment approaches that can be utilised to provide an understanding of urban water system performance, multi-criteria decision analysis (MCDA) is a body of techniques and research methodologies that explicitly considers multiple criteria in a decision making environment to improve ‘the transparency, auditability and analytical rigour of these decisions’ (Hajkowicz and Collins 2007, p. 1553). MCDA methodologies have been widely utilised for urban water system analysis, especially in water policy and supply planning and infrastructure selection (Abrishamchi et al. 2005, Sahely et al. 2005, Hajkowicz and Collins 2007, Mutikanga et al. 2011) and have been used in both industrialised and developing country contexts (De Carvalho et al. 2009, Lennartsson et al. 2009). MCDA has advantages in that it allows for the aggregation of various forms of data without requiring monetisation of non-financial aspects, and incorporates stakeholder or policy makers’ values for different criteria and weightings (Lai et al. 2009). Critiques of MCDA identify the need for subjective weightings as a weakness of the MCDA approach (Sparrevik et al. 2011), however it also ensures transparency of preferences and results in robust negotiation of values.

MCDA methodologies regularly rely on extensive data to determine quantitative performance for the selected criteria (e.g. economic costs, quantities of water or wastewater to be treated, energy requirements, COD, BOD or nutrient releases, potential nutrient/energy recovery etc. as demonstrated by the data requirements of Abrishamchi et al. 2005, Sahely et al. 2005). However, in developing contexts like the South West Pacific, access to such data is very limited. Rather than exclude these regions from systematic MCDA for future urban water infrastructure investment, the authors suggest that expert elicitation can be utilised to assess the likely or expected performance of various technological alternatives. Therefore, while all results in the paper are based on expert elicitation, which can be seen as a weakness when contrasted against reliable measured data, the authors suggest that when suitable experts are selected, valuable policy contributions can be generated.

4. Methods

Sparrevik et al. (2011) described MCDA as a five-step process that can lead to informed policy development: (i) generation of alternatives (ii) assessment criteria development, (iii) performance assessment; (iv) weighting; and (v) assessment analysis. The proposed methodology for assessing the suitable level of centralisation of urban water systems follows this logic, as explained below.
4.1 Generation of alternatives for urban water infrastructure

For the South West Pacific case study, technical infrastructure alternatives were identified for (1) water supply, (2) wastewater and (3) stormwater, including (i) water source and discharge location, (ii) treatment process, and (iii) collection and distribution alternatives. These alternatives form the components of the servicing solutions (Table 2), and were developed from the literature (Otterpohl et al. 2003, Parkinson and Tayler 2003, Vojinovic and Van Teeffelen 2007, Sobsey et al. 2008, Tilley et al. 2008, Larsen et al. 2009, Massoud et al. 2009, Norton 2009, Peter-Varbanets et al. 2009) and existing case studies (due to the number of ADB and World Bank Technical Reports reviewed, not all of the references appear in the reference list).

These alternatives were then integrated to create ‘combined systems’ for supply, sewage and stormwater servicing; representing all technically viable combinations of source, treatment and distribution for water supply, and collection, treatment and discharge alternatives for wastewater and stormwater (Supplemental data - Table S1). An example of a water supply combined system is a groundwater source, a centralised piping distribution system and centralised disinfection treatment. This resulted in the generation of 38, 84, and 24 possible combined systems for water supply, wastewater, and stormwater systems respectively (for the full list see Table S1). Each combined system was then classified as either centralised or decentralised, as determined by its physical characteristics.

4.2 Assessment criteria development

The following, widely used criteria for MCDA (e.g., Foxon et al. 2002, Sahely et al. 2005), were included: (1) technical performance, (2) economic performance and (3) environmental performance. Additionally, a fourth criterion of (4) resilience performance, which has a socio-cultural and vulnerability underpinning, was adopted. This was selected

| System component | Water supply | System component | Wastewater | Stormwater |
|------------------|-------------|-----------------|------------|-----------|
| (i) Source       | Groundwater | (i) Discharge   | Lotic waterways | Lotic waterways |
|                  | Surface water | Location       | Lakes/Wetlands | Lakes/Wetlands |
|                  | Recycled wastewater | | Estuarine | Estuarine |
|                  | Recycled stormwater | | Open marine | Open marine |
|                  | Recycled grey water* | | Irrigation | Irrigation |
|                  | Salt water | | Groundwater | Groundwater |
|                  | Rainwater | | | |
| (ii) Distribution | None required | (ii) Collection | None required | Pipe and pit (or open drains) |
|                  | Truck distribution | | Truck collection | with infiltration and/or |
|                  | Centralised | | Centralised water sewers | detention |
|                  | Centralised third pipe* | | Decentralised waste collectors | |
|                  | Decentralised pumping & piping. | | Vacuum collection | |
| (iii) Treatment  | No treatment* | (iii) Treatment | Centralised primary treatment | Direct discharge – no treatment |
|                  | Centralised disinfection | | Centralised secondary | End of pipe only |
|                  | Centralised disinfection & filtration | | Centralised ‘passive’ secondary | Source only |
|                  | Centralised advanced treatment** | | Centralised tertiary | Source and end of pipe |
|                  | Water recycling plant** | | Composting toilets/ source separation | |
|                  | Centralised desalination** | | Decentralised primary (septic tanks) | |
|                  | Decentralised disinfection | | Decentralised ‘passive’ secondary | |
|                  | Decentralised disinfection & filtration | | Packaged secondary treatment plants | |
|                  | | | Packaged tertiary treatment plants | |

Notes: 1 - Includes both potable and non-potable water use except as determined by asterisks.
* - used for non-potable water only. ** - used for potable water only
since it has been argued in literature, e.g. Milman and Short (2007) and de Graaf (2009), that the traditional approach to urban water systems assessment failed to account for the ability of the system to cope with future stresses (that are often of uncertain nature), extreme events or socio-cultural elements. Balkema et al. (2002) states that despite being hard to quantify, socio-cultural criteria are important for the successful implementation and uptake of infrastructure. These continue to be less common with Hajkowicz and Collins (2007, p. 1562) identifying that ‘fairness and equity’, ‘political and legal feasibility’ and ‘human health’ all featured less regularly than traditional indicators relating to technical and economic performance.

Under each of the four criteria, several performance indicators, presented in Table 3, were developed to assess the relative performance of each of the technological alternatives (see Supplemental data Table S1). These performance indicators formed a performance matrix for each stream: water supply, wastewater and stormwater (Supplemental data - Tables S2 to S5). All indicators are drawn from an extensive review of MCDA literature with most indicators being sourced from multiple publications. The performance indicators, the rationale for their adoption and the literature sources are all listed in Table 3. Since these performance indicators have been used in a large number of cases, covering a wide range of contexts of urban water development scenarios, it can be confidently presumed that these performance indicators are case study independent and suitable to be applied to small urban centres in developing regions. Further refinement and validation of these performance indicators will continue to strengthen the presented methodology.

### 4.3 Expert selection

In the absence of reliable data required for traditional MCDA methodologies, informed opinions from the region’s leading urban water professionals were sought. Seven leading academics, consultants and practitioners were identified and invited to provide performance scores based on current best practice and their expert judgment. Five of these seven experts provided performance assessments. This methodology was based on the questionnaire methods outlined in Sa-nguanduan and Nititvattananon (2011) and Martin et al. (2007), and experts were specifically selected based on their extensive experience in the region.

Respondent one is a technical expert: an urban water infrastructure specialist from an international development bank with in excess of ten years’ experience in urban water infrastructure project delivery in the Asian-Pacific Region. The second respondent is a world leading technical practitioner with over twenty-five years of experience on the implementation of SUWM (his experience in the region includes assisting in developing urban water management in Timor Leste and other small Asia-Pacific nations). The third is a governance expert: an international consultant who has worked extensively through the region for more than 15 years, advising governments on urban water policies, legislation and implementation of infrastructure projects. The fourth is an academic: a civil engineering and urban water infrastructure researcher with both research and practical experience in the region. The fifth is a socio-technical researcher and practitioner with specific experience within the Pacific region; he has worked within government departments in the region to identify technical capacity limitations, as well as with development banks, providing technical advice of possible future urban water solutions. These selected individuals were identified as a cross sectorial expert group, with each individual demonstrating suitable levels of experience and knowledge to assess the technical, economic, environmental and resilience performance of the various infrastructural alternatives within the South West Pacific region.

The authors recognise that the number of respondents is less than ideal. However, for the regional case study of the South West Pacific, it is suggested that these respondents will still present valid results for the following reasons: (1) limited expert pool and selection of only leading experts and (2) previous literature.

Previous research in the region has shown that without focused capacity training, practitioners lack technical knowledge (Poustie et al. in press). Therefore, increasing the pool of ‘expert’ respondents and inviting more participants will not automatically improve the robustness or validity of results. (e.g. Ugwu and Haupt (2007) included responses from 44 respondents but only five of them had heard of the United Nation Commission for Sustainable Development and less than 30% had any self-identified involvement in sustainability driven projects, thus suggesting that at a maximum these 13 individuals were ‘experts’ suited for making sustainability assessments.) This study endeavoured to avoid this problem by seeking only highly informed individuals who reflected best management practices and could confidently assess the four criteria themes. Within the region seven suitable individuals were identified who confidently meet these selection criteria and five undertook the performance assessment.

Additionally, the selection of only a small number of experts was supported by literature (e.g. Lenth 2001, Arnell et al. 2005), which suggests that there is no rule regarding the number of experts selected, but rather the suitability and knowledge of experts is essential. Similar studies looking at the development of performance measures with the urban water sector in Melbourne Australia utilised six experts to represent the water sector and six environmental interests (Kodikara et al. 2010).

The authors commonly noted key points: ...
Table 3. Performance indicators selected for expert opinion analysis.

| Criteria theme | Performance indicator: | Indicator for | Rationale |
|----------------|------------------------|---------------|-----------|
| Technical      | sustainable resource capacity | water supply | Able to supply a suitable quantity of water without depleting resources for future years. (Lundin and Morrison 2002, Sahely et al. 2005) |
|                | supply reliability     | water supply  | Able to ensure continuous, year-round supply (Lundie et al. 2004, Sahely et al. 2005) |
|                | risk of failure to meet water quality guidelines | water supply | Able to ensure that the water provided into homes for potable use meets standards. (Hellström et al. 2000) |
|                | reliability of system – quantity | wastewater | Able to collect and treat all wastewater required. This includes the efficacy of the collection system. (Morrison et al. 2001, Ashley and Hopkinson 2002) |
|                | reliability of system – quality | wastewater | Able to ensure the effluent is treated to an acceptable level prior to discharge into the environment. (Morrison et al. 2001, Ashley and Hopkinson 2002) |
|                | risk to receiving water | wastewater, stormwater | Able to minimise the impacts on the receiving environment depending on discharge location. (Ellis et al. 2004, Ashley et al. 2008). |
|                | meet flood protection guidelines | stormwater | Able to provide flood protection for public and private assets from urban inundation (Ellis et al. 2004, Ashley et al. 2008). |
|                | meet stormwater quality guidelines | stormwater | Able to meet stormwater quality guidelines (Morrison et al. 2001, Ellis et al. 2004, Ashley et al. 2008). |
| Economic       | capital costs          | all streams  | Capital costs for construction (Hellström et al. 2000, Ellis et al. 2004, Sahely et al. 2005, Ashley et al. 2008) |
|                | O & M costs            | all streams  | Ongoing O & M costs for any system should be minimised (Hellström et al. 2000, Sahely et al. 2005, Ashley et al. 2008) |
|                | affordability          | all streams  | Water system users must be able to afford the costs associated with using the services offered. Both connection and service fees (Morrison et al. 2001, Ellis et al. 2004, Sahely et al. 2005, Ashley et al. 2008) |
|                | incremental investment capacity | all streams | The system needs to be able to be expanded to meet future needs in an incremental manner (Sahely et al. 2005, Ashley et al. 2008) |
| Environmental  | energy use             | all streams  | Minimise energy use (Hellström et al. 2000, Morrison et al. 2001, Lundin and Morrison 2002, Sahely et al. 2005). |
|                | chemical use           | water supply, wastewater | Minimise chemical use (Hellström et al. 2000, Morrison et al. 2001, Lundin and Morrison 2002, Sahely et al. 2005). |
|                | impact on source environment | water supply | The water source should not be detrimentally impacted by the extraction of water for urban use. |
|                | impact on receiving environment | wastewater, stormwater | The discharge location for any effluent must minimise the detrimental effects on the receiving environment (Morrison et al. 2001, Ellis et al. 2004, Ashley et al. 2008) |
|                | waste production       | wastewater, stormwater | Minimise waste production - any waste produced must be treated and disposed. (Hellström et al. 2000, Lundin et al. 2000, Sahely et al. 2005, Ashley et al. 2008, Loucks and Gladwell 2008). |
|                | resource recovery      | wastewater, stormwater | Ability to recover and reuse energy, nutrients and water (Lundin et al. 2000, Morrison et al. 2001, Ellis et al. 2004, Sahely et al. 2005) |
| Resilience     | human technical capability | all streams | Suitable and appropriate for the level of technical skills locally available. (Hellström et al. 2000, Ashley et al. 2008) |
|                | flexibility for changing operational demands | all streams | Able to be flexible to change with urban patterns and uncertainty (Sahely et al. 2005, Ashley et al. 2008, Milman and Short 2008) |
|                | vulnerability to whole of system failure | water supply, wastewater | Able to minimise the coverage of disturbance in the case of destructive event or system stress (Sahely et al. 2005, Milman and Short 2008) |
|                | community fit          | all streams  | Able to meet the expectations or desires of the local community and address an identified need. (Hellström et al. 2000, Ellis et al. 2004, Ashley et al. 2008) |
|                | political support      | all streams  | Able to receive adequate political support (Hellström et al. 2000) |
|                | multi-functionality    | stormwater  | Able to provide multiple benefits such as aesthetics, public open space as well as flood protection (Ellis et al. 2004) |

4.4 Performance assessment

4.4.1 Scoring the technical alternatives

The experts were requested to fill in the performance matrix (Supplemental data - Tables S2–S5) for all technology alternatives (Table 2) against all performance indicators (Table 3). Each technology alternative was assigned a score by each expert, an integer number between 1 to 5, where 1 is regarded as a low performing
alternative and 5 a high performing alternative against the given indicators.

Prior to assigning scores the experts were requested to read thorough narrative descriptions of both the technology alternatives and the performance indicators to ensure a common understanding and to provide clarity of boundary conditions. Experts were asked to complete scoring of all technologies for one indicator prior to moving to the next. This ensured that each technology’s score for each performance indicator is relative to other technology alternatives.

To consolidate the five sets of expert opinions, and to minimise the impacts of any outliers, the median score was calculated for each of the 24 performance indicators against each of the 51 technology alternatives (see Supplemental data - Tables S2–S5). As previously stated, it is not only the sample size but also the quality of experts that determines suitability of expert elicitation. To assess the consistency of scores between experts, the percentage of responses that were one point different from this median was calculated.

For each technology alternative a criteria theme score was calculated for each of the technical, economical, environmental and resilience criteria. This was calculated as the mean value of that criterion’s performance indicators’ scores (see Supplemental data - Tables S2–S5). Thus, each technology alternative finished with a technical, economical, environmental and resilience performance score (Supplemental data - Tables S6).

Subsequently, for each combined system (comprising a source/destination, treatment and collection/distribution component, Section 4.1), criteria scores were calculated as the average of the three components’ scores. Thus, the final outcome was a technical, economical, environmental and resilience performance score for each combined system.

4.4.2 Calculating performance scores for each level of centralisation

Urban centres can be serviced by multiple combined systems, each providing any fraction of the urban water service (e.g. water supplied can be 60% from surface water, 30% from groundwater, and 10% from desalination). There are therefore many variations that are possible for each of the urban water streams. Using the mathematical programming environment ‘R’, a code was developed that generated all possible variations of contributions for each urban water stream. Variations allowed for each combined system alternative to provide a percentage of the overall water service, at increments of 10% from each of the identified alternatives (e.g. any alternative can supply 10, 20, 30…90, 100% of the overall service). For water supply, additional constraints required a minimum of 30% from potable water supply sources to ensure the presence of a minimum supply of potable water for drinking and potable kitchen and bathroom requirements (Gleick 1996).

Generated variations were then assigned ‘degrees of centralisation’ from fully centralised (only centralised technical alternatives contributing) through to fully decentralised (only decentralised systems) with increments of 10%. Each of these increments is referred to as a ‘step’. Monte-Carlo random sampling then selected 20,000 variations from each step. For each variation the percentage contribution of each combined system was multiplied by the combined systems’ criteria performance score. This resulted in each variation in each step receiving a score for its technical, economic, environmental, and resilience performance.

4.5 Weighting

A weighted summation methodology was applied to generate overall system scores. Weighted summation is the simplest and most widely applied approach for MCDA (Hajkowicz and Higgins 2008) and was selected given the number of indicators included in this study (n = 24), the number of technical alternatives (n = 51) and the lack of clearly defined relationships between indicators’ performance, all of which rendered more complex multi-objective multi-criteria assessments unsuitable. (These approaches are commonly used in urban water modelling based multi-criteria assessments (Rozos et al. 2010)).

To reflect the full spectrum of values potentially held by decision makers, rather than selecting author generated weighting regimes, as has often been used in previous MCDA research, all possible weighting scenarios were analysed. This was achieved through ensuring that all combinations of technical, economic, environmental and resilience weights were generated, where each theme is weighted at rates between 0 and 1, at 10 steps scale (0, 0.1, 0.2, ..., 1), generating 286 different weighting regimes.

Prior to combining the scores for each of the criteria themes into a single weighted score, the criteria theme scores were normalised to ensure a mean of 1.0. This would ensure that their gradient was preserved to reflect the impact of each degree of centralisation, but that each criteria theme had a normalised average, therefore removing the risk on any one criteria score biasing the overall performance.

The final step of the process was to apply each of the 286 weighting regimes to the 20,000 variations at each step of centralisation. The results were presented graphically using the mean scores of the weighting regimes plotted against levels of centralisation (see Figure 2).

4.6 Application to a city case study: Port Vila

Following the regional case study utilising expert elicitation in the South West Pacific Region, the results
of the analysis were used to inform a city scale case study in Port Vila, Vanuatu. The results from the analysis were compared with both historical infrastructure recommendations from international consulting firms and the current infrastructure desires of local government planners and engineers.

Firstly, recommendations made for infrastructure investments for Port Vila’s urban water system over the past 20 years (ADB 1994, 1996, 1998, 2010) were systematically contrasted with the results of the presented regional MCDA analysis.

Secondly, in February 2013, a 4 hour technical workshop was held in Port Vila to gather current infrastructure desires from Government officials involved with urban planning and urban water engineering. This workshop was specifically targeted at identifying possible urban water infrastructure to assist in delivering a sustainable urban water future. It was attended by 12 representatives from the Department of Environment, Department of Geology, Mines and Water Resources and the Public Works Department. Attendees included the second in charge from each of these departments along with technical staff and engineers. None of these individuals had participated in the regional MCDA assessment. Consequently, the two results can be regarded as truly independent.

In this technology selection workshop all technological alternatives available for consideration were discussed at length to ensure a consistency of understanding. Following this, large maps of Port Vila were used to assist individuals to determine which technologies would be of greatest benefit in Port Vila; considering the local context’s technical, social, environmental and economic situation. The technologies, locations, other insights and comments were all recorded on urban water system maps, one each for water supply, wastewater and stormwater. Following the workshops these maps were analysed with all infrastructural recommendations being recorded. These recommendations were combined with census data to determine the percentage of population serves by each recommended technology.

All workshops in the TM process were facilitated by the authors but according to TM methodology, the outcomes of these sessions were developed by the participants with no input from the facilitators. The outcomes of the workshops were reported back to the participants in the following workshop to ensure accuracy of reporting and to validate outcomes.

5. Results and discussions

5.1 Performance against single criteria for the Pacific Region case study

The performance of the three urban water streams against the four criteria themes and for each step of centralisation is presented in Figure 1. These results utilised the median expert opinion scores (Supporting Information Tables S2–S5). There was strong agreement on technical performance between respondents, with 68% of all responses within 1 of the median (97% within two of the median).

5.1.1 Technical performance

The technical results in Figure 1 (a and e) show that water supply and wastewater’s technical performance is understood by experts to increase with centralisation. This is consistent with previous literature stating that decentralised systems may not be suitable for water supply and wastewater treatment in urban centres due to an inability to ensure quality and reliability (Libralato et al. 2012) and that technically there are perceived benefits in centralised systems.

However, the perceived technical performance of stormwater systems decreased with centralisation. This result demonstrated the benefits of decentralised urban stormwater systems for the treatment of stormwater (Wong 2006). When the criteria and results focused only on flood protection, the fully centralised stormwater system out-performed the decentralised approach. Again reflecting the engineering paradigm of the past century (Drangert et al. 2002).

5.1.2 Economic performance

The results of the water supply and wastewater systems behave similarly (Figure 1b and f), demonstrating a negative trend with centralisation, reflecting an understanding that decentralised systems are cheaper and more economically viable in the region. The water supply performance is also characterised by a highly variable performance, demonstrating that the selection of systems installed has a considerable impact on economic performance. Within each degree of centralisation, care must still be taken in selecting appropriate technologies.

These results support qualitative arguments presented by both Newman (2001) and Rosemarin (2005), and quantitative work of Prihandrijanti et al. (2008) and Malisie (2008), who stated that in developing contexts the capital and ongoing costs associated with conventional water supply and wastewater systems deem them unsustainable. This analysis supports the conclusion that decentralised or hybrid systems may prove beneficial for the developing world. In contrast, the stormwater system’s economic performance (Figure 1j) increases with centralisation; reflecting the increased construction and maintenance costs associated with decentralised stormwater treatment systems.
A shortcoming of this analysis is that one economic criterion which was not included was the economic benefits associated with wastewater reuse or stormwater harvesting. This analysis does not account for decreased costs associated with decreased water supply demand, nitrogen or phosphorous recycling or the minimisation of environmental remediation costs. When these are accounted for in literature, it has been found that decentralised stormwater and wastewater systems with water sensitive urban design features perform better economically than traditional systems (Sharma et al. 2009).

5.1.3 Environmental performance

Uniform trends in perceived performance are observed for all three urban water streams (Figure 1c, g and k), showing decreasing environmental performance with centralisation. Stormwater demonstrates the most significant environmental benefits in decentralised approaches. This supports literature that discusses the environmental benefits of water sensitive urban design (WSUD), sustainable urban drainage systems (SUDS) and low impact development (LID) approaches to stormwater management, and the need for integrated, decentralised stormwater management in developing urban centres (Parkinson and Tayler 2003, Vojinovic and Van Teeffelen 2007). Whilst not as pronounced, water supply and wastewater still demonstrate potential environmental benefits with decentralised systems, as hypothesised qualitatively by Newman (2001) and Rosemarin (2005).

5.1.4 Resilience performance

The three streams display very limited change in perceived resilience performance with centralisation. Water supply and wastewater systems have higher gradients than the stormwater system, for which decreases in centralisation result in only slight increases in resilience. These were surprising results, since de Graaf (2009) stated that moving away from sole dependence on traditional centralised approaches will increase resilience, especially regarding urban flood management.

Close examination of the scoring cards (see Supplemental data - Tables S2–S5) explains this behaviour. The criteria of political support and community suitability scored better for centralised technologies than decentralised alternatives. This is a result of the perceived favouring of the familiar systems to more unfamiliar technologies, as argued by Walker (2000) and Marks (2006). Conversely, the physical aspects of resilience, such as the criteria on multi-functionality or ability to meet changing demands, favoured decentralisation as these systems are perceived to be more flexible, (De Graaf et al. 2009). This interplay between social and physical
resilience criteria resulted in the almost ‘flat’ response to the level of centralisation. However, it could be speculated that this may change in future in favour of decentralised systems; literature states that the introduction of innovative or alternative technologies requires a period of several years prior to widespread adoption to enable building trust and familiarity, and gaining political support and community acceptance (Rip and Kemp 1998).

5.2 Overall performance: Weighting scenarios for the Pacific Region case study

Figure 2 (a–c) shows the multi-criteria performance of the urban water supply, wastewater and stormwater systems against different steps of centralisation for each of the 286 weighting scenarios (composed of all possible weightings of the technical, economical, environmental, and resilient scores). It is clear that, when either fully centralised or fully decentralised infrastructure is constructed, there will be a wide disparity between levels of satisfaction felt by proponents of differing world views. This demonstrates that to advocate a fully centralised or fully decentralised approach to urban water management, fails to acknowledge the complexities of modern urban water management, and the diverging views of stakeholders. When different world views and priorities are considered, a hybrid solution will be required. This hybrid approach will present a compromise, which has suitable performance against all criteria, and can represent an agreed outcome by holders of differing world views, and thus can result in an increased robustness of infrastructural policy.

All the graphs in Figure 2 display a point, or a narrow range (in the case of water supply), where all weighting scenarios intersect. This point (range) is the level of decentralisation where there is very little sensitivity of performance to weightings regimes. These results demonstrate that when multi-criteria decision making processes are utilised, the systems with most consistent performance, regardless of decision makers’ values, are hybrid systems that integrate centralised and decentralised system components.

The results of Figure 2 are surprising. It would have been expected that the results would have suggested more centralised water supply infrastructure than for wastewater or stormwater but Figure 2 suggests centralised infrastructure comprising 20–40% for water supply and 30% and 50% for stormwater and wastewater respectively. In practice these systems are not being implemented, with a continued reliance on conventional infrastructure throughout the region.

5.3 City case study results: Port Vila

The infrastructural investment recommendations for Port Vila urban water system by international consultants over the past 20 years are presented in Table 4. It is clear that conventional centralised urban water supply and stormwater infrastructure have consistently been recommended. Similarly, proposed wastewater systems have consistently included a centralised wastewater collection and treatment approach to treat the CBD’s wastewater.

These proposed infrastructural developments, from 1994 until 2010, present markedly different infrastructure development pathways to the results presented in the above MCDA analysis; the international consultants’ proposals continually recommend centralised approaches, in contrast to the MCDA analysis, which supports the introduction of more hybrid systems.

Applying the water supply proposals presented over the past 20 years (Table 4) to Figure 1 would suggest that, based on regional expert opinions, these systems would be technically sound, but are perceived to perform poorly regarding economic, environmental and resilience performance. Similarly, the stormwater proposals are perceived to perform well economically, but would perform poorly regarding technical and environmental performance, with resilience performance slightly decreased.

Figure 2. Multi-criteria performance results for all 286 weighting schemes.
The recommendations and desires that were identified through the March 2013 workshop on planning urban water infrastructure in Port Vila (Table 5) closely correlate with the outcomes of the presented MCDA analysis. Water supply and stormwater both reflect the hybrid opportunities present in Port Vila. These are in line with the results presented in Figure 2 (and significantly divergent from recommendations made in international consultants’ proposals). The desires and recommendations for wastewater management from the workshop outcomes echo the hybrid nature of proposals by international consultants, thus validating the presented MCDA methodology and results.

The outcomes from the MCDA methodology utilising expert opinions, Figure 2, suggest that throughout the South West Pacific, discussions regarding the hybrid nature of urban water systems would benefit from initially considering centralisation degrees of between 20% and 40% for water supply and approximately 30% and 50% for stormwater and wastewater, respectively. Results from the workshops with engineers and technical staff in Port Vila, appear to support these ranges, potentially suggesting a larger fraction centralised for water supply. However, these ideas continue to be omitted in the technical recommendations from international consultants. There appear to be potential benefits that could be realised by

| Year                  | Water supply                                                                 | Wastewater/Sanitation                                                                 | Stormwater drainage                                                                 |
|-----------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| 1994: Infrastructure plan (ADB 1994) | • Centralised system remains.                                                 | • Bore sewer systems to collect and convey the wastewater to the designated treatment facilities | • The existing drainage system is considered adequate and does not require any improvements |
|                       | • Need to augment for increasing demand.                                       | • Two wastewater treatment plants to treat all the collected effluent.                |
|                       | • Need to find new groundwater source and pumping location                     | Summary: 100% centralised                                                          |
|                       | **Summary:** 100% centralised                                                 | **Summary:** 80% centralised, 10% septic systems, 10% small treatment plants         |
| 1998: Sanitation masterplan (ADB 1998) | • Centralised system remains.                                                 | • Modified sewerage system for the CBD and surrounding suburbs initially. Other suburbs improved septic tank management and with time be connected into the sewerage system |
|                       | • Need to augment for increasing demand.                                       | **Summary:** 100% centralised                                                      |
|                       | • Need to find new groundwater source and pumping location                     | **Summary:** Approx. 40% centralised initially, increased number of centralised connections with time |
|                       | **Summary:** 100% centralised                                                 | **Summary:** 100% centralised                                                      |
| 2010: Port Vila urban development project (ADB 2010) | • Centralised system remains.                                                 | Option 1:                                                                            | • Expansion of the existing system.                                                |
|                       | • Mentioned that rainwater can be collected but not advocated.                | • Gravity sewerage system. Prediction of 50% connected to centralised system. Remaining population serviced by private septic systems (40%) or communal toilet systems (10%) |
|                       | • No other alternative water supply sources discussed                          | • Centralised sludge treatment facilities.                                           |
|                       | **Summary:** 100% centralised                                                 | **Summary:** 50% centralised and 50% decentralised collection, and 100% centralised sludge treatment |
|                       |                                                                            | Option 2:                                                                            | • Expansion of the existing system.                                                |
|                       |                                                                            | • No centralised wastewater collection system                                       |
|                       |                                                                            | • Improved septic tank management (90%) and communal toilets (10%)                  |
|                       |                                                                            | • Centralised sludge treatment plant.                                               |
|                       |                                                                            | **Summary:** 100% decentralised collection 100% centralised treatment               |
|                       |                                                                            | **Summary:** 100% centralised                                                      |

Table 4. Twenty years of infrastructural recommendations for Port Vila.
incorporating increased decentralised approaches into the management and treatment of water supply and stormwater systems.

6. Implications for Policy

6.1 General developing context policy implications

6.1.1 Uncertainty in expert elicitation

It could be argued that the presented MCDA methodology has advantages regarding its suitability for contexts where numeric data is sparse as expert elicitation overcomes these data shortages. However, uncertainties remain. Criteria that are dominated by technical or scientific knowledge, or whose economic scores can be accurately transposed from other contexts, usually have a satisfactory level of reliability. In contrast, the ability to accurately assess public perception and acceptance, political support or community fit, is more subjective, and therefore less certain. Furthermore, temporal variation of perceptions, especially regarding socio-political acceptance, performance and reliability will increase the potential for variability and uncertainty of results.

Here it is suggested that such variability should not be viewed as an inherent weakness of this methodology involving perceptions, but rather features as an additional component of analysis; it not only allows a policymaker to map out what the current most acceptable infrastructural mix would be; it also allows an assessment of how this infrastructural mix could change over time, or could be influenced through education, experience and community involvement. This is because the ‘ideal mix’ is highly dependent on the choice of the weightings used for each of the four – technical, economic, environmental and resilience – criteria. Depending on whether more weight is attributed to, for example, environmental performance, the ‘ideal mix’ will shift towards decentralised approaches. When more weight is attributed to technical performance, the ‘ideal mix’ would shift towards centralised approaches. The choice of weightings therefore represents the value set behind the assessment of what an ‘ideal mix’ would be. An important conclusion can immediately be drawn from this, namely that the interesting parameter in the policymaking process is not the assessed performance, but the value set that yielded it. And, consequently, the stakeholder discussions and deliberations should not be about what mix has the highest performance, but what value set the stakeholders can agree upon. This will translate into a weighting scheme, which will produce an acceptable balance of centralised and decentralised contributions for those values.

6.1.2 Acceptance of urban water systems

Some further conclusions can be drawn when the graphs in Figure 2 are observed, where the overall performance results are plotted for all weighting schemes. At the extreme ends, that is, completely centralised or completely decentralised, there is maximum disagreement on the performance of the system: the performances according to the different weightings are maximally spread out. From this alone it can be concluded that some degree of hybridisation is desirable, since it is at the extremes where one stakeholder’s ‘ideal mix’ can represent another’s ‘nightmare mix’. As already discussed there is a point (or narrow range)

| Water supply | Wastewater/sanitation | Stormwater drainage |
|--------------|-----------------------|---------------------|
| • Centralised system remains in place and expands to areas not currently served | • Centralised system for the CBD. | • Maintain existing drainage system in CBD and main highway. |
| • Desire to minimise water supply demand through augmenting it with rainwater for all kitchen requirements, and any other uses as available. | • Majority of suburban areas - improved septic tanks with improved pumping rates and sludge treatment. | • Improved use of SUDS principles in all other areas. |
| | • Low cost and low technology closed system approaches for informal settlement in river reserves. | • Prioritise capture of rainwater, infiltration through rain-gardens, or biofiltration systems, sediment management through swales or buffer strips. |
| | • Higher standard onsite wastewater management for residential properties and accommodation along the foreshore. | |
| | • High quality package WWTP for all medium or large hotels on foreshore or within 50m of beach. | |
| | • Wastewater treatment plant, with sludge drying facilities. | |

Summary: 60% from centralised service and 40% from rainwater

Summary: 30% centralised, 10% composting/closed systems, 10% small treatment plants, 50% improved septic tanks

Summary: approx. 30% centralised, and approx. 70% decentralised
where the performance of the mix is hardly dependent on the weighting regime; i.e. there is a reasonably well defined degree of decentralisation for which all stakeholders, regardless of values, agree upon the system’s performance. This usually is not their ideal mix, nor their nightmare mix, but it is a mix with which all stakeholders would be equally satisfied or dis-satisfied. It seems that in the context of a participatory process with multiple stakeholders, this should be the starting point in the discussion.

6.2 South West Pacific and Port Vila policy implications

6.2.1 Encourage hybrid infrastructure

The results have highlighted the fact that centralised and decentralised systems both have strengths and weaknesses to offer in the region; the centralised systems for water supply and wastewater are perceived to have more technical reliability than decentralised systems, but lag behind against the other three criteria themes (environmental, resilience and economical). This is not surprising, as it is in line with the past literature (e.g. Pearce-Oroz (2006) and Libralato (2012)). Therefore, it should be encouraged that future policy development and infrastructure investment endeavours to balance the technical reliability of centralised infrastructure with the economic, environmental and resilience benefits associated with available decentralised technologies.

In the Pacific region this may be reflected in water supply policies that encourage continued use and expansion of centralised potable water systems to ensure equity of access, while also encouraging secondary sources such as rainwater tanks or local groundwater supplies for non-potable water use to minimise centralised demand. Wastewater and stormwater systems will in similar ways also benefit from a degree of hybridity. Therefore, policy makers should engage stakeholders in meaningful discussions to determine the suitability of decentralised systems to provide optimised performance prior to making significant infrastructure investments.

Future investments in Port Vila’s urban water system should endeavour to reflect the multi-faceted requirements of modern infrastructure requirements. Choices both of consulting engineers and infrastructure, should now be based on multi-criteria assessment, incorporating both environmental and resilience credentials, which reflect current best management practices, as well as the traditional requirements of technical reliability and economic performance.

6.2.2 Selection of consultants

Ensuring that future consulting engineers are able to accurately engage with the complex ideas of resilience and ensuring that they are cognisant with emerging or innovative water management practices and technologies, is critical. Without up to date awareness of emerging principles and innovations, consulting engineers can potentially recommend infrastructure for developing countries which does not reflect best practices for urban water management, potentially leading to sub-optimal outcomes. Therefore a methodology, like the one presented, has potential to be utilised to review infrastructure recommendations and proposals, or more proactively, this methodology could inform the terms of reference for international consulting firms prior to undertaking detailed design and analysis. The outcomes of this Port Vila case study suggest that both the recommendations resulting from a holistic approach to performance assessment and the desires of the local government stakeholders appear to contradict historical infrastructure proposals. This highlights the importance of selecting and contracting engineering consultants with demonstrated best practice experience and keen awareness of emerging principles, practices and technologies.

7. Conclusion

This paper has presented a methodology that utilises expert elicitation to assess the expected technical, economic, environmental and resilience performance of complex technical alternatives, along with different levels of centralisation for the three main streams of urban water servicing: water supply, sewage and stormwater systems. This methodology can now enable policy makers to utilise a MCDA approach for future water infrastructure planning in contexts where reliable data is lacking. In this paper, experts in urban water management in the South West Pacific region undertook a multi-criteria assessment of all technically viable urban water infrastructure alternatives. This was followed by a robust computational analysis based on a Monte Carlo sampling approach for performance assessment of possible technical variations. The results demonstrated that the level of centralisation is likely to significantly affect the technical, economic, environmental and resilience performance of urban water systems. The overall combined performance scores of the MCDA analysis are highly dependent on world view and value sets reflected by the weighting regimes.

Results of the MCDA analysis suggest that in the South West Pacific, future stakeholder engagement, aimed at guiding the development of sustainable urban water policies, should be focused around discussions on understanding the most suitable levels of hybrid infrastructure. These discussions should start by considering levels of centralisation whereupon the stakeholders agree upon the performance of those proposed systems. These levels were found to be 20–40% for water supply, 30% for stormwater and 50% for wastewater infrastructure.
In the context of Port Vila, local engineers and stakeholders - when engaged in planning workshops - support the adoption and encouragement for hybrid urban water systems for all three aspects of water supply, wastewater and stormwater management, validating the results of the regional MCDA analysis. This is in contrast to the technical recommendations made in numerous consulting reports over the past two decades, which continue to promote centralised systems. As such, the latter are reflective of a traditional paradigm in urban water engineering.

This paper presents a MCDA methodology which aims to be an additional supporting tool in the development of urban water policy that addresses a more complex reality, where hybrid infrastructure is used in developing contexts. This methodology is broadly applicable to individual cities, countries or regions, allowing holistic assessment, which incorporates technical, economic, environmental and resilience performance considerations, where data for traditional MCDA approaches is missing.

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