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REPORT

Modeling integrated urban water systems in developing countries: case study of Port Vila, Vanuatu

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Abstract Developing countries struggle to provide adequate urban water services, failing to match infrastructure with urban expansion. Despite requiring an improved understanding of alternative infrastructure performance when considering future investments, integrated modeling of urban water systems is infrequent in developing contexts. This paper presents an integrated modeling methodology that can assist strategic planning processes, using Port Vila, Vanuatu, as a case study. 49 future model scenarios designed for the year 2050, developed through extensive stakeholder participation, were modeled with UVQ (Urban Volume and Quality). The results were contrasted with a 2015 model based on current infrastructure, climate, and water demand patterns. Analysis demonstrated that alternative water servicing approaches can reduce Port Vila's water demand by 35 %, stormwater generation by 38 %, and nutrient release by 80 % in comparison to providing no infrastructural development. This paper demonstrates that traditional centralized infrastructure will not solve the wastewater and stormwater challenges facing rapidly growing urban cities in developing countries.

Keywords Developing countries · Sustainable urban water management · Simulation modeling · Strategic infrastructure planning · Scenario analysis

INTRODUCTION

Rapid urbanization, population growth, and changing climate patterns are magnifying the challenges that urban water infrastructure is facing in developing countries (Stephenson 2001). Governments struggle to provide adequate water services, failing to match infrastructure with urban expansion; water supply services are often inconsistent, while poor management of wastewater and stormwater results in public health and environmental issues (World Water Assessment Programme 2009; ISF-UTS 2011).

The literature promotes the use of alternative water supply sources in developing countries (Makropoulos and Butler 2010; Srinivasan et al. 2010). Alternatives to large scale, traditional end-of-pipe approaches to wastewater and stormwater management are also advocated (Butler and Parkinson 1997; Larsen et al. 2001; Otterpohl et al. 2003; Larsen et al. 2009). However, these are rarely implemented, and developing countries continue to import large engineered systems—concreted stormwater canals, and sewerage systems with large centralized wastewater treatment plants. Although this engineering approach has brought advances in public health and flood protection, it has been suggested that it also results in ongoing negative social, ecological, and economic impacts (e.g., Gleick 2003).

Advancements in engineering and governance now suggest that there are opportunities for transformational change in developing countries (Westley et al. 2011), enabling them to by-pass conventional infrastructure and implement innovative technologies—"technological leapfrogging" (Perkins 2003). Leapfrogging has occurred in the telecommunication and the automotive industries (Lee and Lim 2001; Mu and Lee 2005) but is only beginning to be promoted within the water sector (Binz et al. 2012).

One mechanism helpful in promoting leapfrogging is to increase the understanding of water and nutrient flows through the urban system, thus assisting governments to assess infrastructural alternatives for the future. This has been done utilizing materials flows analysis (MFA) in both developed (Jeppsson and Hellstrm 2002) and developing

contexts where data are lacking (Huang et al. 2007; Montangero et al. 2007; Montangero and Belevi 2008). MFA methodologies have predominately been applied on yearly averages and are therefore unable to model a number of urban water components (usually alternative technologies) that require high time resolutions; e.g., rainwater tanks or seasonal variations in water supply sources which need at least daily modeling steps. More complex urban water cycle models, such as UVQ (Urban Volume and Quality) and Aqualcycle, have also been used in both developed (Mitchell and Diaper 2005b, 2006), transitioning (Martinez et al. 2011; Thi Hoang Duong et al. 2011) and developing urban centers (Situmorang 2008). Shortcomings associated with their application in developing contexts to date have been the heavy dependence on assumptions from industrialized contexts or approximations for input parameters due to a lack of reliable local data; removing the ability to undertake calibration and compromising the robustness of conclusions.

The promotion of sustainable urban water infrastructure requires more than effective computer modeling of water and nutrient flows. It is recognized that strategic planning for water infrastructure requires effective stakeholder engagement (Dominguez et al. 2011). The modeling approach to urban water management has previously neglected this with scenarios and technical alternatives often developed without rigorous stakeholder discussions, and scenarios limited to a small number of alternatives per analysis (Huang et al. 2007; Montangero et al. 2007; Montangero and Belevi 2008; Do-Thu et al. 2011). It is suggested that a broader range of alternatives developed through stakeholder participation should be tested to inform governments' infrastructure policies.

This paper presents a methodology of how extensive stakeholder engagement can be integrated with a robust modeling approach to inform urban water infrastructure development in developing country contexts. This integrated, discursive modeling approach is applied to the rapidly growing urban center of Port Vila, Vanuatu.

MATERIALS AND METHODS

This research utilized a four phase methodology as outlined in Fig. 1. The phases' objectives and their outcomes are (1) study area context analysis: the analysis of all existing information on Port Vila and its urban water systems; (2) field data collection: the collection throughout the catchment of all data essential for accurate daily time step modeling, including monitoring of water quantity and quality; (3) development of urban water infrastructure scenarios in collaboration with key stakeholders: the selection of infrastructure alternatives (e.g., different technological solutions) and context scenarios (e.g., projections on climate and population changes) through discursive stakeholder engagement; and (4) integrated water and contaminant modeling, including model selection, calibration, and sensitivity analysis: to assess the pollution reduction potential of alternative technologies under different future scenarios and therefore make potential policy recommendations for improving the environmental sustainability of Port Vila's urban water system.

Study area context analysis

Port Vila is the rapidly growing capital of Vanuatu, located in the South West Pacific region. As the principal urban, business, and tourism centre in Vanuatu, it has undergone significant socio-economic growth and urbanization since independence in 1980. It now has a population of approximately 60 000 with a current growth rate around 4 % and a transient tourist population of up to an addition 10 % during the peak season (VSO 2012) with more than 2300 rooms and in excess of 330 000 visitors in 2012.

The Port Vila (Fig. 2) is built upon terraced raised reef limestone geology (Ash et al. 1978). A shallow, unconfined aquifer flows below Port Vila from recharge zones in the mountainous island interior toward the south west where it discharges into Tagabe River, Port Vila Harbor, Mele Bay, and the lagoons (Depledge 1994). The groundwater table in the urban area varies from within 2 m to more than 40 m from the ground surface. The Tagabe River, as Port Vila's only urban river, flows through densely populated formal and informal urban regions, past industry (e.g., brewery and paint factory) and then discharges heavily polluted into Mele Bay.

Port Vila is serviced by a privately operated piped water supply system. This system relies upon a single groundwater pumping station located 3.5 km north–west from the Central Business District (CBD), next to the Tagabe River (Fig. 2). Following rapid urbanization, residential dwellings and sanitation units are now within 400 m of the pump station, raising concerns of supply contamination. Additionally, some informal communities utilize the river for bathing and washing (with poor water quality leading to health concerns), while other communities are supplied by private water vendors at premium rates.

Port Vila relies predominately on septic systems for wastewater management, exceptions being a small piped system servicing the hospital, a few "package" plants within large hotels, and pit latrines in informal communities. Since 1994 the government has investigated improvements in wastewater management without any improvements in service delivery (ADB 1994, 1996, 1998, 2010).

Much of Port Vila lacks proper stormwater drainage, resulting in frequent flooding. The CBD and arterial roads

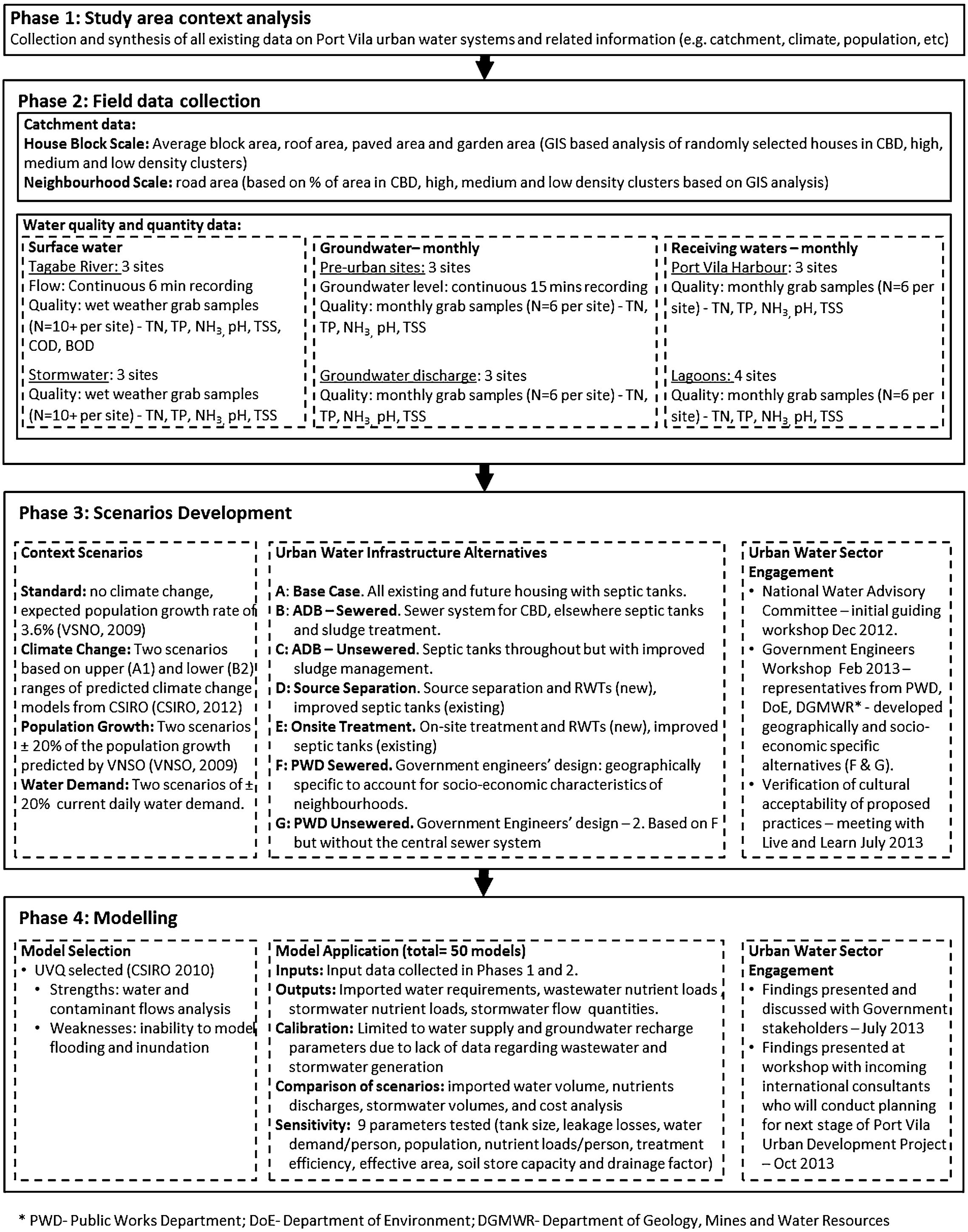


Fig. 1 Diagrammatic representation of the research methodology used

are serviced with piped drainage, but due to urbanization, poor maintenance, and tropical rainfall events, these systems' capacity is often exceeded; inundation causes significant disruption and public nuisance.

Economic growth has resulted in improved water supply reliability and coverage of flush toilets but has subsequently led to the pollution of surrounding water bodies. The Tagabe River, Port Vila Harbor, Mele Bay, Emten, and Erakor Lagoons [traditionally nutrient deficient tropical water bodies, (Mosley and Aalbesberg 2003)] are already negatively impacted by increased nutrient inflows (ADB 2010).

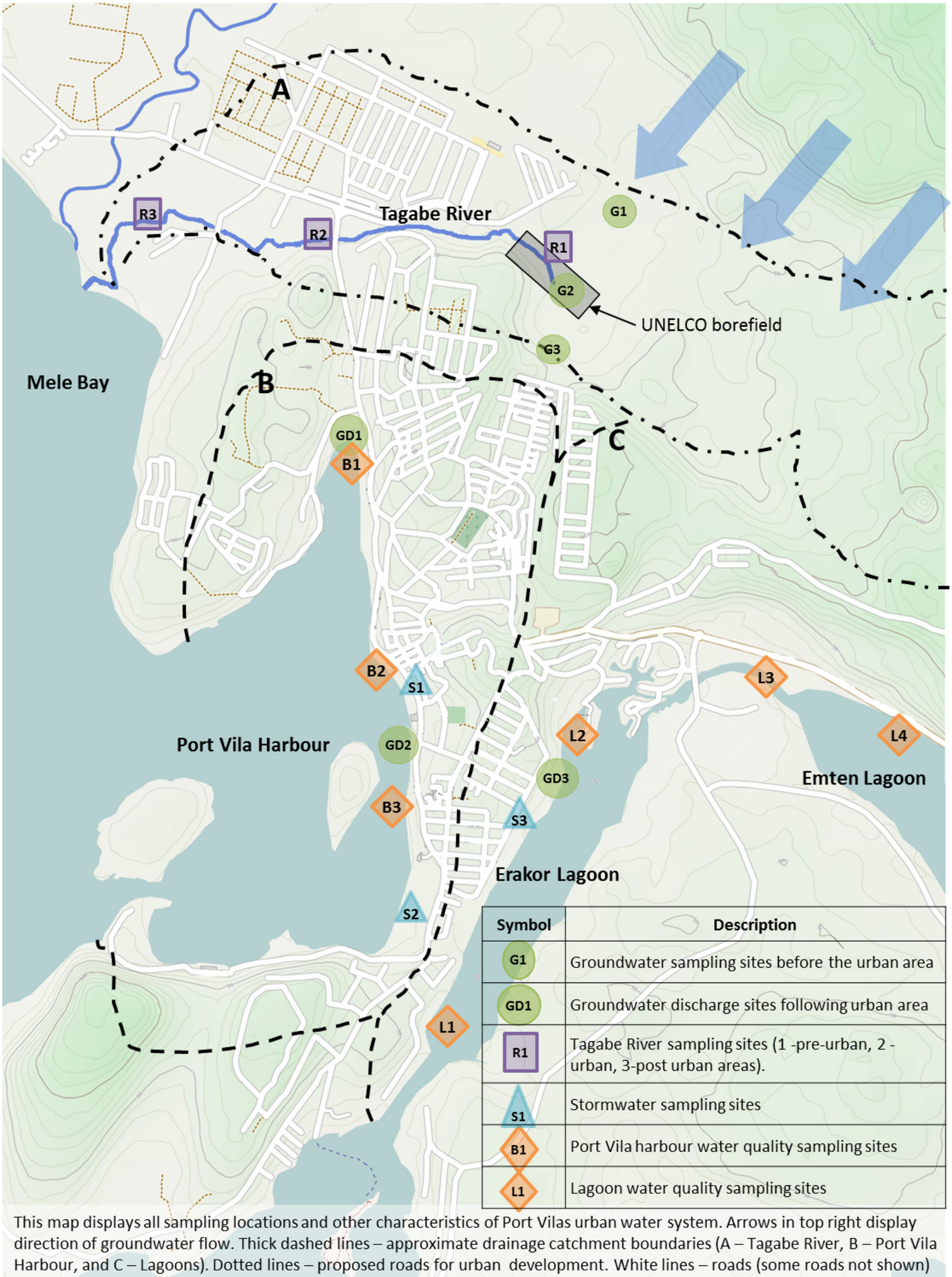


Fig. 2 Port Vila: current water infrastructure and all field sampling sites (refer to Fig. 1)

Data on the water system in Port Vila remain scarce. Rainfall and evaporation data, flow rates and water quality of the Tagabe River, and groundwater levels monitored by the Government. These data sources, as well as daily groundwater extraction rates (2006–2011) and total monthly billed volumes (2006–2011) collected by UNELCO, were used in this research. Socio-economic data were sourced from the 2009 national census (VSO 2010).

Field data collection

Catchment data

Existing GIS and satellite imagery were utilized to estimate catchment area and land uses (e.g., road, roof, garden and paved area). These estimates were validated through randomly selected site visits which provided measured physical data and checked the accuracy of Government census data.

Water data

Additional hydrological and water quality data were collected between November 2011 and May 2012. As presented in Figs. 1 and 2, the monitoring program assessed surface water, groundwater, stormwater, and receiving water characteristics (Fig. 2 shows all monitoring points' positions).

Groundwater levels were monitored continuously (15-min intervals) at 3 boreholes located north-east of Port Vila (G1–3, Fig. 2). Grab samples were collected monthly from 3 groundwater discharge locations near the CBD (D1–3, Fig. 2). Three sites along the Tagabe River were selected: upstream, within, and downstream of the urban area (R1–3, Fig. 2). Sites R1 and R3 had water level gages, although high flow data were not used as readings during high flow events were unreliable and clearly inaccurate due to monitoring system failure. During rainfall events, river grab samples were collected and analyzed. Stormwater grab samples were also collected during rainfall events from within stormwater drains (S1–3, Fig. 2). Water quality parameters were monitored on a monthly basis within Port Vila Harbor (B1–3, Fig. 2) and the lagoons (L1–4). All water samples were analyzed by the UNELCO water laboratory and the water laboratory of the Department of Geology, Mines and Water Resources.

Scenarios development

Through engagement with stakeholders, seven different technical alternatives and seven different future context scenarios were developed for 2050, resulting in 49 alternative future scenarios.

Urban water sector engagement

As a discursive approach is required for robust urban water planning (Dominguez et al. 2011), Port Vila's urban water sector was engaged throughout the scenario development process. This included engagement with the National Water Advisory Committee (NWAC) and middle to senior level government officers.

Technological alternatives

Figure 1 and Table 1 list all technological scenarios. Alternative A-2015 reflects the current state of infrastructure, incorporates 2015 population projections, and assumes the completion of the Port Vila Urban Development Project's (PVUDP) drainage and road redevelopments (ADB 2010). Alternative A-2050 assumes the same infrastructure but with population projections for 2050. Alternatives B-2050 and C-2050 were based on infrastructure proposals from the PVUDP (ADB 2010). Alternatives D-2050 and E-2050 were developed to incorporate innovative management approaches into the urban water sector. These five alternatives were initially proposed and presented to the NWAC in December 2012. The authors refined these alternatives as per feedback from the NWAC and from government directors and director generals.

Alternatives F-2050 and G-2050 were developed by Vanuatu government representatives (mainly engineers and scientists) during a technical workshop held in Port Vila in March 2013. Geographical and urban planning information (e.g., large maps and local knowledge of topology, demographics, land use, future development pathways, etc.) were used to assist the group to determine which alternative technologies would be of greatest benefit to specific areas within Port Vila. The technologies and their best suited locations were recorded on system maps, creating the scenarios of future infrastructure planning for water supply, wastewater, and stormwater to generate Alternatives F-2050 and G-2050.

Acceptance of alternatives

Critical for the successful implementation, use, and maintenance of new infrastructure is an acceptance and ownership from individual users, corporate society, and politicians (Poustie et al. in press). A summary of the acceptance of the alternatives from both public and political perspectives is presented in Table 2. During the alternative development stage, both governmental and public acceptance were discussed with the National Water Advisory Committee and with Live and Learn representatives (Vanuatu's largest grass roots, community engagement NGO working in the water and sanitation sector).

Table 1 Summary of technology alternatives used for modeling

Alternative*	Name	Water supply	Wastewater	Stormwater
A-2015	Base 2015	Groundwater extraction and central piped distribution	Septic systems throughout with poor removal efficiency	Increased connectivity and increased pit-pipe system. With no stormwater treatment. No modeling of urban flooding
A-2050	Base 2050		Septic systems throughout: existing systems have poor removal efficiency; new dwellings have average removal efficiency	
B-2050	ADB—sewered		Sewered system to WWTP in CBD	
			Septic tanks in the rest: all septic systems have improved removal efficiency, and sludge is treated at a central facility	
C-2050	ADB—unsewered		Septic systems throughout: all septic systems have improved removal efficiency, and sludge is treated at a central facility	
D-2050	Source separation	Groundwater extraction and central piped distribution	Source separation in new dwelling:	Increased connectivity and increased pit-pipe system. With no stormwater treatment
		2KL tank in new dwellings	Septic tanks in the existing dwellings: all septic systems have improved removal efficiency, and sludge is treated at a central facility	Rainwater tanks installed in new dwellings
E-2050	Onsite treatment		Onsite post-septic tank wastewater treatment in new dwellings (suitable for developing country/tropical conditions)	No modeling of urban flooding
			Septic tanks in the existing dwellings: all septic systems have improved removal efficiency, and sludge is treated at a central facility	
F-2050	PWD—sewered		Sewered system to WWTP in CBD and central clusters for both new and existing dwellings	
			Septic tanks in the existing dwellings: all septic systems have improved removal efficiency, and sludge is treated at a central facility	
			Onsite post-septic tank wastewater treatment in new dwellings in wealthy communities	
			Source separation and composing toilets in new dwellings in low socio-economic areas	
G-2050	PWD—unsewered		Septic tanks in the existing dwellings including CBD: all septic systems have improved removal efficiency, and sludge is treated at a central facility	
			Onsite post-septic tank wastewater treatment in new dwellings in wealthy communities	
			Source separation and composing toilets in new dwellings in low socio-economic areas	

Table 2 Socio-political acceptance of technical alternatives

Alternative A: Base 2050	Not desired by Government due to fear of impacts on environment and tourism. Not desired by public but due to past policy failures the public expects status quo
Alternative B: ADB sewered	Desired by Government as it reflects Australian/New Zealand conditions reflecting an infrastructure "expectational lock-in." Desired by public but they perceive there to be very little chance of successful implementation and operation. Economically viable but government not yet willing to undertake loan required for implementation
Alternative C: ADB unsewered	Also desired by government, as it will address urban inundation. Will begin to improve wastewater management without the perceived prohibitive economic capital costs of Alternative B. Supported by public as it removed the nuisance of inundation. Minimal impact on public from wastewater management changes
Alternative D: Source separation; and Alternative E: On-site treatment	These two alternatives (developed by authors prior to the stakeholder engagement processes) reflect the most significant changes in public behavior and therefore would be more challenging to gain political support and community ownership. Engagement with the National Water Advisory Committee suggests that these alternatives would require the most significant non-structural engagement process to develop community acceptance
Alternative F: PWD—sewered; and Alternative G: PWD—unsewered	These two alternatives (developed by the Public Works Department (PWD)) are both desired by technical government officials. Politicians and the wider public would likely still prefer B due to perceived risk and lack of knowledge of innovative infrastructure solutions proposed.
	Similar to Alternative B, the sewer system (Alternative F) is perceived as having minimal chance of implementation. Alternative G is more viable, with extensive support. Innovative components reflect socio-economic ability to implement

A further discussion addressing the economic suitability of the alternatives in light of the current economic state of the Government of Vanuatu is presented in "Economic Analysis" section.

Context scenarios

Context scenarios were designed to assess changes that are outside stakeholders' control. This paper identified context scenarios relating to climatic, population, and water demand pressures over a 35 year timeframe (Fig. 1; details in Table 3). Two climate change context scenarios were developed from existing Australian Bureau of Meteorology, and CSIRO (2011a, b), representing high emission ("climate change—high") and low emission projections ("climate change—low"). Context scenarios based upon changes in population growth patterns (growth rate of 3.0, 3.7 and 4.3 %, for low, standard and high) and indoor water use requirements (reflecting 20 % increased and 20 % decreased water demand from current usage) were also included. The context scenarios were broadly developed by the authors and further refined at the workshop with NWAC; final scenarios are presented in Table 3. Standard 2015 was applied only to Alternative A-2015, while other contexts were applied to all other technological alternatives, creating 50 scenarios for modeling.

Scenario modeling

Model selection

Assessment of the future urban water alternatives was conducted using Urban Volume and Quality (UVQ) model, a conceptual integrated urban water model (Mitchell and Diaper 2005b). UVQ allows application of both conventional and non-conventional technologies for water supply and wastewater management (and to some extent stormwater management) and assesses both volumes and contaminant fluxes from source to discharge (Mitchell and Diaper 2006). Unlike other similar studies in developing countries which utilize yearly averages (Huang et al. 2007; Montangero et al. 2007; Do-Thu et al. 2011), UVQ enabled this study to use a daily time step. UVQ is a lumped parameter model that requires a modest level of input data, and this was a main driver for its selection over more data intensive models (such as MOUSE, MIKE URBAN, or SWMM). A trade-off made was the lack of spatial representation and inability to model the hydraulics of urban drainage systems, thus removing the possibility of assessing urban flooding implications. However, UVQ was able to assess the key stormwater pollution load implications of the alternatives.

The UVQ model was selected as it is able to (i) compare water supply and wastewater management alternatives against the traditional approaches, (ii) quantify key relationships between different urban water streams (e.g., impact of rain harvesting on both water demand and pollution control), (iii) run with modest data inputs, and (iv) run fast, allowing for the exploration of 50 different scenarios.

UVQ is shown diagrammatically in Fig. 3; details can be found in Mitchell and Diaper (2005a). A nested spatial scale representation of urban areas is used that includes the house scale, the neighborhood "cluster" scale, and the city scale. The house comprises roof, paved, and garden areas; the cluster scale comprises street and public open space areas in addition to multiple identical house blocks, while the city

Table 3 Context scenarios and input data for UVQ modeling

Context scenario parameters	Standard 2015	Standard 2050	Population growth[b]		Climate change[b]		Water demand[b]		Confidence
			High	Low	High	Low	Increased	Decreased	
Population[a]	62 055	150 872	181 047	120 698	150 872	150 872	150 872	150 872	Low
People/household[a]	4.8	6	7.2	4.8	6	6	6	6	High
Water demand (l/p/d)[a]	208	208	208	208	208	208	249	166	Medium
Precipitation (mm/yr)[a]	2066	2066	2066	2066	2129	2087	2066	2066	Medium
Evaporation[a]	1860	1860	1860	1860	1970	1970	1860	1860	Low

Infrastructure alternatives	Units	A-2015	A-2050	B-2050	C-2050	D-2050	E-2050	F- and G- 2050	Confidence
Water demand[L1]									
Kitchen	L/p/d	39	39	39	39	39	39	See below	Medium
Bathroom	L/p/d	86	86	86	86	86	86		Medium
Toilet	L/p/d	47	47	47	47	7[L1a]	47		Medium
Laundry	L/p/d	36	36	36	36	36	36		Medium
Rainwater tank	m^3	0	0	0	0	2	2		High
TN removal									
Existing homes	%	10[L2]	10[L2]	30[L3]	30[L3]	30[L3]	30[L3]		Medium
New homes	%	N/A	15[L2]	30[L3]	30[L3]	79[L5]	84[L6]		Medium
Centralized WWTP	%	N/A	N/A	N/A	75[L4]	N/A	N/A		Medium
TP removal									
Existing homes	%	10[L2]	10[L2]	35[L3]	35[L3]	35[L3]	35[L3]		Medium
New homes	%	N/A	15[L2]	35[L3]	35[L3]	70[L5]	97[L6]		Medium
Centralized WWTP	%	N/A	N/A	N/A	80[L4]	N/A	N/A		Medium

Cluster specific parameters	Units	Socio demographic context				
Alternative F-2050 and (G-2050)		CBD[4]	High[4]	Medium[4]	Low[4]	Confidence
Water demand						
Kitchen	L/p/d	39	49	39	20	Medium
Bathroom	L/p/d	86	96	86	43	Medium
Toilet	L/p/d	47	57	47	23	Medium
Laundry	L/p/d	36	46	36	18	Medium
Rain tanks						
New dwellings	KL	2	2	2	2	High
TN removal						
Existing homes (G)	%	75[L4] (30[L3])	30[L3]	30[L3]	30[L3]	Medium
New homes (G)	%	75[L4] (30[L3])	84[L6]	52.5[L7]	79[L8]	Medium
TP removal						
Existing homes (G)	%	80[L4] (35[L3])	35[L3]	35[L3]	35[L3]	Medium
New homes (G)	%	80[L4] (35[L3])	97[L6]	57.5[L7]	70[L8]	Medium

Cluster specific parameters	Units	Cluster density (A-2015)			Cluster density (A-2050–F-2050)				
		CBD	Medium	Low	CBD	High	Medium	Low	Confidence
Average block size[b]	m^2	1314	600	1092	450–800	180–250	400–600	600–800	High
Average roof size[b]	m^2	907	250	320	200–400	150	150–200	150–200	High
Average paved area[b]	m^2	296	0	0	230–300	0	0	0	High
Average garden size[b]	m^2	111	350	772	20–200	30–100	250	450–650	High
Road area (% of cluster area)[b]	%	9–11	7.0–9.0	4.0–5.5	9–11	8–10	7.5–8.5	5.0–6.0	Medium

Table 3 continued

Constant parameters	Units		Confidence	Calibration values		Confidence
Nutrients to wastewater[L9]				Roof area initial loss[L10]	0.5	Medium
Kitchen—N	g/p/d	0.3	Medium	Effective roof area[b]	50–85 %	Medium
Kitchen—P	g/p/d	0.1	Medium	Paved area initial loss[L10]	0.1	Medium
Bathroom—N	g/p/d	0.35	Medium	Effective paved area[b]	50–85 %	Medium
Bathroom—P	g/p/d	0.2	Medium	Road surface initial loss[L10]	0.2	Medium
Toilet—N	g/p/d	8.2	Medium	Effective road surface area[b]	50–85 %	Medium
Toilet—P	g/p/d	1.2	Medium	Contaminant soil store removal[L10]	0	Low
Laundry—N	g/p/d	0.28	Medium	Wastewater infiltration index[L10]	0.001	Low
Laundry—P	g/p/d	0.2	Medium	Garden irrigation[a]	0	High
Stormwater quality[b]						
TN	mg/L	1.3	High	Public open space irrigation[a]	0	High
TP	mg/L	0.34	High			

[a] Data collected through field measurement throughout entire study area

[b] Data collected through field measurements within study from a limited number of sites and extrapolated to entire study area

[L] Literature. Input parameters sourced from the local or international literature and assumed to be accurate and acceptable values for application in Port Vila

[L1] The ratio of indoor water use is based on the literature (Huang et al. 2007)

[L1a] Allows for 7L/p/d for feces flush, with urine diverting toilets (Huang et al. 2007)

[L2] Nutrient removal in poor performing septic systems (Montangero and Belevi 2008) this reflects known condition of majority of septic systems in Port Vila (ADB 1998)

[L3] Best possible nutrient removal efficiency of septic systems expected in Port Vila (von Sperling et al. 2005)

[L4] Proposed wastewater treatment plant nutrient removal efficiency (ADB 2010)

[L5] Allows for 80 % successful urine diversion and nutrient collection. Then standard nutrient removal for feces/misdirected urine in septic system

[L6] Total removal efficiency after septic treatment then onsite effluent treatment (Chang et al. 2011) suitable in developing, tropical context (Parkinson and Taylor 2003)

[L7] Allows for 50 % connection to WWTP and 50 % septic systems (ADB 2010)

[L8] Allows for 80 % successful urine diversion and nutrient collection. Then standard nutrient removal for feces/misdirected urine in septic system

[L9] Nutrients per person per day to excreta are diet dependent with no local data. Parameter values based on Huang et al. (2007)

[L10] These stormwater and wastewater parameter values based on Mitchell and Diaper (2005b)

[L11] CBD—2 clusters; high density—2 clusters; medium density—2 clusters; low density—3 clusters

scale incorporates all of the clusters allowing for similar or different water servicing options between clusters.

The model contains three inter-related and connected sub-modules that simulate water supply volumes, wastewater discharges, and the stormwater discharges (but not peak flows needed for flood assessment). The UVQ model is based on a mass balance approach using known relationships between the water stores and flow paths (Fig. 3) to calculate water fluxes at daily intervals.

Model application: selection of inputs and calibration

UVQ inputs were based on data gathered in Stages 1 and 2 of this project (Fig. 1), and in some cases assumed from the literature, as outlined in Table 3.

Water supply module: National census data (VSO 2010) determined residents per household and households per cluster. The average daily water demand per person is approximately 208 L/p/day (ADB 2010) within the range reported in the literature from other tropical developing contexts (Otaki et al. 2008). The breakdown of internal water consumption patterns (Table 3) was based on the international literature values (Huang et al. 2007; Otaki et al. 2008). Outdoor irrigation parameters were set to zero, due to the year-round wet tropical climate. Water supply system leakage was 20 % (UNELCO unpubl.).

The model calculated imported water volumes for each cluster, accounting for varying indoor water demand, use of water from rainwater tanks (if present), including the reliability of rainwater tanks and the percentage of water supplied from alternative sources.

Wastewater module: There have been no studies on nutrients in human urine, excreta or graywater in Vanuatu or other Melanesian countries, so data from Vietnam and

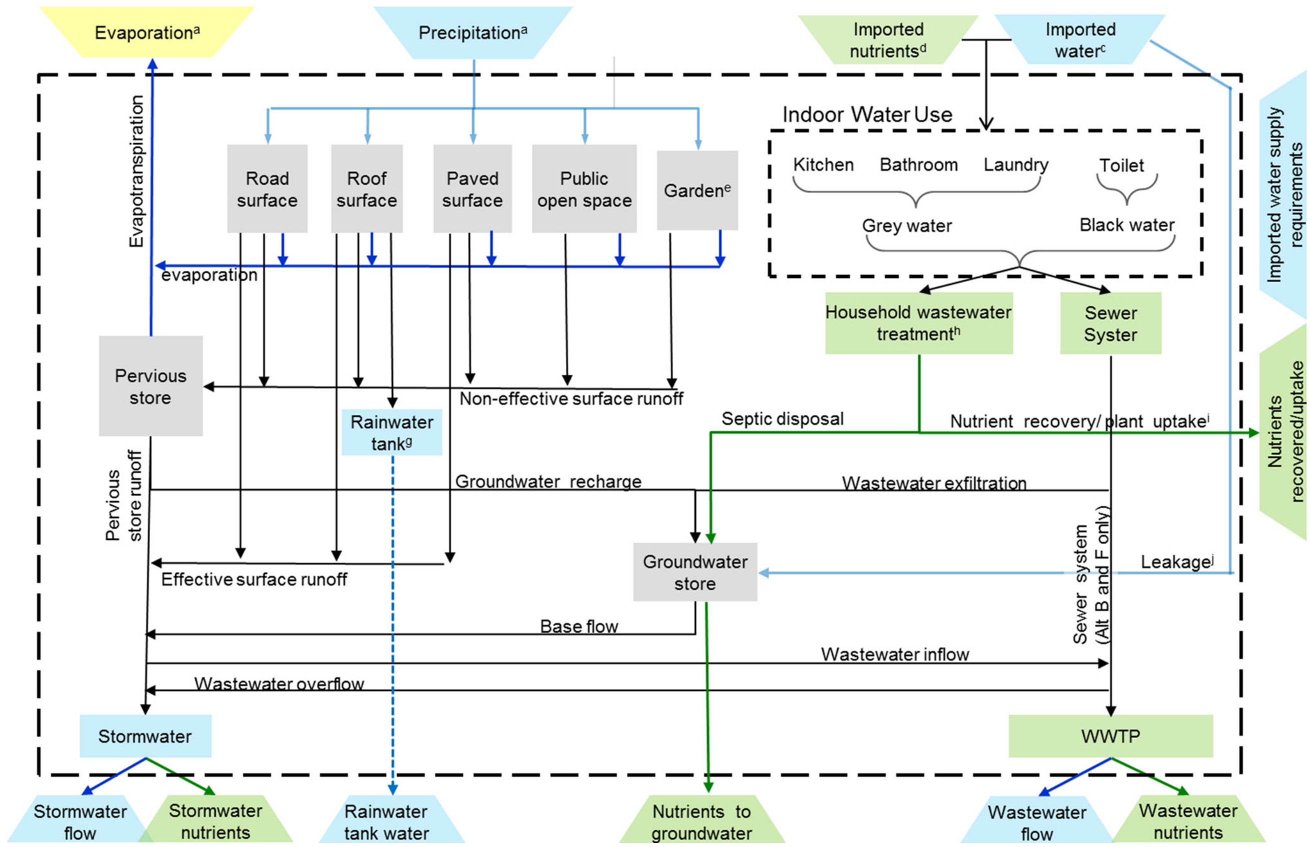


Fig. 3 Diagram of model relationships. Adapted from Mitchell and Diaper (2005b)

China have been used (Jönsson and Vinneraas 2004; Huang et al. 2007; Montangero and Belevi 2008). Nitrogen and phosphorous effluent loads were characterized as either (i) recoverable (sludge production for agricultural use or captured in closed systems), (ii) infiltrated into groundwater, (iii) discharged from centralized wastewater treatment facilities into the bay, or (iv) utilized by plants through biological treatment processes ("plant uptake").

Stormwater module: Climate data used were the daily precipitation and evaporation data collected by the Vanuatu Meteorological Services (VMS unpublished). The total imperviousness of individual households was calculated using GIS analysis of aerial imagery; calculating total roof, paved and garden areas. Data for road areas within clusters were calculated using the total road length per cluster and the average road width as per the PVUDP (ADB 2010). However, approximation was required to determine the effective imperviousness, based upon estimations made by the international consulting team for the PVUDP. An effective imperviousness of 0.75–0.85 in the CBD and high density clusters and 0.5–0.6 in medium and low density clusters was selected (Williams, pers. comm.).

Calibration of a further five model parameters, listed in Table 4, was required. The water supply module was calibrated (i.e., water supply leakage) using Port Vila's groundwater extraction and total billable usage data. The stormwater module parameters (drainage factor ratio, soil store capacity, soil store field capacity, and maximum daily drainage depth) were calibrated to reflect the groundwater recharge as 30 % of annual rainfall as estimated by Depledge (1994) for exposed limestone [which correlates with field based groundwater monitoring and the work of Ash et al. (1978)]. Calibration was conducted by the stepwise adjustment of the four parameters in an entirely undeveloped cluster (zero impervious area), until the average annual groundwater recharge was 30 % of rainfall, accurate to 0.5 %.

Since there are currently no data collected on wastewater production, the wastewater module was not calibrated—it fully relied upon assumed parameters values.

Model application: scenario comparison and sensitivity

Following calibration, the model was run for the 50 scenarios. Scenarios were compared for imported water requirements, the magnitude and pathways of nutrients loads from wastewater, and the quantity of stormwater generation. An economic assessment was conducted to contrast the approximate costs of the technical alternatives,

Table 4 Calibration parameters and relevant objective functions

Parameter	Objective function utilized in calibrations	Initial value	Initial confidence	Calibrated value
Water supply leakage (%)	Modeled water consumed in households equals UNELCO volume measured	20	Medium	27
Soil store capacity (mm)	Modeled groundwater infiltration equals 30 % of rainfall from non-developed pervious surfaces	200	Low	230
Soil store field capacity (mm)		150	Low	160
Maximum daily drainage depth (mm)		150	Low	210
Drainage factor ratio		0.5	Low	0.8

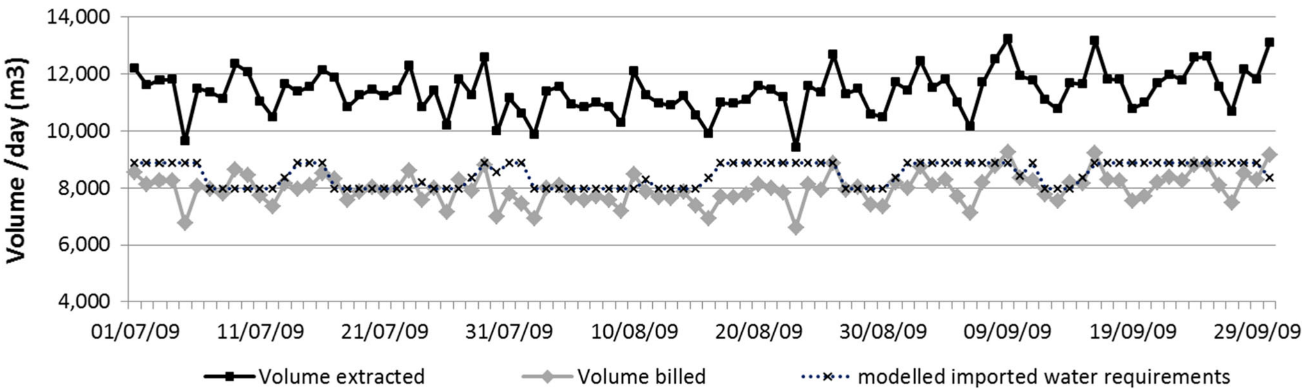


Fig. 4 Comparison of extracted volume, volume billed allowing for pipe system losses (27 %), and the calibrated model results

including both cost per ton reduction in nutrient released, and a capital and maintenance cost analysis. Data used for the capital and maintenance cost assessment were drawn from the PVUDP documentation, or where local cost estimates were not available, and estimates from Australian case studies or literature were used.

A sensitivity analysis of the model's input parameters was undertaken. Input parameters, which according to the literature should be sensitive (Mitchell and Diaper 2005a; Montangero and Belevi 2008; Martinez et al. 2011) were selected for water supply (size of rainwater tank, water supply leakage loss, per person water demand, and population), wastewater (excreta nutrient loads, treatment removal efficiency, and population) and stormwater (effective area, soil store capacity, and drainage factor). These parameters were systematically altered by 10 % above and below the original values (Table 3), and the impacts were recorded.

RESULTS

Water supply

During calibration of the water supply module, the water supply leakage parameter was adjusted from 20 to 27 %, so that modeled and billed (measured) imported volumes match, as shown in Fig. 4.

Results show (Fig. 5a) that technical alternatives significantly impacted the imported water requirements. Alternatives A-2050, B-2050, and C-2050 all incorporated high water use flush toilets and resulted in the largest imported water requirements. Alternative E-2050 decreased the imported water supply requirement by 23 % through the introduction of rainwater tanks into new residential dwellings. Alternative D-2050 decreased imported water requirements by a further 12 % totalling a 35 % reduction from Alternative A-2050 through the combination of both urine diverting toilets (low flush requirements) and rainwater tanks. Alternatives F-2050 and G-2050 resulted in a 22 % drop in imported water requirements, the result of the introduction of rainwater tanks in new dwellings in wealthy clusters and source separation, and composting toilets in low socio-economic clusters.

Population increases (Fig. 5a) and water usage variation strongly influenced imported water requirements. Based on current patterns of demand, the predicted increase in population between 2015 and 2050 will result in a 400 % increase in imported water supply requirements (likely requiring a new water source with significant capital investment).

Imported water supply requirements were impacted negligibly by climate change. Alternatives D-2050, E-2050, F-2050, and G-2050 which all incorporate rainwater tanks were the only changes, and they only recorded a 3 % decrease in water supply requirements for the high

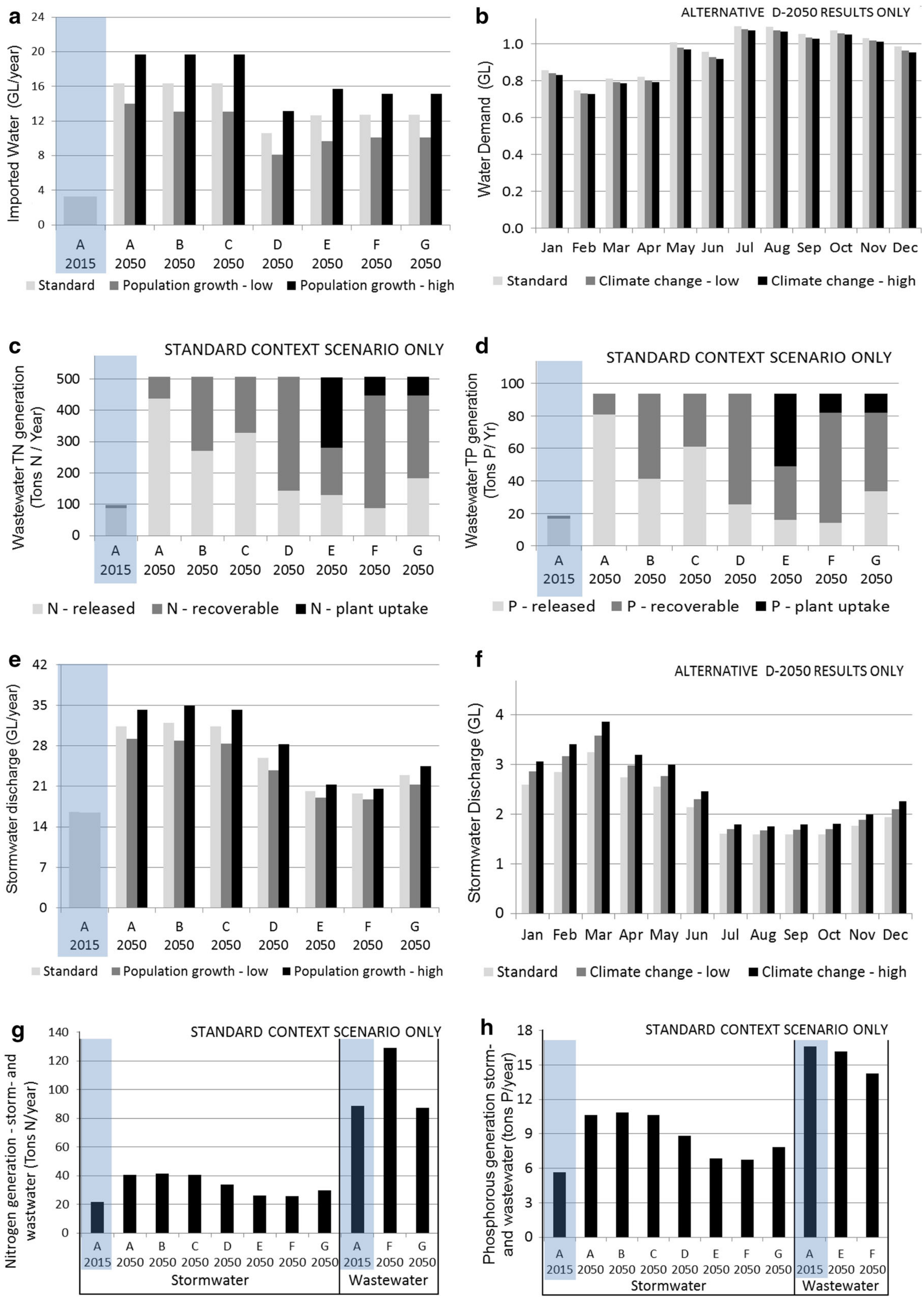


Fig. 5 Results of UVQ modeling for Port Vila: **a** imported water demand, **b** impact of climate change on imported water requirements for Alternative D by month, **c** nitrogen and **d** phosphorous loads for the standard context scenario, **e** stormwater quantity generation with population growth scenarios, **f** impacts of climate change on stormwater generation for Alternative D by month, **g** nitrogen and **h** phosphorous loads from stormwater and wastewater

emissions scenario despite its predicted increase in annual rainfall (Fig. 5b).

The most sensitive parameters for water supply were population, daily water demand, and leakage losses which all resulted in a 10 % change in water supply requirements. The size of rainwater tank was much less sensitive with a 10 % increase in tank size only decreasing water supply requirement by 1.2 %.

Wastewater

Figure 5c and d shows that the selection of wastewater infrastructure resulted in both a range of nutrients pathways and impacted the magnitude of flows. Alternative A-2050 had the largest increase of nutrient loads released to groundwater. Alternatives B-2050 and C-2050 resulted in a 38 and 25 % decrease of nutrients released in comparison to A-2050. Alternative D-2050 produced significant reductions in nutrients loads, 66 % from A-2050. Alternative E-2050 resulted in a 70 % reduction, the use of onsite wetland systems directed 44 % of the total nutrient load to absorption by plant uptake, 30 % recoverable through dried sludge and 26 % released to groundwater. Alternative F-2050 performed the best and released fewer nutrients than the 2015 scenario, an 80 % decrease from A-2050 as the result of a sewerage treatment system in the CBD, improved septic treatment in new dwellings in high socio-economic clusters, and composting and source separation toilets in lower socio-economic clusters. Alternative G-2050 resulted in a 58 % decrease from A-2050; in comparison to F-2050, this decrease in performance was due to not upgrading septic systems to a sewerage treatment system in the CBD and central clusters.

The population change scenarios were the only context scenarios which impacted wastewater nutrient loads. There was a direct one-to-one relationship; 20 % increase in total population resulted in a 20 % increase in nutrient loads generated. Climate change and water demand scenarios did not impact nutrient loads.

The most sensitive parameters impacting contaminants released were population size and daily per person contaminant loads. The impact of increasing the removal efficiency by 10 % ranged from between 4.5 and 10 % decrease in nutrient released depending on the technical wastewater combinations incorporated into the alternatives.

Stormwater

Calibration of stormwater infiltration parameters resulted in increased parameter values, Table 4; these results represented the high infiltration capacity of limestone based geology.

All technical alternatives for 2050 displayed increased stormwater generation compared to 2015 (Fig. 5e). Alternatives A-2050, B-2050, and C-2050 resulted in the greatest quantity of runoff. The introduction of rainwater tanks (alternatives D-2050, E-2050, F-2050, and G-2050) resulted in a decrease between 18 and 38 % from Alternative A-2050. Alternatives E-2050 and F-2050 utilized greater volumes of collected rainwater, leading to increased tank space for stormwater capture and larger decreases in stormwater generation, see Fig. 5e.

The context scenarios demonstrated the potential impacts of population growth and climate change on stormwater generation (Fig. 5e, f). The high population growth scenario also resulted in increased run off (Fig. 5e), as did both climate models (Fig. 5f).

There continues to be significant uncertainty around the impacts of climate change in the South West Pacific region with the current literature suggesting a possible change in annual precipitation for different climate scenarios of between +1 % (±12) and +3 % (±16) (Australian Bureau of Meteorology and CSIRO 2011a). There is greater certainty of the seasonal impacts with wetter wet seasons and longer and more extreme seasons of dry weather (Australian Bureau of Meteorology and CSIRO 2011b), with likely more intense and larger rainfall events increasing urban drainage pressures.

Within the stormwater module, there remained significant parameter uncertainty. The most sensitive parameters were the effective area (roof, paved, and road areas) which resulted in an increase of 8.5 % and roof area (7 % increase). Drainage factor and daily drainage depth were relatively insensitive, supporting the work of Martinez et al. (2011).

Stormwater and wastewater nutrient loads comparison

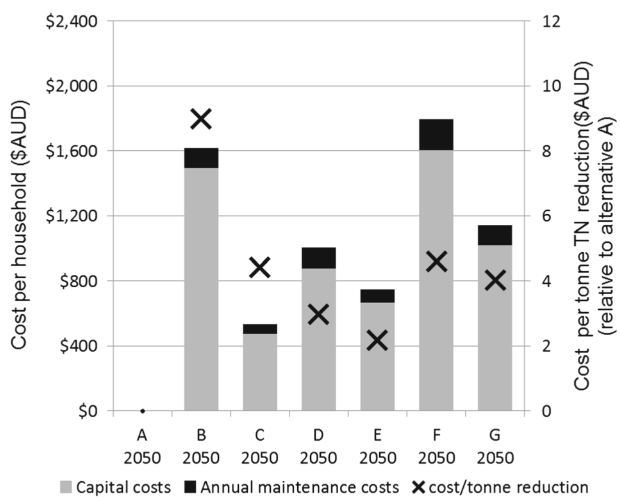
In A-2015, wastewater released through septic systems contributed the majority of nutrient loads (80 % of nitrogen and 75 % of phosphorous), with the remaining component from stormwater (Fig. 5g, h). Future scenarios demonstrated that by 2050, nutrient loads from stormwater contributed significantly due to increased stormwater quantity, and the possibility of decreased wastewater nutrient loads due to alternative infrastructure alternatives. By 2050, Alternatives A-2050, B-2050, and C-2050 (Fig. 5g, h) resulted in the stormwater nitrogen and phosphorous loads doubling in comparison to A-2015. Stormwater loads therefore potentially contributing up to 76 and 48 % of the phosphorous and nitrogen loads from wastewater, respectively.

Economic analysis

Figure 6 presents the results of the economic analysis for both cost per ton nutrient reduction relative to A-2050 and the combined capital and maintenance costs. Based on cost per ton of nitrogen reduction, Alternative B-2050 was the most expensive resulting in AUD$8.98 per ton of total nitrogen reduction. Alternatives D-2050 and E-2050 were the most economically efficient systems reducing nitrogen at $2.99 and $2.17 per ton, respectively. Alternative B-2050 and Alternative F were the most expensive to implement due to sewerage system construction costs greater than AUD$1,500 per house (not including on lot construction costs—ABD 2010). Alternative C-2050 was the cheapest alternative at less than $500 per house plus maintenance. Alternatives D-2050, E-2050, and G-2050 were within these extremes, but the total cost for these alternatives was dependent on the value of government subsidy attached to any decentralized solutions. Therefore, from both a total costs and an economic efficiency perspective, alternatives D-2050, E-2050 and G-2050 outperform the alternatives recommended by the ADB.

Economic capacity

The ability of the Government of Vanuatu to independently undertake extensive infrastructure investment is limited based due to the national economic capacity. However, it is greatly enhanced through the enabling support from the Governments of Australia and New Zealand which support "critical nation building infrastructure projects" (Government of Australia 2014). The combined support from these nations along with access to loans from international development banks makes all of the alternatives presented viable (Director General—Ministry for Internal Affairs, pers. comm.).



Assumptions and data for economic analysis

A-2050 – No costs associated with A-2050 - base comparison for all other cost assessments.

B-2050 – Based on ADB detailed costings (ADB, 2010).Includes construction of mains sewer and wastewater treatment plant. As outlined by ADB (2010) does not include any costs associated with connections from sewer mains to individual houses as these costs were to be carried by households, nor does it account for economic and business losses associated with road closures during construction.

C-2050 – Based on ADB detailed costings (ADB, 2010). Includes construction of sludge drying and nutrient recover plant, purchase of additional sludge tankers.

D-2050 and E-2050 – based on 'C' for sludge drying facility, plus government contribution for rainwater tanks (A$400), wetland construction (A$300) and source separation toilet (A$300) for new dwellings. Acceptable to require some purchase costs to be carried by households to remain comparable to alternative B.

F-2050 and G-2050 – based on 2/3 cost of 'B' for sewer system (servicing only CBD and central clusters, plus government contribution for other technologies as outlined in D and E, plus composting toilets fully funded to low socio-economic areas (A$500)

Fig. 6 Economic assessment: displaying capital and maintenance costs calculated per house, and cost per ton decreased nitrogen released on secondary axis. All assumptions and data requirements are outlined in text

DISCUSSION

Projected population growth and the shortcomings of the current water system suggest that radical improvements and infrastructure investments are required. This section discusses the implications of the results.

Uncertainty and limitations

Despite field-based data gathering, uncertainties remain due to both assumed input values and inaccuracies in data collected. Sensitivity analysis found that the most sensitive parameters were population, nutrient emissions, and effective areas. These parameters are independent of infrastructural alternatives and therefore do not impact the relative performance. The greatest uncertainty affecting performance is the release of nutrients due to wastewater treatment efficiency input parameters. Uncertainty of treatment efficiency is consistent across MFA research, with previous work suggesting that despite uncertainty, the relative performance ranking of alternatives will not be impacted (Huang et al. 2007; Montangero et al. 2007).

Without removing all uncertainty, this methodology increases the confidence of calculated contaminant flows, demonstrates relative performance of alternatives, and highlights the potential for innovative solutions to persistent urban water problems in Port Vila.

Water supply

To accommodate the predicted increases in imported water requirements, alternative water sources and water demand management should be proactively promoted. Rainwater tanks present an effective alternative source given the year-round rainfall patterns. In addition to increasing supply diversity, water demand management including both structural means (e.g., supply loss minimization and water saving technologies) and non-structural means (e.g., public education campaigns and financial incentives/disincentives) is required to stymie total imported water demand growth.

Wastewater

Urine diversion (Larsen et al. 2009) and dry sanitation should be considered for implementation in sanitation planning. Their pollution reduction is significant (Vinnerås and Jönsson 2002), and their suitability continues to be demonstrated in tropical urban contexts both generally (Zhang et al. 2013) and specifically for Port Vila (Live and Learn Vanuatu, pers. comm. 2013).

An increased dependence on agricultural fertilizer is predicted in the next decade (Molyneux et al. 2012), so the use of recycled nutrients from alternative sanitation presents a potential source of organic fertilizer (Etter et al. 2011). This is a preferred alternative to the economic burden and environmental risk of high nutrient runoff associated with synthetic fertilizer (Mosley and Aalbesberg 2003).

The treatment of septic effluent in small constructed wetlands presents another possibility in wastewater management. Enabling plant-based nutrient uptake (Chang et al. 2011), it is a cheap, low technology, low energy approach to wastewater management and in warm tropical climates; it promotes rapid plant growth and nutrient removal, while enabling local urban agriculture and can be used as a source of local fresh produce.

Stormwater

Stormwater, while currently not the major concern in Port Vila, will increasingly contribute to the nutrient loading of Port Vila's receiving waters. Results suggest the importance of incorporating stormwater management into current infrastructure planning, rather than retrofitting sustainable drainage management approaches into an established, environmentally degrading system in 35 years. These measures to reduce stormwater quantity and to treat stormwater prior to release will assist Port Vila avoid future environmental degradation. Port Vila's porous geology and relatively low density development present suitable conditions for the implementation of sustainable drainage technologies, particularly through promoting infiltration, decreasing stormwater generated, and improving stormwater quality released into receiving waters. Future stormwater policy can implement sustainable urban drainage and water sensitive principles to minimize potential degradation.

Future scenario impacts

Climate change poses very real challenges to Vanuatu and other small island developing states (Barnett et al. 2007). It has potential to negatively impact fisheries (Robin South et al. 2004; Allison et al. 2009), agriculture (Molyneux et al. 2012), and tourism (Moreno and Becken 2009). However, results presented in this paper suggest that rapid urban population growth is posing greater and more imminent pressure than climate change on the urban water sector [similar to previous research findings regarding food security in East Timor (Molyneux et al. 2012)]. Urban water infrastructure policy should primarily concentrate on ensuring infrastructure and services availability to the

growing urban population, while ensuring technical designs allow for potential climate changes impacts.

Implications for urban water infrastructure planning in the developing world

It is critical that results and implications from a single case study, as presented here, are translated into broadly applicable implications for other small urban centers in the developing world. This section draws on previous academic findings and the changing policy platforms of international development banks, as well as the results of this case study, in an attempt to support general policy and infrastructure planning recommendations.

Water supply

Rainwater storage and capture in the wet tropics, and indeed, in all contexts, present an opportunity to increase the efficacy of rainwater utilization for either domestic use or urban agriculture (Thomas 1998; Mwenge Kahinda and Taigbenu 2011; Islam et al. 2010; Srinivasan et al. 2010). The implementation of rainwater capture should be incorporated into government development policies and into enforceable drainage or building codes, as already recommended by Che-Ani et al. (2009) for the wet tropical context of Malaysia. These findings, while endorsed in ADB policies (ADB 2003), are not current practice for implementation in developing contexts. In conclusion, rainwater capture, in conjunction with increased water efficiency, and demand management should be proactively promoted throughout the developing world to relieve existing pressures on water supply systems and delay expensive upgrades, augmentation, and expansion.

Wastewater

There is a need to adopt more sustainable urban wastewater practices and management throughout the developing world. Previous studies have suggested that the conventional approaches to wastewater management are not the most economical or ecologically sensitive options both generally (Daigger 2009; Zimmerman et al. 2008) and in developing country contexts (Engin and Demir 2006; Massoud et al. 2009). Parkinson and Taylor (2003) propose theoretically the use of decentralized wastewater in urban and peri-urban contexts in South Asia. While Huang et al. (2007) found that for a case study in China, conventional wastewater infrastructure would fail to protect against fresh water eutrophication. Similarly, Erni et al. (2011) proposed innovative wastewater management incorporating reuse and decentralized management as the optimal solutions in an African case study. These principles favoring novel and cluster scale wastewater management are increasingly reflected in updated wastewater management policies of the Asian Development Bank (ADB 2013), whereby innovative and decentralized approaches are theoretically promoted and endorsed throughout the Asia–Pacific region.

Therefore, on the basis of previous simplified wastewater modeling and updated policies of international development banks, the findings of this study supporting distributed wastewater management can confidently be generalized to other small urban centers requiring upgrading or implementation of wastewater infrastructure.

Stormwater

The recent literature has continued to highlight the need for stormwater management in both developed and developing contexts to transition toward more sustainable approaches (Armitage 2011; Barbosa et al. 2012; Khatri et al. 2012). An understanding that stormwater contributes to urban water pollution and nutrient loads, leads to a requirement to provide treatment, attenuation, and minimization of stormwater generated in urban centers in both developed (e.g., Roy et al. 2008) and developing contexts (Lariyah et al. 2011; Armitage 2011; Khatri et al. 2012).

Sustainable stormwater management has been advocated in recent regional urban water management dialogs in Africa (Khatri et al. 2012) and more broadly there has been theoretical advocacy for improved stormwater management in developing countries (Duffy and Jefferies 2011). However, the literature has continued to lack demonstrated empirical impacts of improved stormwater management in developing contexts. Based on evidence from practice, theoretical discussions promoting sustainable stormwater management, and in light of the case study presented here, governments, aid agencies, and international development banks should continue to promote sustainable urban drainage principles into urban infrastructure proposals.

Integrated management

Central to the improvement of urban water service delivery will be a change in paradigm from viewing any one of the urban water streams in isolation, toward an integrated understanding of urban water management (Chocat et al. 2001; Rozos et al. 2013). Understanding the potential to utilize "waste" streams such as rainwater and septic sludge for beneficial uses such as meeting non-potable water demand (Makropoulos and Butler 2010) and urban agriculture (Smit and Nasar 1992; Molyneux et al. 2012), while simultaneously decreasing the environmental impacts of nutrient release.

The integrated nature of urban water management will require a cross-disciplinary approach and an increased level of receptivity toward sustainable practices, brought about by increased political support, strong leadership, and capacity training (Poustie et al. in press).

CONCLUSIONS

The urban water model UVQ was employed to quantify flows and contaminant loads in the urban water system of Port Vila, Vanuatu. Extensive engagement with the urban water sector ensured the development of a range of plausible urban water technical alternatives and future context scenarios.

Alternative sources, especially the potential of rainwater tanks, water saving technologies, and demand management should be encouraged for implementation as their introduction will both reduce groundwater extraction requirements (potential decrease of up to 23 %) and decrease Port Vila's stormwater generation by up to 38 %.

It is imperative that wastewater in Port Vila is managed appropriately in the coming decades. Following the current infrastructure trajectory will see a 400 % increase in nutrient loads infiltrated into Port Vila's groundwater. Infrastructural intervention is urgently required. Traditional recommendations of a centralized sewer and treatment system, or increased septic tank pumping rates fail to reflect the diversity of innovative solutions available for implementation. Alternatives such as source separation or on-site treatment of septide could provide improved environmental outcomes, at lower costs. Similarly, a traditional approach to stormwater management will result in increased stormwater generation and nutrient loads. An integrated approach to stormwater management is required simultaneously with an improved approach to wastewater management.

On the basis of the previous literature and the results of this case study, there is an increasingly strengthening argument suggesting that fundamental progress toward environmental sustainability in urban water systems will not be achieved in developing countries by following the conventional infrastructure of the industrialized world. Rather greater understanding of the conventional approaches' limitations should lead to a wide ranging search for infrastructure selection, considering both conventional and innovative solutions. The integrated management of urban water streams, utilizing innovative approaches to service provision, may assist urban centers in the developing world toward sustainable urban water management. These implications and the methodology presented within this paper can be broadly recommended to other small urban centers in developing contexts which are yet to implement improved urban water management strategies.

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