Title: Limits to Growth defined by Water Resource, Waiheke Island Case Study

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In this paper, three models were developed to estimate the sustainable population limit bound by the freshwater collection capacity; (1) an annual water balance model, (2) water use-component model and (3) a daily-step rainwater harvest simulation. The current freshwater supply capacity of Waiheke Island fails even at 5-year return drought events and the current water collection capacity cannot properly sustain the further growth of population or other activities. Sustainable population count under current collection capacity was 6,730 people with 95% supply reliability (failure occurring once in 20 years). Capacity expansion options are possible but they cannot expand indefinitely and are bound by the physiographical environmental limits. These environmental limits for capacity growth are translated into supportable population estimates of 100,000~140,000 at 95% supply reliability.

Intended category: Limits to Growth, Water resources

1 Introduction

As the awareness increased on interconnectedness in hydrological and biochemical cycles in earth's hydrosphere, the knowledge demands has been steadily increasing to create holistic representations of the integrated catchment scale processes for water management policy development. Engineers have great potentials to be major contributors in this regards, transcribing the knowledge gained in physical science domain to holistic designing tools that are compatible for the sustainability issues (Cruickshank & Fenner, 2007). Every engineering toolbox must provide engineers with effective and stable means to probe and control (or augment at some degrees) the system of interest. The toolboxes of local project-based or product-based systems level were well developed and flourished in engineering community but the toolboxes of regional-scale systems levels were not well transcribed because of the "softness" of the system elements. Building of clearly articulated toolbox for regional level is essential to motivate more engineers to join and develop the regional sustainability design toolbox.

This paper develops a model that adds to such toolbox for regional-level water supply system, which is only one of subsystems of regional socio-environmental system. In particular, the carrying capacity associated with the infrastructure investment and the minimum hydraulic requirement for natural water cycle is considered. This concept is used to estimate the maximum habitable population based on a water availability model.

Waiheke Island of 92km^2 has been chosen for the modelling study as the island exhibits the typical seasonal supply reliability issue noted as "increased water use & decreased water availability during dry season" in a small, closed setting. Larger regional supply systems share the common issue. The island provides suburban residence to about 8,420 people near the Central Auckland City (2009 estimate). There are vineyards, olive groves and other small farms as well as tourism attractions during summer holiday. Along the coasts, non-abstractive use of water, beaches and mussel-oyster aquaculture, exist. The passenger ferry service connects the downtown to the island's Matiatia Wharf within 40 minutes. Electricity has been connected via undersea cable across Tamaki straight but no water supply main has been connected from the mainland. In terms of water supply, the island is a closed system that the water resources have to be managed within its boundary. The residential population is projected to grow to 11,300 by the year 2031 (Statistics New Zealand, 2007).

Waiheke Island utilises fully distributed approaches for both water supply and wastewater. The primary freshwater acquisition method on Waiheke Island is the rooftop rainwater harvesting. Rainfalls received on rooftop are collected and stored in rainwater tanks to be used later. If this supply-storage system fails, groundwater take supplements the quantity in case of shortage during dry summer.

2 Methodology and Materials

It is known for the residents of the island that the water supply problem occurs during peak seasons of summer when the rainfall is least and the demand is highest. The island inhabitants experienced heavy drought during the summer of early 2010. This prior knowledge indicates that the intra-annual variations of the rainfall and demand are the important aspect of water supply of the island. Four aspects of the system were primary interest to the modelling exercise of this paper; probabilistic nature of intra-annual variability, capacity of the built collection structures, seasonal demand variation and demand growth by population growth.

2.1 Island-wide Water Balance Model

The island-wide annual water balance model was constructed to identify the proportion of human abstraction to the natural water cycle fluxes. Data sources listed in Table 1 were used to estimate the island-wide collection capacity. Rooftop rainwater and groundwater (GW) take are the primary means to divert natural water cycle into the human system uses. Stream take are not suitable for domestic use because of health issues and only a small quantity is used for farm irrigations.

2.2 Use component model

The Water use-component model was constructed to be entered in the Harvest-pump model from compilation of data sources (Table 1) and visualised in Fig.2. Water use rates of some components are relatively constant throughout the year. Irrigation and hotel accommodation for summer visitors were seasonal users and their uses increased during dry summer. To reflect this variation, daily use rates for each month were prepared to be entered to the Harvest-pump simulation (Table 2).

Component	Data Sources
Household Uses	
Population and Household count	Statistics New Zealand (2006, 2007)
Drinking, Cooking, Food Prep.	WHO (2006).
Dishwashing, Shower	Heinrich (2007).
Toilet, Laundry	Use scenario set to match Heinrich (2007).
Car Washing	Assumption.
Irrigation use	
Agricultural Categories	Agriculture business with large share of employee counts (Statistics New Zealand, 2010).
Vineyard Irrigation Rate	Logan (2009).
Vineyard Area	Digital Aerial Photo supplied by Auckland City Council (2009).
Olive Irrigation Rate	Olives Australia (2009) and FAO Water (2010).
Olive Area	Digital Aerial Photo supplied by Auckland City Council (2009).
Animal Water-use Rate	Stewart & Rout (2007).
Animal Count	Stringleman (2005) for cattle and sheep. Assumption for horses.
Other Crops Irrigation Rate	Australian farm stats (Queensland Goverment, 2009).
Other Crops Plantation Area	Assumption.
Commercial uses	
Commercial Categories	Intensive water user businesses (Statistics New Zealand, 2010).
Visitor Count	Season visits scenario based on Waiheke Community Board (2008).
Office & Workforce	Assumption - 2 flushes+2 hand washes + drinks per worker for a working day. 300 working days per year.
Fire Station	Scion (2007) and Cote (2003; p.374).
Wine Production per year	Scaled from national stats (NZ Wine Growers Association, 2010).
Concrete Water use rate	Portland Cement Association (2010).
Concrete Mixing per year	Scaled from national stats (Gaimster, 2009).
Others	Assumptions.
Collection Instruments	
Rainfall Data	NIWA (2007).
Roof area	Auckland City Council GIS layer
Water Balance Ratio	Calibration study by SKM (2007).
Roof connection rate	Assumption. 80%.
Rainwater Tank	Average tank volume 15400L (WRCG Ltd, 2004).
FF Diverter	0.14ML temp store volume in proportion to collection roof area (Texas Water Development Board, 2005). Assumption of 0.07ML/day drip rate.
Collection Efficiency	Simulation result in section 3.2.
Pump Count	Auckland Regional Council GW Consent Files
Pump Yield	Scenario built based on water resource allocation report (ARC, 2008).

Table 1. Input data sources for the model.

2.3 Daily-step Harvest Pump Model

Based on the water use component model, the daily time step simulation of the rainwater harvesting was constructed to assess the performance of the current freshwater acquisition capacity to sustain the use components (for a review of formulation details; Ward, Memon, & Butler, 2010). The input parameters such as daily use rates, roof area and tank storage volume were lumped at island-wide level. The first flush diverter was also included in the simulation. The First Flush diverter mechanism (FFD) is a small storage installed prior to the main rainwater tank that provides a temporary trap for the initial run-off with high level of contaminant wash-offs from the roof (Texas Water Development Board, 2005). The simulation model thus is effectively a two-stage tank overflow model (Fig.1). Recent 10-year rainfall time series were used to drive the model (NIWA, 2007). In the simulation, if the rainwater tank ran out and the simulated storage value became negative, the deficit was acknowledged as supplemented volume from GW and the storage was set to zero. Each month, the supplemented volume was summed and was reported as the percentage of operation (%) to the pump rate capacity derived from the island-wide water balance model. In reality, the houses with household bore will use their own bore to fill the rain tank as an emergency measure. This monthly % pump operation is the key output of the daily-step harvest model that assesses the failure/success of the overall water acquisition system. As this % approaches to 100%, the water supply planner must be alarmed and devise a way to increase the freshwater collection capacity of the island. If this % exceeds 100% in at least one month in a particular year, the supply system is recognised as failed in that year.

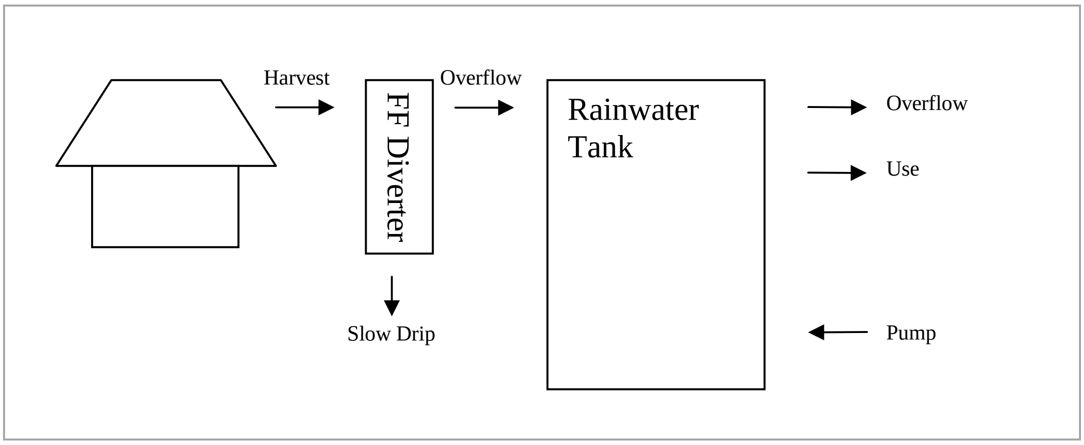


Figure 1. Rainwater Harvesting Simulation Structure. One-roof, two-tanks. The collected volume is first passed through the First Flush Diverter (FFD). The overflow of the FFD is stored in the main Rainwater Tank.

Table 2. Daily Water Use Rate Schedule. Unit=ML/day. The last row unit=ML/year.

Month	Days	Residential Steady	Residential Seasonal	Irrigation Steady	Irrigation Seasonal	Hotel	Commercial	Workforce	Total Daily
Jan	31	1.116	0.044	0.057	0.024	0.707	0.065	0.039	2.052
Feb	28	1.116	0.044	0.057	0.024	0.248	0.065	0.039	1.593
Mar	31	1.116	0.044	0.057	0.024	0.085	0.065	0.039	1.430
Apr	30	1.116	0.000	0.057	0.000	0.015	0.065	0.039	1.292
May	31	1.116	0.000	0.057	0.000	0.015	0.065	0.039	1.292
Jun	30	1.116	0.000	0.057	0.000	0.015	0.065	0.039	1.292
Jul	31	1.116	0.000	0.057	0.000	0.015	0.065	0.039	1.292
Aug	31	1.116	0.000	0.057	0.000	0.015	0.065	0.039	1.292
Sep	30	1.116	0.000	0.057	0.000	0.015	0.065	0.039	1.292
Oct	31	1.116	0.000	0.057	0.000	0.015	0.065	0.039	1.292
Nov	30	1.116	0.044	0.057	0.024	0.015	0.065	0.039	1.360
Dec	31	1.116	0.044	0.057	0.024	0.707	0.065	0.039	2.052
Year Total		**407.5**	**6.6**	**20.8**	**3.6**	**57.1**	**23.6**	**14.2**	**533.4**

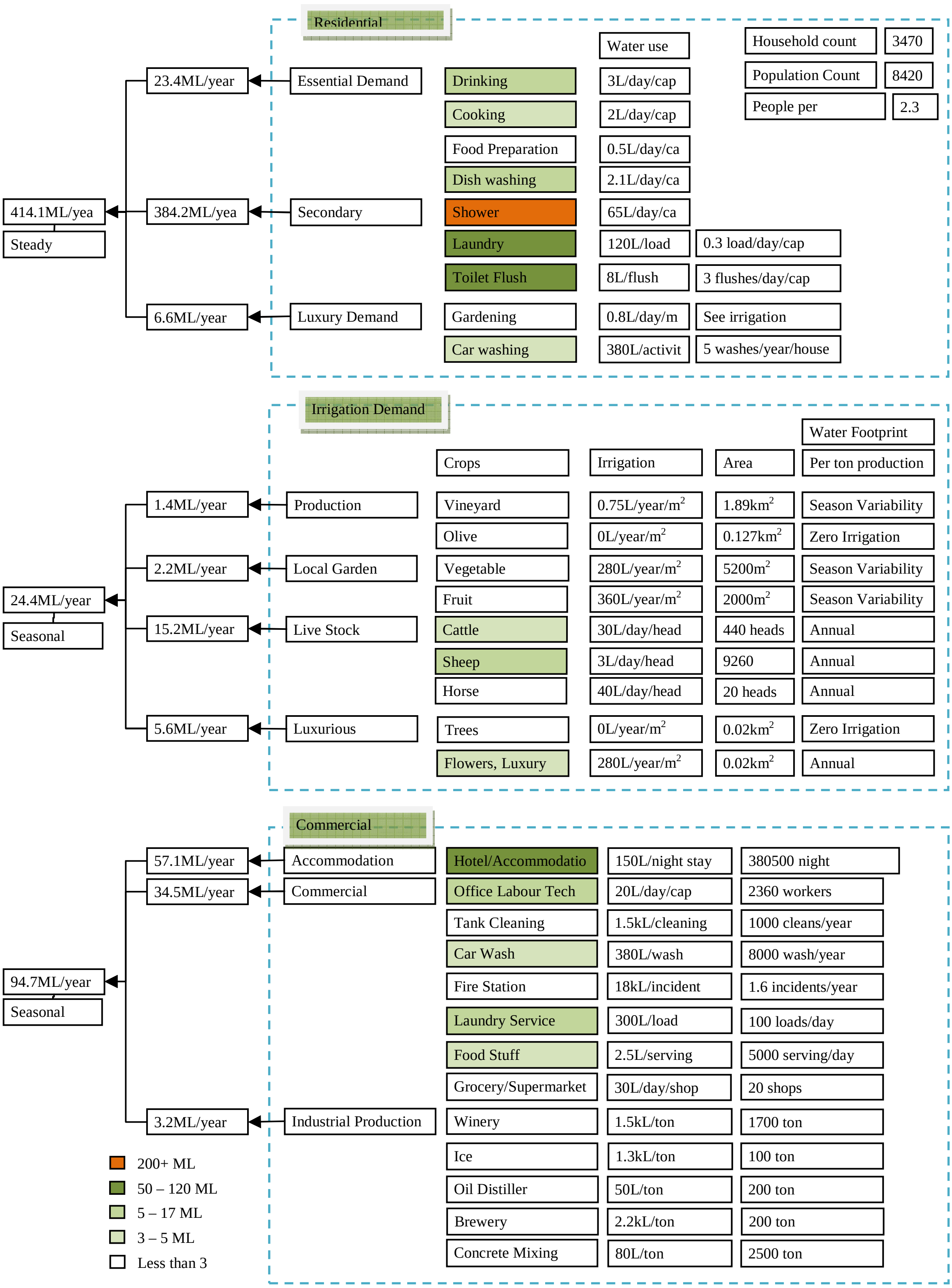


Figure 2. Water Use Components. Monthly surpluses were calculated by monthly supply minus monthly demand. Shower was the heaviest single user of the water on the island. Hotel was the heaviest concentrated seasonal consumer of the water; 60% of its annual use was assumed to be concentrated over only 10 days of summer holidays at 3ML/day based on a visitor counts estimate (see data source Table 1). Hotel and accommodation facility were modelled to triple the daily water use during these 10 days.

3 Results

3.1 Island-wide Hydrology Model

Intra-annual variability of rainfall of the island is shown in Fig.3. Recent 20-year average rainfall was 1265mm (NIWA, 2007) and the corresponding annual precipitation volume (APV) was 116,400ML/year (= Annual rain depth x Island area). SKM (2007) reports the water balance ratio from a calibration study on a stream gauge and soil moisture time series; around 64% of the APV is returned to atmosphere by evapo-transpiration (ET) and annual stream run-off volume (ASV) is 31% of APV and deep infiltration volume (DIV) below root zone is 5% of APV. The deep infiltration is the soil moisture that percolated well below the root zone and base flow pathways, making it irrecoverable back to surface. This proportion returns to the sea via groundwater-seawater interface mixing (Michael, Mulligan, & Harvey, 2005) and submarine groundwater discharge (Burnett, Taniguchi, & Oberdorfer, 2001). This proportion corresponds to recharge to the confined fractured greywacke aquifer, which is the ubiquitous aquifer on the island that bores tap into.

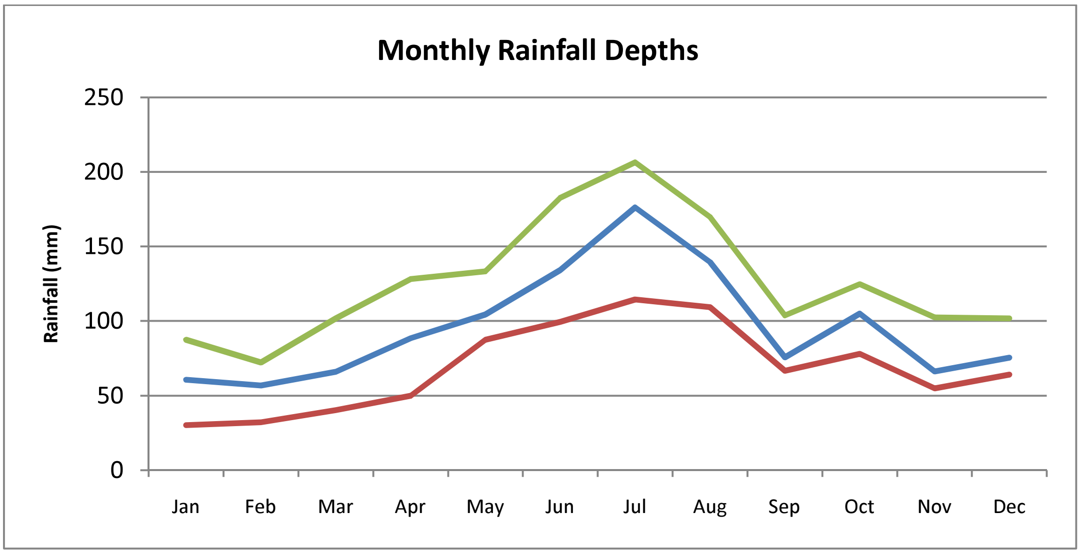


Figure 3. Intra-annual Rainfall Distribution. Plotted are medians and quartiles of recent 20-year monthly rainfalls. Recent 20-year average annual rainfall depth was 1265mm/year.

The island-wide capacity of roof rain harvest was 554ML/year (= Rainfall depth x Total connected roof area x efficiency) based on the GIS measurement of island-wide total roof area 847,000m^2, an assumption of 80% roof connection to the rainwater collection and the simulation result of annual collection efficiency was 65% (section 3.2). The building footprint measurement included auxiliary structures such as small garages and rainwater tanks which do not contribute to the collection.

The island-wide groundwater abstractive capacity was 427ML/year (7% of deep infiltration) based on estimates of 260 abstractive bores drilled to date, 16 July 2009. Of these, 38 bores were large scale currently consented bores, whose annual pump rates and allocations have been reported by ARC (2008) with average allocations of 17.7m^3/day per bore. 165 household-scale bores of ~3m^3/day max yield are not regulated by ARC and are not included in the published report. There were 37 consent-expired bores and they are not included in current abstractive capacity but may be available as emergency supplies (section 4.1). A stream water take consent existed at 40ML/year allocation (ARC, 2008).

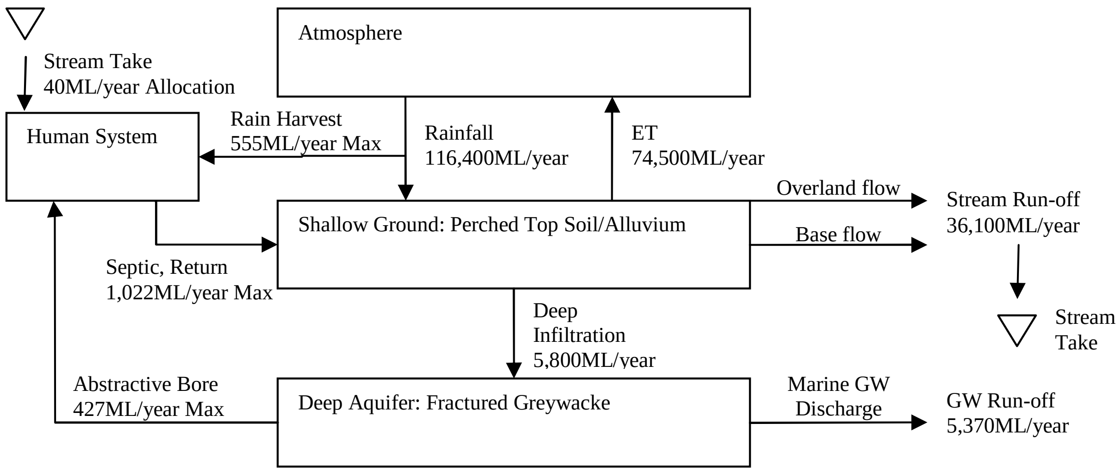


Figure 4. Conceptual Model and Component Scale. GW=groundwater.

The island-wide total of annual acquisition capacity with current level of infrastructure was 1,022ML/year. This is only 2.4% of island-wide annual renewed freshwater volume (ARFV), 41,900ML/year (= Rainfall – ET); UNESCO (2009) reports this quantity as total renewable water resource available for a basin. The island's utility rate of the ARFV was very low because only the western part of the island was being utilised for freshwater collections (Fig.8). The ARFV is the absolute upper limit of the long term water acquisition rate from natural water cycle, disregarding any appropriation for the hydraulic or environmental system integrity.

3.2 Daily-step Rainwater Harvest Model

Key outcome of the daily-step model is the pump operation level. The pump operation acts as fail safe measure for the situation rain harvesting supply fails. Even though the annual collection capacity (1,022ML/year; Fig.4) exceeds the annual use volume (533ML/year; table 2), because of the temporal out-phase of the demand and supply, the temporary failure to supply adequate amount during dry summer can occur. Unlike other resources, human systems cannot tolerate even several days of water supply outage. In summer days the population demands pump supply when their rain tanks start to run out by prolonged no-rain days. The daily pump rate capacity of 1.17ML/day (=427ML/365) should not be exceeded by the demand. If the groundwater pump supply fails, which is the fail-safe measure, the overall supply system is regarded to have failed.

The simulation result of the recent 10-year, the monthly operation % to pump capacity, is presented in Fig.5. The summer of 2010 was commented to be the worst year ever by one of the commercial water tanker operators (anonymous personal communication). The simulation showed the same result, showing the pump operation level required in Feb 2010 to be 105% of the current pumping capacity. This means the current pump capacity has already been breached this year.

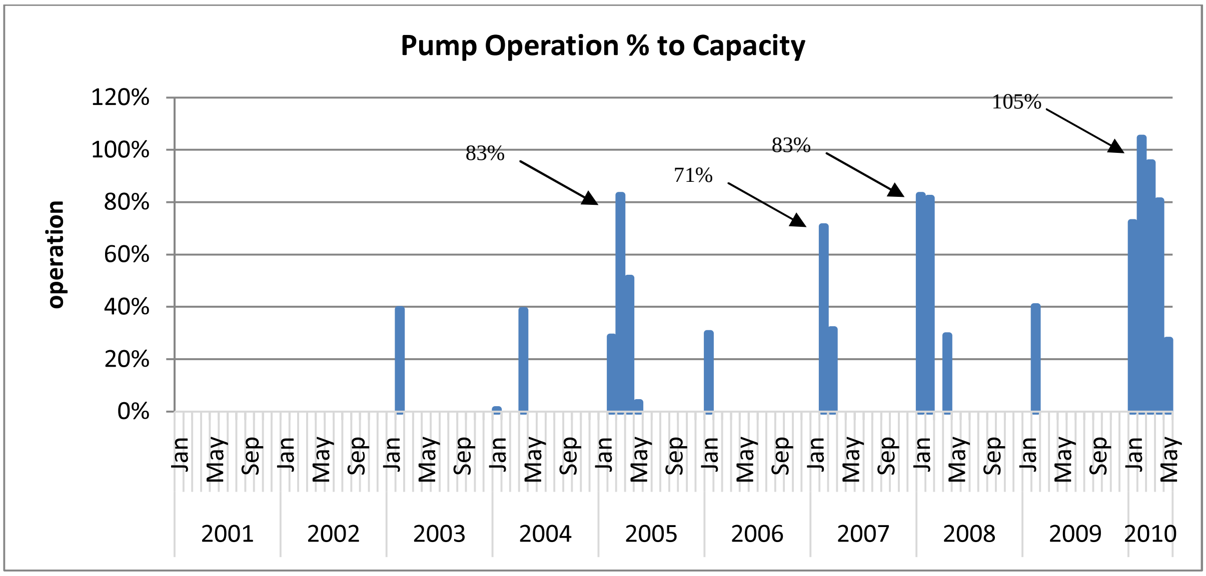


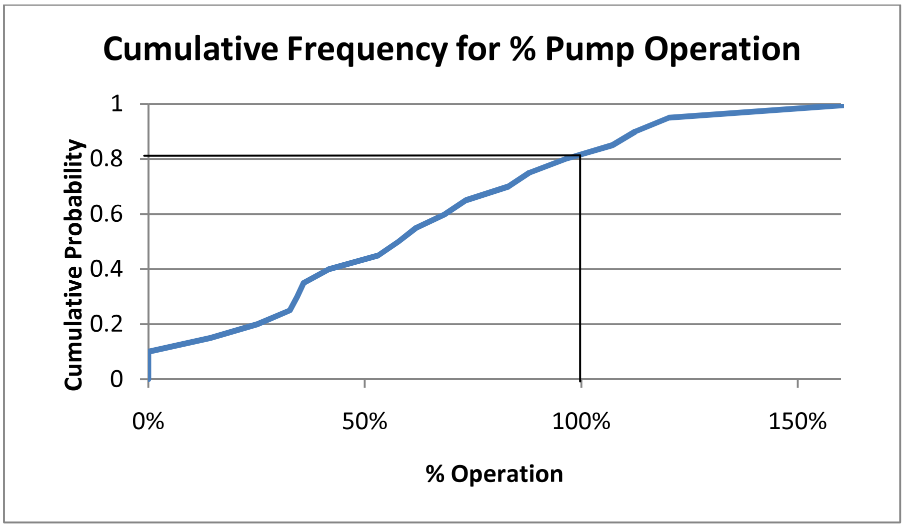
Figure 5. Seasonal Operation of Pumps. Monthly bore water supplement required was calculated from daily-step rain-harvest-pump simulation and divided by the current island-wide instantaneous pump rate capacity of 427ML/year. The island-wide pumps were frequently running at risky levels of reaching the capacity cap in many summer seasons and the pump capacity was finally breached in February 2010.

A simulation run with 95-year historic rainfall time series with current collection scheme predicted that the failing rate of pump water supply in dry period is once in every 4.3-year. Fig.6a shows the frequency distribution of the pump operation level required for the worst month in each year. Out of 95 years, 22 years showed the breach of 100% capacity in their summer months. The current pump-supplemented rain harvest system capacity is prone to peak-season failure even with 4.3-year (=95/22) return drought. Previous years have not experienced this as the water demand on the island was less. Therefore it is concluded that the sustainability of community water supply has not been met by the current collection infrastructure capacity. The sustainability is breached because of the peak-season demand driven by the visitors and prolonged no-rain days during summer.

If the current acquisition capacity cannot sustain the population and other water uses, what is the sustainable population of the current freshwater acquisition capacity? In order to answer this question, the response of daily water use schedule to population growth had to be established. 51% of island workforce was employed to residential support activities such as water supply, waste disposals, education, health, real estate and property management, automobile repair and public transport (Statistics New Zealand, 2010). The use rate of Residential, Commercial and 51% of Workforce were set to vary proportionally to population count. Irrigation and Hotel were assumed to be non-reactive to population variation; their levels of activities depend on external market conditions and comparative advantage with respect to business demography and geography.

It is commonly accepted that 95% reliability is to be achieved for the urban water supply system (reliable against 20-year drought). The simulation model was modified to incorporate the population change by implementing the daily use rate response to population growth described in the previous paragraph. Several simulation runs with different population input were performed until the simulation run achieved drought reliability of 95%. The population that the current system achieves 95% reliability was 6,730. This population count that achieves 95% supply reliability is termed the sustainable population of the freshwater acquisition system and is the major topic of discussion in section 4.

Consistent 35% losses of harvested volume due to the overflow during wet seasons were observed in the simulation (Fig.6b). This indicates the potential of bringing rapid increase of water availability by rain tank retrofit extensions. The simulation indicated that the loss due to the first flush diverter was only 2% of the harvested volume.



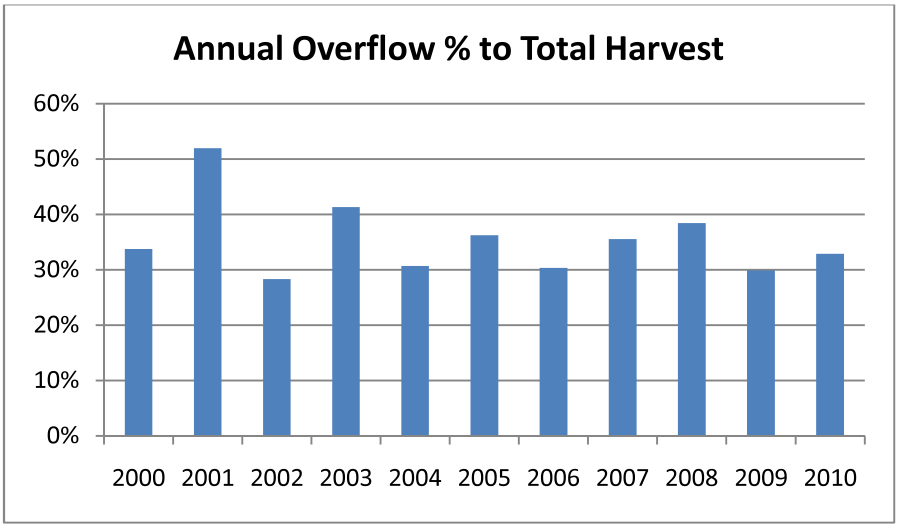


Figure 6. (Top) Operation % performed over Historic Rainfall. Rain-Harvest-Pump simulation run over 95-year historic rainfall data showed that the current water supply system has slightly over 80% (20% failure rate). This means the current water supply system capacity fails once in every 5-year on average if the historic rainfall pattern continues in the future. **(Bottom) Simulated Overflows.** A consistent 30% loss of the roof collected volume was observed in the simulation. The rain-harvesting system is running inefficiently because of the inadequate tank volume design that matches the roof area for the collection.

4 Discussions

4.1 Increase of Acquisition Capacity

Immediate residential responses of the water shortage experiences were the application of more bore drills. This is an effective solution to the problem, but there are five quick and cheap alternative solutions to increase dry period supply reliability.

- Utilising currently inactive bores
- Installing extra rainwater tanks
- Drilling more bores
- Connecting more auxiliary building roofs to collection
- Creating extra impervious areas for collection

The first option does not involve any installation. It gives immediate emergency capacity of 0.65ML/day from 37 currently inactive bores although the quality of water obtained from these unmaintained bores may be questionable. The sustainable population utilising this emergency source increased population capacity to 9,550 which is enough to support current population through summer. Next cheap option is to increase the rainwater tank capacity. Doubling the island-wide tank capacity increased the supportable population to 8,480 which is comparable to current island population. Other scenarios require further installations and it would be interesting as a future project to plot the cost projection along with the increase in population capacity to find optimal strategy to increase the water supply capacity for the island. Table 3 shows the sustainable population that further installations would bring about based on the simulations.

Table 2. Development Options and Corresponding Sustainable Population. Current population count is 8,420 (2009 estimate).

Upgrades	Sustainable Population
Base Line	6,730
Free Emergency Supply	
Running Inactive Bore	9,550
Rain Tank Installations	
2x RainTank	8,480
2x RainTank + Inactive Bore	11,040
3x RainTank	10,430
3x RainTank + Inactive Bore	11,870
Bore Explorations	
2x Bores	12,050
3x Bores	20,120
Impervious Area Connections	
2x Roof	11,850
3x Roof	17,700

4.2 Limits to Capacity Growth

The infrastructure capacity cannot expand indefinitely. The roof harvesting capacity is limited by the building footprint. The building footprint ratio of the most intensely built residential area can go up as high as 45% (Pan, Zhao, Chen, Liang, & Sun, 2008). For Waiheke Island, the most intensely built catchment had 7.8% building footprint ratio. The Waiheke development strategy (Auckland City Planning, 2000) exerts the expansion of the metropolitan urban limit (MUL) to be considered when 90% of the urban parcels become occupied. However, it seems difficult to find the suitable expansion sites in the island because most areas with gentle terrains have been already sub-sectioned for current urban developments. Even within current MUL, some sub-sectioned parcels reported difficulties to build houses because of the steep slopes and site access problems (Rawson, 2006). Therefore, the development will likely be intensification rather than expansion. Assuming maximum future MUL expansion to be 50% of current MUL coverage and the maximum intensification of the building footprint to be around 45% of urban area, the maximum roof area increase is by 8.6-fold. With increase of the roof area, tank size was assumed to increase proportionally to the roof area increase.

The limiting factor of the additional groundwater pump construction over the coastal aquifer such as Waiheke Island is the saline intrusion (Fetter, 2001). Inland freshwater recharge provides the freshwater flow rate that pushes the seawater-freshwater interface, which maintains the geometry of the freshwater zone. Reduction of the flow rate by pumping interception means the shrinkage of the freshwater zone. Hypothetical situation that pumping bores located only one side of the island is depicted (Fig.7). The affected areas (yellow) are the union of the bore capture zone and it can be constructed from the geometry of lateral GW flow lines radiating from central region of the island to the coast. So the elevated risk regions manifest as threatened coastlines. Blue lines on the left indicate the coastline that are affected by bores (Fig.7a and 8).

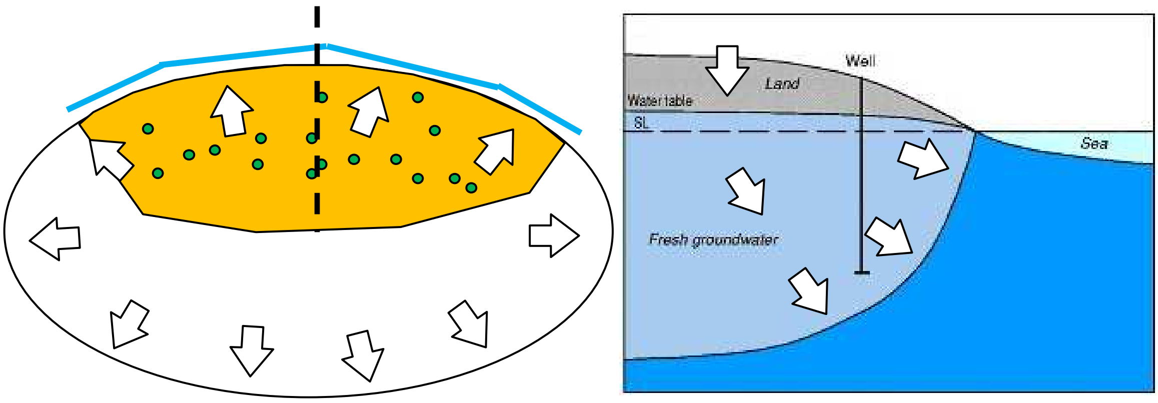


Figure 7. (Left) Hydraulic Push on a Hypothetical Island and (Right) the Vertical Cross-Section. Green dots represent bore pumps. Cross-section source: OzCoast (2010).

A general rule of thumb is that 15% of the groundwater flow is to be left unused for hydraulic push of saline-freshwater interface (Wujkowski, 2004). The important parameter that determines the water supply sustainability is the instantaneous pump rate (quasi-daily pump rate) during drought situation. The maximum groundwater pump rate from this consideration is 13.5ML/day spread throughout the island (11.5-fold increase from the current pump rate). How they should be arranged to avoid localised saline intrusion is another topic of study (da Silva & Haie, 2007), which will not be discussed here; it will only be noted that there are areas in the island that bores can be further developed (Fig.8).

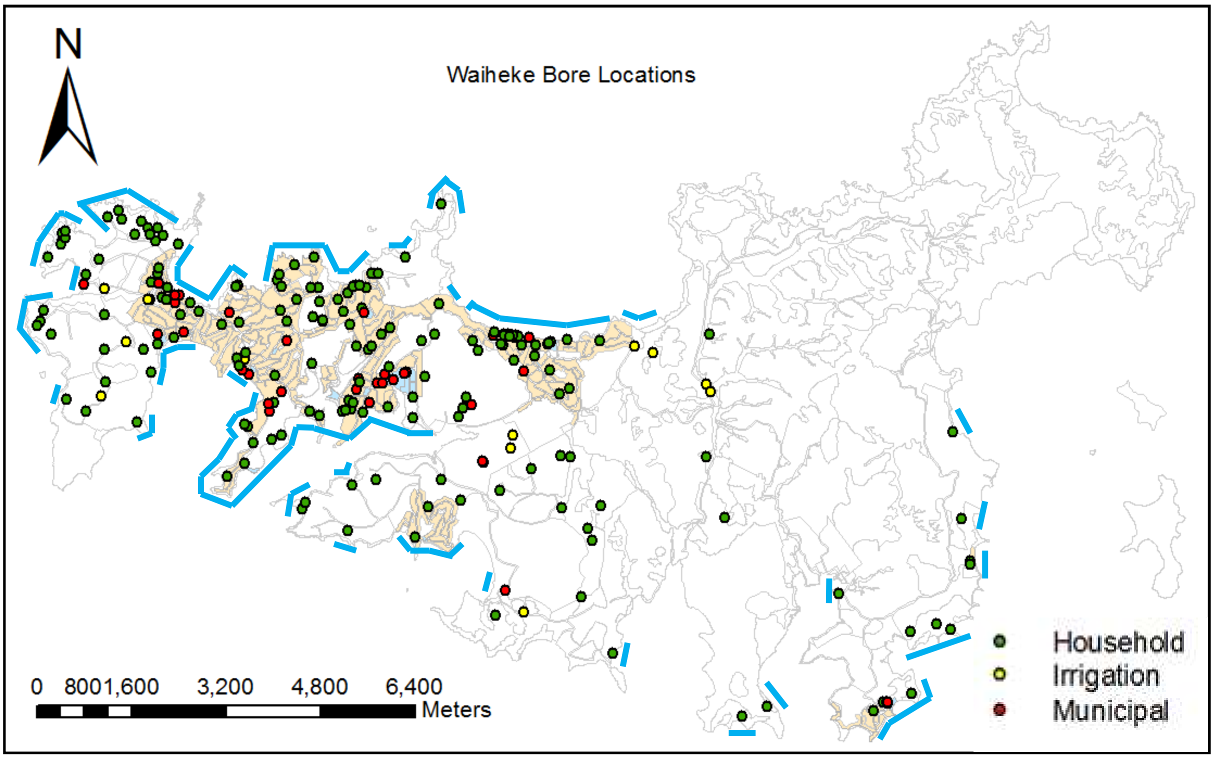


Figure 8. Bore Locations and Saline Intrusion Risk. Bores are agglomerated in the narrow western part of the island which are urbanised. Beige-coloured areas are the planned urban areas. Blue lines note the coastlines that are affected by the pumps and have elevated risk of saline intrusion. Those coastlines without the blue lines are capable of accommodating further groundwater developments.

Based on the environmental limits for roof harvesting and pumping rates, maximally sustainable population can be evaluated using the same method as in section 3.2 and 4.1 (Table 3). The maximum sustainable population were estimated to be 100,000~140,000 depending on the level of adopted water saving fixtures. Are these realistic numbers? The answer is yes. The current MUL has an area of 7.53km^2. If above population is fit into the current MUL, the urban population density of 13,000~18,000/km^2 develops. This level of urban density is observed in many cities of the world; for example, Mogadishu in Somalia of 13,100/km^2 and Gaya in India of 18,100/km^2 (Demographia, 2010). They are feasible number in a long-term time horizon, if adequate development pressures towards such intensification are exerted on the island.

Table 3. Population Limits by Water Resource. 50% Max means the development made to half to island's maximum. 2x RainTank means the installation ratio of raintanks to roof area has doubled.

Upgrades		Sustainable Population
Expansive Limits		
	50% Max Roof	25,990
	50% Max Bore	41,360
	50% Max Roof + 50% Max Bore	48,960
	Max Roof	52,220
	Max Bore	87,290
	Max Bore + Max Roof	100,640
	Max Bore + Max Roof + 2x RainTank	108,450
	Max Bore + Max Roof + 3x RainTank	115,530
With Water Saving Fixtures		
	Base Line	8,200
	Running Inactive Bore	11,630
	2x RainTank	10,270
	Max Bore + Max Roof + 3x RainTank	140,500

Water saving fixtures will reduce the daily water uses and increase the maximum sustainable population. These fixtures reduce the water uses of the largest use-components; shower, laundry, toilet flush, hotel and worker uses. The water saving cannot be properly estimated from the ratio of flow rate reduction but from the use case studies to incorporate the human behavioural factors to the reduced flow rates. Bidhendi et al. (2008) provides the ratio of water use reduction of the water saving fixtures placed in action (Table 4). Island-wide retrofit of water saving fixtures achieves more or less suitable reliability for the current island population without any further infrastructure investments (Baseline with fixtures; table 3).

Table 4. Potential Reduction Factors by Retrofitting Water Saving Fixtures (Bidhendi, et al., 2008).

Use	% Reduction
Washing Machine	15
Kitchen sink	23
Hand-wash Basin	34
Toilet	6
Shower/bath	27

5 Conclusion and Recommendations

The sustainable population capacity of the current Waiheke freshwater acquisition system was 6,730 and is susceptible to peak season failure to 4.3-year return drought. This problem can be adequately mitigated by employing currently inactive bores as emergency supply or increasing household rainwater tanks to twice the current volume. The expansion of acquisition system capacity is bounded by physiographic environmental constraints and the maximum sustainable population limit on the island was estimated to be 100,000~140,000.

This estimation was purely based on the available volume for roof harvesting and groundwater pumping in order to estimate the population limit posed by the conventional water supply strategy already implemented in Waiheke Island. The island has small intermittent streams only and they are not economically suitable for reservoir constructions to increase water supply reliability. The water sensitive urban designs (WSUD's) provide promising paradigms to increase the water supply capacity by providing small cost-effective multi-purpose components that utilise diverse water sources (Wong & Brown, 2009). These designs may be more effective in increasing the sustainable population than water saving fixtures. In particular, (1) stormwater storage (e.g. Myers, Beecham, van Leeuwen, & Keegan, 2009), (2) artificial aquifer recharge (e.g. Bouwer, 2002; Freni, Mannina, & Viviani, 2009) and (3) wastewater reuse & recycle planning (e.g. Brauer et al., 2001) are worth analysing within the island's context. The best practices documentations and experiences of the integrated WSUD components are slowly accumulating (Roy et al., 2008; Shrestha, Samuel, Ronaldson, & Riley, 2009) and implementing WSUD tools may provide more cost-effective and environmentally-sound solutions than the conventional approaches considered in this paper. Therefore, the cost comparison of the aforementioned WSUD's to the conventional development approaches is expected to form a valuable research outcome that accelerate integrated adoptions of these effective solutions to increase the sustainable water supply limits.

There are other constraints to population growths, for example, soil stability for intense housing, increased erosion and flood risk as response to urbanisation, social and planning acceptance and relative costs of urbanisation to surrounding Auckland region. Fruitful limits research is expected from developing ways to evaluate the feasible intersections of the several constraining factors (Koh & Boyle, 2008). The use-component model leads to white-box hierarchical system approaches to water demand forecasting, as a contrast to prevalent black-box statistical approach to forecast from time-series data (Herrera, Torgo, Izquierdo, & Pérez-García, 2010). The white-box approach naturally opens up research on causal relationships with super-, sub-, or lateral-systems in the way to refine the limit estimations. The causal dynamics of each component can be studied separately and combined to overview the estimates of the upper level system. The subject of the causal study may extend to other flows such as monetary flow, population flow, energy flow, material flow and pollution flows; this may lead to regional multidisciplinary model super structure that can be used for larger sustainability limit analysis (Meadows, Randers, & Meadows, 2004).

Acknowledgement

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