A systems approach to urban water services in the context of integrated energy and water planning: A City of Cape Town case study

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Abstract
The City of Cape Town derives the bulk of its present water supply from surface water resources and is the central water service authority for metropolitan consumers. The City is also a provider of bulk water to neighbouring municipalities. An exploration of the energy consumption for water and sanitation services for the City of Cape Town was conducted with an emphasis on water supply augmentation options for the near future (2011-2030). A systems analysis of municipal urban water services was undertaken to examine the energy requirements of supply alternatives and the efficacy of the alternatives in respect of supply availability and reliability. This was achieved using scenario based analysis incorporating a simple additive value function, to obtain a basic performance score, to rank alternatives and facilitate a quantitative comparison. Utilising the Water Evaluation and Planning hydrological modelling tool, a model for urban water services was developed for the City and used to conduct scenario analyses for a representative portfolio of previously identified options. Within the scope of the research objectives, the scenario analyses examines the direct energy consumption for the provision of water services for the City as influenced by external factors such as population growth, surface water runoff variability, available alternatives and the policies that are adopted which ultimately determine the future planning. It is contended that the modelling process presented here integrates energy and water planning for an assessment of water and energy resources required for future growth, and the optimal measures that could be pursued to reconcile the demand for water and the concomitant energy requirements.

Keywords: City of Cape Town, energy and water planning, water evaluation and planning

Introduction

South Africa is a country with a precarious energy and water resource landscape. Both sectors suffer from ageing infrastructure and the capacity to function sustainably (Coetzer, 2012; Gaunt, 2010). The energy capacity crisis of 2007/8 led to power shortages with a direct impact on economic growth (Eberhard, 2008). In the Vaal Triangle, the economic and industrial heart of the country, the water stressed industry has expressed concerned that a drought in the near future could have drastic economic consequences (Davies 2012). In the recent past in the Western Cape Province, located in the south west of South Africa, a decline in surface water storage required the imposition of water restrictions in the City of Cape Town in 2000/1 and 2004/5 (DWAF, 2007c). An investigation of future water requirements for the CCT suggested that, without any interventions, demand would exceed the available supply by 2020 for a low population and economic growth scenario and earlier if higher growth is experienced (DWAF, 2007c).

The expansion of water services infrastructure to meet growing demand in a future of increasing environmental and energy constraints requires the consideration of alternative water supplies as the capacity of the present system is reached. South Africa's White Paper on the National Climate Change Response (2011) emphasizes the investigation of other sources, beyond the traditional reliance on surface water systems, as a key element in water sector growth and security, stating the importance of 'exploring new and unused resources, particularly groundwater, re-use of effluent, and desalination'.

The scope of this study is restricted to urban municipal water services for the City of Cape Town and excludes any energy used directly by consumers in the use and disposal of water and sewage. Figure 1 illustrates the municipal water services cycle in the context of this study. Similarly, agricultural water demands in the region are also not examined in detail except where water resources are shared such as the surface water schemes, for example.

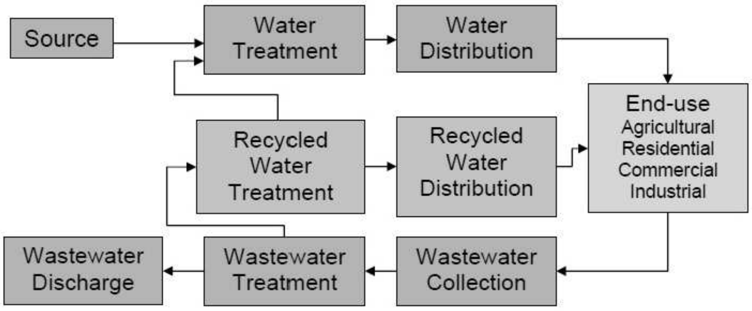


Figure 1: The municipal water services cycle
Adapted from California Sustainability Alliance 2008

It was estimated that the provision of water and sanitation services for the period 2007/08 accounted for half of the City's electricity consumption with a third attributed to waste water treatment alone (Jennings 2012). The potential for an increase in energy consumption for future water and sanitation services motivated this study which aimed to complement previous studies that have quantified the energy demands of water services (Cooley and Wilkinson, 2012; deMonsabert and Bakhshi 2009; Larabee *et al.,* 2011; Olsson, 2011).

From 'source to discharge' as water is abstracted, transformed and conveyed for the needs of the urban sector, the study aimed to evaluate the energy implications and efficacy of reconciling demand and supply of a portfolio of alternate intervention measures, which cater for future scenarios comprising: population and economic growth; reduced surface water availability (e.g. environmental constraints); and more energy intensive treatment processes. This was achieved using scenario based analysis incorporating a simple additive value function, to obtain a basic performance score, to rank alternatives and facilitate a quantitative comparison in respect of supply availability, reliability and energy intensity.

Utilising the Water Evaluation and Planning (WEAP) hydrological modelling tool (SEI, 2012b), a model for urban water services was developed for the City, as shown in Figure 2 and used to conduct scenario analyses for a representative portfolio of options previously identified by the National Department of Water Affairs (DWAF, 2007c). The modelling emphasises the direct energy consumption as studies have indicated that the operational phase is typically the most energy intensive over the life span of water and sanitation infrastructure (Buckley *et al.,* 2011; Lui, 2012; Stokes and Horvath, 2006).

The WEAP application program interface enables direct access to the WEAP model via MS-Excel in the Visual Basic Application (VBA) programming environment. This allowed water supply volumes to the City (aggregated with its bulk customers) to be to collated and categorised by type (e.g. ground water, desalination etc.) and linked with the associated energy cost path (or water transmission path). The categories utilised are indicated in Table 1.

Within the VBA environment, the transmissions paths were determined by scrutinizing the relevant WEAP data structures. Referring to Figure 2, trans-

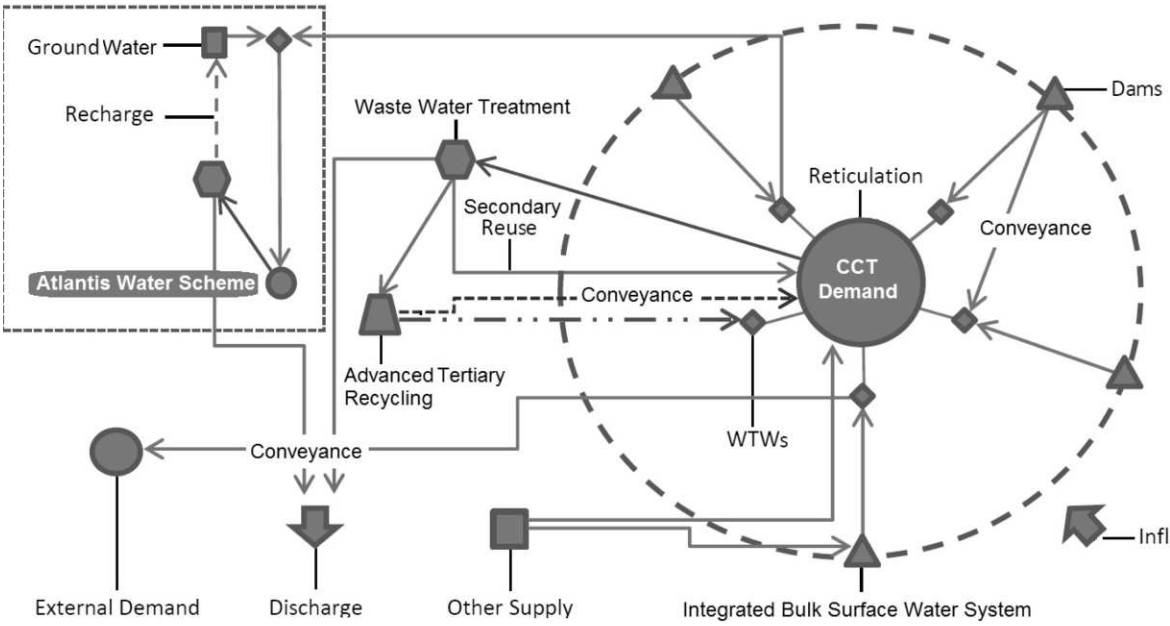


Figure 2: Conceptual municipal water services model developed for the systems analyses

Table 1: Stages or categories of the urban water cycle as implemented in WEAP

WEAP object prefix	*Description*	*Example WEAP object*
WTW	Water treatment works	'CCT WTW Faure' (Individual City WTW plant)
WWTP	Waste water treatment works	'CCT WWTP' (Lumped treatment process)
GW	Ground water	'GW TMG THK' (Specific option: Table Mountain Group)
DIST	Potable water distribution	'CCT Dist' (The City's distribution network)
SWD	Sea water desalination	'CCT SWD' (Lumped SWD option for the City)
WWR	Waste water reclamation	'CCT WWR NEWater' (Specific treatment process)
n/a	Other	Refers to conveyance of water across the system that is not accounted for (e.g. pump stations for water transfers)

mission links within WEAP connect the various stages of the water use cycle. Dams can be interconnected and linked to demand sites which are then, for example, linked to waste water treatment plants (WWTP) which process the return flows (effluent). In the model depicted, for example, these paths are located in the WEAP data branches:

- 'Supply and Resources\Transmission Links\to CCT Dist' (Supply to City's distribution network)
- 'Supply and Resources\Transmission Links\to CCT EX BULK Dist' (Supply to City's external customers)
- 'Supply and Resources\Transmission Links\to CCT Dist Atlantis_Mamre' (Supply to City's Atlantis Water Scheme)

The most recent issue of WEAP includes functionality to link directly with its companion energy modelling software tool, Long-term Energy Alternatives Planning (LEAP) system, to facilitate water-energy modelling (SEI, 2012a). At the time this research was conducted, this functionality was lacking. Therefore, energy consumption was incorporated using WEAP's financial analysis module by incorporating a user defined 'energy currency' based on the energy intensity or specific energy of a process. These 'costs' need to be assigned to the various stages of the water use cycle. This is either derived from empirical data or a first principle calculation. For example, the theoretical hydraulic energy required transporting water via a pipeline across known topography; or the energy generated at a WTW exploiting the existing hydraulic gradient (SACN, 2011) as approximated by Equation 1:

$$E(kWh)/\text{ month} = 1/e * pg\, QH/3.6MJ$$
$$E(kWh)/\text{ month} = 1/e * 0.002725\, QH \qquad (1)$$

Where e = system efficiency, Q =flow rate (m^3/month), H = Head (m), p = density of water (kg/m^3), g = gravity m/s^2

The net energy cost for water and sanitation services is then the linear sum of the product of the energy intensities and the volumes of water (or effluent) that is processed at each stage. This is mathematically expressed in Equation 2. The methodology is similar to that adopted in LEAP.

$$E(kWh) = \sum_{k=1}^{n} e_k s_k \qquad (2)$$

Where e = energy intensity (kWh/m^3); s=stage (m^3); k=WEAP object

In further discussion, the specific energy or energy intensity of the water sector is defined as the energy consumption per m^3 of water supplied to the distribution network or effluent conveyed and treated.

Empirical energy data for the City's Reticulation and Bulk Water Supply network were not available at the time requests were made (Allpass, 2012; Mashoko, 2012; Moll, 2012). In their absence, estimates are used as reported in the literature. Reported data was scrutinised for their applicability to Cape Town's environment as topography as well as the manner of water supply and conveyance is an important factor in the energy consumption of the water sector (Friedrich *et al.,* 2009; Kenway *et al.,* 2008). Figure 3 illustrates the modelling process.

Table 2 and Table 3 list the individual options and class of interventions comprising the options used for this case study. The interventions represent an orientation towards a particular category of supply or demand management. That is, an intervention programme which prefers sea water desalination, surface water, ground water or effluent recycling options. The interventions are also compared against a partial or continued water conservation and water demand management (WC/WDM) program.

Unrestricted and regulated usage of dam volumes for urban water consumption are also examined and compared for their relative performance. It is assumed that this simulates drought mitigation measures or water rationing that the National Department of Water Affairs and City practices to ensure a minimum reserve. In contrast, the unrestricted usage of water from the dams (aside from the allocations to agriculture) is also modelled as a comparison of the water supply and energy consumption requirements.

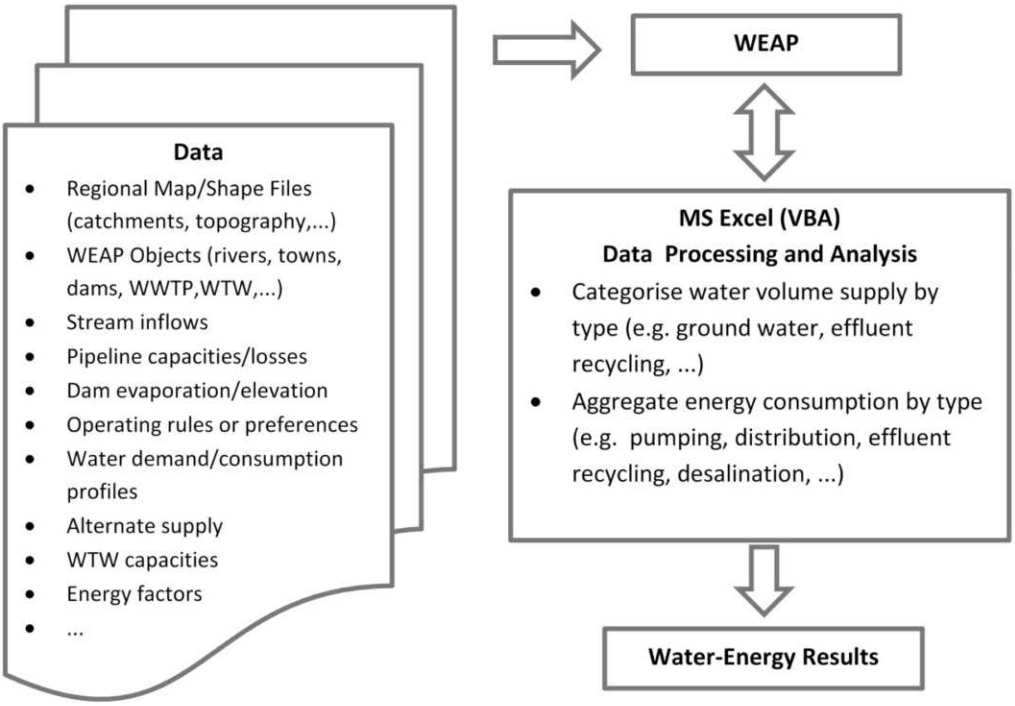


Figure 3: The integrated water-energy modelling process

Table 2: A summary of policy options for water supply and demand reconciliation in the model

(1)	Water Conservation / Water Demand Management (WC/WDM) (a): limited programme
(2)	WC/WDM (b) : extended programme
(3)	Ground Water Augmentation of Theewaterskloof dam from TMG (TMG-THK)
(4)	Additional Surface Water Options
(5)	Reuse of Secondary Treated Effluent
(6)	Advanced Recycling of Effluent (including potable augmentation)
(7)	Sea Water Desalination
(8)	Regulation of Water Releases from the Berg River and Theewaterskloof Dams

Table 3: Candidate interventions comprising the policy options modelled in WEAP

Intervention	Policy option preference
(a)	WC/WDM (1) > Ground water (3) > Reuse (5) > Desalination (7)
(b)	WC/WDM (1) > Surface (4) > Reuse (5) > Ground water (3) > Recycling-Potable (6)
(c)	WC/WDM (2) > Desalination (7) > Reuse (5)
(d)	WC/WDM (2) > Reuse (5) > Recycling-Potable (6) > Ground water (3)

The interventions are illustrative of the impact of policy decisions and do not represent an exhaustive analysis of the complete range of possibilities but rather serve to highlight the modelling process as well, which attempts to address three dimensions of water and energy planning. These are: energy consumption, water availability and assurance of supply.

The scenarios modelled are summarised in Table 4.

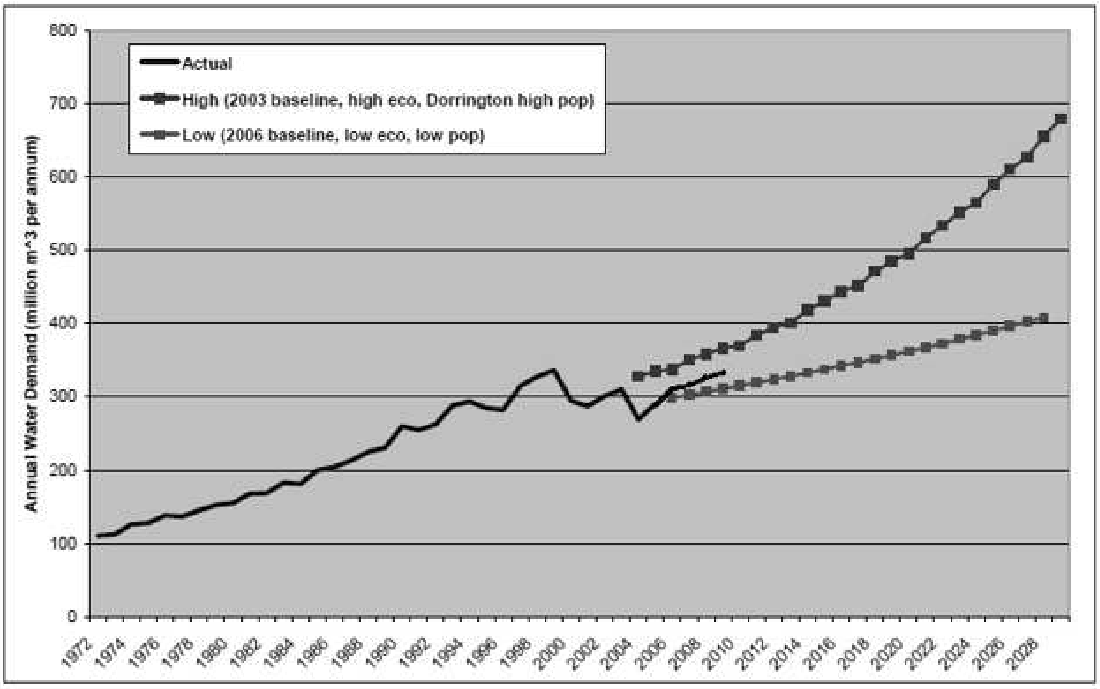
The water demand scenarios are based on the DWAF Future Water Requirements Study (2007), where two water demand scenarios account for a combination of high economic and population growth and conversely low economic and population growth. The 2007 DWAF forecast is depicted in Figure 4, which includes the actual demand up to the period 2009/10 along with the economic and population growth rates used. Figure 5 contrasts the DWAF forecast with the adjusted WEAP demand scenarios which utilise 2009/10 as the base year.

Water availability is quantified with a comparison of the surface water storage of the major dams at the start and end of the period. A 'System Storage Index' is created and refers to the ratio of minimum dam storage (occurring about the month of April) at the end of the period to that at the start, based on a four year average. The WEAP Reliability variable which quantifies the extent that supply is able to meet demand over the period is used to indicate the assurance of supply for a particular intervention. Within WEAP, the system reliability indicates the percentage of time that demand is met for the period (i.e. 100% = no unmet demand for the period and 50% = half the time there is unmet demand).

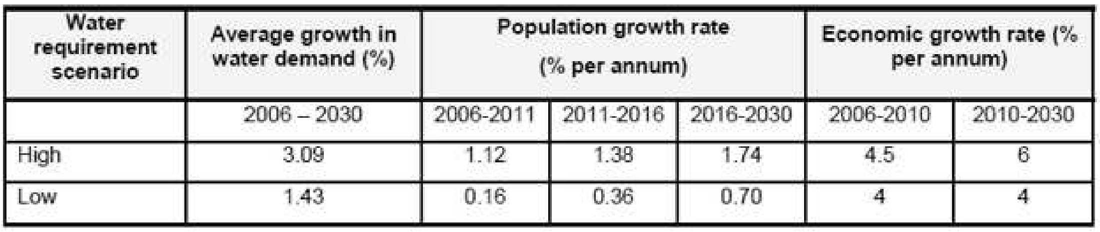
To facilitate a performance comparison of the interventions in relation to the three parameters mentioned, a basic performance index (α) is used. In the context of the research presented here, a favourable intervention is that which minimises

Table 4: A summary of the scenarios modelled with WEAP

Scenario	*Water demand*	*Surface inflow*	*Water quality*	*Dam waters*	*Comments*
1	High	Historic	Low degradation	Regulated	Reference Case
2	High	Historic	Low degradation	Unrestricted	
3	High	Reduced Inflow	Higher degradation	Regulated	Worst case
4	High	Reduced Inflow	Higher degradation	Unrestricted	
5	Low	Historic	Low degradation	Regulated	
6	Low	Reduced Inflow	Higher degradation	Unrestricted	



Actual and forecasted water requirement for the period 1972 to 2030 (CCT, Drakenstein and Stellenbosch)



Water requirement scenario	Average growth in water demand (%)	Population growth rate (% per annum)			Economic growth rate (% per annum)	
	2006 – 2030	2006-2011	2011-2016	2016-2030	2006-2010	2010-2030
High	3.09	1.12	1.38	1.74	4.5	6
Low	1.43	0.16	0.36	0.70	4	4

Figure 4: DWAF aggregated demand forecast for CCT (including bulk customers) with economic and population forecast growth rates

energy consumption (i.e. low energy intensity) and maximises water availability and supply. Therefore, the performance index consists of the unweighted (or neutral) product of the inverse of the system energy intensity (Ei), and the system reliability and system storage index. Expressed in Equation 3, the resultant magnitude of α suggests a more favourable intervention where α is larger.

$$\alpha = 1/Ei * \text{Reliability} * \text{System Storage Index} \quad (3)$$

Expressed in logarithmic terms, as shown in Equation 4, it can be viewed as a simple additive value function which forms the basis of decision analysis in Multi-Attribute Value Theory (MAVT) whereby selected alternatives are evaluated according to set criteria and ranked by an aggregated score as calculated by a value function (van Herwijnen, 2012). The logarithmic expression is given below in Equation 5.

$$A = \ln(\alpha) = \ln(1/Ei) + \ln(\text{Reliability}) + \ln(\text{System Storage Index}) \quad (4)$$

Although no scaling is applied to the indicators for the analyses conducted here, it should be noted that due to the logarithmic summation, a ratio preference scaling is implied for this expression. In

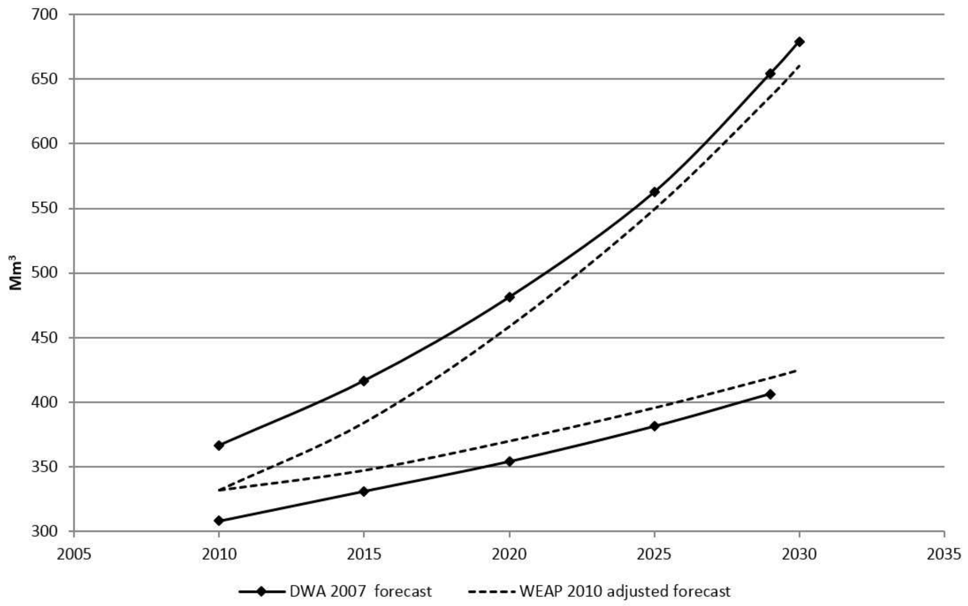


Figure 5: Aggregated demand forecast for CCT (including bulk customers) compared to the 2007 DWAF forecast

MAVT, ratio scaling provides an indication of the relative preference of one option to another by assuming that criteria are directly comparable by their weighting value (Simpson, 1994).

Results and discussion

The analyses focused on the case of high growth in water demand by the City. The options which were implemented are a representative sample of the identified set and it is likely that these are subject to future revision with improved analysis. Therefore, it is important to note that the interventions are primarily illustrative of the modelling approach itself, which provides a tool for scenario analyses where 'what if' questions can be quantitatively examined for their outcomes and compared with alternatives; and that the accuracy and precision of the results reflect the best available estimates and knowledge of the model parameters at the time.

The calculation of separate energy intensities (or specific energies) for the supply of potable water and that for sanitation becomes intractable when interventions are considered because the boundaries of the two branches become more inter-connected as in the case of effluent recycling for potable consumption or reuse. Therefore, as a comparative measure, the energy intensity of the urban cycle is used which is taken to be the ratio of the annual total energy consumed by the water sector (kWh) to the annual volume of water produced (m^3) inclusive of system losses. This would include the supply, treatment and distribution of raw, potable and waste water.

The case of prioritising the existing surface water supply system with desalination as a secondary supply option is also compared. In this case, supply from desalination is endogenously determined as a supplementary supply when other options are insufficient to reconcile demand. This is contrasted with the default implementation in which desalination operates conjunctively with the surface water system and capacities are exogenously determined.

The performance of the interventions

A reference value is used to provide a comparative figure for the performance (α) of the interventions against the aforementioned criteria for the selected scenarios. This value is obtained with the combination of the energy intensity of the reference scenario, an ideal reliability of 100% and a status quo surface water storage (i.e. storage index = 1). This gives a reference performance index of $\underline{\alpha} = 164$.

Table 5 displays the overall performance where the best performing intervention for each scenario is underlined for emphasis. The average performance of scenarios 1 and 3, which represent the extremes of scenario factors, is ca. 49 and is 20% greater than the alternate grouping of scenarios 2 and 4 for which the value is 39. However, in the context of no interventions, if assurance of supply is preferred at the expense of strategic water storage in the near future then, depending on the relative weighting, a reliable water supply system may be considered more resilient. The resultant performance can be further weighted by scenario such that, for example, the reduced inflow scenarios are given more prominence. The results for the implementation of the suggested interventions, as expected, show an improvement in reliability for all scenarios and interventions. The general pattern that emerges is that unrestricted usage increases reliability at the expense of system storage. The data in Table 5 further indicates that the intervention (d) that maximises effluent reuse-recycling in tandem with a

Table 5: The performance (α) of the candidate interventions for the case of high water demand

Scenario	*none*	*a*	*b*	*c*	*d*
1	62	80	117	96	132
2	45	96	137	104	151
3	37	49	36	71	89
4	33	46	40	59	65

continued WC/WDM programme is the best option for each of the possible scenarios considered.

A scenario comprising historical average inflows to the system dams does not reflect the historic variation in system storage and therefore a reduced inflow scenario was included to gauge the system response between the two extremes. Thus, if inflows to the system were reduced or simply less water available from the dams, then the intervention (c) comprising desalination with a continued WC/WDM programme provides the next best performance. Between the two extremes of surface water availability with (d) providing the best performance, (c) is the next preferred intervention based on the reduced inflow performance as indicated.

Referring to Table 6, the energy intensities are similar for all scenarios with no interventions as the existing infrastructure essentially remains a surface water scheme. For the case of no interventions, scenarios 2 and 4 for which dam usage is unrestricted, result in the lowest unmet demands and thus have higher reliability values. However, their storage index is lower as a result of the increased discharge of dam waters. In contrast, for the case of regulated releases, the system reliability is reduced to 60% of the latter option with ca. 50% of water demand being unmet over the period, but with enhanced water storage. This is the case for both surface water inflow scenarios (average and reduced) suggesting a more resilient intervention as existing water volumes are strategically managed or conserved.

Table 6: The performance of the candidate interventions against the individual criteria for the case of high water demand

		Indicator or category		
Intervention	*Scenario*	*Energy intensity*	*Reliability*	*System storage index*
none	1 (reference)	0.61	49	0.77
	2	0.58	85	0.31
	3	0.63	48	0.48
	4	0.59	80	0.24
a	1	1.01	84	0.97
	2	1	99	0.97
	3	1.06	84	0.61
	4	1.03	99	0.48
b	1	0.73	89	0.96
	2	0.72	100	0.99
	3	0.76	87	0.31
	4	0.73	98	0.29
c	1	0.96	92	1.00
	2	0.95	100	0.99
	3	0.98	89	0.78
	4	0.96	100	0.56
d	1	0.66	91	0.96
	2	0.65	100	0.98
	3	0.69	90	0.68
	4	0.67	100	0.44

The ground water option (3) features in all the interventions except (c). Based on the performance of (c), which includes the continued WC/WDM option, ground water appears less important as a municipal supply option for the Greater Cape in the near future. This is in contrast to the key options identified by their performance which includes desalination, effluent reuse-recycling and WC/WDM. However, since the City's WC/WDM programme includes an increase of end-user exploitation of ground water, the impact may be considered indirectly via the success of this component within the WC/WDM programme although the volumes suggested (3.6 Mm^3/a) would still represent a minor contribution should the high water demand growth trajectory be realised.

The case of low growth in water demand

The performance of the existing water supply system, as approximated in the model, is given in Table 7 for the case of low growth in water demand. Reliability and storage are similar to that of the high water demand scenarios with interventions applied. Scenario 6, for unrestricted dam usage and average surface water availability, results in no unmet demand over the period with a comparable performance in storage to scenario 5 and 7 where dam usage is restricted. This scenario has the highest overall performance and the system performance indicates that minimal additional supply augmentation would be required in the near future if water demand approaches the low growth trajectory. Allowing for the uncertainty in surface water inflows, as represented by scenario 7, a full implementation of WC/WDM would require no additional measures. A partial WC/WDM programme would potentially necessitate intervention in the period 2027/30.

The scenario interventions

Figure 6 compares dam storage and unmet demand for the scenarios with no interventions applied. Relative to the reference case, scenario 3 experiences similar unmet demand at the expense of dam

Table 7: The system performance for the low water demand scenarios without interventions

Intervention	*Scenario*	*Indicator* *Energy intensity*	 *Reliability*	 *System storage index*	*α*
none	5	0.61	78	0.93	119
	6	0.59	100	0.86	146
	7	0.62	76	0.87	107

storage. Scenarios 2 and 4 display very different unmet demands over the period which is due to the unrestricted operation of the dams. In this mode of operation, the supply system is less resilient by comparison to the grouping of scenarios 1 and 3.

Municipal energy consumption

The energy intensities of the scenarios without any interventions are displayed in Figure 7.

Scenario 2 and 4, by grouping, display similar characteristics to the grouping of the reference scenario and scenario 3. Scenario 3 departs from the reference scenario due to the increased cost of water treatment, in terms of energy consumption, from the year 2015 although the average energy cost of the urban water cycle for the two predominantly surface water interventions over the period is similar. When comparing the average energy inten-

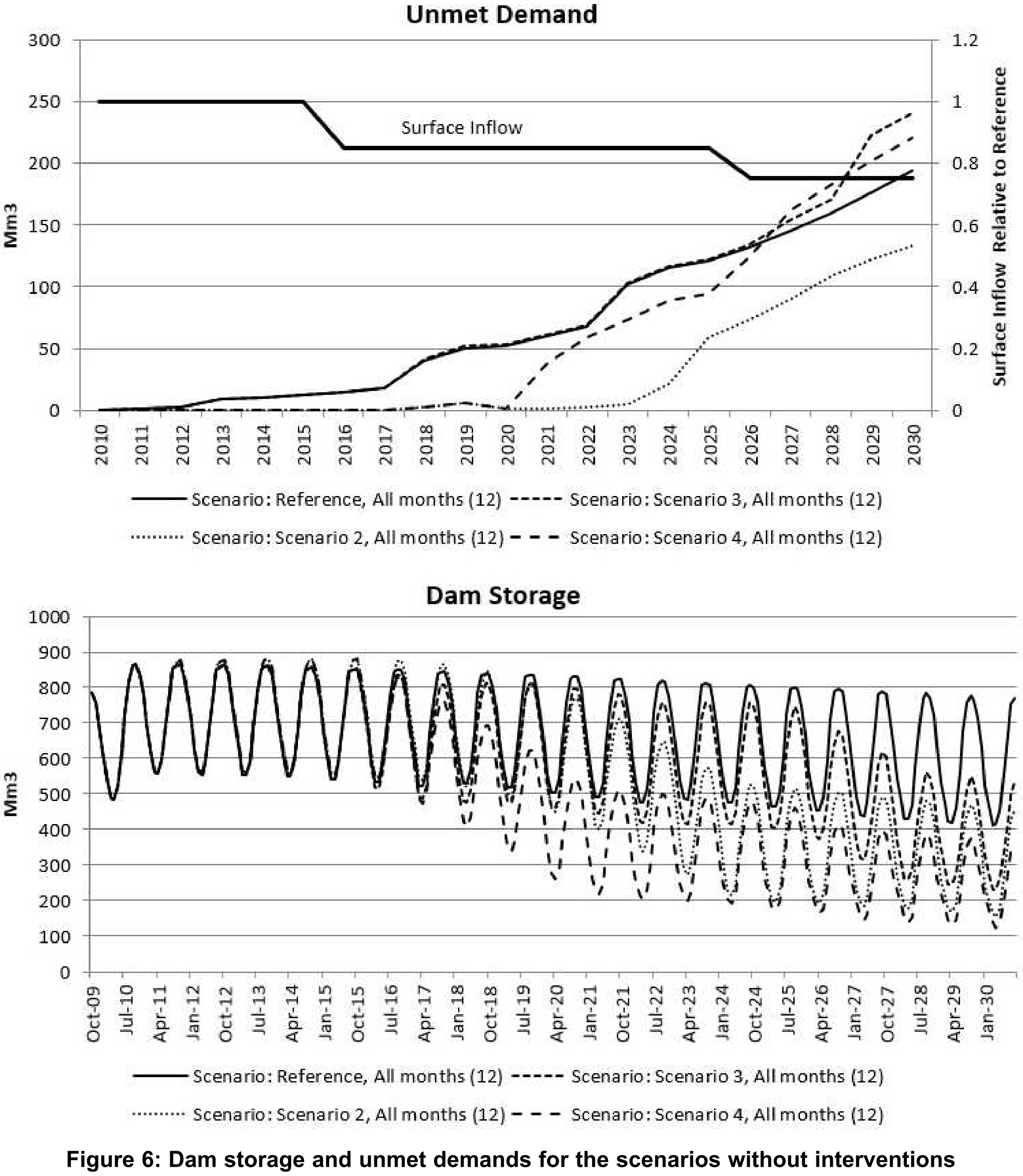


Figure 6: Dam storage and unmet demands for the scenarios without interventions

sity by five year intervals, the difference in energy consumption doubles every five years reaching 8% by 2030. The increase in energy consumption is primarily borne by the potable water treatment processes as displayed in Figure 8, which is dominated by the City's Voelvlei WTW.

In scenario 3, the Voelvlei WTW comprises 95% of water treatment energy consumption, which reduces to 75% by 2026/30. The contribution of the other WTWs is due to the influence of the continued reduction in surface inflows, which impacts the mini-hydro energy generation capacity at these plants while the WTWs at Pniel and Atlantis are modelled with no onsite generation. The peaking of energy consumption at the Voelvlei WTW correlates with the reduction in water supply from Voelvlei dam. The proportion of the total energy consumed, in scenario 3, for water treatment grows from an initial 4% (2011/15) to 11% (2026/30). This compares to the reference case, where WTWs comprise 3% to 4% of total energy consumption for the period 2011/30.

The total energy consumption of the interventions for the scenarios are given in Table 8. Figure 9 illustrates their relative impact by energy intensity – note that the energy intensities for scenarios 2 and 4 are similar for the reference case and scenario 3.

Table 8: Total energy consumption for the period 2011/30 (GWh)

Scenario	*Intervention*			
	(a)	*(b)*	*(c)*	*(d)*
1	9577	6783	8293	5499
2	9615	6740	8275	5501
3	10076	7017	8461	5794
4	9983	6794	8347	5705

An examination of the data reveals that, for a given growth demand scenario, the energy intensity of the interventions are similar between the scenarios such that the influence of surface water inflows and treatment is marginal in terms of the direct energy consumption required for the urban water cycle. This similarity is due to the equal priority of supply options in the model for the urban sector. As the bulk of the existing surface water supply options are shared with the agricultural sector, the solver within the model attempts to satisfy the urban demand with the alternative supply options firstly, in order to ensure adequate water availability for agricultural users.

Within WEAP, users with equal (demand) priority of a shared resource are granted equal privileges and unmet demands are calculated in proportion to the volume of water required. For example, with urban and agricultural users the full capacity of an alternative option such as desalination is utilised causing increased energy consumption in order to ensure minimal unmet demand for both users (assuming they have equal demand priority to the dams).

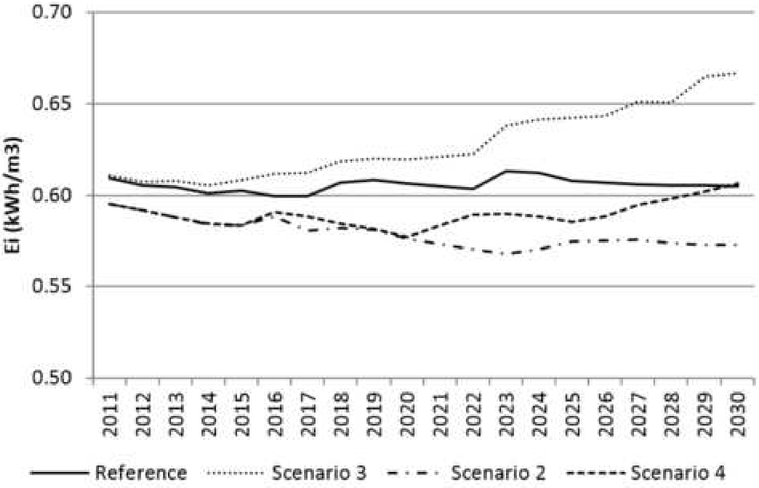


Figure 7: Energy intensities for the scenarios without interventions

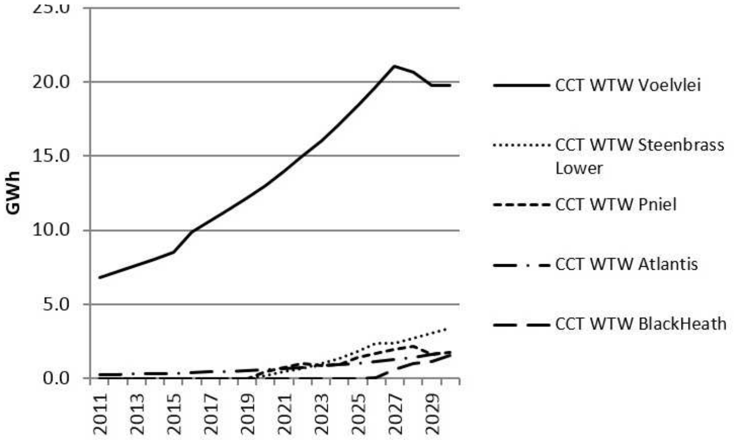


Figure 8: The estimated energy consumption for water treatment in Scenario 3 with no interventions

If the existing relatively low energy surface water interventions are prioritised over the more energy intensive desalination option, the requirement for supply augmentation by desalination varies according to whether dam water releases are regulated or not.

With desalination given secondary preference to surface water supply, the energy consumption for interventions (a) and (c) which implement desalination are listed in Table 9, while Figure 10 depicts the energy intensities. It is noted that the energy consumption for intervention (a) is now similar to the equal supply priority desalination option with a continued WC/WDM program as would occur in intervention (c). For a secondary desalination supply, intervention (c) is similar in energy consumption to the effluent oriented intervention (d).

An examination of Figure 10 highlights the grouping of the energy intensity of the scenarios by surface water usage.

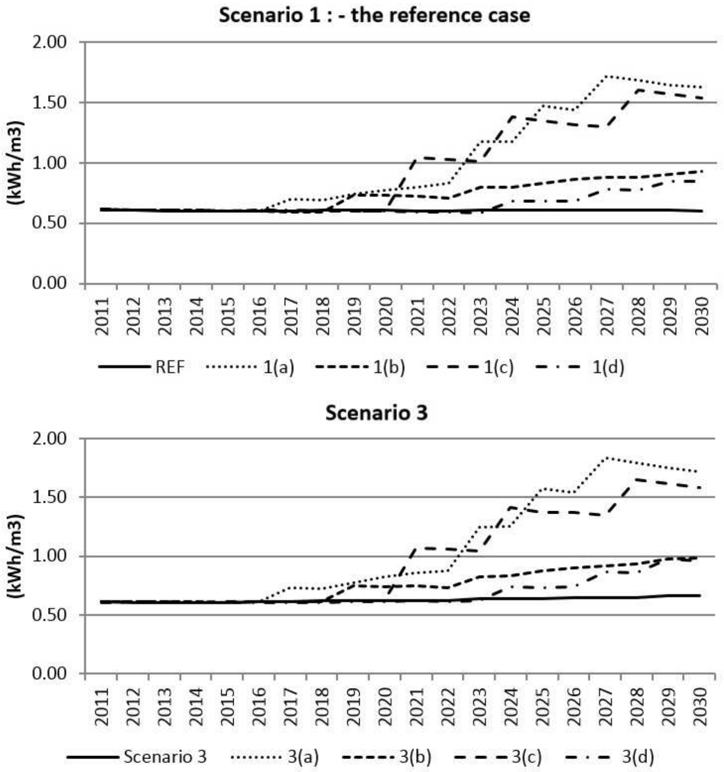


Figure 9: The relative energy intensities of the different interventions for Scenarios 1 and 3

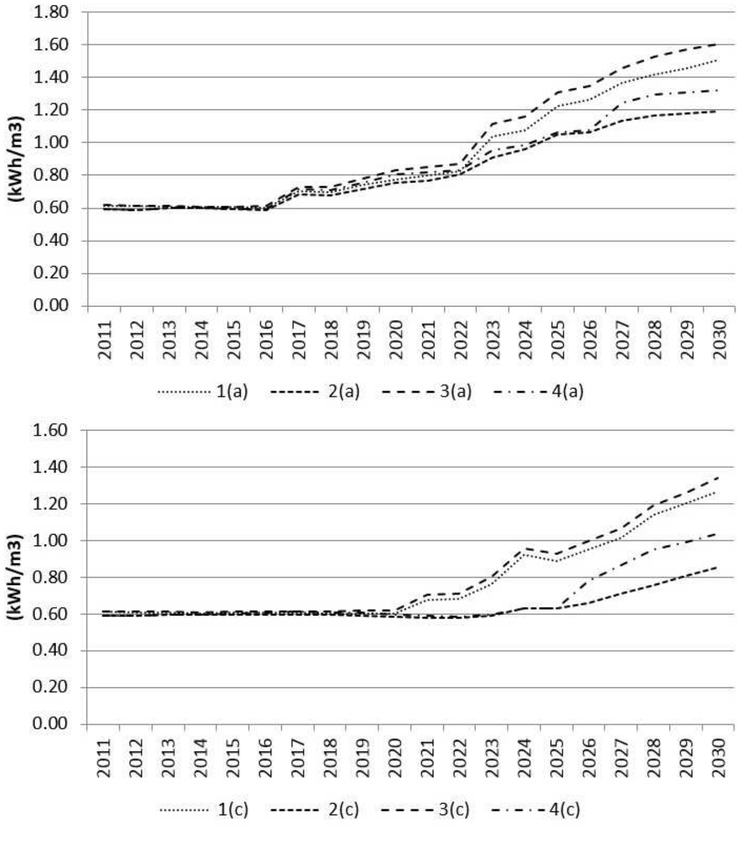


Figure 10: The energy intensity of the scenarios with surface water supplies prioritised and sea water desalination as a secondary supply

Table 9: Total energy consumption for the period 2011/30 for the urban water cycle with desalination as a secondary augmentation option

Scenario	*Intervention*	
	(a)	*(c)*
	Total (GWh)	Total (GWh)
1	8684	6537
2	7877	5421
3	9163	6749
4	8122	5738

With the surface water options prioritised, dam storage displays greater variation for the unrestricted case, while unmet demands are more susceptible to disruptions in surface inflows.

This is observed by the divergence in energy intensities for the grouping of scenarios 2 and 4 as surface water inflow is reduced. In scenario 4 an increased reliance on desalination occurs in response to a reduction in supply from the dams if desalination favoured policy were pursued in combination with unregulated usage of surface water from the dams.

Conclusions

The research presented here demonstrates the flexibility and importance of a systems approach to water resources planning. The results are indicative of a holistic appraisal of the water and sanitation sector in the context of urban municipal water services. In specific, a strategic analysis of the energy intensity of water services, comprising a suite of supply and demand options, for the City of Cape Town was conducted via a systems analysis process. The value of the research presented here, it is believed, lies primarily in the flexibility of the systems modelling approach to incorporate a multitude of water resources options (e.g. demand management or supply augmentation) in order to evaluate their performance by specific criteria for given objectives.

A systems perspective or integrated assessment further allows the examination of the interrelationship of the different stages of the urban water cycle and assists in identifying key linkages. For example, the effect of a WC/WDM programme on the extent of waste water reclamation; pumping energy for water services; or the energy intensity of water or waste water treatment for specific processes. The model parameters can be applied to specific infrastructure (e.g. Voelvlei WTW) or aggregated in the case of data paucity. The scope of analysis is also a determining factor in the necessary refinement of parameters. For example, the energy intensity of the distribution network can be aggregated when conducting a strategic appraisal. For strategic analyses the WC/WDM options were aggregated as a potential bulk yield although the model allows for a more detailed analysis with specific emphasis on particular WC/WDM measures. This may involve a *bottom-up* sectorial analysis (e.g. residential, food and beverage industry, etc.) which would be implemented to gauge the impact of specific water (or energy) efficient technologies or processes. For example, water demand elasticity functions can be included to model the response to tariffs by consumers and the resultant impact on water and energy resources.

The interventions as proposed within this analysis were examined within a context of energy and water planning for the City of Cape Town such that energy considerations or costing could be incorporated within the long term marginal costing of future water and sanitation infrastructure (Ratnayaka *et al.,* 2009). As such, the modelling process facilitated an exploration of the water–energy nexus in the context of urban municipal water services.

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