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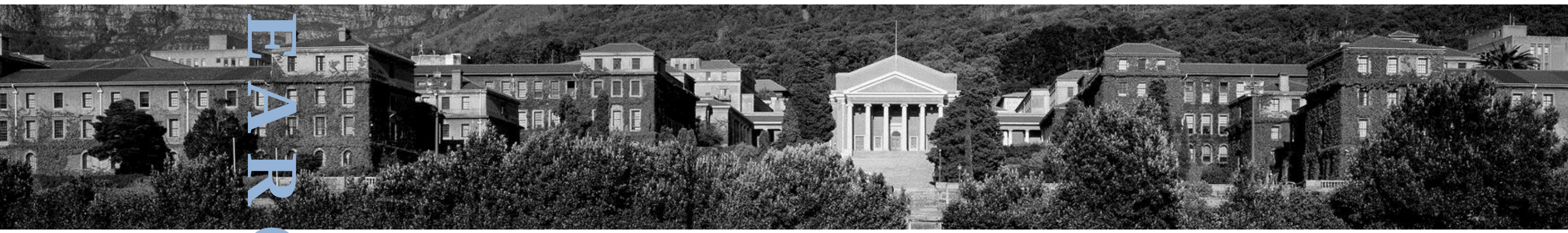

Climate, land, energy and water strategies in the City of Cape Town

FADIEL AHJUM, ALISON HUGHES AND CHAS FANT

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Energy Research Centre
University of Cape Town
Private Bag X3
Rondebosch 7701
South Africa

Tel: +27 (0)21 650 2521
Fax: +27 (0)21 650 2830
Email: erc@erc.uct.ac.za
Website: www.erc.uct.ac.za

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1. Introduction

South Africa is a middle-income country with high inequality and unemployment.[1] In order to meet development aspirations, growth is needed in both industry and agriculture. In addition, basic services,[2] including water and sanitation, must be extended to all citizens. Economic growth and the extension of basic services, along with the growth needed in the power sector,[3] combine to stress the scarce water resources across the country.

South Africa is experiencing water shortages (Walter, 2011). Average rainfall in the country is low, estimated to be 450mm per year,[4] evaporation is comparatively high and surface and underground water are limited and distributed unevenly across the country. Of the rain, 43% falls on 13% of the land, largely in the east of the country. South Africa has also been getting increasingly hotter over the past four decades, experiencing an average temperature increase of 0.13°C a decade between 1960 and 2003 (Benhin, 2006). Locally, in the economic and industrial heart of the country, which lies in an arid zone to the north of South Africa commonly referred to as the Vaal Triangle, industries have expressed concern that a drought in the near future could have drastic economic consequences (Davies 2012). In the Western Cape region, which lies in the south of South Africa, water shortages required stringent water restrictions in both 2000/01 and 2004/05 (South Africa, DWAF 2007h).

The agricultural sector has by far the largest water needs, using an estimated 60%, followed by demand in urban centres. Other large users are the mining and bulk industrial sectors, power generators and afforestation. Concern over the ability to sustainably supply future water and energy needs has been gaining momentum in South Africa over the past decade. Adapting to water resource scarcity requires addressing the inefficient, inequitable and unsustainable use and management of water, as well as growing competition between water users (Walter, 2011). At national, regional, and municipal levels, the energy and water sectors are currently struggling with an infrastructure that is both aging and, in many cases, insufficient to supply current needs (Coetzer 2012; Gaunt 2010).

Because of concerns over water shortages, and the interacting demands for water and electricity, water use has been included as one of the criteria against which power generation investments are evaluated.[5] In response, all new coal-fired power stations are equipped with dry cooling technology, which sacrifices thermal efficiency in return for a 15-fold reduction in water usage (Eskom 2013)[6].

Water supply, in turn, requires energy for both the treatment and movement of water from its source to where it is needed and used. Labaree (2011) presents a framework (Figure 1) for conceptualising the link between water supply and the electricity required for its treatment and delivery. The framework includes a climate change link, climate change being a driver which could increase or decrease the supply of water and the demand for water services. The energy footprint of municipal water supply and waste water services is a key component of effective

1 The GINI coefficient is 0.69 (StatsSA 2014), using a broad definition of unemployment which includes all those currently without work that would like to work, 34.6% of South Africans are currently unemployed (StatsSA 2015).

2 The historical neglect of vast areas of the country under apartheid has left an urgent need to address service provision in order to meet basic service delivery requirements or basic needs. These include access to water, sanitation, housing and modern energy services.

3 Since 2007, South Africa has periodically had periods of rolling blackouts in order to stabilise the national grid, as demand for electricity has increased beyond the capacity to supply it.

4 Only 10% of the country receives rainfall of more than 750mm/year.

5 For example, the Integrated Resource Plan (2010), a planning framework under the Department of Energy which looks at the optimal power generation mix for South Africa over the medium-to-long term, now includes water availability as an additional decision criteria.

6 For example, Eskom's Majuba power station, which has both wet and dry cooled units, provides for an interesting comparison. The wet-cooled units have just over 5.1% greater efficiency but use 10 times as much water per unit sent out compared to the indirect dry cooled units. The wet-cooled Tutuka Power station has a design efficiency of 38% compared to the similarly vintage direct dry cooled Matimba's design efficiency of 35.6% (Eskom n.d.).

water management strategies, so that assessing water infrastructure expansion from an energy perspective will be an important component of future water and energy planning at the local level (deMonsabert and Bakhsh 2009; Marsh 2008).

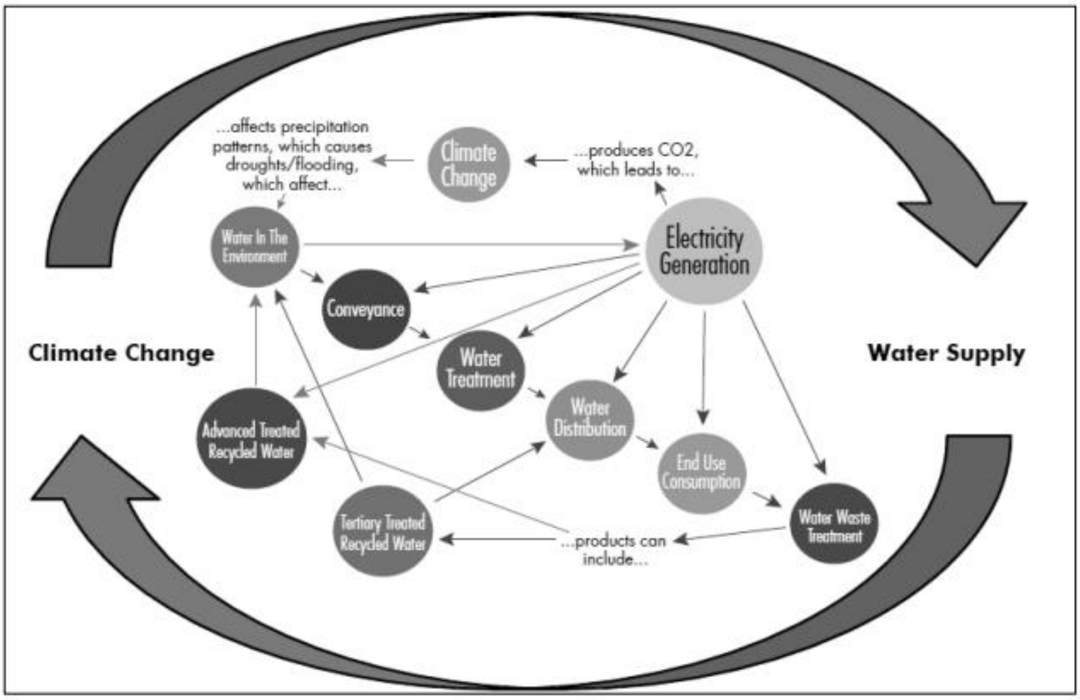

Figure 1: The consumptive water-energy cycle
(Labaree et al. 2011)

Water allocations and the management of water resources in South Africa are governed by the Water Services Act (Act No. 108 of 1997) and the National Water Act (1998) (NWA). The National Water Act (1998) prioritises the equitable and sustainable use of the nation's water resources. It introduces a 'reserve' as a constitutional requirement when determining the potential sustainable yield of a water source. The reserve has two key components. The first component, the basic human needs reserve, secures 25 litres per person per day for those who are supplied from or rely on a water resource before any other water use is assigned. The second component, the ecological reserve, protects the health of ecosystems by ensuring the sustainable development and use of the water resource. The ecological component of the reserve restricts the use of surface and ground water resources in order to compensate for natural variations in the hydrological cycle. For surface water resources this translates to a stipulation of instream flow requirements or environmental water releases for river systems that are anthropogenically modified.

Increasing urbanisation also requires municipalities, which are the primary water service providers, to incorporate effective planning tools to manage the water resources available to them and to cater for increasing water demands. Concomitantly, in an environment of electricity supply restrictions, the energy supply (predominately electricity) required for the provision of water services has become an important factor in municipal strategic planning. For example, using seawater desalination to augment supply may require a further consideration of electricity supply options in order to plan for a cost-effective water-energy supply system.

The climate change, land-use, energy and water strategies (CLEWS) framework, first proposed by Bazilian et al (2011), provides an integrated energy and resource planning framework to address future water and energy needs. CLEWS adopts as a first principle the idea that water, land and energy are integrated and therefore cannot be planned for sustainably as separate or disconnected entities. In addition, the use of land, energy and water both contributes to, and is affected by, climate change, making climate change an important component of the nexus framework.

The CLEWs framework has now been applied in a number of studies globally. This study was a first attempt to apply it in an urban centre in South Africa. Municipal operations occur largely at the sub-catchment level, so that focusing on the municipal water-energy nexus allows local (water and energy) supply and resource management options to be examined that may be overlooked when analysis is carried out at a regional or national scale. The area chosen for the study is the City of Cape Town (CCT) – the metropolitan municipality which governs the city of Cape Town and its suburbs and exurbs. The CCT lies in one of the higher rainfall areas of South Africa, but is nevertheless water-stressed and, like many other urban centres in South Africa, faces challenges related to infrastructure and service delivery. Two areas that lie at the heart of social development in the CCT are those of formal housing provision and the expansion of water and sanitation services.

This study adopts the CLEWS framework to look at the energy implications of expanding the CCT's current water supply to meet future water demand, using a range of demand scenarios and supply augmentation options. In addition the study looks at the potential impact on water demand of relocating agricultural production from land within the city boundary to land outside of it in order to accommodate housing. The horticultural area of Phillipi, which lies within the city boundary and which has been identified as a possible low-cost housing development area, is the focus of this scoping study.

The simulation modelling framework used was developed at the University of Cape Town's Energy Research Centre under the IAEA CLEWS program. The simulation modelling framework, Cape Town Water Energy System Analysis Tool (Cape Town-WESAT), was built around the Stockholm Environment Institute's water evaluation and planning system platform. It provides the means to evaluate the impact of scenarios of variation in demand, inflows, water degradation and dam management on the water supply balance and the energy intensity of water supply given different slates of policy interventions, typically represented by augmentation scheme options like wastewater recycling, groundwater extraction and desalination implemented at different levels and in different timeframes. Essentially, this enables a detailed assessment of the reliability (security of supply) of water supply and the energy intensity of different planning options and interventions.

Core scenarios were developed and analysed using Cape Town-WESAT and the results published as part of a Masters dissertation (Ahjum, 2012). This research is reproduced here, in brief, to bring it into the public domain in a more accessible form and because the scoping study applies the modelling framework and scenarios developed for the earlier work.

The Cape Town-WESAT tool was applied to the case study in conjunction with a crop-water demand model, SAPWAT3, provided by the South African Water Research Commission. This software was used to estimate the additional water demand for irrigation that would likely result from relocating the current agricultural production of the Phillipi horticultural area (PHA), which is located on an aquifer and is groundwater-irrigated, to an area outside of the city's urban boundary.

The report is presented in four parts, after this introductory section. Section 2 provides an overview of the CCT. Section 3 provides an overview of water and energy services within the municipality. Section 4 looks at the reliability and energy intensity of supplying water and water services in the CCT under different demand scenarios and with a range of technically feasible supply augmentation options. Demand scenarios include demand-side measures and potential climate change impacts; supply augmentation includes expansion of ground water use, introducing desalination plants and water recycling. Section 5 presents the PHA scoping study. An appendix briefly outlines four additional studies from the Energy Research Centre exploring elements of the CLEW nexus that have begun since the inception of this study.

2. Overview of the City of Cape Town

The CCT municipality is located in the Western Cape Province in South Africa and covers an area of 2461km^2. It lies in a semi-arid region with a mean average rainfall of 450mm per annum (Figure 2). Rainfall in the region is highly variable both spatially and temporally (over seasons and years). The majority of rainfall occurs between April and October, a period that accounts for about 30% of annual water demand. The topography includes the Table Mountain range that lies within the city boundary, and lower-lying areas which are close to sea level. The latter are drier, experiencing rainfall of between 300 and 500 mm each year, while the higher more mountainous areas receive 1000–2600 mm of rainfall annually (South Africa DWAF 2007c).

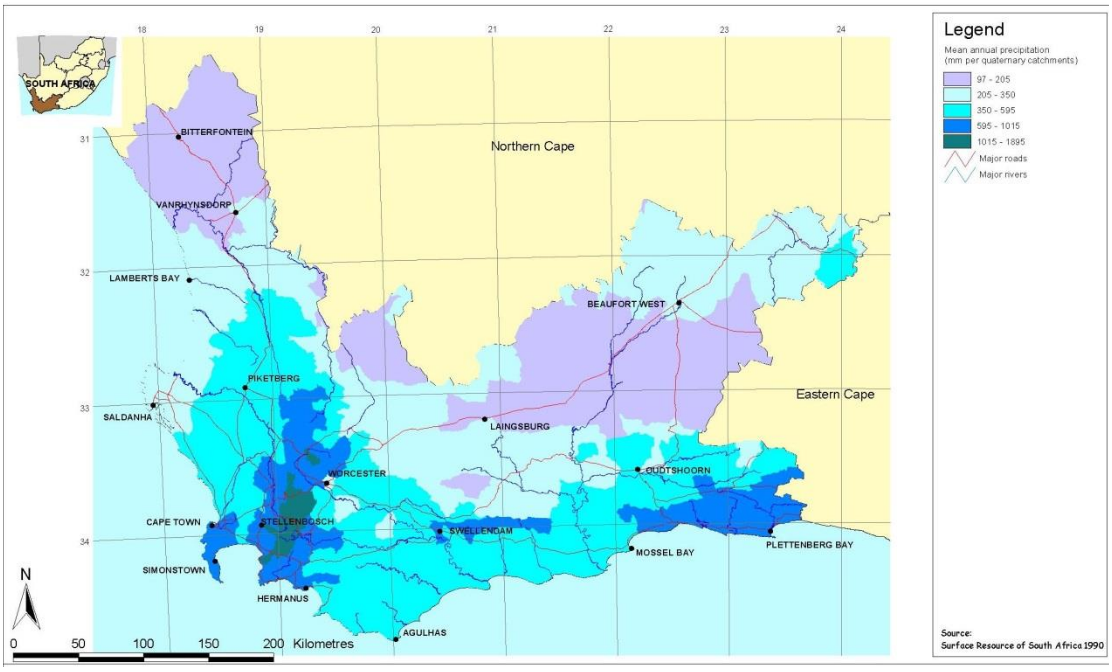

Figure 2: Rainfall in the Western Cape

The CCT is, in terms of population, the second-largest municipality in South Africa, with roughly 3.7 million people living in 1.069 million households (STATSSA, 2011). The municipality is amongst the more prosperous in South Africa, ranking second in terms of GDP per capita after Johannesburg.[7] Despite the relative affluence, nearly 36% of households have an income below the poverty line (less than R3 500 or $426/month)[8] and there is a dire need for housing and improved service delivery for the poor.

Within the city, 11.6% of households live in informal, or shack, housing (STATSSA, 2011) often with minimal water and sanitation services. The city is struggling to keep up with the housing and service delivery backlog, which is continually increasing due to population growth and urbanisation. The annual growth in households between 2001 and 2011 was 2.57%, and the number of households is expected to continue to increase in the future, making housing and service delivery a long-term concern.

Zoning schemes within Cape Town stipulate the type of buildings and activities allowed. The city is an amalgamation of smaller local authorities, which has resulted in over 20 different zoning schemes, which are currently being integrated into the integrated zoning scheme. In the Urban Agriculture Policy of the City of Cape Town (2007) agriculture is formally recognised as an urban land use, but much of the land previously used for agricultural purposes within the urban edge has been converted to other urban land uses, and the remaining agricultural land is under development pressure (Geyer, 2011). Housing areas within the city are growing rapidly, the main growth area being towards the north although there are other areas within the city where housing development is also taking place rapidly. Urban agriculture, on the other hand, provides much-needed employment for the poor, and is an important contributor to food security.

Housing projects within the City aim to redress poverty, by providing either rental houses, opportunities for ownership, or serviced sites at subsidised rates. The City estimates that over

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7 http://www.capetown.gov.za/en/ehd/pages/economicStatistics.aspx.

8 At an exchange rate of R8.2=$1.

23 000 low-cost housing units have been delivered since 2003. One of the challenges which the housing projects face is locating sufficient suitable sites. The search for land causes competition between housing and other land uses. Geyer (2011) found that low-density residential development was the major consumer of high-potential agricultural land within the urban edge, and that commercial, industrial and informal residential developments, in comparison, had relatively little impact.

Investigations into water requirements for the CCT suggest that, without interventions, in a scenario of low population and economic growth, demand for water will exceed supply by 2020. Growth in demand for water is driven primarily by increasing demand in the residential sector that uses between 60% and 70%. Commerce and industry consume 15% and 18% respectively (Cape Town 2011). Mukheiber and Ziervogel (2006) suggested that the CCT is likely to be the first urban region in South Africa where demand for water will exceed supply under scenarios of high GDP and population growth, or if expected climate change impacts are realised.[9] At the same time, rising energy costs or additional more stringent water treatment requirements, in a scenario where water quality decreases (for example due to increased urban and agricultural runoff), will increase the cost and difficulty of supplying residential water in the region.

The following section examines water use and delivery and the associated energy requirements in the CCT.

3. Water and energy in the CCT

3.1 Water demand

The CCT falls within the Berg Water Management Area (WMA).[10] Urban areas are the largest consumers of water in the WMA, using over 50% of the water, in contrast to the surrounding WMAs, where agricultural use dominates (see Figure 3). The region has a negative water balance and relies on water transfers from the adjacent Breede WMA to supplement supply. The reliance on transfers to meet demand within the region is likely to increase in the future as demands grow.

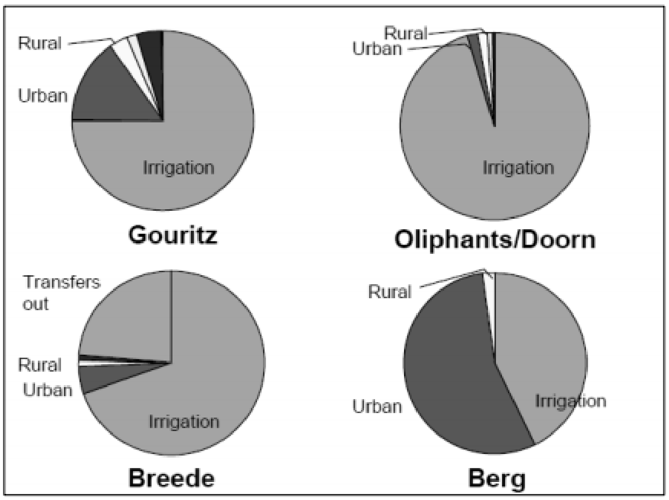

Figure 3: Sectoral water consumption of the predominate WMAs of the Western Cape

Consumption of water in urban areas is influenced by the prevailing climate, the extent and type of economic activity, household socio-economic circumstances such as income and size, and the extent of water and sanitation infrastructure. Residential users within the CCT urban area are the largest demand sector, accounting for close to 70% of the city's potable water usage (Cape Town 2011). In the CCT, climate plays an important role in the seasonal variation of demand. Garden

9 Climate studies suggest that increases in mean annual temperatures and increased variation in precipitation are likely to act as additional water stressors.

10 The Berg WMA is one of 19 WMAs within South Africa.

irrigation is high in the summer months, accounting for as much as 70% of total water usage (Jacobs 2008, Siebrits 2012). There are several low-income residential areas in the CCT where water is provided through a communal tap or unmetered standpipe,[11] residents having to transport water between the communal standpipes and their homes. There are also several areas where flush toilets are not available.[12] The extension of services to these areas is likely to increase residential water usage.

Rising demand for water, with limited options for increasing supply, as well as droughts in recent years, have led to targeted demand-side management initiatives and conservation measures. Several of the measures aim to reduce both energy and water requirements, such as low-flow showerheads. There have also been water restrictions[13] and a rising block tariff system that aims to discourage excessive consumption by charging a progressively higher price to users in higher usage tiers, is now in place for residential users.[14] Jansen and Schulz (2006) estimate the price elasticity of water demand for urban households within the CCT and find that poor households tend to be insensitive to tariffs, whilst wealthier households were more responsive to pricing. In the Cape Flats area, which is home to the majority of the city's poor, price elasticity for poor households has been estimated at –0.23 in contrast to wealthier households that exhibited a price elasticity of –0.99 (Ratnayaka, 2009). Table 1 shows the average annual daily demand for water, by sector, within the CCT.

Table 1: Sectoral daily water demand in the CCT (2009/10) (excluding Atlantis and Mamre)

Sector	*Average annual daily demand (thousand m^3)*
Residential	423
Commercial	69.8
Industry	21.3
Government	36.5
Other	34.7

3.2 Water supply, reticulation and transfers

The bulk of the water supplied to the region originates from the Western Cape water supply system (WCWSS). The WCWSS is a regional network of dams and transmission links drawing largely on surface water runoff in the Berg WMA and transfers from neighbouring WMAs. Within the Berg WMA, the Upper-Berg River catchment is the main source of surface water runoff (WISA 2010). Surface water supplies over 98% of the Cape Town's water needs, groundwater sources supplying the remainder. Around 13% of the CCT's water needs are met by sources within the metropolitan boundary (Cape Town 2011).

There are six major dams, providing 905 Mm^3 of water storage. Three of these are connected via pipelines and a bi-directional tunnel system that enhances overall storage and supply. The annual yield of the WCWSS is 556 Mm^3. This volume is based on planning for a 1 in 50 year probability of drought (i.e. no inflows) but on average, once every five years, the total volume is not reached and water restrictions may be enforced. Currently the city's allocation from the supply system is 398Mm^3 a year, with the remainder allocated to agriculture and to other urban areas in the region.

Figure 4 depicts the water transfers into the Berg WMA from the Breede WMA. Transfers are needed largely for urban consumption, and are extracted from Theewaterskloof dam and the Palmiet River. Theewaterskloof also receives water from the Upper Berg catchment downstream

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11 Around 913 000 households have formal water connections, but a further 190 000 use communal standpipes.

12 According to the STATSSA 2011 Census, 88.2% of houses had flush toilets.

13 Water conservation programmes were in place in 2000/01 and 2004/05, when low dam storage volumes required a reduction in demand of 10% and 20% respectively.

14 For example, the 2015 water tariff is structured as follows: the first 6kl of water are free, the following 4.5kl are charged at R9.98/kl, the following 4.5kl at R14.3/kl etc. For further tariff information see www.savingwater.co.za.

of Berg River Dam. The network of tunnels, pipelines and pump stations which link the Berg River and Theewaterskloof is shown in Figure 5.

The Sandveld Group of aquifers which comprises the Cape Flats, Langebaan and Atlantis aquifers (Cape Town 2001) and Table Mountain group of aquifers are alternative ground water sources and important potential sources with which to augment supply. The Atlantis aquifer already provides 2% of municipal supply, and farmers in the horticultural area of Phillipi (PHA) retrieve water from the Cape Flats aquifer, which is currently the largest withdrawal of water from an aquifer for water use within the CCT. Water withdrawals at PHA are estimated to be in the range of $5Mm^3/a$ (DWAF 2008c) to $19Mm^3/a$ (Meerkotter, 2012). The Cape Flats aquifer, which is estimated to recharge at a rate of 53.4 Mm^3/a, is a possible source of water that could be used to augment current supplies. Use of aquifers for residential purposes using boreholes does not require registration with the DWA and withdrawal from aquifers by residential users is not quantified. Figure 6 presents a conceptual diagram of water flows within the CCT.

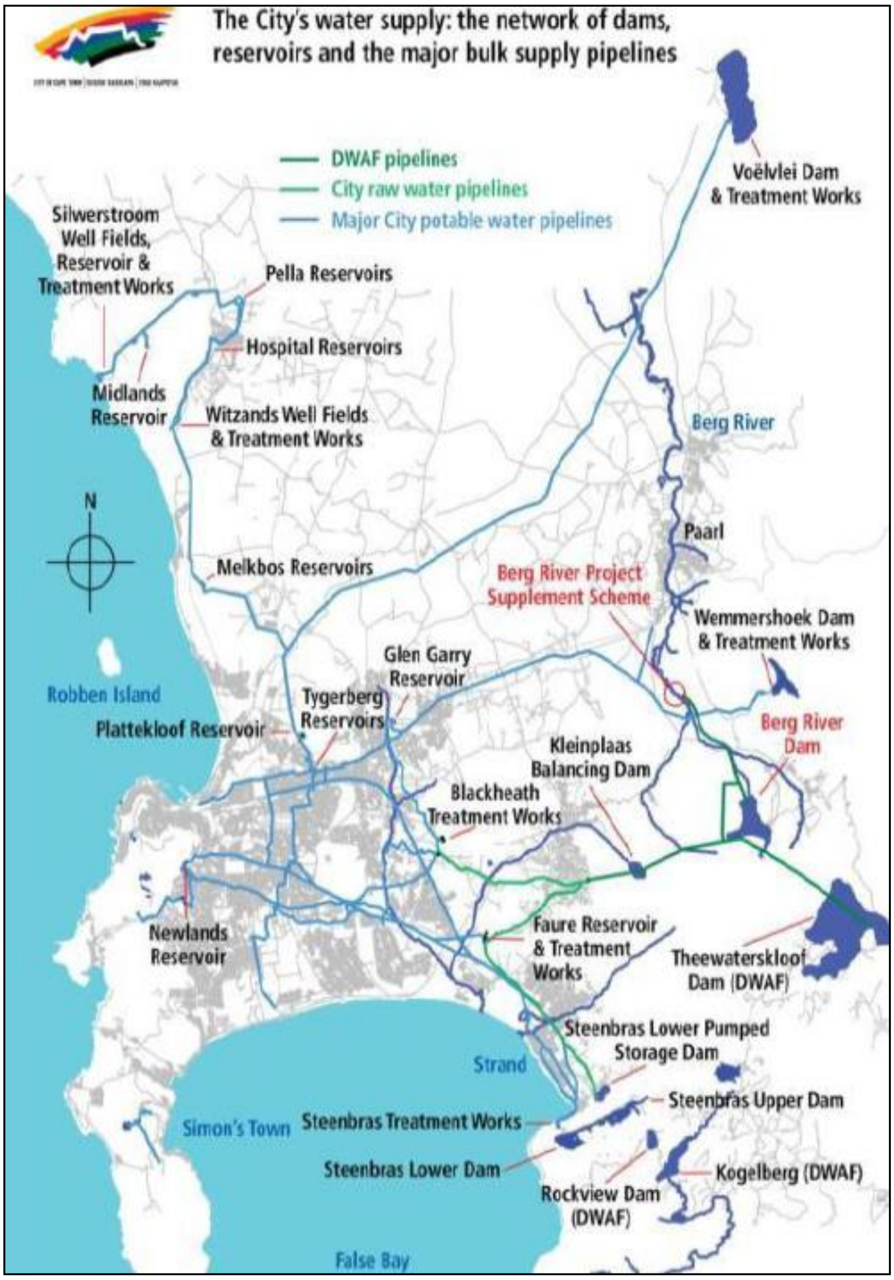

Figure 4: Water supply infrastructure (Interbasin transfers from the Breede WMA indicated by arrows

(Hloyi and Flower, 2012)

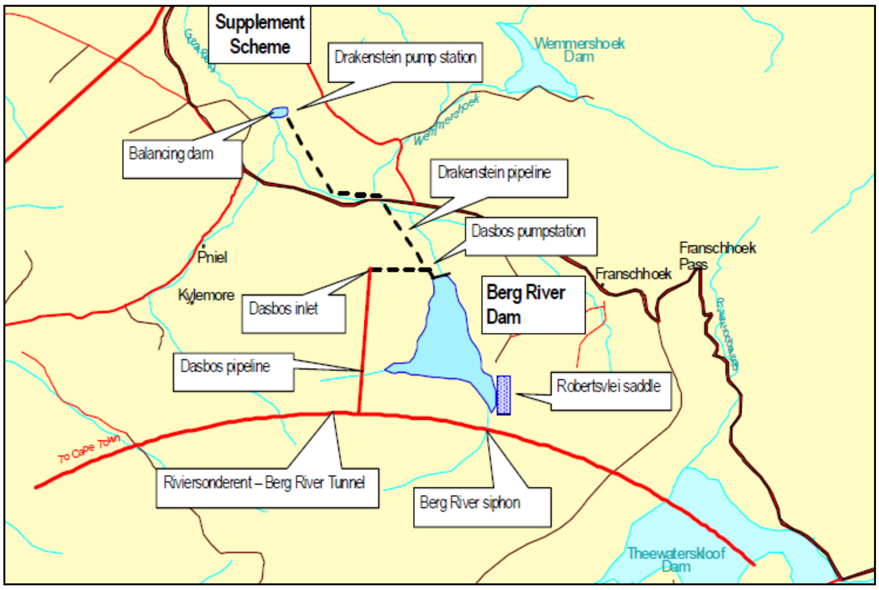

Figure 5: Riviersonderend and Berg River Supplement Scheme
(CSIR, 2008)

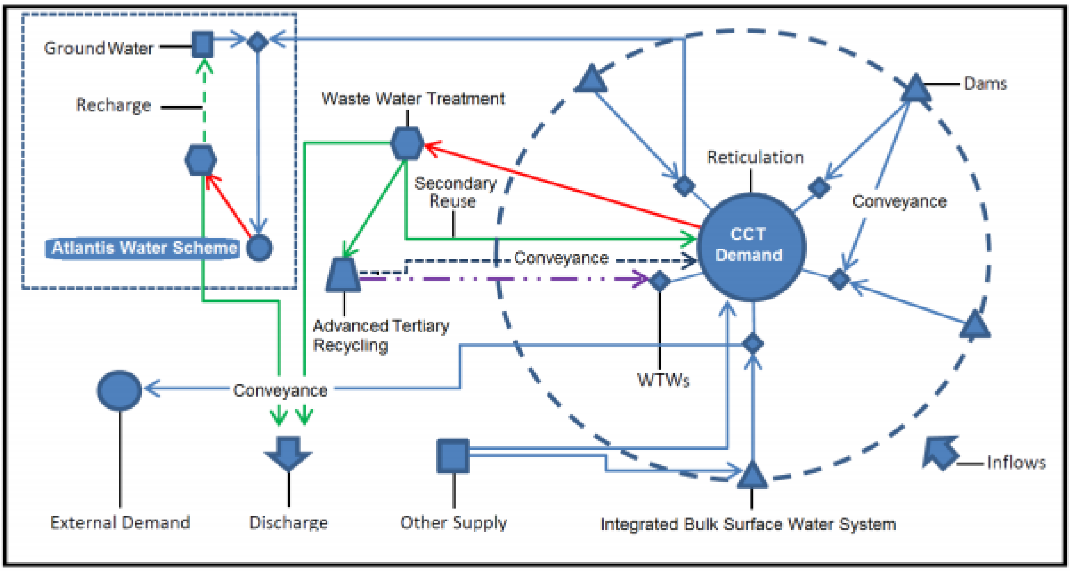

Figure 6: Conceptual diagram of water flows within the CCT

3.3 Electricity

The majority of electricity used in the CCT is supplied via the national grid, a network of transmission lines that extend across the country. There are a few generation facilities that lie in or close to Cape Town that feed into the national grid. Of these, Koeberg, an 1800 MW nuclear power plant is the largest. Koeberg, which is on the West Coast, uses seawater from the Atlantic Ocean for cooling. There are diesel open cycle gas turbines at Athlone (40MW), Roggebaai (50MW) and Ankerlig (1000MW), and two pumped storage stations: Palmiet (400MW), and Steenbras (160MW)[15], which are largely used to meet demand over peak periods.

The CCT used 48 PJ (13 TWh) of electricity in 2007 (Cape Town, 2011), and it supplies around 39% of the municipality's energy needs. Energy expenditure on water treatment and transport, including wastewater treatment, is an important consideration for municipalities in South Africa, as they are typically the primary water service providers. Factors such as the quality of water and topography impact the energy required to treat and move water; however, there is historically a

15 Currently the CCT operates the Steenbras Pumped Storage Plant, all the rest are operated and owned by Eskom.

poor correlation between energy requirements and the volume of water supplied (Lui, 2012). In the CCT, water services account for around 50% of local government's electricity demand, with waste treatment works and bulk water supply using 81 GWh and 41 GWh in 2007 respectively (Cape Town 2010, ERC 2007, Cape Town 2011).

3.4 Municipal water treatment services

Figure 7 shows the urban water cycle, which relies on three main infrastructural components, namely:

- Conveyancing of water: This generally refers to the transport of water in bulk, either in treated or untreated form. The transport of bulk water requires either gravity or mechanical aid and includes, for example, the transport of water from dams to water treatment plants.
- Treatment and distribution of water to the consumer.
- Waste water collection and treatment after use.

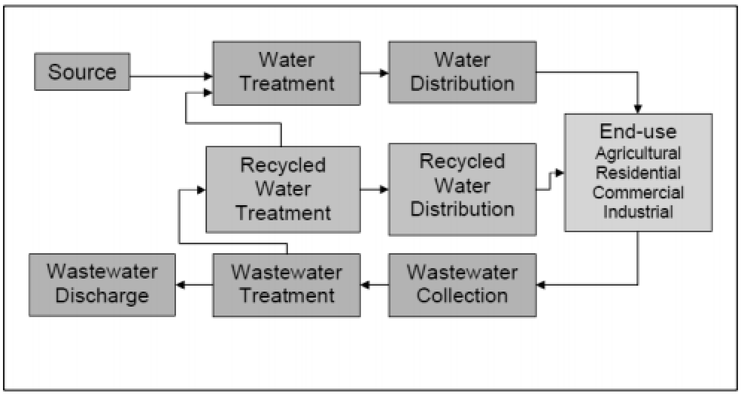

Figure 7: The urban water cycle
(Adapted from California Sustainability Alliance, 2008)

The city's Bulk Water Branch runs the water treatment works from which bulk water is distributed via pipelines and reservoirs to districts. Water is distributed from the districts to consumers through a secondary network. The elevation of the dams around the city allows the majority of the water to be distributed using only gravity flows. In addition, the elevation of the dams creates sufficient head for the generation of electricity at the water treatment works using mini-hydro facilities that can provide sufficient electricity to meet process requirements. Where gravitational flow is inadequate, pump stations are used to move the bulk water. The CCT's reticulation network includes in excess of 200 electrical pumps for water distribution and 500 electrical pumps for sewage collection.

Sanitation services are provided by 26 wastewater treatment facilities. The treatment of wastewater is responsible for around 67% of the energy consumption of Cape Town's water and sanitation services. Water from sources with negligible human interaction can generally be treated to potable standards by basic filtration and disinfection (Moore 1989). Water treatment is classed as being either conventional or advanced depending on the process involved. Additional treatments with more advanced technologies are needed to remove contaminants such as nitrates, pesticides, metals, inorganic salts, pathogens, chemicals and endocrine disrupters.

Conventional fresh water treatment processes require between 0.05 and 0.15 kWh per cubic meter of potable water produced. Physical membrane water treatment processes such as micro- or ultra-filtration require between 0.1 and 0.2 kWh/m^3 (Vince et al. 2008). Advanced fresh water membrane treatment processes such as nano-filtration requires 0.4-0.7 kWh/m^3. In the CCT the energy intensity of potable water provision (including distribution) is estimated at 0.16 kWh/m^3 while that of wastewater treatment (including sewage-pumping) is estimated at 0.43 kWh/m^3 (Mashoko 2012).

Wastewater in the CCT is largely potable water that has been used and discharged into the sewerage network or the environment (although the water generally requires treatment, and is treated, before being thus discharged). The CCT is primarily responsible for wastewater treatment, and under Section 21 of the National Water Act has to comply with regulations for the discharge of wastewater into the environment. Regulations governing industrial wastewater are stipulated by the municipal bylaws as mandated by the Water Services Act (Cape Town 2006; DWAF 1984; DWAF 1997). In South Africa, the general standard for the purification of water requires a level of chemical oxygen demand of no more than 75mg/L with no detectable faecal *coli* per 100ml (Cape Town 2006).

Waste-water treatment falls into primary, secondary or tertiary/advanced treatment categories (FAO 2012). After initial preliminary screening to remove larger solid material, primary treatment is done to further separate and remove suspended matter by sedimentation and surface skimming. Secondary treatment requires the use of biological agents to metabolise or biodegrade organic constituents of primary treated effluent by aerobic digestion, followed by secondary separation of the solid-liquid suspension. Tertiary treatment incorporates secondary and primary treatment with further processing of the effluent. This may consist of additional chemical treatment (e.g. coagulation and flocculation) to precipitate dissolved contaminants such as phosphorus or heavy metals that are then removed by filtration.

Typical energy requirements of the primary process are between 0.1 and 0.372 kWh/m^3; secondary treatment typically requires between 0.258 and 2.96 kWh/m^3; tertiary treatment requires 0.392–11 kWh/m^3. Differences in energy consumption occur due to factors such as the retention time of the effluent in aeration tanks and onsite pumping requirements.

3.5 System losses

Water losses are characterised by the International Water Association as either apparent or real (Ratnayaka 2009). Apparent losses refer to unauthorised consumption, whereas real or physical losses refer to leakages in the conveyance of water from the source to the consumer, i.e. they can occur in either the bulk supply or distribution network. Three system losses are captured in the CCT water balance shown in Table 2. These are water losses from the water supply system, water losses from the bulk water system, and water losses from the reticulation supply system, estimated to be 25.2%, 8% and 20.7% of the water conveyed by these systems respectively.

Table 2: CCT water balance for the period 2009/10
Source: Cape Town (2011)

CITY OF CAPE TOWN WATER BALANCE	Volume (Mℓ)	
City of Cape Town Water Supply System		
Potable water produced	331 062	
Water supplied to consumers within City's area	218 462	
Water supplied to neighbouring municipalities and consumers outside City's area	29 325	
Water loss	83 275	
Percentage water loss from Water Supply System	25.2%	
Bulk Water Supply System		
Potable water produced	331 062	
Water supplied to neighbouring municipalities and consumers outside of the City's area	29 325	
Water supplied to Reticulation System	275 321	
Water loss from Bulk Water Supply System	26 416	
Percentage water loss from Bulk Water Supply System	8.0%	
Reticulation Supply System		
Water supplied to the Reticulation System	275 321	
Water supplied to consumers within the City's area	218 462	*100.0%*
Commercial	*25 541*	*11.7%*
Domestic	*156 656*	*71.7%*
Government	*4 457*	*2.0%*
Industrial	*8 532*	*3.9%*
Miscellaneous	*9 389*	*4.3%*
Municipal	*8 612*	*3.9%*
Shared Water Meters	*44*	*0.0%*
Standpipes	*385*	*0.2%*
Homeless Shelters	*171*	*0.1%*
Schools and Sportfields	*4 699*	*2.2%*
Balance amount	*-24*	*0.0%*
Water loss from Reticulation Supply System	56 859	
Percentage water loss from Reticulation Supply System	20.7%	

3.6 Impact of climate on water availability

Climate variability reflects the long-term variation of hydrological cycles, and climate change will likely alter precipitation cycles further. In the Berg WMA, climate change is likely to act as an additional stressor on water sources, due, in part, to the anticipated increase in mean annual temperature, which will increase evaporation, and the expected variation of both the intensity and duration of precipitation, resulting in longer drought periods and 'heat-waves' (Ludwig et al 2009; Lumsden et al 2011; Western Cape DEADP 2011a). These two factors will probably combine to increase irrigation demands, in an area where irrigation already forms a large part of water demand.

4. Water supply options and their energy consumption

Several possibilities have been identified to meet the growing need for water in the CCT. On the demand side they focus on water conservation and demand-side management; and on augmenting existing supplies with additional water resources, on the supply side. Demand-side studies have estimated that 106–118 Mm^3/year in water savings could be realised, and that combined water conservation and demand-side management measures could defer the need for new water supply options by between 5 and 17 years. Similarly, supply-side augmentation options of approximately 300 Mm^3 capacity would add significantly to the current supply level. The energy implications for the municipality vary considerably based on the augmentation options selected.

This study uses the Water Evaluation and Planning tool (WEAP) to simulate water services in the CCT and the energy required to increase and augment supply in line with projected demands. The water system as modelled in WEAP is shown in Figure 6. Dams are connected to demand sites via water treatment works, which in turn are connected to waste-water treatment plants which process the return flows. WEAP interfaces with the Long Range Energy Alternatives Planning tool (LEAP), to allow both the water and energy demands and costs associated with supplying water to be calculated. Costs incorporated into the model include fixed and variable operation and maintenance costs and the capital costs of infrastructure. The net energy required for water and sanitation services is the sum of the product of energy intensity and the volume of water or effluent that is processed at each stage. The energy intensity of the water sector is the energy consumed per cubic metre of water distributed or effluent treated.

Estimating the long-term energy footprint of the water sector is the primary objective of this research and therefore a detailed hydrological model of the Berg WMA was not required, and is not included in the WEAP model; instead, the WEAP 'water year method' (WYM)[16] was used to create a representative account of system flows. The WYM allows the use of historical data to create a class of hydrological year as the initial state. Five classes of hydrological conditions exist, namely: normal, very dry, dry, wet, and very wet. The WYM thus allows for scenarios of alternative future stream inflows to dams using user-defined hydrological years over the modelling timeframe. Future upstream demands on rivers are incorporated as reduced inflows into the surface water system. Currently ground water contributions to surface water flows are relatively small and were therefore not included.

Water requirements and supply in 2009/10 are shown in Table 2. The historical monthly water consumption profile is shown in Figure 8. Average daily demand in 2009/10 was 585 Mm^3. Bulk water losses of 8% and reticulation losses of 21% are applied in the model.

The Atlantis Water Scheme is modelled separately, as ground-water constitutes a major source of supply to the Atlantis and Mamre communities, and therefore the Atlantis-Mamre demand has been disaggregated from the bulk city demand.

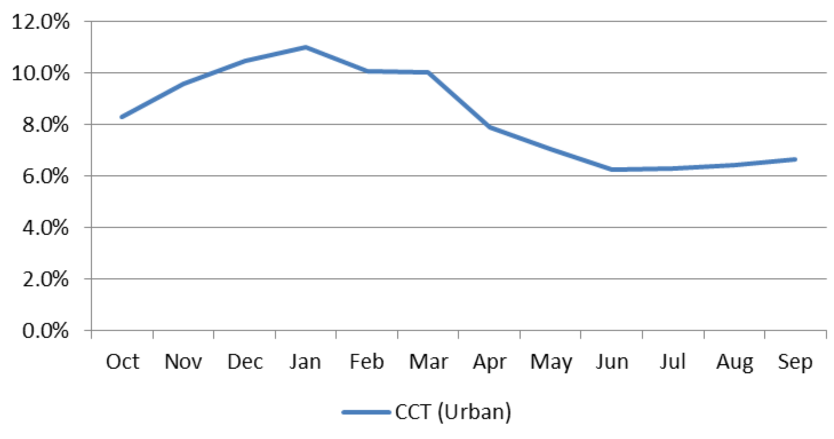

Figure 8: Historical monthly variation in total water consumption for the CCT

16 Further information on the water year method can be found in the WEAP User Guide available from http://www.weap21.org/downloads/WEAP_User_Guide.pdf.

Irrigation allocations to agriculture are shown in Table 3. Water releases for agriculture are seasonal, requiring the highest volumes between October and May. Monthly variations in total water demand for agriculture are shown in Figure 9.

Table 3: Irrigation allocations from the WCWSS

WCWSS	*Allocation (Mm^3 per annum)*
Voelvlei dam: Lower Berg irrigators	18
Berg River dam: Upper Berg irrigators	50
Theewaterskloof dam: Riviersonderend irrigators (Summer release from Theewaterskloof)	50 (33.4)
Total	151

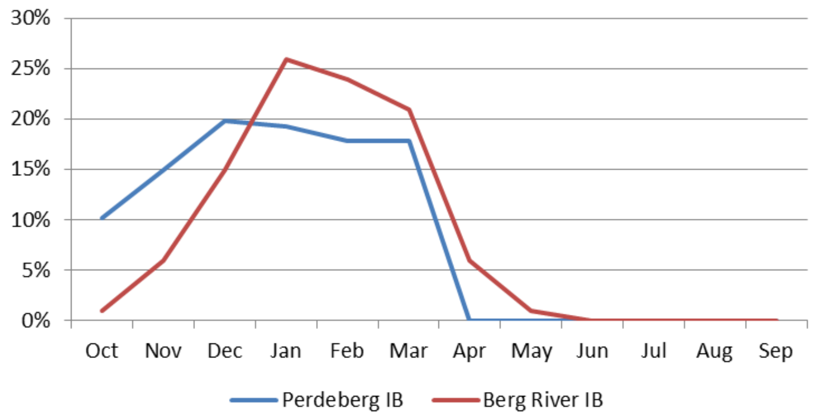

Figure 9: Monthly water consumption profile as a percentage of total consumption for agricultural users in the WCWSS

The large dams, which supply 97% of surface water, are included in the model. These are: Theewaterskloof, the Berg River, Voelvlei, Wemmershoek, and Upper and Lower Steenbras dams. Due to their higher evaporative losses, water from Voelvlei and Theewaterskloof dams were given preference in terms of withdrawals, i.e. they have the lowest priority amongst the dams for water storage. The simulated dam storage levels modelled in WEAP, using historic dam inflows under scenarios of low and high water demand are shown in Figure 10.

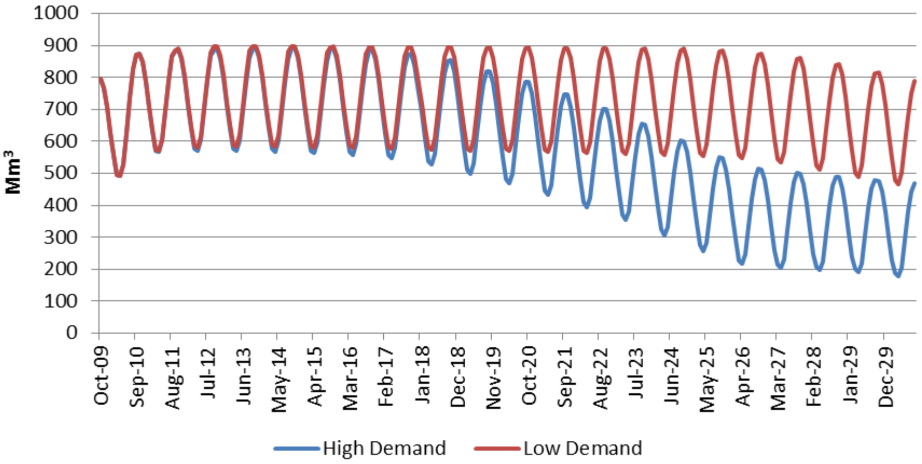

Figure 10: Simulated dam storage (Mm^3) within WEAP for the CCT's water demand with historic dam inflows

Water treatment works (WTWs) are not explicitly modelled in WEAP. Rather, they are represented as reservoirs with minimal capacity while transmission links incorporate pumping requirements. The five largest WTWs account for 97.5% of daily capacity requirements, minor plants (such as Constantia Nek) were not included. An additional plant of 500 Ml/day, in accordance with future City plans, which will utilise the Riviersonderend scheme is also included in the model. The scheme is implemented in two phases to simulate the planned phased construction build. The first phase is to be implemented in 2020, and has a capacity of 250ml/day[17], the second in 2025,increasing capacity to 500ml/day.

Table 4: CCT water treatment facilities included in the model

Water treatment works	Capacity (Ml/day)
Faure	500
Blackheath	420
Wemmershoek	250
Voelvlei	270
Steenbras	150
Atlantis (Witzands and Silwerstroom)	17
Pniel (future)	250 + 250

4.1 Energy required for water treatment

Due to the high use of gravity flow and the predominance of chemical WTWs (Rhode 2008), a value of 0.045 kWh/m^3 is initially assumed for all WTW plants,[18] the only exception being the one at Voelvlei. This value is based on a case study by Vince et al (2008) and applies to conventional treatment; in other words it does not consider the energy required for ozonation, prefiltration and ultrafiltration. For Voelvlei WTW a conventional value of 0.1 kWh/m^3 was used due to the topography, which does not allow for hydropower generation or gravity-based distribution.

As stated earlier, the majority of energy demands for water treatment are met through mini-hydro-turbine schemes that effectively offset the electricity demand, (Cape Town 2001; Cape Town 2010a; Singels 2012). The energy generation potential of the schemes can be calculated using the following formula:

$$E = \frac{\rho g Q H}{e * 3.6} \ (MJ)$$

where E is the energy used in kWh/month, e is the system efficiency, Q is the flow rate in cubic meters per month, H is the head (m), ρ is the density (kg/m^3) and g is gravity (m/s^2). The efficiency of the turbines is assumed to be 60%, which represents the lower end of typical system efficiencies of hydropower schemes.[19]

The only bulk ground-water source contributing to potable water is the Atlantis Water Scheme,[20] and the CCT values for water treatment are applied to this water.

4.1.1 Base year energy consumption

Table 5 shows the volume of water and effluent treated, as well as the CCT's reported electricity consumption in 2007/8 along with the model estimates for the 2009/10 base year. The energy intensity of waste-water collection and treatment is around 0.42 kWh/m^3, while that of the potable

17 The CCT has stated that 'due to the uncertainty associated with the availability of raw water resources, it is anticipated that any new water treatment plant capacity which is required will initially be implemented in increments of 250ml/day (CCT, 2001).

18 This energy intensity is based on a case study by Vince et al (2008).

19 Hydro-power schemes typically have efficiencies of between 50% and 90% (EUT 2006).

20 Albion Springs is an additional ground water source, but its contribution is small and the treatment required is also small.

water system is around 0.26 kWh/m^3. Energy-intensity estimates for the potable system include auxiliary pumping needed for Palmiet inter-basin transfers (average historical volume) and the Berg River Project pump stations (i.e. Drakenstein and Dasbos).

Table 5: Energy consumption for water and sanitation based on 2009/10 CCT demand with average dam inflows

	Model estimates (2009/10)			*CCT (2007/8)*	
Stage	*Energy (GWh)*	*error*[1]	*Volume (Mm^3)*	*Energy*[5] *(GWh)*	*Volume*[4] *(Mm^3)*
Waste water treatment	91.2	±30%	256.4[2]	81.7	232.0 (2007/8) 257.5 (2009/10)
Water distribution	27.4	±25%	274.4[2]	41.4	Bulk water treated: 315.6 (2007/8) 331.1 (2009/10)
Effluent collection (sewage)	18.6	±25%	133.1		
Potable water treatment and supply	39.6	±25%	327.5		Bulk water supplied to reticulation network: 261.2 (2007/8) 275.3 (2009/10)
Palmiet River import	21.2	±10%	21.3[3]	Unspecified	Unspecified[6]
Berg River project	6.4	±10%	69.3	Unspecified	n/a
Total	204.4			123.1	

1. **Errors are estimated from the maximum and minimum deviations in data or the standard deviation when applicable.**
2. **Cape Town (2011).**
3. **Historical average (South Africa Department of Water Affairs and Forestry, 2009).**
4. **Cape Town (2009).**
5. **Cape Town (2010).**
6. **Palmiet river transfers vary annually.**

The CCT's account of energy consumption[21] excludes the direct supply of electricity by Eskom to municipal facilities. The absence of Eskom sales data is noteworthy, as the pump stations and WTW at Voelvlei are supplied directly by Eskom and the treatment and supply of water from Voelvlei represents a large portion of the expenditure of the Bulk Water Branch (Singels, 2012).

4.2 Scenarios

The scenarios considered include changes in the growth in demand for water services and the availability and quality of the water resources (driven by population growth, economic growth and climate variability) as well as possible alternative water treatment options. On the supply side, the augmentation of existing supply with either surface water runoff from other areas, salt water desalination, or increasing ground water withdrawals. All of these have implications for the energy intensity of meeting water needs.

4.2.1 Water demand

The water demand projections are used in the model based on a Department of Water Affairs (DWAF) study, *Determination of future water requirements* (2007). The DWAF study looks at historic water usage by the city, and the influence which population growth, economic growth and alternative policies might have on the growth in demand for water within the CCT. Residential sector demand is also influenced by the possible migration of low-income households in informal dwellings to higher service levels as formal housing increases in the city.

[21] Uncertainties with regard to the collation of the reported data require attention (CCT 2010; Ross 2012). For example, in the 2007/8 City report the remainder of the unaccounted electricity consumption data was equally apportioned between municipal buildings and the municipality's Bulk Water and Reticulation branches (Jennings 2012).

Two possible demand growth paths are considered:

1. High water demand – which represents a scenario of high population and economic growth.
2. Low water demand – which represents a scenario of lower population and economic growth.

Figure 11 shows the forecast for both the high and low demand scenarios used in the modelling. Actual supply data from 2009/10 was used as the base year for the projections. The projections are linked to economic and population growth rates shown in Table 6 (drawn from the DWAF study). Growth in water demand in commerce and industry is linked to economic growth, growth in water demand in the residential sector, government and other sectors are based on population growth.

Table 6: Growth rates for water, economy and population within the CCT
(DWAF, 2007e)

Water demand	*Average growth in water demand (%)*	*Population growth rate (% per annum)*		*Economic growth rate (% per annum)*
	2011-2030	*2011-2016*	*2016-2030*	*2010-2030*
High	3.09	1.38	1.74	6
Low	1.43	0.36	0.7	4

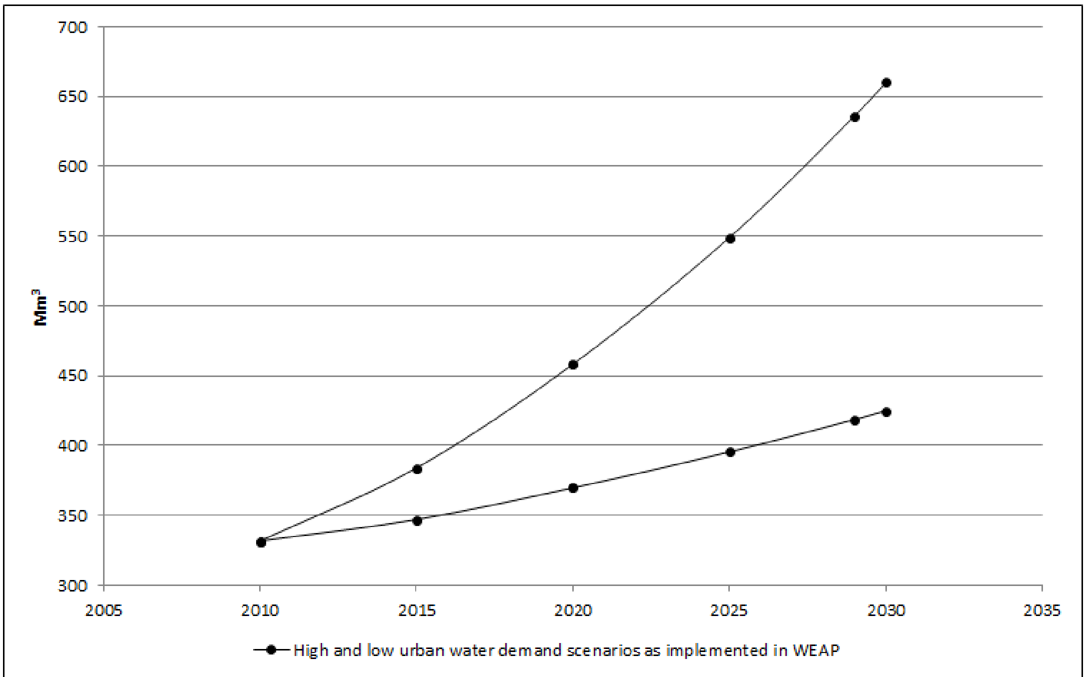

Figure 11: Forecast water requirements for the period 2010 to 2030 (Cape Town, Drakenstein and Stellenbosch)

4.2.2 Supply

Surface inflows are likely to reduce over time due to the increased use of river water upstream of dams. The amount of water available is likely to be further impacted by the implementation of the Ecological Reserve (specified under the National Water Act, 1998). Studies estimating the likely impact of climate variability and climate change on the Berg River and Berg River catchment predict both increasing (Louw 2012) and decreasing precipitation (Callaway et al 2009). However, demands in the arid interior are likely to increase if temperatures rise.

Two inflow scenarios, which reflect the impact of surface water variability on supply, were developed. They are used to reflect an upper and lower bound for the WCWSS dams:

1. Historic inflow – which adopts the historic average.

2. Reduced inflow – 15% reduction of surface inflows for the period 2016–2025 (dry) and 25% for the period 2026–2030 (very dry).

4.2.3 Water quality

Increased pollution of aquifers and surface waters would require that water receive additional treatment.[22] Two water treatment scenarios were developed, to reflect the treatment required as water quality changes, namely:

1. Low degradation – which includes only conventional treatment without oxidation, prefiltration and ultrafiltration.
2. High degradation – where ultrafiltration and brackish water reverse osmosis is required.

In the high degradation case, the energy required for water treatment is escalated with elasticity to population growth of 4. Using this elasticity, the energy-intensity of water treatment approaches what is required for ultrafiltration (0.2 kWh/m^3) by 2030. The water treatment requirements assumed for scenarios of low and high degradation, and their typical energy intensities (in terms of kWh/m^3), are shown in Table 7.

Table 7: Water quality scenarios and associated treatment processes
Source: Ratnayaka (2009); Vince et al (2008)

Scenario	*Process*	*Typical energy intensity*
Low degradation	Conventional treatment process inputs	WTW's (0.045 kWh/m^3) Voelvlei WTW (0.1 kWh/m^3)
High degradation	Ultrafiltration process	0.2 kWh/m^3 (0.001 particle size)
	Brackish water reverse osmosis	1.2 kWh/m^3
		Voelvlei WTW conventional + UF (0.1 +0.2 kWh/m^3)

4.2.4 Policy alternatives

The policy alternatives considered focus on water conservation and demand-side management, augmenting supply with water from additional surface and ground-water sources and the recycling of effluent.

Water conservation and demand management

This is possible, on the demand side, through pressure reduction in the reticulation network, reuse of wastewater, and consumer education (in addition to the block tariff already in place). On the supply side, water conservation and demand management occurs through the reduction of losses in the reticulation network. Losses in 2010/11 were 21%; it is assumed that these can be reduced to 17% by 2030. Bulk water conveyance losses are assumed to remain constant at 8%.

Two water conservation and water demand management scenarios are considered. The savings assumed for each scenario are shown in Table 8.

Table 8: Water conservation and demand management

Water conservation and water demand management scenarios (WC/WDM)	
(a)	Savings of 44.8 Mm^3/a representing partial fulfilment of the savings potential in the DWAF Reconciliation Strategy adopted by the CCT for the 2006 to 2013 period
(b)	Savings of 106 Mm^3/a representing the full savings identified in the DWAF Reconciliation Strategy (2007)

22 Additional energy requirements associated with the production of chemicals used for treatment is not considered.

Surface water

There are a number of surface water options for augmenting existing surface water supplies, and these are presented in Table 9.

Table 9: Surface water augmentation options

Surface water options	*Indicated lead time (years)*	*Yield (Mm3/a)*	*Pump station (kWh/m3)*
Voelvlei Augmentation phase 1	*10*	*35*	*0.2*
Molenaars River diversion to the Berg River Dam	*14*	*27*	*0.2*
Raising of the lower Steenbras dam	*11*	*21.3*	*n/a*
Lourens River Diversion	*10*	*19*	*0.015*
Upper Wit Diversion	*10*	*10*	*n/a*

Ground water

Ground water is currently only used in the Atlantis Water Scheme, and it is estimated that the use of ground-water up to an additional 238.8Mm^3/a is possible (Riemann et al 2010; DWAF 2007). The largest physical potential for groundwater augmentation lies in the Table Mountain Group (TMG) of aquifers, although the feasibility of large scale abstraction from these aquifers remains contentious. Three other, far smaller sources, namely Cape Flats, Newlands[23] and West Coast, with potential yields of 18 Mm^3/a, 7 Mm^3/a and 13.8 Mm^3/a respectively, present additional opportunities, although supply from these smaller aquifers may be far less, as it would compete with withdrawals made by existing borehole users. Due to the concern over the physical volumes that could be drawn from the smaller reservoirs, and the economic feasibility of using groundwater to augment supply, only the TMG-THK site was included. A withdrawal rate of 60 Mm^3/a is assumed as viable rate from the Wemmershoek and Kogelberg-Steenbras sites.

The model includes three possible treatment options for augmenting supply with recycled water. Each option has implications for the energy intensity of supply and pumping requirements. Table 10 shows the assumed effluent volume and energy requirements for the treatment options considered and the appropriate application for the treated water.

Table 10: Energy intensity of water treatment

Process	*End use*	*Effluent volume (Mm^3/a)*	*Pumping requirements (kWh/m^3)*	*Energy intensity excluding pumping (kWh/m^3)*
Secondary treatment	To Cape Town irrigation and industry	40	0.1	0.35
Potable treatment	To Faure WTW	34	0.015	0.58
Advanced recycling	To Cape Town reticulation	35 (35)*	0.1	0.97
* Additional volume allowed in the high water demand scenario towards the end of the period as water utilisation increases.				

Seawater desalination

Desalination of seawater up to a maximum capacity of 150Mm^3/a and at a build rate of 50Mm^3/a is included.[24] An additional water-pumping requirement of 0.2kWh/m^3 is assumed for water coming from these plants. The treatment of seawater to make it potable requires reducing the salt concentration. Large-scale desalination involves either thermal desalination or membrane reverse osmosis. In thermal desalination, heat is used to produce water vapour using either the multistage flash, multi effect desalination or vapour compression processes. The membrane reverse osmosis

[23] Although additional use of this aquifer may negatively affect existing users.

[24] Technically, desalination is limited only by the amount of energy available and therefore the limit imposed is somewhat artificial.

process uses pressure and a semi-permeable membrane, which permits the passage of water while rejecting that of dissolved salt, to separate the salt from the water. Thermal desalination is more energy-intensive. In the Middle East, where it is the most common method of desalination, it is often integrated with electricity production.

Reverse osmosis, which has lower capital costs and energy requirements, has become the preferred method of desalination. The technology is able to make use of advances in membrane technology (Cooley 2011; Karagiannis and Soldatos 2008) and allows some energy recovery through the capture of waste energy by using hydro turbines when the saline brine, which remains at a high pressure, is discharged. The energy requirements assumed for desalination plants are shown in Table 11.

Table 11: Energy requirements for sea water desalination
(Riedinger and Hickam, 1982; Thomson, 2005)

	kWh/m³
Theoretical minimum	0.695
Distillation	637
Thermal Desalination	6-16
Typical membrane reverse osmosis	3-8
'Best practice' reverse osmosis	2

Urban water allocations

These regulate the release of dam waters to maintain a sustainable annual yield. Modelling both the regulated and unregulated release of water from the dams (aside from the allocations to agriculture) gives an indication of the importance of water allocations in maintaining the long-term reliability of the system under different supply and demand scenarios.

4.2.5 Intervention criteria and ranking for policy options

The policy options are modelled as illustrative paths, and do not represent an exhaustive analysis. They are chosen in order to address three dimensions of water and energy planning: energy consumption; water availability; and supply security. In order to represent preferences for certain policy options, four different 'intervention' paths were modelled in WEAP. These are listed in Table 12 from (a) to (d). The intervention paths are distinctive in terms of both the policy options included, as well as the order[25] in which the options are implemented (the order is indicated by the number in brackets in Table 12).

Table 12: Interventions and policy options modelled in WEAP

Intervention pathway	*WC/WDM*	*Ground water augmentation (TMG-THK)*	*Additional surface water*	*Reuse of secondary treated effluent*	*Advanced effluent recycling[1]*	*Sea water desalination*
(a)	Limited programme	(1)		(2)		(3)
(b)	Limited programme	(3)	(1)	(2)	(4)	
(c)	Extended programme			(2)		(1)
(d)	Extended programme	(3)		(1)	(2)	

1. Includes potable recycling.

25 Each intervention pathway has a primary intervention, reuse of secondary treated effluent is implemented second in all cases except (d) where it is implemented as the primary intervention. The interventions are based on the portfolio of interventions presented by the CCT in the WC Reconciliation Strategy Study (DWAF, 2007d)

4.2.6 Scenario analyses summary

Water demand and management are modelled as seven scenarios, each representing a combination of either high or low water demand, historic or reduced inflow, a low or higher level of water degradation and regulated or unregulated dam storage. The aspects included in each scenario are summarised in Table 13 and Table 14. Scenario 1 is the reference case, it is a combination of: high demand; historic inflows; low degradation; and regulated dam waters. Scenario 3 represents a worst case scenario where demand is high, but inflows and water quality decline and dam waters remain regulated.

Table 13: Summary of external factors influencing scenario paths

Demand	Inflows	Water Quality
1. High 2. Low	1. Historic 2. Reduced Inflow	1. Low degradation 2. Higher degradation

Table 14: Selected scenarios modelled with WEAP

Scenario	Water demand	Inflow	Water quality	Dam Waters	Comments
1	High	Historic	Low degradation	Regulated	Reference scenario
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	Historic	Low degradation	Unrestricted	
7	Low	Reduced Inflow	Higher degradation	Regulated	

These scenarios, which combine external factors and dam regulation, are combined with the policy interventions (a-d), which augment supply and curtail demand, in order to assess water security in the CCT under a range of supply conditions and regulated or unregulated dam releases (including a simulated best and worst case scenario). For example, one of the scenarios used for the case study described in Section 4 is Scenario 3 (d), which combines Scenario 3 with policy intervention (d). Scenario 3 is characterised by high water demand, low inflows to storage, high levels of degradation of the water resource and regulated dam outflows (see Table 14). Policy overlay (d) is assumed to be an extended (as opposed to limited) program implementing, firstly reuse of secondary treated effluent, secondly advanced effluent recycling and thirdly ground water augmentation (see Table 12).

4.3 Evaluating and ranking scenarios

In order to evaluate the effectiveness of the suite of policy options considered, three criteria are used, namely water supply reliability (or system reliability), system storage, and energy intensity. The water supply reliability indicator is a measure of the ability to supply an uninterrupted service (supply adequacy) and reflects the percentage of time that demand is met over the period. The system storage index is a measure of water availability in that it compares the surface water storage of the major dams at the start and end of the period. This is quantified with a simple ratio based on a four-year average of the minimum system storage. The minimum system storage refers to the minimum level of water storage in the system at the end of the hydrological year and after water demands have been catered for. This typically occurs at the end of the month of April, which marks the start of the rainfall period. 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). Energy intensity reflects the energy required for the supply, treatment and distribution of raw, potable and wastewater. It is the ratio of the annual total energy consumed by the water sector (kWh) to the annual volume of water produced (m^3), including system losses. System reliability and storage capture the tradeoff between lower storage levels and therefore a reduction in the long-term reliability of the system and maintaining the short-term reliability of the system.

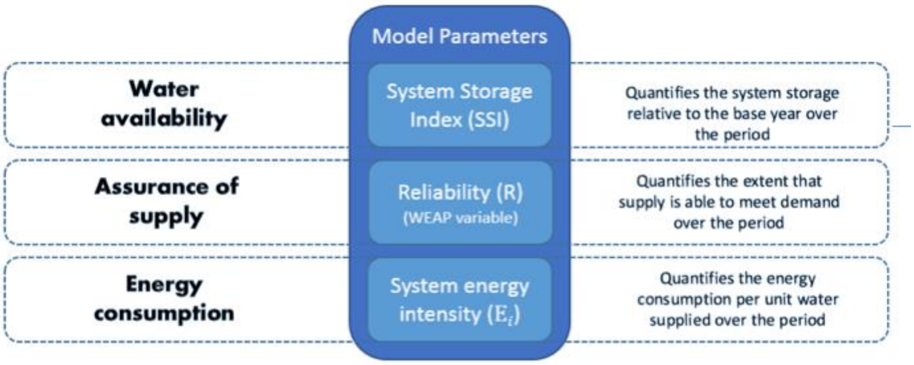

Figure 12: Quantifying the comparative performance of alternatives (interventions)

Thus a basic performance index (α), which is a composite index of energy intensity (Ei), water supply reliability and the system storage index is used to compare the scenario outcomes. A larger α indicates a preferred intervention. The indicator is a geometric aggregation of the three dimensions. Geometric aggregation is preferred to additive aggregation as it does not allow poor performance in some dimensions to be compensated for by high performance in others. Energy intensity is indirectly proportional to the performance index, a system with higher energy intensity will therefore have a lower performance index.

$$\alpha = \frac{water\ supply\ reliability * System\ Storage\ Index}{E_i}$$

It should be noted that α refers to water supply performance and not the sanitation performance which is assumed to comply with secondary treatment standards for which the activated sludge process is predominant. The relative performance is assessed without weighting the individual criteria in order to ascertain their combined impact (or the system resilience) without the addition of weighting bias. If, for example, assurance of supply is preferred at the expense of strategic water storage in the near future then the criteria could be weighted to reflect this.

4.4 Results

4.4.1 The case of low growth in water demand

Minimal supply augmentation is needed when the growth in water demand remains low. The performance of the existing water supply system with a low growth in water demand is shown in Table 17. In Scenario 6, which simulates unrestricted dam usage and average surface water availability, there is no unmet demand over the period and storage is comparable to that of Scenarios 5 and 7, in which dam usage is regulated. Growth in water use in the low-demand forecast is however significantly lower than that of the high-demand forecast, largely due to the extremely low population growth rates assumed in the demand projections.

Table 15: The system performance for the low water demand scenarios without interventions

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

4.4.2 The impact of allocations or regulated usage of dam waters

The registered annual entitlement of the CCT from Theewaterskloof and Berg River dams (the amount of water the city is allowed to take) are 118 Mm^3/a and 80 Mm^3/a respectively (though restrictions can be relaxed if agriculture has not used its entitlement). However, the CCT typically exceeds the registered entitlement from Theewaterskloof, and therefore the model is allowed to exceed the entitlement limit until a threshold is reached (Cape Town, 2005). The amount of water which the CCT draws each year in the reference scenario, from Theewaterskloof and Berg River dams is shown in Figure 13. As demand grows, the release of water from the dams is regulated to maintain an adequate reserve.

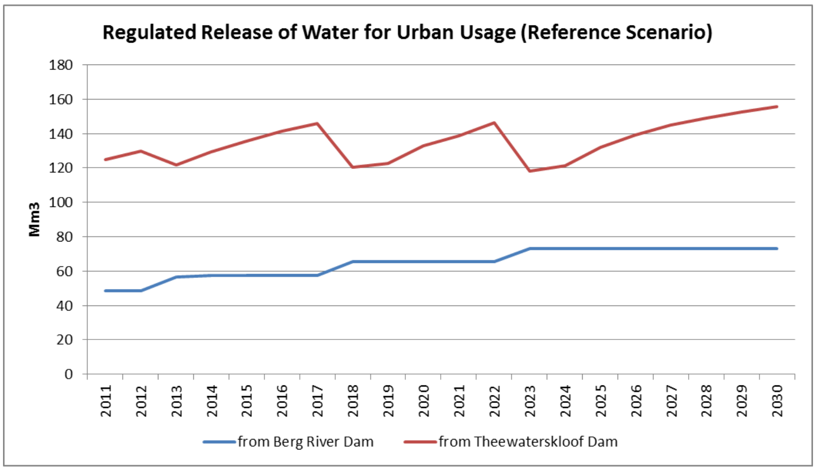

Figure 13: Water abstracted from the Berg River and Theewaterskloof dams for urban demands under a regulated option

Figure 14 shows the impact that removing the allocation has on unmet demand and dam storage. A new WTW at Pniel results in minimal unmet demands until around 2023 (±1 year) after which there is a sharp increase in unmet demand which reaches 130 Mm^3 by 2030. Removing the allocation results in the early drawdown of Theewaterskloof, which has no environmental water releases stipulated for the Riviersonderend. As a result, stream releases, which are not required for agriculture, are reduced to nil by 2016/17.

High water demand results in a marked decline in dam storage, and as a result the system has no drought tolerance and may be more vulnerable to climate variability. When releases are regulated, the decline in storage is more gradual, however there is a large amount of unmet demand, therefore the regulation of releases is a trade-off between long-term water security and short-term reliability.

4.4.3 Scenario 1: The reference case – no interventions

Figure 15 shows the water supply to the CCT and its bulk water customers, and the energy required and the percentage of energy consumed by each stage of the supply chain. The bulk of energy (56%) goes to waste water services followed by surface water supply and treatment (18%) and distribution (14%). Supply is predominately surface water with a minor addition of ground water from the Atlantis Water Supply Scheme.

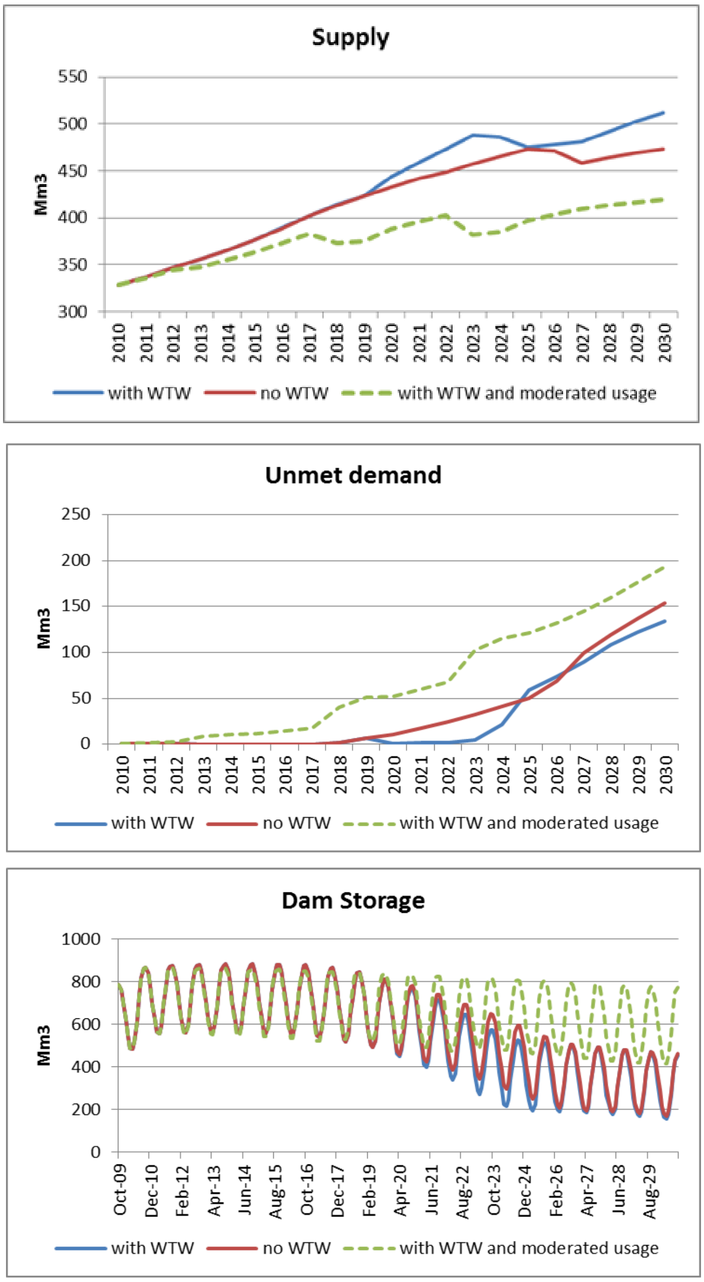

Figure 14: Water supply to the CCT and its bulk customers with unmet demand and storage for the WCWSS

Comparative energy consumption

The change in the energy intensity of supplying water and treating waste with regulated releases from dams (i.e. Reference case and Scenario 2) is shown in Figure 16. The removal of water allocations in sScenario 2 increases energy intensity of sanitation services largely due to the pumping requirements as groundwater ingress contributes to the sewage pumping load. Conversely, the energy intensity of potable water supply decreases. This appears largely due to the full utilisation of the existing bulk water infrastructure; in particular the reliance on the Riviersonderend scheme, which has, on average, low energy requirements.

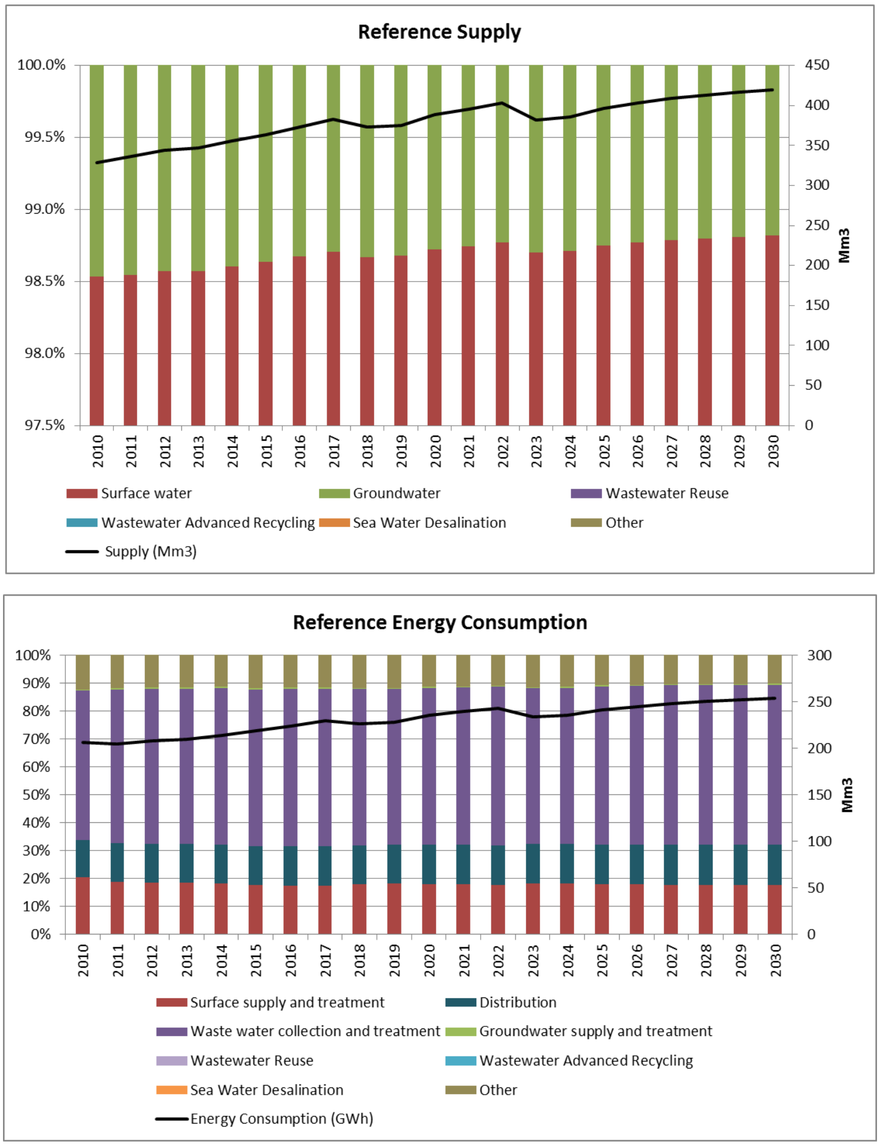

Figure 15: Reference scenario with no interventions

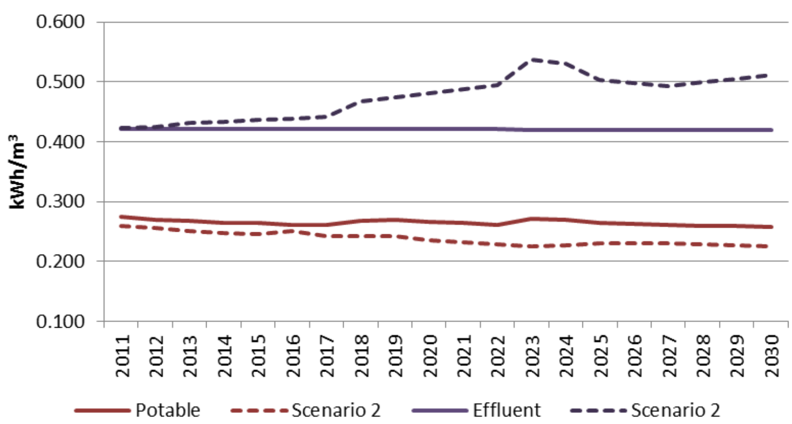

Figure 16: The energy intensity for water and sanitation service in the reference scenario

4.4.4 The scenario interventions

Figure 17 shows the implementation schedule used for the scenario interventions as well as the allocations from the Berg River and Theewaterskloof dams.

Figure 18 shows the total yield delivered by the interventions. Intervention pathway (d) (and to an extent (c)) are dominated by the WC/WDM programme, (a) and (b) which have a less aggressive WC/WDM programme require more aggressive adoption of the other supply options.

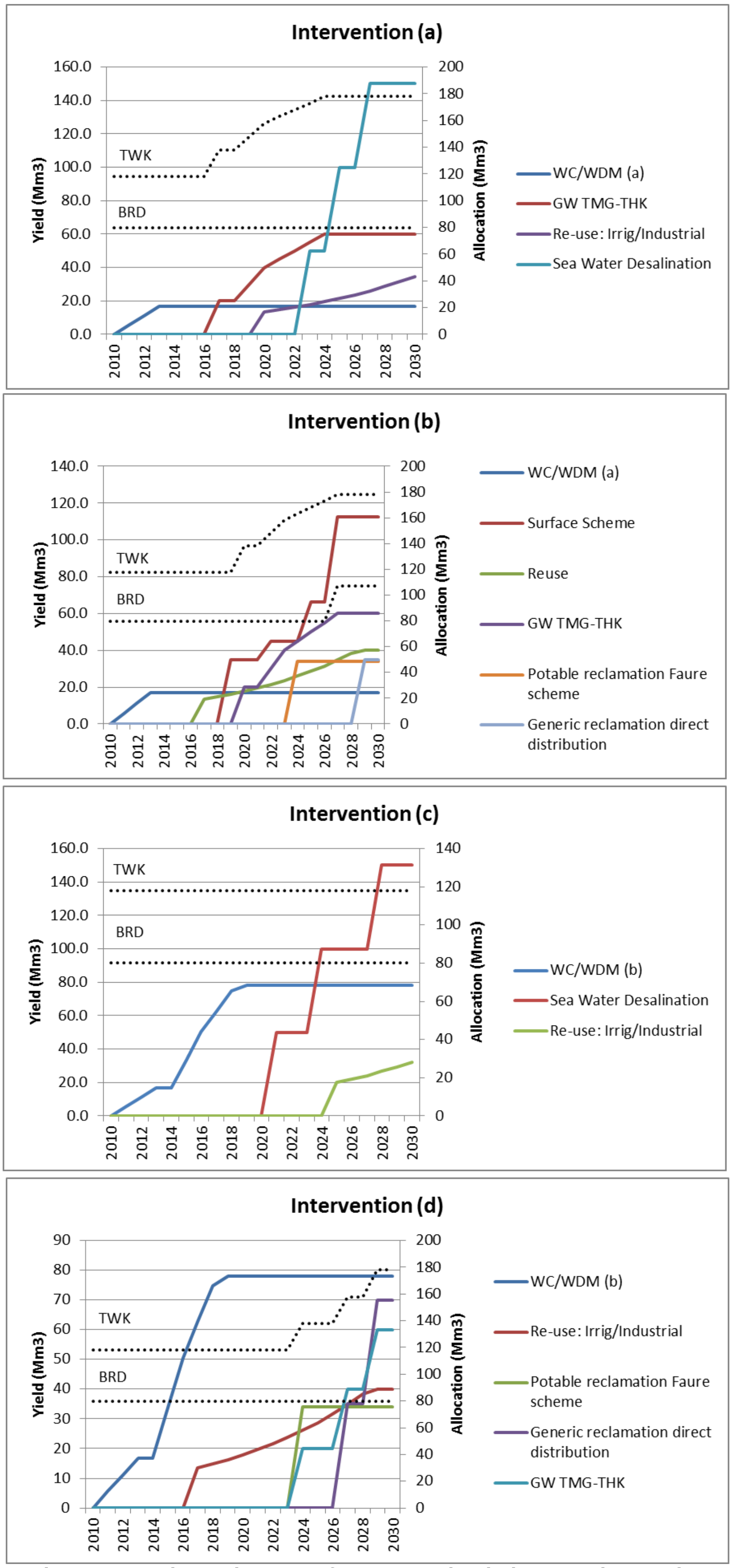

Figure 17: Order and extent of augmentation in interventions a-d

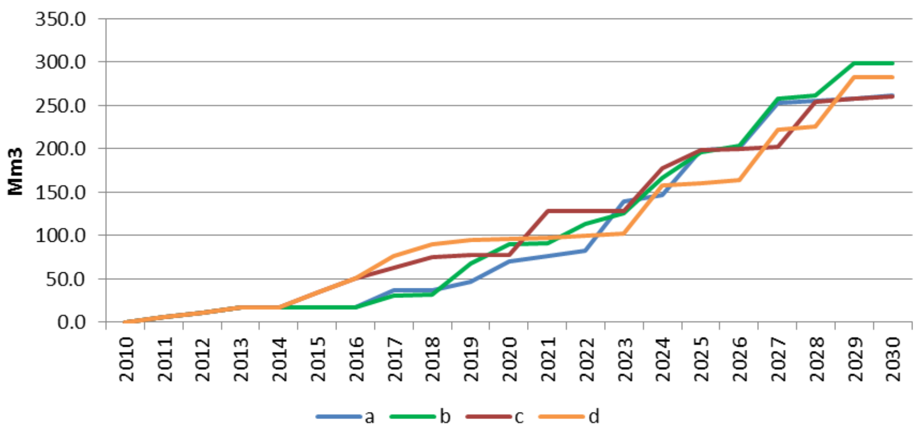

Figure 18: The cumulative yield of the selected options for each intervention

In the reference case, supply constraints are experienced by 2013/14, introducing WC/WDM option (a) – the partial programme – defers supply constraints to 2015/16 without any additional interventions, WC/WDM option (b) defers the date further to 2020/21.

Figure 19 shows dam storage and unmet demand for Scenarios 1–4 without any interventions. It highlights the trade-off between the regulated and unrestricted use of dam waters and the additional negative impact on dam levels if inflow is reduced due to climate change. Without regulation, under conditions of both historic inflow and reduced inflow, dam storage declines rapidly. The combination of high demand, low inflow and no regulation (Scenario 4) results in a slight delay in unmet demand early on, but unmet demand quickly rises to that of the reference case and Scenario 3 in which releases are regulated. The removal of regulation combined with lower inflows results in a large reduction in overall supply security from an early stage. By the end of the period, unmet demand in all scenarios is between 150 and 250 Mm^3, which is roughly 22–37% of the CCT demand at that time. Figure 19 shows that, without augmentation of supply or demand management measures, the CCT moves quickly into a situation of supply deficit which is removed in the short term only if dam releases are unregulated.

It is worth noting that in the unregulated case unmet demands are experienced before dams are depleted. This is because the transmission infrastructure is at full capacity and therefore unable to meet the required demand without additional dam water.

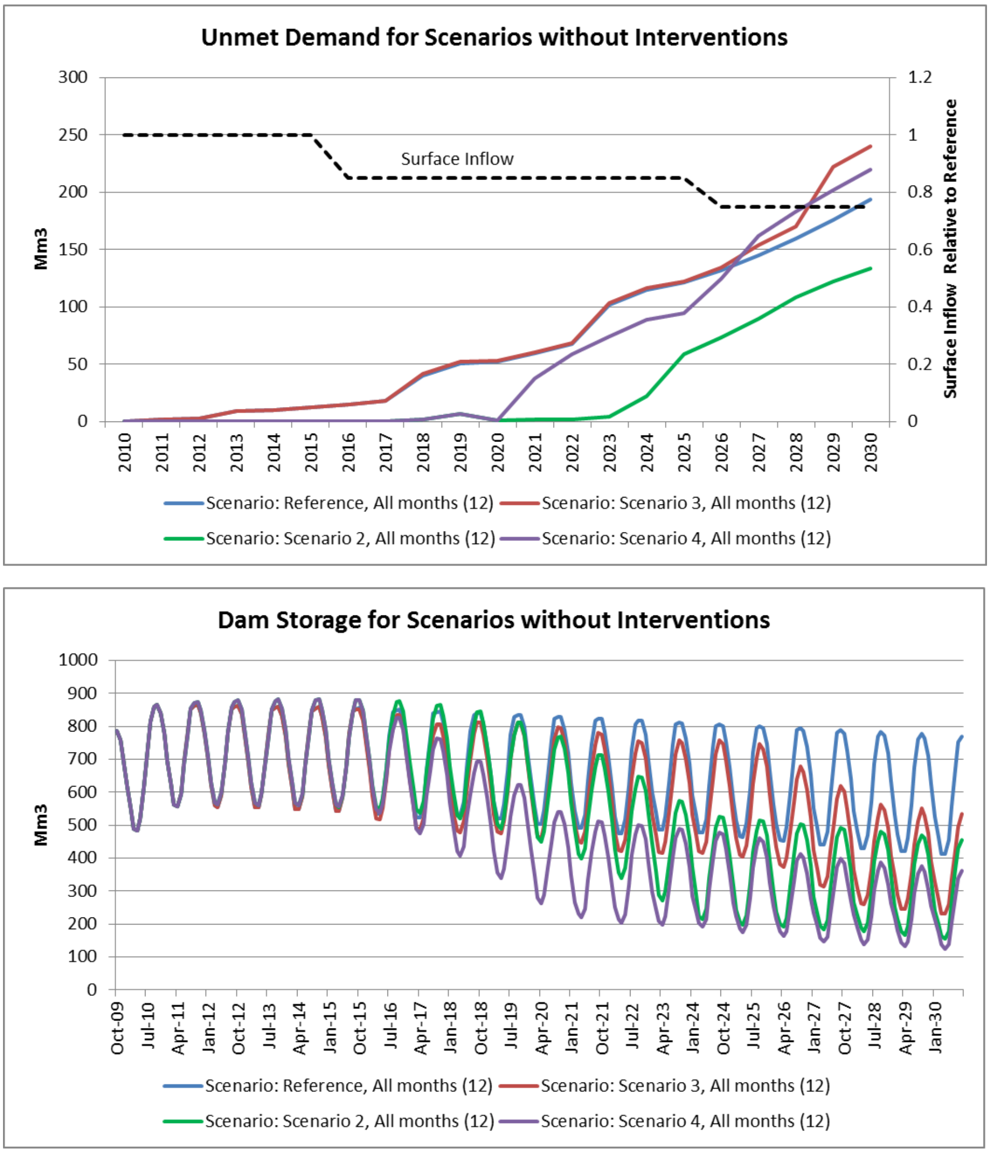

Figure 19: Dam storage and unmet demands for the scenarios without interventions

The energy intensities of the scenarios are shown in Figure 20. Scenario 3, which has similar unmet demand to the reference scenario, differs in energy intensity from the reference scenario due to the increase in the energy intensity of water treatment from 2015 onwards. The reference case has an average energy intensity of 0.61 kWh/m^3 compared to 0.63 kWh/m^3 for Scenario 3 (Table 16). The increase in energy intensity is primarily due to the potable water treatment processes dominated by the Voelvlei WTW.

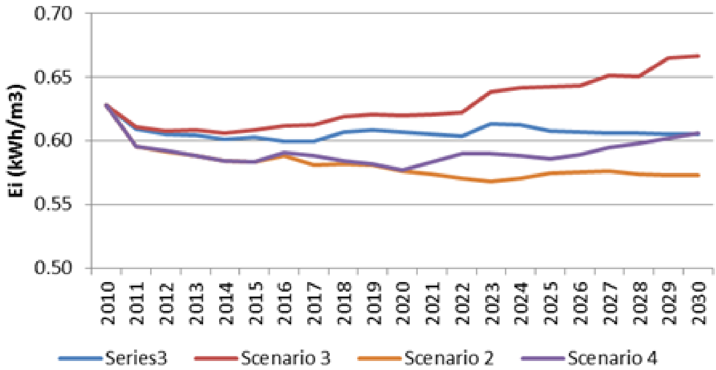

Figure 20: Energy intensities for the scenarios without interventions

In Figure 20, the energy intensity of Scenarios 2 and 4 are similar until 2020 due to their reliance on the exploitation of the existing surface water supply system. The increase in energy intensity of Scenario 4 in the latter period correlates with the reduction in surface water inflows and the adoption of alternatives with higher energy intensities.

Impact of interventions on dam storage

Figure 21 shows the impact on dam storage under both regulated (Scenarios 1 and 3) and unregulated (Scenarios 2 and 4) conditions when supply interventions are included. In Scenarios 1 and 2, demand is high, but the historic inflows are sufficient to keep up with demand and dam storage remains stable. In Scenarios 3 and 4, where inflows are reduced, the augmentation options included are not sufficient to meet demand and dam levels drop over the period.

Figure 22 shows the energy required for water treatment in Scenario 3 (the worst case scenario). It highlights the impact, which reduced water quality, and inflows can have on the energy required to treat water. The increasing use of Voelvlei, which treats water with lower quality, increases the energy required for water treatment. In addition, inflows decline and dam levels drop resulting in a reduction in the energy that can be generated through the micro-hydro schemes.

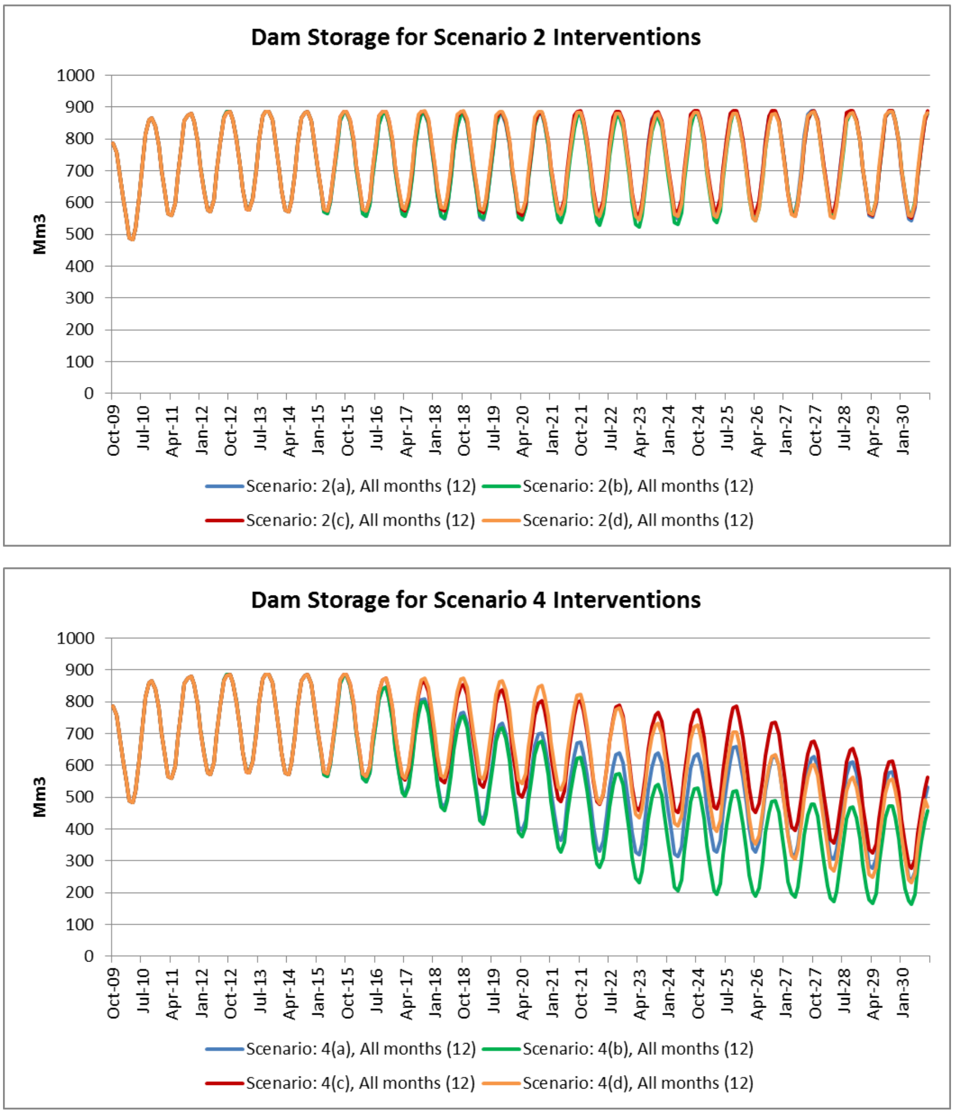

Figure 21: A comparison of system storage for unrestricted dam usage

Figure 23 shows the impact that the intervention pathways have on the relative energy intensity of water supply and treatment in a scenario where demand is high, inflow is low and water quality reduces, in other words the worst-case scenario (Scenario 3). The introduction of SWD in (a) and (c) has a large impact on energy intensity. (b) and (d) which rely more on the recycling and reuse of water have a far lower energy intensity per unit of water treated. Worth noting is that the choice of augmentation options has a greater impact on energy intensity than extending the WC/WDM programme. The relative intensity of (b) is higher than that of (d) as surface water use requires more pumping and has higher system losses, compared to the marginal increase in energy required for additional wastewater treatment.

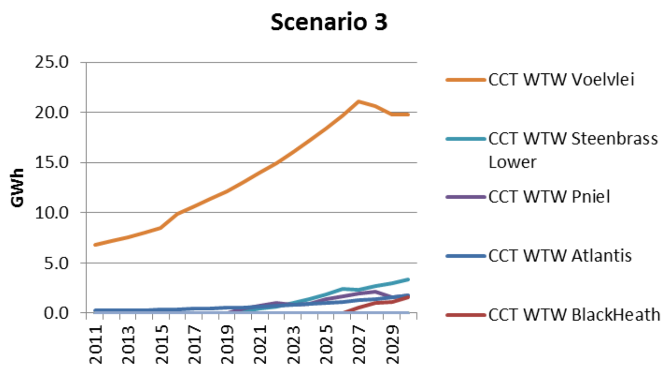

Figure 22: The estimated energy consumption for water treatment in Scenario 3 with no interventions

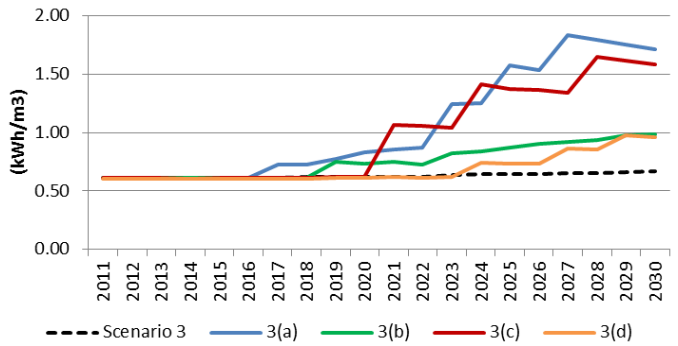

Figure 23: The relative energy intensities of the different interventions for Scenario 3

The energy intensity of all the scenarios and interventions are shown in Table 16 and Table 17. Energy intensity does not change much between scenarios, but the adoption of different suites of interventions alters energy intensity dramatically, reflecting the large differences in the energy intensities of future supply options such as sea water desalination, groundwater, water-recycling and water conservation or demand management and the level of pumping required.

Table 16: Average energy intensity of the interventions by period (kWh/m³)

Intervention	*Scenario*	*Energy intensity by period (kWh/m³)*				
		2011- 15	*2016-20*	*2021-25*	*2026-30*	*2011-30*
None	1 (Reference)	0.60	0.60	0.61	0.61	0.61
	2	0.59	0.58	0.57	0.57	0.58
	3	0.61	0.62	0.63	0.66	0.63
	4	0.59	0.58	0.59	0.60	0.59
(a)	1	0.61	0.70	1.09	1.63	1.01
	2	0.59	0.68	1.07	1.63	1.00
	3	0.61	0.73	1.16	1.73	1.06
	4	0.59	0.71	1.13	1.70	1.03

Intervention	Scenario	Energy intensity by period (kWh/m³)				
		2011- 15	2016-20	2021-25	2026-30	2011-30
(b)	1	0.61	0.65	0.77	0.89	0.73
	2	0.59	0.64	0.76	0.87	0.72
	3	0.61	0.66	0.80	0.94	0.76
	4	0.59	0.64	0.76	0.92	0.73
(c)	1	0.61	0.60	1.16	1.47	0.96
	2	0.59	0.59	1.16	1.46	0.95
	3	0.61	0.62	1.19	1.51	0.98
	4	0.59	0.61	1.17	1.47	0.96
(d)	1	0.61	0.60	0.63	0.79	0.66
	2	0.59	0.60	0.62	0.79	0.65
	3	0.60	0.61	0.67	0.88	0.69
	4	0.59	0.61	0.64	0.85	0.67

Table 17: Total energy consumption for the period (GWh)

Total energy consumed 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

4.4.5 Secondary augmentation of supply with salt water desalination

Salt water desalination (SWD) adds around 130 Mm^3 to 140 Mm^3 (excluding distribution losses) to water supply between 2026 and 2030. It accounts for 50–60% of the total energy consumed by water and sanitation services but only contributes 25% towards supply. Adjusting the amount of WC/WDM adopted reduces the need for SWD and the additional energy needed to reach the required supply volumes.

The energy consumption for interventions (a) and (c), in which SWD is given secondary preference to surface water supply, are listed in Table 18. It is noted that the energy consumption of intervention (a) is now similar to the equal supply priority SWD option with a continued WC/WDM programme as would occur in intervention (c). For a secondary SWD supply, intervention (c) is similar in energy consumption to the effluent oriented intervention (d).

Table 18: Total energy consumption for urban water cycle with SWD as a secondary augmentation option

Energy intensity (Ei) and total energy consumed for the period 2011/30				
Scenario	Intervention			
	(a)		(c)	
	Total (GWh)	Ei (kWh/m³)	Total (GWh)	Ei (kWh/m³)
1	8684	0.93	6537	0.78
2	7877	0.83	5421	0.64
3	9163	0.98	6749	0.80
4	8122	0.87	5738	0.68

When surface water options are prioritised in the unregulated case, there is greater variation in dam storage, and this in turn increases unmet demand when there are disruptions in surface inflows (seen in Scenarios 2 and 4). Of interest is the greater unmet demand for intervention (c) compared with (a) for Scenarios 1 and 3. Intervention (c) has a lesser supply requirement than intervention (a) owing to the continued WC/WDM option but is more sensitive to changes in SWD supply. This is because, while intervention (a) includes ground water augmentation via Theewaterskloof and effluent reuse, intervention (c) has only effluent reuse (introduced fairly late) as an additional supply option. Thus for the years 2026–30, intervention (a) requires 100 Mm^3 of SWD compared to intervention (c) which requires 75 Mm^3. The comparative unmet demand for the period is in the neighbourhood of 25 Mm^3 for intervention (c) and 15 Mm^3 for intervention (a).

4.4.6 Scenario ranking

The value of α for the reference case (α = 164) is a combination of the energy intensity of the reference scenario, an ideal reliability of 100% and no change in surface water storage (i.e. a storage index of 1). Table 19 shows the energy intensity, reliability and system storage index for Scenarios 1–4. Table 20 shows the overall performance (α) of the scenarios (the best performing intervention for each scenario is underlined).

Energy intensity is similar in all scenarios, as the system remains predominantly a surface water system, but differs considerably between interventions. The general pattern that emerges is that unrestricted usage increases reliability at the expense of system storage and therefore long term water security. When dam usage is not regulated, (Scenarios 2 and 4), unmet demands are lowest in the short term. In contrast, when dam releases are regulated, the short-term system reliability is reduced to 60% with around 50% of water demand remaining unmet indicating that further demand-side measures or supply-side augmentation is needed over the medium-to-long term.

Table 19: The performance of interventions against the criteria for the case of high water demand

Intervention	*Scenario*	*Indicator or category*		
		Energy intensity	*Water supply 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

Table 20: The performance (α) of the candidate interventions for the case of high water demand

Scenario	*Performance values for the Intervention*				
	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

Intervention pathway (d), which includes reuse, recycling, ground water augmentation and the extended WC/WDM programme, performs best in all scenarios. The combination of advanced effluent recycling and reuse of secondary treated effluent allow storage levels in the dams to remain high; (d) performs better than (b) in terms of energy intensity because the reticulation losses are lower and because (b) has increased surface water use and therefore requires more pumping.

The scenarios use average inflows to the dams each year and therefore do not reflect the historic variation in inflow between years. A reduced inflow scenario was developed in order to simulate the impact of extremes in inflow variation on storage. When inflow to the system was reduced, water available from the dams was reduced and intervention (c), which uses seawater desalination and an extended WC/WDM programme, performed best.

It is worth noting that, whilst (c) does not include the large-scale use of groundwater augmentation, the WC/WDM programme does include an increased use of ground-water by end users in the city, although at a volume of 3.6 Mm^3/a ground-water use would still represent a minor contribution to overall supply.

4.4.7 Sensitivity analysis

The energy intensity of the components of the urban water cycle are subject to uncertainties. In this section the sensitivity of results to the energy intensity of pumping requirements is tested. As the energy intensity of all the scenarios is comparable by intervention, only the reference scenario was used to investigate the impact on energy consumption.

Figure 24 shows the energy consumption of the reference scenario with intervention (b). Intervention (b) includes ground-water supply augmentation and additional surface water use, and therefore represents a pumping intensive intervention. Ground-water abstraction is the dominant pumping energy requirement with the conveyance from the Voelvlei WTW contributing the bulk of energy consumption for surface water supply and treatment. The requirements for auxiliary or 'other' pumping includes the transfer of water from the Palmiet River, the Berg River supplement scheme and the additional surface water options.

Figure 25 highlights the sensitivity of ground water pumping to changes in water depth. At an equivalent head of 700m, which represents a lower extreme in terms of water depth, the energy for ground water pumping is similar to the energy consumption for surface water treatment and supply. The energy consumed by auxiliary pumping is between 5% and 15% of the annual total within uncertainty bounds.

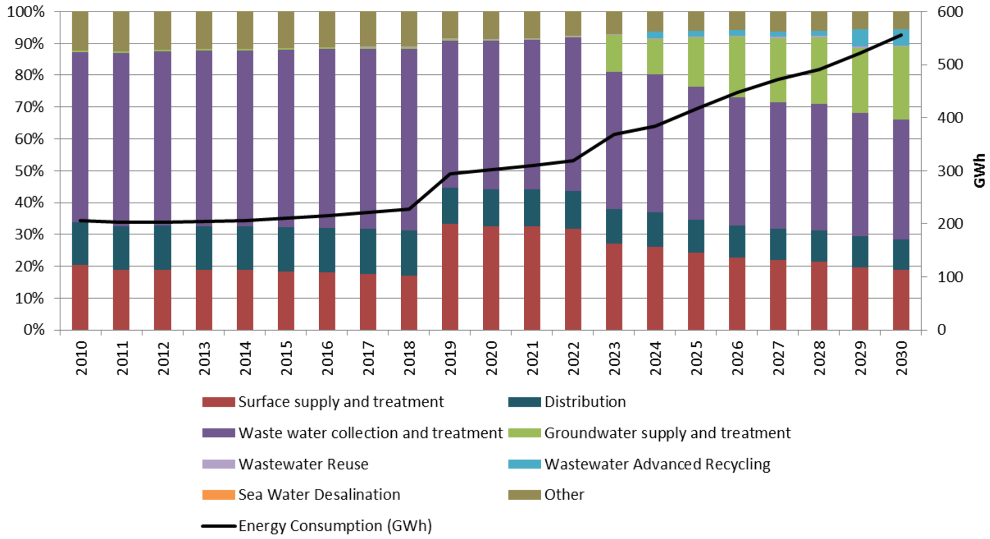

Figure 24: Energy consumption by stage for the reference scenario with the surface water oriented intervention (b)

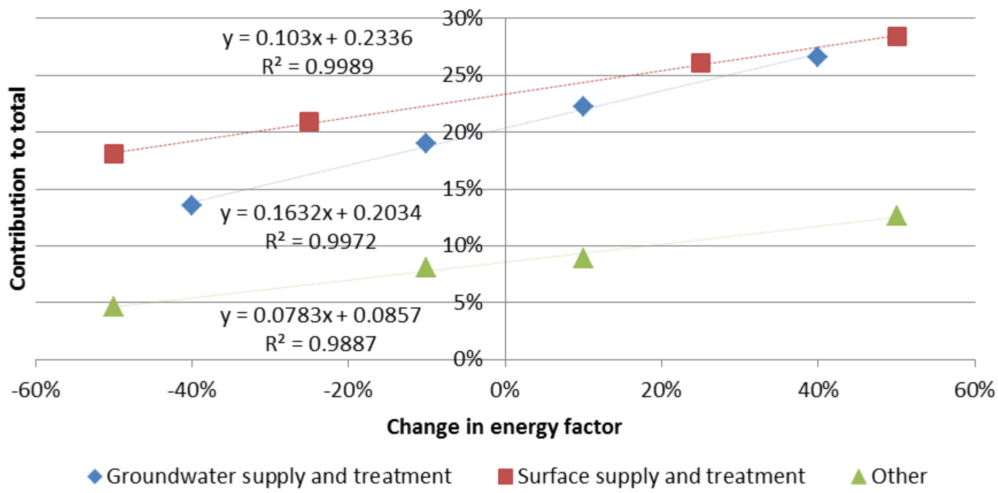

Figure 25: The sensitivity of total energy consumption to uncertainties in the energy intensity of pumping

4.5 Summary

The CCT's surface water-based supply system is highly susceptible to any climate variability, which reduces surface water inflows. The analysis has attempted to capture several of the uncertainties which the CCT faces in terms of both the demand and supply of water. Under a high growth scenario (which captures both high population and GDP growth), meeting demand for water will almost certainly require early implementation of supply interventions by the City. Unrestricted supply from dams provides relief in the short term, but over the longer term leaves the CCT in a situation of supply insecurity and the potential for far larger unmet demands as dam levels drop.

Augmenting surface supply with SWD, recycling and reuse, or additional surface water transfers delay the onset of unmet demand, however, in a scenario of a high demand, low inflow, and low WC/WDM unmet demand could be significant. It is likely that the CCT will need to adopt a combination of measures to avoid unmet demand. The modelling completed here is not prescriptive, but demonstrates how combinations of options compliment each other to reduce unmet demand. It also demonstrates how the choice of options can impact significantly on the energy intensity of supply. For example, SWD increases supply security, but adds greatly to the energy intensity of water services compared to water recycling in combination with water conservation and water demand management. The latter options similarly mitigate against the reliance on surface water supply with significantly less impact on energy consumption.

The topography of the CCT reduces the energy intensity of supply as it allows the use of gravity instead of pumping and the use of micro hydro. Increasing demand growth increases the reliance on pumping which increases the intensity of water supply.

5. A scoping study of competing land uses in the Phillipi horticultural area

The number of people living within the city in informal housing, and the growing backlog in formal housing is a political, social and developmental concern for the CCT.[26] The supply of low-cost formal housing is therefore a high priority. In South Africa there is a social housing programme, known as the Reconstruction and Development Plan (RDP), whereby qualifying representatives of a household are eligible for a subsidy through a state housing project that is implemented at the municipal level. Houses are awarded to those on the housing ‘waiting lists’. 36% of households in the CCT are informal, and more than half of these have been on a waiting list for more than five years, and the list is widely believed to be growing rather than shrinking (Tissington et al., 2013).

Recently there has been a movement towards developing parts of the Phillipi horticultural area (PHA), a high-yield agricultural area within the CCT boundary, with low-cost housing that would form part of the city’s housing programme. Agricultural land use in Phillipi dates back to the 1800s (or even earlier) and it is estimated that the PHA, which is one of the last remaining agricultural areas within the built up city boundary, currently supplies 50–80% of the city’s vegetable needs.[27] Phillipi, which is centrally located, and surrounded by built-up areas, is marked as area 7 in Figure 26.

[26] The number of households living in informal housing grew from 142 982 to 218 780 between 2001 and 2011, more than any other city in South Africa (Turok & Borel-Saladin, 2014).

[27] There are three types of agriculture practiced within the city boundary: viticulture, horticulture and grain production.

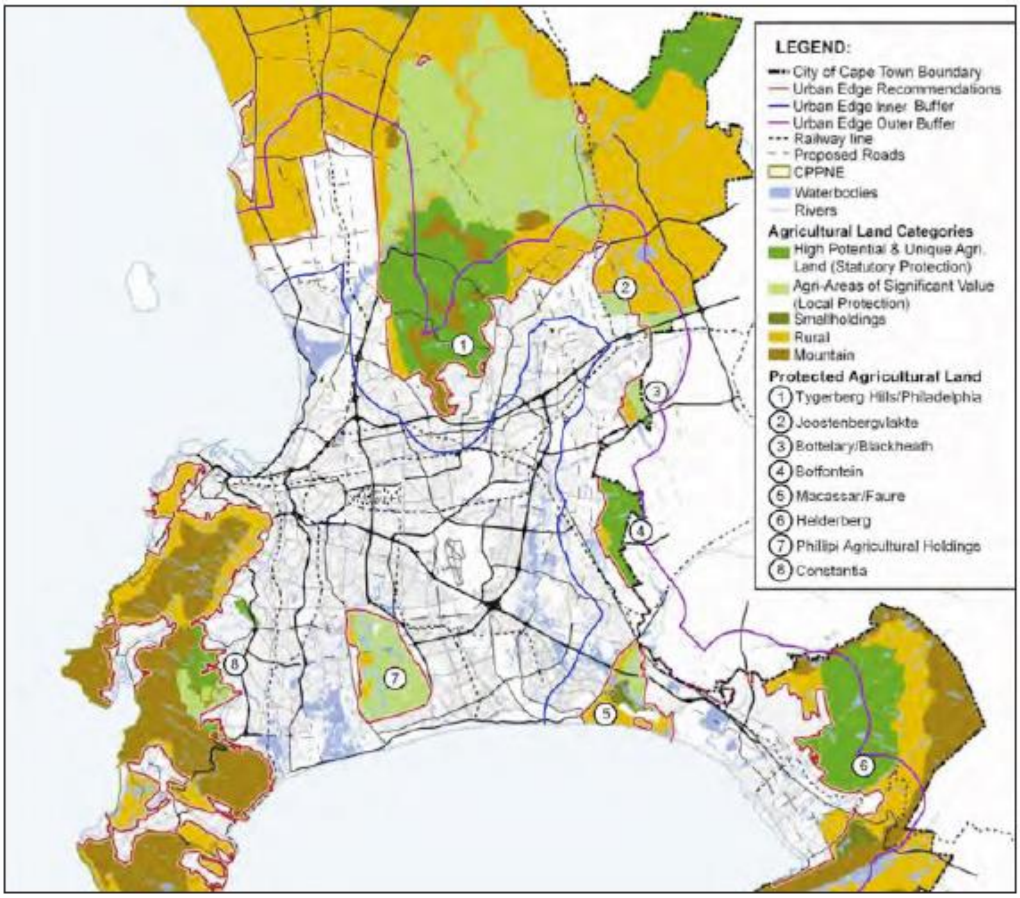

Figure 26: Location of Phillipi and other agricultural land within the CCT
(City of Cape Town, Spatial Development Framework)

Being located within the urban area is both advantage and disadvantage. Lack of storm water reticulation systems cause groundwater pollution, and informal waste disposal or dumping is a further concern. The compromised wetland functionality impacts groundwater recharge rates and groundwater is under threat from too much usage. Due to the demand for land, over the years the horticultural area in Phillipi has slowly been taken over by other non-agricultural and mixed land uses and has also been subject to land invasions. Additional challenges to the PHA are produce theft and the lack of clarity over future zoning, which discourage investment. The area is also subject to land speculation due to its proposed alternative use for formal low-cost housing development. The PHA footprint has been reduced as a result of recent rezoning for urban housing, as shown in Figure 28 where Area 4 indicates the encroachment of informal housing on what was agricultural land.

Despite these land use and water concerns, the PHA is described as an area of significant agricultural value, with some 1 250ha of horticultural production, growing 50 different crops, producing just under 100 000 tonnes of fresh produce annually.[28] The agricultural zoning and use of land for agricultural purposes in Phillipi is valuable for several reasons. The PHA lies within a very favourable agro-climatic zone in terms of microclimate, soil and groundwater availability. Competing agricultural areas around the CCT lie in warmer and drier regions. Farmers in the PHA can produce up to five crops a year, and lie in close proximity to urban markets; they can therefore sell directly to supermarket chains or through the Epping Market. Figure 27 shows the climatic zones in the CCT and the competing agricultural areas of Phillipi, Joostenberg Vlakte and Botvontein, as well as the distance they lie from the Epping Market.

28 Estimates of production for Phillipi differ, but generally the number is in the order of 90 000 to 100 000 tonnes. It is difficult to obtain accurate estimates because some farms are small and sell by item and not by tonne.

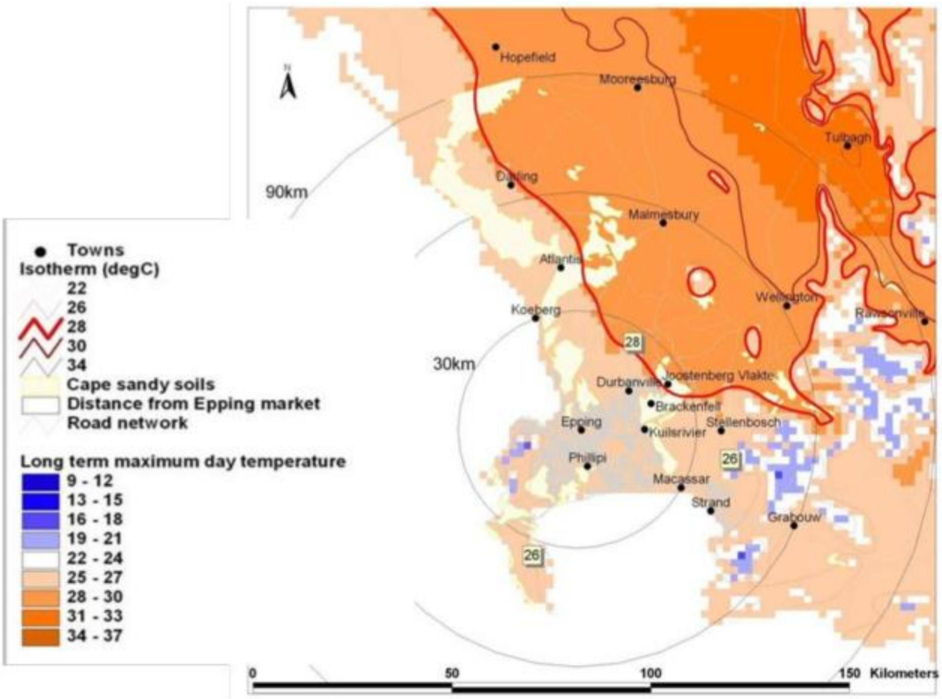

Figure 27: Climatic zones and distances to other markets
Source: Battersby-Lennard and Haysom (2012)

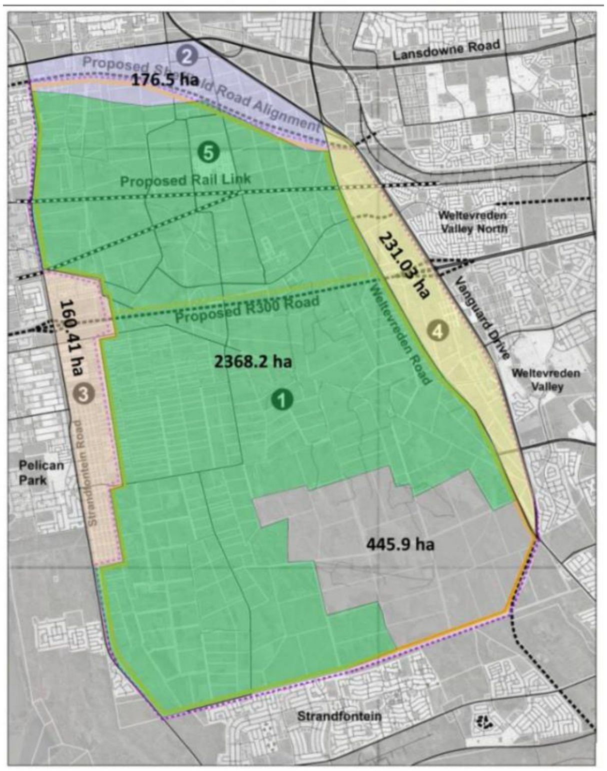

Figure 28: Phillipi: Agricultural zones: Areas 1&5; light industry: Area 2; formal residential housing: 3; informal residential housing: Area 4
Source: Battersby-Lennard and Haysom (2012)

PHA is socially valuable in that it borders on some of the poorer neighbourhoods in the CCT. It provides food security to surrounding areas as well as supporting significant micro-enterprise. Farming of vegetables provides valuable employment opportunities in the area. Around 2.5 full time workers are employed on each hectare farmed, and 1.5 temporary workers (between December and the end of April). This amounts to around 2 350 much-needed full-time jobs and

1 410 part-time jobs over the year. The work is also particularly valuable as it gives employment to many low-skilled workers, including over 2 600 women. Phillipi has also been said to act as a moderator or buffer to higher food prices in the CCT. Figure 28 shows the current Phillipi area and land zoning.

The purpose of the PHA case study is to understand the potential impact on the CCT water supply system that would result from relocating horticultural production from the PHA to other areas around the CCT in order to accommodate housing developments within the PHA. It does not look at transport requirements, impacts on the local economy, and many other concerns. The study was completed in two steps:

(i) the total irrigation demand required to meet the same production levels as the PHA at a suitable relocation site was estimated; and
(ii) the Cape Town water supply system was modelled with and without the additional irrigation demands.

The steps are described further below.

5.1 Irrigation demand modelling

To model the effect which relocating horticulture from the PHA could have on the water resource system, the irrigation demands of the relocation site were estimated using the SAPWAT3 model (http://sapwat.org.za/). SAPWAT3, an update of a previous model, SAPWAT, was developed specifically to estimate irrigation demand requirements in South Africa. The model makes extensive use of the procedures outlined in the Food and Agriculture Organisation's Irrigation and Drainage Paper 56 (Allen et al. 1998), and therefore utilises the same procedures that are used in a number of irrigation water demand models (e.g., CROPWAT). SAPWAT focuses on estimating how irrigation demands change under varying weather conditions in South Africa, making this an ideal model for the study at hand.

In lieu of a detailed study on suitable sites for the relocation of the PHA's agricultural production, the following modelling scheme was applied. Firstly, PHA was modelled as it stands today, adjusting irrigation management to match total annual irrigation withdrawal estimates. Then, the model was run with new climate data representative of a relocation site outside the urban area of the city but proximate to the city and making withdrawals from the city's water supply system.

The actual source of water withdrawal necessitates further study and therefore, for simplicity, it is assumed that the PHA relocation site will draw water from the Western Cape Water Supply System via the Theewaterskloof reservoir.

Irrigation withdrawal in PHA is estimated to be about 19 million m^3 per year with a total of about 1 100 ha of irrigated area (PEPCO 2009). PHA crops consist mostly of vegetables. The most prominent vegetables grown, as reported by Battersby-Lennard and Haysom (2012), are listed in Table 21. No data was available for the share of crops currently grown in PHA; as a consequence it was assumed that the crops are grown in equal amounts by area as shown in Table 21. For the existing PHA, daily climate data from quaternary catchment G22D for the years 1951-1999 was used. For the irrigation demands of the relocation site, climate records for the quaternary catchment G21E were used, for the period 1951–1999. The annual mean values for each crop as well as the total annual irrigation demands are shown in Table 21.

Table 21: Irrigation demands by vegetable for the crops modelled, both for PHA and the PHA relocation site

Crop	Assumed irrigated areas (ha)	Calculated PHA annual irrigation demands (mill. m^3)	Calculated PHA relocation annual irrigation demands (mill. m^3)
Broccoli	140	1.9	2.6
Cabbage	140	2.0	2.6
Carrots	140	2.7	3.4
Cauliflower	140	2.5	3.4
Lettuce	140	2.3	3.2
Potatoes	140	2.4	3.2
Spinach	140	2.9	3.7
Tomatoes	140	2.8	3.7
Total	1 120	19.2	25.9

To understand how the assumption of equal crop shares by area may impact the results, a minimum (low) and maximum (high) irrigation demand was calculated, assuming the irrigated area is dominated by the crop with the least demand per hectare (the low scenario) and by the crop with the most demand per hectare (high scenario). These demands over the season are shown in Figure 29, along with the 'medium' scenario, with the original equal-area assumption. While the range is not immaterial at the extremes—the largest is about 1 Mm^3 in January— given the high diversity of crops produced in the PHA we can assume a somewhat narrower band of variation in actual demand and therefore the assumption of equal area should not have significant impacts on the results.

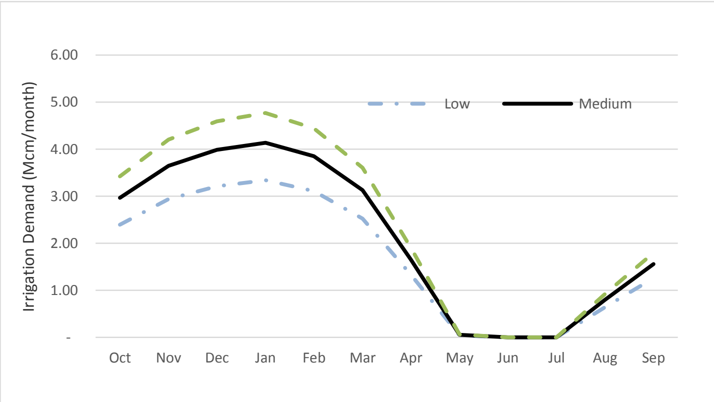

Figure 29: PHA relocation irrigation demands over the year for the high, medium, and low estimates

5.2 Water resource modelling

Two sets of scenarios were modelled in the WEAP system model developed for the CCT (described in Section 3). The first set of scenarios represents the CCT water system without the PHA relocation and the second set represents the system with the added irrigation demands of the relocation site. It is assumed that the full demand of the PHA relocation will be added from the year 2020. Scenarios 1 and 3 (described in Section 3) were modelled with the additional water requirements. The two scenarios, which represent the reference case and a worst-case scenario, adequately characterise the extremes of water resource availability and the energy intensities of providing water in the CCT.

Note that, while there are two scenarios on inflows,[29] the additional irrigation demands resulting from the relocation are applied at the same level in both scenarios and over all policy pathways to provide clearer scenario comparison (i.e., it can be established with certainty that the differences in water stress between the scenarios are a result of the inflows rather than differences in irrigation demand estimations).

5.3 Results

Two indicators from the WEAP model were used to understand the effect of the additional irrigation demands on the CCT water supply system. First, since the PHA relocation site is diverting water directly from Theewaterskloof, changes to the storage volume of Theewaterskloof are shown. Figure 30 shows the percent change over the first ten years of the model, 2011–2020, compared to the last ten years, 2021–2030. A negative percent change, in this case, indicates a decreasing trend in the reservoir storage supply. For example, a value of -10% implies that the reservoir storage is decreasing at a rate of 10% in each period and will be completely dry in 100 years if the trend continues. While these trends are rarely steady, due to variations in climate, a large negative value does indicate a larger risk of severe water stress for regions dependent on Theewaterskloof, either directly or through its outflow, for water supply.

As expected, given that supply to the relocated site is withdrawn directly from Theewaterskloof, the scenarios with the PHA relocation show larger decreases in reservoir volume for all cases compared to the scenarios without the PHA relocation, shown as the 'Reference' scenarios. There is, however, a stark difference between the policy cases for the reference scenario of typical inflows (Scenario 1) and the scenario of reduced inflows (Scenario 3). When inflows are reduced (3), PHA relocation exacerbates the decline in storage in all cases. The pattern is similar to that of the reference case, where the relative change in storage is larger for the policy cases that have limited reliance on additional surface water schemes. This is due to the fact the PHA relocation is assumed to obtain its water supply directly from Theewaterskloof and therefore has a direct impact on the available water volume from the dam.

In the reference case 3(b), the dam's water volume is at its lowest and the dam is empty towards the end of the planning period. Therefore further withdrawals have a greater impact on the available volume than a relative change. This is depicted in Figure 31, which contrasts cases 3(b) and 3(c) where option (b) is reliant on surface water options and (c) reliant on seawater desalination.

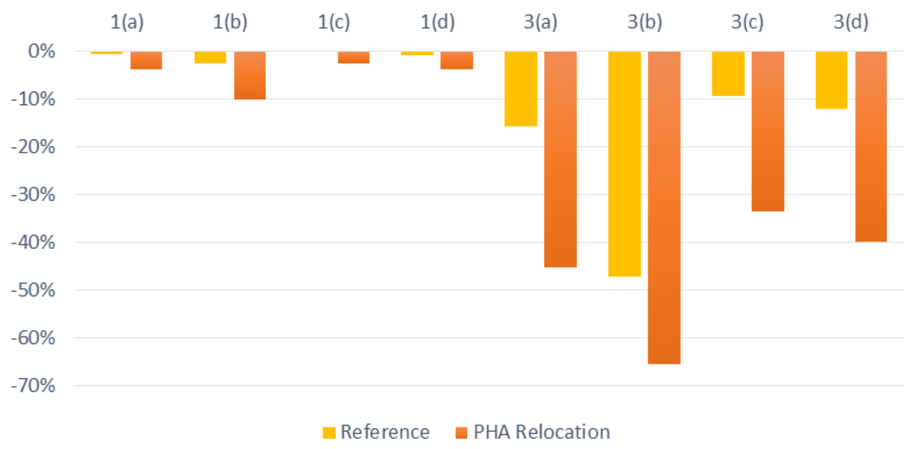

Figure 30: Changes in Theewaterskloof storage volume due to the impact of the PHA relocation for scenarios of typical current inflows (1) and reduced inflows due to climate change (3) with 4 cases of policy intervention (a–d)

[29] Scenarios 1 and 3 both assume high water demand and regulated dam usage, the difference between the scenarios lies in the water quality and in the assumption of historic inflows adopted in Scenario 1 and reduced inflows adopted in Scenario 3 (the worst case scenario).

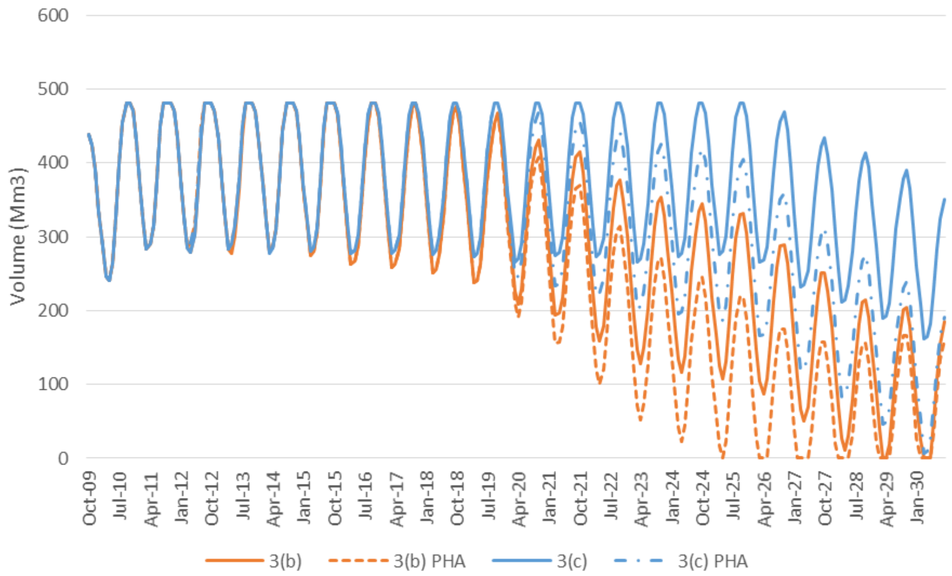

Figure 31: The change in volume of water storage in Theewaterskloof Dam for cases 3(b) and 3(c) where the water demand for the PHA relocation is compared against the reference.

Figure 32 shows the changes in the ten-year mean unmet demand between 2020 and 2030 of the entire system for the intervention pathways (a-d) in scenarios 1 and 3. These unmet water demands represent system-wide water stress for the CCT. The percent changes shown are indicative of a water stress trend in the system, where positive values suggest that the water system in the CCT is digressing toward more water scarcity. The results have been adjusted to reflect inherent uncertainties in the system. To avoid overestimating the potential water shortfall, an average of ~7 Mm^3/a in unmet demand is subtracted from all cases with negative values set to nil. 7 Mm^3/a is based on a calibration run comparing near future results to historical data.

Of interest, though not unexpected, is that case 3(b) which relies on extensive additional surface water schemes is prominent as the only case where Cape Town's water demands are not completely satisfied. In comparison to Figure 30, for Scenario 3 – that of reduced surface water availability – the additional water demands of PHA are catered for at the expense of dam water storage and therefore long term system reliability. The average annual unmet demand of ~10 Mm^3 ± 10Mm^3 for 3(b) suggests that the system approaches its limit of water provision for the supply options considered.

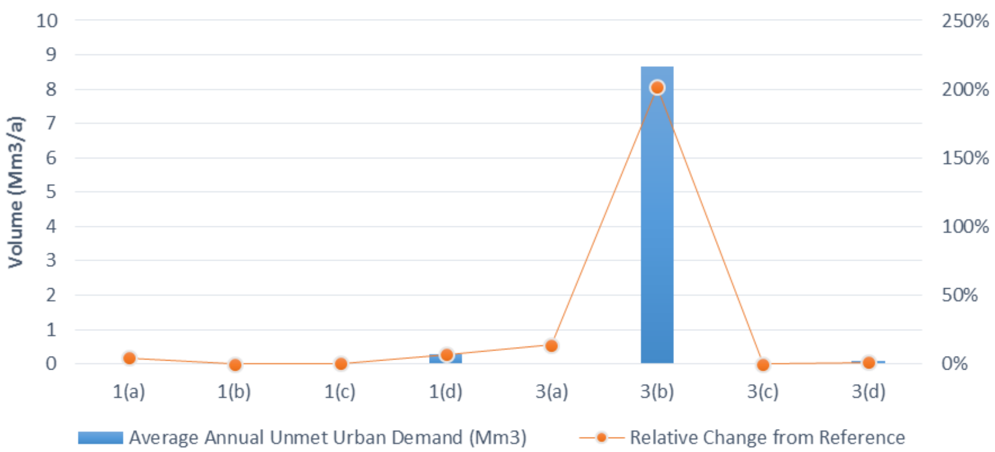

Figure 32: Changes in unmet demand in the WCWSS due to the impact of the PHA Relocation for scenarios of typical current inflows (1) and reduced inflows due to climate change (3) with 4 cases of policy intervention (a–d)

5.4 Summary

The results shown illustrate the effects and risks associated with introducing an additional irrigated area, of the same production value as the existing PHA, to the CCT water system, which is already under stressed conditions. Of course, there are other alternatives to relocating PHA, but the plan represented in this study represents an alternative that would provide a similar economic service to the CCT that PHA currently provides. Other alternatives would likely be far outside the city and therefore require substantial transportation costs, amongst other concerns. Essentially, by modelling this simple relocation plan, this study has demonstrated the value of PHA to the CCT, from the perspective of the water system. That value is shown as noticeable but moderate decreases in reservoir levels as well as increases in unmet demand, given that the climate behaves as it has in the past. However, there is a substantial risk of more drastic increases in water stress if the future climate is drier than the historical measurements.

The relocation of the agricultural production of the PHA in favour of other uses could potentially have a negative impact on the provision of water supply services. These impacts under climate stress were not only severe for the levels of the Theewaterskloof reservoir, which was assumed to supply the alternative location directly, but also for Cape Town’s water supply system as a whole. The study assessed one alternative location and only one dimension of impacts – that of water security of supply – but the limited results produced strongly suggest that the risks and impacts of relocating the agricultural production from the PHA need to be better understood and weighed up against the costs and benefits of alternative uses of the PHA. The results furthermore speak to the value of integrated planning and pooling the assessments of different disciplines in analysing this sort of complex trade-off.

The findings of this scoping case study indicate that further work would be of value in understanding the complex nexus trade-offs facing CCT planners and decision makers. The following avenues for new work are proposed:

- Expand the analysis to a range of relocation sites in collaboration with agricultural experts.
- Include the direct costs and externality costs of the additional transport required for relocated agricultural production in the assessment of impacts.
- Broaden the cost benefit analysis to the potential of the PHA to provide a site for housing and the alternative if it does not.
- Develop an analytical framework to fully assess the trade-off between using the PHA for agriculture or for housing or for some intermediate medium that would include all the important dimensions of this particular nexus: energy, water, food, land and housing.

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Appendix

The following includes a brief description of projects that have been initiated since the IAEA CLEWS project began; each one applies an adaptation of the CLEWS framework to research questions which are important for South Africa.

Thirsty Energy South Africa

Under the World Bank's Thirsty Energy Programme, SATIM has been adapted to include the supply of water in the energy supply chain. A framework for integrated water-energy analysis is implemented as the South Africa TIMES Energy-Water (SATIM-W) model, providing a tool that offers insight into the trade-offs that may exist when accounting for the linkages between water and energy systems in sustainable cost-effective resource utilisation.

The analysis currently underway in this study attempts to quantify the extent to which the cost of water determines new energy sector investments across South Africa by including estimates of future marginal water supply costs to regions of interest where competition for water resources are likely to be experienced with further growth of the energy sector. The modelling includes scenario analyses of future water supplies under climate change and stricter environmental policies. Incorporating the cost of water, including its treatment for environmental discharge, in the energy supply chain reflects a more representative cost of energy supply in the modelling cost-optimisation process. It attempts to determine the opportunity cost of water in the energy sector by contrasting the generation cost of competing technologies in areas of the country with varying water supply constraints. It is hoped that the modelling outcomes highlights the importance of considering the regional nuances of water supply, in terms of quality and quantity, when conducting strategic energy supply modelling.

Optimisation of a PV–wind hybrid system under limited water resources

Journal of Renewable and Sustainable Energy Reviews 47 (July 2015)

Amos Madhlopa, Debbie Sparks, Samantha Keen, Mascha Moorlach, Pieter Krog, Thuli Dlamini

Abstract

Water plays a vital role in various economic sectors, including energy production. It is required in various stages of the energy production chain including fuel acquisition, processing and transportation. However, there are growing concerns about the mounting demand for water arising from population and industrial growth, especially in water-stressed regions. Climate change and environmental pollution are exacerbating the situation, and the exploitation of renewable energy resources is perceived as one pillar of mitigating the negative effects of climate change. In this regard, solar photovoltaic (PV) and wind power plants are promising renewable energy technologies, and previous studies have demonstrated that these two energy technologies are less water-intensive. However, the effect of available water on the optimisation of a hybrid PV–wind system has not been extensively explored. In this study, a model for investigating water-efficient optimisation of PV–wind hybrid systems has been proposed. The demand for water, in the production of energy from PV and wind power plants was expressed as a linear function of the numbers of PV panels and wind turbines. The proposed model was applied to the design of a grid-connected PV–wind hybrid system, using meteorological data from Bonfoi Stellenbosch weather station (33.935°S, 18.782°E) in South Africa. The hybrid system was designed to generate about 100,000 MW h/year under the prevailing meteorological conditions. In addition, the Levelized Cost of Energy (LCOE) was optimized with (60,000 m3) and without a water constraint. It was found that the water-constrained scenario reduced water demand by 24%. The optimal LCOE of the system declined by 23% when available water was increased from 60,000 m3 to 75,000 m3. It is therefore concluded that water availability is an important factor in the economic optimisation of a hybrid PV–wind system.

Renewable energy choices and their water requirements in South Africa

Journal of Energy in Southern Africa 25(4)

Debbie Sparks, Amos Madhlopa, Samantha Keen, Mascha Moorlach, Anthony Dane, Pieter Krog, Thuli Dlamini

Abstract

South Africa is an arid country, where water supply is often obtained from a distant source. There is increasing pressure on the limited water resources due to economic and population growth, with a concomitant increase in the energy requirement for water production. This problem will be exacerbated by the onset of climate change. Recently, there have been concerns about negative impacts arising from the exploitation of energy resources. In particular, the burning of fossil fuels is significantly contributing to climate change through the emission of carbon dioxide, a major greenhouse gas. In addition, fossil fuels are being depleted, and contributing to decreased energy security. As a result of this, the international community has initiated various interventions, including the transformation of policy and regulatory instruments, to promote sustainable energy. With this in mind, South Africa is making policy and regulatory shifts in line with international developments. Renewable energy is being promoted as one way of achieving sustainable energy provision in the country. However, some issues require scrutiny in order to understand the water footprint of renewable energy production. Due to the large gap that exists between water supply and demand, trade-offs in water allocation amongst different users are critical. In this vein, the main objective of this study was to investigate and review renewable energy choices and water requirements in South Africa. Data were acquired through a combination of a desktop study and expert interviews. Water withdrawal and consumption levels at a given stage of energy production were investigated. Most of the data was collected from secondary sources.

Results show that there is limited data on all aspects of water usage in the production chain of energy, accounting in part for the significant variations in the values of water intensity that are reported in the literature. It is vital to take into account all aspects of the energy life cycle to enable isolation of stages where significant amounts of water are used. It is found that conventional fuels (nuclear and fossil fuels) withdraw significant quantities of water over the life-cycle of energy production, especially for thermoelectric power plants operated with a wetcooling system. The quality of water is also adversely affected in some stages of energy production from these fuels. On the other hand, solar photovoltaic and wind energy exhibit the lowest demand for water, and could perhaps be considered the most viable renewable options in terms of water withdrawal and consumption.

Towards the development of an energy-water-food security nexus based modelling framework as a policy and planning tool for South Africa

Conference paper presented at: Towards Carnegie III: Strategies to Overcome Poverty and Inequality, 2012, Cape Town, South Africa (full paper available at www.saldru.uct.ac.za/projects/current-projects/carnegie-conferences)

Gisela Prasad, Adrian Stone, Alison Hughes & Theodor Stewart

Abstract

With the increasing pressure of population on global resources and the imperative of climate change there is a growing interest in the idea of the 'Energy-Water-Food Security Nexus', essentially an application of systems thinking to planning that recognises that the resources in the nexus are intimately linked and need to be considered together. This paper describes a project, currently at the funding stage, to develop a modelling framework for South Africa to be used as a tool for policy development and the planning of practical interventions. The need for the modelling framework was identified in the course of a desktop study on the nexus in the context of climate change and this paper explores a portion of this work and the rationale for a modelling framework. This background material examines how water and energy are treated separately or are combined and outlines research needs to realize the opportunities an analysis of the nexus can provide in terms of resource use efficiency and policy coherence.

Traditional energy and water modelling is orientated toward large infrastructure planning and large commercial irrigation projects. This project has as its goal the development of a modelling framework that will tackle the former with a nexus approach but also attempt to provide an

effective policy tool for the interlinked water, energy and food security problems of remote and impoverished areas, possibly including climate change as another layer of complexity These areas will usually not be attractive for large scale industrial or agricultural interventions and other means may be necessary to sustainably supply the rural poor with energy, water and sufficient food.

A case study has been developed centred around the municipality of Elundini, located in the North of the Eastern Cape. The area is a catchment for the Umzimvubu River and is characterised by rugged, mountainous terrain. The catchment area has been the subject of many engineering studies because of the abundance of water, one of which observed, 'The Mzimvubu River is the catchment which simultaneously has both the most available water and the greatest poverty in South Africa.'. Typically such studies have however shown that because of the remote and rugged terrain, infrastructure like hydropower plants are at best marginally feasible in economic terms. Similarly commercial scale irrigation schemes have been deemed inappropriate given the terrain and prevailing land tenure practices and skills levels.

The case study will seek to apply a nexus orientated modelling framework to develop practical interventions for not only supplying power and piped water where it is lacking but also improving current agricultural practices by, for instance, providing a framework for evaluating the feasibility of localised gravity fed irrigation schemes. The issue of the type of agricultural products to target with these schemes is central and as has been seen in other countries, needs to be not only high value but supported by institutions that underwrite and emphasise the purity and naturalness of mountain produce as value added. Such produce has been seen to also greatly enhance the tourism potential of such areas. Technology is seldom now the barrier to such initiatives and the sustainability of interventions is more dependent on local skills development and on-going institutional development and support, aspects which will be central to the modelling framework.