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THE IMPLICATION OF MINING PROSPECTS ON WATER DEMAND AND SUPPLY IN THE ERONGO REGION, NAMIBIA

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A research report submitted to the Faculty of Science, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Masters of Science

Johannesburg, July 2010

DECLARATION

I declare that this research report is my own, unaided work. It is being submitted in partial fulfilment for the degree of Masters of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

_____ _____

Name of Candidate Signature

Signed on_____ day of_____2010.

ABSTRACT

Namibia is one of the most arid countries in the world. The pressure on freshwater resources is felt the most in parts of the Erongo region where groundwater is the only available water source. This resource is under immense pressure from increasing urban population and industrial growth as well as mining.

System Dynamics Modelling (SDM) was used to quantify the amount of water which will be required by consumers in the central west coast of Namibia (Erongo region) in the future. The effect of new mines on water supply and urban growth were modelled over a period of 20 years (2010-2030). The study also looked at the effect of alternative water sources (sea water desalination, recycling, fog harvesting, and demand management) on the overall demand and supply for the area under study.

Major findings of the study reveal that water demand (22 672 480 m^3/year in 2010) could exceed total available supply (16 200 000 m^3/year) by 2010 with a deficit of up to 6 472 480 m^3/year, if no management intervention are implemented. Management interventions (recycling and demand management strategies) would prolong supply on until 2012, Where after demand will exceed supply. Demand is projected to be 424 488 071 m^3/year, for the year 2030. Fog harvesting has been found to have the potential of supply only less than 2% of the total deficit. This leaves sea water desalination as the one reliable and sufficient source for long-term bulk water supply.

It is recommendable that a modular sea water desalination plant be built-one which allows and increase or reduction in capacity according to demand. To boost water supply, recycled wastewater could be used for artificial recharge.

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DEDICATION

In memory of my mother

Klaudia Iita

1948-2007

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ACRONYMS

ARND	ARANDIS
ASML	ABOVE MEAN SEA LEVEL
CBS	CENTRAL BUREAU OF STATISTICS
CIX	CONTINOUS ION EXCHANGE
FCDs	FOG COLLECTING DEVICES
GDP	GROSS DOMESTIC PRODUCT
HB	HENTIES BAY
MAWF	MINISTRY OF AGRICULTURE WATER AND FORESTRY
NAMWATER	NAMIBIA CORPORATION LTD (PTY)
SADC	SOUTH AFRICAN DEVELOPMENT COMMUNITY
SD	SYSTEM DYNAMICS
SDM	SYSTEM DYNAMICS MODELLING
SX	SOLVENT EXTRACTION
SWKP	SWAKOPMUND
WB	WALVIS BAY
WASSP	WATER SUPPLY AND SANITATION POLICY
WDM	WATER DEMAND MANAGEMENT
USA	UNITED STATES OF AMERICA

CHAPTER ONE

GENERAL INTRODUCTION

"*We forget that the water cycle and the life cycle are one*" –Jacques Cousteau

1.1 General Introduction

Water is known to be a basis for life on earth, which would explain why this resource is under immense pressure (Tarrass, *et al*., 2008). This follows that water resources are on top of the most important ecosystem services that the natural environment offers (Rahm, *et al*., 2006). Many countries in the world, at present, are faced with problems linked to freshwater resource (Khawaji 2008; Kojiri, *et al*., 2008). Kojiri, *et al*., (2008) estimated that half of the people on earth are likely to be faced with freshwater shortages by the year 2025. This is so despite the fact that there is known to be enough freshwater in the world to meet the needs of its people (Malley, *et al*., 2009), although in places where there may be sufficient freshwater, it has become difficult for supply infrastructure to meet growing demand (Dube and van der Zaag, 2003).

The increase in human population is expected to drive the world into a freshwater crisis by the year 2050 (Malley, *et al*., 2009). This is mainly because freshwater availability and accessibility is known to attract economic growth as well as social development, particularly in Africa (Global Environment Outlook, 2000; Odada, 2006). This is because the use of freshwater affects almost all the economic sectors of any nation (Rahm, *et al*., 2006).

The economic growth includes the establishing of new industry such as mining and fisheries, while social development includes the expansion of urban areas as people migrate from rural areas into urban centres, in search for employment and better living conditions.

Africa is one of the two continents in the world faced with greatest issues of water supply (Global Environment Outlook, 2000), leaving half of its population at the risk of "water stress and scarcity" by the year 2025 (Niemczynowicz, 1999). Gumbo, *et al.*, (2005) estimate that half the Southern African Development Community (SADC) will be experiencing physical water shortages by the same year. Water demand in the same region is estimated to continue increasing at an annual rate of 3% until the year 2020 (Global Environment Outlook, 2000).

Already 14 African countries either face water stress or water scarcity, with those in the northern parts of Africa the hardest hit (Global Environment Outlook, 2000). This could partly be due to the rainfall patterns over the African continent. Odada (2006) observed that extreme rainfall variability in Africa has led to inequitable distribution of surface and groundwater resources, as evident in areas that are (such as Namibia) severely arid with few freshwater sources, compared to areas with abundant freshwater. Countries with arid and semi-arid conditions face much harder freshwater problems than the others, with the situation made worse by increasing human populations (Tarrass, *et al*., 2008). In arid areas, and many parts of Africa, groundwater provides relief to the inhabitants of these areas- groundwater being the primary source of water for humans and animals in these areas, for example by supplying close to 80% of freshwater in Botswana and 40% or more in Namibia, whilst 95% of all Libya's freshwater withdrawals come from groundwater (Global Environment Outlook 2000; UN-Water Africa, 2006).

Many countries in Africa cannot use water resources from rivers and lake basins as they wish because they share some of their rivers and lake basins with other neighbouring African countries. There is a total number of 80 internationally shared rivers and lake basins on African continent (Odada, 2006). Namibia is among the countries in Africa which share their river and lake basins. It becomes even harder for Namibia because all of the internal rivers in Namibia are ephemeral (Bethune, *et al*., 2005).

Namibia, a south-west African country, covers a total area of 824 269 km^2 (van der Merwe and McCormick, 1999). The latest national census of the year 2001 estimated the country population to be around 1.8 million people (Census Office, 2003), with a per capita water consumption of 144 m^3/year (Ndokosho, *et al.*, 2007). Namibia was, in 1998, estimated to have a growth rate of approximately 3% per annum, with urban centres said to be growing at 5% per annum especially due to migration from rural areas (van der Merwe and McCormick, 1999). According to Namibia's Central Bureau of Statistics (CBS), the majority of the people migrating to urban areas do so with the hope of getting employment (CBS, 2006 b). Many of them, however, end up with no employment which consequently renders them unable to afford descent housing. Instead they resort to informal housing where there is no proper hygiene and sanitation. It is also difficult to get estimates of the number of inhabitants in these settlements. This makes the planning for service delivery to such areas very difficult.

1.2 Aims and objectives

The aim of this study was to establish whether or not there would be enough water in central Erongo region to cater for the needs of current users, for prospective mines, as well as for the ever-expanding urban centres in the region. The project also aimed at raising awareness of the water shortages and other environmental problems that will be inevitable should the current trends in socio-economic development and urban expansions and consumption rates remain the same. Finally, the project also explored the feasibility of alternative water sources aimed at increasing supply. Alternative water sources such as reduction of water use through behaviour change by users; recycling; fog harvesting; desalinating seawater and artificial aquifer recharge were explored.

1.3 Questions and hypothesis

It is hypothesised that the available freshwater resources in the Erongo region will not be sufficient to cater for the prospective mines and the growing population of the region-this would inevitably put more pressure on municipalities to provide different consumers with water services.

The study is aimed at answering the following key questions:

1. What are the impacts of prospective mine in the Erongo region on water demand and supply for the study area?
2. How much water can be generated through alternative water sources?
3. How much water can be saved through demand management measures?

1.4 Limitations of the project

The following potential limitations can be associated with this study:

- The project relies on secondary data and therefore any inaccuracy in the data will consequently be carried over to the findings of this study.
- Use of modelling and associated limitations.
- Uranium prices have a great impact on the mine production and consequent water use. Any unexpected changes in prices of uranium will affect the model predictions. Also, if uranium prices decrease substantially, some prospective mines might not be commissioned, or those already in operation could close down or scale down on their production, all these causing the water demand estimates to be over-estimated.
- Due to different methods of mining that might be employed to mine uranium, the amount of water used might be over-estimated or under-

estimated. This is because some methods of uranium extraction are less water intensive (Chamber of Mines, 2006).

1.5 Outline of the report

The outline of the rest of the reports is as follows:

- Chapter two presents the literature relating to this research.
- The materials and methods used during the study are presented in Chapter three.
- Chapter four contains the research findings and discussions for the study.
- Conclusion and recommendations are presented in Chapter five.
- Chapter six contains the references.
- Appendices are available in Chapters six and seven respectively.

CHAPTER TWO

LITERATURE REVIEW

2.1 Freshwater in Namibia

Surface and groundwater resources in Namibia are owned by the state; and the state is to ensure the protection of these resources (Government Gazette, 2004). Namibia is known to be one of the driest countries in sub-Saharan Africa (Kluge, *et al*., 2008), in fact it is the second most arid country in Africa (van der Merwe and McCormick, 1999; AQUASTAT survey, 2005) and the driest in sub-Saharan Africa, with close to 80% of the area being either desert, arid and semi-arid (Lange, 1998; Ndokosho, *et al*., 2007). Namibia receives a mean annual rainfall of 250 mm with net evaporation rate as high as 3 700 mm per annum (van der Merwe and McCormick, 1999). Annual rainfall varies from less than 50 mm/year at the coast to 600 mm/year in the north-eastern part of Namibia (Bethune, *et al*., 2005; Ndokosho, *et al*., 2007). Of all the precipitation received annually, about 83% evaporates; 1% is used as recharge for groundwater, while 14% is used up by vegetation and runoff only constitutes 2% of annual precipitation (van der Merwe and McCormick 1999).

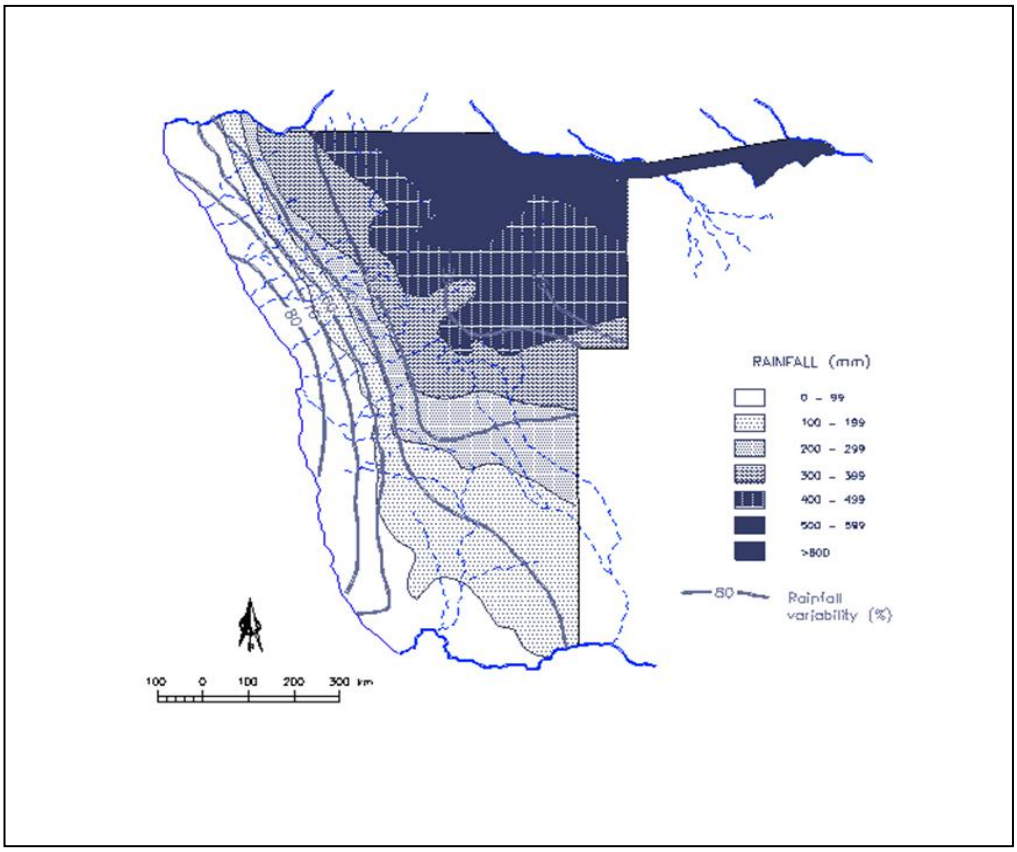

Figure 2.1 Rainfall Variability Map of Namibia

(Source**: http://www.iiasa.ac.at/Research/POP/pde/Maps/na-rainfall.html)**

Namibia's rainfall decreases from northwest to southwest and the majority of the country is characterised by desert conditions (Henschel, *et al*., 1998). In addition to low rainfall, Namibia also experiences high rainfall variability over a greater part of the country (Lange, 1998). **Figure 2.1** shows the rainfall distribution over the country. Namibia has no perennial rivers within its borders (Lange, 1998; Bethune, *et al*., 2005). This makes the water availability situation direr, especially in the driest parts of the country. In addition to the ephemeral rivers and boreholes as the main water sources, providing 22% and 50% of Namibia's freshwater respectively, the only other source is perennial rivers which are at Namibia's borders with the neighbouring countries; and thus Namibians cannot use these rivers as a source for large water extractions without the consent of the neighbours (Lange, 1998; van der Merwe and McCormick, 1999). This is because Namibia

has international obligations regarding the abstraction of water from these rivers, as well as other uses (Government Gazette, 2004).

Instead of having a sustained surface flow, Namibian ephemeral rivers feed the groundwater table, causing Namibia to have a wide range of aquifer containing groundwater-with an overall national groundwater safe yield of 300 million m^3/year (AQUASTAT survey, 2005). Safe yield refers to the rate of groundwater abstraction-a rate not exceeding the rate of replenishing the aquifers (Voudouris, 2006). However, groundwater resources in Namibia are vulnerable to over abstraction and pollution (AQUASTAT survey, 2005). According to the Government Gazette (2004), the minister sets the safe yield of the aquifers and puts measures which guard against over-abstraction, pollution as well as directing programs for recharging the aquifers (Government Gazette, 2004; Ndokosho, *et al*., 2007).

In the year 1993 a total of about 200 million cubic metres of freshwater was used in Namibia for both industrial, domestic as well agricultural purposes with the mining and housing (urban) sectors using up 11% and 22% respectively; and the rest going into agriculture (61%) and other sectors (6%) (Lange, 1998). Agricultural water use was reported to be increasing by 16% per year. Most of the bulk water users get their supply from the Namibia water corporation (NAMWATER). According to Ndokosho, *et al*., (2007), nationally NAMWATER supplied 70 Mm^3 for drinking, whilst 57 Mm^3 was supplied for irrigation. In urban centres across the world most of the water is consumed for residential purposes (Stave, 2003).

The shortage of water clearly calls for intervention by the relevant water authorities as well as action from all the consumers. In our quest to meet the needs through using these freshwater sources, it is important to consider the sustainability of the environment. It is said that the ability of the environment to continue providing water is connected to its ensured sustainability (Malley, *et al*., 2009). It is, therefore, necessary that the sustainability of the water sources and their environments be well looked after in order for the provision of freshwater to

continue. For example, capturing of ephemeral surface water may affect downstream users as well as the natural environment (ecosystems) which leads to insufficient vegetation for livestock as well as little or no freshwater for groundwater recharge (Lange, 1998).

Despite a shortage of water the economy of Namibia is largely dependent on other natural resources occurring in the country. These include fauna and flora, fisheries as well as minerals; which include diamond and uranium (Lange, 1998).

The Benguela current ecosystem is one of the nutritious marine ecosystems in the world; making Namibian fisheries one of the most productive in the world (Lange, 1998). This has led to many fishing factories at the coast. Demand for freshwater by fishing factories exerts more pressure on the already stressed water resources in these areas. The other big consumers of water are the mines (Ndokosho, *et al*., 2007).

Due to international uranium prices that are going up, Namibia has offered prospecting and mining licences to a number of new mines that are expected to be commissioned in the near future with uranium increasingly being considered as a source for long-term clean energy; and this is largely motivated by the current debate on clean energy and climate change (Cunningham, 2008).. The price of uranium had increased by 300% between 2002 and 2008 (Schneider and Shivolo, 2008). Additional mines will inevitably lead to an increase in demand for freshwater due to high demands for water from the uranium mine productions, placing huge stress on the few water resources available (Schalken, 2008).

Mining is one of the mainstays of the Namibian economy, contributing greatly to the country's gross domestic product (GDP) (Lange, 1998). Currently Namibia is number one uranium producer in Africa, with Niger and South Africa in second and third places respectively (Wise uranium, 2007). The region which is known to contain most uranium deposits in Namibia is the Erongo region. Rapid economic growth is being experienced in this region as a result of the uranium exploration

and mining, which is expected to increase in the next five years (Wise uranium, 2007) and is likely to result in a number of environmental problems. There are many environmentally important as well as important tourist sites in Erongo region due to its desert conditions, but these are threatened by expanding uranium activities in the area; also, most of the deposits are being discovered within or next to one of the biggest nature reserve, posing a direct threat to biodiversity and conservation in this area (Schalken, 2008).

2.2 Current and alternative water sources in Erongo Region (Study Area)

The Erongo region encompasses the central coast of Namibia which is one of the areas in Namibia where there is rapid urban development (van der Merwe and McCormick, 1999). The main source of water in the Erongo region is groundwater and this is due to the fact that this part of Namibia receives less than 22 mm of rainfall per annum (Henschel, *et al*., 1998). From its source, the water is transported by a 350 km pipeline from the source to the towns and mines as indicated in **Figure 2.2**.

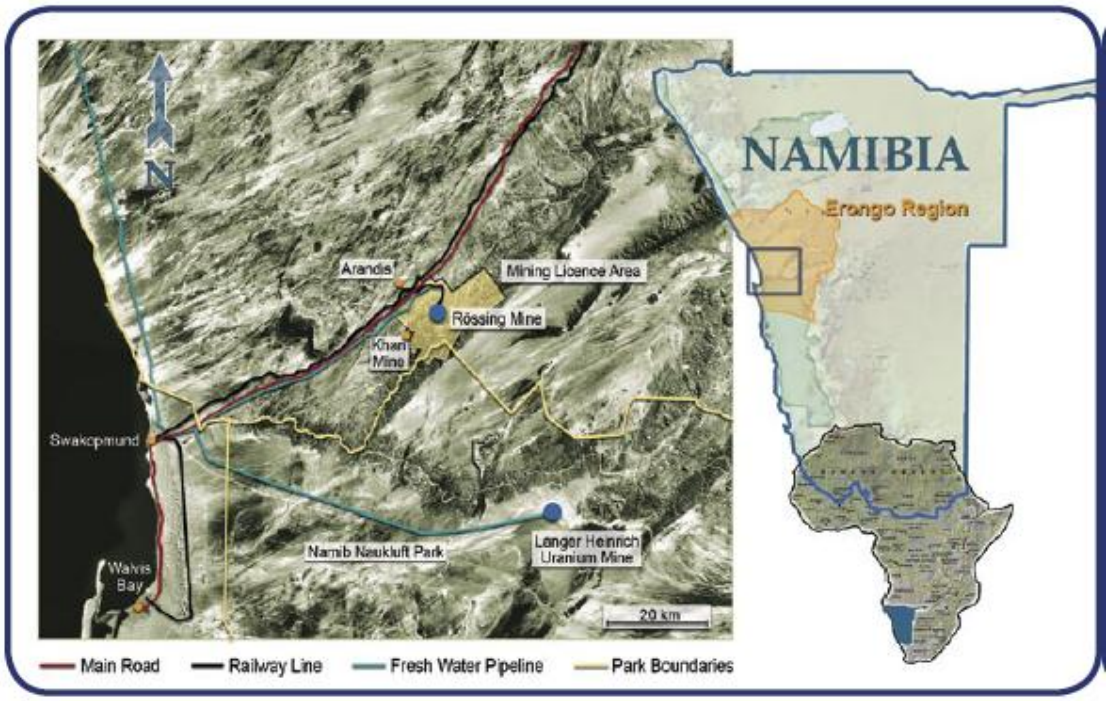

Figure 2.2 Location Map of Namibia and Erongo region

(**Source: Rössing Uranium Stakeholders report, 2007)**

The groundwater reserves are recharged through rainfall which falls over 200 km away from the region, with some people in this region obtaining water from wells; which is done manually, while others obtain water from boreholes (Henschel, *et al*., 1998). One of the direct impacts of low precipitation is limited supply of freshwater (Malley, *et al*., 2009).

Limited artificial recharge takes place but only during years with abnormally high rainfall, which is a rare occasion (W. Siemons 2008, pers.comm).

The question that arises when one observes all these prospective mines is whether there would be enough water to sustain all the socio-economic activities of the region? It has been observed that due to increasing demand, abstraction rates in recent years have exceeded recharge rates leading to over-abstraction (Henschel, *et al*., 1998), leading to a temporary licence to abstract beyond the safe yield issued (A.Brummer, 2009, pers.comm). Water supply determines how stable a settlement will be as well as the number of people a settlement can sustain

(Whitehead, *et al*., 2008). In addition to rapid urban development in the parts if this region, other economic development projects include mining, fishing and tourism (van der Merwe and McCormick, 1999).

The Central Namib Water Scheme (**Figure 2.3**) is the system of water supply for the vast majority of urban inhabitants of the Erongo region and it comprises of alluvial aquifers in two ephemeral rivers; namely the Kuiseb River and the Omaruru River (Henschel, *et al*., 1998). According to the Namibia Water Supply and Sanitation Policy (WASSP) of 2008, the Ministry of Agriculture Water and Forestry (MAWF), through the minister, is responsible for the management of all the water resources in the country which ought to be done on a sustainable basis, in order to meet the needs of the people while sustaining the environment (Government Gazette, 2004; MAWF, 2008). The minister makes decision on the allocation of water, with advice for the Water Advisory Council (Government Gazette, 2004). This coupled with increased urban population presents a difficult task for water managers. Water supply and sanitation in urban areas should be improved to cater for the current and future number of urban dwellers, which is rapidly increasing (MAWF, 2008).

Mines in this area also receive water from this scheme, which is administered by the Namibian water cooperation (NAMWATER). NAMWATER is a publicly-administered institution which supplies bulk water; and it is one of the two institutions tasked with the responsibility of supplying water to the end users whilst Rural Water Supply another institution which falls under the ministry of Agriculture, Water and Forestry and makes use of small-scale technology, as opposed to bulk water supply which uses *"large-scale dams, transport, and storage technology",* with their end users being mining companies, other industries, urban centres etc, and whose water is transferred over much longer distances (Lange, 1998). NAMWATER was established in the year 1998, as part of the public sector reform aimed at improving service delivery (Ndokosho, *et al*., 2007).

Priority for water supply is given to domestic use followed by the allocation to agricultural and economic activities (Government Gazette, 2004). The allocation of water for economic activities shall consider each individual activity according to its overall importance and contribution to the growth of the country (MAWF, 2008). In this case, mining activities are very important to the Namibian economy, due to the amounts of taxes and royalties paid to the government, as well as the number of people employed in this sector. **Figure 2.3** depicts the distribution of water from the water source to the end users. All the four towns and the two mines are supplied from this scheme (A. Mutota, 2008).

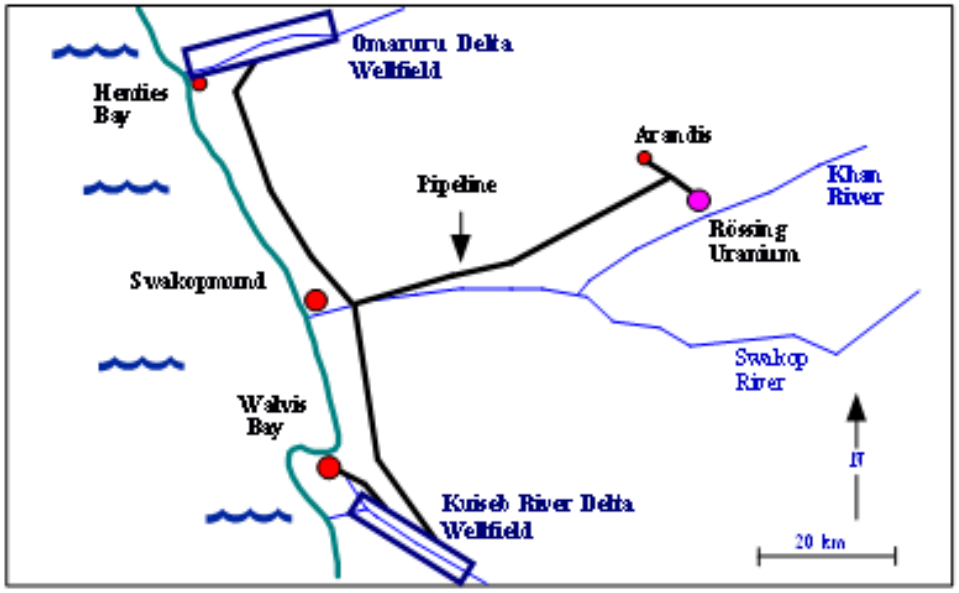

Figure 2.3 The Central Namib Area Water Scheme
(Source: W. Siemons, 2008)

In the Erongo region; Rössing Uranium mine, Langer Heinrich Uranium mine as well as three urban centres are supplied by NAMWATER with groundwater extracted from aquifers situated 350 kilometres away from the mines and the urban centres such as Swakopmund. The water is taken to its end users by a pipeline. The total human population of the Erongo region is estimated to be 112 813 (CBS, 2006 a). In 1998, the towns of Swakopmund and Walvis Bay supplied

by through the Central water scheme, had a combined population of over 100 000 people (Henschel, *et al*., 1998). The majority of these reside in urban areas.

Besides the water supply issue other environmental and social issues can also arise as a consequence of setting up new mines-these include:

1. Physical disturbance of unique desert environment. For example, a pipeline that carries water to one of the new mines is expected to disturb unique lichen fields found only in this area (Wise uranium, 2007).

2. Conflicting users. Mines will conflict with the interest of other users in the area, such as farmers. An example is a case where a mine was granted rights to abstract groundwater, but the community was not happy and the matter ended up in court (Menges, 2008).

3. Risk of depleting groundwater resources. Since it already appears that not enough consideration has been given to the exact percentage of available groundwater resources, there is a risk of granting more licences without considering other factors that will increase water use, such as the subsequent expansion of urban areas due to these mines. An example is the temporary abstraction licence referred to earlier in this chapter on page 11.

4. Growth in the number of informal settlements. People will flock to this region for job prospects. However, usually these job seekers end up finding no job; and with no means of acquiring formal housing they resort to living in informal settlements. There are many environmental as well as social problems associated with these settlements, including lack of proper sanitation facilities; environmental pollution; health care for the people in these settlements etc, hence putting natural resources under pressure because municipalities will not have planned for their provisions (Mapani, 2005).

Since the Erongo region is so dry, there will be a need for alternative water sources (Henschel, *et al*., 1998) if demand is to be met in the future. In order for us to secure sustainable water supply for the future; we need to expand our water use plans to reach many years in the future (Rahm, *et al*., 2006). Caution should be taken though with regards to making long-term projections because of the effects of variable environments as well climate change. Steps have to be taken well in advance in order to avoid these water problems (Kojiri, *et al*., 2008).

Water Demand Management (WDM) works toward achieving economic, social and ecological objectives through promoting efficiency, equity and sustainability for water use and distribution as well as its sources (Gumbo, *et al*., 2005). One way of doing this is to align our development plans with the available freshwater resource, and determine if the available resources will sufficiently cater for our socio-economic developments. If the available freshwater resources are found to be insufficient, then the second step would be to explore alternatives for increasing supply.

Alternative water sources can serve to solve part or all of the problems of freshwater availability because they increase the supply of freshwater (Tarrass, *et al.*, 2008). Lange (1998) identified two main alternative water sources that could be used to bolster bulk water supply in Namibia- sea water desalination and the transfer of water from international rivers into the inland areas,with these two alternatives both quite expensive. Due to advances in technology though, desalination is increasingly becoming much cheaper (Tsiourtis, 2008). Both these sources will also result in environmental disturbance; ranging from the deficit that will be left after extraction of water from the rivers (in case of transferring from rivers) as well as the construction of the transfer infrastructure such as the setting up of desalination plants and the pipelines. In addition to finding alternative water sources, greater effort is increasingly being focused on using the available resource more sparingly (Tarrass, *et al*., 2008).

There are also other alternative sources that could boost water supply, including recycling; fog harvesting and artificial recharge of the aquifers. As has been mentioned earlier, however, artificial recharge does not hold much potential due to low rainfalls (W. Siemons, 2008, pers.comm). Behaviour change of consumers can also have a significant impact on the amount of water consumed. In addition, water management plans and strategies should also aim at keeping demand as low as possible in the long run (Rahm, *et al*., 2006).

Therefore, for planning purposes, there is the need to quantify the amount of water required to meet the growing demand, which is driven by rapid growth in human populations as well as industrial growth. This should be done with the view to protecting the environment from over-exploitation at the expense of economic returns by amongst others finding sustainable alternative water sources. There is need to find a balance in this regard.

2.3 Water requirements for Uranium mining

Uranium mining operations require large amounts of water throughout their operations. The first use of water in a uranium mine is for dust suppression on the roads and the site of rock destabilisation- this makes the operations much more smoothly resulting in health and safety benefits to the employees, due to prevention of dust inhalation and visibility respectively. **Figure 2.4** indicates the amount of water used in a uranium mine daily, an example of Rössing Uranium, a mine in Namibia. The majority of the water is , as it is evident in **Figure 2.4**, in the processing plant and the tailings facilities (Rössing Stakeholder Report, 20

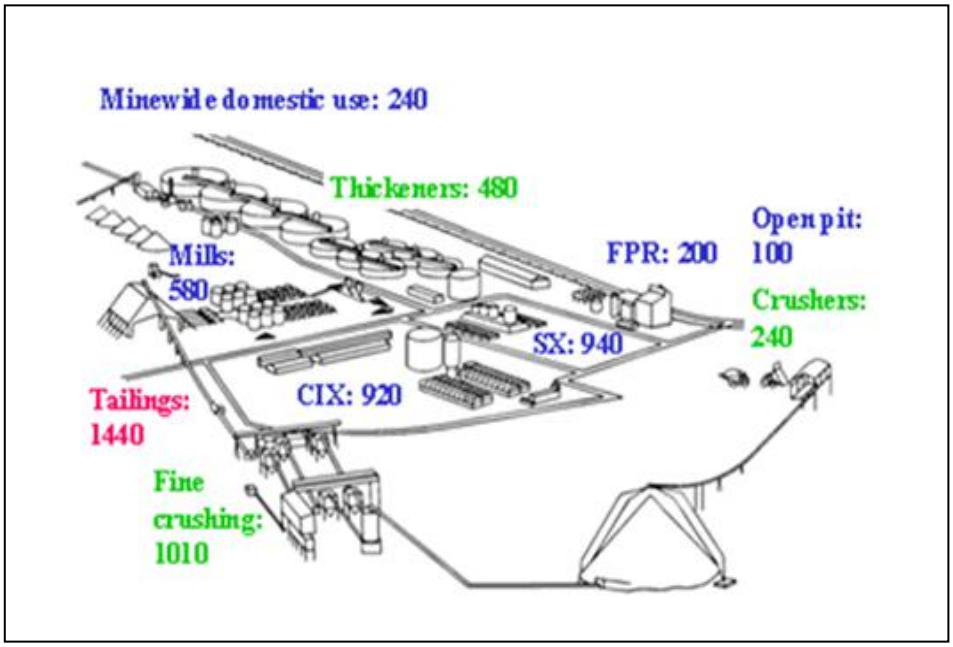

Figure 1.4 Water use (m^3) per day in Rössing Uranium mine

(**Source**: Rio Tinto intranet, 2009)

The amount of water consumed by a mine depends on the tonnes of uranium ore milled (Rössing Stakeholder Report, 2007). **Figure 2.5** shows the amount of water which was consumed per month and per tonne of uranium ore produced in the year 2007 at Rössing Uranium. The following acronyms stand for: CIX=Continuous ion exchange, SX= Solvent extraction (Rössing Stakeholder Report, 2007).

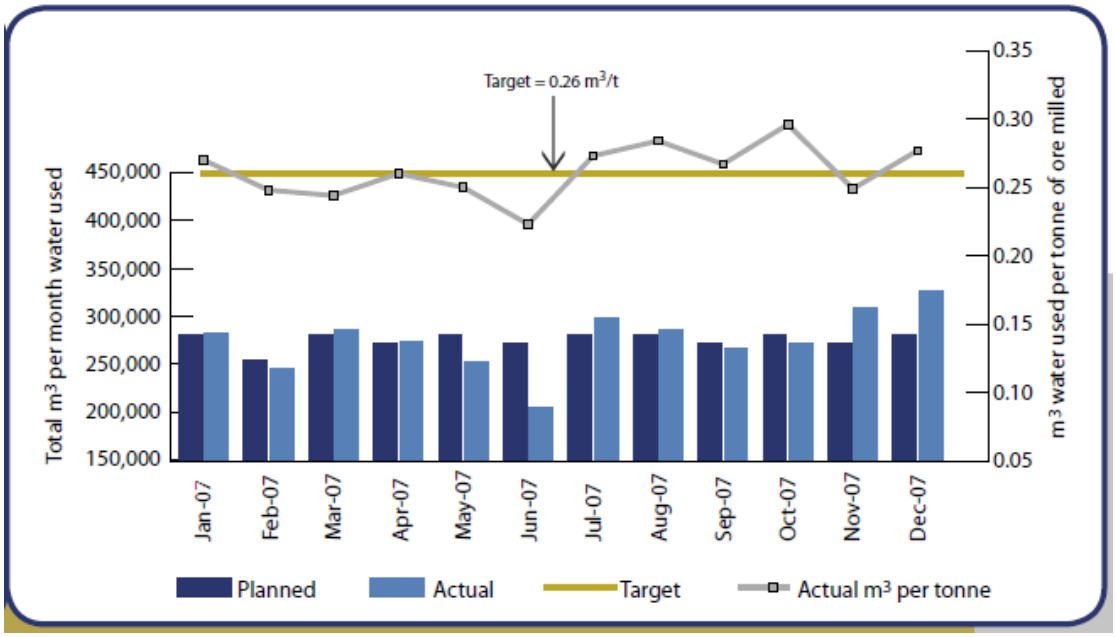

Figure 2.5 Monthly water use (per tonne of ore milled) at Rössing mine

(**Source**: Rossing Uranium Stakeholders Report, 2007)

The uranium mines in the Erongo region consumed a total of 4 506 122 m^3 in 2007 (Walvis Bay, 2008), with a total uranium production of over 5 000 tonnes (Chamber of mines, 2007; Rössing Stakeholder Report, 2008). In the same year (2007), Rössing consumed a total of 3 303 000 m^3 and produced a total of 4 049 tonnes of uranium oxide (Rössing Stakeholder Report, 2007). If the total amount of water is divided by the number of tonnes produced, it means 815.76 m^3 of water have been consumed per tonne produced (3 303 000/4049=815.76). Of the total freshwater consumed by the mines in the study area, in the year 2007, 288 000 m^3 are only provided temporarily (temporary licence) whilst the mine Trekkopje is constructing a private desalination plant with the capacity of producing 20 million cubic meters per annum (Walvis Bay, 2008). The total consumption by current and potential mines is expected to reach a total of close to 40 million m^3 per annum in the near future (Walvis Bay, 2008).

2.4 Recycling wastewater

Wastewater recycling is a viable alternative freshwater source for many water users including urban centres and industries such as mines. In addition to providing sanitation to urban inhabitants (Hellström, *et al*., 2000), wastewater systems are also important because they allow for recycling which provides additional freshwater to urban dwellers. When considering wastewater recycling it is important to take into account both the economic as well as environmental dimensions (Tarrass, *et al*., 2008). Some (at least eight) Namibian towns recycle wastewater, but only the capital city Windhoek recycles the wastewater to the quality of potable water, whilst the rest treat wastewater to a quality falling short of potable water quality and hence this water is only used for purposes such as landscape irrigation (AQUASTAT survey, 2005).

Walvis Bay is one of the towns which recycle wastewater for the purpose of watering parks and gardens (Walvis Bay, 2008). A total of 35% of potable water in Windhoek, Namibia, is provided through recycling (du Pisani, 2006). Recycling does not only have the benefit of increasing available supply, but also the benefit to the environment by reducing the amount of waste that would otherwise be discharged into the natural environment (Tarrass, *et al*., 2008).

2.5 Seawater desalination

More than 97% of water on earth is sea water, while freshwater constitutes only 2% of freshwater resources on earth, most of which is groundwater (Khawaji, *et al*., 2008). It is against this background that desalination is fast becoming a popular viable alternative for water supply as countries grapple with limited freshwater resources (Tsiourtis, 2008). It (desalination) is seen as a good solution to freshwater supply especially in arid countries (Busch and Mickols, 2004) such as Namibia. Due to increased population, better living standards as well as economic development, there is an urgent need for additional freshwater resources in many parts of the world (Khawaji, et al., 2008). Desalination is currently being

used in all Arab countries (Gulf States) (Tsiourtis, 2008) and is a source of freshwater (as well brackish water) to an estimated 75 million people across the world (Khawaji, *et al*., 2008). Due to advances in technology, seawater desalination is not as expensive as it was in the past; and for this reason more desalination plants are expected to be set up in many countries in the future (Tsiourtis, 2008).

The idea of setting up desalination plants is usually met with negative feelings by some community members who feel that such plants will impact negatively on the environment (Tsiourtis, 2008). One of the possible reasons for rejecting the idea of desalination would be the visual impact which it would have on tourists' attraction, whose sector contributes greatly to the economy of the Namibia. It is for this reason that agreed economic, social and environmental standards must be in place before any plant is set up (Tsiourtis, 2008). A Seawater desalination plant is planned for one of the new mining projects in the Erongo region and another one for supplying both industry and municipalities (NAMWATER, 2009).

2.6 Fog harvesting

According to Batisha (2003), fog is a feasible source of supplementary water supply in arid regions. Fog harvesting has proven a success in different parts of the world (Shanyengana, *et al*., 2002). It has been practiced as far back in time as the year 1901 on a small scale in South Africa's Table Mountain (Mousavi-baygi, 2008). However, it was only implemented on a large scale in an arid coastal area in Chile (Olivier and de Rautenbach, 2002; Mousavi-baygi, 2008), where it is being used as a source of water for domestic as well as agricultural consumption (Eckardt and Schemenauer, 1998).

The collection of fog water has successfully been implemented, with low cost technology, in many parts of the arid world; places such as South Africa, Chile and the Dominican Republic (Mousavi-baygi, 2008). This makes it affordable to

the rural poor and a cheap method of providing urban centres and industries. It has also been found that the quality of fog water was suitable for human consumption as well as other purposes including agriculture (Batisha, 2003).

Parts of the coast of Namibia can go for long periods of time without recording any rainfall. According to Kimura (2005), Swakopmund (one of the four towns in the area under study) is under mild climatic conditions throughout the year. It (Swakopmund) is known to have gone for as long as 10 years without rainfall and this means fog harvesting could be a reliable supplementary source of water for areas such as these (along the Namibian coast), where its feasibility was first investigated in the year 1995 (Shanyengana, et al., 2002). Fog harvesting is already being explored by local Namibian communities as an alternative water source along the Kuiseb River, where low stratus clouds promote fog episodes and fog deposition (Eckardt and Schemenauer, 1998).

In addition to low rainfall in coastal areas, fog occurs on up to 200 days per year and reaches distances of up 60 km inland and at the coast of Namibia, the amount of precipitation received from fog is said to be seven times higher than that received as rainfall (Shanyengana, *et al*., 2002). Winds from the coast which travel over the ocean serve as agents for fog transportation, particularly in mountainous areas which are more exposed to such winds (Eckardt and Schemenauer, 1998).

So far in Namibia only evaluation projects have been conducted (Mousavi-baygi, 2008), and it was found that as much as 5.3L/m^2/day and 13.4 L/m^2/day of water can be harvested dependent on season and other factors, such as the numbers and types of devices used to harvest fog (Karkee, 2005). The amount of water that can be collected, however, would mainly depend on three main factors, namely: fog bearing winds; the persistent occurrence of fog episodes and; high fog occurrence (Olivier and de Rautenbach, 2002).

Whilst rainfall in Namibia is variable and unpredictable, Shanyengana, *et al*., (2002) found that fog deposition is much more predictable, and was found to be highest at about 30 km inland, where fog harvesting could also be combined very well with groundwater extraction in this region especially because the increase in seasonal salination of the groundwater coincides with the time of the year when fog deposition is highest in the inland areas (Shanyengana, *et al*., 2002). Therefore, in order to enhance the quality of water which reaches consumers, the two (groundwater and fog harvested water) could be mixed (Shanyengana, *et al*., 2002). This can be done by means of artificial recharge or other means. It may be thought as ambitious to recommend fog water for the artificial recharge of the aquifers. However, it can certainly be a good source for local communities.

Fog harvesting is thought to be sustainable because the sources of fog remain unchanged for long periods of time (Batisha, 2003). Also, the methods for collecting fog water are very ecological friendly, since it only uses water which is heading for the atmosphere and hardly deprives the ecosystems off freshwater (Mousavi-baygi, 2008). It could, however, be influenced by climate change.

Therefore, when a suitable fog yielding place is identified, only limiting factors to fog harvesting would be the number of collectors (Batisha, 2003; Mousavi-baygi, 2008) and the availability of space (Mousavi-baygi, 2008). Although there is plenty of space in the Namibian west coast, the erection of fog harvesting collectors could have similar visual impacts as those expected from desalination plants. In Namibia it was also found during the evaluation stages, that the fog collection materials were not coping well with the climatic conditions (Makuti, *et al*., 2003). Therefore, the challenge in this regard will be to find suitable material, or there will be a need to replace the material more regularly than it is done in other places. This would inevitably push up the overall cost for the whole operation. **Figure 2.6** is an example of the type of material used for fog harvesting at pilot project in the Namib Desert.

Although fog harvesting will not have the capacity to relief all water needs, it also serves as a supplementary source for other water freshwater sources (Mousavi-baygi, 2008). Fog harvesting can particularly make a difference in areas where freshwater resources are already under stress from both climatic and human influences (Batisha, 2003). One such area includes part of the Erongo Region where rapid urbanisation combined with mining is compounding pressure on the available freshwater resources.

Caution should be taken though if fog harvesting is to be implemented. Technology cannot simply be imported from areas where it has been successful (Batisha, 2003). There is the need to consider other location-specific factors which might affect the success of fog harvesting.

In a study conducted in the Namib Desert on the origin of fog in the Namib Desert, Kimura (2005) classified the fog into six types (slope, mixing, radiation, advection, steam and frontal fog). Simulations in this study on fog harvesting, however, do not specify which type of fog is modelled but the term fog is used as a collective of the types of fog mentioned above. Therefore, before fog harvesting is adopted as an alternative water source, there might be the need to classify the type of fog occurring in the study area. Further specific studies will need to be carried out in order to determine the exact amounts of water harvestable from the fog.



Figure 2.6 Fog harvesting equipment
(Source: University of Namibia website, 2009)

2.7 Other water management strategies

Water conservation measures can make a substantial difference on the amount of water consumed both by industry and for residential purposes. According to Gumbo, *et al.*, (2005), water users in southern Africa seldom utilise water conservatively; whilst most municipalities cannot account for all of their water. The Namibian Water Resources Management Act has, as one of its fundamental principles, the facilitation and promotion of awareness among consumers on areas of water conservation and environmental protection (Government Gazette, 2004).

Advocating behaviour change by consumers is a challenge to water managers, but it is instrumental in helping consumers appreciate the need for conserving water (Stave, 2003). Through public education, water managers can educate the consumers on how to reduce the amount of water used both outside and inside their households. According to du Pisani (2006), a public water-saving awareness

campaign carried out in the City of Windhoek in Namibia was said to have significantly reduced the amount of water used by residents in the city of Windhoek.

It has been found that the greater percentage of urban residential water is not used for the most essential needs, and that this amount could be reduced if consumers are educated about the potential problems that could result from water wastages as well as on the prospects of future freshwater availability. Cooking and drinking is said to constitute only a small percentage of the total residential water used in any household (Niemczynowicz, 1999). A study carried out in Las Vegas indicates that, of the total municipal water consumed as residential, 60-65% of the water was used outside the household (Stave, 2003). In Melbourne, Australia, 35% of water supplied to residents is used for watering lawns and gardens (Abrashinsky, 2004).

A sure way by which water consumption can be reduced is by converting gardens into indigenous gardens and resorting to the use of landscaping techniques which require less water (C. Fabricius 2007, pers.comm). Landscaping techniques such as paving can save considerable amounts of water (Jansen and Schulz, 2006), which would otherwise have been used for watering lawns and other water intensive plants.

Reducing the number of bathrooms per household is also likely to have a positive impact because this would inevitably reduce the amount of time spent in the bathroom because of the need to share the bathrooms amongst the members household, and in addition, low-flow shower heads and taps and low flush toilets can also greatly influence the amount of water consumed inside the household (C. Fabricius 2007, pers.comm).

In order for water resources to be managed appropriately, there is a need for proper inter-sectoral coordination, in the area of mining, agriculture, energy as well as trade and industry (Lange, 1998). Local municipalities as well as rural

users should also be included. Without the input of different sectors into the planning and protection and utilisation of the water resources, the remaining available resources will be exposed to risks of over-exploitation, pollution and other forms of mismanagement.

There are also other measures that could be employed to influence the amount of water used. Such measures include pricing; reducing leakages and increasing the accountability for water currently "unaccounted for". The Water Resources Management Act of 2004 identifies pricing as one of the practices which could be used to encourage efficient water use (Government Gazette, 2004). The WASSP also encourages pricing as a tool to encourage water conservation. With water being very scarce in Namibia, water conservation and reduction of wastage can be encouraged through the tariff structure (MAWF, 2008). Coordination on water resources management also needs to take place among different countries in the Southern Africa Development Community (SADC), because water is a shared resource among many of these countries (Lange, 1998).

2.8 Use of computer models in resources planning, development and management

In order to quantify the amount of water which would be required by various users in the future, a computer modelling technique was used. Firstly, a model was constructed for the purpose of analysing the change in demand for freshwater, as both population and industry continue to grow in the parts of the Erongo region under review. The mining industry and the municipal water (of which the majority is allocated for domestic use) uses are the main drivers of water demand in this part of the Erongo region.

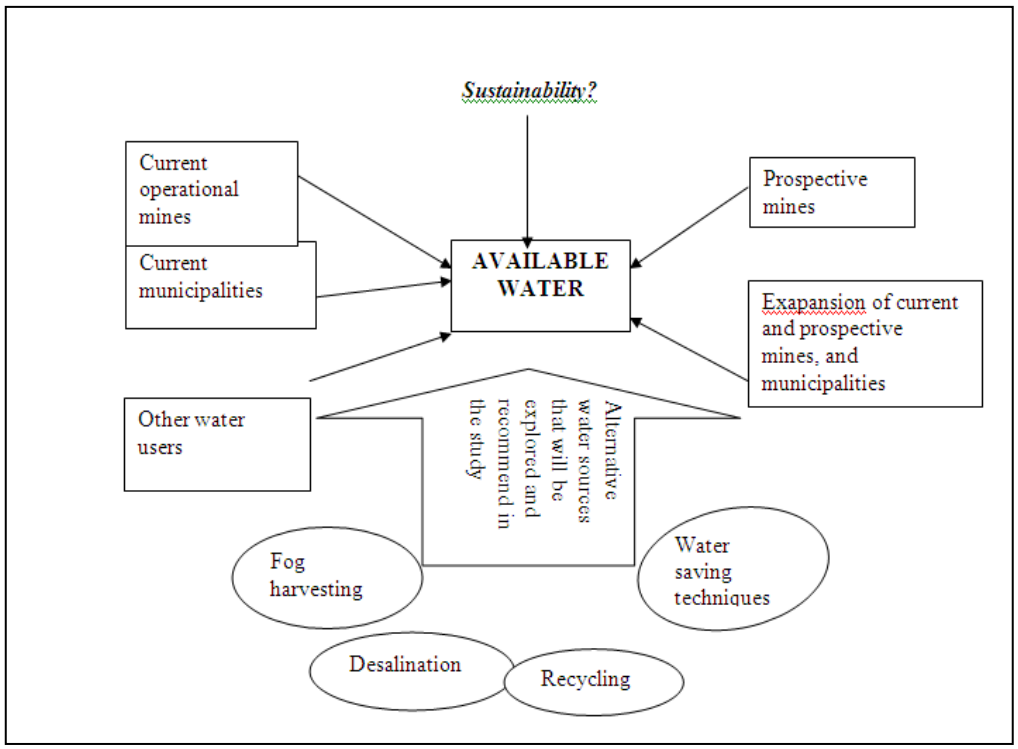

Figure 2.7 Conceptual model indicating current and potential users

The process of developing a computer model began with the construction of a conceptual model **(Figure 2.7)** which would later serve as a guide in constructing the computer model **(Figure 3.6)** which is used in the analysis. Conceptual models are a reflection of a mental simulation performed by the modeller (Saysel, 2007); and in this case, it reflects a picture of the current water uses as well as the expected water use in the future. Also, the conceptual model indicates the current and alternative (expected) freshwater sources. The completion of a conceptual model was followed by the actual systems model on which the simulations for this research are based. A model in system dynamics can be defined as "…a high-order, non-linear system of differential (or difference) equations solved and analyzed by numeric simulation" (Saysel, 2007).

Models are a simplified way of representing the real and complex world and are useful in allowing researchers to apply and test real-world problems in the

laboratory successfully in a cost-effective manner and in less time (Winz, *et al.*, 2009).

The use of computer software and system dynamics (SD) in the planning of water resources has increased considerably-since its first application in the 1960s; and this owes to the fact that most of the software are easy in both understanding and application (Saysel, 2007). This is evident in the numerous numbers of applications of system dynamics in water systems, including: water basin planning, use in drought studies, monitoring and prediction of sea level rise, managing scarce water resources, water policy analysis, flood control and long-term water resource planning (Ahmad and Simonovic, 2004). The study makes use of computer simulation to project water demand and supply for the next 20 years.

The computer package used for carrying out simulations in this study is called STELLA®. STELLA® is a high performance modelling package, whose application is common in the planning for water resource use and development and it is a preferable package for modelling because its programming is friendly and flexible (Mendoza-Espinonsa, *et al.,* 2006). STELLA® avails an object-oriented modelling platform with the ability to study many different dynamic systems (Tangirala, *et al.,* 2003).

STELLA® models are made up of stocks and flows as building blocks (Mendoza-Espinonsa, *et al.,* 2006). These building blocks are the objects which control the behaviour of the system under investigation (Tangirala, *et al.,* 2003). In a STELLA® model, a stock is shown as a rectangle and it indicates the state of the system and represents accumulations in the system (Richmond, 2005; Saysel, 2007). A flow is presented on the model as an arrow directed into and out of the stock; and it runs into or out of variables which affect the conditions of stocks (Richmond, 2005). Flows indicate the rates of change in the stocks (Saysel, 2007). Additional building blocks in STELLA® are the connectors and the convertors (Tangirala, *et al.,* 2003). Connectors are carriers of information, whilst convertors

handle the functional relationships between the building blocks (Tangirala, *et al.*, 2003). In **Figure 3.1,** an example of a stock is the number of houses in Walvis Bay, while an example of a variable is growth rate (*rate of Walvis Bay increase*).

Water resource management is very complex due to the several numbers of natural as well as anthropogenic influences that affect the hydrological cycle (Schulze, 2003; Ahmad and Simonovic, 2004). This is primarily due to the dynamic issues dealt with in water management, which are themselves driven by dynamic factors which change over time and space,and it involves issues such as water pollution and shortage of freshwater sources (Saysel, 2007).

The recognising that human activities affect the natural water systems in various ways calls for the need to finding different ways of planning and managing our water resources (Winz, *et al.*, 2009). It is for this reason that it requires analytic techniques which asses a combination of the multiple factors and thereby assist decision makers with decisions on development, protection and use of water resources (Saysel, 2007). The ability to handle the complexity of a system, such that it can be looked at in a holistic manner should be a leading characteristic of any technique which is to be employed in attempting to understand a dynamic system (Ahmad and Simonovic, 2004).

System dynamics applications are well equipped to consider the complexity of the real world in a holistic manner-which encapsulates social, physical, economic and environmental factors; and thus be able to positively influence the policies which guide water management (Ahmad and Simonovic, 2004; Saysel, 2007). A holistic approach to water management enables the implementation of an integrated approach to water management (da Silva, *et al.*, 2006; Chang, *et al.*, 2008).

System Dynamics Modelling (SDM) is one of the approaches that can be applied to water resource planning and management problems. System dynamics (SD) is a tool used for understanding interrelated systems (Chang, *et al.*, 2008) and

comprises of both quantitative (numerical) and qualitative (conceptual) modelling techniques (Winz, *et al.,* 2009

The application of system dynamics to water management has been prompted by the lack of a technique that addresses the complexity of many of the problems and policy issues which are dealt with in water resource planning and development (Ahmad and Simonovic, 2004; Saysel, 2007).

The process of SDM can be said to begin with identifying the nature of the problem at hand (Saysel, 2007), followed by identifying the structure of the system under observation (Winz, *et al.*, 2009).

The models are based on the structure of a system; which consist of "positive and negative relationships between variables, feedback loops, system archetypes, and delays" (Winz, *et al.*, 2009; pp 1304). Following the construction of the system structure; once understood, it is believed that the model's behaviour is predictable and thus its future behaviour can be projected (Winz, *et al.*, 2009). This is followed by four processes, namely the construction of the model structure; identifying the stock and flow variables and the feedback loops in which they exist; validation of the models and; analysis of the simulations (Saysel, 2007).

The use of computer simulations to model future water use is important in enhancing a proactive approach to planning and management because this will help the systems to adapt to changing demands (Winz, *et al.,* 2009). Another advantage is that we will be aware of how much resources are available for use, and would call for our action to utilise them efficiently. Appropriate management interventions will also be undertaken if the results are properly addressed.

SDM allows us to anticipate the future changes, well ahead of time incorporating changes and interventions, whilst allowing for testing the performance of the systems through repetitions and iteration (Winz, *et al.*, 2009). In the process of projecting demand for the future, computer analyses make use of historical behaviour of the system under study, to determine what the system's future

behaviour will be (Saysel, 2007). Knowing the currently prevailing conditions or conditions that existed in the past allows us to compute future conditions and therefore, a model will be considered useful when it addresses the problem for which it is developed (Winz, *et al.*, 2009). This would provide a glimpse of what the future looks like and would allow us to make decisions.

Overall, if the model depicts reality to some extent, the modelling exercise would provide better understanding of the problems at hand and would contribute to sustainability and allows for change in our approach to manage the resources . Caution should be taken though when making use of model results. This is because models are only an imitation of reality and a number of assumptions are made during the process. Model prediction therefore will be better used as guiding tools not exact predictions.

SDM also allows us to analyse a problem over long periods of time. In the northwest of the United States of America (USA), SDM was applied to analyse developments in one river for a period of a hundred years (Saysel, 2007). The analysis of water management issues over a long period of time allows water managers to cater for the sustainability of the resource with regards to supply and environmental protection across generations (da Silva, *et al.*, 2006). Sustainability is important for the future of the water resource. Therefore, whilst developing water resources for the present generations, it is important to remain cognitive of the needs of the future generations because it is an inherent characteristic of water projects that their effects stretch across generation (Saysel, 2007).

SD is mostly used for, amongst others, purposes of improving understanding of systems, as tools for evaluating strategies and policy and for the testing of theories (Winz, *et al.*, 2009). It is imperative to note that modelling and simulations do not provide answers to the problems; but that they simply provide a better understanding of the problems being investigated (Winz, *et al.*, 2009), and with the problem better understood, this renders water managers and policy makers better equipped when they make decision regarding water management (Ahmad

and Simonovic, 2004). This understanding is achieved through the use of simple mathematical equations (Tangirala, *et al.,* 2003).

Since modelling is a simpler presentation of the complex world, it is true that the outcomes of such an exercise are based on a number of assumptions. In water resource modelling, some of the assumptions that are made include that of population size and consumer behaviour. However, we know that due to a complexity of factors which affect our systems, some of the assumption might not hold. These complexities present a lot of uncertainties to water managers; which include climate change and economic constraints (da Silva, *et al.,* 2006).

Population growth, for example, is influenced by many factors, which are difficult to predict and may thus impair our predictions about the amount of water that would be required in the future (Saysel, 2007). These factors include access to health care; pollution and standard of living (Saysel, 2007). Factors such as institutional changes might also affect our predictions for the amount of water use, such as the policies which might influence the demand for water (Saysel, 2007).

One important aspect of system dynamics is the use of scenarios. A scenario is defined as "…an internally consistent (plausible) pathway (new values for state variables, flows and information) into the system's future within the context of different causal frameworks" and these are carried out in order to give a projection of the future state, based on a number of assumptions about some key causal factors (da Silva, *et al.,* 2006).

System dynamics modelling has some disadvantages, for example, it is said that although system dynamics have many useful applications especially with regards to the temporal dynamics of systems, they are not well equipped to sufficiently deal with spatial dynamics of a system (Ahmad and Simonovic, 2004).

2.9 Feedback causal loops

The traditional approach to resolving water management problems has been centred on considering the most obvious and visible problems, without considering other less obvious issues, embedded in the causal feedback loops and which have equally got great or more influence on the water management issues (da Silva, *et al.,* 2006).

Causal loop diagrams show the relationships that exist between various variables in a system and make it easier to understand the overall functions of systems (Chang, *et al.,* 2008). The idea behind feedback loop diagrams is to show the responses of systems to changes; either by reinforcing or counteracting such changes (Khan, *et al*., 2007). Considering all the possible causal factors within a system is an important way of identifying the root causes for the problems as well as the interactions between the causal factors (da Silva, *et al.,* 2006).

Feedback loops either take a negative or positive polarity (Saysel, 2007). Positive feedback loops reinforce changes that occur in the system, whilst negative feedback loops are counteractive to changes occurring in the system in which they are a part (Khan, *et al*., 2007). They are nonlinear, not easily predictable and they are complex in nature (Ahmad and Simonovic, 2004; Saysel, 2007; Chang, *et al.*, 2008). A complete system dynamic model would comprise of many feedback loops, changing with time in order to reflect dynamic complexity (Saysel, 2007).

Dynamic systems are driven by feedback loops, whose relationships are not easy to detect and hence, contribute to the hardship in understanding systems dynamics (Ahmad and Simonovic, 2004). Although much care ought to be taken during the modelling process, there is a possibility of over-looking key factors which affect the problems and the likelihood of detecting such omissions are not guaranteed (Winz, *et al.,* 2009).

2.10 Model validation

In order to boost the confidence in the results of the models, there is need to carry out validation tests. Validation in system dynamics can be defined as the process of ascertaining confidence in a model; regarding its usefulness to serve the purpose for which it is built (Barlas, 1994; Qudrat-Ullah, 2005).

Model validation is a very important process in the system dynamics modelling and it is concerned with determining how valid the structure of the model is (Barlas, 1994; Grčić and Munitić, 1996). This is because the validity of the model will determine the validity of the results (Barlas, 1994). The process of validating the structure of the model can be guided by the global rules of modelling (Grčić and Munitić, 1996). A model is thought to be valid when it correctly depicts the system's responses although , it is also argued that since the use of models resulted from our inability to fully understand reality, then models themselves are never valid (Winz, *et al.*, 2009).

There are a number of test which can be carried out to validate the system dynamic models (Grčić and Munitić, 1996), which include: (1) replication; (2) sensitivity and (3) prediction. Additional validity tests can be employed once the modeller is confident enough about with the validity in the structure of the model (Barlas, 1994).

In order to increase the accuracy in the model predictions and behaviour, models are tested regularly to allow for consistence in behaviour (Winz, *et al.*, 2009). This would be true when testing for the accuracy in the model behaviour. When testing for the accuracy in the model behaviour, some degree of confidence can be acquired if the model simulation produces expected results (Grčić and Munitić, 1996). Validation is not a ones-off process; it takes place throughout the process of modelling- beginning at the level of constructing a conceptual model, although it becomes more rigorous just before simulations (Barlas, 1994).

In summary, validation is carried out in two major steps: (1) validating the model structure; and (2) testing for the accuracy of the model behaviour (Barlas, 1994). It is evident from literature on validation that there is no universal method of validating systems dynamics model that each system dynamics model is treated on its own merit (Grčić and Munitić, 1996).

CHAPTER THREE

MATERIALS AND METHODS

"All models are 'wrong', but some models are useful" …W. Edwards Deming

3.1 Data used and model description

This study made use of secondary data which was collected from various people and institutions. Some data were also obtained from literature: book, reports and the web. The simulations in this study are run for a period of 20 years-beginning the year 2010 until the year 2030.

The complete model **(Figure 3.6)** is made up of different sub-models such as the urban sub-models, the mining sub-models as well as the water supply sub-models. This sub-section gives explanation of the model structure and the data used for individual sub-models. Also, the towns are within close proximity to each other and it is thus assumed that water consumption patterns are similar. For data relating to the urban centres, the municipality of Walvis Bay has availed sufficient water consumption data which was also used to model the consumption in the remaining towns of Arandis, Henties Bay and Swakopmund. This is primarily due to the unavailability of sufficient water consumption data from these three towns. For the mining sector, data on water consumption and percentage of employees residing in the urban areas (except Henties Bay) are based on the information on Rössing Uranium mine because of availability of data, and the fact that Rössing oldest uranium mine in the study area and the country.

3.2 Urban sub-model

There are four different urban sub-models in this simulation, each representing one of the four towns in the study area. All four towns depend on the groundwater sources in the area for freshwater supply. These towns are: Arandis;

Henties Bay; Swakopmund and Walvis Bay. Based on existing (secondary) data, the projections on different variables have been carried out. The variables included in the model are those that are known to influence the amount of water use in urban centres. The number of houses in each town, and the historical residential and industrial water consumption patterns are used in predicting the total amount of water required for the future. This is influenced directly or indirectly by factors such as residential annual water use per household; annual growth rate for the town; and the effects on water demand by the expected increases in mining activities. Industrial consumption was factored in the model in order to complete the total water requirements for each town.

The urban sub-model also includes the effect of unconventional water sources on the demand and supply of freshwater for the towns. The unconventional sources of water considered and modelled into each of the towns' sub-model. These are recycling of wastewater to potable level and the water management strategies to reduce the usage of freshwater.

On each of the sub-models for the four towns, the only stock is the number of houses in Walvis Bay (WB) (e.g., *Number of WB houses*). This is influenced by the number of additional houses per annum (*new houses per year in WB*). Annual per household water consumption in each town was calculated based on historical water consumption figures for each town as well as the number of inhabitants per household. The number of inhabitants was taken to be 5.7 people per household, for all four towns, a figure borrowed from the statistics of Walvis Bay. Consequently, per household consumption was used to calculate the per capita consumption (for e.g., *WB per capita water consumption*). The per capita consumption was used to determine the effect of mining on the water consumption of urban centres.

The hypothetical maximum number of houses that a town can accommodate (e.g., *target number of houses in WB*) is set to no specific value because it is simply used for calculation purposes- it could be set at any figure. The figure was set at

close to double the number of houses for each town. The number of housing development per year (e.g., *new houses per year in WB*) is calculated by multiplying the difference between the target number of houses (e.g., *difference WB*) and the actual number of houses (e.g., *target number of houses in WB-Number of WB houses*).

The percentage water consumption by industry in (*percentage indu consp WB*) Walvis Bay is calculated from previous consumption data. The same percentage (industrial consumption) for the rest of the towns was estimated depending on the industrialisation of the specific town and was kept within the national average of 5%. All the equations each town are available in appendices for **(Appendix 1-4)**.

The effect of new mining developments on each town's water demand (*mines' driven demand*) was modelled using the number of potential new residents in each town who are expected to be employed in the prospective mines. This figure assumes that these employees will be coming from elsewhere and not from people currently residing in the four towns. The percentages used here are based on the percentages of residency for Rössing Uranium employees. This is the percentage used to estimate what number of employees in the new mines will be residing in which of the three towns. Henties Bay is not expected to accommodate any mine employees due to the distance from the mining area. This number is calculated by multiplying the number of new mines' employees (e.g., *WB employees in new mines*) with the percentage of employees expected to be living in that town (e.g., *perc employees*).

Ultimately the number of new employees is multiplied by the per capita consumption for the specific town and its overall influence on residential water consumption for each town.

Literatures estimate that between 35% and 80% of residential water is used up in outside (outdoor) activities of the household (Abrashinsky, 2004; Syme, *et al.*, 2004; Fresenburg, 2006), for example watering the gardens, as opposed to being

used in essential needs inside the house-needs such as drinking and cooking. In this study, a percentage of 30% (*percentage management strategies*) has been chosen as a percentage of total residential water used that could be saved if management strategies (*water management strategies*) are employed. This percentage is multiplied with the total amount of residential water use to give an estimation of how much water will be "acquired" or saved through water management strategies.

A total of 20% is used to estimate the amount of water that could be generated through the recycling of wastewater. This water would increase the available supply of potable water to the towns. Approximately 35% of potable water used in Windhoek is acquired through recycling (du Pisani, 2007). However, specific for the towns in the study, the percentage of recycling has been lowered due to the size of these towns. The costs of implementing recycling might limit achieving the same level of recycling as that of the capital city Windhoek, where the budget is much higher.

Still using statistics from Rössing mine, the number of residents employed in the existing mines has been taken as 12%, 25% and 63% for the towns of Walvis Bay, Arandis and Swakopmund respectively (L. Matthew 2009, pers.comm). This is the percentages used to estimate the number of new mines' employees who will be residing in the three urban areas. This number is calculated by multiplying the number of new mines' employees with the respective percentage of the town.

3.3 Walvis Bay sub-model

Figure 3.1 is a sub-model showing the factors and relationships that affect water use in the town of Walvis Bay. According to the Walvis Bay municipality (2008) there were 10 549 houses in Walvis Bay by the end 2008, each household consuming a total of approximately 367.02 m^3 annually; with each house having an average of 5.7 inhabitants. Per capita consumption of potable water in Walvis Bay was 64.04 m^3 or (365.02/5.7) annually. The average growth rate for the town

of Walvis Bay is approximately 5.5 % or (0.055) per year. The maximum number of houses that Walvis Bay can accommodate is set at 17 000 in this study. Industry in Walvis Bay consumes a total of 19.1 % of the total amount of potable water used in Walvis Bay annually. These figures were obtained from a combination of water consumption data in the end-year report as well as historical water consumption data obtained from the municipality of Walvis Bay. The percentage of Walvis Bay residents employed in existing mines is 12% and this percentage is used in calculating the effect of new mines on water consumption in Walvis Bay.

The percentage of water to be saved through water management strategies is set at 30% of the total residential water used. Recycling for Walvis Bay is set at 20%. **Appendix 1** gives the full equations of the relationships of variables in the Walvis Bay sub-model.

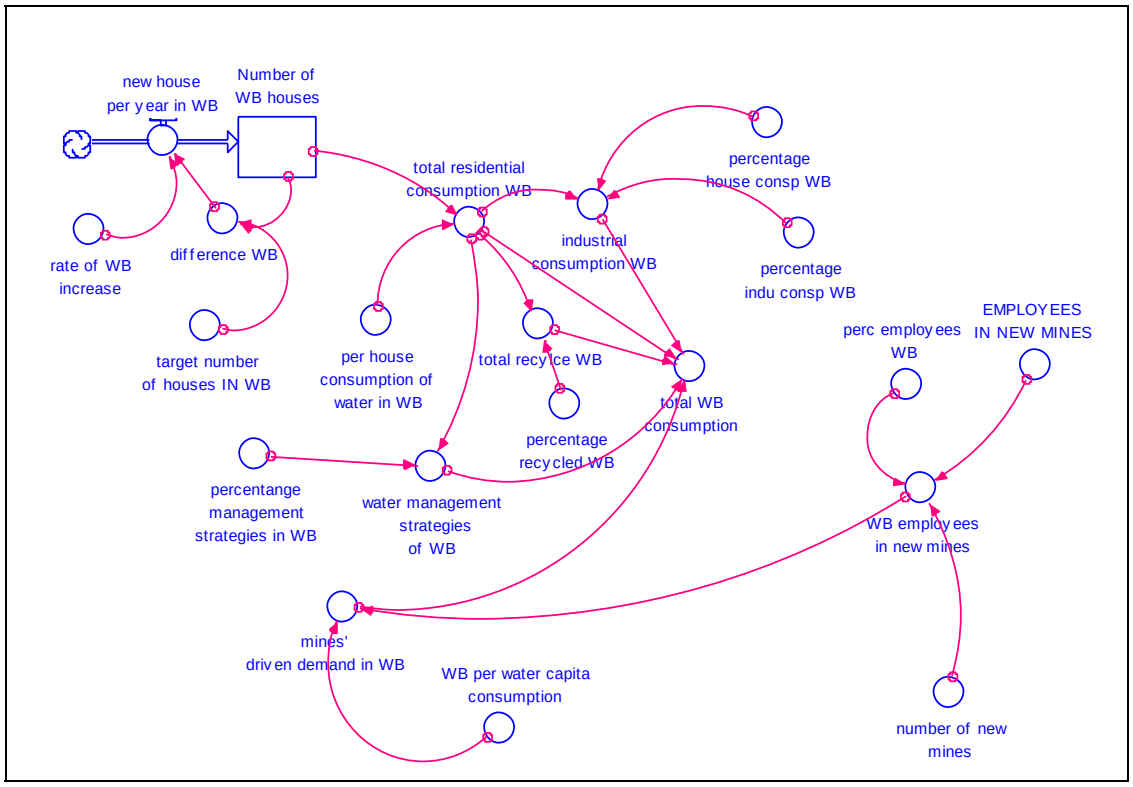

Figure 3.1 Walvis Bay sub-model

3.4 Swakopmund sub-model

Figure 3.2 is a sub-model showing the factors and relationships that affect water use in the town of Swakopmund. There were 8 822 houses in Swakopmund at the beginning of 2009 (P, Britz 2009, pers.comm), consuming a total of approximately 367.02 m^3 annually; with each house having an average of 5.7 inhabitants. Per capita consumption of potable water per year in Swakopmund is taken as 64.04 m^3 annually. These figures are taken to be the same as those of Walvis Bay.

The average growth rate for the town of Swakopmund is approximately 4% per year (G. Hullsman 2009, pers.comm). The maximum number of houses that Swakopmund can accommodate is set at 17 000 in this study. In Swakopmund industry consumes a total of 5% of the total amount of potable water used in Swakopmund annually. This figure is the national average of water use by industry in urban areas (Lange, 1998).

The percentage of Swakopmund residents employed by the existing mines stands at 63% (L. Matthew 2009, pers.comm). This is the percentage used to estimate the number of employees by the new mines who will be residing in Swakopmund, by multiplying the number of new mines' employees with the Swakopmund percentage (0.63).

Water management strategies for Swakopmund are set to cut demand by 30% of the total residential water used. Recycling for Swakopmund is also set at 20%. **Appendix 2** gives the full equations of the relationships of variables in the Swakopmund sub-model.

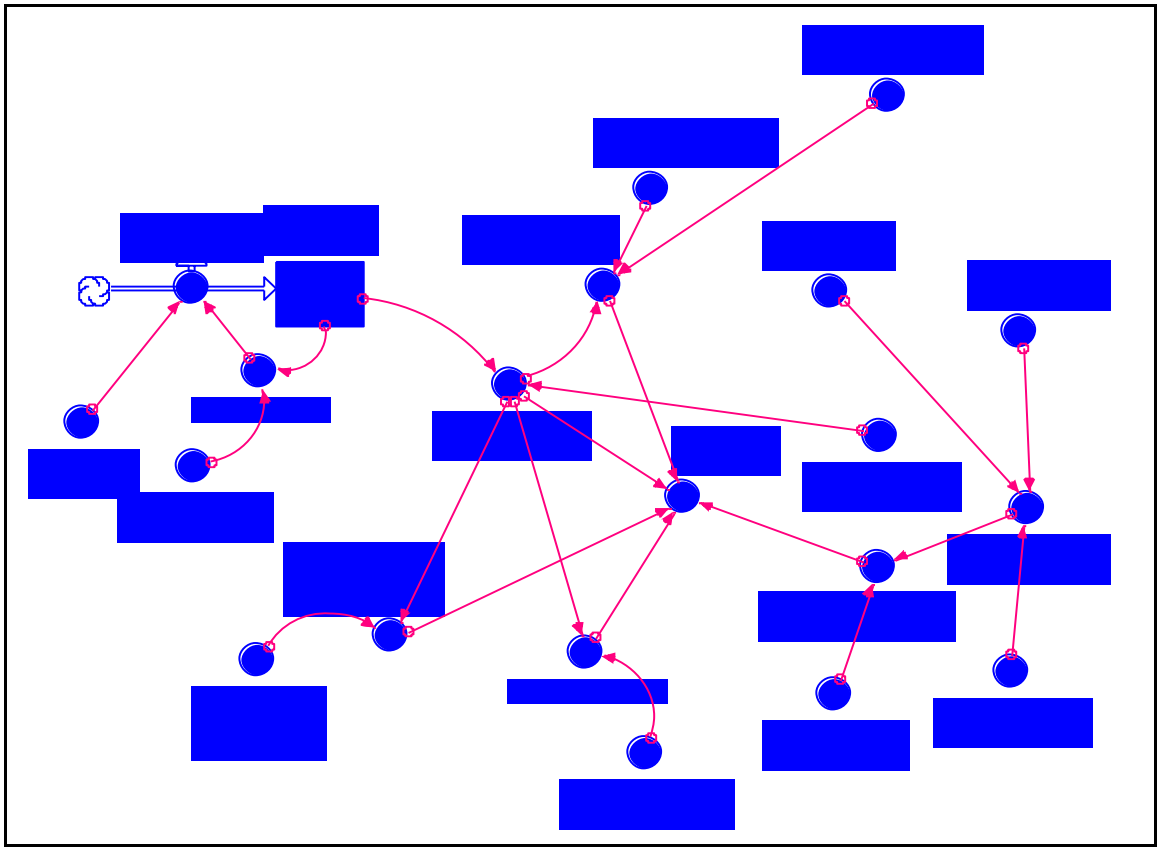

Figure 3.2 Swakopmund sub-model

3.5 Arandis sub-model

The factors and relationships that affect water use in the town of Arandis are presented in **Figure 3.3**. There were 902 houses in Arandis by the beginning of 2009 (C. Namene 2009, pers.comm), consuming a total of approximately 367.02 m^3 annually; with each house having an average of 5.7 inhabitants. Per capita consumption of potable water in Arandis is taken as 64.04 m^3 annually. The average growth rate for the town of Arandis is approximately 2% per year (C. Namene 2009, pers.comm). The maximum number of houses that Arandis can accommodate is set at 2000 in this study. Industry in Arandis consumes an estimated 2 % of the total amount of potable water used in Arandis annually. This figure is lower than the national average of water used by industry in urban areas because Arandis has fewer industries (C. Namene 2009, pers.comm).

The number of Arandis residents employed by the existing mines stands at 25% (L. Matthew 2009, pers.comm). This is the percentage used to estimate the number of employees by the new mines who will be residing in Arandis. This number is calculated from multiplying the number of new mines' employees with the Arandis percentage (0.25).

In this study, water management strategies for Arandis are set to reduce demand by 30% of the total residential water used, whilst recycling for Arandis is also set at 20%,

Appendix 3 presents the full equations of the relationships of variables in the Arandis sub-model.

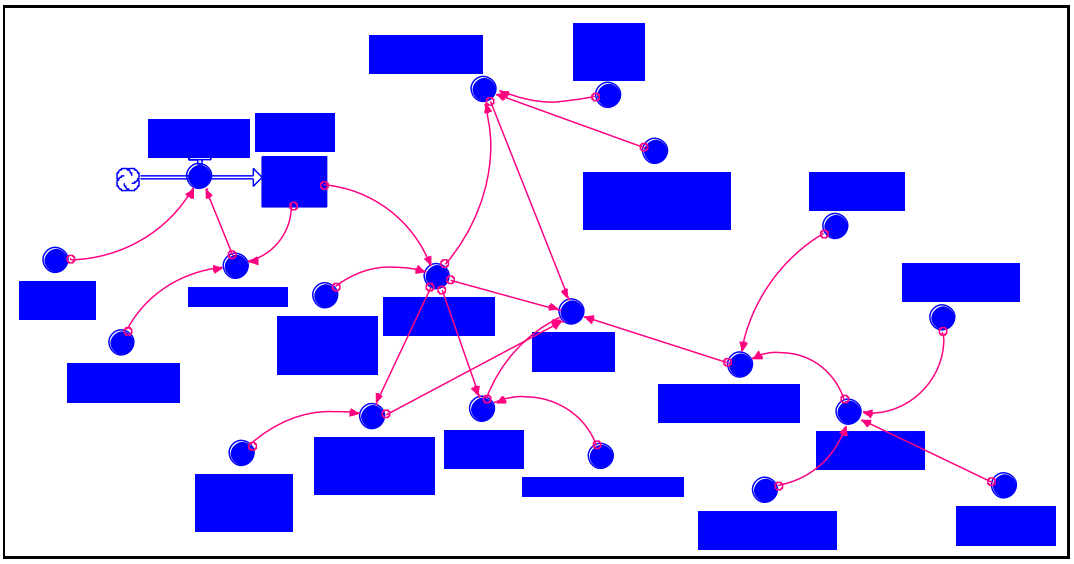

Figure 3.3 Arandis sub-model

3.6 Henties Bay sub-model

Water demand modelling for Henties Bay is presented in **figure 3.4**- a sub-model showing the factors and relationships that affect water use in the town. Henties Bay is bigger than Arandis but smaller than Walvis Bay and Swakopmund. There is no record of employees in the existing mines (based on Rössing Uranium mine)

residing from Henties Bay due to the distance from the Henties Bay to the mining areas. Henties Bay is not expected to experience an influx (like other towns) of job seekers in the new mines, and hence the effect of mining on water consumption has been excluded for Henties Bay. However, the inclusion of Henties Bay is due to the fact that Henties Bay depends on the same source of freshwater which supplies the mines and the three other towns. Therefore, water consumption in Henties Bay is modelled only based on the natural growth rate.

There were 2 000 houses in Henties Bay at the beginning of 2009, each consumes house an average of 192.55 m^3 annually and inhabited by an average of 5.7 people. The average growth rate for the town of Henties Bay is approximately 3% per year. The maximum number of houses that Henties Bay can accommodate is set at 6 000 in this study. Industry in Henties Bay consumes a total of 5 % of the total amount of potable water used in Henties Bay annually. This figure is taken as the same as the national average for industrial water use in urban areas (Lange, 1998).

Water management strategies for Henties Bay are set to reduce demand by 30% of the total residential water used. Recycling for Henties Bay is also set at 20%. **Appendix 4** presents the full equations of the relationships of variables in the Henties Bay sub-model.

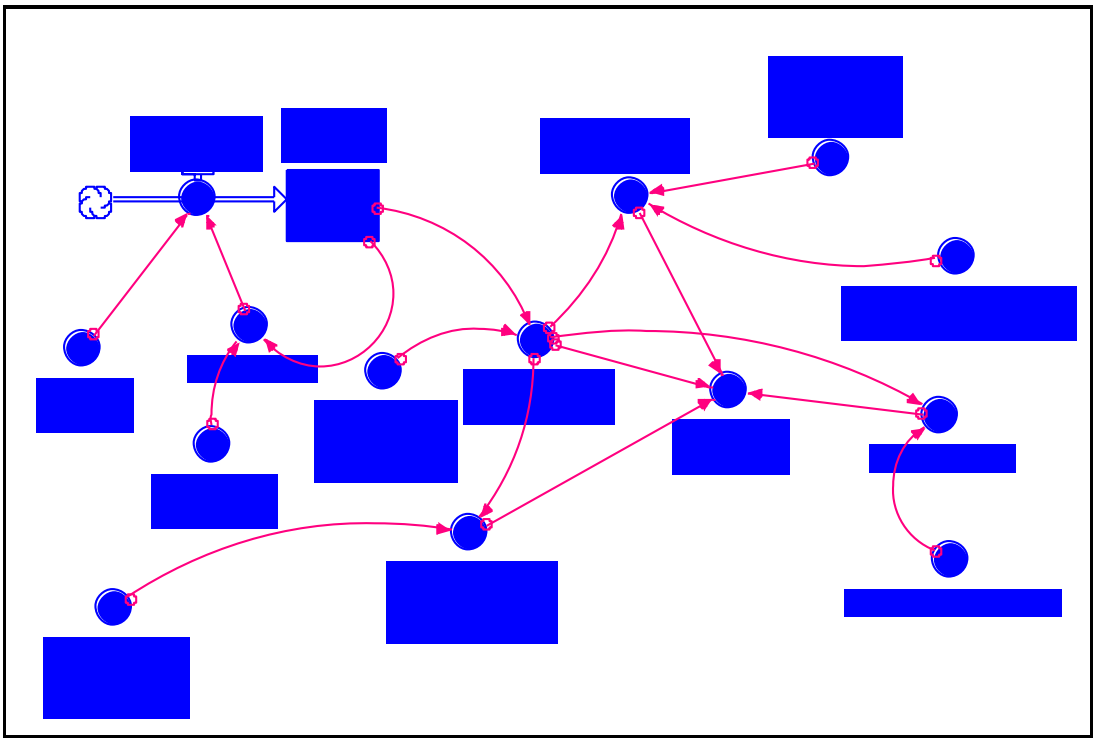

Figure 3.4 Henties Bay sub-model

3.7 Mining sub-model

Information on the consumption of water by the new mines is based on the consumption trends of Rössing Uranium mine. Rössing Uranium is the best place to base water consumption models because of its long history of uranium mining, and hence has sufficient historical data on water consumption. Langer-Heinrich, the second uranium mine in Namibia has only been in operation since the year 2005 and thus the data gathered so far remains inferior to data from Rössing Uranium and might not be sufficient for basing long-term projections.

Rössing Uranium's water use for the past 9 years was on average 815.75 m^3 per tonne of Uranium produced. This is indicated on the model (**Figure 3.5**) as *water use per tonne uranium produced*. Rössing has produced an average of 3 396 tonnes per year over the past 6 years, and continues to expand (Rössing Stakeholder Report, 2007). The average annual change in the amount of tonnes

produced is used as the expansion or growth rate (*rate of addition*) for both existing and new mines.

Currently there are three Uranium mines in Namibia, all located in the Erongo Region. They are, Rössing Uranium, Langer-Heinrich (since 2005) and Trekkjoppe (first production expected at the end of 2009). Langer-Heinrich mine produces an average of 1 080 tonnes per year (Chamber of Mines, 2006). while Trekkopje is expected to produce an average of 3 500 tonnes per year (Mukumbira, 2008).

It is estimated that up to 5 new mines could be commissioned by the year 2015 (Swiegers, 2008), while other sources estimate that up to 12 new mines are expected to be commissioned by the year 2015 (Weidlich, 2008). This means there will approximately be an addition of 2 new mines each year (*new mines per year*). The amount of tonnes produced by both existing and new mines is used to calculate the total demand of water by mines (*TOTAL DEMAND BY MINES*). This demand will exclude 60% of Rössing Uranium's water consumption. This is because Rössing recycles 60% of water used per year (Rössing *recycled water*). If both the existing mines and new mines, should recycle their water at 60%, the effect of such practice is represented on the model by *TOTAL DEMAND BY MINES AFTER RECYCLING*. **Appendix 5** provides the complete equations used to define relationships between mine productivity and water consumption.

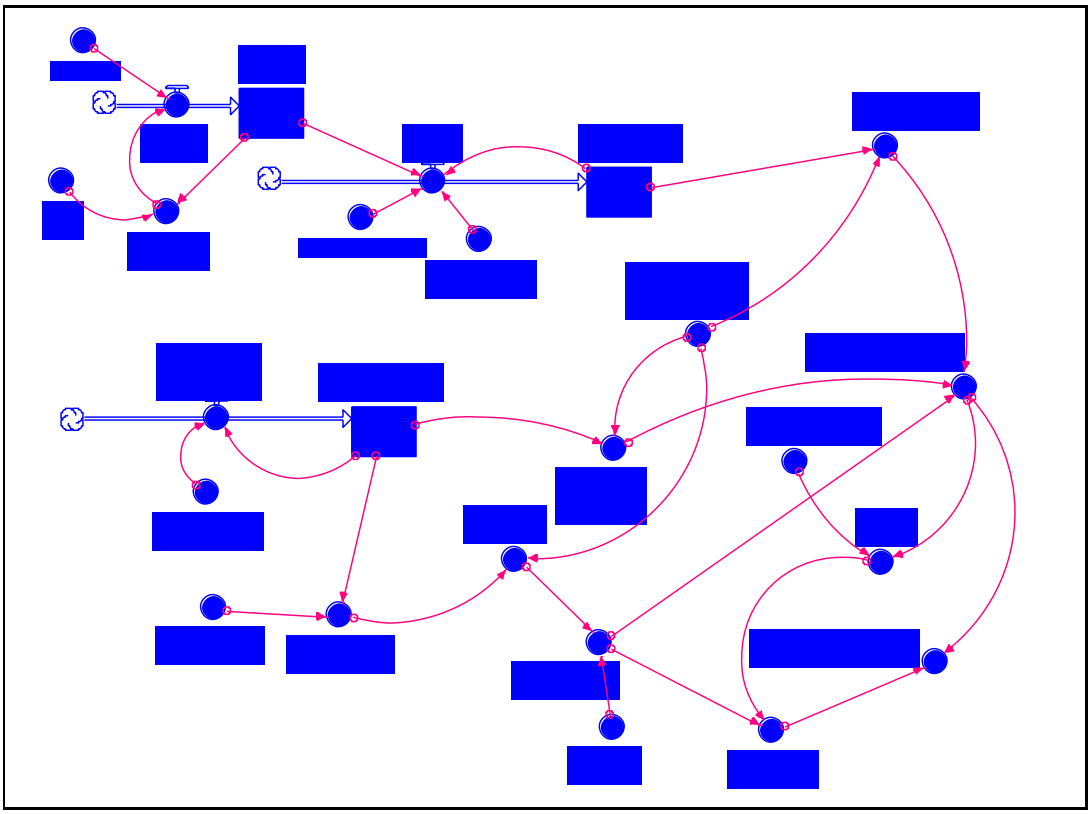

Figure 3.5 The mining sub-model

3.8 Complete model

A combination of sub-models (**Figure 3.1-3.4**) is presented in **Figure 3.6**. There are additional variables which do not feature on any of the sub-models presented above. These variables include the supply from alternative water sources- *DESALINATION* and *FOG HARVESTING* as well as the current available groundwater supply (groundwater *safe yield*). On the users' side the additional variable is water use by other consumers (*other users*). The category of other users is made up of very small-scale farmers and other unspecified users, who consume a total of 515 021 m^3/year (A.Brummer 2008, pers.comm). In this study it is assumed that the other users' water use will be consistent over the simulation period. The meeting point of all the sub-models is the point of water demand, where the over-all water requirement for the study area is projected. Total demand

is made up of the addition of total water used by the urban areas, other users as well as the mining sector.

Finally, all the water requirements are summed up and compared to the available supply. The difference between the amount of available water (*total supply*) and the demand from all users (*total demand*) is presented on the model as *EXCESS*. The recycling of wastewater by the municipalities is regarded as an unconventional source of water and hence it is added to the available supply as an alternative water source. Total effect of the new mines on the three coastal towns (except Henties Bay) is summed up under *MINES URBAN WATER DRIVEN DEMAND*. Complete details of **Figure 3.6** are available in **Appendix 6**.

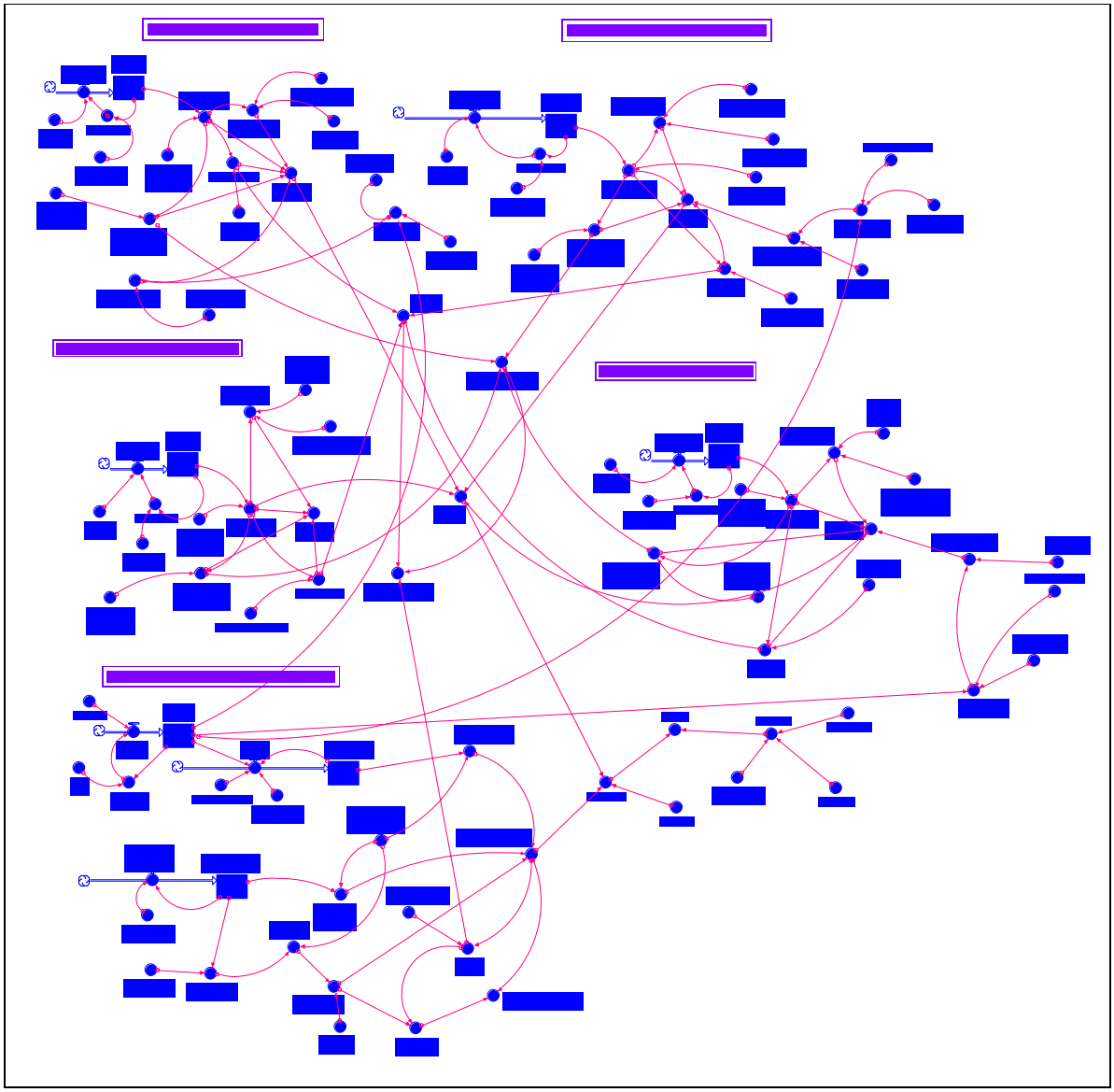

Figure 3.6 Complete model depicting water demand and supply

CHAPTER FOUR

RESULTS AND DISCUSSIONS

"Don't empty the water jar until the rain falls"- Phillipine proverb

4.1 Introduction

This chapter presents the results and discussions from the simulations on future water demand and supply for the coastal area of the Erongo Region. Water demand projections for individual municipalities are initially presented separately, and a combination of water demand for all the municipalities is presented in the later sections of this chapter. Municipal water demand projections are simulated under four different scenarios over a period of 20 years (2010 to 2030), and the scenarios are:

Scenario 1: Water demand at current consumption and growth rates (shown on figures as *0% alternatives*).

Scenario 2: Water consumption at current rates combined with 20% supply from recycling of residential wastewater (shown on figures as *20% recycling*).

Scenario 3: A 30% reduction in water demand through demand management strategies (shown on figures as 30% demand management).

Scenario 4: Consumption at current rates with a combination of 20% recycling and 30% demand management measures (shown on figures as *20% recycling; 30% demand management*).

These projections are followed, for each municipality, by the expected effect of new mining developments on the total municipal water demand.

This is followed by projections for water demand by the mining sector-firstly for the existing mines, then the projections for a combination of the existing and expected new mining developments. In the projections for demand by mines, two scenarios are represented namely: consumption without recycling and consumption with a 60% percentage of recycling (60% recycling is based on the percentage recycling of wastewater by Rössing Uranium). The water needs for all the users in the study area are summed up to give a figure for expected total water demand for the simulation period.

In addition to alternatives such as recycling and demand management measures, this chapter also includes a section of two other alternative water sources namely desalination and fog harvesting. In this regard, the total effect of alternatives on water demand is also summed up and presented at the end of chapter four.

4.2 Walvis Bay

Water demand projections are presented in this section under four different scenarios of water demand for the town of Walvis Bay. The projections are made for a period of 20 years (from 2010 to 2030) and are shown in **figure 4.1**.

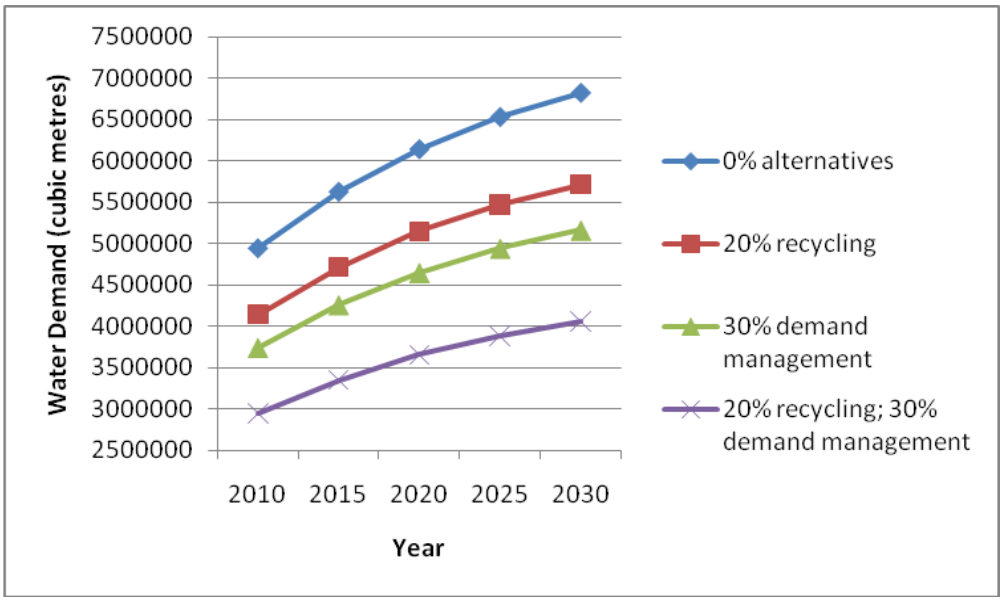

Figure 4.1 Water demand for Walvis at current consumption trends

The first scenario presents water demand at current growth and consumption rates, and without the influence of potential new mines. The simulations under the first scenario showed that water demand for this scenario is expected to be 4 946 742 m^3/year for the year 2010. Demand could move up to 6 820 264 m^3/year by 2030 under the same scenario. This marks a total increase of 37.8% over the simulation period.

The second scenario simulated water demand for Walvis Bay with 20% recycling of total residential water use. This figure essentially means that 20% of the water would be obtained from recycling and recycling serves as an unconventional source of water. This scenario showed that if 20% of residential water use is recycled, total demand is reduced in 2010 from 4 946 742 m^3/year to 4 146 359 m^3/year, a reduction of about 16.2% in comparison to the first scenario. By the year 2030 simulations for the second scenario showed that total water demand will be 5 716 745 m^3/year compared to 6 820 264 m^3/year expected under the first scenario.

Scenario three looked at the effect of water demand strategies (demand management) on total water demand. If demand management measures are effective in reducing water demand by 30%, without recycling wastewater, this

would reduce demand from 4 946 742 m^3/year to 3 746 168 m^3/year by 2010. Total water demand is shown to be 5 164 986 m^3/year for the year 2030.

Scenario four is a combination of recycling (20%) of wastewater and 30% reduction in demand through demand management. Under this scenario water use in Walvis Bay is reduced to, only 2 945 785 m^3/year at the end of 2010 compared to 3 746 168 m^3/year under scenario three, and to 4 061 467 m^3/year compared to 5 164 986 m^3/year in 2030. This marks a reduction in water demand of 40.4% (from the first scenario), 28.9% (from the second scenario) and 21.4% (from the third scenario) in the year 2010. All the projections (intermediary years) are available in **Appendix 7**.

With the expected commissioning of new mines, the amount of water used in Walvis Bay is expected to also increase. This is depicted in **Figure 4.2**, where new mines are projected to push demand from the current 4 946 742 m^3/year to 4 958 731 m^3/year in the year 2010, an increase of 0.24% and an increase of 2.1% at the end of 2030 (from 6 820 264 m^3/year to 6 965 582 m^3/year).

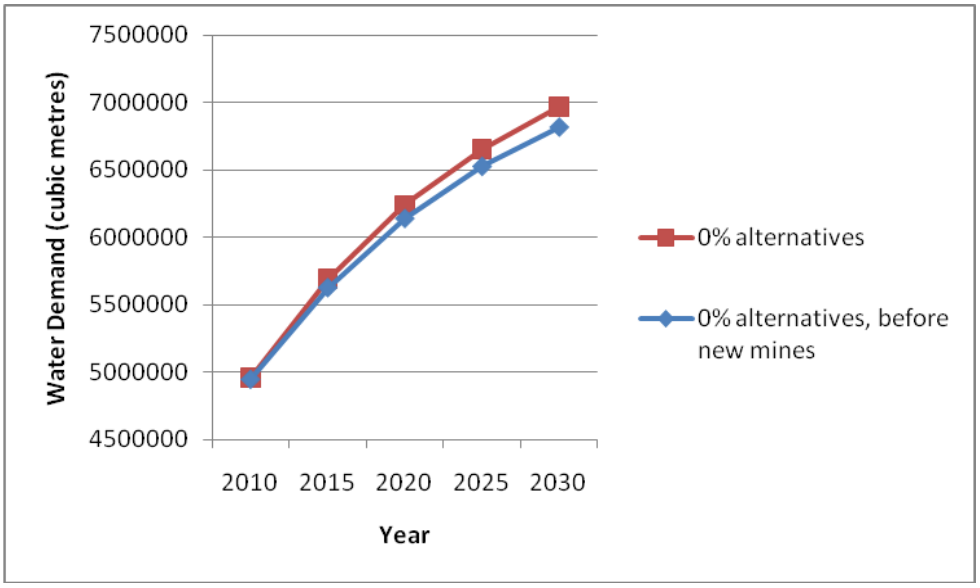

Figure 4.2 Effect of new mines on water demand for Walvis Bay

4.3 Swakopmund

Simulations for the town of Swakopmund are done in a similar way to those of Walvis Bay, and are also carried out under four scenarios and are presented in **Figure 4.3**. This figure showed water demand projections without the effect of new mines.

Scenario one (shown on in **Figure 4.3** as *0% alternatives*) showed that water demand by the municipality of Swakopmund stood at 3 534 642 m^3/year for the year 2010 and at 5 227 096 m^3/year by the year 2030, an overall increase of 47.8%.

The second scenario looked at the effect of 20% of wastewater recycling on total water demand for Swakopmund. Recycling reduced total water demand from 3 534 642 m^3/year to 2 863 060 m^3/year in 2010 and to 4 233 948 m^3/year in 2030 compared to 5 227 096 m^3/year for the same year under scenario one.

The effect of demand management on total water demand in Swakopmund is presented under scenario three. A 30% reduction in demand due to demand management alone reduced demand for the year 2010 to 2 527 269 m^3/year from 3 534 462 m^3/year under scenario one. The reduction in water demand for 2030 is from 5 227 096 m^3/year (first scenario) to 3 737 373 m^3/year.

The final scenario (scenario four) is a combination of 20% recycling of wastewater and a 30% reduction as a result of demand management. This scenario showed that water demand for Swakopmund was reduced to 1 855 687 m^3/year from 3 534 642 m^3/year (first scenario) and from 2 863 060 m^3/year (second scenario) and from 2 527 269 m^3/year (third scenario) for the year 2010. For the year 2030, demand is expected to be 2 744 225 m^3/year. All the details for water demand projections for Swakopmund over the simulation period are available in **Appendix 8**.

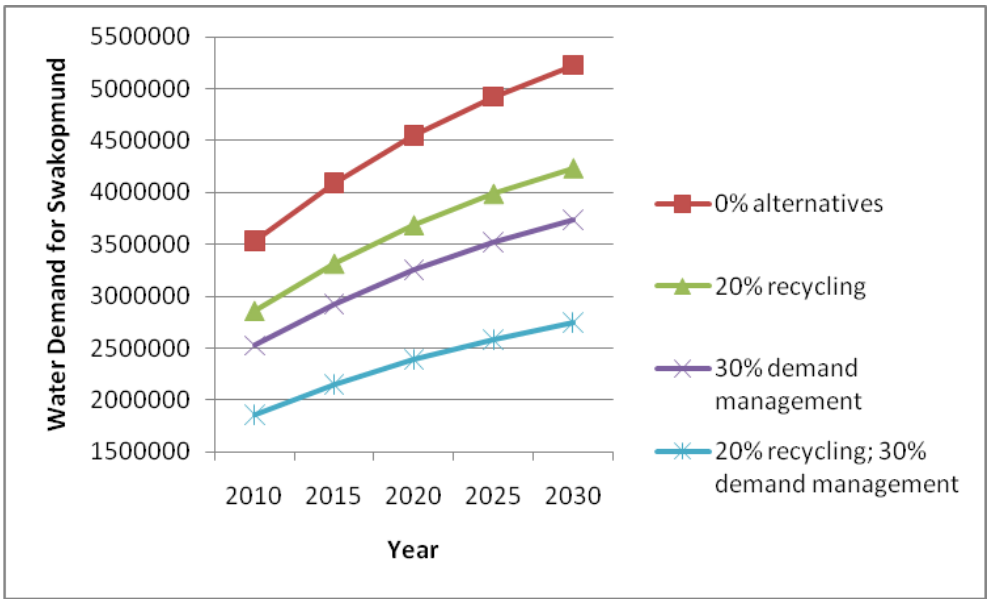

Figure 4.3 Water demand for Swakopmund at current consumption trends

The impact of new mines on the total water demand for Swakopmund is shown in **Figure 4.4**. The simulations showed that water demand increased from the expected 3 534 642 m^3/year (scenario one) to 3 597 587 m^3/year for the year 2010. By the year 2030, **Figure 4.4** showed that total water demand in Swakopmund would be approximately 6 000 000 m^3/year.

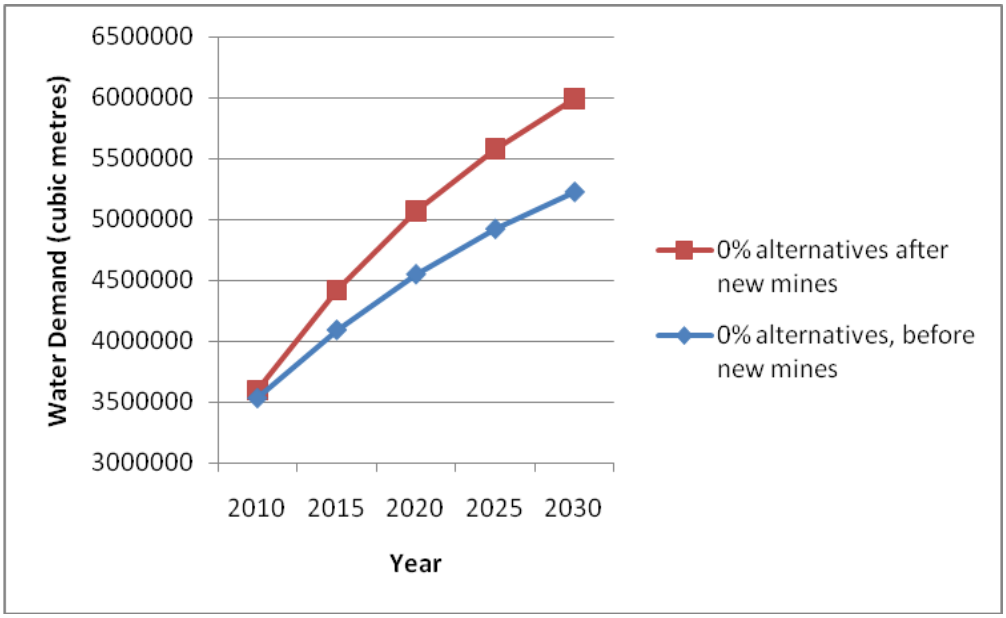

Figure 4.4 Effect of new mines on water demand for Swakopmund

4.4 Arandis

Water demand projections for Arandis are presented in **Figure 4.5**. Simulations in the first scenario (current consumption and growth rates) showed that water demand for Arandis will be 340 778 m^3/year for the year 2010, and 544 725 m^3/year by the end of 2030 for the same scenario, marking an increase of 59.8%. Water demand is projected to be around 457 064 m^3/year in 2015 under this scenario.

The second scenario showed that freshwater consumption for Arandis would decrease from 340 778 m^3/year to 281 221 m^3/year in 2010 and from 544 725 m^3/year to 437 959 m^3/year in 2030. Mid-way through the simulation period (2020), water demand would be 367 479 m^3/year under the second scenario.

Scenario three shows the effect of water deamnd management on total demand for freshwater in Arandis. The results showed that freshwater demand in Arandis would be reduced from 340 778 m^3/year (scenario one) to 246 943 m^3/year at the end of 2010, and from 544 725 m^3/year in 2010 (scenario one) to 384 576 m^3/year in 2030.

A combination of recycling and demand management could reduce water demand, this is presented under scenario four where water demand is expected to be 178 387 m^3/year in 2010; a reduction of 47.6% from the 340 778 m^3/year in the first scenario. Instead of 544 725 m^3/year by 2030 (as it was under the first scenario), under scenario four, total water demand for Arandis is projected to be 277 810 m^3/year, which is 48.9% less. Details used for the four scenarios of water demand projections in Arandis are available in **Appendix 9.**

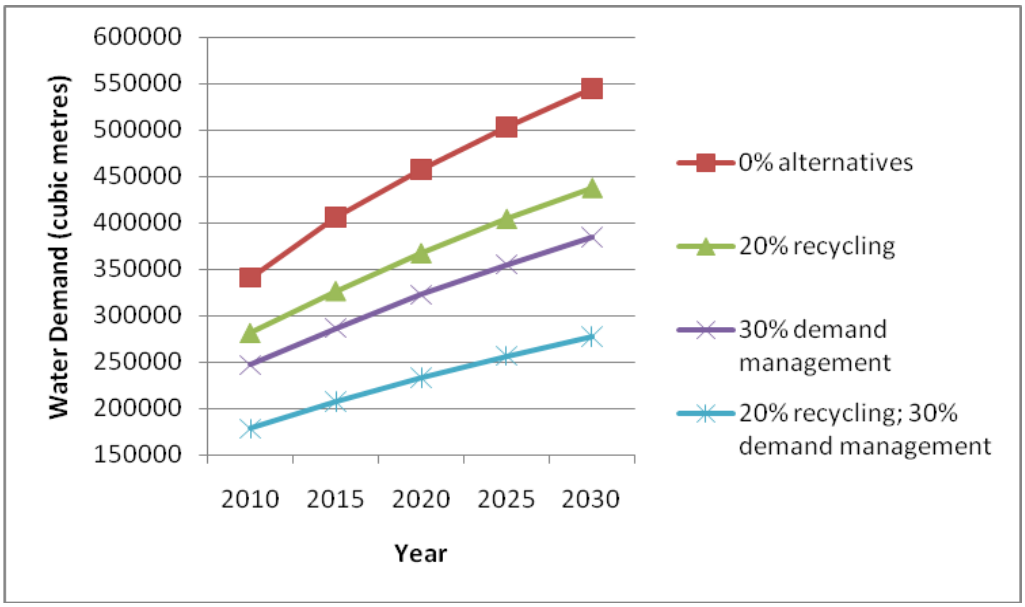

Figure 4.5 Water demand for Arandis at current consumption trends

The effect of new mining projects on the water demand projections of Arandis is shown in **Figure 4.6**. This **Figure 4.6** shows water demand projections before (shown on the figure as *0% alternatives before new mines*) and after (shown on figure as *0% alternative after new mines*). With the introduction of new mines, water demand in Arandis is expected to shift from 340 778 m^3/year in 2010 to 374 742 m^3/year in the same year, an increase of 9.9 %. For the year 2030, new mines have pushed water demand from 544 725 m^3/year to 810 975 m^3/year, an increase of 48.8%.

Amongst the three towns expected to be affected by mining, Arandis has the highest expected effect. The commissioning of new mines will have the greatest impact on the water demand or Arandis, followed by Swakopmund and then Walvis Bay. Water demand in Arandis was pushed up by new mines by 9% in 2010 compared to 1.7% and 0.2% for Swakopmund and Walvis Bay respectively. For the year 2030, Arandis has an increase of 48.8% whilst Swakopmund and Walvis Bay experienced an increase of 14.5 % and 2.1% respectively. The reason for such a difference is down to the fact that there is higher percentage of Rössing employees living in Arandis.

Rössing is the mine on which the simulations are based. Since the locations of the other potential mines are not explored in this study, and since the employees are likely to settle in the nearest town, it might be that the Rössing sample may not reflect the future settlement of new employees. This might affect the projections on the effect of mining on water demand for specific towns, but the overall urban trajectory will not be affected because the overall amount of employees would remain unaltered.

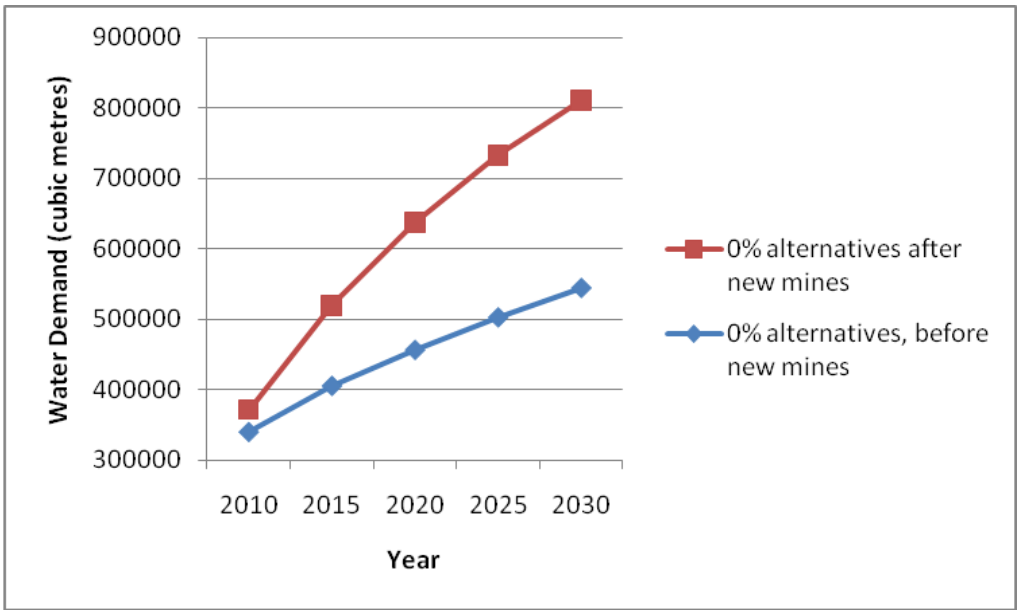

Figure 4.6 Effect of new mines on water demand for Arandis

4.5 Henties Bay

In the simulations for water demand in Henties Bay it is not expected that Henties Bay be affected by the commissioning of new mines, hence the only projections presented here are those following current growth and consumption rates. This is presented in **Figure 4.7** also over four scenarios as with the three preceding towns. Scenario one projects water demand to be 849 941 m^3/year in 2010 and 1 791 735 m^3/year by 2030. This marks an increase in water demand of 110.8% over a period of 20 years.

The second scenario showed that recycling reduced demand from 849 941 m^3/year to 688 452 m^3/year in 2010. The same scenario showed a percentage reduction of 19% in water demand projections for 2030-from 1 791 735 m^3/year to 1 451 305 m^3/year.

Scenario three shows 30% demand management which reduces water demand to 607 708 m^3/year from 849 941 m^3/year (scenario one) in 2010. In the same scenario, water demand in the year 2030 was found to have reduced from 1 791 735 m^3/year to 1 261 286 m^3/year.

When combined, as shown in scenario three, recycling (20%) and water demand management (30%), reduced the amount of water demand to 526 963 m^3/year in 2010 from the initial 849 941 m^3/year, and to 1 110 876 m^3/year in 2030 from 1 791 735 m^3/year. The full set of equations for Henties Bay water demand simulations, for all four scenarios is available in **Appendix 10**.

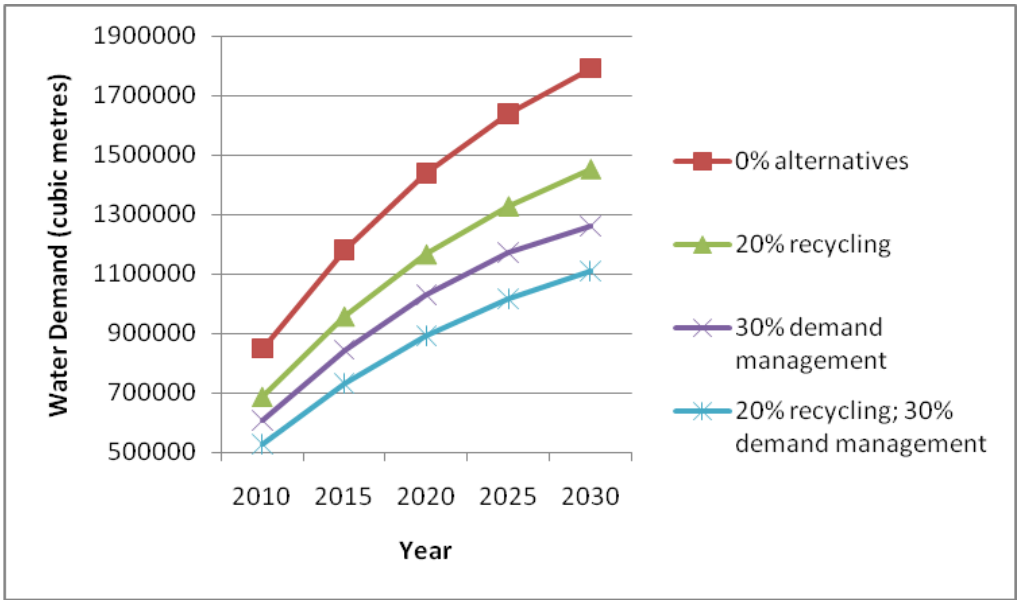

Figure 4.7 Water demand for Henties Bay at current consumption trends

4.6 Total Coastal Urban Demand

Total water demand projections for coastal urban areas of the Erongo Region are presented in **Figure 4.8**. As with individual towns, projections of water demand are also presented in four scenarios. Each scenario under this sub-section is a summation of the corresponding scenario for all the towns. This figure holds under the assumption that no new mines are commissioned.

Scenario one gives the total water demand for the coast (shown on **Figure 4.8** as *0% new alternatives before new mines*). Water demand under this scenario is projected to be 9 672 103 m^3/year in the year 2010, and 14 383 820 m^3/year in 2030, and overall increase of 48.7% over the 20 years. Recycling 20% of the residential water use (scenario two) reduced total urban water demand for the study area to 7 979 092 m^3/year in 2010 from 9 672 103 m^3/year in 2010 and from 14 383 820 m^3/year to 11 839 957 m^3/year in 2030. Also, if 30% demand management measures alone are implemented, water demand would be reduced to 7 128 088 m^3/year in 2010.

A combination of 20% recycling of residential water use and 30% demand management for the urban coastal municipalities resulted in total water demand of 5 506 822 m^3/year in 2010, a reduction of 43%.

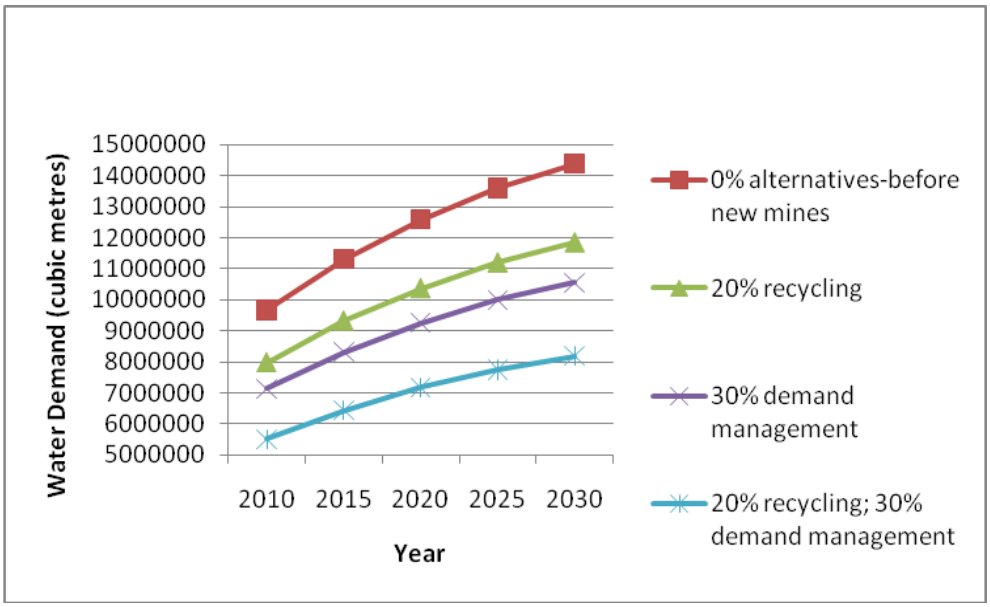

Figure 4.8 Total coastal urban water demand

The effect of new mines on the total water demand for coastal municipalities is shown in **Figure 4.9**. The simulations showed under scenario one that at current consumption and growth rates with no recycling or demand management, total water demand would be 9 777 995 m^3/year in 2010 a shift from 9 672 103 m^3/year in the same year under the assumption of no new mines (**Figure 4.8**), an increase of just about 1%. Simulations also showed that water demand will be increased by new mines from 14 383 820 m^3/year to 15 558 308 m^3/year in 2030, which represents a percentage increase of 8%.

The simulations in the second scenario showed that water demand for the study area will be 8 075 985 m^3/year in 2010 and 13 014 444 m^3/year by 2030. Scenario three, estimated total water demand to be 7 224 980 m^3/year in 2010 and to be 11 722 709 m^3/year by 2030. When demand management and recycling were combined in scenario four demand was reduced to 5 540 774 m^3/year and 8 605 946 m^3/year for the years 2010 and 2030 respectively. The full set of the data used in **Figure 4.9** are available in **Appendix 12**.

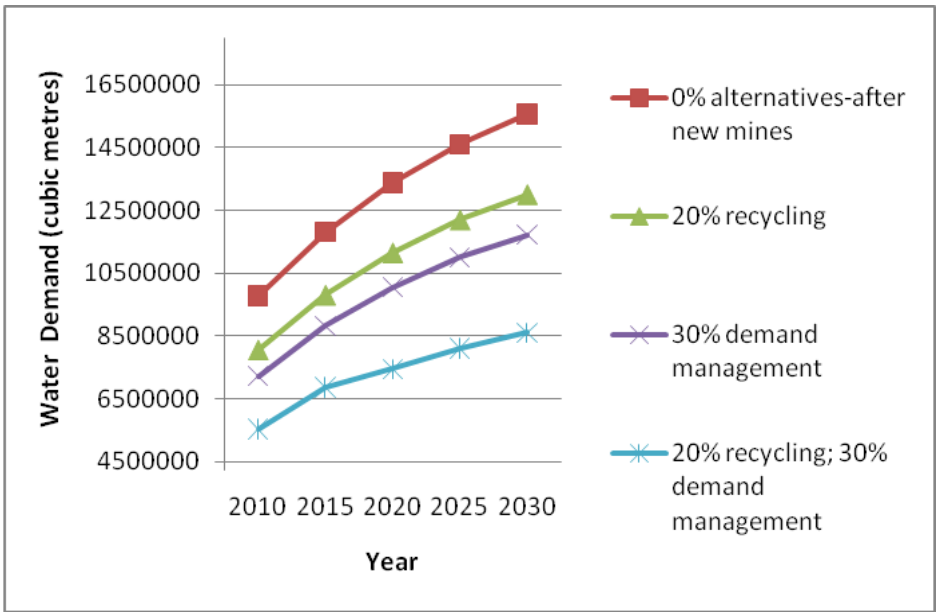

Figure 4.9 Effect of new mines on total coastal demand from coastal towns

4.7 Mining Sector

This sub-section presents the projections for water demand by both existing and potential mines. Firstly, **Figure 4.10** showed the water demand projections from existing mines alone. Only one of the existing mines is known to recycle water and this recycling is included in the projections in **Figure 4.10**. Simulations showed that total water demand from existing mines is expected to be 11 080 330 m^3/year for 2010 and up to 23 316 477 m^3/year by 2030, an increase of 110.4% over the period of 20 years. This is the trend of consumption that would be expected if no new mines are commissioned.

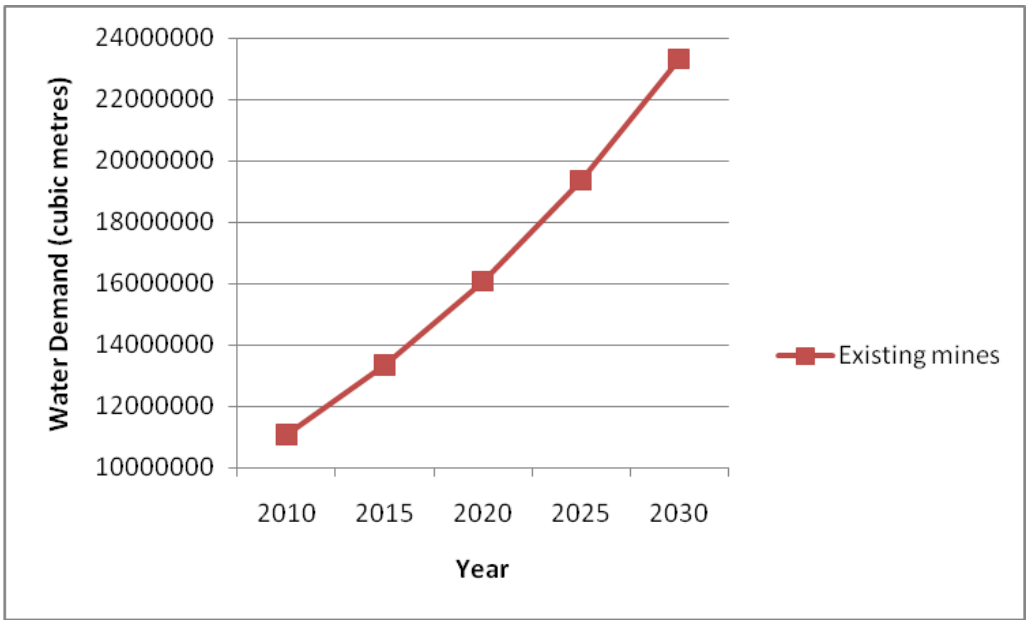

Figure 4.10 Total water demand by existing mines

Another simulation, which is presented in **Figure 4.11**, showed the projections for total water demand from both existing and potential new mines over the simulation period. This is presented under two scenarios, one where water demand estimations for existing mines are summed up with the estimations for new mines, and the second scenario where recycling is factored in on the total consumption of all the mines (new and existing).

The first scenario showed that a total of 12 379 464 m^3/year is expected to be consumed by all the mines by the end of 2010, and a total of 408 414 742 m^3/year by 2030. However, if, all the mines implemented 60% (60% of total water demand is supplied from recycling) recycling of wastewater, total demand would be reduced from 12 379 464 m^3/year to 7 039 320 m^3/year in 2010, and from 408 414 742 m^3/year to 167 758 721 m^3/year by 2030, marking a percentage decrease of 58.9%. A full set of projections used in **Figures 4.10** and **figure 4.11** for the simulation period are available in **Appendix 13**.

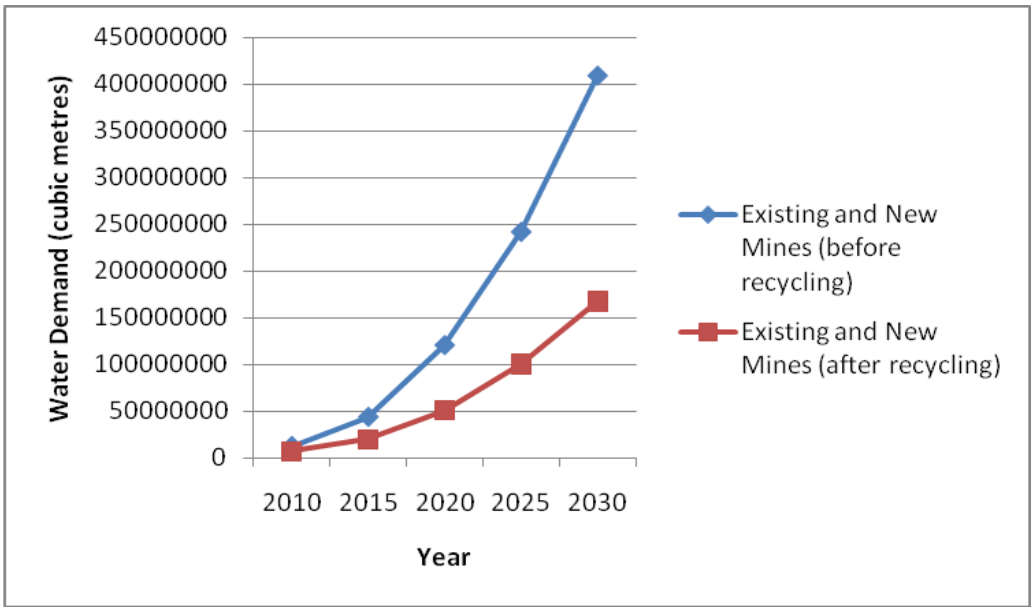

Figure 4.11 Water demand for new and existing mines before and after recycling

4.8 Total Demand

The total water demand for the Erongo coastal region (study area) in comparison to the available water supply is presented in **Figure 4.12**. This figure shows total water demand for all users in the study area (four towns, existing and new mines and other users). Projections are presented under two scenarios. The first scenario projected water demand under current growth and consumption rates, without recycling or demand management measures.

This scenario projected water demand for the study area to be 22 672 480 m^3/year in 2010 and 424 488 071 m^3/year by 2030. The second scenario showed water demand to be 13 061 163 m^3/year for 2010 and 176 468 120 m^3/year by 2030. The current total available supply for the coastal area of the Erongo Region stands at 16 200 000 m^3/year (safe yield) from the aquifers. This is shown as a constant line (*Total available supply*) in **Figure 4.12**. It is evident from **Figure 4.12** that demand will exceed supply by the year 2012, under the second scenario, where demand management and recycling are implemented. However, without any

demand management or recycling, demand will exceed supply already by 2010. Full set of the data used for **Figure 4.12** are available in **Appendix 13**.

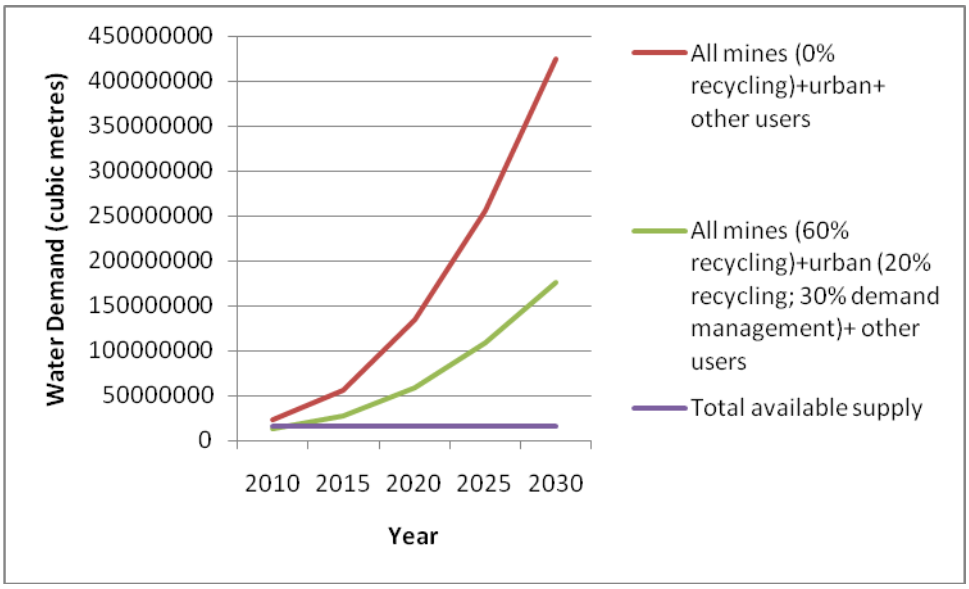

Figure 4.12 Total water demand versus total available supply

4.9 Alternative water sources

Since demand is already poised to exceed supply by the year 2010 or 2012 depending on the two scenarios in **Figure 4.13**, it is important to explore feasible alternative water sources which will be able to close up the difference in demand and supply. This sub-section explores two potential alternative water sources, namely desalination and fog water harvesting. Firstly before exploring the potential for the above-mentioned alternative source of freshwater, it is imperative to determine how much water would be required from these alternatives. Two scenarios are explored for calculating these estimations.

The first scenario (**Figure 4.13**) shows the amount of additional water required to meet demand, if current consumption and growth rates are maintained, combined with recyling or demand management measures by the users. The amount of water

required from alternatives in this scenario is shown in **Figure 4.13** as *Alternatives required1*. This amount of additional water required from alteratives is calculated as the difference between total demand and total available supply. As mentioned under sections **3.8** (Total Demand), total available freshwater is constant at 16 200 000 m^3/year, and this is clearly shown in **Figure 4.13**. The water required from alternatives was shown to be increasing at a rapid rate, following a similar trend as that followed by total water demand. An additional 6 472 480 m^3/year of water will be required to meet water demand in the year 2010, and 408 288 071 m^3/year by 2030.

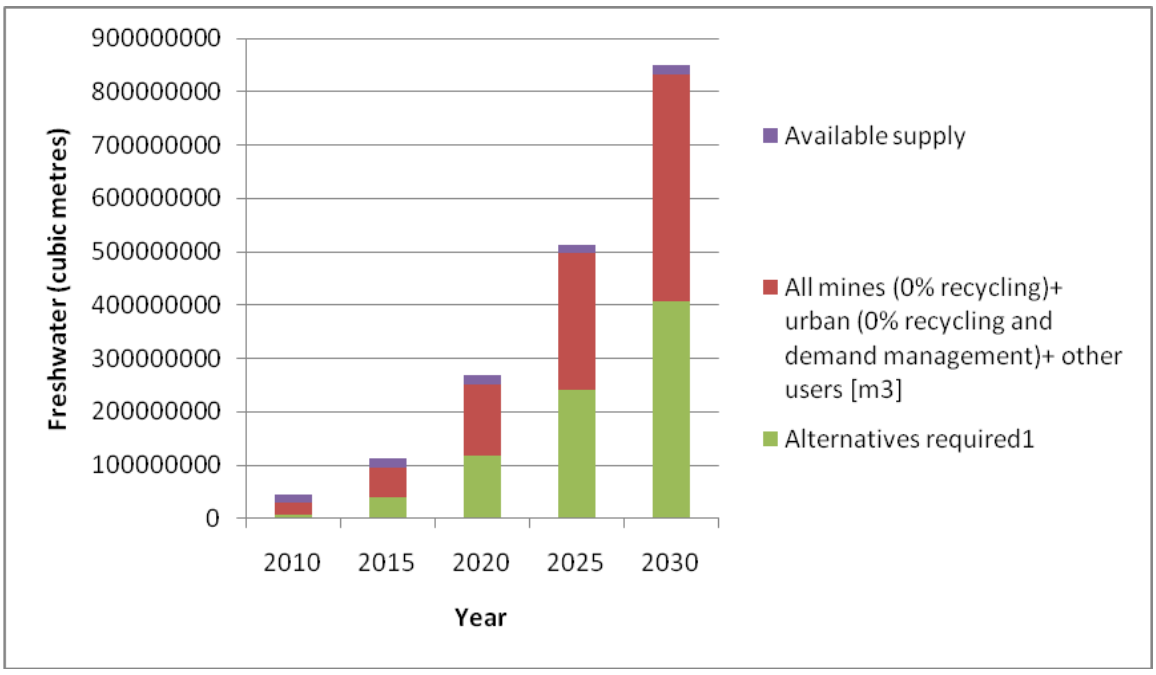

Figure 4.13 Water required from alternative water sources

The introduction of alternative and management strategies such as recycling and demand management was shown to delay demand from exceeding supply for only the first two years of the simulation period. As shown in **Figure 4.14**, in 2010 there is still a surplus in water supply of 3 138 837 m^3/year but only until 2012. It is for this reason that in 2010, the bar representing water required from alternatives in this scenario (*Alternatives required2*) still falls in the negative axis. In 2015, a total of 10 667 125 m^3/year is required from alternative sources in order

to meet demand. This represents a reduction in demand of 73% from a total of 39 618 308 m^3/year required under the first scenario (**Figure 4.13**) in the same period. The amount required from alternatives by the year 2030 in the second scenario stands at 160 268 120 m^3/year. This is 60.7% less than what would be required at the same time under the first scenario (**Figure 4.13**). Detailed equations used to produce **Figures 4.13 and 4.14** are available in **Appendix 15**.

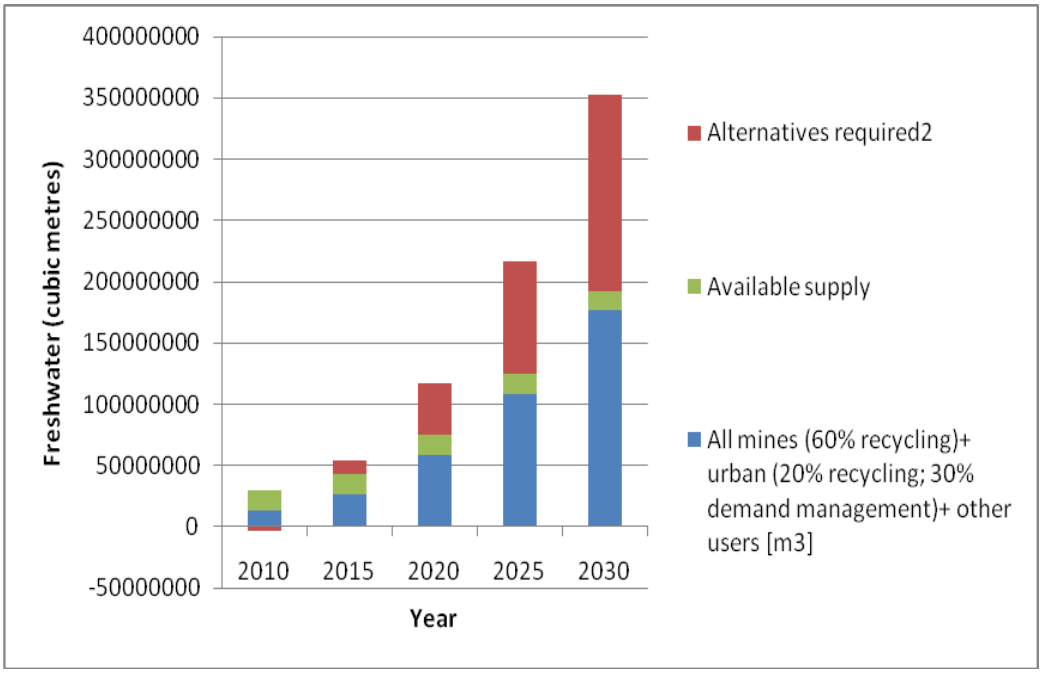

Figure 4.14 Alternative water sources for the Erongo coastal area

4.10 Fog harvesting-an alternative water source

In addition to sea water desalination, recycling and water management measures in the study; fog harvesting was explored as an alternative source (unconventional) of freshwater aimed at supplementing available supply. Estimates of the potential fog yields used in this study are combined from previous research which was carried out in along the Namibian coast.

The analysis is carried out under various scenarios and combinations revolving around the number of FCD (Fog Collector Devices), the annual number of fog days (number of days when fog occurs), and elevation –metres above mean sea level (amsl) and distance from sea. The lowest annual number of fog days in this study was 60 whilst the most number of days on which fog occurred was taken to be 200 days per year. This is the range of observed fog occurring days. The lowest number of FCDs was 20 FCDs and the most was 150 FCDs. Two different combinations of elevation and distance from sea were used. The first one was 408 m amsl and 56 km inland. The second combination was 352 m amsl and 46 km inland.

At the first elevation and distance from sea (408 m amsl and 56 km inland) the fog harvesting yields are presented in **Table 4.1**. The number of FCDs is varied from 20-150 FCDs; each FCD was taken to be 100 m^2. The amount of water collected using 20 FCDs is 60.95 m^3/year when there were 60 days of fog occurrence. With an increase in the number of FCDs, the amount of water collected from fog increased to 152.4 m^3/year with 50 FCDs and a yield of 457.2 m^3/year from 150 FCDs, still at 60 days of fog occurrence. With 200 days of fog occurrence, the yields are as follows: 203.2 m^3/year from 20 FCDs; 508 m^3/year with 50 FCDs; 1016 m^3/year from 100 FCDs and 1 542 m^3/year when using 150 FCDs. Estimates of potential fog harvestable used for this study are taken from results achieved in previous studies carried out in the area. These studies have already been highlighted in the literature review chapter (chapter two). They are 1) Henschel *et al* (1998); 2) Kimura (2005); 3) Schemenauer (1998) and; 4) Shanyengana *et al* (2002).

Table 4.1 Fog yields from 100 m2 at elevation 1

Annual Fog days	20 LCD yields (m^3/year)	50 LCD yields (m^3/year)	100 LCD yields (m^3/year)	150 LCD yields (m^3/year)
60	60.95	152.4	304.8	457.2
100	101.6	254	508	762
200	203.2	508	1016	1524

The amount of fog harvesting yields are compared (by percentage) to the total coastal freshwater deficit (difference between total available supply and expected demand). This is done in order to determine the potential contribution of fog harvesting on the amount of water required from alternative water sources.

The contribution from fog harvesting to the total amount of freshwater required from alternative sources is presented in **Table 4.2**, where the percentage contributions of fog harvesting over the simulation period at elevation 1 with 20 and 150 FCDs,for 60 and 200 days of fog occurrence are summarised. With the deficit in water supply for the year 2010 set to be 6 472 480 m^3/year, given 60 days of fog occurrence and 20 FCDs at elevation 1, water from fog harvesting seem to have minimal influence on the overall demand-providing only 0.0009% of total deficit. This percentage decreases over the simulation period and stood at 0.00001% at the end of 2030. For 200 days of fog occurrence, the contribution from fog harvesting with 20 FCDs increased from 0.0009% at 60 days to 0.0031% in the 2010 and from 0.00001% to 0.00009%.

The following analysis, also in **Table 4.2**, looks at the annual fog harvesting yields for 150 FCDs. At 60 days of fog occurrence, the yields of freshwater from fog harvesting can only make up for 0.0007% of the total 2010 deficit (6 472 480 m^3/year) and only about 0.0001% of the 408 288 071 m^3/year. A much higher percentage is achieved, however, when the number of fog days increased from 60

days to 200 days. The analysis showed that fog yields contributed 0.023% of total amount of freshwater required from alternative sources in 2010 and 0.0003% in 2030. Although this percentage contribution seems minimal, it can provide nearly half of freshwater demand in Arandis (the smallest of the four towns under review) for the year 2010, and is more than double the amount required from *other users* in the study area.

Table 4.2 Percentage contribution of fog water at elevation 1 to alternatives

Year	Alternatives required1	Elevation 1: 20 FCDs;60 days	Elevation 1: 20 FCDs;200 days	Elevation 1: 150 FCDs;60 days	Elevation 1: 150 FCDs;200 days
2010	6472480	0.000942	0.003139	0.00706	0.023546
2015	39618308	0.000154	0.000513	0.00115	0.003847
2020	117890738	5.17E-05	0.000172	0.00039	0.001293
2025	240277072	2.54E-05	8.46E-05	0.00019	0.000634
2030	408288071	1.49E-05	4.98E-05	0.00011	0.000373

The amount of fog harvestable at elevation 2 (352 amsl and 46 km inland) are summarized in **Table 4.3**. The data used to calculate these yields estimates were obtained from the studies cited earlier. It is shown that the minimum amount of fog yields are those from a combination of 60 days of fog occurrence and 20 FCDs-producing an amount of 406.6 m^3/year. As the number of FCDs is increased to 150 whilst the number of days remained at 60 days, the yield increased from 406.6 m^3/year to 3 042 m^3/year-an increase of 648%. Much higher yields are obtained from 200 days of fog occurrence. With 200 FCDs a total of 1323.2 m^3/year (in 2010) is obtainable at elevation 2 whilst 9 999 m^3/year is obtainable with 150 FCDs for 200 fog days.

Table 4.3 Fog yields from 100 m2 at elevation 2

Annual Fog days	20 FCD yields (m^3/year)	50 FCD yields (m^3/year)	100 FCD yields (m^3/year)	150 FCD yields (m^3/year)
60	406.6	1014	2028	3042
100	661.6	1654	3308	4962
200	1323.2	3308	6616	9924

Table 4.4 presents percentage contributions of freshwater by fog harvesting at elevation 2. The projections for overall water demand in the study area determined that demand could exceed supply by 6 472 480 m3/year by 2010, with this figure increasing to 408 288 071 m^3/year by 2030. As indicated in **Table 4.4,** fog harvesting would be able to supply 0.006% of the required 6 472 480 m^3/year in 2010. This amount was made possible with the use of 20 FCDs during 60 days of fog occurrence. With changes in the number of fog days and the number of FCDs the rest of contributions of freshwater from fog harvesting were as follows: 0.02% from 200 days of fog occurrence using 20 FCDs, 0.046% from 60 days of fog occurrence with 150 FCDs and 0.153% with 150 FCDs from 200 days of fog occurrence. With an ever increasing amount of water required from alternatives overtime, 150 FCDs and 200 days of fog occurrence could only supply 0.002% of the water additional supply required in 2030.

Table 4.4 Fog yields from 100 m2 at elevation 2

Year	Alternatives required1	Elevation 2: 20 FCDs;60 days	Elevation 2: 20 FCDs;200 days	Elevation 2: 150 FCDs;60 days	Elevation 2: 150 FCDs;200 days
2010	6472480	0.0062665	0.02044348	0.04699899	0.153326082
2015	39618308	0.0010238	0.00333987	0.00767827	0.025049025
2020	117890738	0.000344	0.0011224	0.00258036	0.008417964
2025	240277072	0.0001688	0.0005507	0.00126604	0.004130232
2030	408288071	9.934E-05	0.00032408	0.00074506	0.002430637

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

"*When you drink the water, remember the spring"*-Chinese proverb

5.1 Conclusions

This research was aimed at quantifying the amount of water needs in central coast of the Erongo region and at comparing the demand to current available supply. The main interest developed due to prospects of new uranium mines coming in, which were expected and have been found to be accompanied by great demand for freshwater.

Water demand for Walvis Bay, is presented under various scenarios in Tables 5.2 and 5.2. As Table 5.1 reflects, at current growth and consumption rates, demand is expected to be 4 946 742 m^3/year in 2010 and to be 6 820 264 m^3/year by 2030, marking an increase of 37.8%. If 20% of all residential water use is recycled, however, total demand would be 4 146 359 m^3/year in 2010 and 5 176 745 m^3/year in 2030. Demand management measures alone if effective at reducing 30% of demand, the consumption is expected to be 3 746 168 m^3/year in 2010 and 5 164 986 m^3/year in 2030. A combination of 20% recycling of wastewater and 30% reduction from water demand management measures reduces to a mere 2 945 785 m^3/year in 2010 and 4 061 467 m^3/year in 2030.

Table 5.1 Walvis Bay water demand before new mines

Year	0% alternatives (m^3)	20% recycling (m^3)	30% demand management (m^3)	20% recycling; 30% demand management (m^3)
2010	4946742	4146359	3746168	2945785
2015	5628116	4717487	4262174	3351543
2020	6141620	5147906	4651049	3657335
2025	6528614	5472284	4944119	3887789
2030	6820264	5716745	5164986	4061467

Table 5.2 indicates the effect of new mining activities on water demand. New mines increased the demand for 2010 (scenario one) from the expected 4 946 742 m^3/year to 4 958 731 m^3/year, and from 6 820 264 m^3/year to approximately 6 965 582 m^3/year in 2030.

Table 5.2 Walvis Bay water demand after new mines

Year	0% alternatives (m^3)	20% recycling (m^3)	30% demand management (m^3)	20% recycling; 30% demand management (m^3)
2010	4958731	4158348	3758156	2957773
2015	5690081	4779452	4324138	3413508
2020	4240264	5246550	4749693	3755979
2025	6654176	5597846	5069681	4013352
2030	6965582	5862063	5310304	4206785

Current and future water demand for Swakopmund is reflected in Tables 5.3 and 5.4. As indicated in Table 5.3, water demand in Swakopmund, at current growth and consumption rates, is expected to be 3 534 642 m^3/year in 2010 and to be 5 227 096 m^3/year by 2030, marking an increase of 47.8%. If 20% of all residential water use is recycled, however, total demand would be 2 863 060 m^3/year in 2010 and 4 233 948 m^3/year in 2030. Demand management measures alone if effective at reducing 30% of demand, the consumption is expected to be 2 527 269 m^3/year in 2010 and 3 737 373 m^3/year in 2030. A combination of 20% recycling of

wastewater and 30% reduction from water demand management measures reduces to a mere 1 855 687 m^3/year in 2010 and 2 744 225 m^3/year in 2030.

Table 5.3 Swakopmund water demand before new mines

Year	0% alternatives (m^3)	20% recycling (m^3)	30% demand managemen (m^3)	20% recycling; 30% demand management (m^3)
2010	3534642	2863060	2527269	1855687
2015	4094632	3316652	2927662	2149682
2020	4551233	3686499	3254132	2389397
2025	4923533	3988061	3520326	2584855
2030	5227096	4233948	3737373	2744225

The effect on new mines on water demand for Swakopmund is shown in Table 5.4. New mining activities increased the demand for 2010 (scenario one) from the expected 3 534 642 m^3/year (Table 5.3), to 3 597 581 m^3/year and from 5 227 096 m^3/year to 5 990 016 m^3/year in 2030.

Table 5.4 Swakopmund water demand after new mines

Year	0% alternatives (m^3)	20% recycling (m^3)	30% demand management (m^3)	20% recycling; 30% demand management (m^3)
2010	3597581	2925999	2590208	1855687
2015	4419951	3641971	3252981	2389397
2020	5069114	4204380	3772013	2389397
2025	5582736	4647264	4179529	2584855
2030	5990016	4996867	4500293	2744225

Water demand in Arandis, under various management scenarios, is presented in Tables 5.5 and 5.6. At current growth and consumption rates, water demand is expected to be 340 778 m^3/year in 2010 and to be 544 725 m^3/year by 2030, marking an increase of 59.8%. If 20% of all residential water use is recycled, however, total demand would be 281 221 m^3/year in 2010 and 437 959 m^3/year in

2030. Demand management measures alone if effective at reducing 30% of demand, the consumption is expected to be 246 943 m^3/year in 2010 and 384 576 m^3/year in 2030. A combination of 20% recycling of wastewater and 30% reduction from water demand management measures reduces to a mere 178 387 m^3/year in 2010 and 277 810 m^3/year in 2030.

Table 5.5 Arandis water demand before new mines

Year	**0% alternatives** (m^3)	**20% recycling** (m^3)	**30% demand management** (m^3)	**20% recycling; 30% demand management** (m^3)
2010	340778	281221	246943	178387
2015	406128	326527	286726	207125
2020	457064	367479	322687	233103
2025	503106	404497	355193	256584
2030	544725	437959	384576	277810

The effect of new mining on water demand for Arandis is reflected in Table 5.6. New mining activities increased the demand for 2010 (scenario one) from the expected 340 778 m^3/year to 371 742 m^3/year, and from 544 725 m^3/year to approximately 810 975 m^3/year in 2030.

Table 5.6 Arandis water demand after new mines

Year	**0% alternatives** (m^3)	**20% recycling** (m^3)	**30% demand management** (m^3)	**20% recycling; 30% demand management** (m^3)
2010	371742	303186	268908	200351
2015	519660	440059	400259	320658
2020	637798	548214	503422	413837
2025	733160	634551	585247	486638
2030	810975	704209	650826	544060

Water demand in Henties Bay, at current growth and consumption rates, is presented in Table 5.7. Water demand, is expected to be 849 941 m^3/year in 2010

and to be 1 791 735 m^3/year by 2030, marking an increase of 110.8%. If 20% of all residential water use is recycled, however, total demand would be 688 452 m^3/year in 2010 and 1 451 305 m^3/year in 2030. Demand management measures alone if effective at reducing 30% of demand, the consumption is expected to be 607 708 m^3/year in 2010 and 1 261 286 m^3/year in 2030. A combination of 20% recycling of wastewater and 30% reduction from water demand management measures reduces to a mere 526 963 m^3/year in 2010 and 1 110 876 m^3/year in 2030. Henties Bay is not expected to be affected by the new mines, and thus no water demand projections have been carried out.

Table 5.7 Henties Bay water demand

Year	0% alternatives (m^3)	20% recycling (m^3)	30% demand management (m^3)	20% recycling; 30% demand management (m^3)
2010	849941	688452	607708	526963
2015	1182049	957459	845165	732870
2020	1439027	1165612	1028905	892197
2025	1637872	1326677	1171079	1015481
2030	1791735	1451305	1261286	1110876

Projections for water demand from existing and future mining activities is presented in Table 5.8. Also, Table 5.8 shows the effect of mining activities on total water demand for the coastal area. The mining sector is projected to continue its influence on water demand in the region, with existing mines expected to consume 11 080 330 m^3/year in 2010, and up to 23 316 477 m^3/year by 2030. With the introduction of new mines, demand is expected to be 12 379 464 m^3/year by 2010 and 408 414 742 m^3/year in 2030. These estimates are based on the assumptions that water consumption rates and trends will follow those of the currently established mines. These figures are also true if the new mines do not implement recycling. Instead of 12 379 464 m^3/year in 2010, recycling by new mines would reduce demand to 7 039 320 m^3/year, whilst demand would move

down from 408 414 742 m^3/year in 2030 to a 176 758 721 m^3/year. These figures highlight the potential for recycling in reducing demand.

Table 5.8 Mining effect on total coastal water demand

Year	Existing mines (m^3)	Existing and New Mines (before recycling) (m^3)	Existing and New Mines (after recycling) (m^3)
2010	11080330	12379464	7039320
2015	13345359	43491546	19910884
2020	16073402	120189514	51104034
2025	19359109	241354107	100188899
2030	23316477	408414742	167758721

The overall water demand for the region will clearly outstrip supply. This conclusion is shown in Table 5.9 .With an overall supply of 16 200 000 m^3/year, demand for the whole study area is projected to be 22 672 480 m3/year in 2010, creating a water deficit of 6 472 480 m^3/year (under the scenario of no recycling or water management strategies from neither the mines nor the municipalities). Total demand for the study area is set to be 424 488 071 m^3/year by 2030. However, with recycling, by both mines and municipalities, and with the reduction in municipalities due to management strategies, total demand could be reduced to 13 061 163 m3/year, leading to a surplus of 3 138 837 m3/year in 2010. This surplus will all be consumed in the following two year, when demand will equal supply around 2012.

Table 5.9 Effect of management measures on coastal water demand

Year	0% alternatives-after new mines (m^3)	Existing and New Mines (before recycling) (m^3)	Existing and New Mines (after recycling) (m^3)	20% recycling; 30% demand management (m^3)	Other users (m^3)	New and existing mines 0% recycling+urban 0% alternative+other users (m^3)	New and existing mines 60% recycling+ urban 20% recyling; 30% demand management+ other users (m^3)
2010	9777995	12379464	7039320	5506822	515021	22672480	13061163
2015	11811741	43491546	19910884	6441220	515021	55818308	26867125
2020	13386203	120189514	51104034	7172032	515021	134090738	58791087
2025	14607944	241354107	100188899	7744709	515021	256477072	108448629
2030	15558308	408414742	167758721	8194378	515021	424488071	176468120

The study reveals that water demand will exceed supply by the year 2010, at current consumption and growth rates, if no management interventions are implemented or if implemented demand will exceed supply by the end of 2012. However, seeing how close 2010 is, it is unlikely that all management interventions will be implemented before this time. For example, for a town to successfully implement recycling there is a need to set up the right infrastructure (such as recycling plant) which requires some time. Equally, for demand management measures, such as public awareness, it also requires longer intervention period before the results reflect in the demand for water.

Artificial recharge, although a good option in some areas, was found to be almost impossible in the study area because of low rainfall. Regarding the amount of destruction (physical and biological) which would be caused by the mining activities and the construction of desalination plants (and consequence transfer of water to the users), it is assumed that this consequences have been taken care of in the Environmental Impact Assessment studies which have been carried out.

The expected deficits in water supply, therefore, can only be obtained from alternative water sources, such as desalination and fog harvesting. Fog harvesting

was found to be a viable source of freshwater on a small scale. The calculated yields at an elevation of 408 m amsl and at 56 km inland ranged from 60.95 m^3/year (60 days of fog occurrence) to 1 524 m^3/year (200 days of fog occurrence). At an elevation of 325 m and 46 km inland, fog yields ranged from 406.6 m^3/year to 9 924 m^3/year, dependent on the number of fog days as well as the number FCDs.

These yields, although low in percentage contribution to total water required, could be of significant importance especially for small-scale users. The highest contribution to water deficit from yields at elevation 408 m amsl was 0.02%, and 0.15%, both for 2010. It is, therefore, important to consider fog harvesting as a good source for water supply to especially rural areas. Fog water could also be used for artificial recharge. Due high temperatures in the region, artificial recharge would prevent this water from evaporating. Fog water could also be used for diluting semi-desalinated sea water, thereby saving energy.

With fog harvesting only having the potential to provide less than 2% of this deficit, the rest would need to be supplied from sea water desalination. Although there are plans of sourcing excess water from the desalination plant which was recently commissioned (Hartman, 2009), this excess supply will still fall short of total demand because the total demand from urban and existing mines is already expected to be 20 752 433 m^3/year by 2010. This will call for a much more robust desalination plant with an adjustable capacity to cater for the necessary increases when necessary. In 2010, a total of 6 472 480 m^3/year would be required from alternatives, and 408 288 071 m^3/year by 2030. Since fog harvesting can only provide up to 2% of required alternatives, the remaining supply (approximately 98%) will need to come from desalination.

5.2 Recommendations

The following recommendations can be drawn from the conclusions of this study.

1. The use of a modular desalination plant which allows for additions and reductions in capacity. This would be important for saving not only water but the resource required in desalinating sea water.
2. Wastewater (recycled) and fog water could be used for artificial recharge.
3. Future studies could explore the risk of radioactivity ending up in drinking water should recycling be implemented.
4. Future studies could also explore the water needs associated with enrichment facilities (nuclear power generation).
5. It would be important to establish the sustainability of informal settlements, their impacts on the environment and on human health.

CHAPTER SIX

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CHAPTER SEVEN

APPENDICES

"Water is a very good servant, but it is a cruel master" C.G.D Roberts

Appendix 1: WALVIS BAY (WB) EQUATIONS

Number_of__WB_houses(t) = Number_of__WB_houses(t - dt) + (new_house__per_year_in_WB) * dt

INIT Number_of__WB_houses = 10549 {houses}

INFLOWS:

new_house__per_year_in_WB = rate_of_WB_increase*difference_WB {houses}

difference_WB = target_number__of_houses_IN_WB-Number_of__WB_houses {houses}

industrial__consumption_WB = (total_residential__consumption_WB*percentage_indu_consp_WB)/percentage_house_consp_WB {m^3/year}

mines'_driven_demand_in_WB = WB_employees_in_new_mines*WB_per_water_capita_consumption {m^3/year}

percentage_house_consp_WB = 0.809 {1/100}

percentage_indu_consp_WB = 0.191 {1/100}

percentange_management_strategies_in_WB = 0.30 {m^3/year}

perc_employees__WB = 0.12 {1/100}
per_house__consumption_of_water_in_WB = 367.02 {m^3/year}

rate_of_WB_increase = 0.055 {1/year}

target_number__of_houses_IN_WB = 17000 {houses}

total_recylce_WB =
percentage__recycled_WB*total_residential__consumption_WB {m^3/year}

total_residential__consumption_WB =
Number_of__WB_houses*per_house__consumption_of_water_in_WB
{m3/year}

total_WB_consumption =
(industrial__consumption_WB+mines'_driven_demand_in_WB+total_residential__consumption_WB)-
(total_recylce_WB+water_management__strategies_of_WB) {m^3/year}

water_management__strategies_of_WB =
percentange_management_strategies_in_WB*total_residential__consumption_WB {m3/year}

WB_per_water_capita_consumption = 64.04 {m^3/year}

Appendix 2: SWAKOPUMD (Swkp) EQUATIONS

Number_of__Swkp_houses(t) = Number_of__Swkp_houses(t - dt) +
(new_house__per_year_in_Swkp) * dt

INIT Number_of__Swkp_houses = 8822 {houses}

INFLOWS:

new_house__per_year_in_Swkp = difference_swkp*rate_of_Swkp_increase {houses/year}

difference_swkp = target_number__of_houses_in_swkp-Number_of__Swkp_houses {houses}

industrial__consumption_swkp = (total_residential__consumption_Swkp*percentage_industrial__consumption_Swkp)/percentage_residential_consumption {m3/year}

mines'_driven_demand_in_Swkp = Swakp_employees__in_new_mines*Swakp_per_capita_consumption {m3/year}

percentage_industrial__consumption_Swkp = 0.05 {1/100}

percentage_recycled__Swkp = 0 {1/100}

percentage_residential_consumption = 0.95 {1/100}

percentange_management_strategies_Swkp = 0 {1/100}

per_house_consumption_Swkp = 367.02 {m3/year}

rate_of_Swkp_increase = 0.04 {1/100}

Swakp_per_capita_consumption = 64.04 {m^3/year}

target_number__of_houses_in_swkp = 17000 {houses}

total_recylce_Swkp = percentage_recycled__Swkp*total_residential__consumption_Swkp {m^3/year}

total_residential__consumption_Swkp = Number_of__Swkp_houses*per_house_consumption_Swkp {m^3/year}

total_swkp_consumption = (industrial__consumption_swkp+mines'_driven_demand_in_Swkp+total_residential__consumption_Swkp)-(water_management__strategies_of_Swkp+total_recylce_Swkp) {m^3/year}

water_management__strategies_of_Swkp = percentange_management_strategies_Swkp*total_residential__consumption_Swkp {m^3/year}

Appendix 3: ARANDIS EQUATIONS

Number_of__Arnd_houses(t) = Number_of__Arnd_houses(t - dt) + (new_houses__per_year_in_Arnd) * dt

INIT Number_of__Arnd_houses = 1300 {houses}

INFLOWS:

new_houses__per_year_in_Arnd = difference_Arnd*rate_of_Arnd_increase {houses}

Arnd_employees__in_new_mines = 0 {1/100}

Arnd_per_capita_consumption = 64.04 {m^3/year}

difference_Arnd = target_number__of_houses_in_Arnd-Number_of__Arnd_houses {houses}

industrial__consumption_Arnd =
(total_residential__consumption_arnd*percentage_industry__cosmptn)/percentage_residential_consumption_Arnd {m^3/year}

mines'_driven_demand_in_Arnd =
Arnd_employees__in_new_mines*Arnd_per_capita_consumption {m^3/year}

percentage_industry__cosmptn = 0.02 {1/100}

percentage_recycled_Arnd = 0.2 {1/100}

percentage_residential_consumption_Arnd = 0.98 {1/100}

percentange_management_strategies_Arnd = 0 {m^3/year}

perc_Arnd_employess__in_mines = 0 {1/100}

per_household__consumption_of_water_Arnd = 321 {m^3/year}

rate_of_Arnd_increase = 0.02 {1/year}

target_number__of_houses_in_Arnd = 4000 {houses}

total_Arnd_consumption =
(industrial__consumption_Arnd+total_residential__consumption_arnd+mines'_driven_demand_in_Arnd)-
(water_management__strategies_of_Arnd+total_recylce__Arnd) {m^3/year}

total_recylce__Arnd =
percentage_recycled_Arnd*total_residential__consumption_arnd {m^3/year}

total_residential__consumption_arnd = Number_of__Arnd_houses*per_household__consumption_of_water_Arnd {m^3/year}

water_management__strategies_of_Arnd = percentange_management_strategies_Arnd*total_residential__consumption_arnd {m^3/year}

Appendix 4: HENTIES BAY EQUATIONS

Number_of__HB_houses(t) = Number_of__HB_houses(t - dt) + (new_house__per_year_in_HB) * dt

INIT Number_of__HB_houses = 2020 {houses}

INFLOWS:
new_house__per_year_in_HB = difference_HB*rate_of_HB_increase {houses}

difference_HB = target_houses_in_HB-Number_of__HB_houses {houses}

industrial__consumption_HB = (total_residential__consumption_HB*percentage_industry__cosmptn_in_HB)/percentage_residential_consump_in_HB {m3/year}

percentage_industry__cosmptn_in_HB = 0.05 {1/100}

percentage_recycled_HB = 0.20 {1/100}

percentage_residential_consump_in_HB = 0.95 {1/100}

percentange_management_strategies_in_HB = 0 {1/100}

per_household__consumption_of_water_HB = 192.55 {m^3/year}

rate_of_HB_increase = 0.03 {1/year}

target_houses_in_HB = 4000 {houses}

total_HB_consumption =
(industrial__consumption_HB+total_residential__consumption_HB)-
(water_management__strategies_of_in_HB+total_recylce_HB) {m^3/year}

total_recylce_HB =
percentage_recycled_HB*total_residential__consumption_HB {m^3/year}

total_residential__consumption_HB =
Number_of__HB_houses*per_household__consumption_of_water_HB {m^3/year}

water_management__strategies_of_in_HB =
percentange_management_strategies_in_HB*total_residential__consumption_HB
{m^3/year}

Appendix 5: MINING SECTORE EQUATIONS

number_of_new_mines(t) = number_of_new_mines(t - dt) +
(new_mines_per_year) * dt

INIT number_of_new_mines = 0 {mines}

INFLOWS:
new_mines_per_year = difference_in_new_mines*growth_rate {mines/year}

tonnes_produced_by_existing_mines(t) =
tonnes_produced_by_existing_mines(t - dt) +
(additional_tonnes_per_year_by_Rossing) * dt

INIT tonnes_produced_by_existing_mines = 13087 {tonnes}

INFLOWS:
additional_tonnes_per_year_by_Rossing =
tonnes_produced_by_existing_mines*rate_of_expansion_existing_mines
{tonnes/year}

tonnes_produced__by_newmines(t) = tonnes_produced__by_newmines(t - dt) +
(additional__tonnes) * dt

INIT tonnes_produced__by_newmines = 4000 {tonnes}

INFLOWS:
additional__tonnes =
(number_of_new_mines*tonnes_per_new_mine)+(tonnes_produced__by_newmi
nes*rate_of_expansion_new_mines) {tonnes/year}

difference_in_new_mines = target_mines-number_of_new_mines {mines}

exisitng_mines__water__consumption =
tonnes_produced_by_existing_mines*water_use_per_tonne_uranium__produced
{m^3/year}

growth_rate = 0.06 {1/100}

percentage_of_rossing_tonnes = 0.314 {1/100}

percentage_recycling__by_mines = 0.6 {1/100}

percentage__recycle = 0.6 {1/100}

rate_of_expansion_existing_mines = 0.0379 {1/year}

rate_of_expansion_new_mines = 0.0379 {1/year}

recycling__by_mines = percentage_recycling__by_mines*TOTAL_WATER_DEMAND__BY_MINES {m^3/year}

rossing_recycled__water = percentage__recycle*rossing_water_use {m^3/year}

rossing_water_use = tonnes_produced__by_rossing*water_use_per_tonne_uranium__produced {m^3/year}

target_mines = 20 {mines}

tonnes_per_new_mine = 2000 {tonnes}

tonnes_produced__by_rossing = tonnes_produced_by_existing_mines*percentage_of_rossing_tonnes {tonnes/year}

TOTAL_DEMAND_BY_MINES_AFTER_RECYLING = TOTAL_WATER_DEMAND__BY_MINES-total_recycling_by_all_mines {m^3/year}

total_recycling_by_all_mines = recycling__by_mines-rossing_recycled__water {m^3/year}

TOTAL_WATER_DEMAND__BY_MINES =
(exisitng_mines__water__consumption+water_consumed_by__new_mines)-
rossing_recycled__water {m^3/year}

water_consumed_by__new_mines =
tonnes_produced__by_newmines*water_use_per_tonne_uranium__produced
{m^3/year}

water_use_per_tonne_uranium__produced = 815.75 {m^3/tonne}

Appendix 6: COMPLETE MODEL EQUATIONS

number_of_new_mines(t) = number_of_new_mines(t - dt) +
(new_mines_per_year) * dt

INIT number_of_new_mines = 0 {mines}

INFLOWS:
new_mines_per_year = difference_in_new_mines*growth_rate {mines/year}

tonnes_produced_by_existing_mines(t) =
tonnes_produced_by_existing_mines(t - dt) +
(additional_tonnes_per_year_by_Rossing) * dt

INIT tonnes_produced_by_existing_mines = 13087 {tonnes}

INFLOWS:
additional_tonnes_per_year_by_Rossing =
tonnes_produced_by_existing_mines*rate_of_expansion_existing_mines
{tonnes/year}

tonnes_produced__by_newmines(t) = tonnes_produced__by_newmines(t - dt) + (additional__tonnes) * dt

INIT tonnes_produced__by_newmines = 4000 {tonnes}

INFLOWS:

additional__tonnes = (number_of_new_mines*tonnes_per_new_mine)+(tonnes_produced__by_newmines*rate_of_expansion_new_mines) {tonnes/year}

difference_in_new_mines = target_mines-number_of_new_mines {mines}

exisitng_mines__water__consumption = tonnes_produced_by_existing_mines*water_use_per_tonne_uranium__produced {m^3/year

growth_rate = 0.06 {1/100}

percentage_recycling__by_mines = 0.6 {1/100}

percentage__recycle = 0.6 {1/100}

rate_of_expansion_existing_mines = 0.0379 {1/year}

rate_of_expansion_new_mines = 0.0379 {1/year}

recycling__by_mines = percentage_recycling__by_mines*TOTAL_WATER_DEMAND__BY_MINES {m^3/year}

rossing_recycled__water = percentage__recycle*rossing_water_use {m^3/year}

rossing_water_use =
tonnes_produced__by_rossing*water_use_per_tonne_uranium__produced
{m^3/year}

target_mines = 20 {mines}

tonnes_per_new_mine = 2000 {tonnes}

tonnes_produced__by_rossing =
tonnes_produced_by_existing_mines*percentage_of_rossing_tonnes
{tonnes/year}

TOTAL_DEMAND_BY_MINES_AFTER_RECYLING =
TOTAL_WATER_DEMAND__BY_MINES-total_recycling_by_all_mines
{m^3/year}

total_recycling_by_all_mines = recycling__by_mines-rossing_recycled__water
{m^3/year}
TOTAL_WATER_DEMAND__BY_MINES =
(exisitng_mines__water__consumption+water_consumed_by__new_mines)-
rossing_recycled__water {m^3/year}

water_consumed_by__new_mines =
tonnes_produced__by_newmines*water_use_per_tonne_uranium__produced
{m^3/year}

water_use_per_tonne_uranium__produced = 815.75 {m^3/tonne}

Appendix 7: WATER DEMAND PROJECTIONS FOR WALVIS BAY BEFORE NEW MINES

Year	0% alternatives [m^3]	20% recycling [m^3]	30% demand management [m^3]	20% recycling; 30% demand management [m^3]
2010	4946742	4146359	3746168	2945785
2015	5628116	4717487	4262174	3351543
2020	6141620	5147906	4651049	3657335
2025	6528614	5472284	4944119	3887789
2030	6820264	5716745	5164986	4061467

Appendix 8: WATER DEMAND PROJECTIOS FOR SWAKOPMUND BEFORE NEW MINES

Year	0% alternatives [m^3]	20% recycling [m^3]	30% demand management [m^3]	20% recycling; 30% demand management [m^3]
2010	3534642	2863060	2527269	1855687
2015	4094632	3316652	2927662	2149682
2020	4551233	3686499	3254132	2389397
2025	4923533	3988061	3520326	2584855
2030	5227096	4233948	3737373	2744225

Appendix 9: WATER DEMAND PROJECTIONS FOR ARANDIS BEFORE NEW MINES

Year	0% alternatives [m^3]	20% recycling [m^3]	30% demand management [m^3]	20% recycling; 30% demand management [m^3]
2010	340778	281221	246943	178387
2015	406128	326527	286726	207125
2020	457064	367479	322687	233103
2025	503106	404497	355193	256584
2030	544725	437959	384576	277810

Appendix 10: WATER DEMAND PROJECTION FOR HENTIES BAY

Year	0% alternatives [m^3]	20% recycling [m^3]	30% demand management [m^3]	20% recycling; 30% demand management [m^3]
2010	849941	688452	607708	526963
2015	1182049	957459	845165	732870
2020	1439027	1165612	1028905	892197
2025	1637872	1326677	1171079	1015481
2030	1791735	1451305	1261286	1110876

Appendix 11: TOTAL WATER DEMAND FOR COASTAL TOWNS BEFORE NEW MINES

Year	0% alternatives-before new mines **[m^3]**	20% recycling **[m^3]**	30% demand management **[m^3]**	20% recycling; 30% demand management **[m^3]**
2010	9672103	7979092	7128088	5506822
2015	11310925	9318125	8321727	6441220
2020	12588944	10367496	9256773	7172032
2025	13593125	11191519	9990717	7744709
2030	14383820	11839957	10548221	8194378

Appendix 12: PROJECTIONS OF WATER DEMAND AS IT IS INFLUENCED BY NEW MINES

Year	0% alternatives-after new mines **[m^3]**	20% recycling **[m^3]**	30% demand management **[m^3]**	20% recycling; 30% demand management **[m^3]**
2010	9777995	8075985	7224980	5540774
2015	11811741	9818941	8822543	6856433
2020	13386203	11164756	10054033	7451410
2025	14607944	12206338	11005536	8100326
2030	15558308	13014444	11722709	8605946

Appendix 13: MINING EFFECT ON TOTAL COASTAL WATER DEMAND

Year	Existing mines [m^3]	Existing and New Mines (before recycling) [m^3]	Existing and New Mines (after recycling) [m^3]
2010	11080330	12379464	7039320
2015	13345359	43491546	19910884
2020	16073402	120189514	51104034
2025	19359109	241354107	100188899
2030	23316477	408414742	167758721

Appendix 14: TOTAL COASTAL DEMAND

Year	All mines (0% recycling)+ urban (0% recycling and demand management)+ other users [m^3]	All mines (60% recycling)+ urban (20% recycling; 30% demand management)+ other users [m^3]
2010	22672480	13061163
2015	55818308	26867125
2020	134090738	58791087
2025	256477072	108448629
2030	424488071	176468120

Appendix 15: TOTAL WATER REQUIRED FROM ALTERNATIVE SOURCES

Year	All mines (0% recycling)+ urban (0% recycling and demand management)+ other users [m^3]	All mines (60% recycling)+ urban (20% recycling; 30% demand management)+ other users [m^3]
2010	6472480	-3138837
2015	39618308	10667125
2020	117890738	42591087
2025	240277072	92248629
2030	408288071	160268120