# GROUNDWATER RESOURCE EVALUATION AND PROTECTION IN THE CAPE FLATS, SOUTH AFRICA

*by*

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Doctor of Philosophy



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# DECLARATION

I declare that ***Groundwater resource evaluation and protection of the Cape Flats, South Africa*** is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledge by complete references.

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Date: August 20, 2010

Signed

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## ABSTRACT

The Cape Flats are characterised by a flat sandy subsurface, consisting of the ‘Late-Tertiary and Recent sands’ unit up to 50 m thick; and with long-term mean annual precipitation (MAP) of 600 mm/a. The vegetation belongs to the Cape Flora group invaded by xerophytic species and thick Coastal Fynbos in the Cape Flats Nature Reserve. The sandy aquifer is underlain by an impervious shaly bedrock aquifer (Malmesbury Shale). This thesis reviews the history and problems of groundwater development, and provides extensive information on the geology, hydrology, hydrogeology, recharge quantification, and groundwater chemistry in the Cape Flats. The aim is to utilize all of the information to aid conceptual understanding as well as develop a method suitable for the aquifer’s vulnerability assessment.and mapping to set the stage for groundwater protection.

The analysis of geologic, hydrologic and hydrogeologic data interpreted to give the characteristics of the Cape Flats aquifer showed the quality of groundwater from the aquifer is suitable for development as a water resource. The conceptual model of the Cape Flats sand shows an unconfined sandy aquifer, grading into semi-confined conditions in some places where thick lenses of clay and peat exists. Recharge rates through the saturated zone of the Cape Flats aquifer have been determined by water table fluctuation (WTF), rainfall-recharge relationship, soil water balance and chloride mass balance methods (CMB). Recharge rates using the WTF vary considerably between wet and dry years and between locations, with a range of 17.3% to 47.5%. Values obtained from empirical rainfall-recharge equation (method 2) agree with those of the WTF. Recharge estimates from the water balance model are comparatively lower but are within the range calculated using empirical method 2 (i.e. 87 – 194 mm or 4 – 21% of MAP). These recharge rates also agree with estimates from the series of other methods applied to sites located in the north-western coast of Western Cape and are comparable to recharge rates obtained elsewhere in the world.

Hydrochemical evaluation of groundwater in the Cape Flats identified the following geochemical processes: ion exchange, mixing, dissolution and weathering. These control the evolution of groundwater in the aquifer and influence its quality in relationship to other aquifers in the study area. Various graphical plots, ionic ratios and statistical analyses have been interpreted to reveal the chemical water types and ionic constituents of groundwater in the area. Na-Cl, Na-Ca-Cl-$HCO_3$ and Ca-Na-$HCO_3$ are dominant; and the general groundwater composition reflect the influence of seawater on rainwater due to the proximity to the sea (although 82% of >1,000 hydrochemical data interpreted are classified as fresh with TDS less than 1,000 ppm). The stable isotope ($^{18}O$ and $^{2}H$) is considerably dispersed, reflecting direct recharge and the shallow nature of groundwater. The recharge mechanism obtained from isotopic evidence (direct recharge from rainfall) confirms field observations.

A vulnerability assessment method (CALOD) developed and used for vulnerability mapping of the Cape Flats aquifer, confirms the highly susceptible nature of the aquifer to pollution from the surface and compares well with a common method with acronym "GOD" (Groundwater occurrence; Overlying strata and Depth to groundwater). The vulnerability map shows areas on the Cape Flats susceptible to pollution with rankings: Low-medium, medium-to-high, high to very high. Low indexes represent aquifer that is better protected from contaminant leaching by the natural environment while a high pollution potential index indicates the capacity of the hydrogeologic environment to readily transport contaminants into the groundwater system. Sensitivity analysis was carried out to validate and evaluate the consistency of the analytical results forms the basis for evaluation of the vulnerability maps and showed the order of sensitivity of the, parameters.

Finally, implications from the analyses of results of aquifer parameters recharge mechanisms and conceptual understanding of flow characteristics and aquifer vulnerability contributed to increased understanding of the aquifer system. The Cape Flats aquifer is highly vulnerable to pollution because of its lithological units; vulnerable to drought because of the decreasing (fluctuating) rainfall pattern and consequently recharge. Therefore, the emphasis is to plan before development and set adequate protection measures.

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**Publication page**

The following publications and presentations have been based on data from this research thesis for which I acknowledge all relevant organizations whose database were accessed during course of this work (particularly DWAF Bellville, City of Cape Town, SA Weather Bureau, and CSIR):

***Book Chapters/accepted case studies***

(1) ADELANA, S.M.A.; XU, Y. (2006): Contamination and protection of the Cape Flats Aquifer, South Africa. In Xu & Usher (eds): Groundwater pollution in Africa, Taylor & Francis, London, pp.265-277.
(2) ADELANA, S.M.A.; TAMIRU, A.; NKHUWA D.C.W.; TINDIMUGAYA, C.; Oga, M.S. (2008): Urban groundwater management and protection in sub-Saharan Africa. In S.M.A. Adelana & A.M. MacDonald (eds), Applied groundwater studies in Africa, London: Taylor & Francis, 231-260.
(3) ADELANA, S.M.A.; XU Y.; VRBKA, P. (2010) A conceptual model for the development and management of the Cape Flats aquifer, South Africa. Water SA, Vol.36, No.4, pp 461-474.
(4) ADELANA, S.M.A.; TAMIRU, A.; NKHUWA D.C.W.; NEDAW, D. Urban groundwater under conditions of climate change: Case studies from Sub-Saharan Africa. Accepted In: Environmental Research Letters (ERL) focus issue on groundwater and climate.

***Conference Proceedings***

(4) ADELANA, S. M. A., XU, Y (2008) Impacts of land-use changes on a shallow coastal aquifer, South-Western Cape, South Africa. Proc. XXXVI Congress of the International Association of Hydrogeologists (IAH), Toyama, Japan, 26 October -1 November
(5) ADELANA, S. M. A.; XU, Y.; ADAMS S. (2006) Identifying sources and mechanism of groundwater recharge in the Cape Flats, South Africa: Implications for sustainable resource management. Proc. XXXIV Congress of the International Association of Hydrogeologists (IAH), Beijing, China, 9-13 October 2006.
(6) ADELANA, S. M. A (2006) Groundwater recharge in an unconfined aquifer around Cape Town, South Africa. Research Open Day Book of Abstracts, Faculty of Science, University of the Western Cape, South Africa, 9-10 November 2006.
(7) ADELANA, S. M. A.; XU, Y. (2005) Vulnerability assessment of the Cape Flats Aquifer: Any relevance to nitrate pollution? In: Acworth R.I., Macky G., Merrick N.P. (eds.) Where Waters Meet. Proc. NZHS-IAH-NZSSS Conference, Auckland, 28 Nov. – 2 Dec.
(8) ADELANA, S. M. A.; XU, Y. (2005) Vulnerability assessment of the Cape Flats Aquifer, South Africa. Proc. International Conference on Aquifer Vulnerability at Risk (AVR 05), Parma, Italy, 21 – 23 Sep.

***Report***

(1) Final report on UNEP project on Vulnerability Assessment in 11 African Countries:
Vulnerability assessment and protection of the Cape Flats Aquifer, South Africa by Segun Adelana, Shafick Adams, Yongxin Xu. A 36-page report submitted to UNEP, Nairobi, Kenya, January 2006.

***Journal Submissions***

(1) ADELANA, S. M. A.; XU, Y. Estimation of groundwater recharge in the Cape Flats, South Africa. Journal of Hydrology, Elsevier
(2) Hydrochemical characterisation of groundwater in the Cape Flats area, South Africa.Total Environment Journal, Elsevier

# CHAPTER 1: GENERAL INTRODUCTION

## 1.1 Inventory of the water resources in the Western Cape

The Cape Flats is located within the boundaries of the City of Cape Town in the Western Cape Province. The Cape Flats covers a surface area of 630 $km^2$ and is positioned between 33˚30´ and 34˚10´ south-latitude and between 18˚20´ and 19˚00´ east-longitude. The large undulating sandy area connecting the hardrock of the Cape Peninsula with the mainland is known in the literature as the Cape Flats (Schalke 1973, Theron 1974, Theron et al. 1992). Presently, most of the area underlain by the Cape Flats aquifer is built up, from the City main bowl to the northern and southern suburbs. The City of Cape Town and its suburbs are entirely underlain by Cenozoic sands, which form the Cape Flats aquifer. Detailed physiographic description and scope of the present study are given in chapter 3.

Water resources in the Western Cape can be divided into six interrelated categories: sources or headwaters; rivers; wetlands; estuaries; groundwater and human-made facilities, all of which form part of catchments. There are 10 major and 4 minor catchments in the Cape Metropolitan Area (Figure 1). Catchments in the Cape Metropolitan Area (CMA) display a high seasonal variability, given that the CMA receives most of its rain in the winter months. The upper reaches of a river are referred to as the headwaters or the mountain stream zone. Headwaters are generally steep gradient, high-energy (turbulent flow) systems. In general, sources and headwaters of the rivers of the CMA are relatively undisturbed and in a good ecological state, however, they are sensitive to anthropogenic disturbance. Several upper catchments within the CMA are planted with pine trees, usually *Pinus pinaster*, that reduces runoff (CCT 1997). The specific state of the rivers in the CMA varies greatly between catchments, depending largely on the degree of urbanization within the catchment (Inland Waters Management Team 1994).

The groundwater situation reveals there are three significant aquifers within the CMA: the Newlands aquifer, the Atlantis aquifer and the Cape Flats aquifer; although the TMG (TMG) aquifer borders and underlain parts of the region. The sandy substrate of the Cape Flats has a low filtering efficiency and, rendering thegroundwater resource particularly vulnerable to pollution from human activities.

The City of Cape Town has over the last few decades had a history of water shortages and water restrictions before the new water augmentation schemes were constructed (Bishop & Killick 2002). The most recent water shortage faced by the city was from 2002-2005 that necessitated imposition of water restrictions in the year 2005. This has been due to decreasing dam levels subsequent to fluctuating rainfall pattern and climatic conditions in the last decade. Presently, the Bulk Water Transfer from the Berg River (located outside the CMA) now brings the City in to a good situation with respect to water supply. All the same, the measure is for few years after which the situation with water supply may be tight again. This is why the City of Cape Town is looking at several options, particularly using groundwater in the augmentation scheme. Therefore, groundwater use in CMA is expected to increase in the nearest future. As groundwater use becomes critical to the municipality, it is also expected to be more at risk of pollution.



Recent studies on hydrochemistry, recharge estimation, and the impacts of groundwater-dependent ecosystem in the TMG (e.g. Wu 2005, Jia 2007) and selected groundwater regions in South Africa have yielded valuable information that is useful for groundwater resources exploitation in the Western Cape. However, such current information that can aid full groundwater development and management of the Cape Flats aquifer is still lacking or inadequate. Therefore the importance of resource evaluation in the Cape Flats cannot be over-emphasised.


Figure 1: CMA map showing major and minor catchments (CMC 1999)

***Utilization and development***

In the city of Cape Town, groundwater is by far less utilized than surface water. With increasing scarcity of fresh water resources and variable climate in the region, the Cape Flats aquifer represents an important potential source of water for the Cape Town Metropolitan Area. However, the city is expanding in terms of commercial and industrial activities, which presents a threat to the sustainability of the water resources. Activities of the increasing population in the metropolitan city, the use of chemicals and generation of both domestic and industrial wastes tend to constitute potential sources of contamination in this area.

Table 1 shows the water supplied by the City of Cape Town to the Municipal Local Authorities for 1997/1998. The City's metering system was set up to measure water consumption was also extended to calculate the amount of water that is unaccounted for or lost from the mains. For example, in 1993/1994, figures for the City of Cape Town, which then included the South Peninsula area, indicated a total consumption of $1.1 \times 10^8$ $m^3$ with 22.8 % of this being unaccounted for (Inland Waters Management Team 1994). The bulk of the water not accounted is usually lost through leakages, pipe burst and wastage.



Table 1: Water supplied to local authorities (1 July 1997 to 30 June 1998)

| **Local authority** | **Amount (kl)** |
|---|---|
| Blaauwberg Municipality | 27 985 557 |
| City of Cape Town | 95 160 582 |
| Helderberg Municipality | 11 371 496 |
| Oostenberg Municipality | 20 310 808 |
| South Peninsula Municipality | 42 328 905 |
| City of Tygerberg | 82 828 004 |
| Total | 279 985 352 |

Note: The six municipal (local) authorities combine to form the present City of Cape Town as shown in Appendix 1.1
Source: CMC Water Department, 1998

The three significant aquifers within the CMA have varied degree of utilization: (i) the Atlantis aquifer, which is used most intensively for water supply to Atlantis and Mamre townships, yields approximately 5.5 x $10^6$ $m^3$ per annum (Cave et al.1996); (ii) the TMG aquifer, with approximately 3.6 x $10^6$ $m^3$ of water per annum abstracted for irrigation of sports fields and for usage in Ohlssons (Newlands) Brewery; and (iii) the Cape Flats aquifer, which is presently abstracted on an *ad hoc* basis for watering lawns and gardens. Of these, the Cape Flats aquifer has been identified has having the greatest potential, yet remains the most under-utilized (Fraser & Weaver 2000) and therefore represents a potential source to be fully utilized to augment the City's water supply. The envisaged initial quantity for abstraction was estimated at 18 × $10^6$ $m^3$/year (Gerber 1981, Vandoolaeghe 1990). Recently, groundwater use for the City of Cape Town has been divided into 3 categories (Bishop & Killick 2002):

(i) groundwater for general bulk water supply purposes; the Cape Flats and TMG aquifers fall into this category

(ii) groundwater for strategic supply purposes; the Atlantis and the TMG aquifer in the South Peninsula are in this category;

(iii) groundwater for irrigation purposes; the Cape Flats aquifer is currently being utilized for this purpose.



*1.1.2 Water demand and supply quality situation*

In the Western Cape, agricultural sector is one of the largest users of water resources. Moreover, rapid economic development and population growth is generating increased pressure on water supplies; that may soon lead to greater dependence on groundwater. The growth in urban water demand in the Greater Cape Town Metropolitan Area was projected to increase from 243 million $m^3$ in 1990 to 456 million $m^3$ in 2010; whereas for irrigation water demand the increase is from 56 million $m^3$ in 1991 to 193 million $m^3$ in 2010 (Ninham Shand 1994). The total urban and irrigation demand was estimated at 470 million $m^3$ in 1998 and is expected to reach 664 million $m^3$ by 2010. Over 60 % of the annual urban demand and 90 % of the irrigation demand occurs in summer.

The shortage of surface water, which is fully utilized in the study area, makes groundwater a potential source for development. This shortage of water resources could become a serious restraining factor for economic development in the Western Cape if proper management schemes are not in place. Due to the increasing tendency to develop and exploit this aquifer for municipal water supply the knowledge of the groundwater quantity, the recharge rates and hydrochemical characteristics become significant issues. In a broad sense, resource management in the City of Cape Town needs to address quality issues along with quantity.

Generally, the quality of the water in the rivers and streams arising in the mountains in the CMA is good. As streams pass from the footslopes into lower-lying areas where urban and industrial developments dominate the landscape, water quality is influenced by the quality of runoff arising from these areas. Rivers in seven major catchments in the CMA received effluent from sewage works (CCT 1997). As a result, many of the rivers of the CMA show signs of pollution (measured in terms of faecal coliform content). The increase in the faecal coliform counts of a number of rivers in the CMA (1993-1996) and the water quality measurements for a selection of rivers and vleis in the Cape Metropolitan Area are presented in the Catchment, Stormwater and River Management (CSRM) 2004/2005 report.



Much of the CMA's water supply has been diverted from rivers that are located beyond its boundaries. The water is brought into the CMA via inter-basin water transfer schemes (IBTs). The Riviersonderend/Berg River Government Water Scheme regulates the flows from the Riviersonderend, the Berg River and the Eerste River for urban, industrial and agricultural use (CCT 1997). The Riviersonderend/Berg River is located several kilometers outside the study area. During summer, algal blooms threaten some of the reservoirs in these catchments. According to the City of Cape Town report, the water from these sources requires extensive treatment before consumption and this is a costly and time-consuming process. Sewage ponds and reservoirs, although unnatural, provide habitat for aquatic fauna and flora. Aside the quality issues, the dam levels have been dropping since the last ten years. These further increases the needs for reassessment and proper evaluation of groundwater resources of the City of Cape Town in order to meet the projected increase in water demand.

In the city of Cape Town, it has been established that groundwater may be contaminated through a wide variety of human activities. These include the land disposal of waste materials, disposal of sewage and particularly sanitary landfills and pipeline outlet, the leaching of fertilizers and pesticides, accidental spills of hazardous materials, and underground fuel tank leakages (Usher et al. 2004, Adelana & Xu 2006). The issue of unknown quantity and quality of groundwater generated debates in the past over the idea of developing the Cape Flats aquifer (Vandoolaeghe 1990). The intensive land use, as a consequence of development, has been found to repeatedly impact negatively on the quality of groundwater in many cities of the world  Examples of contamination of urban groundwater resources are available in the literature (Foster 1987, Lerner 1992, Scharp et al. 1997, Foster et al. 2002). Some of these issues, like disposal of wastes, landuse, and proximity of sanitary landfills were used as counter argument against the development of the Cape Flats aquifer for groundwater use since the late 1980s to early 1990s. In the Cape Flats area, groundwater pollution trends and source identification were enumerated with the main controlling factors (Adelana & Xu 2006). In considering the Cape Flats aquifer as a water source for the City of Cape Town, the issues raised around the polluting influences are important and require investigation. It is therefore important to study the hydrochemical quality of groundwater in this area. Sequel to point source identification and the various non-point or diffuse sources of pollution, the need for protection zoning in the well fields of the Cape Flats aquifer have also been highlighted and forms part of this study.

*1.1.3 Significance of the current research*

Recent studies on groundwater resource use in the Western Cape have concentrated largely on the TMG and the Atlantis aquifers. Although Henzen (1973) did an extensive study on water resource management and water quality specifically regarding the Cape Flats, recent research efforts are not being directed towards developing the aquifer. Since the work of Henzen (1973) and Gerber (1981) there is need for an integrative and more comprehensive study to justify the use or disuse of the Cape Flats aquifer for the City's water supply. There is the need to put together all such necessary information as relevant for groundwater resource development and management in the Cape Flats (in addition to recent data) in order to have a present-day view on the aquifer.

Only in recent years has the municipal government become aware of the need to assess the impact of the abstraction of bulk groundwater from the Cape Flats aquifer on the natural environment and on the aquifer itself (CMC 1998, Fraser & Weaver 2000). In 2001, a study to simulate alternative groundwater abstraction scenarios in part of the Cape Flats was attempted by the CSIR using the MODFLOW model (CSIR 2000) and following the earlier model by Gerber (1981). Less attention has been given to recharge estimation, partly because groundwater abstractions for water supplies account for only a small proportion of the available groundwater resources in the Western Cape and partly as a result of inadequate data. Now, however, due to growing awareness of the importance of groundwater contributions to the environment and, more specifically, to the introduction of the augmentation scheme by the City Council estimates of reliable recharge are required for the aquifers in the Western Cape region.

Recharge quantification in the TMG aquifer has been carried out (Wu 2005). In the evaluation of groundwater resources of the region, estimation of recharge into the Cape Flats aquifer is significant. Therefore, in the present study, evaluation of the groundwater resource in the Cape Flats incorporates recharge estimates, hydrochemical characterization into the regional groundwater management and planning in meeting Cape Town's water demand. The aims and objectives of the present study are defined in the following section.

***1.1.4 Objectives of the present study***

Many groundwater-related studies, mainly on the TMG, have been conducted in this area since the last decade (e.g. Duvenhage et al. 1993, Weaver et al. 1999, Kotze 2000, 2001, 2002, Xu et al. 2002a, Cleaver et al. 2003, Wu & Xu 2004, Wu 2005, Jia 2007). A number of research projects have also been carried out on the Cape Flats, however, none of the studies conducted have applied an integrated evaluation of the resource. The main focus of this study, therefore, is the evaluation of the Cape Flats aquifer to advice on the possible development of the aquifer for water supply augmentation and the long-term consequences of over-development of the resource as a water supply option to the City of Cape Town. This study also aims at addressing the aspects of groundwater contamination as relevant to future integrated water resources development, and as such presents protection strategies for the Cape Flats aquifer that are adoptable for regional planning purposes. The overall purpose of this study is thus to understand the groundwater conditions in the greater Cape Town area, particularly on the Cape Flats aquifer, by utilizing more integrated and systematic approach. Although the motivation for, and objectives of, the current study are scientific, the results may be used for policy development, resource consent conditioning, and in formulating monitoring plans.

The objectives of this study are then summarised into the following:

1. To collate data on climate, geology, soil, hydrogeology and groundwater in the study area in order to address identified groundwater problems associated with urbanization and human activities.
2. Evaluate groundwater occurrence, aquifer characteristics, groundwater exploitation and recharge, groundwater quality.
3. Prepare conceptual hydrogeological model (based on existing and new data) to set the stage for numerical modeling of the Cape Flats aquifer. This is in attempt to reconstruct the groundwater flow pattern with respect to the local hydrogeologic conditions.
4. Assessment of groundwater recharge rates and establish well-defined concepts on the various recharge processes occurring within (and) or around the aquifer.
5. Establish the physico-chemical characterization of the groundwater in the study area in order to determine evolution and trend.
6. Make recommendations on the need for protection of the aquifer, with specific reference to local conditions prevalent in the Cape Flats area, to form the basis for guiding future land use decisions.

It is hoped that the findings of this study would provide useful information and increase the understanding of the Cape Flats aquifer to better inform the City Management Authorities and the public on groundwater resource estimates. This in turn may support water resource management framework suitable for future water stress times.

### *1.1.5 Delimitation of the present research work*

The impact of urbanisation on groundwater is becoming high and requires adequate investigations. Groundwater quality deterioration and reduced recharge are among the measurable impacts. The general concept is that groundwater quality is worse beneath cities than beneath nearby rural areas due to various factors, some of which are discussed in section 1.2.3 and 1.2.4. Within the Cape Municipality, the size, density and location of settlements have been found to determine the degree or intensity of pollution. The various sources of pollution have been classed according to the varying human activities and presented in Adelana and Xu (2006). The intention was to further link the varying human activities or specific land use pattern with groundwater quality, using the knowledge of the Geographical Information System (GIS) as presented in Adelana and Xu (2008). Incorporating this information into numerical flow model for the Cape Flats aquifer and then defining protection zones based on particle tracking will not be covered in this work. This is therefore presented as recommendation for further studies.

## 1.2 Review of literature

Groundwater is a precious source of drinking water in many parts of the world accounting for about two-thirds of the earth's freshwater resources (Freeze & Cherry 1994, Hiscock 2005). Yet, groundwater contamination is an increasing problem globally (Van Stempvoort et al. 1993). In recent decades, the number and diversity of potential groundwater pollutants, particularly fertilisers, pesticides, and herbicides have increased dramatically (Foster 1987, Foster et al. 2002, Usher et al. 2004). Since the 1980's various chemicals and wastes have been found in groundwater. For example, nitrate, the most ubiquitous contaminant, has been found at levels in excess of drinking water standards in Europe, USA, Canada, Israel, Australia, and New Zealand (Spalding et al. 1993) and in many part of Africa (Adelana & Olasehinde 2003, Tredoux et al. 2001, Faillat 1990, Edmunds & Gaye 1997, Akiti 1982). The discharge of domestic, agricultural, and industrial effluent onto, and into, the ground has also increased because of the high cost of alternative disposal systems. In addition, land based 'treatment' of effluent is actively encouraged in many areas, often without regard to the possibility of groundwater contamination. If contaminated, groundwater may pose a serious health hazard to humans.

Until the 1980s it was thought that soils served as filters with an unlimited capacity for preventing groundwater contamination from the land surface. Soon research began to focus on the fate of contaminants within the subsurface, and on the vulnerability of groundwater resources. Researchers recognized that groundwater resources could not be expected to fulfill the dual roles of a destination for waste and a source of drinking water at the same time (Foster et al. 2002, Sililo et al. 2001). Concern about groundwater pollution relates primarily to the phreatic (unconfined) aquifers, especially where their vadose zone is thin and their water table shallow, but may also arise even where aquifers are semi-confined, if the confining aquitards are relatively thin and permeable (Foster et al. 2002).

Groundwater recharge has been defined as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir (Lerner et al. 1990). In the context in which recharge is implied in this study the definition by Sophocleous and Perry (1985) seems more appropriate: It is water that percolates into the lower limits of the vadose zone, reaching the water table and subsequently, causing a measurable water-table rise. There are two main types of recharge: direct (vertical infiltration of precipitation where it falls on the ground) and indirect (infiltration following runoff). It is generally acknowledged that in semi-arid environments most groundwater replenishment is point recharge (Simmers 1997). However, in certain geological situations, this may be direct forming a crucial addition to the groundwater reservoir.

Howard & Lloyd (1979) describe two key types of direct recharge; potential and actual recharge. Potential recharge is the water that leaves the bottom of the soil zone. If the material in the unsaturated zone does not restrict the vertical movement of water, the actual recharge (the water reaching the water table) equals potential recharge.

Estimating recharge is essential in any analysis of groundwater systems and the impacts of withdrawing water from the aquifer. In water resource investigations, groundwater models are often used to simulate the flow of water in aquifers and, when calibrated, may be used to simulate the long-term behaviour of an aquifer under various management scenarios. Without a good estimate of recharge and its spatiotemporal distribution, these models become unreliable. Thus, without a good estimate of recharge, the impacts of withdrawing groundwater from an aquifer cannot be properly assessed, and the long-term behavior of an aquifer under various management schemes cannot be reliably estimated (Sophocleous 2005). Accurate estimates of recharge and recharge mechanisms are also necessary to assess the risk of groundwater contamination, particularly diffuse agricultural contamination (such as nitrates and pesticides). There are several techniques used in groundwater recharge estimation. Generally, these are divided into categories, with a range of techniques and variations within each category. These categories and techniques are discussed in chapter 5.

### *1.2.1 Review of previous studies on the Cape Flats*

Several studies on exploration, developmental techniques, digital flow modelling and artificial recharge to groundwater in the Cape Flats have been carried out by different research organizations between 1966 and 1989. All were in attempt to develop this groundwater resource and define its relevance to the Cape Metropolitan Area with respect to possible purification and introduction into the municipal water supply system. Intensive exploration of the hydraulic and geologic properties of the sand deposits in the region was initiated by Henzen (1973) primarily to determine the feasibility of artificial recharge and abstraction for the purpose of municipal supply. In the process of this Henzen (1973) prepared maps on surface and groundwater quality for the area. Gerber (1976) carried out additional investigations on the hydraulic conductivity for the entire Cape Flats, which formed a basis for further development of models necessary for optimum groundwater management. The first study with a mathematical model was used to predict the changes in the aquifer caused by changes in stresses on the system as well future water level responses (Gerber 1981).

Several instances of groundwater pollution within the Cape Flats aquifer are available in both published (Tredoux 1984, Weaver & Tworeck 1988, Ball et al. 1994, Engelbrecht 1998, Parsons & Taljard 2000, Saayman et al. 2000) and unpublished reports (Bertram 1989, Saayman 1999, Traut & Stow 1999, Ball & Associates 2003). For the general water quality surveys, boreholes were drilled all over the Cape Flats but a number of the wells were specifically sited at potential pollution points (Tredoux 1984). Although the investigation included observation boreholes all over the Cape Flats, two solid waste disposal sites received special attention with monitoring boreholes in their vicinity. Analytical results of groundwater sampled from both observation and monitoring boreholes indicated that pollution was going on in the Cape Flats.

According to Tredoux (1984), ammonium nitrogen ($NH_4$-N), nitrate (as N), potassium, total alkalinity and COD were present in high concentrations in groundwater within the vicinity of the two solid waste disposal sites and the Sewage Treatment Works. Other parameters like phosphate are occasionally present only at low concentrations. The groundwater quality monitoring indicated increasing trend in pollution between 1979 and 1982; while prior to 1979 no definite sign of groundwater pollution could be discerned. Pollution reached its peak values between 1980 and 1981. Although potassium is not a common pollutant of groundwater, it was used to trace leachates from sanitary landfills and sewage effluents into the Cape Flats aquifer.

In a similar monitoring system, the Coastal Park Landfill monitoring data had accumulated over a period of 20 years to produce clear long-term trends that showed the flux of certain pollution indicator parameters with distance from the landfill (Ball and Novella 2003). The Coastal Park landfill is located adjacent to the outlet of the Zeekoevlei Sewage Works, some 400 m from the coast and separated from the groundwater by a 2 m natural unsaturated zone comprising of the Cape Flats sand (Ball and Stow 2000). In the historical reports, the monitoring of mini-well system has shown that leachate generated from the landfill has entered the groundwater. This has been shown to migrate mainly eastward towards the Zeekoeivlei Outlet, although pollution migration in a southerly direction is now also being detected (Ball and Associates 2003). Furthermore, with the introduction of Differential Depth sampling of boreholes, data relating to pollution with depth became available and showed persistent trend over a period of time. In the case of COD, there are indications of general organic pollution throughout the profile while $NH_4$-N gave indications of high concentrations associated with the top of the profile and attributed to leachate pollution from the landfill. However, the long-term trends for COD and $NH_4$-N provided new insight into the possibility of leachate attenuation (Ball and Associates 2003).

In the study of the interaction between the Cape Flats aquifer and the False Bay, the risk of the aquifer becoming increasingly contaminated from low to medium risk pollution sources has been identified (Giljam and Waldron 2002). According to Giljam and Waldron, the Cape Flats aquifer is vulnerable to many outside influences: the informal settlement of the Khayelitsha (where there is poor sanitation) and the Philippi agricultural area (where fertilizer application takes place regularly) and numerous nodal sources of pollution (e.g. Waste Water Treatment Works, WWTW and the waste disposal sites). One of the methods applied in this study, identified three sections of low salinity. High silicate, nitrate and phosphate concentrations (which confirmed the earlier report of Hartnady and Rogers, 1990 and Grobicki, 2000) were also identified in the Philippi agricultural area. In the same vein, Traut and Stow (2001) identified high $NH_4$-N concentrations at the Swartklip Waster disposal Site. A marked increase in salinity was recorded at eastern boundary of the Cape Flats WWTW. The nitrate, phosphate and silicate concentrations in the berm and behind the surfzone were high in comparison to other sample sites south of the Philippi agricultural area and correspond with the generally high concentrations of these nutrients found recorded in the aquifer in this area.

Also considered in the review is the work of Saayman (1999), which was a case study on the chemical characteristics of a pollution plume and a determination of its direction of movement at the Bellville Waste Disposal site. The aim of this work was to establish whether leaching from the waste disposal site was causing pollution of the groundwater in the area. The results show high concentrations of potassium, sulphate and orthophosphate, with elevated concentrations of other ions (magnesium, chloride, COD, electrical conductivity) and heavy metals (nickel and lead) indicating groundwater pollution in the area. It is important to note that all the observation boreholes around the waste disposal site penetrated the Cape Flats aquifer only to a depth of 15 m (except one that is to a depth of 30 m). Although varying level of pollution of groundwater were observed in this boreholes consequent to the effect of the waste disposal site, the influence of nearby wastewater treatment works on the groundwater was also highlighted. In an attempt to establish which of the sources contribute significantly to groundwater pollution, the boreholes were sampled for isotopes of oxygen and hydrogen (Saayman et al. 2000). The results of the stable isotopes of water molecule successfully defined the level of influence of recharge from surface pollution on the groundwater of this area.

Another report of concern in the Cape area is that of pollution of groundwater by cemeteries. Engelbrecht (1998) reported the occurrence of groundwater pollution in the unconsolidated sands of the Bredasdorp Group by the influence of a cemetery. In a local municipal cemetery, 21 well-points were installed in the cemetery grounds and one well-point outside the cemetery to be used for sampling and quantifying the quality of the groundwater. The results showed an increased of colony forming units (cfu) in the sampled groundwater for all microbiological indicators used indicating that the groundwater within the cemetery area is extremely polluted compared with the expected regional groundwater quality. According to Engelbrecht, the leachate from the cemetery appears to be a nutrient for the micro-organisms rather than a poison. Pathogenic bacteria, viruses, protozoa and helminths that survive consequently reached the groundwater and as such, a significant increase above the regional groundwater quality (as represented by a municipal borehole) for all the chemical parameters was encountered. Apart from high levels of *Escherichia coli*, faecal streptococci and *Staphylococcus aureus* in the groundwater samples, potassium, ammonium-nitrogen, nitrate and nitrite, dissolved organic carbon and electrical conductivity showed increased concentrations in all the 22 well-points in comparison to the municipal borehole. The chemical data as in the case of the microbiological data therefore showed that the groundwater became polluted as a result of the cemetery.



### *1.2.2 Groundwater resources evaluation*

As mentioned in section 1.1.1, there are three significant aquifers and one major spring (Albion spring) within the CMA: the Atlantis aquifer, the Newlands aquifer, and the Cape Flats aquifer. The Atlantis Water Supply Scheme comprises of two well fields, one at Witzands and the other at Silwerstroom; the two together have abstraction potential of 5.5 x $10^6$ $m^3$/a from 30 and 14 boreholes respectively (CCT 2001, Cavé et al 1996). The Atlantis aquifer is used most intensively, and the water supply for the town of Atlantis and Mamre is abstracted from this source. Thus, most monitoring and exploratory work has been focused here in the last few decades (CMC 1998, Snaddon 1998).

The water quality in the Newlands aquifer is relatively good and uncontaminated. This aquifer is a transitional zone that covers the Newlands-Rondebosch-Kenilworth areas, grading towards Wynberg and Plumstead. Currently, approximately 3.6 x $10^6$ $m^3$ of water per annum is extracted from this aquifer (Ninham Shand 1994). It has been identified as a potential source of water for the CMA.

The Albion Spring in Newlands has been in use as a source since 1891. This spring is derived from the Newlands aquifer on the bank of the Liesbeek River (Bishop & Killick 2002). Albion Spring was originally used by Ohlssen's Brewery and in 1892 it was taken over for municipal water supply. Water from Albion Springs is treated with chlorine and lime and then pumped directly into the reticulation system of the City of Cape Town (CCT 2001). It produces a high quality carbonated water, which is treated to reduce its acidity by stripping the dissolved carbon dioxide in a cascade, before being chlorinated and pump into the mains.

Apart from Albion Spring, a number of other springs were recorded in the past as used for portable water supply and are no longer in use but now discharges into the stormwater system. Kotze Spring, which discharges at 0.23 $m^3$/day, is used by Leeuwenhof Estate for irrigation. Kommetjie Spring (Newlands aquifer) yields 4 $m^3$/day and is used by Ohlssen's Brewery; Newlands Springs (Newlands aquifer) is used by the Western Province Cricket Club and Kelvin Grove (flow is not recorded). Most of these springs could not be located during this study. The springs visited and sampled for chemistry during this study are: Main Spring 1 (MS1), Main Spring 2 MS2), Main Spring 3 (MS3), Albion Spring, Kildare Spring (Cottage Home), and Palmboom Spring (see Section 6.8).

The Cape Flats Groundwater Development Pilot Abstraction Scheme was established in Mitchells Plain in the period 1985-1988 jointly by the Department of Water Affairs and Forestry (DWAF) and the City of Cape Town to test the aquifer under concentrated stress conditions. The essence was to observe the yield and aquifer response as well as monitor the quality of the water with respect to abstraction and subsequent environmental impacts. The hydrochemical conditions of the Cape Flats aquifer during the 3-years abstraction scheme (of 18 observation boreholes) revealed that the bulk groundwater supply was portable with a median TDS of 640 ppm, although polluted was induced from a nearby Sewage Works Maturation ponds (Vandoolaeghe 1989). Further deductions were made with respect to the spatial variation in groundwater quality to determine the heterogeneity of the aquifer system on both micro- and macro-scales. No seasonal variations in quality variables and no evidence of contamination or intrusion of the groundwater body by saline seawater were observed (Edwards 1989). According to Vandoolaeghe (1989), too few data points and too much natural fluctuations made the study of the quality changes in the observation wells almost meaningless. This was further complicated by the fact that the pumping exercise homogenizes water abstracted from the different horizons and hydrogeological units masking the detection of any such changes.

The storage capacity of the aquifer was estimated at 128 million cubic metres (CCT 2001). Gerber (1981) earlier estimated about $18 \times 10^6$ $m^3$/year can be extracted from the Cape Flats aquifer without adverse effect on the ecosystem (as this equals the rate of natural recharge to the aquifer). Vandoolaeghe (1989) calculated a mean annual yield of 4.1 $Mm^3$ which was produced from ten production boreholes in the period May 1985 to April 1988. This generated limited regional water table decline under optimal operating efficiency and favourable recharge conditions. The sandy substrate of the Cape Flats and Atlantis areas has a good filtering efficiency but its potential for removal of dissolved pollutants may be low. As groundwater is recharged by slow seepage from the surface, this water resource is particularly vulnerable to pollution from human activities.

The TMG aquifer falls outside the boundaries of the CMA. The potential of the TMG aquifer as a water resource received a significant amount of public attention from late 2000; and the Integrated Water Resource Planning Study has revealed that the potential yield of the aquifer for urban consumption could be as much as 70 million cubic metres per annum (CCT 2001). Detailed study by Jeffares & Green (2002) reveals the yield of the TMG aquifer as $5 \times 10^3$ $m^3$ per day, which can be used to augment supply in the South Peninsula, south of Clovelly area. A quantitative recharge estimate of the TMG aquifer is documented in Wu (2005) while resource estimation and storativity determination of this aquifer were reported in Jia (2007).

*1.2.2.1 Urbanisation and recharge*

Cape Town is unique among most South African cities in the occurrence of significant resources of fresh shallow groundwater in the unconfined, sandy aquifer system that underlies the Coastal Plain of its suburbs. Cape Town Metropolitan Area (with a population of about 3.8 million people), uses less than 5 percent of the total annual water consumption ($3 \times 10^8$ $m^3$) which is extracted from groundwater. The Water Authority (the Department of Water Affairs & Forestry) coordinates and monitor activities such as borehole sinking and is charged with responsibility (under the National Water Act of 1998) of regulating the abstraction of groundwater. But, only a fraction of the boreholes in the Western Cape are registered; a good number of pumped bores are under private domestic ownership.

Urban groundwater in Cape Town Metropolitan Area is under-used despite being a potentially valuable resource. Across the world, urban groundwater (according to Lerner 2004) is now:

(a) a potentially valuable resource,

(b) a problem because water tables are rising, and

(c) either polluted or at risk of pollution.



*1.2.2.2 Urban groundwater recharge*

In its simplest form, urbanisation is viewed as reducing recharge by waterproofing surfaces, or impermeabilization (Lerner & Barret 1996). But several studies have shown that this is not always the case (Barret 2004, Lerner 1989, Price & Reed 1989). The complexity of urban water balance compared with rural catchments is a major challenge for water resources management in cities (Lerner 1990, Foster & Morris 1994). Losses by leakage from the city supply mains, combined sewers, pluvial drains, together with percolation from roof runoff/paved area soak-aways, provide sources of near-surface recharge additional to those available in rural areas. At the same time, impermeabilization of the land surface by buildings and paved areas changes the scope for local precipitation to enter the aquifer (Lerner & Barret 2004). The resultant effect of these complicate both the quantification of net recharge to the aquifer and the prediction of the effects such recharge may have on groundwater quality (Cox et al. 1996, Eiswirth and Hotzl 1994).

### *1.2.3 Groundwater contamination*

Contamination of groundwater can occur whenever there is a source releasing contaminants to the environment. The various sources of groundwater contamination have been classed according to human activities ranging from agricultural practices, sanitation and mining (Adelana & Xu 2006). An idea of the more common types of activity capable of causing significant groundwater pollution hazard can be gained from Table 2. The size, density and the location of a settlement have been found to determine the degree or intensity of pollution or potential pollution to that area within the environment (DWAF 1999). In the Cape Town area, several potential point-pollution sources were identified (Adelana & Xu 2006). These include chemical and pharmaceutical industries, long existence of a major harbour, with reported contaminated waters, urban infrastructure, and particularly sanitary landfills and pipeline outlet disposal. In addition, salt-water intrusion inland from the sea also poses pollution threats to groundwater. This has not attracted much research attention in South Africa, especially in the Western Cape with its long coastline.

### *1.2.4 Strategies for groundwater protection and pollution control*

A common approach to groundwater protection has been to concentrate the protection efforts on capture zones of wells or well fields in order to secure drinking water quality; in order words, wellhead protection zoning (USEPA 1987). The possibilities and limitations to the approach have also been discussed (Lerner & Kumar 1991, Adams et al. 1992, Batt 1993, Evers & Lerner 1998). Wellhead protection zoning fulfils the purpose of protecting the existing use of the groundwater only, without taking into consideration other values or the sustainability of the resource. It is therefore, preferable to issue strong land use restrictions in the whole capture zone of the well, as any contaminant that enters the subsurface may finally end up in the well. However, as these areas can sometimes be extensive, it is often impracticable or economically unjustifiable (Scarp et al. 1997).

Table 2: Common pollution sources and associated groundwater contaminants

| Pollution source | Type of contaminant | Potential impact |
|---|---|---|
| Agricultural Activity | Nitrates; ammonium; pesticides; fecal organisms | Health risk to users (e.g. infant methemoglobinemia), toxic/carcinogenic |
| *In-situ* Sanitation | Nitrates; fecal organisms; trace synthetic hydrocarbons | Health risk to users, eutrophication of water bodies |
| Gasoline Filling Stations & Garages | Benzene; other aromatic hydrocarbons; phenols; some halogenated hydrocarbons | Carcinogens & toxic compounds, odour and taste |
| Solid Waste Disposal | Ammonium; salinity; some halogenated hydrocarbons; heavy metals | Health risk to users, eutrophication of water bodies, odour & taste |
| Metal Industries | Trichloroethylene; tetrachloroethylene; other halogenated hydrocarbons; heavy metals; phenols; cyanide | Carcinogens & toxic elements (As, Cn) |
| Painting and Enamel Works | Alkylbenzene; tetrachloroethylene; other halogenated hydrocarbons; metals; some aromatic hydrocarbons | Carcinogens & toxic elements |
| Timber Industry | Pentachlorophenol; some aromatic hydrocarbons | Carcinogens & toxic elements |
| Dry Cleaning | Trichloroethylene; tetrachloroethylene | Carcinogens & toxic elements |
| Pesticide Manufacture | Various halogenated hydrocarbons; phenols; arsenic | Toxic/carcinogenic compounds |
| Sewage Sludge Disposal | Nitrates; various halogenated hydrocarbons; lead; zinc | Health risk to users, eutrophication of water bodies, odour & tastes |
| Leather Tanneries | Chromium; various halogenated hydrocarbons; phenols | |
| Oil and Gas Exploration/Extraction | Salinity (sodium chloride); aromatic hydrocarbons | May increase concentrations of some compounds to toxic levels |
| Metalliferous and Coal Mining | Acidity; various heavy metals; iron; sulphates | Acidification of groundwater & toxic leached heavy metals |

Source: Adelana & Xu 2006 (modified from Foster et al. 2002)



The practical approach is to divide the capture zone of the well into several zones to allow for differentiation in the land-use restrictions. Comprehensive systems for land-surface zoning taking into consideration protection of the groundwater resource as a whole, as well as capture zones, have been discussed in Adams and Foster (1992), Foster et al. (2002). In modern day terminology, the protection of groundwater resources may be based on different methodologies involving preventive actions (to avoid future pollution) and remediation actions (to control the pollution threat posed by existing and past activities). Prevention of environmental contamination is the key to efficient and effective environmental management. This is particularly true in the case of groundwater. Article 6 of the Groundwater Directive includes measures to prevent or limit inputs of pollutants into groundwater (Directive 2000/60/EC, Water Framework Directive 2006). Incorporating preventive measures like this into the existing water laws will go a long way in ensuring groundwater quality here and elsewhere beyond the region.

The establishment of site-specific protection zones, with regulation of land use within them and the Resource Directed Measures (RDM) under the South African Water Act of 1998 has been seen as a possible way forward in future groundwater management in South Africa.

### *1.3 Outline of chapters*

The various chapters in this thesis are outlined as follows:

Chapter 1: gives the background to the study outlining the inventory of groundwater situation with respect to current groundwater research and socio-economic interests as outlined in the objective. A literature review on groundwater resource evaluation, concept of, and common groundwater pollutants, and previous contamination events in the study area are described in this chapter.

Chapter 2: describes the physical processes and the research methodology employed in the present study, monitoring data, methods of field and laboratory measurements during this study are described. Detailed descriptions of the monitoring network and procedures for water and sediments characteristics are explained. Data availability, data sources and processing are also described.

Chapters 3: gives an outline of the study area in terms of physiographic description (topography and climate), vegetation patterns, soil types, population and land use. A regional and local geology of the study area has been described in details in this chapter.

Chapter 4: presents the hydrogeological framework, conceptual hydrogeological model and analyses of rainfall time series were interpreted and discussed in relation to groundwater recharge. Series of pumping tests carried out at the UWC test site (near the main gate, Bellville South) and at iThemba Labs (Faure), used to determine the aquifer characteristics. This is corroborated with the data obtained by Gerber (1981) and Meyer (2001).

Chapter 5: presents the results of recharge estimation in the study area (using different approaches); recharge processes and mechanism are presented with a conceptual model of recharge in the Cape Flats. Knowledge of the various recharge processes and their relative contributions are of fundamental importance for establishing a realistic water resources development plan for the area. A comparative analysis of the methods applied in the recharge estimation is also presented and discussed. The flow pattern of groundwater with respect to the local hydrogeologic conditions is presented and discussed.

Chapter 6: presents the results of the field and laboratory analyses which have been employed to assess the quality of the waters; and to ascertain the groundwater systematics. Major ion trends, minor and trace element data have been used in the elucidation of physical and chemical processes controlling groundwater chemistry in the study area. Hydrochemical evolution and characteristics of groundwater of the study area were also discussed based on these results.

Chapter 7: gives a framework for groundwater protection in the study area. The assessment of aquifer pollution vulnerability and implications for groundwater resource protection are discussed in this chapter.

Chapter 8: summarizes the main results and findings from this research study. The summary of discussions and synthesis of ideas are presented with implications for groundwater management. Conclusions based on the objectives of this study are drawn with appropriate recommendations.

## OPERATIONAL DEFINITIONS

### Groundwater recharge

In the sense in which recharge is implied in this study the following definition seems more appropriate: It is water that percolates into the lower limits of the vadose zone, reaching the water table and subsequently, causing a measurable water-table rise (Sophocleous and Perry 1985). Such recharge can be from precipitation, from surface watercourses and/or from other aquifers.

### Vulnerability

Throughout this thesis, the term vulnerability will be defined as the likelihood that contaminants will reach the phreatic surface after introduction at some location above the uppermost aquifer. Accordingly, vulnerability refers to the likelihood of groundwater contamination. It is dependent solely on hydrogeologic factors such as soil type and rainfall (Bekesi & McConchie 2000).

### Vulnerability assessments

The term vulnerability assessment defines the process of assigning numbers, ranks, or categories to areas and time intervals thought to effect aquifer vulnerability (Bekesi 1998). It includes the testing and verification of such a vulnerability assessment. The product of a vulnerability assessment is almost always a vulnerability map, or a set of maps.

### Pollution risk

Pollution risk on the other hand is the function of the hydrogeologic conditions and agronomic practices, including contaminant loading and contaminant characteristics. Aquifers with high vulnerability may have no, or negligible, pollution risk because of the absence of any potential contaminants (Foster 1987). An aquifer may also exhibit a high pollution risk to nitrate pollution while having a small risk to heavy metal contamination because of the different characteristics of those contaminants.

**Well and borehole**

The word well or wellbore itself, (from Oil and Gas glossary), includes the openhole or uncased portion of the well, often cylindrical (Wilson and Moore 1998); borehole may refer to the inside diameter of the wellbore wall, the rock face that bounds the drilled hole.

In Civil Engineering, Geophysics, Mining & Quarrying, it is a deep hole or shaft sunk into the earth to obtain water, oil, gas, or brine.

In Geophysics, an exploratory well refer to a small-diameter well drilled especially to obtain water. A borehole refer to the hole drilled by the bit; a wellbore may have casing in it or it may be open (uncased); or part of it may be cased, and part of it may be open; also called a borehole or hole. In this sense in which these words are used and throughout this thesis, the word well and borehole are used to refer a drill hole into groundwater for the purpose of exploitation or monitoring.

# CHAPTER 2: APPROACH AND METHODOLOGY

## 2.1 General description of research methodology

This research project evaluates groundwater occurrence, aquifer characteristics, groundwater recharge and groundwater quality (chemical characteristics and evolution) of the Cape Flats aquifer. The research that went into this thesis can be divided into two main studies: (i) groundwater resources evaluation (ii) the development of a framework for strategic groundwater protection.

The project focused on improving the understanding of groundwater systems in the area of the Western Cape covered by sand. Groundwater recharge rates were determined based on chloride mass balance calculations, groundwater level fluctuation, stream discharge and a number of empirical methods. Aquifer characteristics as well as the behaviour of groundwater movement in the Cape Flats were determined from pumping tests. Hydrochemical evaluation was used to describe the chemical characteristics of groundwater (using major, minor elements and isotope data) and evolution of groundwater in the study area. Integrating the results from hydrochemical-isotopic and hydraulic parameters in order to obtain refined recharge estimates and describe recharge processes in the study area is of paramount importance. The knowledge of recharge rates is fundamental to proper assessment of the extent of groundwater resources and their long-term availability, particularly in the context of water supply planning. The quality and characteristics of this groundwater resource are significant to its development for municipal water supply. Assessment of aquifer vulnerability to the increasing urban polluting influences is paramount to protection of groundwater resources in the study area. Therefore, this research employed a number of methods to estimate recharge, determine aquifer characteristics and hydrochemical evolution of groundwater in the study area and develop strategies for groundwater protection.

## 2.2 Data collection

Compilation of data: Collation of existing data on climate, geology, hydrogeology and hydrochemistry from various databases and maps was done. Available data (i.e. basic borehole information, water levels and chemical data) on the Cape Flats collated from DWAF, CSIR, Council for Geosciences, City of Cape Town and climatic information (from the South African Weather Service) were presented in a workable format, analyzed and interpreted to give useful hydrological characteristics of the study area. Long-term climatic data, water level measurements and stream discharges were analyzed statistically and interpreted to give recharge estimates for the study area.

Field sampling: Fieldwork included sampling of water from boreholes, hand-dug wells, and ponds for physico-chemical and stable isotopic analyses. At each borehole or well site, water was pumped for about 5 minutes to obtain representative water samples. Parameters such as pH, electrical conductivity, as well as temperature were measured immediately at the various sampling points since these parameters are subject to drastic changes with time.

## 2.3 Analytical description



Laboratory analyses: Each water sample collected in the field were further analyzed in the laboratories for total dissolves solids (TDS), major and minor/trace elements as well as stable naturally-occurring isotopes of oxygen (O-18), and hydrogen (H-2).

i. Determination of the main chemical constituents

The main cations and anions determined in the laboratory include: Na, K, Ca, Mg, Cl, $SO_4$, $NO_3$, Br, F, $PO_4$. The content of the major ions for the water samples in the study area would help to explain the groundwater chemistry. The factor controlling the water chemistry were assessed and possible changes in groundwater composition would be traced along the flow path of the coastal aquifer system to give the overall chemical evolution of waters in the study area.

ii. Determination of minor constituents

Minor/trace elements such as Cu, Al, Pb, Zn, As, Cd, Cr, Mn, and $H_2S$ were also analysed for in the water samples using ICP-MS method. The results of these analyses (and isotopic data) were used to assess the quality of the waters and to ascertain the groundwater recharge conditions corroborating. Although major elements generally constitute more than 95 % of the total ionic concentration of groundwaters, some hydrogeochemical processes cannot be identified through the interpretation of major ion chemistry, as the relative variation of the concentrations of elements is small. The analysis of specific minor and trace elements have been used in the past to assist the interpretation of groundwater systems (Edmunds et al. 1987, Edmunds 1995, Edmunds & Smedley 2000, Herczeg & Edmunds 2000, Jankowski & Schofield 2001). Hydrochemical data thus collected were interpreted using various forms of log- and semi-log plots, piper and schoeller diagrams (Piper 1944, Derec & Louvier 1973) and so on.

<u>Recharge estimation techniques</u>

The main techniques used in the estimation of groundwater recharge are classified into physical and chemical methods (Allison 1988, Foster 1988, Cook & Herczeg 2002). The physical methods involve (i) meterologic and soil-crop data processing to determine hydrologic balance or the soilwater balance; (ii) hydrologic data interpretation, including water table fluctuations, and differential stream flow analysis; (iii) The Hydraulic or Darcian approach), including the estimation of water fluxes beneath the root zone using hydraulic conductivity functions and water potential gradient. The chemical methods involve chemical and isotopic analysis of pore fluids from the saturated and unsaturated zones.

In South Africa, the methods previously applied have been summarized in a schematic presentation (Bredenkamp et al. 1995, Xu & Beekman 2003) to provide a logical structure and have been grouped into categories relating to the following:

(i) The unsaturated zone which includes lysimeters studies, soil moisture flow and balances, use of tritium profiles, chloride profiles in the soil overlying an aquifer.

(ii) The saturated zone which includes an analysis of groundwater hydrographs, water balances of delineated aquifers, the analysis of spring flow, the saturated volume fluctuation method, and the cumulative rainfall departure method (CRD).

(iii) Modeling of groundwater flow and the water balance, incorporating the determination of recharge, storativity and transmissivity by inverse solution techniques, the direct parameter estimation method involving a multiple linear regression (inverse) fit of water balance parameters, hydrological models based on conceptual hydrological interrelationships.

(iv) Steady state flow approximations which involves applying Darcy's law, incorporating the flow through a cross-section of the aquifer.

(v) Rainfall-recharge relationship expressed by a regression-type simulation of the groundwater recharge in accordance with some conceptual logic built into the formulae.

(vi) Natural radioisotopes used to reveal mixing and transient flow within an aquifer system.

(vii) Natural stable isotopes such as $^{18}O$ and $^{2}H$ are commonly used to reveal groundwater characteristics and to distinguish between waters of different origin.

The detailed procedure for each of the techniques and adaptation to be used are described in the literature (Bredenkamp et al. 1995, Walker et al. 2002, Xu & Beekman 2003) while those applied in this study are discussed in Chapter 5.



**2.4 Data processing**

The research was designed to assess the National Groundwater Databse and factual materials, in particular, about the state of chemical composition of the Cape Flats aquifer and its variation in time, as well as to identify sources of chemical variations. This is further progress on the earlier work of Henzen (1973) and Vandoolaeghe (1989) on the groundwater quality aspects towards the Cape Flats groundwater development pilot abstraction scheme. A large number of chemical data exist in the DWAF database, which has not been interpreted or published. New sampling will be carried out to fill as many data gaps as possible.

The sources available are groundwater, river water and water from canals or irrigation ponds. The methodology involves analyzing and interpreting the existing chemical data of the NGDB under the Western Cape region. Large datasets have accumulated for the City of Cape Town and suburbs – over 1,000 chemical analyses with the first sets of measurements recorded in 1967.

About 200 boreholes with different yearly records of chemical data are interpreted in Chapter 6. More than a hundred of these wells are screened in the Cape Flats sands and were sampled for major ions and trace element chemistry. The results of this sampling are stored in a database managed by the Department of Water Affairs & Forestry. During the course of this research (2005-2007) sampling for chemistry and stable isotope analyses have also been carried out on selected wells. Series of pumping tests were carried out on three wells from two sites (University of the Western Cape, UWC test site, and iThemba Labs experimental borehole). Field parameters, including water temperature and EC were determined during pumping using standard probes. Samples were also collected during the pumping exercise for full chemical analyses of anions, cations and trace metals. The locations of the sampled boreholes are shown in figures 33, 45 and 47).

Rain samples collected from the rain samplers installed at UWC, iThemba Labs and rainwater from Belhar residential area were analysed for chloride for the purpose of recharge estimation (Adelana et al. 2006). Sampler installed at a private property later became inaccessible due to lack of continued cooperation. Prior to sampling for analysis, groundwater was pumped for about 5 minutes. The samples collected during this research (2005-2007) were in most cases filtered using 0.45-µm millipore filter paper and stored in 150 ml polyethylene bottles. All samples were stored at 4 °C prior to laboratory analysis. The pH, electrical conductivity (EC) and total dissolved solids (TDS) were determined at the site using portable field kits. The carbonate and bicarbonate were determined by acid titration; chloride by $AgNO_3$ titration; sulphate by a titrimetric method using barium perchlorate after passing the samples through cation exchange resin; phosphate by ascorbic acid method using spectrophotometer; calcium and magnesium by EDTA titration; and sodium and potassium by flame photometry in the laboratory (BEMLABS Somerset West, Cape Town).

## 2.5 Accuracy of determinations

Charge balances between cations and anions were determined using Hydrogeochemical Analysis Model in excel (HAM) (Kan et al. 2004) and Aqueous Geochemical data analysis and Plotting, "AquaChem" (Waterloo 1999). The observed charge balance for most locations is within ±10 %, which is acceptable for waters of moderate TDS (Eaton et al. 1995). Ninety percent (90 %) of all the data falls in the ±5 % ionic balance error range while 98 % are within the ±10 % range. Few samples outside these limits have high $HCO_3^-$ concentrations suggesting errors in titration. Analysis of stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) was also performed in order to identify recharge processes since the content of $^{18}O$ may vary as a function of the average altitude of recharge. Stable isotope analyses were performed in two laboratories, Monash University (School of Geosciences, Melbourne, Australia) using a Finnigan MAT 252 mass spectrometer and the Leibniz Institute for Applied Geosciences (GGA, Geochronology and Isotope Hydrology, Hannover, Germany). $\delta^{18}O$ values were measured via equilibration with $CO_2$ at 25 °C for 24–48 h. $\delta^{2}H$ values were measured via reaction with Cr at 850 °C using an automated Finnigan MAT H/Device. $\delta^{18}O$ and $\delta^{2}H$ values were measured relative to internal standards that were calibrated using IAEA SMOW, GISP, and SLAP standards. Data were normalized following Coplen (1988) and are expressed relative to V-SMOW where $\delta^{18}O$ and $\delta^{2}H$ values of SLAP are −55.5‰ and −428‰, respectively. Many samples were analyzed at least twice and the precision (1σ) is: $\delta^{18}O$ = ±0.1‰; $\delta^{2}H$ = ±1‰.

## 2.6 Interpretation methods

The datasets are divided into 3: 1967-2001, 2003-2007 and wells or groundwater sources with consistent few years' record were singled out for separate interpretation (Philippi 1985-1989; Newlands Spring 1994-2006). Besides, 25 boreholes, 6 springs, 8 surface water (included 2 polluted rivers and 6 canals/reservoirs), and selected rain episodes between 2005 and 2006 were sampled for hydrochemical analysis; selection was according to geographic location and accessibility. These, in addition to the dataset 2003-2007 (from the NGDB database), were interpreted to show present day quality status of groundwater from the Cape Flats aquifer. All the data sets were prepared in excel and interpreted with HAM as recommended (Kan et al. 2004) and AquaChem version 3.7 for Windows (Waterloo 1999).

## 2.7 Summary

In Chapters One and Two the various concept of groundwater contamination, urbanization and recharge are defined and described as it relates to resource evaluation. Various aspects relating to water resources availability and ranging from demand to water supply quality, in relation to current research on groundwater have been described. Several previous studies on exploration, developmental techniques, contamination, digital flow modelling and artificial recharge to groundwater in the Cape Flats were reviewed in order to define the objectives and scope of the present work. The general description of research methodology and approach of the present study are highlighted. Mode of data collection, analytical descriptions and accuracy of determinations were also presented. Chapter Three, therefore will focus on physiographic description (topography and climate), vegetation patterns, soil types, population and landuse as well as regional and local geology of the study area.

# CHAPTER 3: PHYSICAL DESCRIPTION AND GEOLOGY OF THE STUDY AREA

## 3.1 Introduction

The Cape Metropolitan Area (CMA) covers an area of 2, 159 $km^2$, and is largely surrounded by the Atlantic Ocean to the west and south with the most prominent landmass being the Cape Peninsula, attached to the mainland by the sandy plain of the Cape Flats. The CMA is enclosed by mountains to the north and east. The key study area discussed in this thesis is located towards the southernmost end of the continent of Africa. The various major and minor catchments of the CMA have been described in Chapter One. The geographical location of the sand-covered coastal plain known as the Cape Flats is shown in figure 2 with the full description given in this chapter. The Cape Flats area is characterized by a high potential for groundwater resources and represents one of the areas of dense human settlement, with increasing industrial and agricultural activities.

## 3.2 Location and coverage of the study area

The Cape Flats therefore represents a region of broad coastal sand between the Cape Peninsula and mainland. The Cape Peninsula is situated near the southernmost western coast of South Africa. The sands, which cover an area of approximately 630 $km^2$, extend in a northerly direction along the west coast (Figure 2). Generally, the Cape Flats is taken to be the area bounded by the Cape Town-Muizenberg, Cape Town-Bellville-Kraaifontein, Bellville-Eerste River-Strand railway lines and the False Bay coast; with a narrow strip of sand along the western coast, extending northwards from Cape Town and Bellville through Blouberstrand up till Atlantis (Figure 2). The selected area is the Cape Flats sands, which is more susceptible to pollution as a result of industrialization, urbanization and intense use of the land area for waste disposal and agricultural purposes. The area extent of this research project is the entire Cenozoic sand cover of the Western Cape, particularly, the southern part where basic data and borehole information are available.

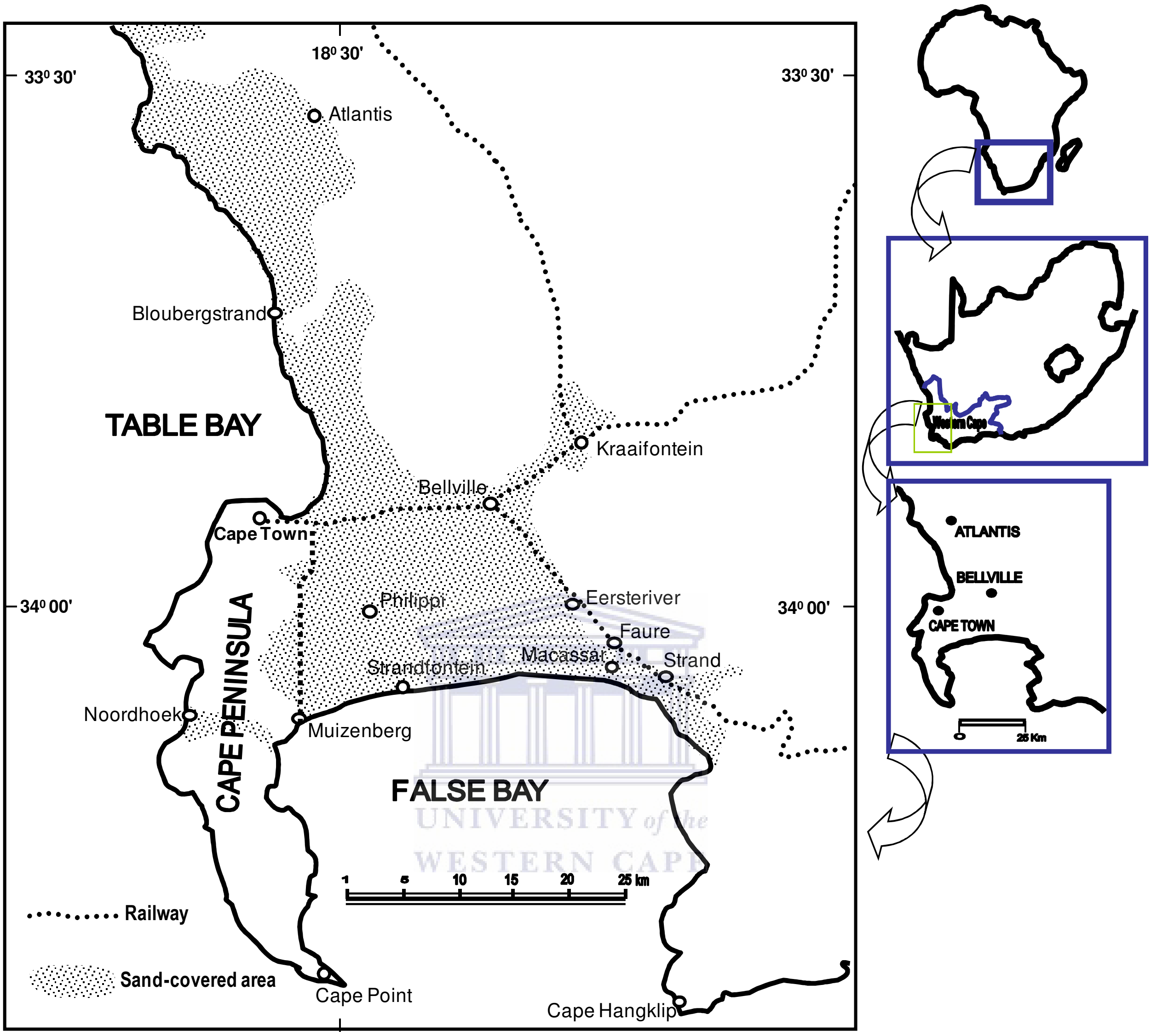



Figure 2: Location of the Cape Flats sand in the Western Cape, South Africa

## 3.3 Physiographic description

### *3.3.1 Topography*

The Cape Flats area is essentially lowland with an average elevation of 30 m. Generally, the CMA has a varied terrain ranging from low-lying sandy plains to rocky mountains. The most dramatic terrain is located along the Cape Peninsula, a spine of mountains extending some 56 kilometres from Table Mountain in the north to Cape Point in the south (Figure 2). The Cape Peninsula mountain chain is a series of peaks, rising to Maclear's Beacon (1038 m) on Table Mountain and dropping dramatically to the sea in many parts of the Peninsula. Topographical features are varied and include narrow flats, kloofs and gorges, cliffs, rocky shores, wave-cut platforms, small bays and sandy and gravel beaches.

On the Cape Flats, sand dunes are frequent with a prevalent southeasterly orientation; and the highest dunes are only 65 m above sea level. The sand is derived from two main sources: (i) weathering followed by deposition, under marine conditions, of the quartzite and sandstone of the Malmesbury Formation and the Table Mountain Series; (ii) the beaches in the area, from where Aeolian sand was deposited as dunes on top of the marine sands. According to Henzen (1973), the marine sands were deposited in accordance with the prevailing sea level and one typically finds that the sand body is horizontally stratified. Portions of the area are covered by calcareous sands and surface limestone deposits while silcrete, marine clays and bottom sediments of small inland water bodies also occur sporadically (Gerber 1976, 1981). The bedrock bounding the deposits was penetrated during several cases of test drilling, from which it was concluded that the bedrock surface may be assumed impermeable (Gerber 1981).

The almost horizontal sandstones of the Table Mountain were originally linked to the same Formations capping the mountains on the eastern fringes of the Cape Flats. Post-Palaeozoic erosion has removed the sandstones between the False Bay and the Table Bay. Rivers have carved valleys to both False Bay and Table Bay, while surf-zone erosion during transgressions has formed marine platforms in the south-east corner of the Cape Flats. This fluvial marine erosion has shaped the topography of deeply weathered Malmesbury Group and Cape Granite bedrock on the Cape Flats (Hartnady and Rogers, 1990). The False Bay is one of the largest natural embayments in South Africa with sides 30 km in length and has an area of 1000 $km^2$. The eastern and western shores are rocky whilst the north shore is a sweeping beach stretching from Muizenberg to Gordon's Bay (CSIR 1982).

### *3.3.2 Climate*

South Africa is situated almost completely within the high pressure belt of the southern hemisphere, which at sea-level is located around 30º S latitude. This is the reason why South African climate is largely arid to semi-arid (Schalke 1973). The high pressure belt is subject to a seasonal displacement of 4º latitude, its centre being located further south in February. Due to unequal heating of the land in summer and in winter, its high pressure belt splits up into two cells, one at the Atlantic side and the other above the Indian Ocean (Schalke 1973). Another important element of the air circulation influencing the climate of South Africa is the presence of the circumpolar Westerly Winds to the south of the high pressure belt. These Westerly Winds, which at sea-level occur at 35˚ S latitude, are found at much lower latitudes in the upper atmosphere. Consequently, the weather changes in South Africa are largely determined by perturbations in the westerly circulation of the Southern Hemisphere, though in summer to a lesser extent than in winter. These phenomena may explain the Mediterranean type of climate prevailing in the south-western coastal region (Schulze 1974).



The Cape Flats has a typical Mediterranean climate but the generally mountainous nature of the Cape Fold Belt results in the entire region having sharp changes in climate. The climate of Cape Town, which is situated at the border of the Cape Flats, reveals annual precipitation of the Cape Flats area varies between 400 and 500 mm, with a dry period from November to April, and that the mean annual temperature is approximately 17˚ C (Figure 3). According to Walter and Leith (1960), a period is to be called arid when the precipitation curve stays below the temperature curve; this is usually the experience in Cape Town area during the summer months. However, the prevailing southeast trade winds in summer are replaced by northwest anti-trade winds in winter, the latter spelling rainy weather. Very strong winds are frequent and characteristic of the Cape Town weather.

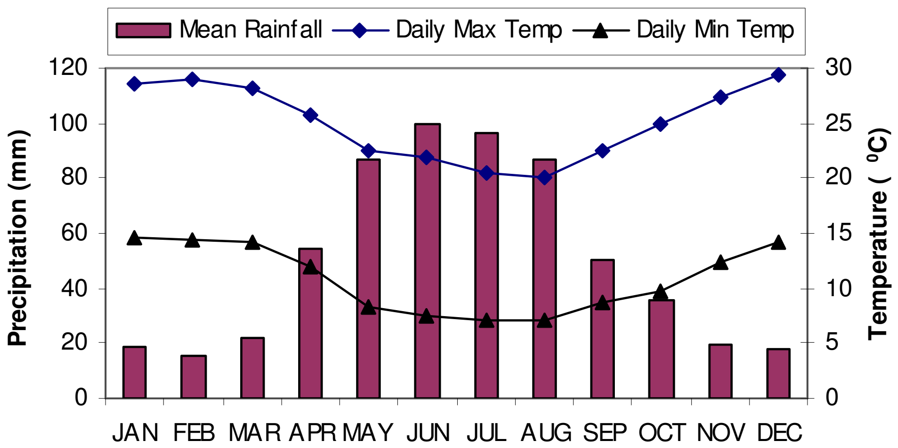



Figure 3: Mean Temperature variation with monthly rainfall in Cape Town (1933-2006)

The continental margin of South Africa causes the deviation of the westerly cold ocean current towards and along the western coast of Africa (see Figure 4). This branch is called the Benguela current and has, of the coast near Cape Town, a mean annual temperature of 12 ˚C with a variation of 2-3 ˚C (Schalke 1973). The Cape Flats, therefore, has a typical Mediterranean climate with cold wet winters and warm dry summers. There is a variable rainfall gradient within the CMA; rainfall is largely controlled by topography and is concentrated within the winter months. The generally mountainous nature of the Cape Fold Belt results in the entire region having sharp changes in climate.

The rainfall over the CMA is influenced by the steep peaks in the Cape Peninsula mountain chain as well as the Helderberg and the Hottentots Holland mountain range to the east of the CMA (see Figure 5). As a result the annual rainfall varies greatly within the CMA – from between 500 mm and 1700 mm on the Cape Peninsula, to between 500 mm and 800 mm on the Cape Flats, and ranging from 800 to over 2600 mm in the mountains to the east of the CMA. Cape Town International Airport situated on the Cape Flats receives 554 mm/a (South African Weather Bureau 2006).

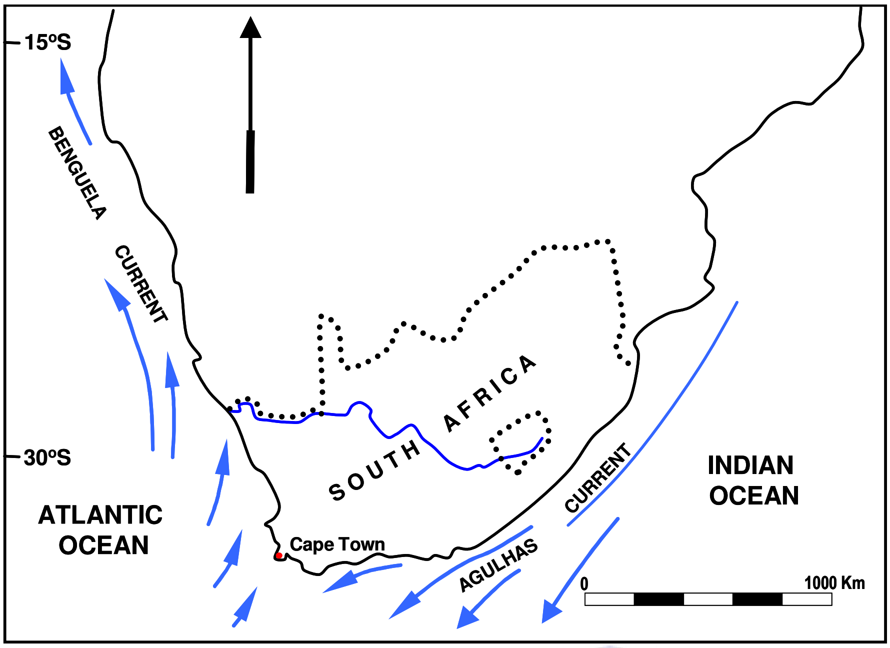



Figure 4: Map of southern Africa showing principal ocean currents

To the northeast of the Cape Flats area lies a semi-arid to arid climatic region with an annual precipitation of less than 250 mm. Temperature fluctuations occur both diurnally and seasonally with a period of frost from June to September each year (see Figure 3). The climate in the coastal region east of the Cape Flats area is rather uniform, having a higher annual precipitation (about 1100 mm in the mountains and 400 mm on the plains) evenly distributed over the year (Schalke 1973). The average daily maximum temperature of the CMA is about 28 °C in mid-summer and 17 °C in mid winter. The variation of the mean annual temperature with precipitation amount for the period 1933 to 2006 has been illustrated in Figure 3. Due to the moderating influence of the sea, temperatures rarely fall below 0 °C or rise above 35 °C. As with rainfall, temperature is also influenced by the topography of the CMA. Temperature can therefore vary depending on micro-climatic conditions that exist in the area.

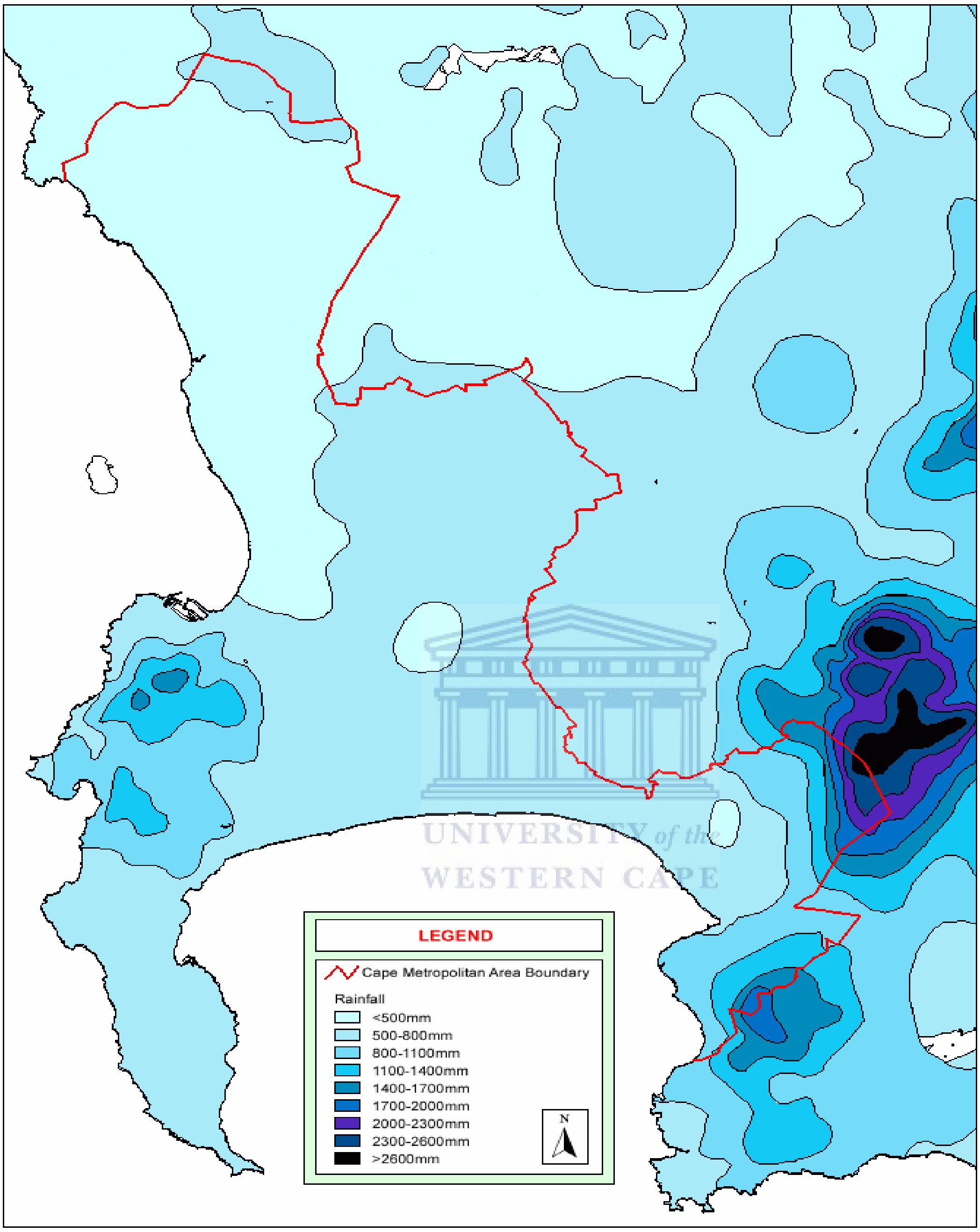



Figure 5: Distribution of rainfall in the Cape Metropolitan Area; E-W along the southern coast is approximately 45 km (CMC 1999)

### *3.3.3 Drainage*

In several depressions, flat marshy sites - locally named 'vleis'- are present which sometimes contain open water and are connected by a river with the sea (Stephens 1929, Schalke 1973). The drainage system is represented by the Eerste River, Kuils River and the Diep River, as well as Zeekoevlei and other open water bodies (Figure 6). Other streams and creeks are Lourens, Elsieskraal, Lotus Hout, Sout, Liesbeek, and Sir Lowry's Pass, which are mostly tributaries discharging into the main rivers.. The Diep and Sout rivers drain southwesterly to the sea at Table Bay while drainage towards the south takes place by the Eerste River and by the Zeekoevlei into False Bay.

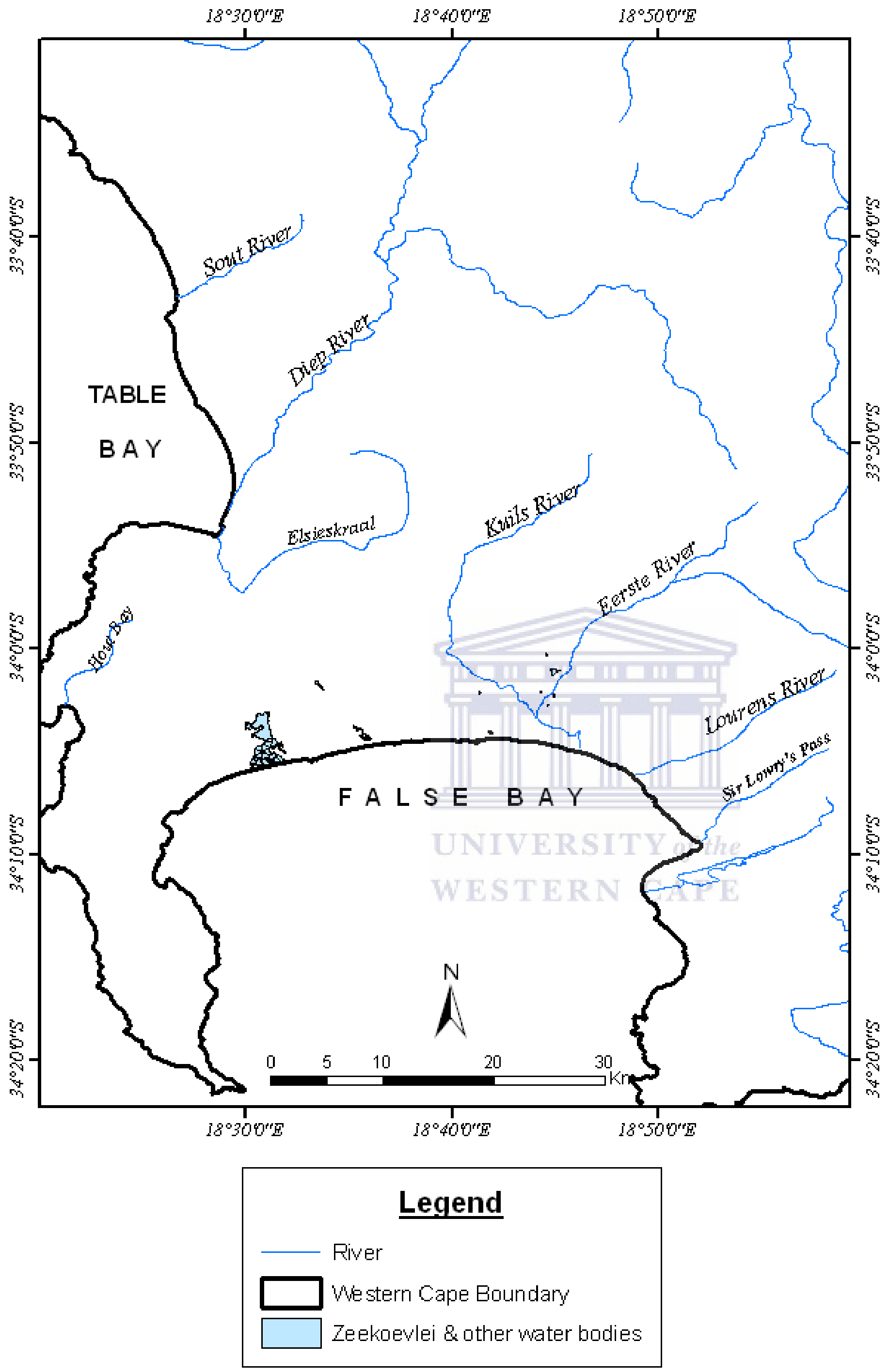



Figure 6: Rivers within CMA catchments

The plains of the Cape Flats extend from the Cape Peninsula to the Hottentots Holland Mountains in the east and Atlantis in the north (CMC 1999). The undulating plains and koppies of the CMA are sandy and interspersed with some larger koppies, with a diversity of slopes and hollows, landforms and drainage lines. False Bay is characterized by long stretches of sandy beaches and coastal dunes. This varied terrain leads to a diversity of habitats and micro-climates.

### *3.3.4 Soil type of the Cape Town area*

In the broad sense, the term soil is used to include surficial material, the product of parent material (geological rock type), slope, and a variety of chiefly climate-driven processes interacting over time. The inorganic component of soil can be regarded as the product of mechanical and chemical weathering. Within the CMA, geology and slope, and soil, are closely allied. The soils of the CMA, which form the basis for all habitats, can be placed in three groupings (McVicar 1991):

(i) Shallow, acidic, sandy soils derived from TMG sandstone. Such soils occur on, or close to mountain slopes. They are nutrient-poor, have poor water retention properties and although they provide an apparently inhospitable medium for plant growth, fynbos vegetation has adapted to these harsh growing conditions.

(ii) Deeper, sandy, calcareous soils of the low-lying areas. They are less acidic than the previous type and their nutrient status, while still low, is higher than the previous group. The low-lying nature of the environment in which they typically occur implies that these soils are often subject to water-logging during the winter months.

(iii) Soils derived from the weathering of parent material which is relatively rich in clay. Typically, these soils are found on granitic suites to the north east of the CMA (Paarl, Stellenbosch areas) as well as on Malmesbury Group shales in the Swartland to the north of the CMA. Because they contain significant proportions of clay, their nutrient status and water-holding capacity is superior to the previous two types. This group displays the widest variety in terms of depth, profiles and mineralogical make-up. However, for the sake of convenience, they are grouped here as one.

Other surfaces in the CMA (as illustrated in Figure 7) comprise the following:

(i) Bare rock surfaces and very thin sandy veneers;

(ii) Wetlands and marshy areas;

(iii) Alluvial soils along drainage lines (in some cases, brackish);

(iv) Talus, rock debris and scree (boulder-rich slope deposits); and

(v) Built and paved areas.

### *3.3.6 Population and land use*

The City of Cape Town is a large urban area with a high population density; one of South Africa's six metropolitan municipalities. It represents centers of economic activity with complex and diverse economies, a single area with integrated development planning and strong interdependent social and economic linkages. The City of Cape Town includes the Cape Metropolitan Council, Blaauwberg, Cape Town CBD, Helderberg, Oostenberg, South Peninsula and Tygerberg (CCT 2006). In 1996, the total population of South Africa was over 40 million (Central Statistical Services 1997). It was estimated that about 4 million people live within the Western Cape Province, with 3.5 million living in urban places (Central Statistical Services 1996). The Western Cape Province has the second highest percentage urbanized population (almost 89 %) in South Africa after Gauteng Province. A selection of pictures in Appendix 2.1 shows current land use and open land surface in the Cape Flats.

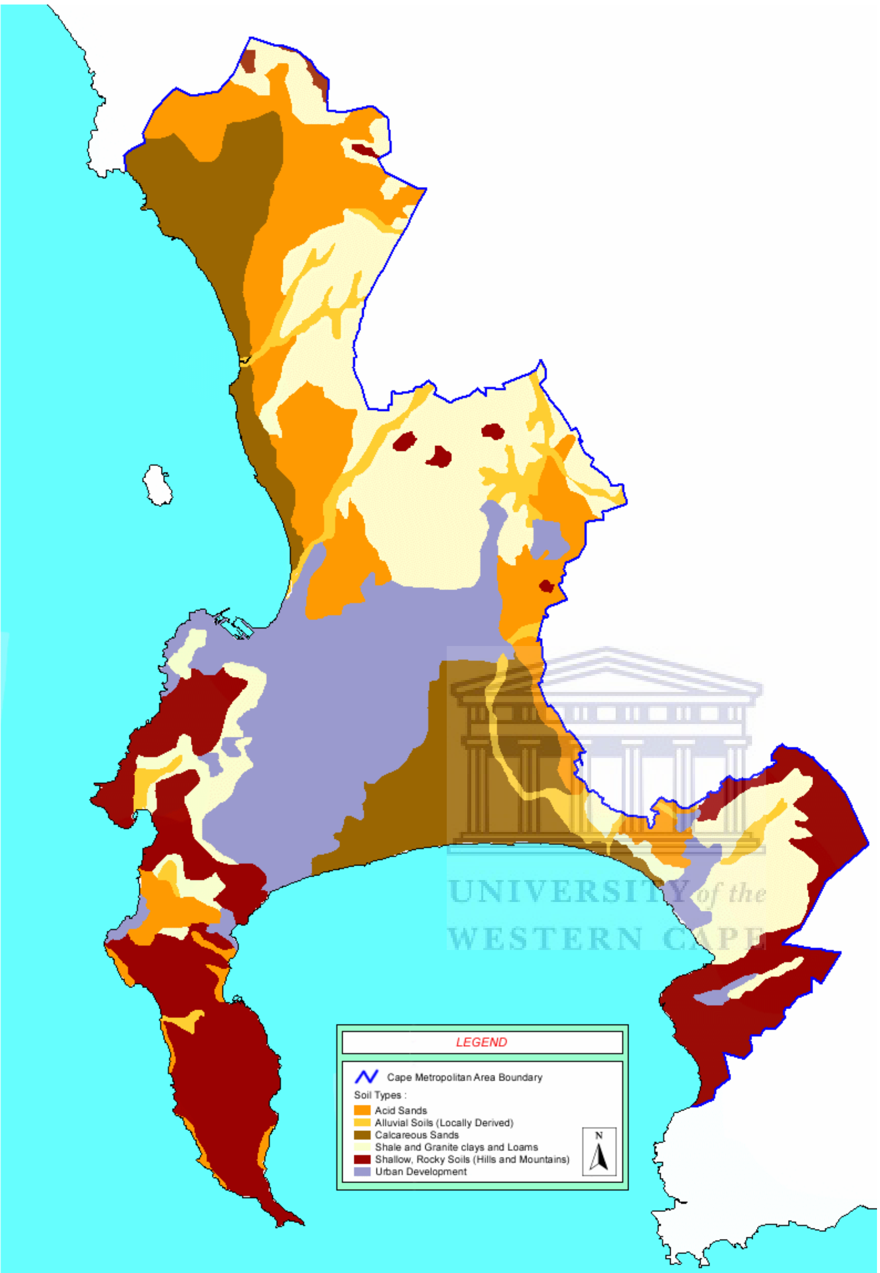




Figure 7: Soil type of the Cape Town area (CMC 1999a/b)

In 1996 the population of the CMA was approximately 2.56 million (Central Statistical Services 1997). Natural population growth, combined with urbanization, gave rise to a population growth rate of approximately 2 % per annum (Bekker & van Zyl 1998). The population estimate for 1998 was 2.9 million (CMC 1999a/b), 3.08 million in 2001 and currently estimated at 3.48 million. This represents an increase of more than 700,000 people between 1996 and 2006 (CCT 2006).

The general distribution of population in the CMA by local metropolitan council areas is shown in Table 3.2.6 and illustrated in Figure 8. Approximately 68 % of the population is found in the City of Cape Town and City of Tygerberg, with the City of Cape Town experiencing the highest population density. The 2001 population density per $km^2$ by suburb produced by the City of Cape Town is presented in Appendix 3.1.



Table 3: Population distribution for the CMA by municipal area (1996)

| LOCAL AUTHORITY | PERCENTAGE POPULATION | PERCENTAGE OF TOTAL AREA |
|---|---|---|
| Blaauwberg Municipality | 4.6% | 25.6% (551 $km^2$ ) |
| City of Cape Town | 36.6% | 13% (280 $km^2$) |
| City of Tygerberg | 32.3% | 19.7% (423 $km^2$) |
| Helderberg Municipality | 4.8% | 15.2% (328 $km^2$) |
| Oostenberg Municipality | 9.3% | 7.5% (162 $km^2$) |
| South Peninsula Municipality | 12.3% | 18.9% (407 $km^2$) |
| **Cape Metropolitan Council (total)** | **100%** | **100% (2 151 $km^2$)** |

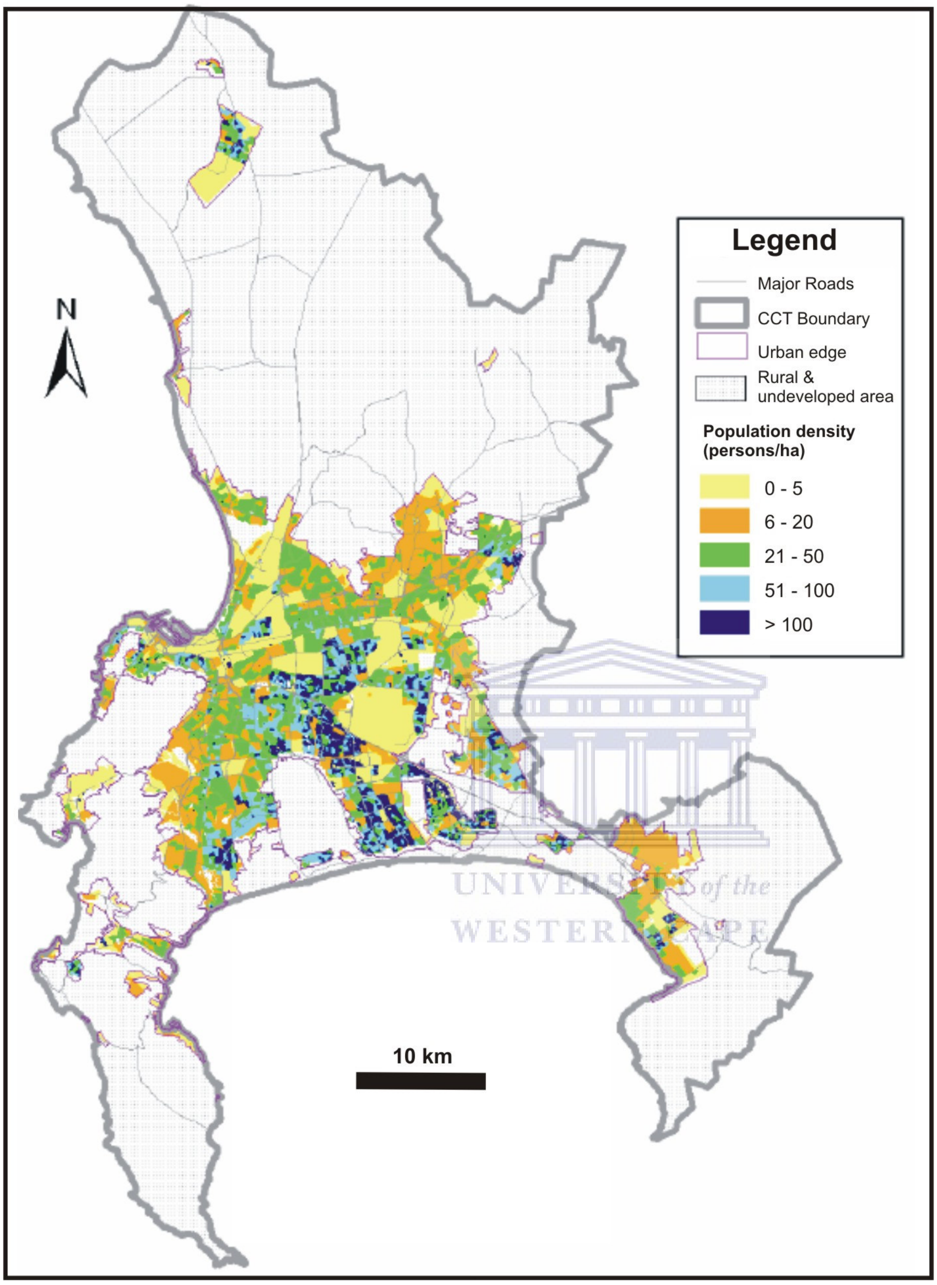



Figure 8: The city of Cape Town Metropolitan Municipality with population density

## 3.4 Geology of the study area

### *3.4.1 Regional geology of the Western Cape*

The oldest rocks in the Western Cape are meta-sediments of the pre-Cambrian Malmesbury Group (Ne), which occupy the coastal plain between Saldanha and False Bay in the west, to the first mountain ranges in the east. Several erosional windows to this group are exposed in mainly fault-controlled valleys further to the east and south, of which the Breede River valley is the most conspicuous (Meyer 2001). The Malmesbury Group consists of low grade metamorphic rocks such as phyllitic shale, quartz and sericitic schist, siltstone, sandstone and greywacke.

Several granite plutons of the Cape Granite Suite (N-Ec) have intruded the Malmesbury Group. About ten plutons have been identified between Saldanha and Somerset West. Apart from the major pre-Cape granite intrusions into the Malmesbury Group, a number of mafic dykes were intruded into the Malmesbury Group and Cape Granite Suite, especially in the Cape Peninsula, Worcester and Wellington areas. These dykes often occur in swams, with a north-westerly to north-easterly strike direction (Gresse & Theron 1992).

The Klipheuwel Group (Ek), which of Cambrian age, is younger than the Cape Granite suite and consists of conglomerate, sandstone and shale. The Cape Supergroup, which occupies most of the Western and Eastern Cape, was deposited in a trough from early Ordovician to late Devonian age (Tankard et al. 1982) and can be differentiated into (from the lowermost to the top): the arenaceous TMG, which unconformably overlie the Malmesbury, Klipheuwel and Cape Granites. This is conformably followed by the argillaceous beds of the Bokkeveld Group and then, finally, the alternating shales and sandstones of the uppermost Witteberg Group (Theron et al. 1992, Meyer 2001).

The Karoo Supergroup is represented by the basal glacial diamectite of the Dwyka Group, followed by the predominantly argillaceous Ecca Group and the shales and sandstones of the Beaufort Group. Deposits of Conglomerate with interbedded sandstone lenses of the late Jurassic Enon Conglomerate Formation (Uitenhage Group) occur along the Worcester Fault between Worcester and Heidelberg (Figure 9).

Late-Tertiary to Recent sediments, up to 50 m thick (ranging in age between 12-0 Ma) overlay the older rocks in this area. Limited occurrences of Coastal Sands were deposited mainly along the coast between Agulhas and the Breede River Mouth (Meyer 2001). Considerable deposits of alluvium consisting of clay, sand pebbles and boulders occur in the valley of the Breed River and its tributaries.

The dominant rock type underlying the soils throughout most of the CMA is from the Malmesbury Group (Theron et al. 1992), which is broadly classified as a type of shale. Shale derived soils (clays) are most easily seen in the Tygerberg area, on the Peninsula and near Somerset West. The two other main rock formations are sandstone from the TMG and granites from the Cape Granite Suite (Theron et al. 1992). Detailed lithological and structural descriptions of the TMG and Cape Granites are given in Wu (2005) and Jia (2007).

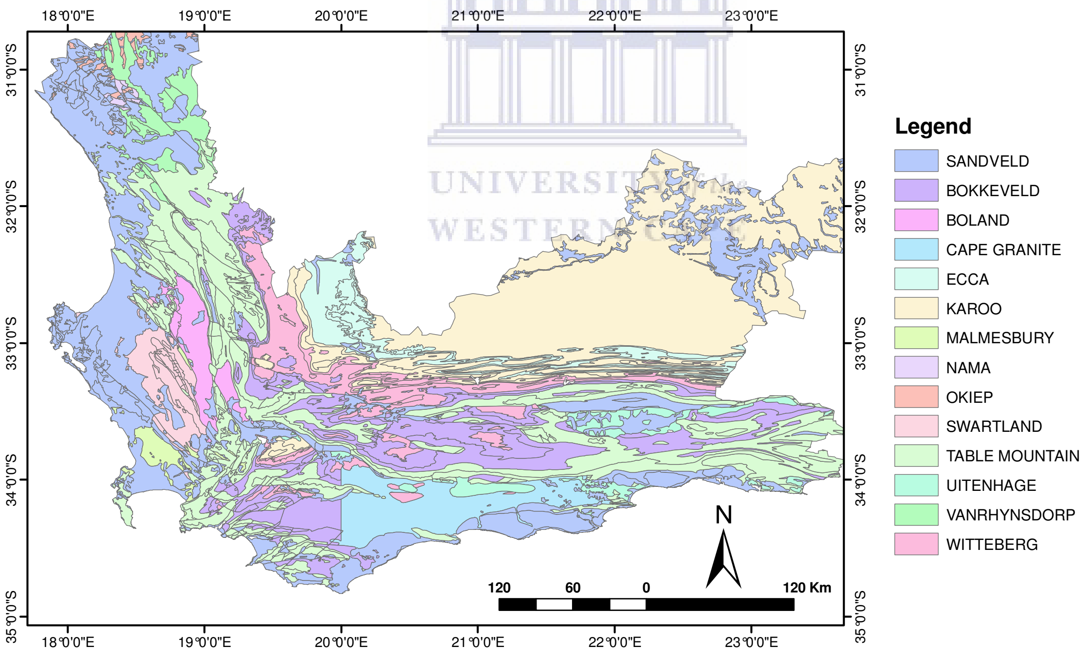



Figure 9: Regional geological map of the Western Cape showing principal lithological units

### *3.4.2 Geology of the Cape Flats*

The Cape Flats is a component of the 'Late-Tertiary and Recent sands' unit of the geological map edited by Haughton (1969) and the revised editions (Theron et al. 1992), which are in places up to 50 m thick (as discussed in Section 3.3.1). Figure 10 shows the location and geological map of the area around the Cape Flats, in the Southwestern Cape. Although this cover is rather thin in relation its wide lateral extent, practically no outcrops occur. On the Cape Flats (and along the coastal plain between Cape Town and Saldanha) are essentially sediments of Quaternary age that blankets the Neogene deposits, of which little is known except from boreholes and quarries (Theron et al. 1992). These are all Cenozoic sediments of the Western Cape (west of Cape Hangklip) now referred to as the ***Sandveld Group***, a name earlier restricted to the Elandsfontein and Varswater Formations by Hendey and Dingle (1983) see Table 4. Thus, the Sandveld Group now includes Quaternary sediments formerly incorporated with the 'Bredasdorp Formation' (Visser & Schoch 1973, Rogers 1982) while the Bredasdorp Group is restricted to Cenozoic Formations east of Cape Hangklip (Malan 1987, Theron et al. 1992).

The basement of the Cape Flats is composed of Precambrian and Palaeozoic rocks belonging to the Cape granite, the Malmesbury Formation, and the Table Mountain Sandstone (Schalke 1973; Theron et al. 1992). The Cape Flats is assumed to have been developed after the closure of the 'Cape Strait', which at one time united False Bay with Table Bay, by lowering of the sea-level and a probable rise of the basement (Walker 1952). Along the coast of the Cape Peninsula and on sites where a cliff-coast is present, raised beaches have been found as evidence of former fluctuations in sea level (Schalke 1973). The ancient beaches at the levels 18-27 m and 5-6 m are the best known (Schalke 1973); and are supposed to be of Eemian age and correlated with the Mediteranean Monasterian levels (Krige 1927). The highest of these beaches exhibits evidence of a fossil warm water fauna, whereas the lower one contains a cool water fauna similar to the recent one. According to Krige (1927), the explanation of this phenomenon can be found in the ancient 'Cape Strait', which at that was a passage for the warm Agulhas current with its accompanying fauna but became closed later on in the Eemian.

The sands are derived from two sources as described in section 3.3. The marine sands were deposited in accordance with the prevailing sea level and the sand body is horizontally stratified with several lithostratigraphic units identified (Table 4). The process of sedimentation was initiated in a shallow marine environment, subsequently progressing into intermediate beach and wind-blown deposits, and finally to Aeolian and marshy conditions, which led to the formation of peaty lenses in the sands.

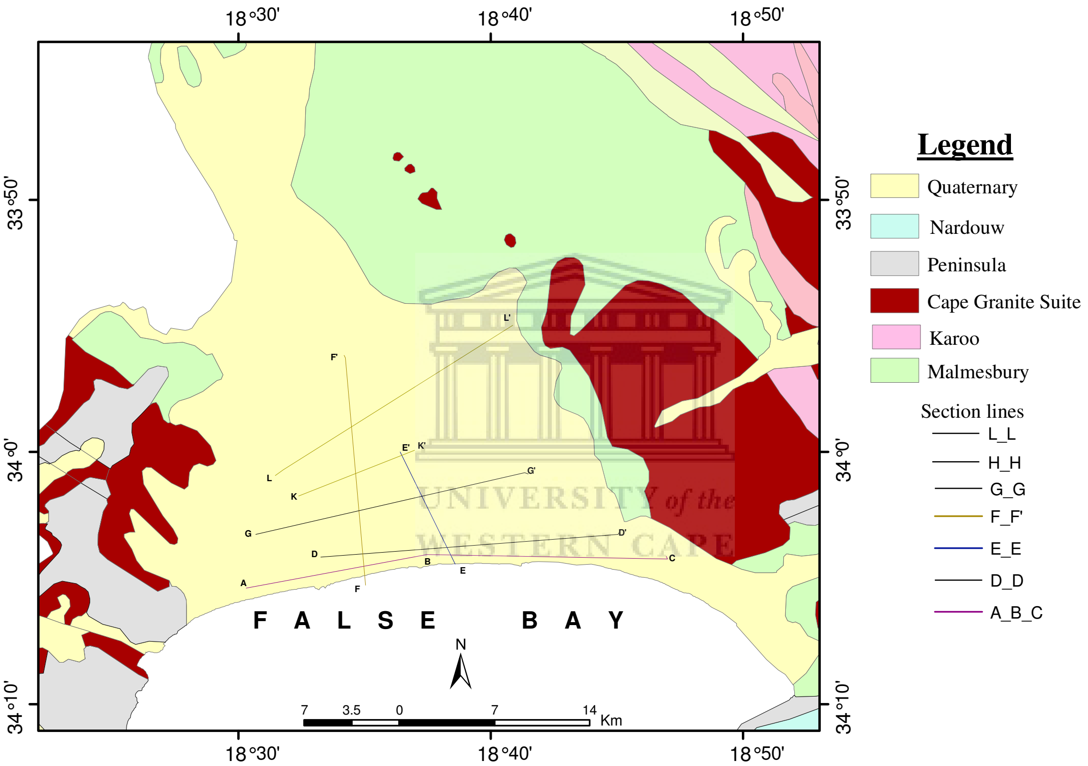



Figure 10: Location and geological map of the area around the Cape Flats

According to Henzen (1973), portions of the area of the Cape Flats (particularly along the False Bay coast between Muizenberg and Macassar) are covered by calcareous sands and surface limestone deposits while silcrete, marine clays and bottom sediments of small inland vlei deposits also occur sporadically (Hartnady & Rogers 1990). The detailed geology of the Cape Flats has been reported in Henzen (1973) and the full description of the various lithostratigraphic units is presented in Section 3.3.2.1. The bedrock topography shows that there is a Palaeo-valley reaching more than 40 m below mean sea level towards the northeastern portion of the area.

### *3.4.2.1 Quaternary Deposits*

The Quaternary deposits of the Sandveld Group consist of the following Formations (with lithology in brackets): the basal Springfontein Formation (well sorted, fine- to medium-grained quartz sand, virtually free of mud), the Milnerton Formation* (Fluvial gravel, marine clay and littoral sand), the Velddrif Formation (partially consolidated lime-rich shelly beds, shellcoquina to clay and sand with shell layers), Langebaan Formation (aeolian, calcrete-capped, calcareous sandstone) and the Witzand Formation (fine- to coarse-grained calcareous coastal dune sand). As shown in Table 4, the quaternary deposits consist largely of aeolian sand, but minor fluvial to marine deposits also occur. The inter-relationships of the various formations are known from many boreholes and exposures within and outside the greater Cape Town area (Theron et al. 1992). Figure 11 shows the various geological sections based on available logs and information. The section lines are indicated on the geological map (see figure 10). Figure 12 illustrates the lithostratigraphic features at the University of the Western Cape (UWC) Test Site. In the following sections, the lithostratigraphic classification of the Quaternary deposits (from top to bottom, young to old) is described.

The Witzand Formation, which consists of very fine to very coarse calcareous sands, is easily recognized by the presence of abundant small shells and shell fragments. These Holocene sands, named the Witzand Formation after the calcareous dunes on Witzand 2, northeast of Melkbosstrand (Rogers 1980, 1982), form extensive system of parabolic, vegetation-bound coastal dunes which may be partially cemented (Theron et al. 1992). The Witzand Formation is light-coloured, calcareous, and distinctly recognizable from the underlying consolidated Langebaan Formation.

The Langebaan Formation is a Limestone Member of the Bredasdorp Group, which has been incorporated (in the recent nomenclature and re-grouping of the Cenozoic sediments) into Quaternary sediments of the Sandveld Group (Malan 1987, Theron et al. 1992). It is locally known as the Wolfgat Member, consisting of calcrete and very fine- to fine- calcareous sand. The limestones of the Langebaan Formation, which are in reality mostly calcarenites, overlie a wide variety of older units and are found from sea level to altitudes over 200 m (Theron et al. 1992).

Table 4: The Cenozoic Formations of the Western Cape (Modified from Theron et al. 1992)

| GROUP | FORMATION | DESCRIPTION | AGE | |
|---|---|---|---|---|
| SANDVELD | Witzand | Aeolian, calcareous, quartzose sand | Holocene | |
| | Langebaan (Wolfgat) | Aeolian, calcrete-capped, calcareous sandstone | Pleistocene | |
| | Velddrif | Littoral, calcrete-capped coquina | | |
| | Milnerton | Fluvial gravel, marine clay & littoral sand | | |
| | Springfontein (Philippi) | Aeolian, quartzose sand with intermittent peaty clays | | |
| | Varswater | Quartzose & muddy sand, and shally gravel, phosphate-rich | Pliocene | |
| | Saldanha | Conglomeratic sandy phosphorite | *Late* | Miocene |
| | Elandsfontein | Angular quartzose gravely sand & peaty clays | *Middle* | |



The Velddrif Formation is a patchy deposit of partially consolidated lime-rich beds of shell and sand with shelly layers; the type section of which is situated close to the Berg River mouth near Velddrif (Tankard 1975, Theron et al. 1992). Along the western shore of Langebaan Lagoon, the Velddrif Formation clearly underlies the aeolian calcareous Langebaan Formation and is exposed below Malgaskop, south of Saldanha, as well as at various localities along the Postberg Peninsula (Theron et al. 1992). Other occurrences are located south of the Modder River on diorite outcrops, at Swartklip parking area on the northern shore of False Bay, and at Noordhoek Beach (Rogers 1980, 1982, 1983; Barwis & Tankard 1983).

The Springfontein Formation is a fine- to medium-grained quartzose sand which, near the coast, is light grey-white to pale red in colour with less than 2 % mud (Rogers 1980). Grain size often increases with depth and thin calcareous clay and peat lenses may locally be present (Vandoolaeghe 1989). Phosphatised shell fragments and shark teeth are also found sporadically at various levels while in excavations, particularly on Duynefontein, a gastropod bed occurs within the basal laminated sand of this formation (Theron et al. 1992).

The Saldanha Formation is Late Miocene in age and consists of consolidated conglomeratic phosphorite, which is in places rich in whale, penguin, shark and mollusc fossils (Simpson 1973, Tankard 1974, 1975). Deposition of the Saldanha Formation clearly reflects a marine transgression in the Middle Miocene which succeeded the fluviatile deposition of the Elandsfontein Formation (described in the following section). The occurrences of these phosphatic exposures have been reported in the Hoedjiespunt Peninsula at Saldanha and on Langeberg (north of the map area), in the foundation excavations at Ysterplaat Air Force Base (east of the Table Bay) and in a quarry at Milnerton (Theron et al. 1992). The fossils indicated a Miocene-Pliocene age for the occurrences; however, Miocene marine sediments are probably more widespread in this area since rolled specimens of Neogene shark teeth are washed up on the Milnerton-Blouberg beach during winter storms (Theron et al. 1992).

### *3.4.2.2 The Neogene Deposits*

Underlying the Quaternary sediments, west of Cape Hangklip, are Neogene deposits which occur below present sea level (Theron 1992). The distribution of these deposits is controlled, to a large extent, by the topography of the bedrock which, from borehole and geophysical logging usually lies below 50 m b.s.l (Rogers 1980, De la Cruz and Du Plessis 1981, Smith 1982, Woodborne 1982, 1983, Timmerman 1988, Grindley et al. 1989). In the Cenozoic sediments of the Western Cape, the Neogene deposits include the Varswater Formation (Pliocene) underlain by the Late and Middle Miocene Saldanha and Elandsfontein Formations respectively (Table 4). The occurrence and lithological variations of this sequence are described in the following sections.

Varswater Formation is a marine deposit made up of very fine to medium silty sand that contains abundant small shells and shell fragments (Vandoolaeghe 1989). The formation constitutes the deposit of phosphatic sand which is internationally known for its rich Pliocene assemblage of vertebrate fossils (Hendey 1981a, b). Timmerman (1988) mapped the distribution of the Varswater Formation and found that this marine deposit is restricted to the western (i.e. seaward) parts of the major bedrock depressions east of Langebaan Lagoon and Saldanha Bay.

The sediments of the Elandsfontein Formation are angular, fine to coarse clayey sands identified as fluviatile deposits in several boreholes within the study area (Rogers 1980, 1982; Vandoolaeghe 1989). This formation is characterized by peat and peaty layers; and sometimes by cycles of angular, quartzose, gravelly sand fining upwards to cohesive (often peaty) clays, as observed in the type section in a borehole on Elandsfontein, west of Hopefield (Rogers 1982).

#### *3.4.2.3 Other Cenozoic Deposits*

There exist a number of other deposits of Cenozoic age, which have no formal names because their occurrences are restricted or as a result of the lack of information relating to interrelationships of the sediments. These include silcrete, ferricrete, scree and pediment gravel, fluvial and marine terrace gravel (Theron et al. 1992). Silcrete and ferricrete are both formed near the surface by groundwater concentrating iron oxide and/or silica derived from underlying weathered rocks. Silcrete varies from a yellow to a light-grey, fine- to coarse- grained, gritty or conglomeratic rock. Silcrete generally occur directly on or in the neighbourhood of weathered Malmesbury rocks, except near Noordhock where buried silcrete beds were encountered in boreholes at several levels to as deep as 40 m below present sea level (Theron et al. 1992). Ferricrete, on the other hand, has a considerably wider distribution in the study area than silcrete, and occur in the soil either as loose nodules or fragments a few millimeters to several centimeters in diameter, or as more compact zones of variable thickness. Ferricrete occur at Plattekloof and De grendel, near Parrow, where it is found as a hard, dark-brown knobbly rock (Theron et al. 1992) with honeycomb texture and more than one metre in thickness. Extensive scree deposits occur in the mountain chains of the Cape Peninsula which sometimes exceed 10 m in thickness and grade into pediment gravel and coarse-grained sands.

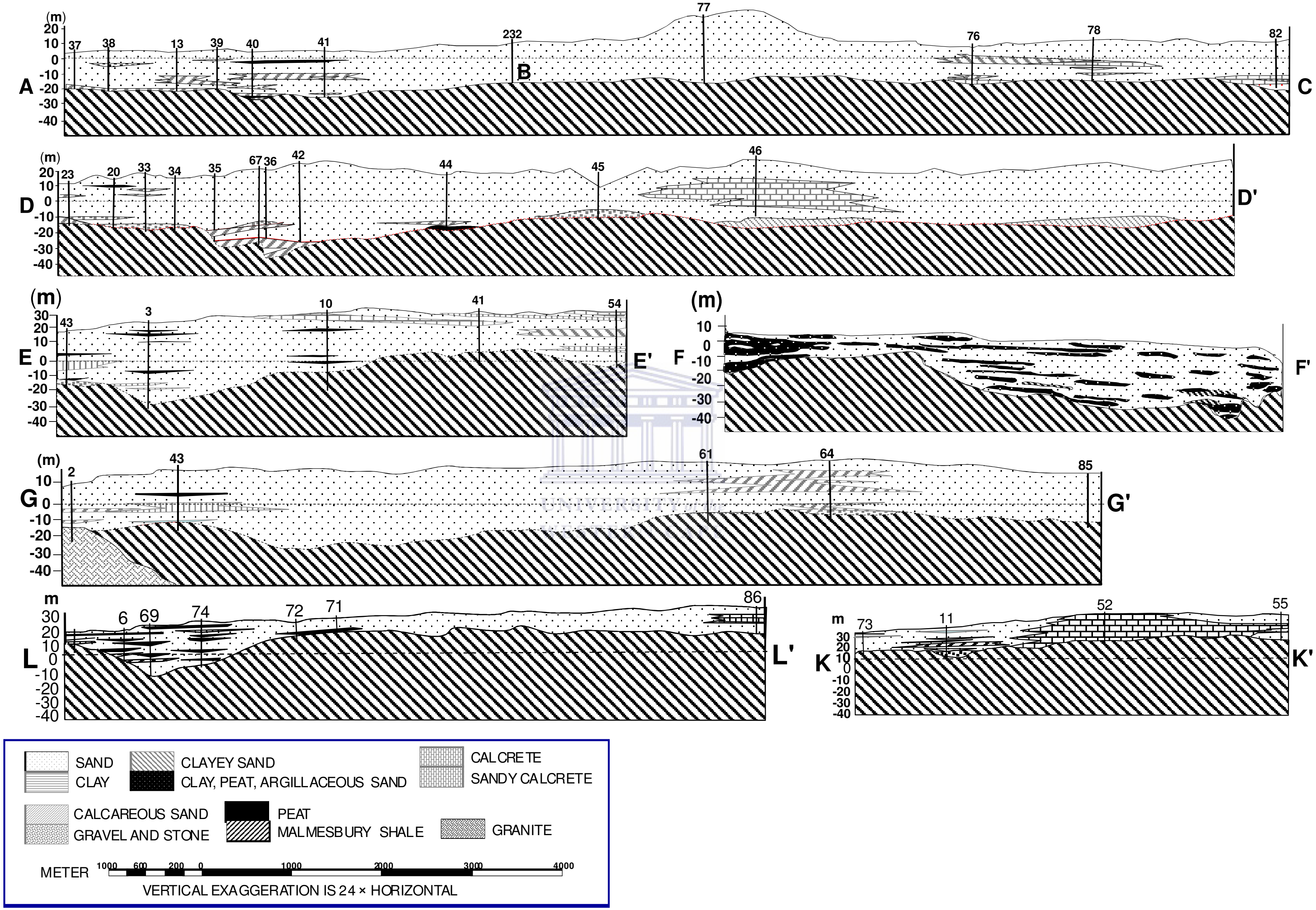



Figure 11: Selected geological cross-sections (lines indicated in figure 10) showing the inter-relationship of sediments in the study area

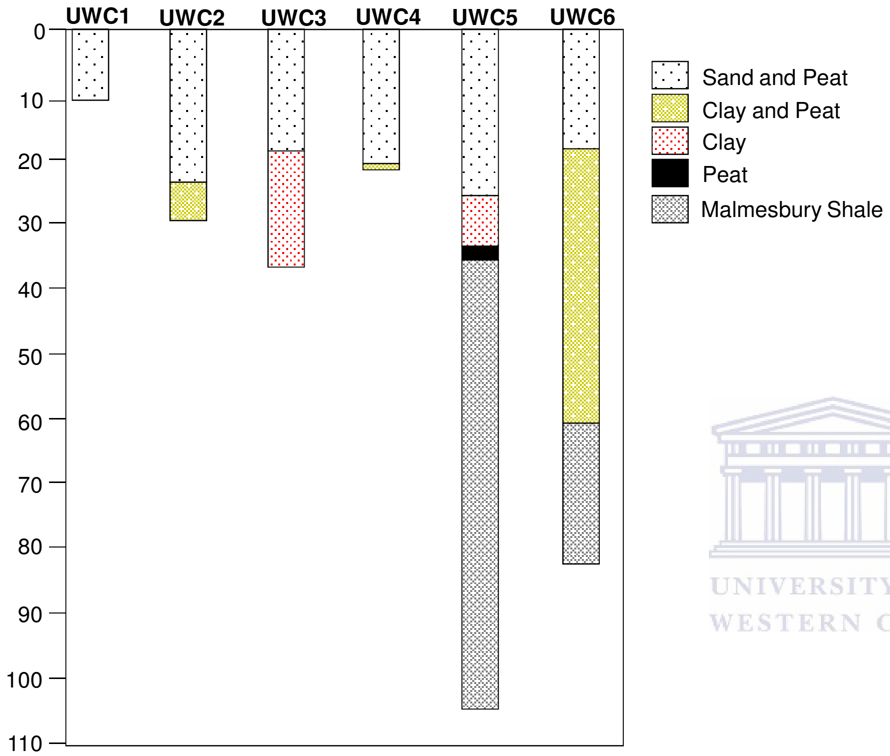



Figure 12: Litho-logs of some typical monitoring wells drilled at the UWC Test Site (vertical distance is in metres, horizontal distance is not to scale). The position of UWC Test Site is indicated in figure 47.

Terrace gravels can be related to either fluvial or marine environments of deposition. Shand (1917) recognized three distinct terraces along the Eerste River near Stellenbosch. The oldest, 14 m above present river level, has a basal, partly cemented conglomerate which is being successively overlain by grit, sand and clay. The middle terrace is 6 m above the river level and is covered with sand and boulders. The youngest terrace, 4 m above present river level, is covered by dark alluvial sands. Along the Berg River and its various tributaries similar terrace gravels occur at intervals from Kylemore to Wellington from 15 to 30 m above river level.

Along the coastline, from Saldannha to Betty's Bay, occur gravel beds on raised-beach terraces, of which several have been reported and described in the literature (Krige 1927, Haughton 1933, Gatehouse 1955, Lamming 1962, Parker 1968, Birch 1968, Visser & Schoch 1973, Davies 1973, Fleming 1977, Theron 1984). These have sometimes cut into granite at various levels on the Postberg Peninsula and islands in the Langebaan Lagoon are covered by shelly gravel and pebbles (Theron et al. 1992).

### *3.4.3 Geological history*

For much of the Peninsula the upper half is mainly Sandstone of the TMG, originally deposited by rivers up to 520 million years ago, overlying older Granite, which is 540 million years old. The oldest rocks are on Signal Hill, north of Lion's Head, which consist of the Malmesbury Group's marine siltstones (560 million years old). Zircon crystals were used for dating these rocks, which formed part of the ancient supercontinent Gondwana. For about 20 million years after the granite intrusion, the high 'Malmesbury' mountains and granites were gradually reduced by erosion to an almost flat surface, before the next cycle of sedimentation began. Then slowly-meandering rivers dropped their loads of sand in deltas and along the beaches of a shoreline very different from what we see today (Norman & Whitfield 2006).

About 250 million years ago – approximately 50 million years after the Cape sedimentation had ended – great welts of crust were seized by convulsions as the Cape Fold Belt was born. The new generation of fold mountains shed their detritus into the Karoo basin to the north for 70 million years, until crustal stretching began and vast tracts of Gondwana were covered by the floods of Drakensberg basalt that surged up the tensional fissures (Tankard et al 1982). As the stretching proceeds, and

Gondwana fragmented, at first the proto-Indian Ocean opened up and then the proto-Atlantic Ocean, 125 million years ago (Noman & Whitfield 2006, McCathy & Rubidge 2005, Tankard et al. 1982). Since Gondwana split up 130 million years ago, the Cape Flats has seen great changes, from high sea levels in the last few million years (which joined Table Bay to False Bay), to low sea levels as recently as 20 000 years ago (the Last Ice Age) when Robben Island, Table Bay and False Bay were all part of the mainland (Krige 1927, Walker 1952, 1956).

From geophysical evidence the sediments of the Malmesbury sequence accumulated partly on oceanic crust (De Beer 1983, De Beer et al. 1982) and the "Malmesbury Geosyncline" developed south and southwest of the Kalahari Craton about 980 to 830 Ma (Burger & Coertze 1973, Hartnady 1987, Theron et al. 1992). The earliest tectonic episode in the Saldanha sub-province (Hartnady 1969, 1987) preceded granitic intrusions dated between 630 and 500 Ma (Schoch 1975). Some of the granite intrusions show evidence of syn- to post-intrusive tectonism; and some of the youngest units of the Malmesbury Group may also post-date the earliest of the intrusive events (Theron et al. 1992). A broader perspective of the earlier tectonic episode in the Saldanha sub-province as well as the Cape Fold Belt and Cape Orogeny are documented and have been discussed exclusively in the literature (Hartnady 1969, 1987, Schoch 1975, Sohnge 1983, Theron 1984, Theron et al. 1992).



**3.5 Summary**

The physical and geological characteristics of the study area have been described. The regional geology of the study area was summarised while the local and the lithological variations of the Cape Flats have been discussed in detail in this chapter. Aspects of hydrology and hydrogeology, groundwater use, and groundwater data availability, which are important for management planning in the region, need to be described. Therefore in Chapter Four existing and new information are discussed to define a hydrogeological framework for the Cape Flats.

# CHAPTER 4: HYDROGEOLOGICAL FRAMEWORK

## 4.1 Hydrological Situation

This section deals with the evaluation of the hydrological characteristics of the study area in relation to groundwater resource management. Before discussion of management policies and impact on groundwater there is need to understand the conditions which prevailed previously in the study area. The most practical way to examine and compare water levels/potentiometric heads over time is the use of hydrographs as compiled from available data (for selected boreholes) and presented in this section.

A rainfall analysis and time series for Cape Town is presented in Section 4.1.1, with the data tabulated and presented in Appendix 4.1 and 4.2. While consistent monthly records exist for climatic data, the monitoring wells in the study area do not show matching and consistent records. From available record on selected DWAF monitoring and private boreholes in the study area seasonal contour maps have been generated and are presented in the appendix (4.3).



### *4.1.1 Climatic-hydrological conditions*

The climatic parameters are described and statistically interpreted. Long-term data are from the South African Weather Service in three stations (Cape Town Observatory/Airport, Somerset West and Kirstenbosch) and one measuring point (UWC test site) managed by the Western Cape Branch of the Department of Water Affairs, Bellville (see Table 5). There are more hydrological stations (managed by various organizations like the DWAF, CCT Catchment Monitoring, CSIR, etc.) in the study area, but for the quality and consistency of the datasets, they are not included in the interpretation and/discussion here. Only data from Cape Town Observatory/Airport (with complete climatic data) have been analyzed and interpreted in this study. Annual means of rainfall for other stations around Cape Town are as follows: Somerset West (576.1 mm), Kirstenbosch (1381.9 mm) and UWC (414 mm). The monthly values of precipitation in the Plain (the Cape Flats) are comparable and fluctuate in a similar pattern. Data from Kirstenbosch (located in the mountain-side) are higher and not comparable to the other stations. The annual difference can be attributed to the altitude.

*4.1.1.1 Analysis of rainfall*

Rainfall data measurement started in 1841 at Cape Town Astronomical Observatory, which was later taken over by Cape Town International Airport observatory. In this write-up, the station will be referred to as Cape Town Airport. Precipitation data from 1841-2006 measured at the Cape Town Airport were examined (Figure 13-16). The mean of total yearly rainfall over this period is 619.1 mm. Spatially averaged rainfall and temperature data were plotted to illustrate annual variability of rainfall in Cape Town. Figure 14 shows the mean of 10-year fluctuating in step-wise. The monthly means of precipitation is as shown in Figure 15 indicating precipitation was not evenly distributed through the year and mostly in the winter months. Rainfall, minimum and maximum temperatures are related to show climate variability over the years, and to illustrate the need for data monitoring in order to assess climate impact on groundwater (figure 16).

The plot of precipitation, minimum and maximum temperatures are shown in Figure 16. The average values with highest records of rainfall and temperature (from available daily records 1961-1991) are tabulated in Table 6.



Table 5: Rainfall stations within Cape Town Municipal used in this study

| Station | Latitude | Longitude | Altitude (m) | Period of Observation | No. of years | Annual Rainfall (mm) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Maximum | Minimum | Mean |
| Cape Town (SAAO)* | 33.97 | 18.6 | 42 | 1841-2006 | 164 | 1037.7 | 229.4 | 619.1 |
| Sommerset West | 34.15 | 18.85 | 10 | 1934-2006 | 71 | 1191.1 | 104.4 | 576.1 |
| Kirstenbosch | 34.00 | 18.43 | 160 | 1914-2006 | 91 | 2295.9 | 893.6 | 1381.9 |
| UWC, Bellville | 33.93 | 18.62 | 42 | 2002-2006 | 4 | 662 | 393. | 414 |

*SAAO = South African Astronomical Observatory; UWC = University of the Western Cape (Test site)

Table 6: Summary of climatological data for Cape Town Airport (1961-1991)

| Month | Temperature (° C) | | | | Precipitation (mm) | | |
|---|---|---|---|---|---|---|---|
| | Highest Recorded | Average Daily Maximum | Average Daily Minimum | Lowest Recorded | Average Monthly | Average Number of days with >= 1mm | Highest 24 Hour Rainfall |
| January | 39 | 26 | 16 | 7 | 15 | 6 | 41 |
| February | 38 | 27 | 16 | 6 | 17 | 5 | 27 |
| March | 41 | 25 | 14 | 5 | 20 | 5 | 42 |
| April | 39 | 23 | 12 | 2 | 41 | 8 | 39 |
| May | 34 | 20 | 9 | 1 | 69 | 11 | 65 |
| June | 30 | 18 | 8 | -1 | 93 | 13 | 58 |
| July | 29 | 18 | 7 | -1 | 82 | 12 | 61 |
| August | 32 | 18 | 8 | 0 | 77 | 14 | 56 |
| September | 33 | 19 | 9 | 0 | 40 | 10 | 29 |
| October | 37 | 21 | 11 | 1 | 30 | 9 | 53 |
| November | 40 | 24 | 13 | 4 | 14 | 5 | 30 |
| December | 35 | 25 | 15 | 6 | 17 | 6 | 21 |
| **Year** | **41** | **22** | **11** | **-1** | **515** | **103** | **65** |



Note: This climatological information is the normal values and, according to World Meteorological Organization (WMO), based on monthly averages for the 30-year period. A longer record of annual mean rainfall is presented in the following figures.

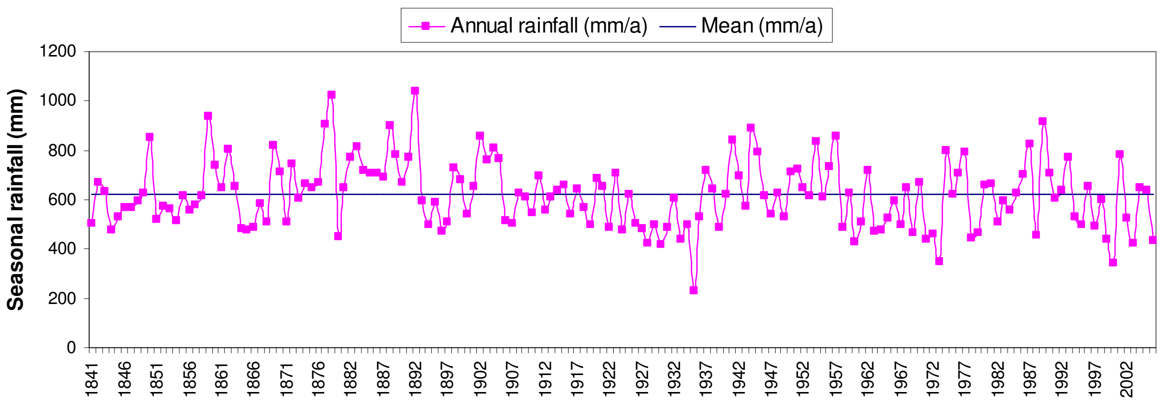



Figure 13: Variability of annual rainfall in Cape Town from a long-term record (1841-2006)

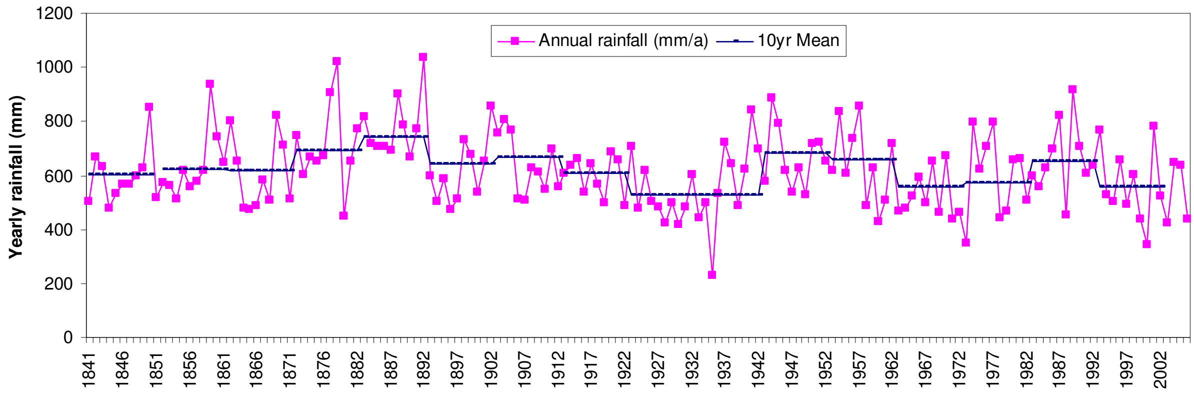



Figure 14: Long-term rainfall in Cape Town with strong variability in the 10-year-means

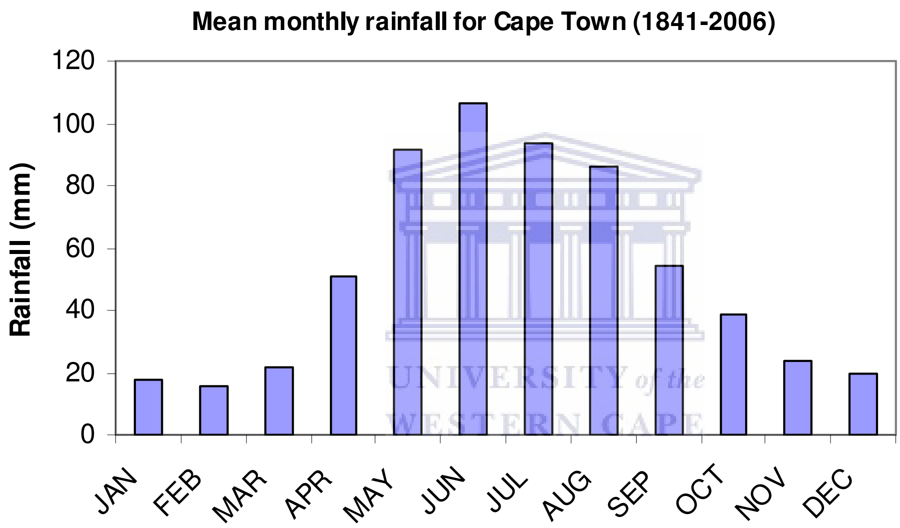



Figure 15: Mean monthly variations of rainfall in Cape Town

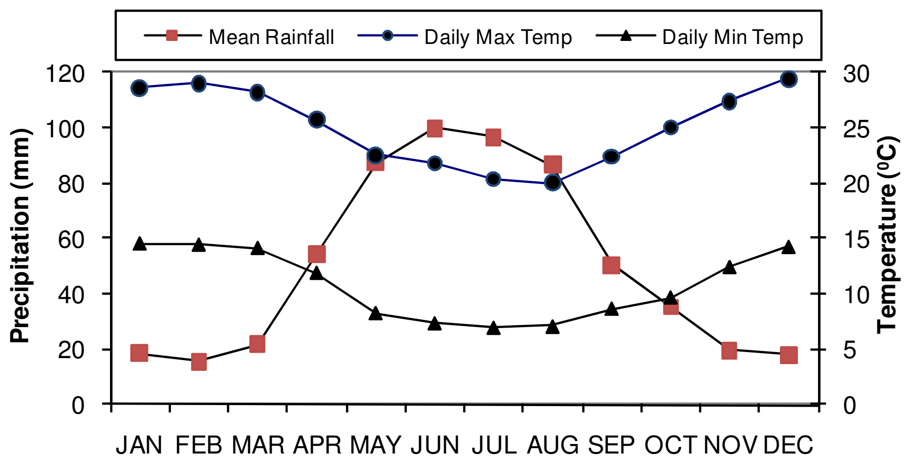



Figure 16: Mean monthly values of climatic data in Cape Town (Note: Rainfall averaged from 1841-2006; Temperature 1933-2006)

In Cape Town, the highest amount of precipitation fell in 1892 (1037 mm), the lowest in 1935 (229 mm). The maximum downpour is in June, while precipitation is in its minimum in February as shown in the mean monthly variations (see figure 15). In order to assess rainfall fluctuations, time series of yearly rainfall data of Cape Town Airport was analysed. The slope is almost nil and not very distinct when the entire period (1841-2006) was considered. However, the features of interest (e.g. positive and negative trend) become evident when the entire time series was analysed in segments as shown in Figure 17 (a,b,c).

Discussion of rainfall analysis

A segment of about 50 years (1841-1891) in the Cape Town Airport series, leads to a significant positive trend (Figure 17a), whereas a significant negative trend is noted when the 50 years segment is taken at the end of the record (Figure 17c). A change of mean was obvious when the average of annual rainfall for the entire record was calculated decade by decade (as shown in Figure 14). This made the pattern and variability of the precipitation in Cape Town obvious. The average of annual rainfall was increasing until 1891 as was shown in Figure 17a.

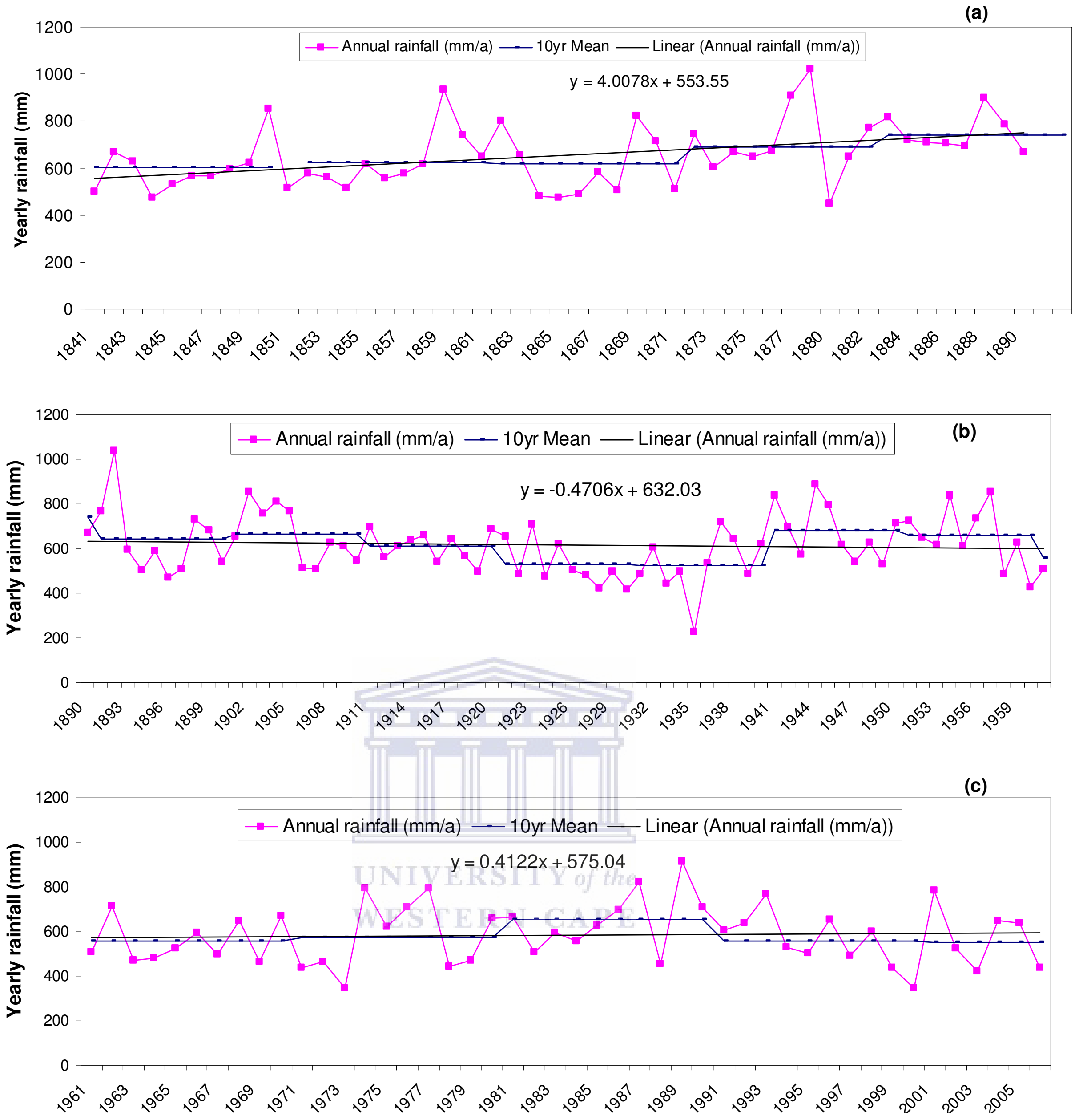



Figure 17 (a,b,c): Cape Town rainfall illustrating trends and mean of decades in segments of 50 years

From 1892 the trend showed continuous decrease up till 1941 but there was a "climatic jump" about 1941-1942. Such climatic jump occurred much later in the Sahel of Western Africa (about 1969-1970) as reported in the study by Hubert & Carbonnel (1987). This coincided with the period when the probability of a sudden change in the mean reached a maximum. Since then there has been much fluctuation in the pattern of rainfall in the study area. This is shown by the 'rising' and 'dropping' averages of the yearly rainfall (Figure 18). The figure shows that the years 1921-1941 were relatively dry periods, in which the least yearly rainfall (229.4 mm in 1935) was recorded. A similar pattern is observed lately (1999-2003) with the exception of year 2001 that showed a wetter record (784 mm). This is further illustrated in the yearly fluctuations and departure of yearly rainfall from the mean (Figure 19). The plots of clearly show the wet and dry years or decades. Consequently, this fluctuation in the rainfall pattern has serious implications for recharge and water management issues in the study area.

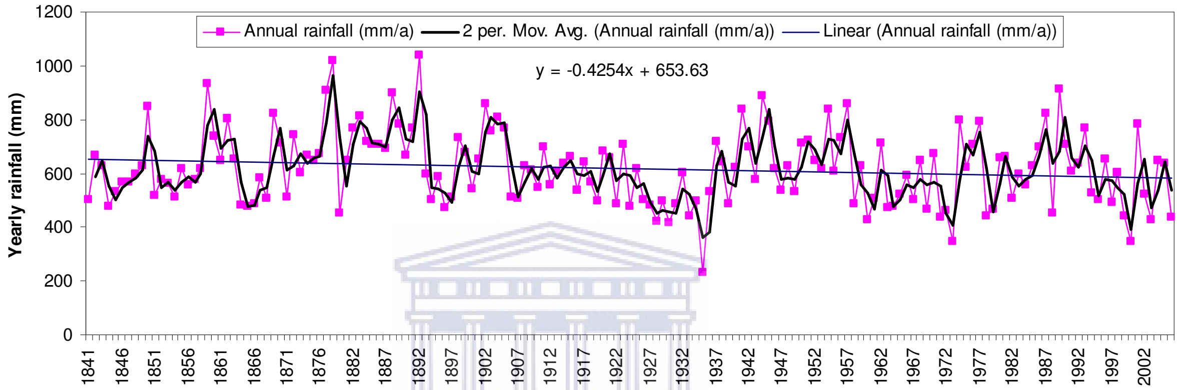



Figure 18: Long-term rainfall in Cape Town with moving average



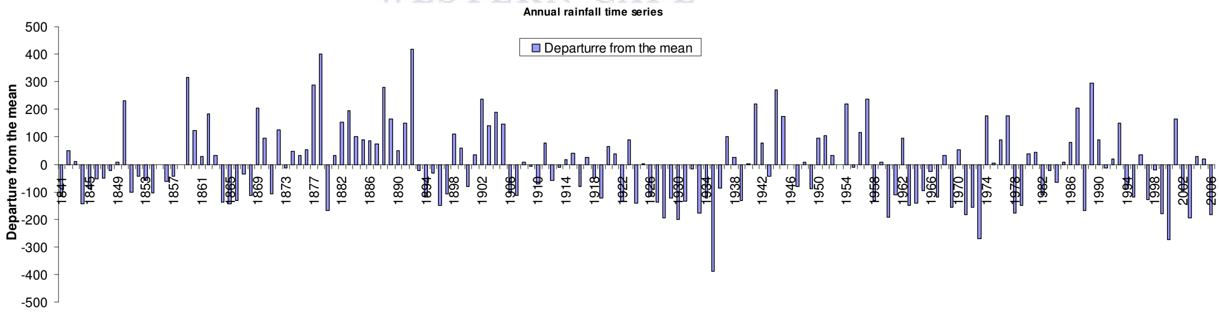



Figure 19: Cape Town rainfall illustrating the yearly departure from the mean

Daily rainfall was analysed for Cape Town Airport and UWC stations because of the rather complete records. The use of one day as a time step is based partly on the availability of data: daily rainfall data are measured at many stations but there are missing gaps in other stations. However, only records of the last five years were analysed for Cape Town Airport and UWC (Figures 20 and 21) in order to study in detail (using daily records) the low rainfall of this period relative to other years and the fluctuating pattern. Nevertheless, daily rainfall measurements still have their defects due to the convective nature of the rainfall pattern. The figure for daily rainfall represents in most cases, one rainfall event (i.e. one downpour only), because the rain gauges are usually read in the mornings (8.00 a.m. in all the stations). The rainfall occurring in the mid-day and extending in some cases into the night are read and attributed to the reading of the following day.

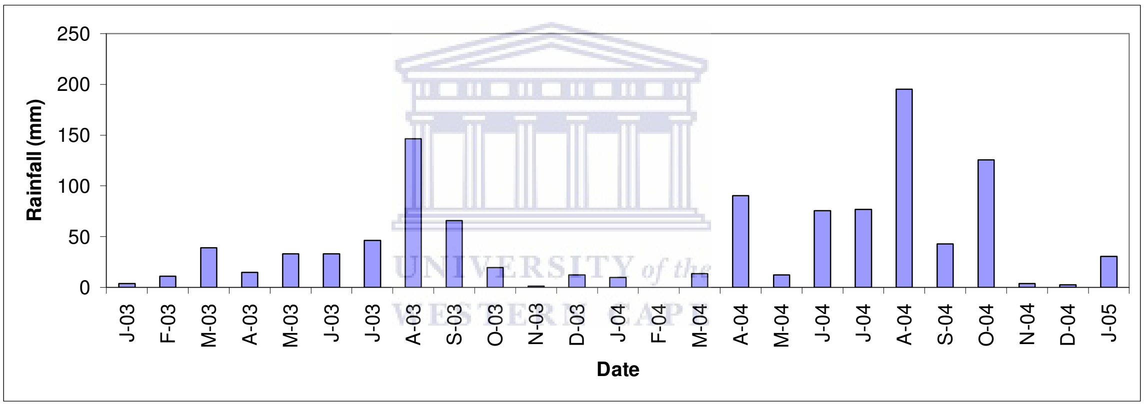



Figure 20: Monthly mean of daily rainfall in Cape Town (2003-2005)

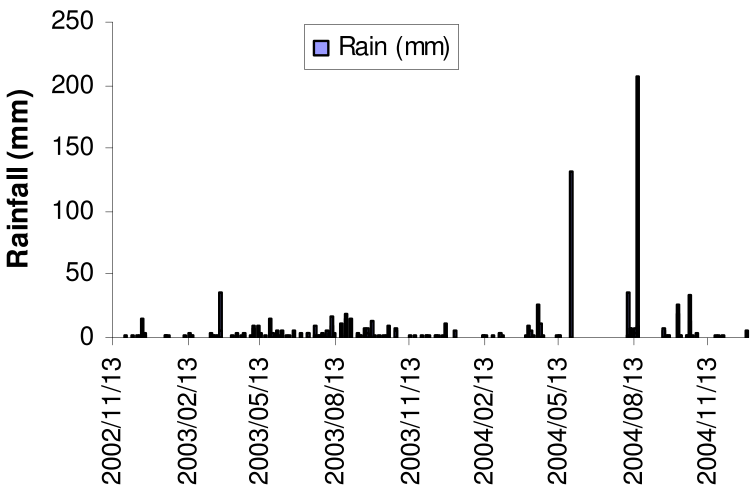



Figure 21: Monthly daily average rainfall in UWC Test Site (2002-2004)

Monthly average of daily rainfall data from the University of the Western Cape (UWC) test site analyzed shows the daily rainfall were low in 2002-2003 compared to that in 2004 (Figure 21). The response of the water level to the daily rainfall is therefore necessary to illustrate impacts of climate variability. This is discussed in detail in Section 5.4.

*4.1.1.2 Temperature and Duration of sunshine*

Figures 22 and 23 show the hydrograph of temperature and Appendix 4.2 the means of minimal and maximal values in Cape Town. Mean annual temperatures (1933-2006) are 13.0 and 22.3 °C for minimum and maximum respectively. The highest temperatures occur in the month of December (29.2 °C) while the lowest is in July/August (7.0 °C). Temporal variation is similar at the other stations. The time series analysis is described in Section 4.1.1.4.

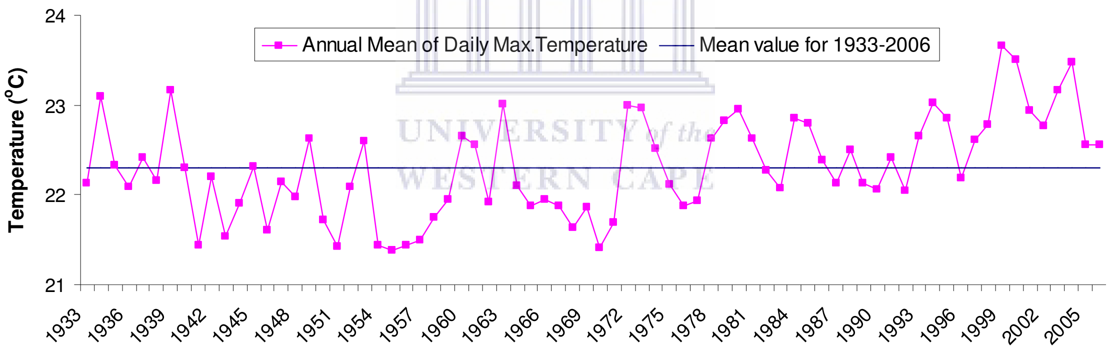



Figure 22: Annual mean of daily maximum temperature in Cape Town

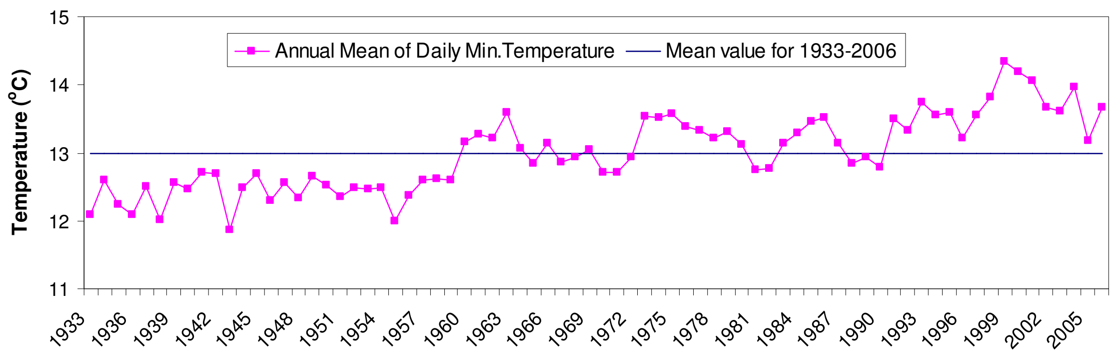



Figure 23: Annual mean of daily minimum temperature in Cape Town

*4.1.1.3 Potential and actual evapotranspiration*

<u>*Theory and methods applied in the study area*</u>

Evaporation is an important factor in hydrology and climatology. It is sometimes necessary and useful to make a distinction between 'evaporation' and 'evapotranspiration'. The former is used to describe water loss from water and bar ground surfaces while the latter is used for water loss from vegetated surfaces where transpiration is of major importance.

The term potential evapotranspiration (PET) was introduced by Thornwaite (1948) as equal to "the water loss which will occur if at no time there is a deficiency of water in the soil for vegetation". The majority of water loss due to evapotranspiration takes place during the summer months, with little loss in the winter. Because there is often not sufficient water available from soil moisture, the term actual evapotranspiration is used to describe the amount of evapotranspiration that occurs under field conditions (Fetter 1994).

From the definition stated above, potential evapotranspiration is a maximum water loss or upper limit of actual evapotranspiration, AET (Domenico & Schwartz 1998). It is a temperature-dependent quantity which reveals the measure of the moisture demand for a region. During most of the year, the actual evapotranspiration is generally less than the potential rate (Domenico & Schwartz 1998). This is usually demonstrated by the ratio of precipitation to potential evapotranspiration. In arid regions, for example, this ratio may be < 0.1. In these areas, precipitation is not sufficient to meet the water demands so that very little grows naturally.

According to Domenico and Schwartz (1998), for any irrigation scheme to be successful in dry regions, water must be supplied at the potential rate. When the ratio of precipitation to potential evapotranspiration ranges from 0.2 to 0.6, it is indicating a need for irrigation water in crop production. When the range is from 0.8 to 1.6 a rather well- balanced situation is indicated and, in some cases, a water surplus. Hence, the presence or absence of vegetation in a region is thus a reflection of the precipitation–potential and evapotranspiration ratio.

Potential evapotranspiration and evaporation can be determined using different methods and formulae. The uncertainties and problems in determining these values are well known. They are naturally changeable depending on geological and hydrogeological values (thickness, permeability of a layer etc.). Hence, there is a source of randomness, and that is why statistical methods (mean and deviation) and laws of spatial distribution have to be taken into consideration.

Water tables near the soil surface often exhibit diurnal fluctuations, declining during daylight hours in response to evapotranspiration and rising through the night when evapotranspiration is virtually zero. This is accordance with the assumptions of White (1932) who developed a formula for estimating evapotranspiration: evapotranspiration is usually taken as zero between midnight and 4:00 AM. Based on this assumption $h'$ is defined as the hourly rate of water table rise during the night hours when no evapotranspiration takes place. The total amount of groundwater discharged during one day, $V_{ET}$, was then calculated using the following relationship (Fetter 1994, Lautz 2008):

$$V_{ET} = S_y\,(24\,h' + s) \quad (4.1.3.1)$$



where $S_y$ is specific yield and s is the water-level elevation at midnight at the beginning of a 24-h period minus the water level elevation at the end of the period.
Under field conditions it is impossible to separate evaporation from transpiration totally. Indeed, the general concern is with total water loss, or evapotranspiration, from a basin.

Evapotranspiration may also be estimated by creating an equation of the water balance of a catchment (or watershed). The equation balances the change in water stored within the basin (S) with inputs and exports:

$$\Delta S = P - ET - Q - D \quad (4.1.3.2)$$

where $\Delta S$ is change in soil water storage.

The input is precipitation (P), and the exports are evapotranspiration (which is to be estimated), streamflow (Q), and groundwater recharge (D). If the change in storage, precipitation, streamflow, and groundwater recharge are all estimated, the missing flux, ET, can be estimated by rearranging the above equation (Christiansen and Awadzi 2000). Another methodology to estimate evapotranspiration is the use of the energy balance.

$$\lambda E = R_n + G - H \tag{4.1.3.3}$$

where $\lambda E$ is the energy needed to change the phase of water from liquid to gas, $R_n$ is the net radiation, G is the soil heat flux and H is the sensible heat flux (Hague 2003). Several researches (Bastiaanssen et al. 1998, 2005, Allen et al. 2005, Su et al. 2005, Gowda et al. 2009) have successfully applied the surface energy balance method to estimate crop water use in irrigated areas. The most general and widely used equation for calculating reference ET is the *Penman equation*. The combination methods were developed by other researchers (Morton 1978, 1983, Le Meur and Zhang 1990) and extended to cropped surfaces by introducing resistance factors (Kovacs 1987, Lu et al. 2005, Stoy et al. 2006). It is now generally referred to as the standard FAO-56 Penman-Monteith equation.



The *Penman-Monteith* variation is recommended by the Food and Agriculture Organization (Allen et al. 1998).

The author has applied models based on FAO Penman-Monteith equation developed by FAO (CROPWAT 8.0) to estimate potential evapotranspiration. A model developed by Cranfield Univeristy in the UK (WASIM) was used to estimate actual evapotranspiration. The model requires daily reference evapotranspiration and rainfall data. Wasim incorporates potential evapotranspiration calculated using FAO 56 Penman-Monteith equation with daily rainfall data and soil-irrigation data to generate actual evapotranspiration.

CROPWAT version 8.0, on the other hand, provides an easy and convenient source by which the regional evapotranspiration anywhere in the world, especially where the supply of water is less abundant, can be estimated (Allen et al. 1998). The FAO Penman-Monteith equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process.

The equation is given as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (4.1.3.5)$$

where

$ET_o$ reference evapotranspiration [mm $day^{-1}$],
$R_n$ net radiation at the crop surface [MJ $m^{-2}$ $day^{-1}$],
G soil heat flux density [MJ $m^{-2}$ $day^{-1}$],
T mean daily air temperature at 2 m height [°C],
$u_2$ wind speed at 2 m height [m $s^{-1}$],
$e_s$ saturation vapour pressure [kPa],
$e_a$ actual vapour pressure [kPa],
$e_s$ - $e_a$ saturation vapour pressure deficit [kPa],
$\Delta$ slope vapour pressure curve [kPa $°C^{-1}$],
$\gamma$ psychrometric constant [kPa $°C^{-1}$].

Several studies have compared evapotranspiration estimates derived theoretically and from direct measurements. Actual evapotranspiration is best measured instrumentally by complex weighting lysimeters (Calder et al. 1986, Essery and Wilcock 1990). Average daily potential evapotranspiration, monthly averages of maximum and minimum temperatures, mean relative humidity, wind speed, sunshine hours, radiation data as well as rainfall and ETo calculated with the FAO Penman-Monteith method are listed appendix 4.4.

<u>*Discussion of results and implications for groundwater recharge*</u>

From estimates in this study, the average annual potential evapotranspiration is 1360 mm per year in the Cape Town area and this exceeds the average annual rainfall generally by a factor of 2.5. Figure 24 shows potential evapotranspiration and actual evapotranspiration for Cape Town (the calculated values are in Appendix 4.4). As expected, the evapotranspiration PET stays relatively low during the months of May-September but increases, to a maximum during December–January and the actual evapotranspiration correspondingly decreases, to a minimum during December–January, because there is not enough water to evaporate.

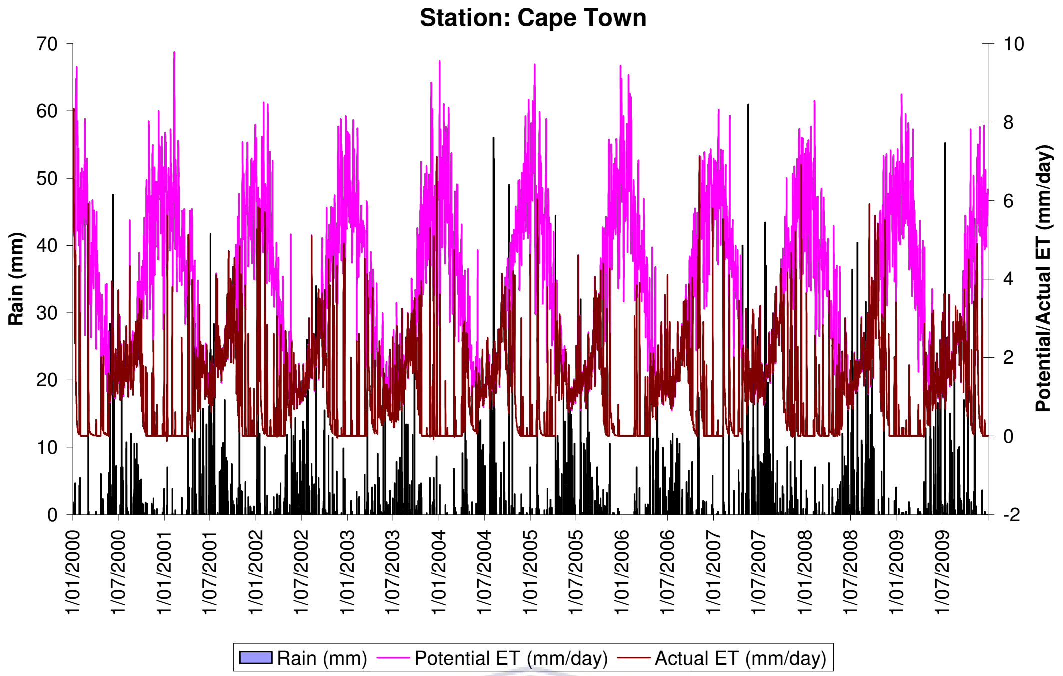



Figure 24: Rainfall, potential and actual evapotranspiration in Cape Town (2000-2009)



From the figure three things are obvious (indicating the time periods):

(i) period when precipitation equals potential evapotranspiration

(ii) period when precipitation is less than potential evapotranspiration

(iii) period when precipitation is greater than potential evapotranspiration.

Figure 25 illustrates the variation of monthly actual and potential evapotranspiration with rainfall for Cape Town while the values as calculated in the water balance using WaSim modeling software (Hess and Counsell 2000) are shown in Appendix 4.5. The values of potential evapotranspiration are higher than the actual evaporation in the summer months as shown in Figure 25. The average daily PET values are similar for the years (2000-2009) as shown in figure 26. These values are much higher than the values for precipitation in the less raining months, such that the precipitation evaporates completely and there should be no groundwater recharge. Groundwater recharge in the study area takes place during the rainy season (May-August), when there is a 'surplus' of precipitation. Rainfall during the months of April and September are usually not of high intensity like these months (May-August) to guarantee such surplus. Most rainfall in Cape Town occur as relatively high intensity rain events, often range from 10 to 61 mm per day during the raining months.

Therefore, on a daily basis, rainfall can exceed potential evapotranspiration within those months (May-September) and thus potentially recharge the aquifer. In general, rainfall of high intensities results in surface runoff and sometimes, flooding episodes are recorded in part of the municipal area.

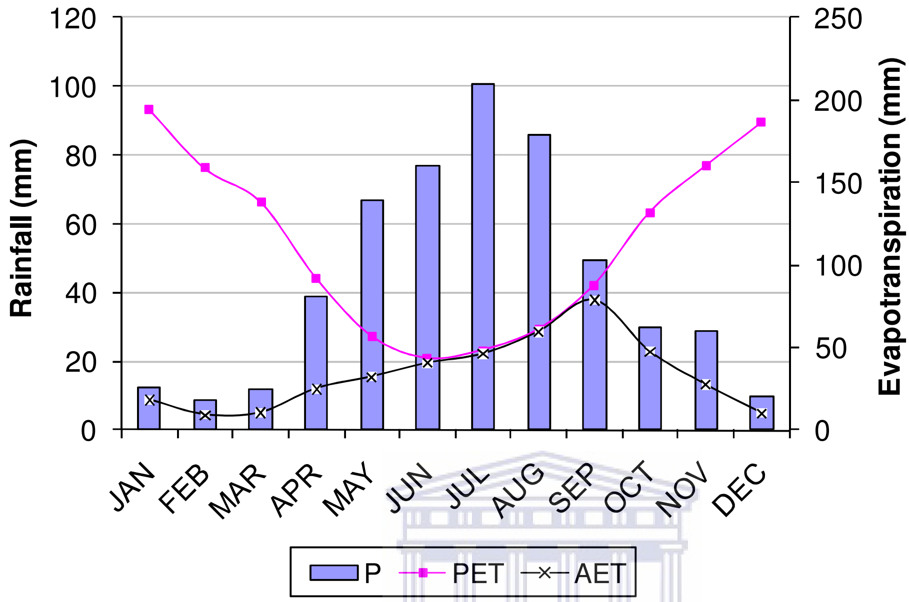



Figure 25: Variation in monthly evapotranspiration for Cape Town Airport (2000-2009)
Note: AET = Actual evapotranspiration, PET = Potential evapotranspiration, P = Precipitation



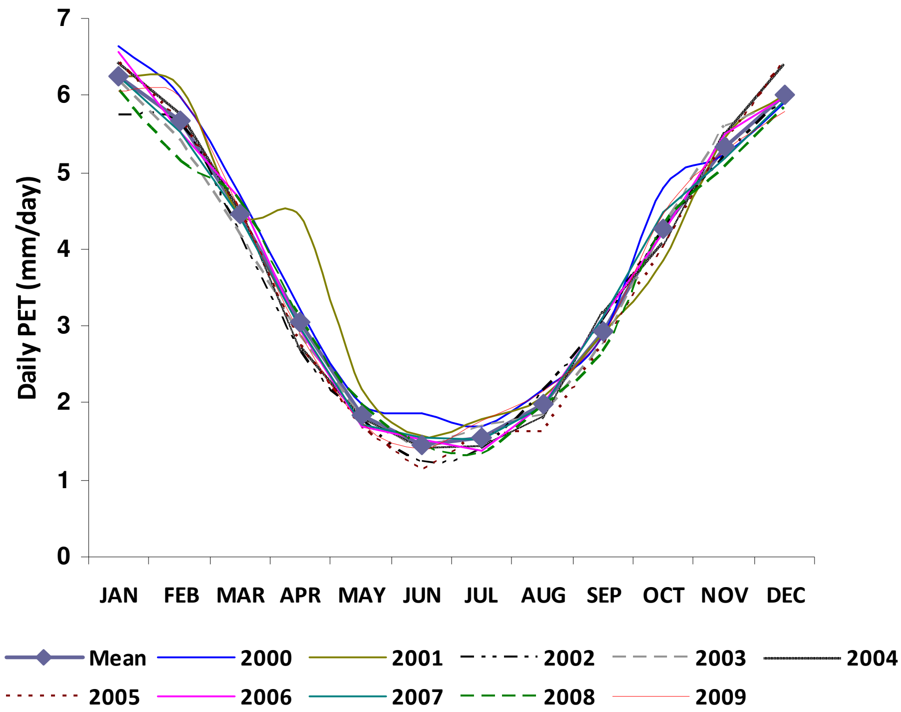



Figure 26: Average daily values of PET for Cape Town over a 10-year period

During the summer months in Cape Town, the actual evapotranspiration is generally less than the potential rate, simply because of the lack or insufficient rainfall or possibly because the soil-moisture storage capacity is limited. In months when the potential evaporation is less than the rainfall, some of the demand will be met by drawing upon moisture stored in the soil. When available soil-moisture is depleted, the actual evapotranspiration will be limited to the monthly precipitation (Fetter 1994, Domenico & Schwartz 1998).

### *4.1.2 Climatic-hydrological balance*

#### *4.1.2.1 Surface run-off*

Runoff is a significant component of the water budget, which has its impact factors similar to that of evapotranspiration. However, the formation mechanism of runoff is completely different from that of evapotranspiration. Surface runoff occurs when the precipitation rate exceeds the soil's infiltration capacity and increases with increasing amounts of precipitation Runoff amounts tend to vary depending on the features of precipitation and land surface. In the present study area, runoff measurements are somehow limited as there are not many rivers and streams running through the area. The main rivers flowing through the study area are Kuils and Eerste Rivers located at the eastern end. Others streams are Lourens, Elsieskraal, Sand, Lotus, Diep, Salt, Liesbeek, Sir Lowry's pass, etc. Data were available from the Department of Water Affairs and Forestry for Eerste, Lourens and Diep.

There was a failed attempt to gauge flow in the drainage canals of the Cape Flats, as there is no continuous record of flow magnitude as such, its relationship to rainfall intensity is little known. The maximum observed flow rate in the Lotus river system at its entry point into Zeekoevlei, using manual measurement was 11,000 $m^3/h$ in response to rainfall intensity of 50 mm/day at the height of the rainy season. The corresponding figure for the upper stretches of the Vygerkraal River, at its crossing with Hein road, was estimated to be at 2,000 $m^3/h$. The "baseflow" component the Great Lotus River was of the order of 400 to 1,000 $m^3/h$ and was maintained during the wet season (Gerber 1981). With knowledge of the baseflow in the Great Lotus River, discharge rate per borehole in this area was estimated at $2.4 \times 10^{-3}$ $m^3/s$ (Gerber 1981). This could not be updated as there are no current data available for the Great Lotus River.

*4.1.2.2 Hydrologic Balance*

Under natural conditions, an aquifer is usually in a state of dynamic equilibrium (Theis 1938). A volume of water recharges the aquifer and an equal volume is discharged. However, the amount of water that recharges an unconfined aquifer (according to Fetter 1994) is determined by three factors:

(i) the amount of precipitation that is not lost by evapotranspiration and runoff and is thus available for recharge;

(ii) the vertical hydraulic conductivity of surficial deposits and other strata in the recharge area of the aquifer; and

(iii) the transmissivity of the aquifer and potentiometric gradient, which determine how much water can move away from the recharge area.

Usually, groundwater recharge can be determined with the help of the climatic-hydrological conditions using the following equation:

Precipitation = evapotranspiration + groundwater recharge + surface runoff

The WaSim water balance simulations have been used with the climate data available in Cape Town. WaSim software package (available from Cranfield University, www.cranfield.ac.uk/sas/naturalresources/research/projects/wasim.jsp) is a daily water balance model that uses rainfall and PE to simulate the soil water relationships in response to different management strategies. The model requires daily reference evapotranspiration and rainfall data. The reference evapotranspiration required by the model was calculated from daily climate data using the FAO56 Penman-Monteith method. The author has applied CROPWAT version 8.0 to calculate potential evapotranspiration (as discussed in section 4.1.1.3).

Climate data was imported from text files and screened for missing or out-of-range data. Data errors are then flagged and can be edited with WaSim. Only Cape Town metereological station has been considered in this model due to climate data requirements for using CROPWAT. It is only the more recent data (2000-2009) that has complete daily record of rainfall, minimum and maximum temperature, humidity, wind speed and sunshine hours. The daily averages of climate parameters input into the model to calculate PE are in the appendix (Appendix 4.5a). Estimates of runoff, precipitation, actual evapotranspiration and recharge (as deep percolation) of Cape Town station are listed in appendix 4.5(a). The parameters of daily and monthly water balance for Cape Town for a period of ten years (2000-2009) are in appendix 4.5b. The groundwater recharge estimation for the present study area using various methods is discussed in the next chapter (Chapter 5).

_Discussion_

Meteorological, soil physical and groundwater information have been used to estimate the different components of the water balance for Cape Town as presented in appendix 4.4 and 4.5. The combination of parameters and these methods proved useful in similar setting (Cook et al. 1998, Anurage et al. 2006); and each of the models used here have been tested under different scenarios. Mean annual rainfall for the period (2000-2009) is 520 mm, with the highest and minimum values as 680 and 376 mm respectively. Annual PET were summed from the the daily calculations generated by CROPWAT and are higher than AET in order of nearly 2.5. The daily averages of PET (Figure 26) are more useful and illustrative.



Most of the rainfall is lost as AET. The analysis of the model results show tht on monthly basis, AET is nearly equal to PET in wet months (as shown in Figure 26) and about 10 - 25% of PET in dry months. These findings are in line with the water balance results of Christianse and Awadzi (2000) showing AET as equal to PET in the wet seasons and about 25% of PET in the dry season. Low AET occurs in periods with limited moisture as shown in the monthly values in the Appendix. The relatively higher positive change in soil and groundwater storage occurred in 2007 and 2008 while the most negative was year 2000 (with only 376 mm of rainfall). The average annual recharge occurring each year were taken as infiltration beyond the root zone regarded in the water balance model as deep percolation. These values range from zero (in year 2000) to 27 mm (year 2008) respresenting about 4.3% of mean annual rainfall. The method presented gives a quantitative indication of vertical movement of water of the represented soil types, neglecting horizontal water movement. No consideration for lateral flow or inter flow.

*Irrigation*

The Department of Water Affairs keeps records of irrigation water use in the study region. In practical field observations, the farmers in the Cape Town area irrigate their crops, particularly during the dry summer months but there are no consistent data to show the extent of irrigation for the study area. Assuming a conservative upper limit of 1000 mm mean annual rainfall over the study region of 630 $km^2$, the total volume of rainfall is 6.30 $\times 10^{11}$ $m^3$/year. There are 211 irrigation permits within the study area (as at February 2006). Assuming a conservative, 60 day long irrigation season, the total amount of returned irrigation water is $1.03 \times 10^8$ $m^3$/year or 0.163 % of the rainfall. Even if the irrigation season was 365 days long, irrigation water would only amount to 0.2 % of the rainfall over the study area.

The interplay of calculated evapotranspiration, pan evaporation and crop irrigation requirements are useful in estimation of total potential recharge and a regional water balance. With the general understanding of the climatic-hydrological balance discussed above combined with the hydrogeological characteristics to be determined in the following section it should be possible to conceptualise and model groundwater flow in the Cape Flats. To start with, the general behaviour of coastal aquifers and water table characteristics in the Cape Flats are presented in the following section to enhance a conceptual modeling.

## 4.2 Hydrogeological situation

### *4.2.1 Characterization of coastal aquifers*

Coastal aquifers can be a sustainable source of fresh water if correctly managed and exploited according to recharge, well pattern and local hydrogeological characteristics. Coastal aquifers share with continental aquifers many hydrogeological characteristics (Custodio 2002). The main difference is the risk of water quality deterioration by salinity increase. This was attributted not only to natural or induced mixing with present sea water, but also to the possible existence of old marine water in deep aquifers and aquitards, and to the generation of saline waters and brines in flat areas at an elevation close to that of current sea level. Current research has shown it is possible to devise coastal aquifers exploitation plans to limit and correct salinization problems (Walraevens 2000, Panteleit et al 2001, Custodio 2002, Pandit 2004).

Coastal aquifers are highly valuable as a freshwater resource, and as a regulating and emergency water reserve, since they are placed at the lower reaches of river basins, in areas that are often flat, with scarce chances to develop other water projects, and where population, its economic activities and tourism concentrate. In general, coastal aquifers show geological characteristics that may be derived from sedimentation in an interfacial environment and the coastal processes. The general behaviour of coastal aquifers is conditioned by the fixed hydraulic head imposed by the sea and the greater density of sea water (Custodio 2002). In most coastal aquifer systems groundwater flows naturally towards the sea driven by the head potential created by inland recharge. Since mean sea water level is practically constant there is no induced flow in it, except for the short range, periodical tidal fluctuations. The equilibrium conditions can be described by the Ghijben-Herzberg (G-H) principle when a sharp interface separates freshwater and seawater. The interface depth is $\alpha$ times the freshwater head, both referred to the local mean sea water elevation.



$\alpha$ means the specific weight

($\gamma$) difference between fresh ($f$) and salt ($s$) water:

$$\alpha = \gamma_f / (\gamma_s - \gamma_f) \tag{4.2.1}$$

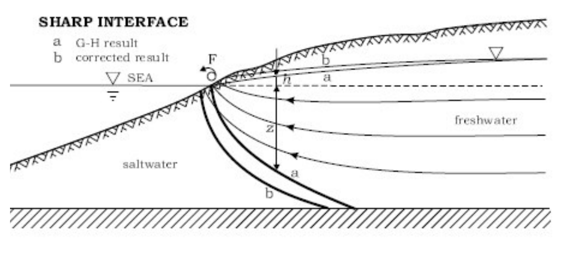
where $\gamma_f$ is specific weight for fresh water and $\gamma_s$ is specific weight for salt water.

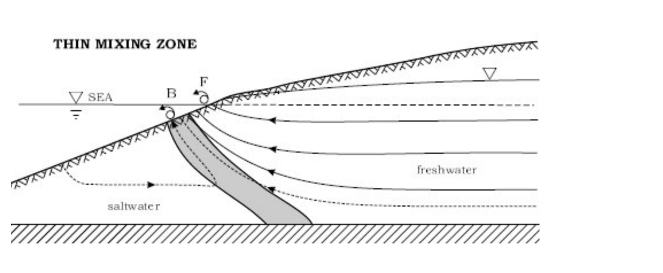
The value of $\alpha$ is approximately 40 for normal circumstances (Custodio & Bruggeman 1987).

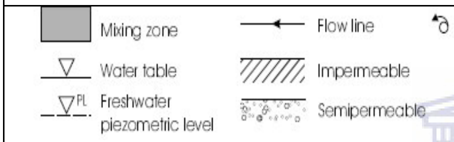
Freshwater flow influences salinity stratification. The resulting iso-concentration surfaces start near the coastline and deep into the ground down to the aquifer system lower boundary. This produces the classical saltwater wedge or the floating freshwater lens. The situation is more complex and has been described in three-dimensional heads (Custodio 2002). According to Custodio (2002), a series of circumstances favour groundwater quality degradation in coastal aquifers by introducing an excess of dissolved salts. Sea water is the most important but not the only source of salinity. Mixing with only 2 % seawater produces a noticeable deterioration. If the fraction is 4 % there is a serious impairment for many uses. If it is 6 % the water is almost unusable but for cooling and flushing purposes.

Real situations may greatly differ from the very simplified conditions under which the principle applies, but even in such cases it is useful to describe and quantify actual behaviour, if it is correctly applied. This means that the actual saltwater head has to be considered, according with the principle of Hubbert (1940) of pressure equilibrium of both fluids at each side of an interface, especially during transient situations or when saline water is being pumped out directly or mixed with freshwater. Relevant examples are documented in Van Dam (1997), Reilly & Goodman (1985), Custodio & Llamas (1983), Custodio & Bruggeman (1987) and Falkland & Custodio (1992). Figure 27 shows the schematic freshwater-saltwater relationships in an idealized homogenous coastal water table and confined aquifers.

The conditions prevailing in the Cape Flats aquifer are such that the total dissolved solids concentration ranging from few hundreds of milligrams per litre to several thousand with corresponding range of density between 1000 and 1025 kg/m$^3$. The aquifer discharges into the sea hence mixing occurs as a result of molecular diffusion; the most effective mechanism of mixing, large turbulence may not take place. Consequently, the boundary between freshwater and saltwater becomes sharp and the thickness of the transition zone is usually ignored (Gerber 1981). Since the density of the sea water is greater than that of freshwater, the former penetrates coastal aquifers to some extent, underlying the lighter freshwater which flows above the sloping interface. Generally, the location of this interface is important in the development of coastal groundwater resources since the intrusion of sea water contaminates both the freshwater and the aquifer. The freshwater-saltwater interface in the Cape Flats and its relation to groundwater quality is discussed in Section 6.6.7. In the application of this to the Cape Flats, the closest approximation to what obtains at the coastline of the False Bay is illustrated in Figure 28. However, it is necessary to first have knowledge of the water table conditions and a conceptual understanding of the boundary conditions. These are discussed in the following section.




Freshwater-saltwater relationships in an idealized, homogeneous coastal water table aquifer in which main recharge comes from other areas to the right-hand side. First figure shows the sharp interface case: no mixing zone and steady saltwater. 'a' is for $z$ □ $h$, being $h$ the water table elevation and $z$ the depth of the interface; 'b' is for true heads along the interface.

Figure 27: Freshwater-saltwater relationships in an idealized, homogeneous coastal water table aquifer



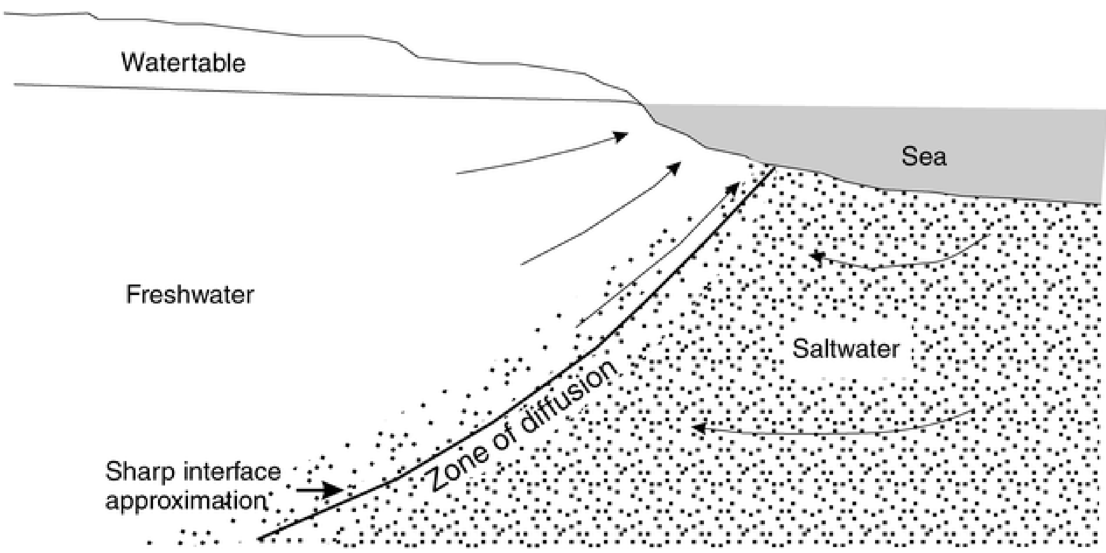



Figure 28: A schematic representation of the coast around the False Bay

### *4.2.2 Occurrence of groundwater in the Cape Flats*

*4.2.2.1 Water table behaviour*

A pilot abstraction study conducted for the Cape Flats Groundwater Development Pilot Abstraction Scheme (1983-1985) revealed the enormous groundwater potential and water table behaviour of the Cape Flats aquifer. The scheme was established in Mitchells Plain by the Department of Water Affairs in cooperation with the City of Cape Town Municipal Council with the objective to test the aquifer under concentrated stress conditions in an urban environment. Groundwater withdrawal over a period of 35 months at an average rate of 162 $m^3$/day from ten boreholes sited within 1 $km^2$ induced aquifer stress (a statistical significant drawdown) over a maximum area of about 8.5 $km^2$. A cone of depression with a maximum diameter of 3.3 km and a maximum estimated depth at its centre of 4 m developed. A mean annual yield of 4.1 $Mm^3yr^{-1}$ was produced from the ten production wells in the period May 1985 to April 1988. The yield, drawdown and constant discharge rate of each of the wells are discussed in Section 4.2.3.4. Maximum drawdown occurred during the month of May 1987 (Vandoolaeghe 1989). The cone of depression contracted cyclically to the minimum after the winter recharges. The combination of reduced evapotranspiration and recharge therefore exceeded abstraction during the winter months. According to Vandoolaeghe (1989), the implication is that the pilot test took place during an above-average recharge cycle (rainfall at Cape Town airport was near or far above average of 534 mm/year from 1983-1987).

In general, the observed regional water table decline (according to Vandoolaeghe 1989) was not as large and extensive as expected for the given abstraction volume for two reasons:

i. there was evidence of higher than average recharge recorded as taking place during the test period. This is evident from the work of Timmerman (1987) where a net recharge, calculated as a percentage of total precipitation for a 100 mm sandy soil profile using the modified Penman method and meteorological data at the Cape Town Airport, range from 14.6-36.9 % (1982-1987).

ii. there was evidence of favourable storage conditions, suggesting that the effective porosity, especially of the Springfontein sands is higher than generally accepted value.

S-values of the order of 30 % for well-sorted and rounded, fine to medium sand was estimated by Morris & Johnson (1967); although Gerber (1981) later calculated the mean specific yield value of 12 %. This was regarded as grossly under-estimated in the work of Vandoolaeghe (1989). According to Vandoolaeghe (1989), there was the evidence of artificial recharge resulting from leakage of the Sewage Works maturation ponds. This, in addition to the suspected upward leakage from the fractured Malmesbury aquifer, may have contributed to the subdued drawdown during the pilot abstraction test.

*4.2.2.2 Conceptual hydrogeological model*

The aquifer configuration and flow direction in the Cape Flats is presented in Figure 29. A general representation indicates flow from western and southeastern direction to the coast. Recharge to the aquifer takes place readily since the aquifer is mostly unconfined and the whole area is entirely flat plain. Obviously, exposures in the mountainous areas bordering the aquifer both west and east represents where recharge is also taking place. The assumptions applied in the conceptual model of the aquifer is that all flow are regionally unconfined and two-dimensional with negligible vertical components; flow across the aquifer boundaries is in a direction normal to the boundary.



The assumptions are based on the data presented by Henzen (1973) and Gerber (1976, 1981), which show water table conditions to be a reasonable concept at regional scale, although water may be semi-confined locally where the primary water-bearing zone is capped by small, local and discontinuous deposits of low permeability (Gerber 1981, Wright & Conrad 1995, Fraser & Weaver 2000). To the south-east, semi-confined conditions may be created by clay lenses and subsurface outflow from the aquifer takes place across the northwestern boundary where the Cape Flats sands is in hydraulic contact with the peninsula granite. The entire region is underlain by the impermeable Malmesbury aquifer. The assumptions that the bedrock is regionally impermeable may be void locally especially where the Malmesbury aquifer has been reported fractured (e.g. near the Sewage Works maturation ponds, where an upward leakage from the Malmesbury into the Cape Flats aquifer was observed, Vandoolaeghe 1989).

Discharge of groundwater by evapotranspiration is likely where depth to groundwater table is relatively shallow. Information about root penetration is scarce (probably due to inadequate research efforts and interest). However, some acacias are known to be able to reach greater depths in search of soil moisture (Fraser & Weaver 2000). Extensive calcrete and silcrete sheets in some parts of the Cape Flats provide ideal conditions for perched water tables. For instances, in most areas depth to the water level in a number of boreholes is less than 3 m. There are a number of Nature Reserves (Core Flora Conservation areas) within Cape Town municipality, mostly located on the Cape Flats. These findings may therefore indicate that a significant amount of soil water is consumed by the available vegetation, in addition to the low annual rainfall (mostly <500 mm in recent years) and loss of moisture by vapour transport are also contributing factors to the generally low recharge estimates.

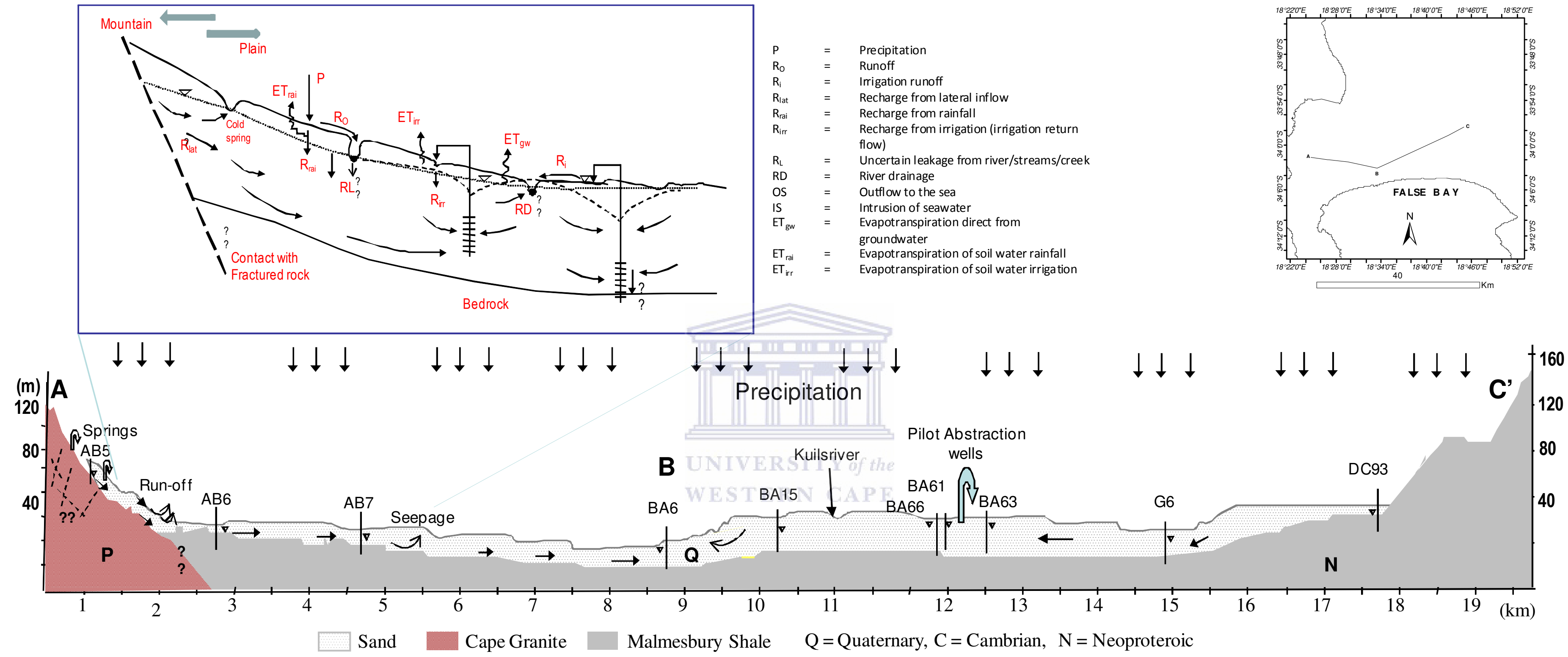



Figure 29: Hydrogeological cross-section and conceptualization of the Cape Flats (inset: indicate the position of the cross-section)

### 4.2.3 The Cape Flats aquifer properties

*4.2.3.1 Aquifer parameters in the study area*

The greater Cape Town Metropolitan Area lies on one of the most extensive sand aquifers in South Africa, and the supply potential of groundwater from this aquifer is highly significant. This extensive sand aquifer, called the Sandveld Group is hydrogeologically divided (according to Meyer 2001) into four main units: the Cape Flats unit, the Silwerstroom-Witzand unit in the Atlantis area, the Grootwater unit in the Yzerfontein region and the Berg River unit in the Saldanha area. Yield analysis of about 497 boreholes in the Sandveld Group indicates that 41 % of boreholes yield 0.5 $m^3$/day and less while 30 % yields 2 $m^3$/day and more (Meyer 2001).

The static water level in the Cape Flat aquifer occurs at shallower depth (about 2 m) than the weathered Malmesbury. There are no indications that groundwater occurrence is controlled by local fractures or fracture zones. It would have been more realistic to consider a common water table assuming that all the aquifer systems are hydraulically connected through relict or fresh fracture zones. Enhanced weathering in the unsaturated zones as well as saturated zones produces a clay-rich material of lower permeability and is responsible for apparent semi-confined conditions in the Cape Flats and weathered (bedrock) aquifers. Generally, permeability contrast among the various layers determines whether the aquifer systems will react as a confined or unconfined condition. However, pumping test results suggest that the weathered Malmesbury aquifer is more transmissive than the weathered crystalline rock aquifers implying unconfined conditions. Table 7 describes the hydrogeological properties of the Sandveld group aquifer (after Meyer 2001).

The potential yield within the different rock types of the Sandveld Group (as shown in Table 7) is highest in Berg River followed by the Cape Flats, Silwerstroom and lowest in Grootwater. The high yield in the Berg River valley may be associated with recharge through alluvium; borehole yield of up to 15.5 $m^3$/day are obtained where recharge through alluvium is evident as compared with the average borehole yield of 3.7 $m^3$/day where alluvium does not occur (Meyer 2001). Comparison of the underlying metamorphic (Malmesbury) bedrocks shows variations in yield due to large argillaceous materials and thus incompetent nature of many lithological units and overall structural complexities. Notable exceptions of high yield in the Malmesbury Group are documented in Meyer (2001) as areas where groundwater recharge into the arenaceous units takes place from overlying alluvium, sites in and along dislocation zones, areas where the more arenaceous units of the Malmesbury Group rocks are located in hydrogeological association with the TMG, and where contact zones with granite bodies, providing favourable conditions for groundwater recharge, exist. The following section describes pumping tests as carried out under the present study.

Table 7: Hydrogeological properties of the Sandveld group aquifer

| Aquifer unit | EC (mS/m) | Potential groundwater yield ($10^6$ $m^3$/a) | Transmissivity ($m^2$/day) | Recharge (%)* | Storage ($10^6$ $m^3$) | MAP (mm) |
|---|---|---|---|---|---|---|
| Cape Flats | 60-135 | 15 | +32-620 | +16-47 | 1500 | +619 |
| Silwerstroom Witzand | 80-110 | 6 | 50-1300 | 15-35 | 400 | 360** |
| Grootwater | 30-250 | 3.5 | 100-1000 | 10 | 250 | 263*** |
| Berg River | <100 | 36 | 200-1000 | 15 | 6000 | 294**** |

MAP = Mean Annual Precipitation
*% of the MAP +Current data (2005-2007)
Data confirmation: **Lamming 1999 ***Timmerman (1986) ****Timmerman (1985)

### *4.2.3.2 Pumping tests*

Pumping tests are commonly used to better understand the aquifer system, to quantify hydraulic characteristics and to assess yield. However, to determine the hydraulic characteristics as well as the relationship between yield (pumping rate) and drawdown, data over longer time periods are required. Typical pumping data during recent pumping tests are listed in appendix 4.6 and previous records in appendix 4.7. A log-log plot of drawdown versus time for two pumping test sites is given in Figure 30. Wells used for pumping test (in the two sites) and other exploited wells in the CMA are shown in Figure 31. Figure 30(a) shows pumping test results from boreholes in iThemba Labs demonstration site (located in Faure) tapping the Cape Flats aquifer; while Figure 30(b) illustrates the close agreement between two pumping tests on UWC5 conducted in two different seasons (November and March, respectively). Figure 30(c) compares pumping test data from the three boreholes.

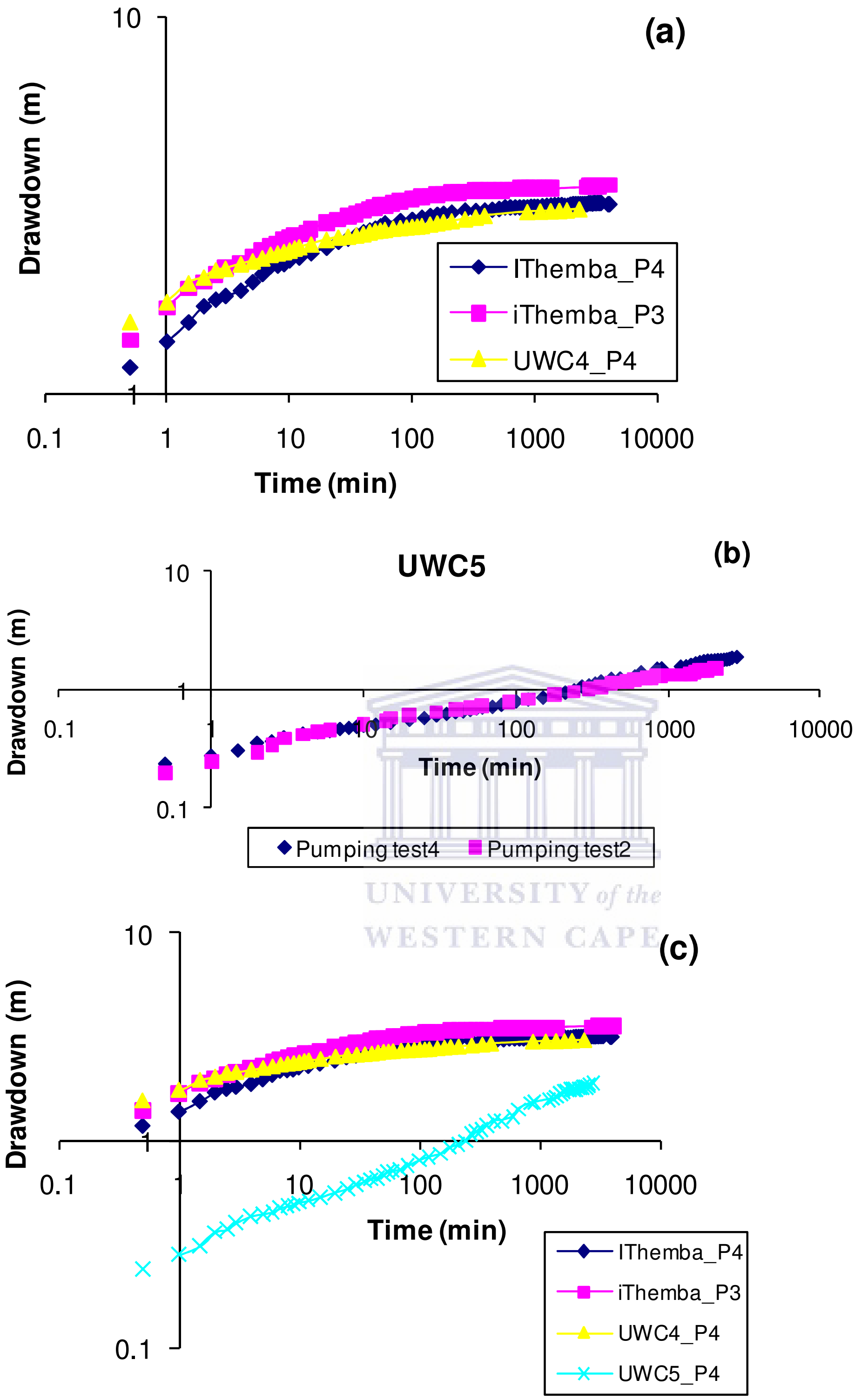



Figure 30: Results of pumping tests conducted on the Cape Flats aquifer and the underlying Malmesbury shale aquifer during 2006-2007 on a log-log plot

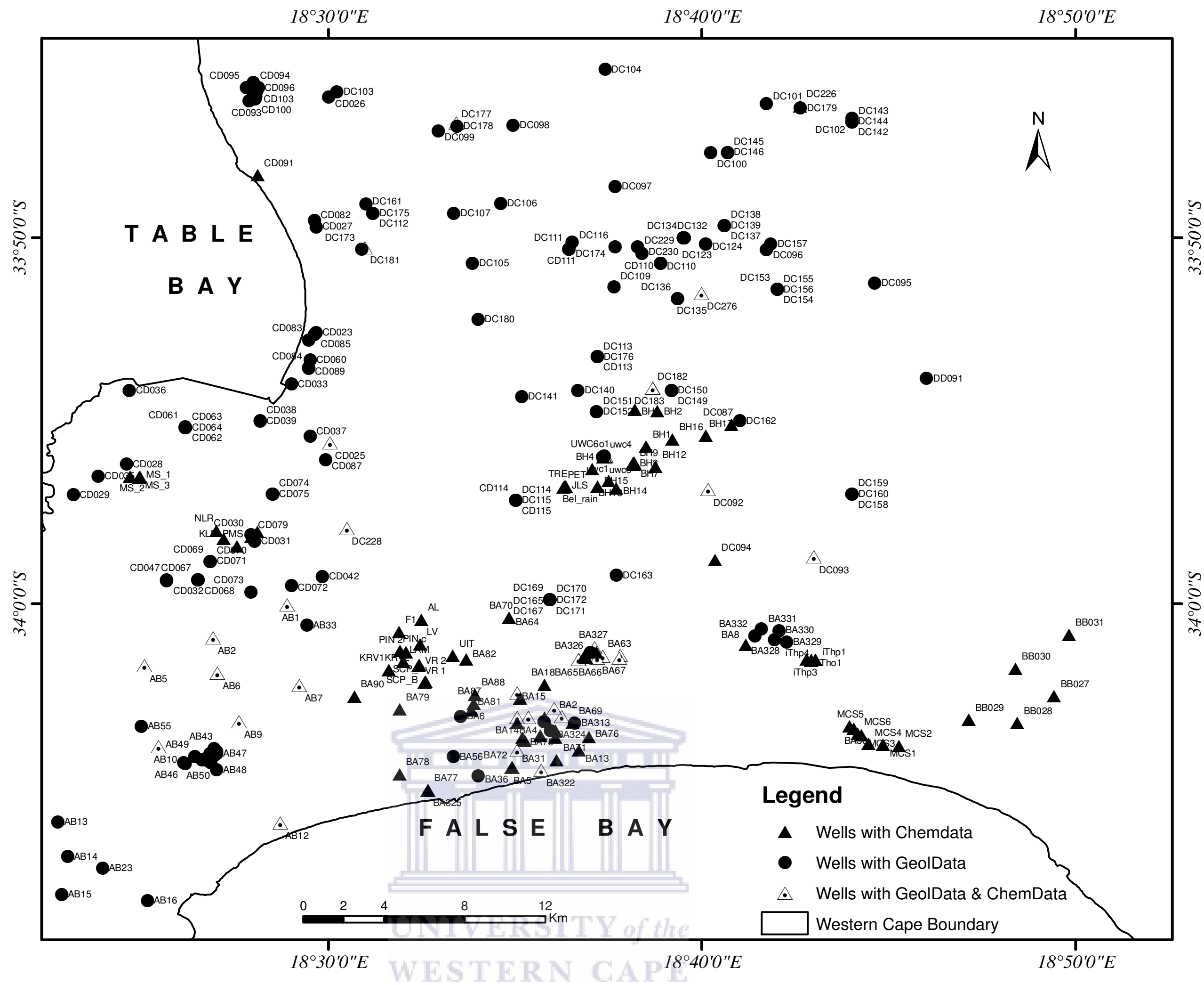





Figure 31: Wells with data on the exploited formation. Symbols represent the well location while numbers indicate the well identification.

The drawdown plot for borehole 5 at UWC (UWC 5) shows a straight line suggesting linear flow. The overlying weathered horizon provides storage for the bedrock aquifer (Malmesbury Shale). For borehole 4 (UWC 4) the curve can be fitted to a Theis type curve suggesting a radial flow pattern, indicating homogeneous conditions in the Cape Flats aquifer, and generally hydraulically similar to those of a porous medium with good storage characteristics in the deeply weathered zone. In spite of similar pumping rates in the two wells, at 0.5 min after pumping started (Figure 30a), the drawdown in borehole 5 (UWC 5) was about 0.25 m but 1.54 m in borehole 4 (UWC 4). This difference indicates that the transmissivity is higher in borehole 5 than in borehole 4.

### *4.2.3.3 Computation of aquifer transmissivity and storage coefficient*

The time-drawdown pumping test data were available for only three wells at two sites: UWC test-site (UWC-4 and UWC-5) and iThemba Labs (see figure 30), from which the hydraulic conductivity values were determined by using Aquifer Test program in excel sheet. With the help of peak groundwater level data and information on aquifer stratigraphy, maximum aquifer saturated thickness was calculated at the two sites for the estimation of k-values. Transmissivity values were then calculated as a product of the corresponding hydraulic conductivity and maximum saturated aquifer thickness. Given the optimal aquifer diffusivity and transmissivity, storage coefficients at sites UWC and iThemba were estimated.

In order to determine the aquifer parameters in the study area, many data sets (from four pumping tests, each on the two sites: UWC and iThemba) have been interpreted both by manual and by EXCEL-written programs. Figure 32 shows a sample of the plots for pumping and recovery tests conducted during the study while the results of aquifer test interpretations are tabulated (Tables 8 and 9).



Table 8: Estimates of k-values from the recent pumping test data using different methods

| Method-> | HURR 1966 | HÖLTING 1984 | BOGOMOLOW 1958 | ZANGAR 1958 | LOGAN (in Kruseman & de Ridder 1994) | ***Average*** |
|---|---|---|---|---|---|---|
| Parameter-> | k | k | k | k | k | ***k*** |
| Unit-> | m/day | m/day | m/day | m/day | m/day | **m/day** |
| iThemba (Test 3) (REC 1. SEGMNT) | 3.80E-01 | 4.58E-01 | 3.37E+00 | 1.30E+01 | 2.68E+01 | ***8.79E+00*** |
| iThemba (Test 2) | 2.94E-01 | 4.92E-01 | 3.63E+00 | 1.38E+01 | 8.64E-01 | ***3.82E+00*** |
| iThemba (Test 1) | 3.37E-01 | 6.22E-01 | 4.67E+00 | 1.73E+01 | 1.12E+00 | ***4.81E+00*** |
| Obs. w. to iThemba (REC 1. SEGMNT) | 4.23E-01 | 1.73E+01 | 1.04E+02 | 4.32E+02 | 2.51E+01 | ***1.16E+02*** |
| UWC BH4 | 1.38E-01 | 1.64E+00 | 3.46E+00 | 2.42E+01 | 1.90E+00 | ***6.27E+00*** |
| Obs. w. to UWC BH4 | 9.50E-02 | 1.30E+01 | 1.64E+01 | 4.06E+02 | 9.50E+00 | ***8.90E+01*** |
| Maximal value | **4.23E-01** | **1.73E+01** | **1.04E+02** | **4.32E+02** | **2.68E+01** | ***1.16E+02*** |
| Minimal value | **9.50E-02** | **4.58E-01** | **3.37E+00** | **1.30E+01** | **8.64E-01** | ***3.55E+00*** |
| Average value | **2.76E-01** | **5.62E+00** | **2.33E+01** | **1.47E+02** | **1.12E+01** | ***3.75E+01*** |
| **Median value** | **3.11E-01** | **1.12E+00** | **4.15E+00** | **2.07E+01** | **5.79E+00** | ***6.42E+00*** |
| UWC BH5 (REC 1. SEGMNT) | 1.56E-01 | 5.01E-01 | 2.51E+00 | 5.44E+00 | 1.38E+00 | ***2.00E+00*** |
| Obs. w. to UWC BH5 (REC 1. SEGMNT) | 9.50E-02 | 1.04E+00 | 4.92E+00 | 1.73E+01 | 2.33E+00 | ***5.13E+00*** |
| *Maximal value* | **4.23E-01** | **1.73E+01** | **1.04E+02** | **4.32E+02** | **2.68E+01** | ***1.16E+02*** |
| *Minimal value* | **9.50E-02** | **4.58E-01** | **2.51E+00** | **5.44E+00** | **8.64E-01** | ***1.87E+00*** |
| *Average value* | **2.58E-01** | **5.90E+00** | **2.93E+01** | **1.50E+02** | **1.07E+01** | ***3.93E+01*** |
| *Median value* | **2.94E-01** | **1.12E+00** | **4.67E+00** | **2.07E+01** | **5.79E+00** | ***6.52E+00*** |

**Holting (1984) and Hurr (1966) methods showed values not comparable with previous data*

**The details of the methods are in the appendix 4,8*

Table 9: Aquifer tests results interpretation, with indication of the exploited formations

| Well number | Type | Exploited formation | *T* ($m^2$ $day^{-1}$) | *S* |
|---|---|---|---|---|
| UWC 4 | Borehole | Cape Flats | 618.82 | 1.00E-02 |
| iThemba 1 | Borehole | Cape Flats | 32.47 | 2.20E-02 |
| UWC 5 | Borehole | Malmesbury | 19.29 | 2.26E-04 |

Notes:
**iThemba1 has several pumping rate changes*
**iThemba1 show a relatively fast recovery compare to other wells*
**Well 5 draw water directly from the Malmesbury Formation, which underlies the Cape Flats*
**T* and *S* values are the results of the best adjustment to the Jacob and Theis models, taking into account well capacity effects, backwater flow disturbance and effective diameter.

#### *4.2.3.4 Hydraulic Characteristics*

Wells in the Cape Flats have a high water storage capacity, but unfortunately most well-points are not available for pumping test (as they are mostly private wells used for gardening) and are not required to be registered. Industrial and agricultural wells with high discharge are also not available for long pumping and recovery times. Despite the legal registration of most industrial wells and their discharge rates, there are no mandatory requirements to include elementary pumping test with water level measurements in the conditions for registration of new borehole. Consequently, no data exist in the study area where such information leading to estimates of hydraulic characteristics or aquifer parameters can be found.

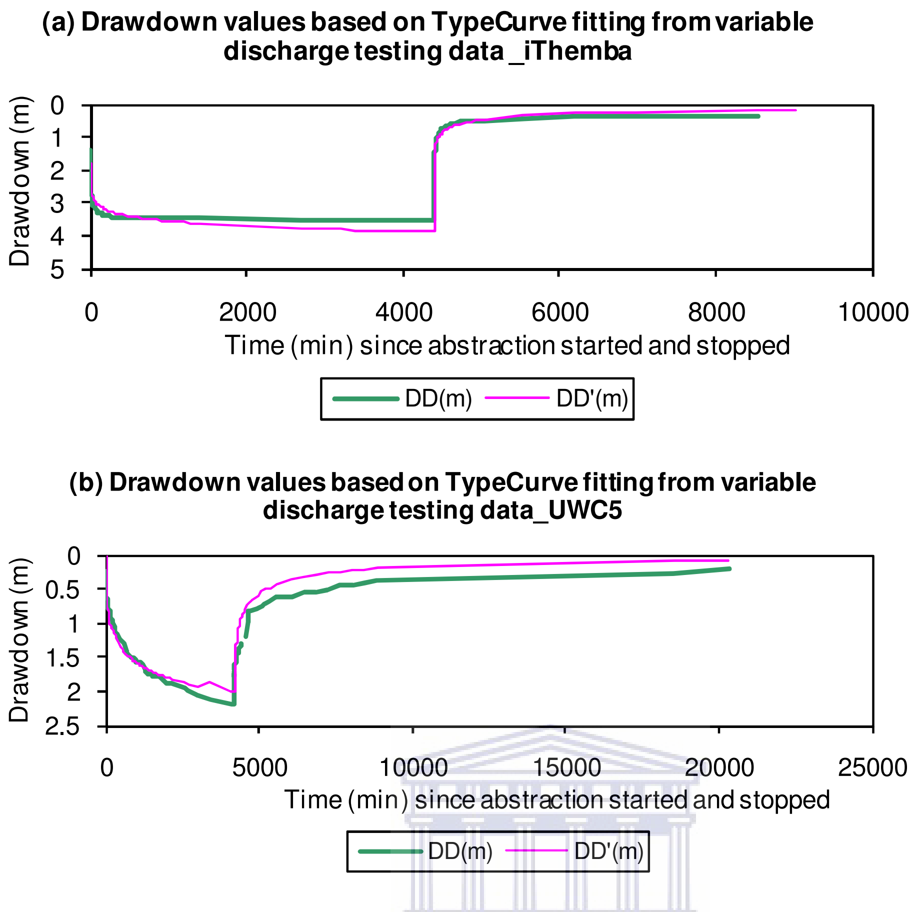



Figure 32: Typical drawdown and recovery data used to estimate T and S in the Cape Flats aquifer (from the recent pumping tests)



Earlier work showed a detailed and broader estimation of aquifer parameter in the Cape Flats (Gerber 1981, Vandoolaeghe 1989). Four production boreholes drilled to facilitate the interpretation of geophysical borehole logs were subjected to two types of tests (Vandoolaeghe 1989). Step drawdown tests were performed to determine the efficiency of the boreholes and the optimal abstraction rates for the subsequent constant discharge rate test. Table 10(a) and Table 10(b) show the results of the step drawdown and constant discharge rates test. The resultant transmissivity and hydraulic conductivity values are given in the Tables (10 a&b). The drawdown-time data were interpreted to indicate that vertical leakage is an important component of flow, at least in the very early (48 hours) stage of pumping. The description of calculations and results, which are given in Table 10, can be found in Vandoolaeghe (1989) and Gerber (1981).

Table 10(a): Constant discharge rate test data (after Vandoolaeghe 1989)

| BH No. | Depth of pumping intake (m) | Yield | | RWL | Max drawdown (m) |
|---|---|---|---|---|---|
| | | $m^3$/day | Kl/d | | |
| G32963 | 20 | 13.7 | 1187 | 3.94 | 5.83 |
| G32965 | 18 | 20.1 | 1735 | 4.25 | 12.28 |
| G32966 | 24 | 12.9 | 1115 | 5.71 | 8.83 |
| G32967 | 27 | 22.9 | 1980 | 7.28 | 8.78 |
| G32968 | 30 | 32.8 | 2838 | 7.36 | 10.28 |
| G32969 | 24 | 10.2 | 879 | 6.12 | 12.52 |
| G32978 | 33 | 22.5 | 2023 | 5.9 | 7.78 |
| G32979 | 18 | 25.8 | 2231 | 4.77 | 9.77 |
| G32981 | 33 | 14 | 1187 | 5.29 | 11.88 |
| Total | | | | 174.9 | 15176 |

Table 10(b): Hydraulic parameters estimated from constant discharge rate tests (Vandoolaeghe 1989)

| BH No. | T ($m^2$/d) | Aquifer Thickness (m) | k (m/d) |
|---|---|---|---|
| G32963 | 133.8 | 32 | 4.2 |
| G32965 | 116 | 28 | 4.1 |
| G32966 | 76.5 | 19 | 4.0 |
| G32967 | 106.5 | 21 | 5.1 |
| G32968 | 117.6 | 27 | 4.3 |
| G32969 | 27.8 | 19 | 1.4 |
| G32978 | 203.8 | 32 | 6.3 |
| G32979 | 115.6 | 32 | 3.6 |



The hydraulic conductivity of the Cape Flats aquifer has been evaluated by different methods in the past. From the work of Gerber (1976, 1981) a transmissivity distribution map (Figure 33) has been produced and refined to delineate the best areas of the Cape Flats for implementing groundwater development schemes. The refined transmissivity values for the Cape Flats aquifer range from <50 $m^2$/d to 600 $m^2$/d (based on Gerber 1981). This is not significantly different from estimates obtained in this study (Table 8) based on 2006-2007 pumping test data.

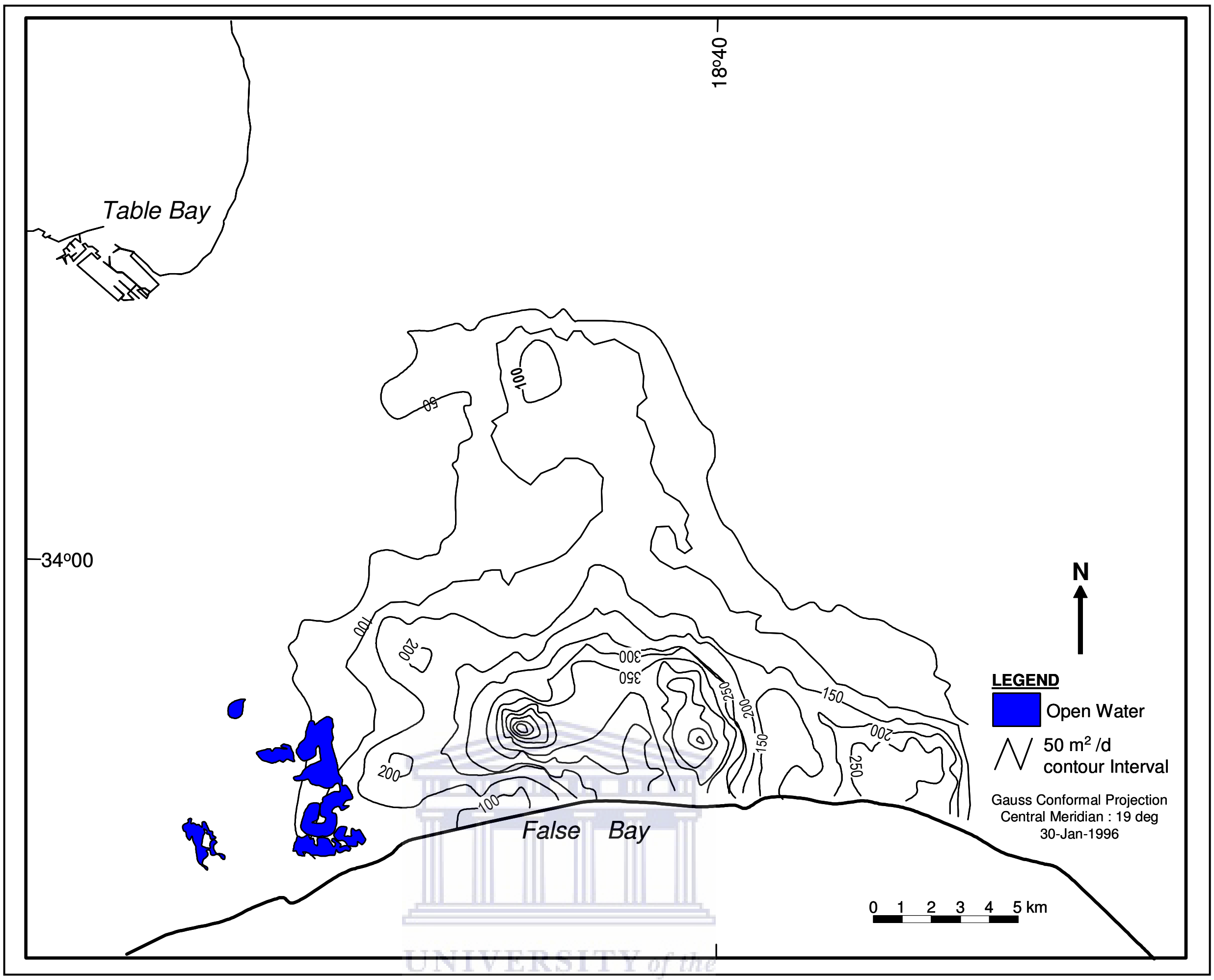





Figure 33: Transmissivity distribution map (after Gerber 1981, Wright & Conrad 1995)

#### *4.2.3.5 Grain size characteristics*

Several studies on coastal sediments bordering on the Cape Flats area have been published by Fuller & Lamming (1967), Bowie et al. (1969), Hill & Theron (1981), and Cole & Viljoen (2001). In these studies, the following properties of the coastal sediments were reported: the deposits consist predominantly of quartz sands with 20-40 % shell debris, the size distribution reflects a clear bimodality of the samples, and the size range lies between 0.06 and 4.00 mm with a dominance of the 0.09-1.50 mm fraction. Sieving results from the shallow (2-4 m) auger holes in the sixties were reported in details by Theron (1966) and Jansen (1967). Samples from 25 deep holes drilled for Geological Survey in the seventies were sampled and sieved in a similar manner and together with the data of Henzen (1973). The recent grain size distribution was obtained from a total of 78 samples from deep boreholes distributed in the greater Cape Town area and reported in Cole & Viljoen (2001); under the more exhaustive sedimentological study of sand along the South-Western Cape coastal plain (including the Cape Flats) undertaken by the Geological Survey.

Figure 34 shows a series of cumulative size-frequency curves of a typical sand succession in a Cape Flats borehole illustrating the size range and the generally well-sorted nature of the Cape sand (Hill & Theron 1981, Cole & Viljoen 2001). The description of the various sand types in the greater Cape Town region is given in Cole & Viljoen (2001). Sieving results from two augured holes (at the UWC test site and iThemba Labs, carried out in 2006) has shown that the sand of both sites is well sorted with grain sizes ranging from 0.75 to 3.25 phi, with minor amounts of granules, silt and clay fractions (Figure 35).

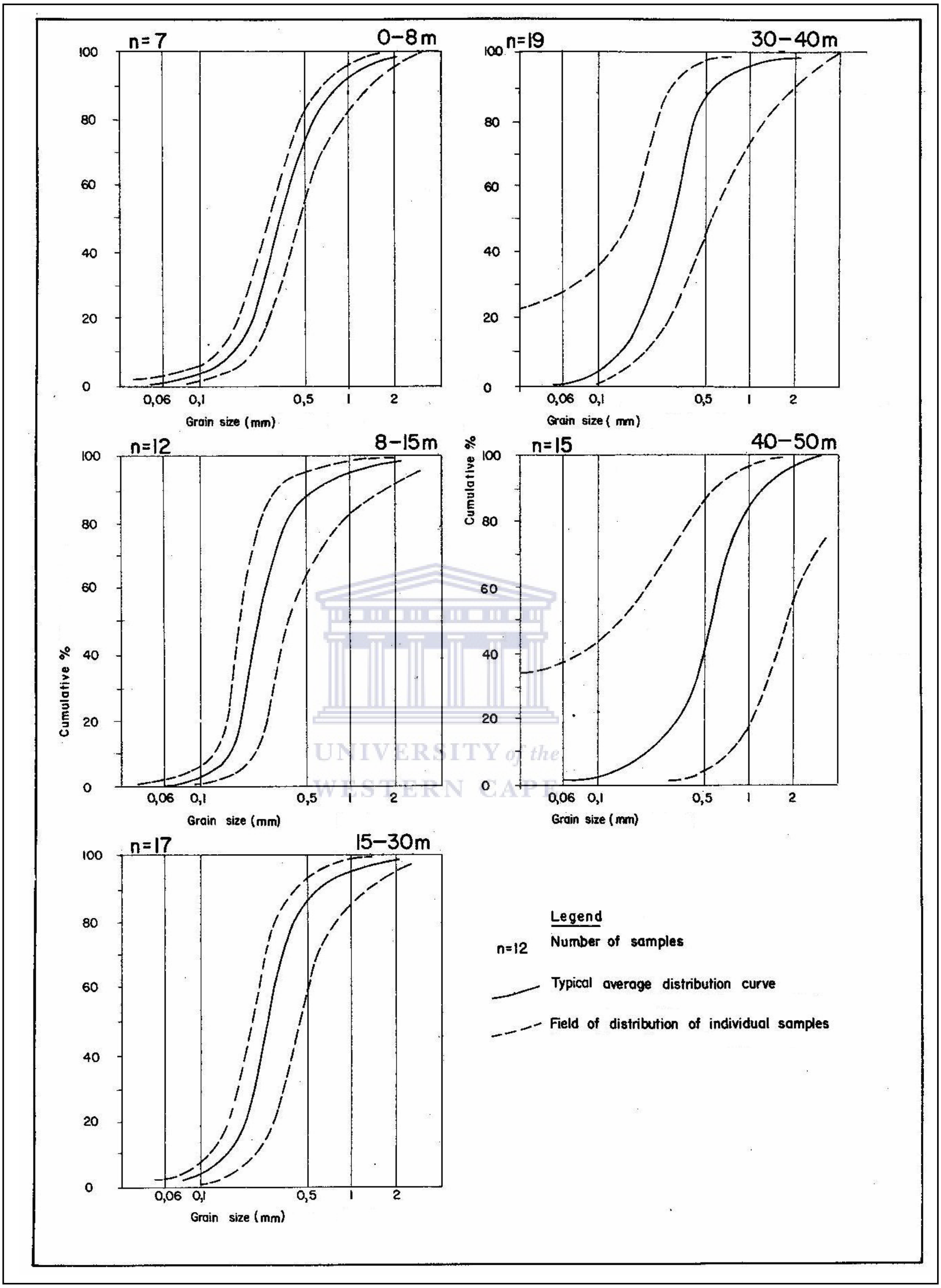
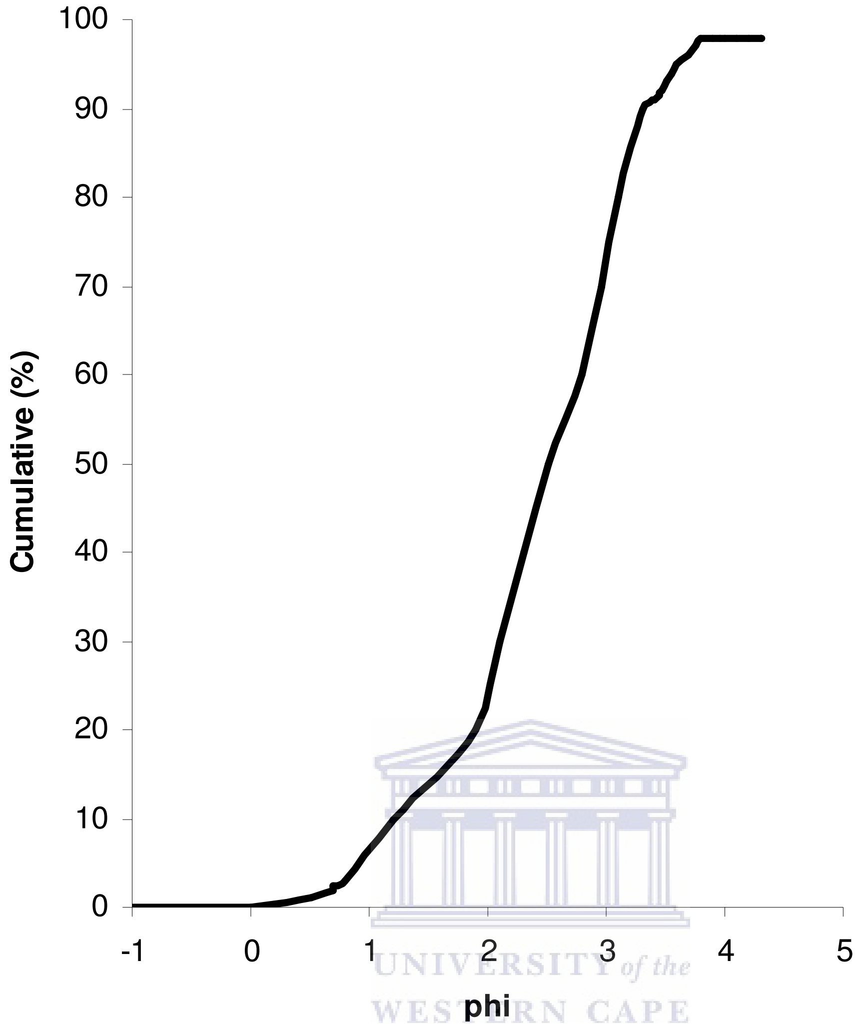





Figure 34: Grain-size frequency curves at various depth intervals in a typical hole on the Cape Flats (After Hill & Theron 1981)






| Gravel | Sand | Silt |
| --- | --- | --- |

Figure 35: Grain size distribution of the unconsolidated Cape Flats aquifer material at the UWC site determined during the present study

## 4.3 Summary

The hydrogeological framework presented in this chapter a better understanding of the Cape Flats aquifer. The climatic parameters have been described and statistically interpreted to show the fluctuating pattern and the impact of climate variability on groundwater. Long-term climatic data shows the dropping level of mean of every ten years (from 1841-2007) and the rising tendency of temperature due to global warming. Analyses of rainfall time series and stream flow hydrographs were interpreted and discussed in relation to groundwater recharge. Groundwater occurs under water table conditions. Series of pumping tests carried out at the UWC test site (near the main gate, Bellville South) and at iThemba Labs (Faure), used to determine the aquifer characteristics. A mean annual yield of 4.1 $Mm^3yr^{-1}$ was calculated from the ten production wells in the period May 1985 to April 1988. The yield, drawdown and constant discharge rate of each of the wells are discussed in section 4.2.3.4. Parameters like transmissivity, specific yield and storage coefficient were estimated. Information available indicated a conceptual model with an unconfined sand aquifer, grading into semi-confined conditions in some places where lenses of clay and peat exist, and underlain by the impervious Malmesbury Shale.

# CHAPTER 5: ESTIMATION OF GROUNDWATER RECHARGE

## 5.1 Introduction

Estimating recharge is essential in any analysis of groundwater systems and the impacts of withdrawing water from the aquifer. Identification of all the recharge mechanisms and the estimation of the magnitude of the different components of recharge are now recognised as one of the most important aspects of groundwater resource studies. Recharge is also an important factor for vulnerability assessment because it provides the contaminant transport mechanisms through the soil and the unsaturated zone. Therefore, the determination of groundwater recharge is a crucial variable in groundwater resources planning. Without a good estimate of recharge, the impacts of withdrawing groundwater from an aquifer cannot be properly assessed, and the long-term behaviour of an aquifer under various management schemes cannot be reliably estimated (Sophocleous 2004).

The Cape Flats represents a highly productive area with intense water use and with multi-stakeholder interest in water. Although previous groundwater use for municipal water supply in the City of Cape Town is less than 5%, plans are now to augment supply from surface water with groundwater. Therefore, to properly manage groundwater resources in the City of Cape Town, in relation with the available surface sources, accurate information about the inputs (recharge) and outputs (natural discharge and pumpage) within the area is needed so that the long-term behaviour of the aquifers and their sustainable yields can be estimated. To assist in this effort, a study of this nature was undertaken to assess the various recharge estimates for the Cape Flats aquifer.



The quantification of recharge of the TMG aquifer (one of the aquifers under consideration for the City of Cape Town water augmentation scheme) have been attempted by Wu (2005) with the most recent results and case studies presented in Xu et al. (2007). Although it has been recognised that all groundwater sources within the city be developed and utilised together, no such quantification or estimation of recharge and recharge processes have been attempted for the Cape Flats aquifer. Knowledge of the recharge rate is crucial for the qualitative assessment of the Cape Flats aquifer and for groundwater management. The quantification of recharge rates and identification of processes, therefore, represents one of the objectives of this research. This chapter provides some estimates of recharge in an attempt to elucidate the path towards sustainable use of the Cape Flats aquifer. Although the focus in this research is on the Cape Flats aquifer, the results and analysis presented are believed to be characteristic of the entire Coastal Plain sands in the Western Cape.

## 5.2 Definition of recharge

Groundwater recharge has been defined in chapter 1 (under operational definitions). According to Beekman & Xu (2003), four main modes of recharge can be distinguished:

i. "Downwards flow of water through the unsaturated zone reaching the water table"
ii. "Lateral and/or vertical inter-aquifer flow"
iii. "recharge from nearby surface water bodies induced by groundwater abstraction"
iv. "Artificial recharge such as from borehole injection or man-made infiltration ponds".

The concept of recharge in this chapter focuses on the first mode: natural recharge by downwards flow of water through the unsaturated zone reaching the water table. This is generally the most important component of recharge in semi-arid to arid areas of Southern Africa (Beekman & Xu 2003).

There are two main types of recharge: direct (vertical infiltration of precipitation where it falls on the ground) and indirect (infiltration following runoff). It is generally acknowledged that in semi-arid environments most groundwater replenishment is point recharge (Simmers 1997). However, in certain geological situations, this may be direct forming a crucial addition to the groundwater reservoir.

## 5.3 Recharge determination in semi-arid regions

There are two main climatic charcterisitcs that challenge the quantification of groundwater recharge in semi-arid climate, and that require an approach different from those often applied in temperate zones. The first characteristic is the high share of evapotranspiration in the water budget. Due to the importance of evapotranspiration combined with the uncertainty in its quantification, the method frequently used in more temperate climates to calculate groundwater recharge as the remaining variable in the water balance is less accurate in semi-arid climates.

Secondly, in many semi-arid zones a large portion of annual rainfalls occurs during storm events. This characteristic renders the recharge mechanism slightly more complex than in temperate climates, as localised infiltration from accumulated run-offs gain importance and direct infiltration through the soil matrix cannot be assumed to be the predominant process. Often, this behaviour causes the result of the recharge measurements to depend on the scale of observation. Lorentz et al. (2003) described the various applied techniques for estimating recharge at the local, hillslope, catchment, regional and national scales in the semi-arid zones of Southern Africa. It is clear that the scale of the problem being investigated is a guiding factor in determining the methods used. It is also evident that the processes inherent in generating events and low flow discharges must be defined.

Beekman & Xu (2003) reviewed groundwater recharge estimation methods in arid and semi-arid regions from three decades of recharge studies in Southern Africa. From this review, principles of methods currently in use are described with references to Southern African region. Although the methods are reviewed in terms of limitations, applicability at different fluxes, temporal and spatial scales, and are rated on accuracy, ease of application and costs, promising recharge techniques were identified. These are: Chloride Mass Balance (CMB), Cumulative Rainfall Departure (CRD), Water Table Fluctuation (WTF), Groundwater Modeling (GM), Saturated Volume Fluctuation (SVF) and Extended model for Aquifer Recharge and moisture Transport through unsaturated Hardrock (EARTH).



Meyer (2005) in the analysis of groundwater level time series in relation to rainfall and recharge, investigated the impact of climate variability and climate change and postulated a number different climatic cycles for Southern Africa. The application of drought indicators to analyse groundwater fluctuations in order to predict Drought Scenarios is now a common global exercise. Meyer (2005) in order to predict the drought scenario of Southern Africa used groundwater level data from 400 monitoring wells in South Africa using the Standard Precipitation Index (SPI) calculated for a 24 months period. The results showed good correlation between the SPI and the groundwater level record of the dataset leading to the development of a "Recharge Index" concept, which incorporates SPI values, groundwater level response and climatic indicators (Meyer 2005). The conclusion of this author is that using groundwater level fluctuations as indication of recharge should result in a measure of the "effective recharge" and that the development of a recharge index (using the SPI approach) will combine the effects of a number of variables and subsequently reduce the uncertainties in recharge estimates in Southern Africa.

More recently is the application of natural isotopes and groundwater quality to improved estimation of recharge and flow in Southern Africa. Bredenkamp et al. (2007), following a bi-modal input of the $^{14}C$ as part of of the recharge and a two-box mixing model, successfully simulated the reappearance of the $^{14}C$ and tritium in the spring discharge. In the two-box mixing model applied, the one box represents the shallow, more recent recharge and the second the deeper flow from a period extending further back in time. This reconciled most of the inconsistencies and not only provided new insights into the recharge characteristics and flow processes, but also a means to derive the mean residence time of water in the aquifer and from that the storage of groundwater in relation to the average recharge. Significant contributions of this research is that new method has been used to derive a more reliable estimates of the chloride of the rainfall, thereby improving recharge estimation using Chloride Mass Balance method. Further, this demonstrates that the $^{14}C$, CFC and tritium modelling improved understanding of the recharge and flow mechanisms in dolomitic and non-dolomitic aquifers in this region.



## 5.4 Recharge estimation techniques in the study area

Recharge to groundwater can be estimated by a number of different methods, ranging from physical to chemical techniques (Sophocleous 2004, Xu & Beekman 2003, Cook & Herczeg 2002). The principles and procedures of various techniques applied in the quantification of recharge estimates for the study area are discussed in the following subsections. Details and the theory of the commonly used methods are in the literature and have been summarized in chapter 2. The most important recharge studies carried out in South Africa (Bredenkamp et al. 1995, van Tonder et al. 2001, Xu & Beekman 2003) have indicated the essentials of different methods of analyzing a groundwater system. Recharge estimates (by whatever methods) are normally subject to large uncertainties and errors (Simmers 1988). Moreover, choosing appropriate techniques is often difficult (Scanlon et al. 2002). Whereas, the determination of recharge variability in space and time is often high and can create a number of unresolved problems or requiring additional investigations (Sophocleous 1991).

The methods used, and the accuracy of predictions will vary at different scales of investigation. Methods appropriate for localised recharge estimation may not be useful for regional scale assessments because of the size of the study region. This size does not allow the use of sophisticated methods generally used at field scale. According to Walker et al. (2002), having varied techniques available, the best technique to use depends on a number of factors. These include: spatial scale of interest, time scale of interest, magnitude of the recharge, accuracy required, cost and access to facilities, time lags associated with processes, whether variability is required and whether predictions of impacts are required.

Generally usable methods for unconfined aquifers like the present study area are:

1) The hydrologic or soil-water balance approach
2) Groundwater-level fluctuation approach
3) The monthly difference between rainfall and potential evapotranspiration
4) Cumulative Rainfall Departure Method
5) Chloride profile in the unsaturated zone/Chloride Mass Balance

The hydrologic or soil-water balance method like the field scale models also normally requires a wealth of detailed soil data which is not available for the Cape Flats area. Soil moisture chloride concentrations reflect hydrological conditions over an estimated period of time, thus making the chloride profile in the unsaturated zone very applicable in unconfined aquifers. However, since the soil-moisture sampler (Eijkelkamp 1201SB Soil moisture sampling system) newly acquired by the Groundwater Group (Earth Sciences Department) failed due to low suction pressure in the pump it was difficult to collate data for this purpose.



The first stage in the estimation of recharge in the study area involved collection and collation of existing data on potential controls of recharge, such as climate, hydrology, geomorphology and geology to develop a conceptual model of recharge into the aquifer system. These have been done (Adelana et al. 2006) and also discussed in Chapters 3 and 4. The conceptual model describing the location, timing, and likely mechanisms of recharge into the Cape Flats aquifer is discussed in this chapter and illustrated in section 5.4.

In a natural situation, recharge is the result of rainfall infiltration or infiltration through the river beds. In the intensively cultivated areas of the Cape Flats (such as the Philippi and Otery areas) irrigation may also contribute to groundwater recharge. Rainfall and potential evapotranspiration in relation to cumulative rainfall have been discussed in the process of analysis of hydrological stresses (Adelana et al. 2006). Several empirical methods using mathematical formulae were only applied as reconnaissance in the interim during the preliminary flow modelling to have a quick estimate of recharge rates. The results of the empirical methods (used as a quick reconnaissance) have been discussed in Adelana et al. (2006) and summarised in the Appendix (5.1-5.2). The same procedure of chloride technique, using chloride and soil moisture can also be used for groundwater for irrigated areas, but require more data relating to the quantitiy of irrigation water, soil moisture content, and crop water requirements in order to determine water balance calculations. Therefore, recharge calculations for the irrigated areas of Cape Town are left for future work when soil water balance can be applied with adequate meteorological data for the same consistent period, and detailed soil moisture budget calculations peformed on a daily or periodic basis. The three approaches therefore adopted in the present study to estimate groundwater recharge: groundwater level fluctuation using borehole water level data, hydrograph separation and chloride techniques are employed for the non-irrigated areas.



### *5.4.1 Recharge estimation using water level*

Water table recharge, often referred to by many authors as water-table fluctuation (WTF) method (Healy & Cook 2002, Gerhart 1986), is based on the premise that rises in groundwater levels in an unconfined aquifer is due to recharging water arriving at the water table. It is generally accepted that there is a relation between water level fluctuations and recharge. The numerous techniques developed in the past in this field are a proof of this assertion (Meyer 2005, Healy & Cook 2002, Scanlon et al. 2002, Rehm et al. 1982).

#### *5.4.1.1 Theoretical background*

The time lag between rainfall events and a rise in the groundwater table, as well as the amplitude of groundwater level fluctuation can give insight into the mechanisms and the quantity of groundwater recharge rates. The water table fluctuation method estimates recharge from changes in groundwater storage. In the consideration of groundwater budget for a basin, changes in subsurface water storage can be attributed to recharge and groundwater flow into the basin minus baseflow (groundwater discharge to streams or springs), evapotranspiration from groundwater, and groundwater flow out of the basin. According to Healy & Cook (2002), the budget can be expressed in the following form:

$$R = \Delta S^{gw} + Q^{bf} + ET^{gw} + Q^{gw}_{off} - Q^{gw}_{on} \qquad (5.2.1)$$

where $R$ is recharge, $\Delta S^{gw}$ is change in groundwater storage, $Q^{bf}$ is baseflow, $ET^{gw}$ is evapotranspiration from groundwater, and $Q^{gw}_{off} - Q^{gw}_{on}$ is net subsurface flow from the study area; all terms are expressed as rates (e.g., mm/year, Healy & Cook 2002).

The Water Table Fluctuation method is based on the assumption that a rise in water level in an unconfined aquifer is caused by only recharge (Healy & Cook 2002) and that the influences of lateral flow and evapotranspiration on groundwater storage are negligible within the evaluated period of time (i.e. all other components of equation 5.2.1 are zero). In this way, is then calculated using the following relationship:

$$R = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \qquad (5.2.2)$$

where $S_y$ is specific yield, $h$ is water-table height, and $t$ is time.

This method has been applied in several previous studies (Meinzer & Sterns 1929, Gerhart 1986, Healy & Cook 2002, Xu & Beekman 2003, Delin et al. 2007) and the conclusion is that it is best applied over short period (few hours or days) in regions having shallow water tables. Ideally, water-level fluctuations occur in response to spatially averaged recharge (Scanlon et al. 2002). Hence, this method can also be applied over longer period or time intervals (either seasonal or annual) to produce an estimate of change in groundwater storage, sometimes referred to as "net" recharge (Healy & Cook 2002). In order to achieve this, Δh is set equal to the difference between the peak of the water level rise and the low point of the extrapolated antecedent recession curve at the time of the peak. According to Healy and Cook (2002) the antecedent recession curve is the trace that the well hydrograph would have followed in the absence of the rise-producing precipitation. In order to account for drainage from the water table that takes place during the rises in water levels, water level prior to each rise was extrapolated to the expected position had there been no rainfall event. The rise was then estimated as the difference between the peak level and the extrapolated antecedent level at the time of the peak (Healy & Cook 2002) and is represented in magnified format (Figure 36) to better illustrate how $\Delta h$ can be estimated.

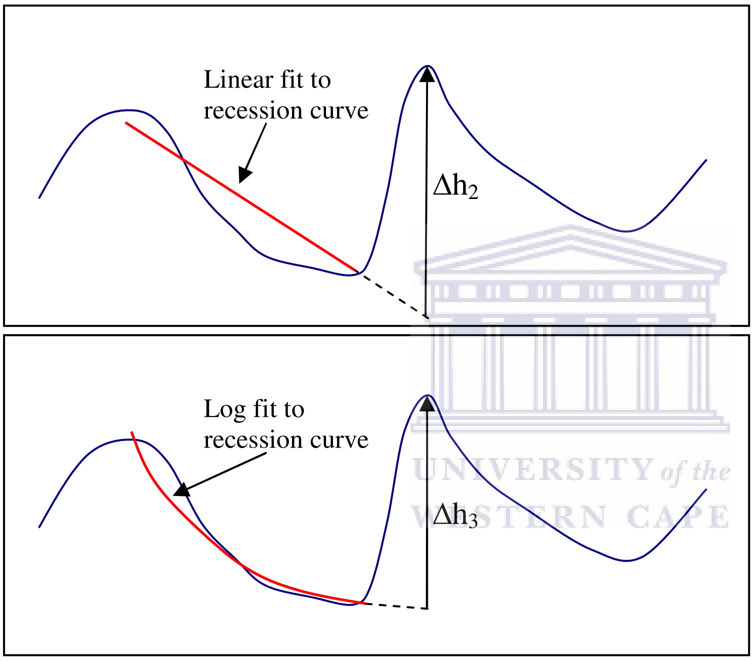



Figure 36: Hypothetical water-level rise in well in response to rainfall to illustrate recharge estimation with WTF method. $\Delta h$ is equal to the difference between the peak of the rise and low point of the extrapolated antecedent recession curve (dashed line)

### *5.4.1.2 Results from water table fluctuation*

Several monitoring well data from the study area were evaluated but a number of these have missing gaps and inconsistent record. The Western Cape DWAF maintains a good groundwater monitoring network, but even then the time series are highly discontinous. Because of the general lack of daily record or the discontinous nature of groundwater level data (of at least monthly intervals), observations of groundwater levels in several of the wells are only sporadic and by all means insufficient to do this recharge computation. In the end, only data from three sites representing clusters of boreholes were used for this recharge estimation and are presented in this section.

After the quantitative assessment for the three sites, the results from the monitoring of water levels are discussed. BA80, BA81, BA83 are monitoring boreholes in Schaapkraal/Mitchells Plain while DC182, DC183, DC184 are monitoring wells in Bellville (Allotment Office) and UWC2, UWC6 (representing the cluster of six boreholes) which are monitored at the UWC test site in Bellville. BA80 were monitored 6-hourly using the automated water level recorder from March 21, 1979 to March 14, 1984. $\Delta h$ was calculated from the weekly record of water level in BA80 (figure 37). The figure shows the average water level representing a cluster of boreholes in Mitchells Plain/Schaapkraal area (Lat 34.04889, Long 18.56417) and total rainfall on a weekly basis for April 21, 1979 through March 21, 1981.

As described previously, $S_y$ was estimated in the present study from pumping test data as 0.01 and 0.022 respectively for the Cape Flat aquifer at UWC and iThemba respectively. The tests were simply insufficient to generalise for the Cape Flats aquifer. However, earlier studies calculated it to be 0.26 from several pumping tests conducted on boreholes drilled through the Cape Flats (Gerber 1976) while from the data of Vandoolaeghe (1989) an average of 0.22 was estimated from the pumping tests in ten production boreholes (pilot abstraction wells) around Mitchells Plain. The value for $S_y$ for this exercise was then taken as 0.22. This value fall within the range of values listed for fine-medium sand by Healy & Cook (2002). Healy & Cook (2002) list values of $S_y$ from different studies and recommend using the usually smaller $S_y$ values determined from pumping tests rather those calculated from laboratory experiments. $\Delta h$ was taken as the cumulative rise in water level for each month (i.e. the sum of all rises that occurred within the month) as explained in Healy & Cook (2002) and presented in section 5.4.1.1.

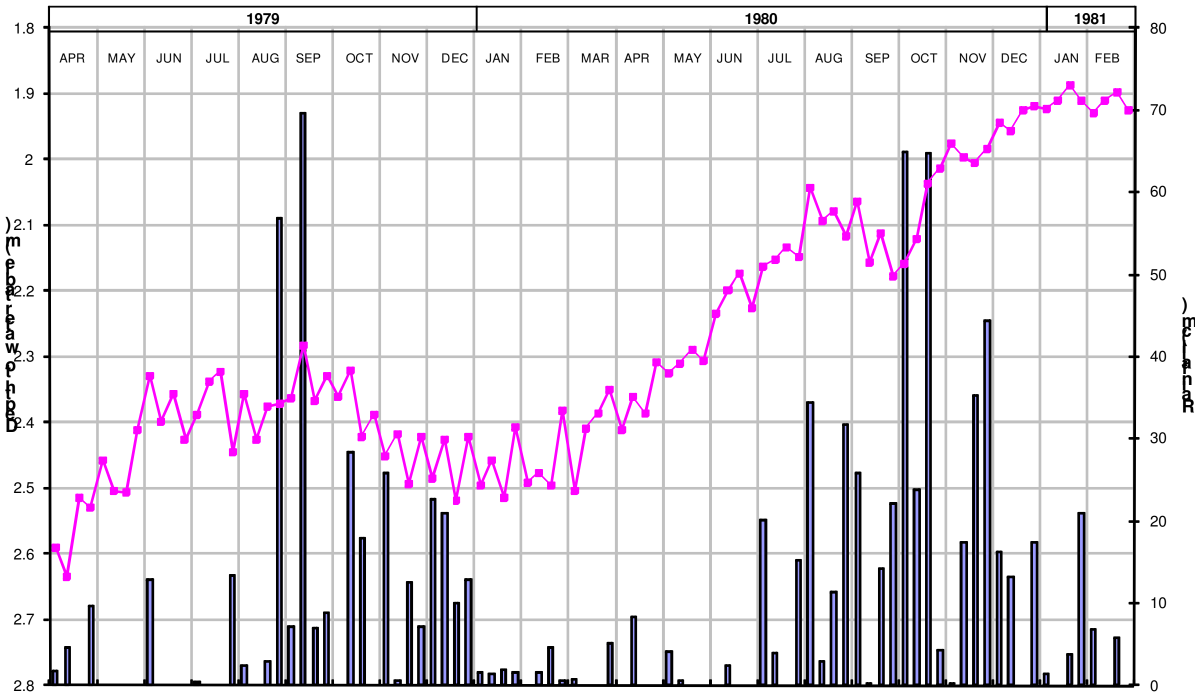



Figure 37: Average water level in wells in Schaapkraal/Mitchells Plain and bar graph of weekly rainfall in the study area

The results of the monthly estimates of groundwater recharge for the period March 1979 through February 1981 are shown in Table 11. Another borehole (BA081) in Schaapkraal, monitored monthly for water level changes was evaluated (Table 12). The result show a rather seasonal water level rise with more or less continuous but gradual rise for 6-8 weeks after the raining events indicating delayed response (Figure 38a). Other monitoring wells (that do not have at least monthly intervals in the meaurements of water levels but are monitored manually three or four times a year) were evaluated for seasonal variation in water level. Results are shown in Table 12 and figures 38(b-f). The delayed responses of water levels shown in these plots reflect slow infiltration in the study area.

Table 11: Monthly change in water level and estimated groundwater recharge for the study area (Mitchells Plain)

| Month | Change in water level, ΔH (cm) | Groundwater recharge, R (cm) |
|---|---|---|
| 1979 | | |
| April | 26.0 | 6.8 |
| May | 15.0 | 3.9 |
| June | 31.0 | 8.1 |
| July | 21.0 | 5.5 |
| August | 19.0 | 4.9 |
| September | 29.0 | 7.5 |
| October | 27.4 | 7.1 |
| November | 28.8 | 7.5 |
| December | 39.9 | 10.4 |
| 1980 | | |
| January | 31.0 | 8.1 |
| February | 30.5 | 7.9 |
| March | 31.0 | 8.1 |
| April | 17.5 | 4.6 |
| May | 4.0 | 1.0 |
| June | 9.0 | 2.3 |
| July | 4.0 | 1.0 |
| August | 26.8 | 7.0 |
| September | 30.5 | 7.9 |
| October | 0.0 | 0.0 |
| November | 11.5 | 3.0 |
| December | 6.0 | 1.6 |
| 1981 | | |
| January | 9.0 | 2.3 |
| February | 4.8 | 1.2 |
| March | 9.0 | 2.3 |



Table 12: Estimated recharge rates for part of the study area using WTF

| Well ID | Recharge estimates from WTF | | | | | |
|---|---|---|---|---|---|---|
| | ***2003*** | | | ***2004*** | | |
| | *Δh (m)* | *R (cm)* | *R (%)* | *Δh (m)* | *R (cm)* | *R (%)* |
| BA83 | 0.82 | 18.04 | 42.52 | 1.25 | 27.5 | 42.41 |
| BA84 | 0.71 | 15.62 | 36.81 | 1.23 | 27.06 | 41.73 |
| BA322 | | | | 0.51 | 11.22 | 17.30 |
| BA326 | 0.52 | 11.44 | 26.97 | 1.4 | 30.8 | 47.49 |
| DC184 | 0.52 | 11.44 | 26.96 | 0.95 | 20.9 | 32.23 |
| UWC2/6 | 0.40 | 8.80 | 22.11 | 0.55 | 12.14 | 38.17 |

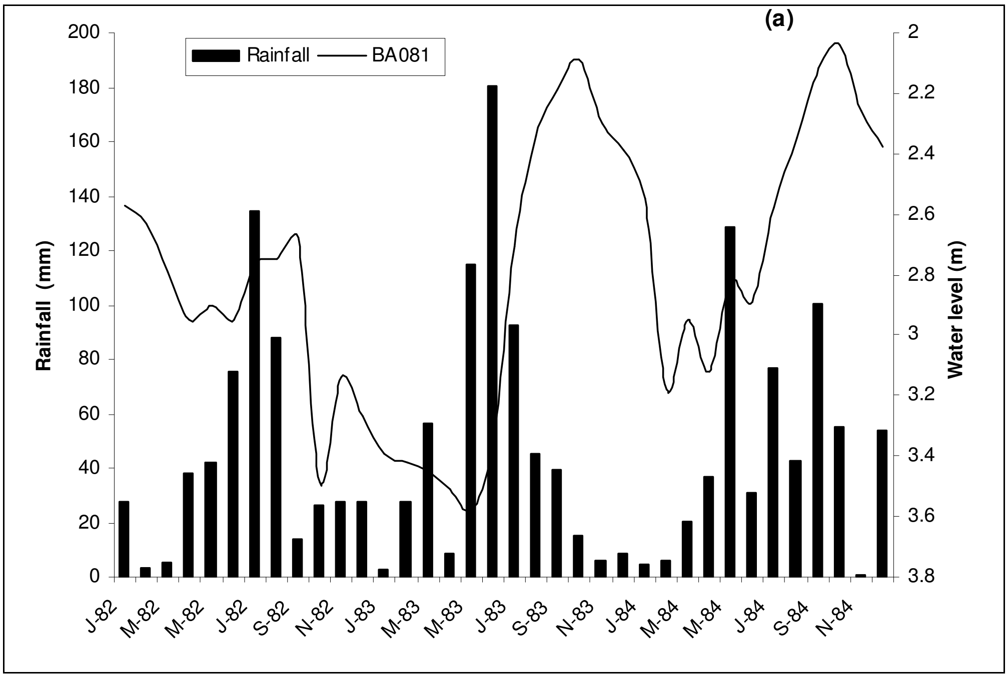



Figure 38(a): Monitoring borehole (BA81) water level with average monthly precipitation



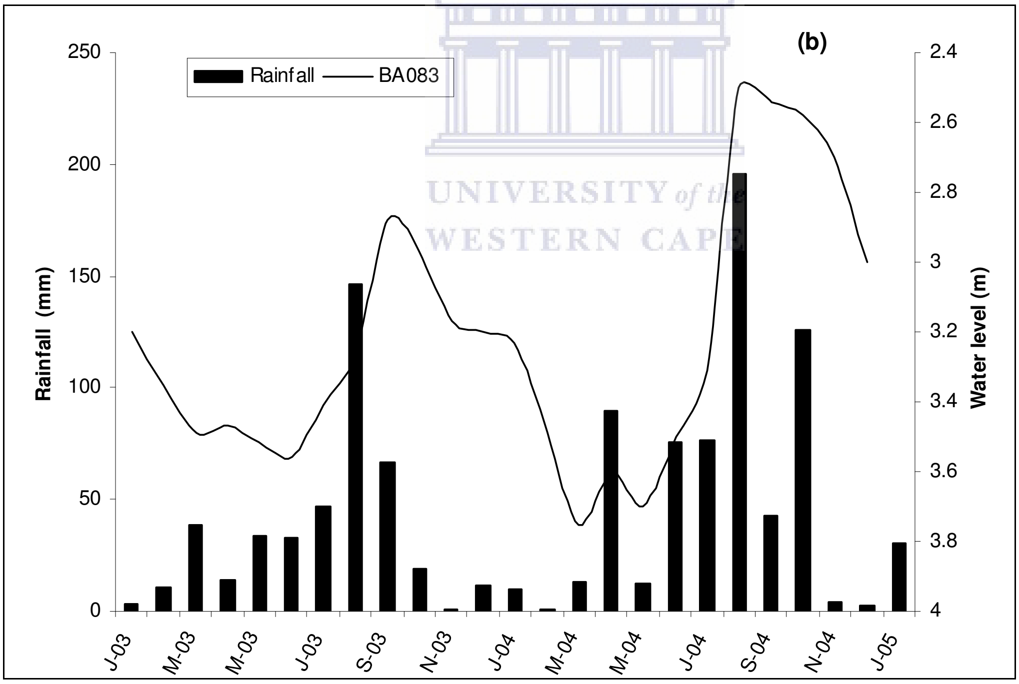



Figure 38(b): Water level of monitoring borehole (BA83) with average monthly precipitation

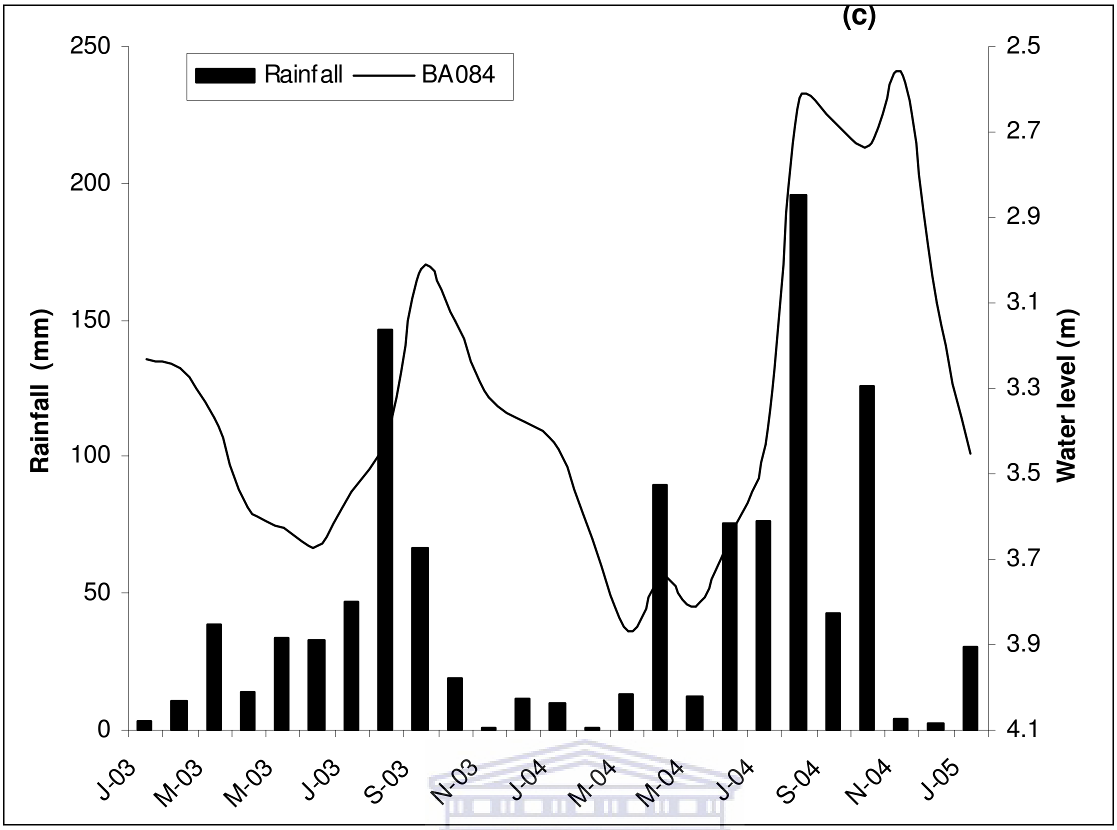



Figure 38(c): Water level of monitoring borehole (BA84) with average monthly precipitation

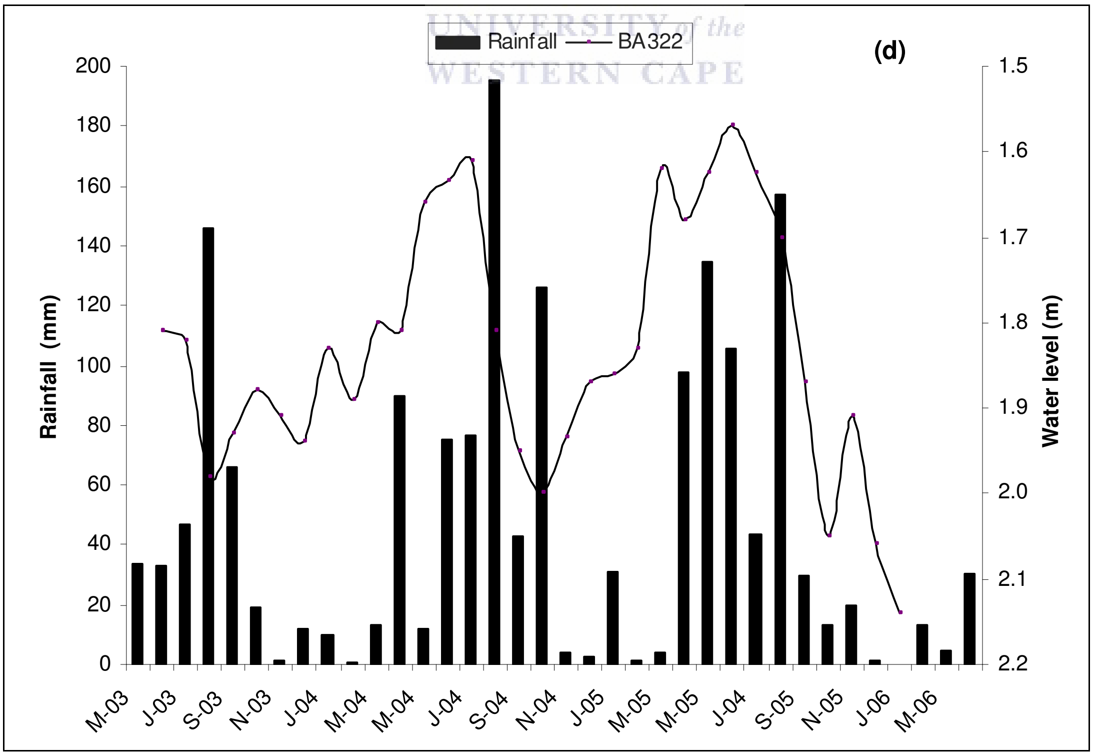



Figure 38(d): Water level of borehole (BA322) with average monthly precipitation

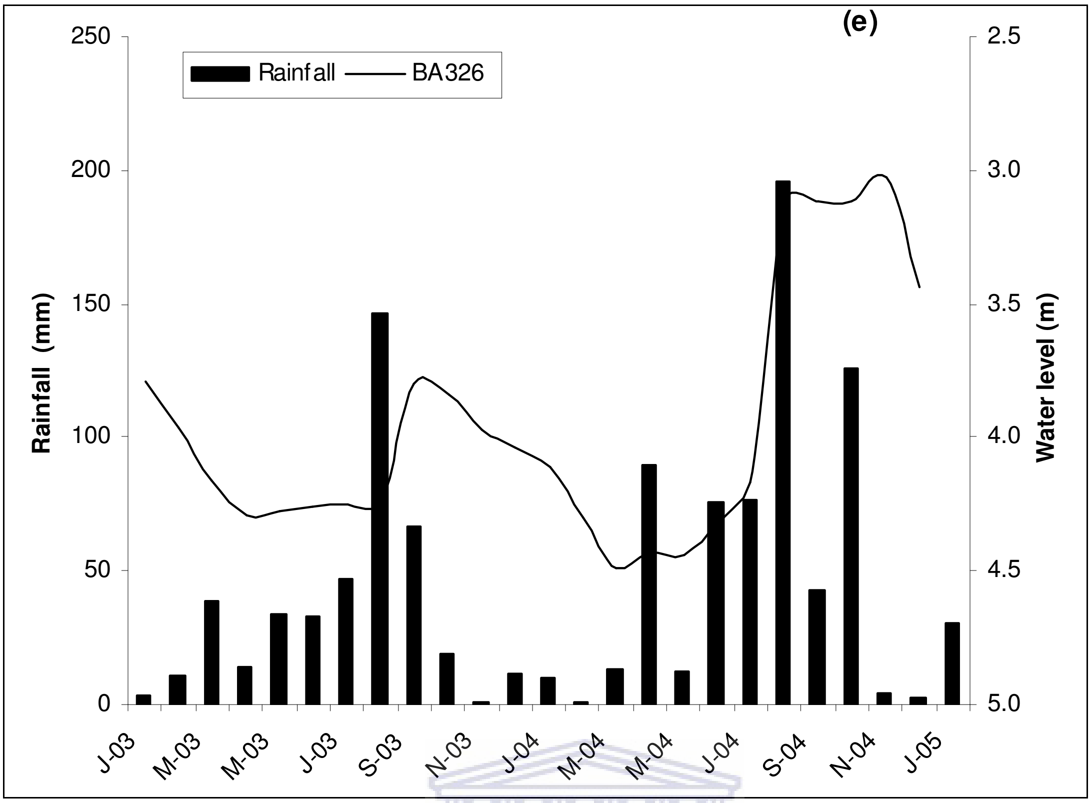



Figure 38(e): Water level of borehole (BA326) with average monthly precipitation

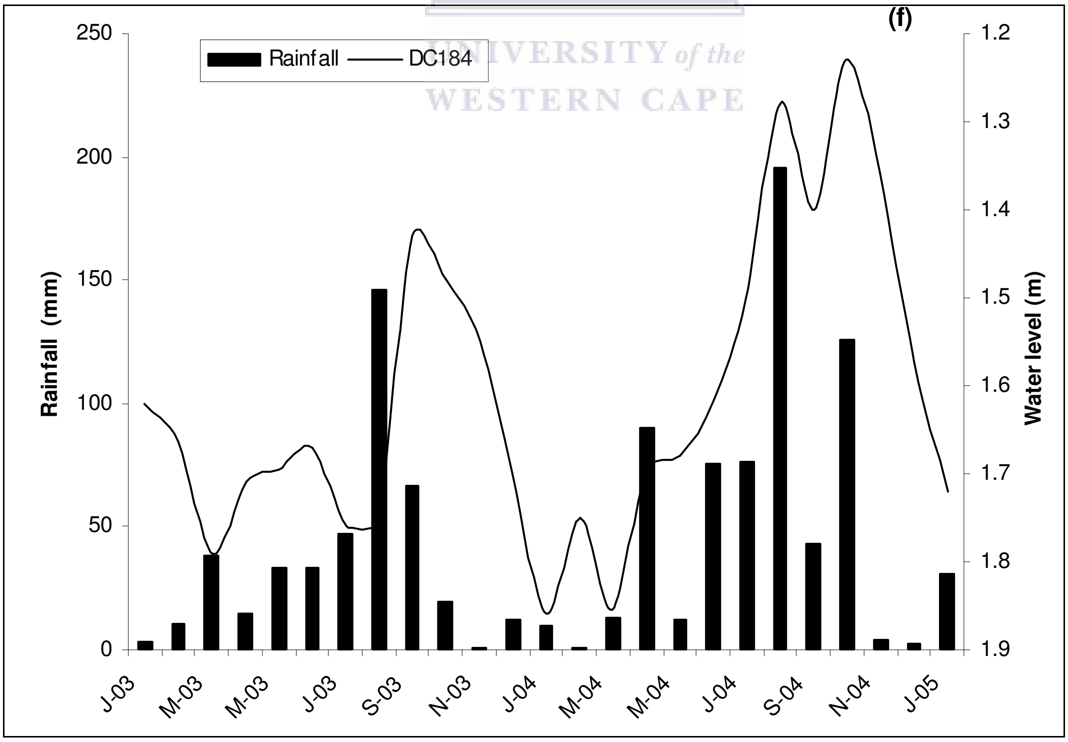



Figure 38(f): Water level of borehole (DC184) with average monthly precipitation

Similarly, precipitation and water level fluctuation at another site (UWC, Bellville South) were used to estimate recharge. UWC2 and UWC6 were monitored on hourly basis using the automated water level recorder from October 10, 2002 to March 13, 2006. UWC 2 is screened in the Cape Flats Sands while UWC 6 is screened in Malmesbury Shale. Figure 39 shows the average water level in the wells and total rainfall on a weekly basis for November 2002 through October 2004.  Precipitation was highest between June and October 2003 and within May to August for 2004. Water level fluctuations in the two wells show similar pattern (figure 39). The water table at this site varies smoothly throughout the year: most rain events do not produce measurable changes in the water level in the short-term. This is not attributed to a lack of recharge, but rather to attenuation of these short-term signals by the large storage capacity of the wells (165 mm PVC).  Recharge was calculated using the same equation 5.2.1. Table 12 shows seasonal change in water level for estimates of recharge for January 2003 through December 2004.

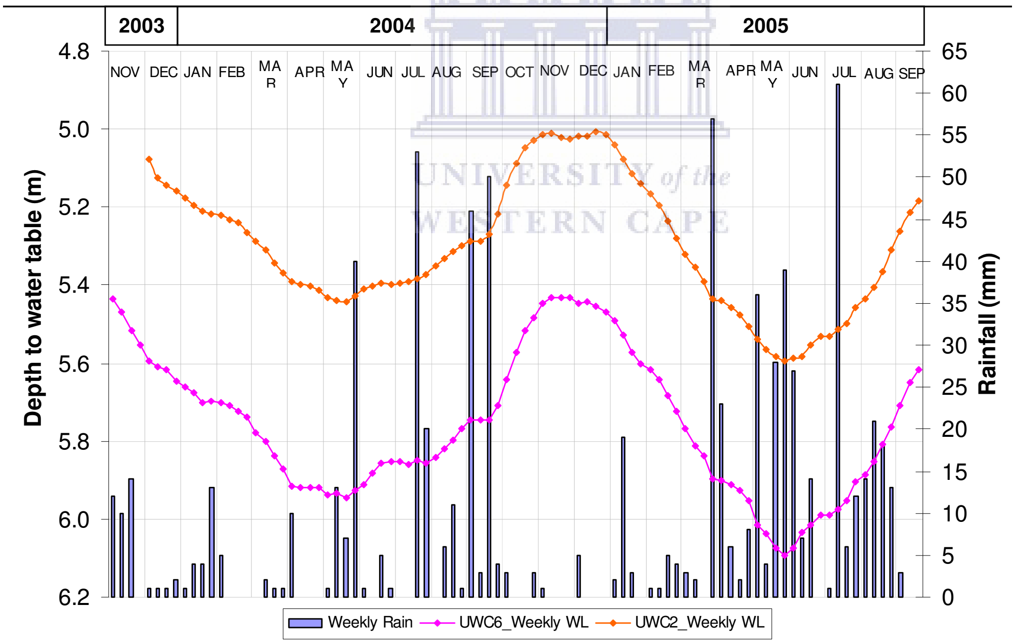





Figure 39: Average water level in wells and bar graph of weekly rainfall in UWC

*Discussion*

The values of recharge estimated and presented in Table 11 tend to be exaggerated than what is actually expected. As stated in section 5.2.1, one of the assumptions of the water table fluctuation method is that rise in water level in an unconfined aquifer is caused by recharge. Rises in the water table could occur after pumping wells are turned off, which is often observed in agricultural settings. This may be true for the site as the period of low or no rainfall (Januray to April 1980) showed positive Δh. It may be under the influence of continuous pumping of the production bores in the pilot abstraction wellfield which was recommended and used as abstraction test in the pre-1980s (Gerber 1980) and mid-1980s (Vandoolaeghe 1989). The unfortunate situation is that data was not available since the situation became controversial and the pilot abstraction project stopped as reported by Vandoolaeghe (1990). The recession extrapolations are sometimes exaggerated, affecting the recharge estimates from this method. There is an on-going research to proffer the best extrapolation technique like linear and log fit estimation, which provides a good approximation of the recession curve and yield reliable recharge estimates (John Sharples, Pers.Com. August 16, 2010).

The delayed response of water levels shows that slow infiltration is common to the investigated sites in the study area. Changes in climate or land use are not reflected immediately at the water table. Time is required for the pressure front from increased deep drainage to move downward through the unsaturated zone (Healy & Cook 2002). This time delay is related to the recharge rate, the soil-water content, and the depth to the water table (Jolly et al. 1989).

Diurnal variations in groundwater levels were observed in most of the wells in November through March. No appreciable diurnal variations were identified during April to September. The occurrence of diurnal fluctuations in these months is assumed to correlate with a period of low moisture storage within the soil profile. For example, the maximum amplitude in groundwater levels observed was 0.05 m in well (UWC2 at the UWC test site) where water table was approximately 5.79 m (Figure 40).

The figure shows rainfall and depth to water table in the borehole for two successive seasons. The water level is in decline for the most of the period from November 13, 2002 (Figure 40a), with the exception of a rise that occurred in response to 36 mm of rainfall on 20 March, 2003 although the effect of delayed response is noticeable. On the other hand, a gradual rise in water level (Figure 40b) is in response to the rainfall occurring almost daily through the wet season, even though 2003 was one of the driest years in Cape Town.

Although there are gaps in the records, the shallower water table and permeable sediments all contributed to the water-level rise at this site. Because the rise in the first few days (in Figure 40b) was long and gradual, some water arriving at the water table was likely lost to evapotranspiration or baseflow prior to the time of water level. These losses, according to Healy & Cook (2002), would not be reflected in the estimated recharge rate. The longer rainless days before each rain event, the higher contribution to rising water level. But, each rain event does not contribute to the same ratio of the rising water level for a precipitation. The effective infiltration rate of rain would depend upon several factors such as no rainy days before a rain event, intensity of rainfall, and precipitation amount as well as the size of reservoir.



The water table fluctuation method is suitable to identify relative changes in seasonal recharge due to differences in rainfall. Inter-annual differences in the estimates of recharge in the analysed observation boreholes can be seen as a percentage of total rainfall in Table 12. Comparing the values of recharge under year 2003 with that of 2004 reveal a rise in annual recharge rates which a reflection of the higher rainfall in 2004. This is similar to annual estimates of Allison et al. (1994) from observed groundwater levels in southern Australia, where climate and soil types are in the same range with the study area, and value consistent with recharge rates determined by other independent methods (Vandoolaeghe 1989).

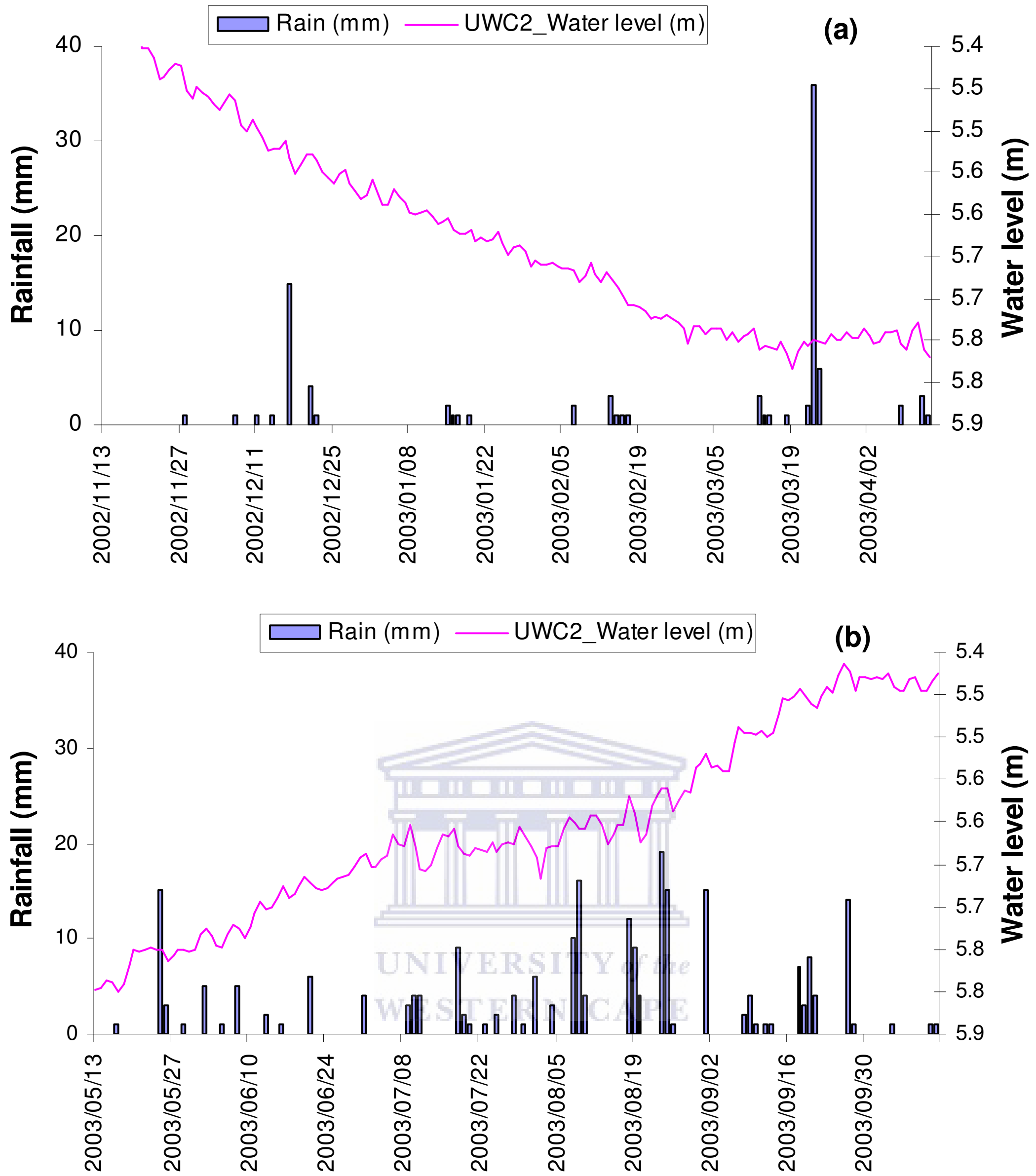



Figure 40: Daily rainfall and depth to water table at UWC showing: (a) dry and (b) wet seasons

Based on annual ET rates (>800 mm/a) that exceed annual precipitation rates (400-800mm/a), that small rain events truly do not reach the water table and thus are not recharge events. If ET is much larger than precipitation, there is likely a strong upward total potential gradient in the vadose zone. Precipitation events would have to overcome this upward gradient to flow downward past the zero-flux plane to intercept the water table. These concepts are described in the literature (Scanlon and Healy 2002, Scanlon and Goldsmith 1997). More closely-related examples are McMahon et al. (2006) and Gurdak et al. (2007) which describe fluctuations in the total potential gradients in the High Plains aquifer in the United States, which in many ways has a very similar climate to South Africa.

Although the water-table fluctuation method is the most widely used method for estimating recharge (Healy & Cook 2002), the method does have its limitations. The linear estimation will tend to over estimate the recharge volume. By linearly extrapolating the projection does not account for the tendency of recession curves to flatten out with time. The attractiveness of the WTF method lies in its simplicity and ease of use. No assumptions are made on the mechanisms by which water travels through the unsaturated zone (Healy & Cook 2002); hence, the presence of preferential flow paths within the unsaturated zone in no way restricts its application. Because the water level measured in an observation well is representative of an area of at least several square meters, the WTF method can be viewed as an integrated approach and less a point measurement than those methods that are based on data in the unsaturated zone (Healy & Cook 2002). In the study area other sources of recharge cannot be overruled; the net positive change in head without a corresponding change in rainfall in some months could be inherent in the limitations of WTF method. This is why other methods of recharge are presented in the following sections.

### *5.4.2 Cumulative Rainfall Departure (CRD)*



The Cumulative Rainfall Departure (CRD) method is very similar to the WTF method as it is also dependent on accurate determination of storativity or specific yield. Because of its versatile and minimal requirements of spatial data, the CRD method gained application in Southern Africa (Beekman & Xu, 2003). However, the method cannot be applied in areas where there are no groundwater level fluctuations and consistent water level data for at least 23 months. For most part of the study area there were no consistent records of groundwater levels to match the long-term rainfall data available in stations around Cape Town. In attempt to validate the recharge estimates by WTF method the CRD and reconstruct the Cape Flats aquifer lag-time, water level and rainfall data in Atlantis (located on the north-western end of the Cape Flats sand, 33.567°S, 18.483°E) were used in the modified CRD model called Recharge Estimation Model in Excel (REME). This is presented in this section.

The CRD method is based on the premise that water level fluctuations are driven by rainfall events. In CRD method, the sum of the departures of monthly rainfall from the long-term average of monthly rainfall is modelled to mimic the groundwater level response. Bredenkamp et al. (1995), Bredenkamp (2000), Bredenkamp & Xu (2003) extensively applied this method with success in South Africa. The method was revised to accommodate for trends in rainfall time series (Xu and Van Tonder, 2001). Recharge is then calculated as follows (Xu and Van Tonder, 2001):

$$R_T = rCRD_i = S_y \Delta h_i + (Q_{pi} + Q_{outi})/A \qquad with$$
$$CRD_i = \sum_{i=1}^{N} P_i - \left(2 - \frac{1}{P_{av} i} \sum_{i=1}^{N} P_i\right) iP_t \tag{5.2.3}$$

where r is that fraction of a CRD which contributes to recharge, $S_y$ is specific yield, $\Delta h_i$ is water level change during month i (L), $Q_p$ is groundwater abstraction ($L^3/T$), $Q_{out}$ is natural outflow, A is recharge area ($L^2$), $P_i$ is rainfall for month i (L/T) and $P_t$ is a threshold value representing aquifer boundary conditions. $P_t$ may range from 0 to $P_{av}$, with 0 representing a closed aquifer (no outflow), and $P_{av}$ representing an open aquifer system (for instance controlled by spring flow). The ratio $r/S_y$ can be estimated based on equation (5.2.3) through an optimisation process which minimises the difference between calculated and observed water level fluctuations over a specific time interval (Beekman and Xu, 2003). The CRD method and estimation of the $r/S_y$ ratio has been built into the REME (a user-friendly Excel program for recharge estimation, Xu and Van Tonder, 2001; Beekman and Xu, 2003, Bredenkamp and Xu, 2003).

This modified CRD method was applied to 8 (eight) well points with similar pattern to the result presented in figure 41. Groundwater level in the Cape Flats is shown in relation to the average rainfall simulated with the CRD model. Noticeable deviations in the plot are due to pumping influences. This method has provision for the influence of abstraction well on the study area. Within the Cape Flats sand in Atlantis (with several boreholes in two wellfields), it was also difficult to find well points meeting the following criteria: (a) a shallow water table, (b) a long record and (c) wells that are far enough from either the recharge basins or the production well fields. The first two criteria also disqualified most well points in Atlantis area. The optimisation is implemented with the term ($Q_{pi} + Q_{out}$) (AS) in equation (5.2.3). Based on the method, an average recharge value of 10% of rainfall was calculated and a lag-time of 4-6 months deduced for the Cape Flats aquifer.

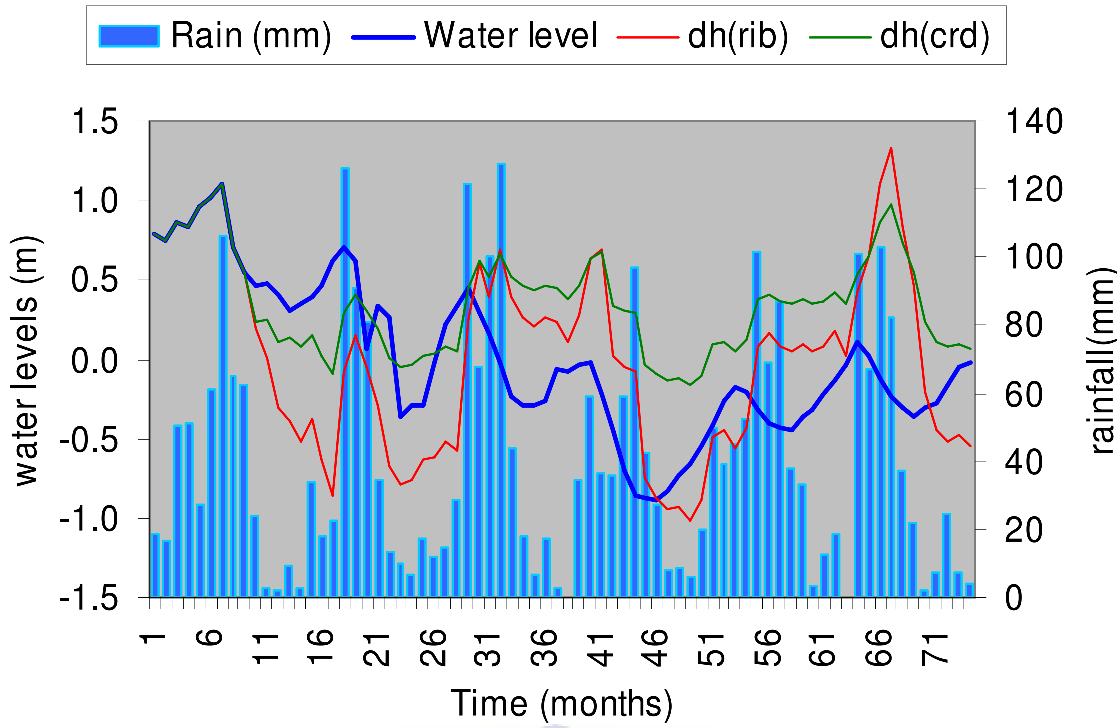



Figure 41: Simulation of groundwater fluctuation using the CRD method based on data from Atlantis (BH G30944; Atlantis rainfall, 1985-2002). dh(rib) and dh(crd) are both simulated head.



### *5.4.3* Rainfall-recharge relationship

Generally, in the estimation of recharge rates many attempts have been made to find simple relationships between rainfall and recharge. This has led to a number of empirical formulae applied (by different authors in different places) to estimate recharge. Particularly with regard to the groundwater level fluctuation approach in relation to the Cumulative rainfall departure method (CRD), discussed in the previous section. Parallel to the latter is the moving average method (MA method) by which groundwater hydrograph could be simulated in relation to rainfall using a simple recharge relationship. These methods are powerful techniques that can be applied for both assessments of the recharge and its dynamic response in relation to the rainfall. These results could be converted to an overall exponential rainfall recharge relationship which is of immense value to reconstruct the recharge over an entire period for which rainfall data are available. This method has been published and applied in South Africa (Bredenkamp 2000, Bredenkamp et al. 2007). Moreover, Bredenkamp et al (2007), used of natural isotopes and groundwater quality (together with these empirical approaches) for improved estimation of recharge and flow in dolomitic aquifers, which is equally applicable to coastal sandy aquifers.

In the present study, however, two empirical methods, using simple mathematical relations were employed in the estimation of recharge following the work of Bredenkamp (1990, 2000), and Sinha and Sharma (1988). These are briefly summarised and results presented in this section. In a quantitative study of groundwater recharge in non-dolomitic aquifers in the Pretoria-Rietondale area (South Africa) a linear rainfall-recharge relationship was obtained (Bredenkamp 1990). This relationship yields a recharge equation as follows:

$$RE = A\ (RF - B) \qquad (5.2.4)$$

where RE is recharge; RF is rainfall (in mm/a): A & B are simulated parameters.

Considering the general applicability of this method and the soil types together with the range of annual rainfall in the study area, the following simulated parameters were applied, bearing in mind the various influences on rainfall; A = 0.35 while B = 360 and thus the relation becomes:

$$RE = 0.35\ (RF - 360) \qquad (5.2.5)$$

From equation (5.2.4), note that 0.35 is the optimised lumped parameters representing threshold rainfall that has to be exceeded to effect recharge while 360 is a constant representing integrated accumulated soil moisture deficit adopted for the area. Sinha and Sharma (1988) applied similar empirical formula to estimate recharge in a semi-arid region in India. Sinha and Sharma (1988) seeing the only variable is rainfall and the local climate is semi-arid, and applied to areas where rainfall is greater than 380 mm/a. Rainfall in Cape Town rarely drop below 380 mm/a in several decades ( exception of 2000). This formula, as applied to define recharge in the study area, is as follows:

$$\mathbf{RE = 50.8\ (RF/25.4\text{-}15)^{0.4}} \qquad (5.2.6)$$

where **RE** and **RF** are as defined in 5.2.4.

The constants are simulated and adjusted parameters.

Each of these was applied to the data in Cape Town during the preliminary recharge assessment of the Cape Flats (Adelana et al. 2006). The results are summarized in Table 13 for annual averages over several years of precipitation data (1933-2009 in appendix 5.1 and 5.2). For years 1935, 1973 and 2000 the values are negative depicting that the threshold value of rainfall that can effect recharge was not reached.

The recharge estimates using method 2 appear exaggerated. This was attributed to the possible errors from the simulation of the parameters used in the empirical formula. It was, however, applied here not only for it's readily usability but as a close comparison with recharge relationship developed by Bredenkamp (1990) employed in the study area as empirical method 1. Comparing the estimates from these two methods for the year 2003/2004 (5-8% for 2003; 15-33% for 2004) with values estimated using WTF (Table 12) show some variations. WTF for the different sites ranged from 22 to 47% in 2003 and 17 to 42% in 2004. The results obtained for annual recharge using method 2 agree closely with those estimated using the WTF method. The values estimated for recharge from this method were thought to be exaggerated because the estimates used to derive the formula were not checked, for example, by a groundwater model as described in Lerner (1986). Moreover, the optimized parameters used in method 1 were simulated from data from Atlantis (section 5.4.2) since there were no long term records of water level measurements to match the record of rainfall data in the present study area.

In summary, the empirical methods were found useful as quick estimates, especially in a semi-arid area where hydrogeological information is sparse but cannot be rely upon for specific hydrological and management planning (Adelana et al. 2006a,b).



Table 13: Summary of results of empirical methods of recharge estimation

| | MAP (mm) | Method 1 | | Method 2 | |
|---|---|---|---|---|---|
| | | Recharge (mm) | % of MAP | Recharge (mm) | % of MAP |
| **Max** | 914 | 194 | 21 | 426 | 47 |
| **Min** | 229 | 14 | 3.6 | 16 | 4 |
| **Mean** | 599 | 87 | 13 | 182 | 28 |

Note: Method 1 (after Brendenkamp 1990)
Mwthod 2 (after Sinha & Sharma 1988)
MAP = Mean Annual Prepecipitation

### *5.4.4 Recharge estimates from water balance model*

#### *5.4.4.1 Background*

Water balance models dates back to the 1940s and 1950s both in their development and applications Thornthwaite (1948) and Thornthwaite and Mather (1957). Their simplicity and ease of applicability have made them appealing (Dripps and Bradbury 2007). Some researchers (e.g., Alley 1984 quoted in Dripps and Bradbury 2008) have applied the original Thornthwaite-Mather model while others (e.g., Eaton 1995; Swanson 1996) have modified various components of the original model in an effort to improve the model's handling of certain constituents of the water budget. According to the analysis of the methods by (Dripps and Bradbury 2007), these latter attempts certainly improve the performance of the water balance original model.

#### *5.4.4.2 The soil-water balance model*

The WaSim water balance simulations have been used with the climate data available in the study area as described in section 4.1.2.2. Daily precipitation (in mm) and potential evapotranspiration (in mm), are input into the model via an Excel spreadsheet. In addition, the crop and soil parameters (and irrigation and drainage) need to be defined. The model code is written in Visual Basic and requires Microsoft Excel 2000 to run. WaSim water balance model is a one-dimensional soil water balance uses readily available climatic data, soil, crop pattern, topographic, and irrigation to estimate groundwater recharge using a simple mass balance calculated at a daily time step. It aims to simulate the soil water storage and rates of input (net rainfall and irrigation) and output (evaporation, transpiration and drainage) of water in response to climate. The upper boundary is the soil surface and the lower boundary is the impermeable layer.

Water is stored between these two boundaries in five stores (layers):

1. the surface (0 – 0.15m) layer,
2. the active root zone (0.15m – root depth),
3. the unsaturated layer below the root zone (root depth – watertable),
4. the saturated layer above drain depth (watertable – drain depth),
5. the saturated layer below drain depth (drain depth –impermeable layer).

The boundary between layers 2 and 3 will change as the roots grow. Before plant roots reach 0.15 m, layer 2 will have zero thickness. Similarly, the boundary between layers 3 and 4 will fluctuate with the watertable. Soil water moves from upper layers to layers below only when the soil water content of the layer exceeds field capacity but the rate of drainage is a function of the amount of the excess water. Upward capillary rise occurs from the water table to the root zone.

Some of the incoming precipitation is intercepted by the vegetation where it is utilized by plants or lost to evaporation, but the rest continues through the canopy as throughfall, reaching the ground surface. Interception is estimated in the model using a black-box model approach in which a daily initial interception storage capacity must be satisfied before precipitation can reach the soil surface. Interception capacities are assigned based on land cover type and season. The full description of procedure and theory of application are in Hess and Counsell (2000, 2001). Water budget components can be exported at daily, monthly, or annual time steps.

#### *5.4.4.3 Results and discussion*

The potential evapotranspiration calculated in section 4.1.1.3 (using CROPWAT 8.0) is imported from text files into the model, with daily rainfall. Daily climate data (2000-2009) from Cape Town airport were used. Estimates of runoff, precipitation, actual evapotranspiration and recharge (as deep percolation) are listed in Appendix 4.5. Table 14 presents the estimates of annual recharge as a percentage of rainfall.



Table 14: Annual average of rainfall and recharge

| Year | Rainfall (mm) | Recharge (mm) | Recharge (as a % of rainfall) |
|---|---|---|---|
| 2001 | 595.3 | 5.6 | 0.94 |
| 2002 | 521.8 | 8 | 1.53 |
| 2003 | 376.1 | 4.3 | 1.14 |
| 2004 | 544.3 | 4.8 | 0.88 |
| 2005 | 517.1 | 7.5 | 1.45 |
| 2006 | 436.1 | 5.6 | 1.28 |
| 2007 | 680.6 | 19.9 | 2.92 |
| 2008 | 628.8 | 26.9 | 4.28 |
| 2009 | 525.4 | 14.7 | 2.8 |

Overall, the calculated values of deep percolation shown in appendix 4.5 may appear lower than what is assumed, but agrees reasonably with the estimates from other sources in similar settings. For example, estimates of 1.2 – 8.5 mm/a (0.4 – 3.4% MAP) has been obtained for Graafwater wellfield, 1.4 – 2.3 mm/a (0.9 – 2% of MAP) for Wadrif wellfield, 1.1 – 4.3 mm/a (0.5 – 2%) for Elands Bay wellfield; all are located in the north-western coast of Western Cape (Conrad et al. 2004).

Deep percolation amounts are smaller for this site when compared to the work of Cook et al. 1998 in the tropical of Northern Australia and the rainforest zone of Ghana (Christianse and Awadzi 2000). The highest rainfall amount does not necesaarily result in maximum deep percolation because the soil can be very dry before the rainfall, and the infiltrated water is then used to fill up the soil water capacity.

Some of the incoming precipitation is intercepted by the vegetation where it is utilized by plants or lost to evaporation, but the rest continues through the canopy as throughfall, reaching the ground surface. Interception is estimated in the model using a bucket model approach in which a daily initial interception storage capacity must be satisfied before precipitation can reach the soil surface. Runoff is routed iteratively for each precipitation event until the daily water input either infiltrates or exits the model domain.



Water that infiltrates helps to satisfy the maximum soil-moisture storage capacity, which is calculated as a function of the cell's soil water holding capacity. Daily infiltration is calculated as the difference between the daily net water input (precipitation + incoming runoff – interception) and the daily total runoff. The model assumes one-dimensional vertical infiltration. If the maximum soil water storage capacity is satisfied in the model cell, any excess water exits from the bottom of the cell as groundwater recharge. The actual timing of the arrival of recharge to the water table will depend to a certain extent on the thickness of the unsaturated zone, which is not explicitly accounted for by the model. The estimated recharge here is only precipitation-induced and does not account for recharge from surface water bodies. Since the unsaturated zone is typically thin (<10 m), and so recharge and the timing of recharge, as estimated by the soil water balance model, should be reasonably comparable.

Although the model provides reasonable estimates of annual, monthly, and in most cases daily, water balance parameters the model does have limitations. WaSim was designed as a teaching material to demonstrate a three-layer soil water balance model to estimate the changes in the soil water content on a daily basis taking into account inputs of rainfall (and irrigation) and outputs of evapotranspiration (modified for the crop cover and soil water status) and deep percolation. It can be used as a simple unsaturated zone water balance model for calculation of potential recharge to a groundwater system. The author fully recognize that more rigorous, and perhaps more accurate, techniques are available to represent many of the hydrologic processes simulated by the model, but the often extensive data requirements and personnel resources required for utilizing the more rigorous techniques limits their use and makes them impractical for many applications. As such, the estimates from the model is intended to provide a physically based, cursory estimate of annual and monthly recharge which could be used for (1) generating recharge values for input into regional groundwater flow models, (2) defining general spatial patterns and the degree of spatial variability of recharge across a region, and (3) assessing annual and monthly temporal patterns and the degree of temporal variability of recharge for an area.

### *5.4.5 Chloride Mass Balance method*

#### *5.4.5.1 Theoretical background*



The chloride mass balance (CMB) method for the estimation of groundwater recharge is by far economic and effective. In attempting to determine the mean annual recharge using the chloride method it is assumed that the only possible source of chloride ion in groundwater of the study area is at the soil surface (either in precipitation or as dry fallout) and that there is no contribution from weathering. Since there are no evaporites in the study area there is unlikely to be any significant contribution of chloride from the weathering of host rocks.

Chloride ion is a highly soluble, non-absorbing, chemically conservative and easily measurable environmental tracer that has successfully been used to estimate recharge in arid and semi-arid areas since the last three decades (Allison & Hughes 1978, Sharma & Hughes 1985, Allison 1988, Cook et al. 1989, Walker et al. 1991, Allison et al. 1994, Edmunds et al. 2002). Different recharge mechanisms have been illustrated by Allison (1988). According to Houston (1990) in different rock types significant relationship exists between rainfall and chloride content suggesting recharge is a function of rainfall. Also, most plant species do not take up significant quantities of chloride from soil water, thus concentrating chloride by evapotranspiration in the root zone (Allison et al. 1994). The conditions for a successful application of the CMB method according to Wood (1999) are:

(1) atmospheric chlorine is the only source for chloride in groundwater,

(2) chloride behaves as a conservative tracer along the flow path,

(3) chloride uptake by roots and anion exclusion are negligible,

(4) leaching of chlorine-containing strata at ground surface and in the soil zone is complete,

(5) groundwater movement in both unsaturated zone and saturated zone can be approximated by one-dimensional piston flow, and

(6) surface run-on and runoff can be neglected.

Based on these assumptions the ratio of chloride (Cl) in rainfall to that in groundwater is proportional to recharge as shown in the following relationship (Allison et al 1994):

$$Recharge = Rain \times \frac{Cl_{rain}}{Cl_{gw}} \qquad (5.2.7)$$

Two different approaches using chloride mass balance analysis can be found in the literature. The first approach is the derivation of groundwater recharge from unsaturated zone pore water profiles of chloride. A description can be found in Hendrix & Walker (1997), Bromley et al. 1997, Edmunds et al. 2002. Ideally the chloride concentration in pore water increases rapidly with depth from the soil surface as residence time and evapotranspiration increase, until the concentration reaches a constant value equal to that in groundwater. Recharge can then be calculated from the chloride gradient. The difficulty in this approach is that pore water profiles can show high spatial variability due to soil heterogeneities, and that recharge from preferential flow paths is not captured (Edmunds et al. 2002).



*5.4.5.2 Sampling and analytical techniques for Chloride method*

Chloride mass balance method is one of the techniques which are often used to estimate moisture fluxes through the unsaturated zone thereby enabling the assessment of recharge to the groundwater. It is one of the promising methods under the review and classification of commonly used recharge methods for semi-arid southern Africa (Beekman & Xu 2003). In the present study, soil moisture chloride profile approach could not be used, because the soil moisture sampler (model Eijkelkamp 12.01 SB) acquired in 2006 for this purpose became faulty.

Four investigation sites were chosen in the study area for rainfall and chloride measurements for the Chloride Mass Balance method (UWC, iThemba Labs, Macassar and Mitchells Plain). Precipitation Cl concentrations were measured in the first three stations in the months of July-August 2006 (during the winter rainy period) while the other are obtained from City of Cape Town Catchment monitoring data. Analysis of stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) was also performed in order to identify recharge processes (see section 5.4.5). Details of the laboratory analytical techniques employed for the chloride and isotope measurements were discussed in chapter 2.

*5.4.5.3 Results of Chloride Mass Balance*

Based on the theory described above chloride method was applied to estimate recharge in the study area. Table 15 shows the results of sampling and measurements in 2006. Groundwater chloride was sampled in the present study at each observation well and by the City of Cape Town Catchment Monitoring Department between 2005 and 2006. The results for each site were averaged to give the concentrations indicated in Table 16. Result gave an overall mean of annual recharge rate of 34.2 mm/a (which is 5.5% of mean annual precipitation, MAP, at Cape Town Airport). The recharge estimated using rainfall data and chloride measurements at UWC Test Site is as follows: 29.0 mm/a (7% of MAP) for the years 2002-2005; and similarly 46.6 mm/a, 8.1% of annual precipitation (at Mitchells Plain). The results show that recharge in the study area represents 5.5-8.1 % of annual rainfall at each of the weather stations. Results from iThemba were considered not useful in the overall recharge estimate from chloride method. This is because of the undue high chloride content in groundwater strongly influenced by the pumping exercise in 2005-2006. Direct evaporation from the shallow water table (1-3 metres) in the coastal plains as well as intense use of chemical fertilizers, particularly in the irrigated areas, could have influence downstream in the wells in Philippi and Otery area, near to Mitchells Plain.

Table 15: δ$^{18}$O and chloride data for Cape Flats (rainfall sampling season 2006)

| Sample ID. | Sampling Date | Latitude S | Longitude E | EC | Cl | $^{18}$O |
|---|---|---|---|---|---|---|
| iThrain3107 | 2006/07/31 | -34.02 | 18.71 | 9.1 | 22.1 | -2.92 |
| iThrain0808 | 2006/08/08 | -34.02 | 18.71 | 2.3 | 8.8 | -2.30 |
| iThrain1909 | 2006/09/19 | -34.02 | 18.71 | 4.5 | 19.4 | -3.08 |
| iThrain3110 | 2006/10/31 | -34.02 | 18.71 | 3.8 | 12.4 | -4.93 |
| Uwcrain0607 | 2006/07/06 | -33.93 | 18.62 | 4.0 | 9.7 | -2.39 |
| Uwcrain1707 | 2006/07/17 | -33.93 | 18.62 | 3.0 | 1.8 | |
| Uwcrain2107 | 2006/07/21 | -33.93 | 18.62 | 3.0 | 2.2 | -1.74 |
| Uwcrain2207 | 2006/07/22 | -33.93 | 18.62 | 14.0 | 39.7 | -7.84 |
| Uwcrain2407 | 2006/07/24 | -33.93 | 18.62 | 9.0 | 24.7 | -3.24 |
| Uwcrain2807 | 2006/08/28 | -33.93 | 18.62 | 13.0 | 23.8 | -3.28 |
| UWCrain0211 | 2006/11/02 | 33.93 | 18.62 | 7.1 | 14.1 | |
| UWCrain0311 | 2006/11/03 | 33.93 | 18.62 | 1.5 | 26.5 | |
| Bel_rain | 2006/11/03 | -33.94 | 18.60 | 2.5 | 17.9 | |

Since chloride tends to remain in solution and is difficult to remove through most of the natural processes, which tend to separate out other major dissolved ions (Davis & De Wiest 1976; Hem 1985), the samples low in Cl- from the eastern as well as the north-western parts of the study area indicate no anthropogenic effect. These samples either originate from relatively deeper wells or from the less cultivated areas. However, these values are higher than the minimum long-term average areal recharge (1.2 ± 0.2%) calculated for the eastern fringe of the Botswana Kalahari (Selaolo 1998) based on Cl and isotope physical approach. This further shows that chloride method is widely applicable in estimating low recharge rates as reported (Scanlon et al. 2002) even though higher values of recharge have also been recorded elsewhere using this method. Samples of rain water for chloride measurements are few and only from three sites in the present study compared to several years of measurements in the Kalahari. It is also useful for a first approximation of the recharge flux estimation in semi-arid and arid zones (Zhu et al. 2003).

Table 16: Recharge estimates in the Cape Flats based on Chloride Method

| Location | UWC | Mitchells Plain | Macassar |
|---|---|---|---|
| *Coordinates (Lat.)* | -33.93 | -34.04 | -34.06 |
| *Coordinates (Long.)* | 18.62 | 18.60 | 18.74 |
| Mean of Cl concentration in groundwater (ppm) | 160.5 | 138.9 | 405.0 |
| Mean of Cl conc. in Rain water (ppm) | 11.2 | 11.3 | 11.3 |
| Annual mean of precipitation (2002-2005) in mm | 414.0 | 642.6 | 576.1 |
| No of samples | 12 | 30 | 7 |
| **Annual recharge in mm** | **29.0** | **52.4** | **16.1** |
| Recharge rate (%) | 7.0 | 8.2 | 2.8 |

## 5.5 Recharge sources and mechanism in the Cape Flats

### *5.5.1 Sources of recharge*

The first stage is the identification of the various recharge sources. In the Cape Flats, rain recharge seems to be dominant. Possible sources of aquifer recharge through surface flux, other than precipitation as highlighted in Adelana et al. (2006) are:

i. Zeekoevlei, an open water body near the south-west coast between Muizenberg and Mitchells Plain

ii. The sewage treatment stabilization ponds located at the south-east of Zeekoevlei, Macassar, Faure, etc.

iii. The Kuils and Eerste rivers, which cut into the eastern part of the aquifer near Faure.

iv. The municipal water supply reservoirs located within the sands such as at Tygerberg, Blackheath, etc.

The Zeekoevlei may appear at the first glance as a major source of recharge but water table analysis shows that this shallow pond is partly maintained by groundwater seepage, with possible exception of short periods after heavy downpours when the quasi-equilibrium system may be disturbed temporarily (Gerber 1981). Moreover, the bottom of the Zeekoevlei appeared sealed to a large extent as a result of mud and clay deposition. Consequently recharge from this water body may be considered insignificant.



The influence of municipal sewage treatment ponds in the Cape Flats was investigated earlier by Henzen (1973), who pin-pointed evidence of sewage infiltration but that the quantities involved in long established ponds were so small compared to the daily flow as to be negligible. This recharge source may not be ignored at such a time as this that the population of Cape Town has grown and the wide expanse of fallow land in the suburbs are now covered with residential and industrial buildings. However, the resources and logistics to investigate this into details are not available at the time of field investigation for this project.

The magnitude and time scale of recharge from the Kuilsriver remain unknown. The Eerste River, to a small extent, contributes to groundwater recharge in the eastern end of the project area. Its contribution to recharge was investigated from stream discharge measurements at two stations with appreciable data. Drainage from the model area into the Lotus and Vygerkraal rivers was reported to take place during the winter rains. The waters conveyed in the Lotus River system are discharged into Zeekoevlei and subsequently into the sea over a weir in its southern outlet. The Vygerkraal River receives storm runoff and seepage originating in the north-western corner of the study area and conveyed through a system of the side feeders. This water eventually discharges into Table Bay.

### *5.5.2 Recharge processes*

For a realistic assessment of groundwater potential and sustainability, it is vital to study the recharge processes and mechanism of groundwater flow. In the last four decades, several research efforts utilizing multi-disciplinary scientific approach has helped in estimating recharge. However, not many of the approaches have been able to explain recharge processes and conditions sufficiently. One of the important approaches to characterization of recharge processes has been the use of isotopic and geochemical methods (Sukhija et al. 2006, Scanlon et al. 2002, de Vries and Simmers 2002). Isotopes and geochemical tracers have been employed extensively to identify the source and movement of groundwater (Vogel 1970, Geyh and Backhaus 1979, Sukhija 1996, Dahan et al. 2000). This section is based on observed isotopic signature and environmental chloride variations of the groundwater system in the study area. The purpose is to study the recharge processes and possible flow dynamics involving unconfined aquifer using environmental isotopes and geochemical tracer (chloride) in the Cape Flats.



The research work was carried out mainly in the suburbs of Cape Town, where there has been a huge population increase and rapid urbanization in the last ten years. Apart from a few reservoirs been used for domestic water supply, like the Newlands, Blackheath, Faure and Tygerberg, many others are evaporating water bodies (like the Vleis and irrigation ponds). Surface waters contain a distinct composition of stable isotopes due to enrichment caused by evaporation. Oxygen-18 ($^{18}O$) stable isotope is utilized to identify the recharge process and mixing of groundwater from different sources. Therefore, $^{18}O$ isotope makes it possible to distinguish between evaporated waters and waters directly recharged from precipitation. Soil and subsurface waters inherit the isotopic characteristics of the meteoric and surface water inputs, and change in isotopic composition occurs as a result of recharge process and mixing with waters of different compositions.

### *5.5.2.1 Isotopic composition of water during recharge processes*

According to (Issar & Gat 1981), $^{18}$O and $^{2}$H in water behave chemically conservatively below temperatures of 60–80 °C, and as such their concentrations are not affected by geochemical reactions in normal aquifers (Hoefs 1997). Therefore, groundwater preserves its isotopic fingerprint reflecting the history and origin before infiltration. This makes it a useful tool to interpret recharge mechanisms. With respect to Craig's relationship (Craig 1961), the long-term arithmetic mean for all stations of the International Atomic Energy Agency (IAEA) network is: $\delta^2 H = (8.17 \pm 0.06)\delta^{18} O + (10.35 \pm 0.65)$ (Rozanski et al. 1993). The last term of the equation, the deuterium excess (d-value), can vary locally, primarily as a function of the vapour-forming process. For the Cape Town area the regional d-value is +12.8 (Harris et al. 1999).

#### *(a) Theoretical background*

The use of oxygen and hydrogen isotopes in studying processes of the water cycle is based on the different behaviour of heavy and light isotopes during phase changes (Clark & Fritz 1997). The tendency of the heavier isotopes $^{18}O$ and $^{2}H$ to accumulate in the liquid phase rather than the vapour phase in contrast to their lighter counterparts $^{16}O$ and $^{1}H$, causes isotopic fractionation during evaporation and condensation processes. In contrast, evapotranspiration doe not cause isotopic fractionation (Kendall & McDonnel 1998). Isotope analysis can therefore be used to distinguish between evaporation and evapotranspiration.

The extent of enrichment of the heavier isotope in the liquid phase can be expressed in terms of fractionation factor, $\alpha$ :

$$\alpha_{l-v} = \frac{R_l}{R_v} = \frac{(^{18}O/^{16}O)_l}{(^{18}O/^{16}O)_v} \qquad (5.2.8)$$

with

$\alpha_{l-v}$ : Fractionation factor from the liquid to the vapour phase

$R_l$ : Isotope ratio in the liquid phase

$R_v$ : isotope ratio in the vapour phase

Other parameters that are frequently used to express fractionation are the enrichment factor $\varepsilon$ or the delta-value $\delta$. Both have units of ‰ and their definition is as follows:

$$\varepsilon_{l-v} = (\frac{R_l}{R_v} - 1) * 1000 = (\alpha_{l-v} - 1) * 1000 \ (‰) \qquad (5.2.9)$$

with

$\varepsilon_{l-v}$ : Enrichment factor from the liquid to vapour phase

$$\delta_{sample} = (\frac{R_{sample}}{R_{s\tan dard}} - 1) * 1000 \ (‰) \qquad (5.2.10)$$

$R_{s\tan dard}$ is the isotope ratio in Vienna Standard Mean Ocean Water (VSMOW). The delta-value of SMOW is by definition 0 ‰. Systems of relative humidity close to 100% can be desribed by the equilibrium enrichment factor $\varepsilon *$.

When $\delta^2 H$ is plotted against $\delta^{18} O$, average rainwater plots along a straight line with a slope of 8 and an intercept of 10. This line is called the Global Meteoric Water Line (GMWL) and is represented by the linear equation:

$$\delta^2 H = 8\delta^{18} O + 10 \qquad (5.2.11)$$



The slope of 8 is due to cloud condensation at 100% relative humidity, while the intercept of 10 – called the Deuterium excess – is caused by an average 10% kinetic enrichment of deuterium during evaporation from the ocean surface (Kendall & McDonnell 1998). Since temperature, altitude and distance from the sea influence $\delta^2 H$ and $\delta^{18} O$, local meteoric water line (LMWL) can be developed to describe the linear relation in rainwater at local conditions.

Craig and Gordon (1965) developed a model to describe kinetic fractionation during evaporation, which was re-established and recently described by Xinping et al. (2005). During the evaporation of water from the surface or soil water, enrichment of $^{18}O$ and $^{2}H$ occurs (Kendall & McDonnel 1998). The rate determining step in this model is the diffusion of water molecules across the liquid-vapour boundary layer. The kinetic enrichment factor $\Delta\varepsilon$ accounts for the resulting additional enrichment of the heavier isotope in the liquid phase. The kinetic enrichment factor depends strongly on relative humidity. The relationship is quantified for $\delta^{18} O$ and $\delta^2 H$ by Gonfiantini (1986):

$$\Delta\varepsilon^{18}O_{l-v} = 14.2(l-h) \quad (‰) \tag{5.2.12}$$

$$\Delta\varepsilon^{2}H_{l-v} = 12.5(l-h) \quad (‰) \tag{5.2.13}$$

The total enrichment factor $\varepsilon$ during evaporation is the sum of the equilibrium enrichment factor $\varepsilon^*$ and the kinetic enrichment factor, $\Delta\varepsilon$. The composition of water that has undergone evaporation deviates from the Meteoric Water Line (MWL). The extent of deviation depends on ambient humidity $h$ and the progress of evaporation while the residual fraction is signified by $f$.

Isotope fractionation is strongly dependent on the temperature. A significant correlation between the mean annual concentrations of stable isotopes in precipitation and mean annual air temperature has been observed (Daansgard 1964). This knowledge found application in the identification of recharge during paleo-climatic periods (e.g. Mazor & Verhagen 1983; Darling et al. 1997), distant mountain recharge (e.g. Clark et al. 1987) or seasonality of recharge in temperate regions (e.g. Rozanski et al. 1982). On the other hand, large rain events are more depleted in isotopic composition than small rain events, due to the preferential rainout of heavy isotopes. This effect is intensified by the enrichment of heavy isotopes, due to evaporation during minor rain events (Levin et al. 1980). Evaporation process alters the original $^{18}O$ - $^{2}H$ relationship of the rainfall resulting in slope lower than +8 and deuterium excess (d-values) lower than +10, as reported in many arid regions (Gat 1980, Mook 2005). The d-values near the coast is smaller than +10‰ and approximately 0 ‰ only in Antarctica. In areas where, or during periods in which, the relative humidity immediately above the ocean is or was below the present mean value, d is greater than +10 ‰ (Merlivat & Jouzel 1979, Mook 2005). Thus, groundwater that has previously been subjected to evaporation can be identified on this basis.

***(b) Results of the application of stable isotopes***

***Isotope composition of rainwater and groundwater***

The local values of the weighted yearly means of precipitation in Cape Town, as well as the long-term average from 1961-2001, were evaluated during this study. The local meteoric water (LMWL) obtained by linear regression of the monthly mean isotope composition display a slope of 5.1 and a deuterium excess of 4.4 (following the relation: $\delta^2 H = 5.1\delta^{18}O + 4.4$ ). The average $\delta^{18}$O and $\delta^2$H values for the months with the highest rainfall are -3.39 and -14.72 respectively. This isotopic composition is taken as the initial composition in the calculation of evaporation fraction using the Rayleigh equation, as seen below. More results and illustrations of the isotopic composition of precipitation are presented in section 6.10.1.

The isotopic composition of groundwater from the Cape Flats aquifer is characterized by relatively lower $\delta^{18}$O and δD values. The range of values of $^{18}$O and $^2$H data are presented in section 6.10.3. The most isotopically depleted groundwater samples represents the largest rainfall events in the area during sampling period and the most enriched groundwater was interpreted to indicate shorter rainfall events. The correlation of $\delta\ ^2$H against $\delta^{18}$O of the recent groundwater sampling (2005-2006), along with springs, rain and surface water in Cape Town area are illustrated and discussed in section 6.10.3.

The composition of water that has undergone evaporation deviates from the Global Meteoric Water Line (see section 6.10). The extent of deviation usually depends on the ambient humidity, *h* and the progress of evaporation. The residual liquid fraction is signified by *f*. The Rayleigh equation describes the evolution of the isotopic composition during progressing evaporation:

$$\delta^{18}O_{final} = \delta^{18}O_{initial} - \varepsilon^{18}O_{l-v} \ln f \qquad (5.2.14)$$

with $\varepsilon_{l-v} = \varepsilon^*_{l-v} + \Delta\varepsilon_{l-v}$

*f : Residual fraction*

Using the Rayleigh equation for oxygen isotopes (as these are determined with more accuracy than with hydrogen isotopes) with an initial $\delta^{18}O$ of -3.39, a final $\delta^{18}O$ of -1.25, and an enrichment factor calculated for a temperature of 10 °C and relative humidity of 0.72 of $\varepsilon^{18}O_{l-v}$ = 10.61 yields a fractionation of:

$$f = \exp\left(\frac{\delta^{18}O_{initial} - \delta^{18}O_{final}}{\varepsilon^{18}O_{l-v}}\right) = \exp\left(\frac{-3.39 + 1.25}{10.61}\right) = 0.82 \qquad (5.2.15)$$

This means that 18% of rainfall is evaporated before the infiltrating water reached the groundwater surface. Evaporation is therefore small but significant.

Figure 42(a) indicates that the evaporative enrichment does not produce significant salinity increases. Although high NaCl is strongly reflected in the iThemba borehole (probably induced by continuous pumping), this is not reflected in other wells. The background information on iThemba area also revealed that there are buried river channels, particularly in the vicinity of the wells. The fact that $^{18}O$ and chloride are not correlated significantly may suggest that the concentration of salts by evaporation is not an important process in the Cape Flats. Low infiltration rates and frequent overland flow indicate that diffuse recharge is not very likely. The probable recharge mechanism obtained from the isotopic evidence and field observations, is direct recharge from rainfall; indirect recharge from surface depressions and from agricultural lands may be another possibility. However, chloride contents in shallow- and intermediate-depth water from agricultural irrigated land on the Cape Flats (where intensive use of fertilizers, which contain chloride, could reach the groundwater table) was not investigated in this study. Furthermore, increases in chloride concentration are not attributed to isotopic enrichment (Figure 42a), which indicates that the presence of chloride is ascribed to meteoric accumulation. Detailed discussion on the source of chloride and evolution of groundwater in the study area is presented in chapter 6.

From figure 42(b), it can be seen that the $^{18}O$ values of springs and shallow groundwater (depth to water table <20 m) and intermediate-depth are similarly distributed, an indication of preferable indirect infiltration for shallow and intermediate water. The isotope content is considerably dispersed, reflecting direct recharge and shallow nature of groundwater as compared to if it was deep water with minimal evaporative effects at depth. The stable isotope ($^{18}O$ and $^{2}H$) contents are a function of a variety of atmospheric conditions such as temperature, distance from vapour source, and rates of evaporation. The mean value coincides with the mean value of shallow water varying within the standard deviation of spring water. Additional modifications are possible and may be due to subsurface processes, such as mixing.

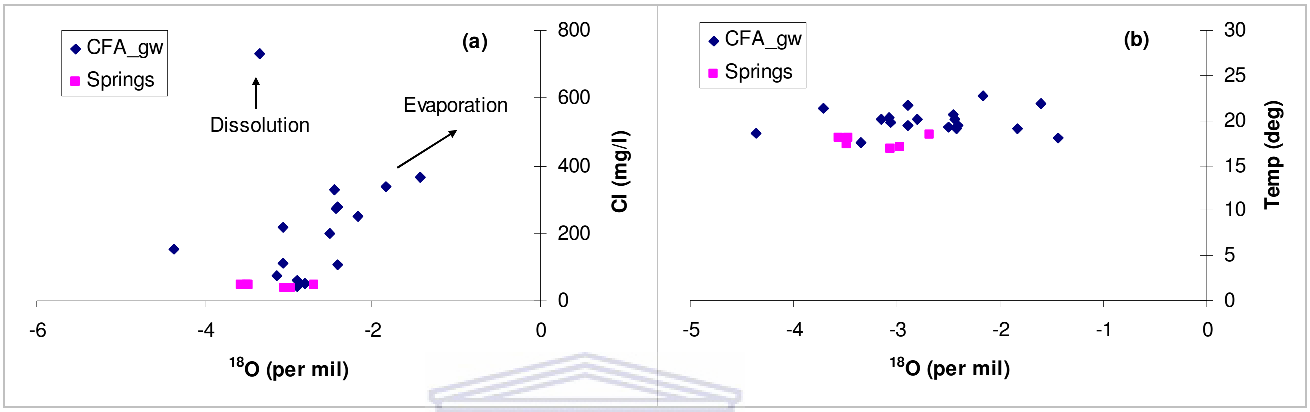



Figure 42: (a) Relationship between chloride and $^{18}O$ in groundwater and springs; (b) $^{18}O$ as function of temperature for groundwater and springs



### *5.5.2.2 Recharge conceptualisation*

A conceptual hydrogeologic model was developed to elucidate various recharge processes and flow mechanisms in the Cape Flats aquifer, based on climate, hydrology, geormophology and geology. The results from isotopic and geochemical investigations are integrated into this conceptual model about recharge and subsequent geochemical evolution of the Cape Flats aquifer (Figure 43). Groundwater of the Cape Flats aquifer is of meteoric origin with an isotopic regression line similar to the regional meteoric water line (see chapter 6). The recharge conditions have probably not changed from what it was in the past; there are no carbon dating data to determine exact age of groundwater at the moment. Most rainwater infiltrates in the mountainous flanks of the western and southwestern (Cape Peninsula and Table Mountains), eastern/southeastern (Cape Granite and Table Mountains) parts of the study area. In these areas, the infiltration rate may locally be a high percentage of the precipitation rate (>800 mm e.g. Kirstenbosch). Runoff passes through overland flow and tributaries to the main discharge (Eeste River).

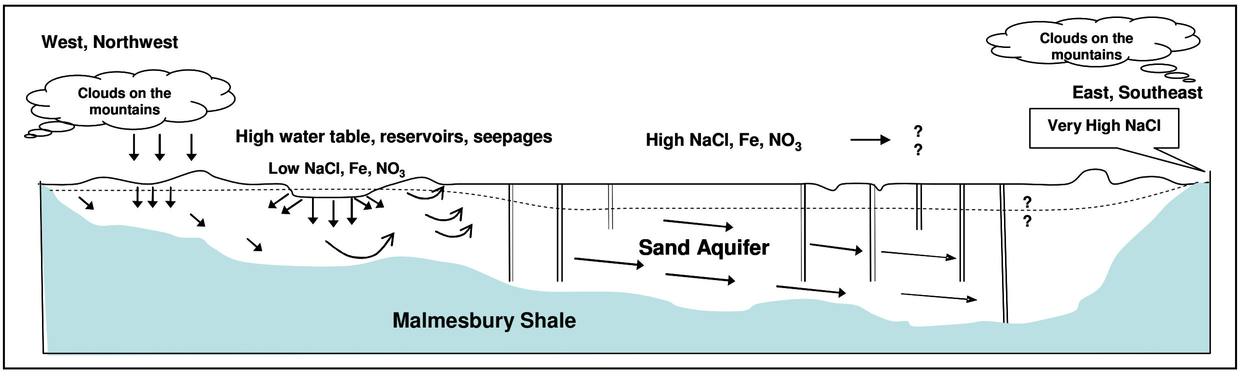



Figure 43: A schematic cross-sectional view of sources of recharge and hydrochemical evolution in the Cape Flats. Geological formations: Malmesbury shale is shown in light-blue; Quaternary sediments in white. Dotted lines show water table and arrowheads indicate general direction of groundwater flow

The model takes into account the following observations: (i) lithology as revealed through a number of boreholes in the study area, (ii) geomorphic variations, (iii) groundwater fluctuations, (iv) qualitative yields of the aquifer, (v) variation of $\delta\ ^{18}O$ and chloride concentration in groundwater. The hydrogeologic model presented above has some similarities with a conceptual model of groundwater flow developed by Gerber (1981) for the Cape Flats aquifer. In this model, on the basis of two aquifer test sites where groups of observation wells were aligned in more than one direction respectively, Gerber presented that there was evidence of anisotropy in the sand deposits of the Cape Flats.



In the hydrogeologic model developed in this study, it is believed that this sandy aquifer, which is connected to the vadose zone, carry recharge water laterally a few hundreds of meters to a few kilometers, which could result in relative ageing of the recharged water. However, in contrast to the above situation, younger ages with similar chemical and isotopic characterization are obtained. This situation may occur due to the fact that the aquifer system is generally unconfined in nature and infiltration and movement of water through the matrix result in apparent young age of groundwater. This situation can be described from the model, in which wells like AB-7 and BA-6 are located where the source of recharge is some distance away. In an actual field situation, the sampled groundwater wells mainly tapping from the Cape Flats aquifer represent the above hydrogeological situation. From hydrochemical and isotopic data and considering extensive fracture zones in the neighboring TMG with good yield (5–7 $m^3$/day) prevalent in the area, it is envisaged that groundwater moves laterally through the sands but not for sufficiently long periods as to have resulted in any significant depth variation.

Furthermore, a significant flux of recharge occurs through fractures under saturated or nearly saturated conditions in the TMG (Wu 2005). Then infiltrated water is expected to travel laterally through the Cape Flats aquifer until intercepted by deep wells in the weathered shale (Malmesbury) and granite. A higher infiltration rate is assumed to take place through fractures in the mountainous area while a lower value of infiltration moves through the sands (inter-mixed with silt, clay and peat in places). If this conceptualization is correct, the pattern of the hydrochemical depth profiles will not necessarily imply the slow passage vertically downward of a 'front' of urban recharge. Instead, a given profile could be the product of a complex series of mixing 'cells', slowly evolving as water moves generally downdip in the recharge area through the sand aquifer and subsequently into the deeper fractured aquifers. This is subject to further investigations and detailed groundwater evolutional studies.

However, despite the fact that the studied area have fractured hard rock aquifer system (with a complex geologic environment comprising unsaturated rock matrix and multiple fracture network) as its immediate neighboring aquifer, the study has identified dominant recharge processes and flow mechanisms operative in the area. The possible sources of errors that would offset the conceptual data from its real value could be recharge contributions from unidentifiable subsurface regimes as well as contribution from multiple fractured basement aquifers during pumping of wells near the west and east boundaries of the Cape Flats. It was regionally assumed that the bedrock is impermeable but report has shown that the Malmesbury (bedrock) aquifer is fractured in places causing upward leakage into the Cape Flats aquifer.



From an agricultural perspective, where irrigation water in farm dams and irrigation canals used for intensive market vegetable gardening and potato cultivation, can contribute to recharge. However, it is these areas which are currently experiencing an explosion of urban development. This includes the informal, and low-cost formal housing of the Cape Flats, and the middle income development of the West Coast (Table View) as well as new developments such as Century City. Such areas do not place any particular constraints on construction. In fact, the nature of the sandy substrate facilitates the digging of foundations and the emplacement of infrastructure (pipes, cables). However, the low-lying nature of these areas and their proximity to the ocean implies a high local water table and, in specific areas, frequent water-logging and localised flooding in the winter (raining) months. Landfill sites, typically sited in such areas in the past, are prone to seepage and groundwater contamination.

## 5.6 Urban recharge in Cape Town in relation to other cities

Recent studies have shown that the stormwater drainage in a city may have a significant effect on recharge to underlying groundwater (Barret 2004, Krothe et al. 2002, Sharp et al., 2000). Lerner (2002) gave an up-to-date review of the methods of estimating recharge in urban areas, while Foster et al. (1998) highlight the fact that the subsurface is often the major receptor for industrial effluents. The effluents may enter directly from casual disposal or indirectly as seepage from waste treatment lagoons or from storage tanks. Although urbanization increases storm runoff, there is no direct evidence that the increase is at the expense of recharge (Lerner 1997, Yang et al. 1999). According to Lerner et al. (1990), urban recharge can be estimated either holistically (equation 5.5.1) or as the sum of the components in the equation (5.5.2):

Net recharge = imports of water + groundwater abstraction – consumptive use – effluent leaving (5.5.1)

Net recharge = rainfall recharge + leakage from mains + leakage from sewers + infiltration from septic tanks etc. (5.5.2)

The impact of urbanisation in the context of the study area (Cape Town) is not viewed in terms of groundwater abstraction but as it affects recharge. The impacts of urban processes on infiltration to the subsurface are shown in Table 17; indicating the normal direct precipitation for non-urbanised areas, impermeabilisation for built-up areas and potential for recharge from mains leakage, sewage and urban drainage (stormwater runoff). The map of the City of Cape Town (figure 44) shows the extent of urbanization and open land surface, where recharge is not restricted or water-proofed. The general concept of urbanisation is that it reduces recharge by water-proofing surfaces or impermeabilisation (Barret 2004, Lerner & Barret 1996), but this is not always correct and in many instances may not be the case (Barret 2004). Urbanisation may result in a net change of overall groundwater recharge, from a major reduction to modest increase as illustrated in figure 45. The effect on recharge arises both from modifications to the natural infiltration system, such as surface impermeabilization and changes in natural drainage, and from the introduction of a water service network, which is invariably associated with large volumes of water mains leakage and wastewater seepage. The net effect of recharge on quality is generally adverse (Foster et al. 1998).

Table 17: Impacts of urban processes on infiltration (Foster et al. 1998)

| Urbanisation process | Rates | Effect on infiltration area | Time base |
|---|---|---|---|
| (A) Modifications to natural system | | | |
| Surface impermeabilisation & drainage | | | |
| - Storm water soakaways* | Increase | Extensive | Intermittent |
| - Mains pluvial drainage | Reduction | Extensive | Intermittent - continuous |
| - Surface water canalisation* | Marginal reduction | Linear | Variable |
| Irrigation of amenity areas* | Increase | Restricted | Seasonal |
| (B) Introduction of water services network | Minimal | Extensive | Continuous |
| Local groundwater abstraction | | | |
| Imported main-water supply leakage | Increase | Extensive | Continuous |
| On-site (unsewered) sanitation** | Major increase | Extensive | Continuous |
| Mains sewerage | | | |
| - In urban areas* | Some increase | Extensive | Continuous |
| - Downstream** | Major increase | Riparian areas | Continuous |

*Also has a minor impact on groundwater quality
**Also has a major impact on groundwater quality

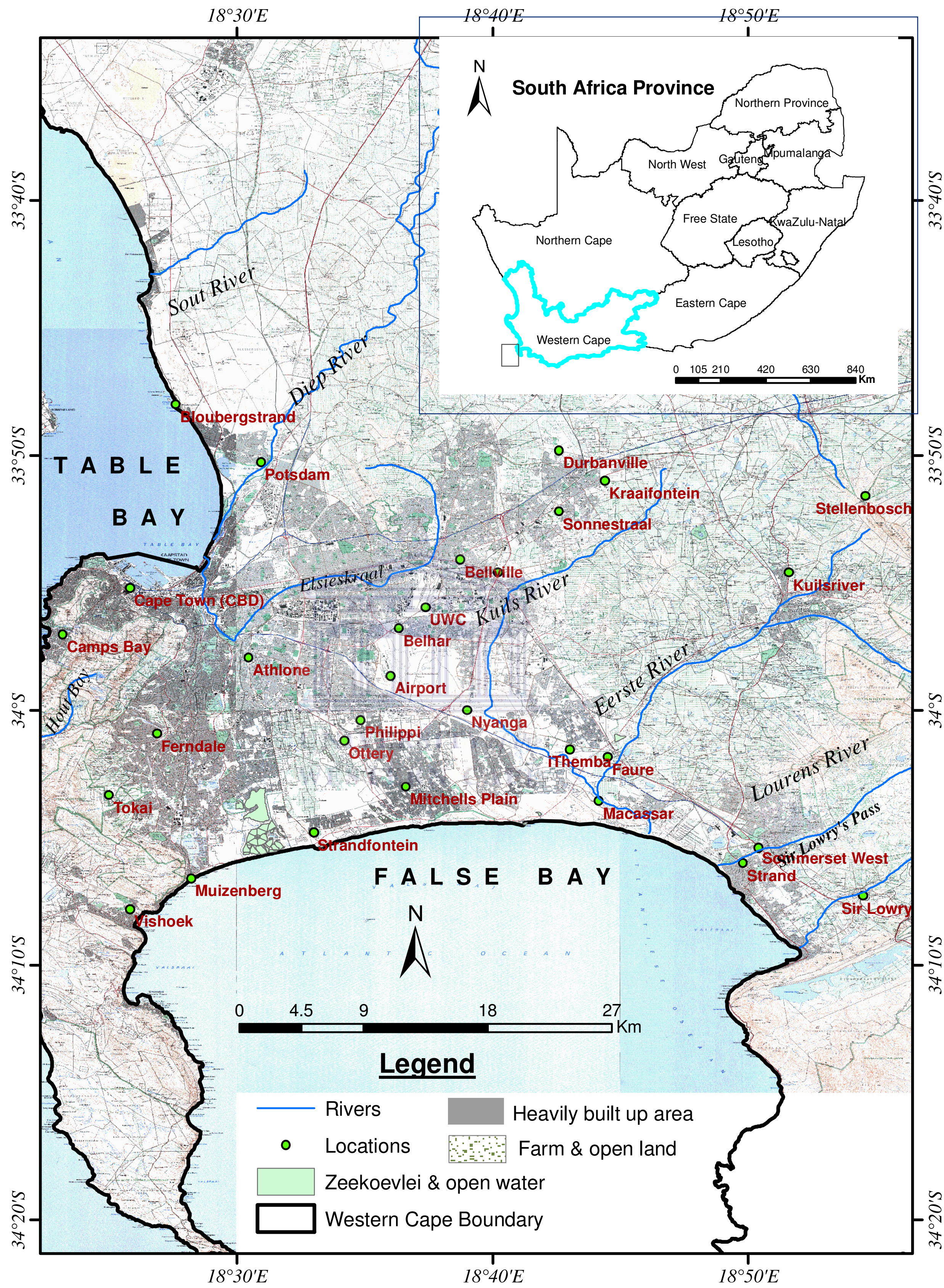



Figure 44: Urbanisation pattern in the City of Cape Town (CCT 2006)

The network of water-carrying pipes under most cities can be leaky, sometimes old and rusty; and in many instances, they are often not water-tight. This in addition to leaking sewers, septic tanks, storm drains constitutes high potential for urban recharge (Table 18). According to Krothe et al. (2002), sewer lines are designed for leakage (typically about 10 %). In Cape Town, it is said that nearly 40 % of the water from the supply dams to consumers are lost through pipe bursts and leakages (comparable to 30 % of recharge from utility system leakage in San Antonio (Sharp et al. 2000); 12 % in Austin, Texas (Lorenzo-Rigney & Sharp 1999)). Although few quantitative data are available, the general belief is that much water is lost through the supply mains and distribution channels. Estimates of water main leakage in 5 urban cities of Sub-Saharan Africa are compared with the City of Cape Town (Adelana et al. 2008). This loss, coupled irrigation of farmlands and gardens within the city may contribute significantly to recharge and should be a subject for further research in the study area.

Table 18: Sources of aquifer recharge in urban areas with implications for groundwater quality (modified Foster *et al.* 1996)

| **Recharge source** | **Importance** | **Water quality** |
|---|---|---|
| Leaking water mains | Major | Good |
| On-site sanitation systems | Major | Poor |
| Leaking sewers | Minor | Poor |
| Surface soakaway drainage | Minor to major | Good to poor |
| Seepage from canals & rivers | Minor to major | Moderate to poor |

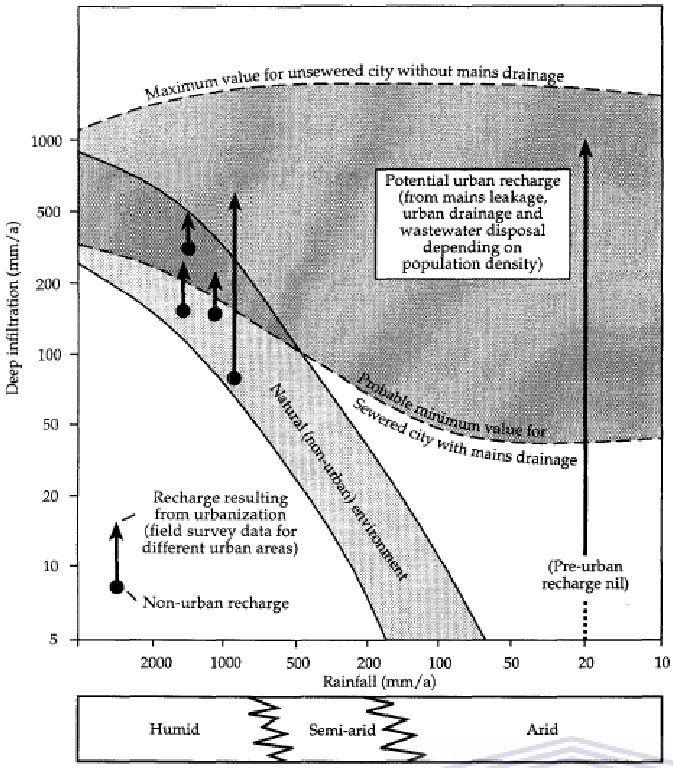



Figure 45: Potential range of subsurface infiltration caused by urbanisation (modified from Barret 2004; original source: Foster et al. 1998)

From the records of the City of Cape Town and DWAF, (with the present population of about 3.8 million people), $3 \times 10^8$ $m^3$ is extracted from groundwater; this represents approximately 2 percent of the total annual water consumption. The consequence of increasing this figure through the groundwater augmentation scheme may not be visible in the next decade but on a longer-term and such increase calls for strategic resource management.

## 5.7 Recharge and relation to groundwater resource management

There are implications for the development and of groundwater under conditions of declining rainfall and high urban growth adequate management measures. In the City of Cape Town the population is growing (from data presented in chapter 3). The effect of climate variability (described and illustrated with rainfall variability in the chapter 4) in the city of Cape Town and its suburbs is expected to increase pressure on water resources. In order to properly manage groundwater resources, reliable information about recharge and quantification of abstraction volumes would be necessary. Sustainable water resource management must go along with spatial planning for projected urban population. Sustainable use of groundwater must ensure that the future resource is not threatened by overuse, and that natural environments that depend on the resource, such as stream baseflows, riparian vegetation, aquatic ecosystems, and wetlands are protected. Regional scale groundwater recharge studies on the TMG aquifer (Wu 2005),

The impact of irrigation and cultivation in the Philippi and Kraalfontein areas on recharge is likely to appreciably increase the amount of recharge, and in some cases to exceed precipitation as the predominant source of recharge as the years go bye and agricultural activities increase. The imbalance between the water input (recharge) to the Cape Flats aquifer and the output (pumpage and stream baseflows) is not fully known, as the aquifer is not intensively used at present. With the impact of recharge on groundwater quality, part of the challenge will be to develop locally-appropriate groundwater protection plans for the city and move towards sustainable development of groundwater in the greater city of Cape Town.

**5.8 Synthesis and summary of results from the different approaches**

Based on the physical conditions and data requirements (with data availability and possibility) for recharge estimation, methods used included the analysis of precipitation and water table fluctuation (WTF and CRD), rainfall-recharge relationship and water balance approachesas well as hydrochemical and isotope physical approach. From the discussion of the results from water table fluctuation, it is obvious that the Cape Flats aquifer shows a seasonal groundwater fluctuation and a delayed response to recharge events. The delay between recharge event and groundwater response is partially due to the lower permeability clay subsoil.



Comparative analysis of the methods applied in this recharge quantification can give useful information. Results from the chloride mass balance have to be regarded as long-term averages, because groundwater samples in this study represents a mixture over the complete residence time of the groundwater body. In contrast the water table fluctuation method and water balance approach apply specifically to the observed years or period for which information is available. The approaches have their justifications. Long-term average recharge rates are most important for water resources planning, and chloride mass balance can serve as an easy and relatively fast means to deliver this information. The advantage of the other two methods is that they provide the timing of recharge events and can be useful in analysing variation of recharge caused by changing rainfall or land use conditions.

Annual recharge rates resulting from the applied methods have been presented in Tables 5.2.1 -5.2.5. Water table fluctuation method gave the higher recharge values. While the WTF can be useful to compare the relative change in recharge for different years and identify the relative impact of changes in rainfall on recharge, it is unlike the chloride method that is generally known to reflect lower recharge rates. Recharge rates vary considerably between wet and dry years and between locations, with a range of 17.3% to 47.5%.

The range of values obtained by the other methods, like the water balance and rainfall-recharge relationship, gave useful guidance in the earlier stages of resource evaluation for the Cape Flats aquifer. Values obtained using empirical rainfall-recharge relationship tends to agree with the recharge estimates from WTF. Although one of the empirical methods showed exaggerated values of annual recharge rates, the percentage ranges are comparable, in particular, to the estimates for the years 2003 and 2004. The soil water balance approach presented gave quantitative indication of vertical movement of water of the represented soil types (sandy clay), although horizontal movement was neglected. Annual deep percolation as calculated from the water balance model are comparatively low but values agree with recharge estimates from series of other methods applied in the north-western end of the Cape Flats sand (Grootwater, Sandvecld group by Conrad et al. 2004). Although the credibility of the estimates generated for deep percolation by the model may be in question.



In locations where groundwater has been exploited for many years the potential recharge estimates from soil water balance, there is need for comparison between the predicted head and actual groundwater head hydrographs. For the present study area where field data are limited, and there are no absolute reference values of deep drainage (or percolation) available for calibration and validation, the concept of plausibility (as used in Carter et al. 2002, Eilers et al. 2007) was adopted. This concept of plausibility includes judgements about the structure and the results of the model. It assumes that if the model is reasonable in representing the complex hydrologic system then it will be able to compute a credible water balance (Eilers et al. 2007). The CMB method presented annual estimates of recharge for the study area (i.e.5-8%) that are comparable to other parts of the world where conditions are similar (Cartwright et al. 2006a, 4–90 mm/yr, i.e. 2 to 14% of rainfall; Cartwright et al. 2006b).

In summary, the variation in recharge rates described in this study is comparable to other documented studies of unconfined sand aquifers like Curragh aquifer in Ireland (Misstear & Brown 2006), Marcondash Reservoir Catchment area near Melbourne, Australia (Campbell et al. 2005), Beaverdam Creek basin, Maryland, USA reported in Healy & Cook (2002), the semi-arid plain environments of Kansas Prairies, USA with relatively shallow water table (Sophocleous 1991). Isotope and geochemical methods has been demonstrated in this study as one of the important approaches to characterization of recharge processes, and possible flow dynamics involving the unconfined aquifer.

Based on observed isotopic signature and environmental chloride variations of the groundwater system in the study area it was possible to identify the source and movement of groundwater. The sources of urban aquifer recharge in Cape Town (sewers, leakages) highlighted in this section has implications for groundwater quality and therefore necessitates detailed evaluation of the chemical characteristics of the Cape Flats aquifer, which is the focus of the next chapter (chapter 6). The implications of groundwater quality in relation to water resources management set the stage for pollution control and aquifer protection strategies which are discussed in chapter 7.

## CHAPTER 6: HYDROCHEMICAL EVALUATION OF GROUNDWATER

### 6.1 Introduction

Information on geological, hydrogeological, and physical-chemical groundwater data from boreholes and well points in the Western Cape is contained in the National Groundwater Database (NGDB). Some of the boreholes listed in NGDB are from different public and private sources, within the study area. The location, the collar elevation, the depth and the source of each well have been so gathered in a detailed database where stratigraphic, piezometric, chemical-physical groundwater data have also archieved. The geological and hydrogeological features of the study area and the chemical-physical groundwater characterisation have been inferred from the data analysis of selected monitoring boreholes.

#### *6.1.1 Existing groundwater monitoring network in the Western Cape*

A more appropriate and adequate dataset is essential for the planning and management of aquifers. Monitoring is, therefore, closely linked to the aquifer management, since the results of monitoring may require changes or modifications in the management practice. The data collected from an aquifer monitoring network may reflect the shortage or redundancy of information.



In the Western Cape different groundwater monitoring networks exist for: (1) groundwater level, (2) groundwater quality. The dataset forms part of the National Groundwater Database (NGDB) which is monitored by the Department of Water Affairs and Forestry (DWAF). The measurement of water level (HYDSTRA) and hydrochemical (WMS) data are the responsibility of the Directorate Geohydrology. All information regarding registered groundwater users are encoded onto WARMS (Water use And Registration Management System) database.

In the Cape Town area, particularly around and within the Cape Flats, the groundwater monitoring data from available records are from 1967-2007 and are also categorized according to the two networks above. A total of 1,984 wells are considered to fall within the Cape Town Municipality (Cape Town and suburbs); these have identification numbers on map and are referenced as site id's on NGDB (e.g. 3318 CD: 1-115; 3318 DA: 1-381; 3318DB:1-386; 3318DC:1-276; 3318DD:1-331; 3418AB:1-77; 3418BA:1-340; 3418BB:1-78). Most of these wells are within the Cape Flats sand area and periphery of the mountains that borders the sand (east, west and northeast). Approximately 160 wells have hydrochemical data but are not being monitored consistently. The groundwater level network measures the water level on a monthly basis, using some of these wells, especially the municipal and agricultural boreholes. The groundwater quality network measures several variables: EC, anions, cations and trace metals. These measurements are now made twice a year (in the past 6 times per year measurements were recorded) using monitoring boreholes in the area.

According to the records on the DWAF database, as at December 2006, there are about 240 registered industrial and agricultural boreholes within the greater City of Cape Town, each with a registered volume of abstraction per year. DWAF keeps the record of water use per individual or industry or agriculture and monitors quality data in the form of discharge information (water use sector, abstraction volume, area value, crop/irrigation type, waste composition, etc.). From this record, there are 211 boreholes used for agriculture, 25 for industry and 2 for water supply within the City of Cape Town municipality. There are a number of unregistered household boreholes that are used for irrigating gardens and lawns especially during the summer season. Nearly every household (especially within the formal settlements) has a borehole or well-point for this purpose as the City Council prohibits the use of municipal tap water for wetting the lawns and gardens.



Another type of monitoring network is the municipal landfill monitoring wells which measure: EC, total dissolved solids (TDS), chloride (Cl), nitrogen (in form of $NO_3$-N, $NH_4$-N), phosphate ($PO_4$), alkalinity and COD/BOD. For this purpose, approximately 12 monitoring wells are used (Ball and Novella 2003). The measurements are made twice a year in the summer and winter. The three networks are used to collect information that describes the status of the groundwater quality and quantity of the Cape Metropolitan area. Table 19 provides a summary of the groundwater monitoring networks in the study area.

Table 19: Summary of the groundwater monitoring networks in the Cape Flats area

| Monitoring Variables | Number of wells (Approximate) | Sampling frequency | Data record since (year) |
|---|---|---|---|
| Groundwater level, pH, EC, TDS [a, z] | 160 | Monthly | 1979-2006 |
| Full groundwater chemistry (Major, minor & trace ions) [b, z] | 200 | Bi-annual | 1967-2006 |
| EC, TDS, Cl, nitrogen (in form of $NO_3$-N, $NH_4$-N), phosphate ($PO_4$), COD/BOD and alkalinity [c] | Several sample lines of multiple mini-wells & borehole | Bi-annual and differential depth sampling | 1986-1992 |
| Routine chemistry [d] | 18 | 4 times per year | 1986-1990 |
| Routine chemistry [e] | 10 | Monthly | 1992-1995 |
| Abstraction volume [f] | 242 | Yearly | 1895-2006 |

[a] Department of Water Affairs & Forestry (DWAF) monthly and bi-annual monitoring
[b] Groundwater chemistry (DWAF)
[c] Groundwater monitoring at Coastal Park sanitary landfill
[d] Groundwater chemistry monitored by the Division of Water Technology, CSIR
[e] Bellville Solid Waste, record kept by the City of Cape Town
[f] 140 wells have current full record (DWAF-WARMS)
[z] Time series for most data not complete; some years are missing, some wells closed/vandalized

### *6.1.2 Groundwater monitoring in the Cape Flats*

Review of the existing groundwater quality monitoring network indicates that the majority of monitoring has been carried out in wells screened in the Cape Flats sand: shallow (unconfined, water table) aquifer. However, a number of wells are screened at deeper level in the Malmesbury bedrock aquifer (essentially weathered shale). From the most recent record available at the Western Cape Regional Office of the Department of Water Affairs, it was found that the total number of active wells in the Cape Flats aquifer could total more than 120 wells. Most of the wells, used for agricultural purposes, are shallow and are typically screened 10–30 m below the water table. As shown in Table 19, 630 well records are available and about 160 of this have been monitored for water quality status in the area around Cape Town (Municipal area and suburbs), mainly the salinity in the form of electrical conductivity and total dissolved solids, since 1967. However, the monitoring wells are not production wells nor installed near pumping wells. A few of the wells are abandoned and vandalized while some are only monitored for groundwater level. The measuring periods are mostly not consistent giving a lot of gaps in the water level and chemical data.

All historical hydrochemical data from 160 (agricultural, industrial or individual) wells were checked and processed. Data quality checks have been made on all the samples discussed in this chapter. In these wells, the starting dates for collecting data on groundwater chemistry were not the same. Moreover, some of these wells have different terminal reading dates. In addition, within the period of measurements, there are missing data. The very few deep wells included in this study are treated separately after analysis, since they represent hydrogeological characteristics of a different aquifer (in this case the Malmesbury shale). The quality of the NGDB chemical data was tested by checking the ionic balance after conversion to milliequivalent as discussed in chapter 2.

## 6.2 Sampling and analytical techniques of the current work

The methodology and data processing have been described in chapter 2. The existing chemical data of the NGDB started from 1967 and these were treated in this thesis as historic data to show the general groundwater chemistry trend during the last four decades. There were no specific quality indices related to the human impact on groundwater, for example, pollution with aromatic or polycyclic hydrocarbons, organochlorines, organoposphorus, volatile organic compounds (VOC's) etc., which are common to many developed cities of the world (Zhang et al. 2004, Juodkazis et al. 2003, Cox 1996, Barber et al. 1996, Grischek et al. 1996).



During the course of this research (2005-2007) sampling for chemistry and stable isotope analyses have also been carried out on selected wells. This sampling was intended at possibly filling the gaps and accommodates recently drilled wells and to show the current trend in groundwater chemistry. It was also aimed at sampling for environmental isotopes analyses which were not carried out previously. Rain sampling was also included as there were no records of rainfall chemistry in the database. Several rain samples collected from the rain samplers installed at UWC, iThemba Laboratory and rainwater from Belhar residential area were analysed for chloride as described in chapter 2. Figure 46 shows the distribution of sampling points in the study area. Series of pumping tests were carried out on three wells from two sites (University of the Western Cape, UWC test site, and iThemba Laboratory experimental borehole). Field parameters, including water temperature and EC were determined following the procedure described in chapter 2.

For the purpose of data interpretation, the dataset was divided into three in accordance to the sequence and consistency of measuring period: 1967-2001, 2003-2007 and wells or groundwater sources with consistent few years' record were singled out for separate interpretation (Philippi 1985-1989; Newlands Spring 1994-2006). Further, 25 boreholes, 6 springs, 8 surface water (included 2 rivers and 6 canals/reservoirs), and selected rain episodes between 2005 and 2006 were sampled for hydrochemical analysis; selection was according to geographic location and accessibility. These, in addition to the dataset 2003-2007 (from the NGDB database), were interpreted to show present day quality status of groundwater from the Cape Flats aquifer. All the data sets were prepared in excel and interpreted with HAM (Kan et al. 2004) and AquaChem version 3.7 for Windows (Waterloo 1999). Charge balances between cations and anions were determined using HAM and AquaChem (Kan et al. 2004, Waterloo 1999) and the accuracy of determinations discussed in section 2.5.

### 6.3 General groundwater chemistry

A chemical and physical characterisation of groundwater in the study area has been carried out. This analysis has been inferred from the tests performed on different groundwater samples (about 1190 in total): 30 samples (from 4 wells) tapping the weathered Malmesbury aquifer and 60 samples (from 7 wells) tapping the Cape granite aquifer while about a thousand samples are from the Cape Flats aquifer (from about 170 wells). The location of the boreholes is shown in figure 46). The chemical data on groundwater from the Malmesbury and Cape Granite are presented and discussed. This is to understand the relationship between the Cape Flats and other aquifers in the area and increase the knowledge about the characteristics of the aquifer and aid its development and management. It is not the intention of this work to discuss the TMG aquifer (TMG). Much knowledge exists in the literature on the TMG aquifer (e.g. Kotze 2000, Xu et al. 2002, Parsons 2009). Several Phd research theses (e.g. Wu 2005, Jia 2007, Roets 2008) are completed on the TMG. The chemical and recharge characteristics of the TMG have been discussed in Wu (2005), the hydrological significance and flow characteristics of the aquifer presented in Jia (2007).

Groundwater temperature ranges between 17.2°C and 23.3°C. The groundwater pH values range from 4.8 up to 9.1 and does not show any trend as the water flows from inland towards the sea. The minimum, the maximum and the mean values of each chemical parameter and the classification according to the lithotype are shown in Table 20. The major ion chemistry data are shown in Appendix 6.1 with the values in ppm.

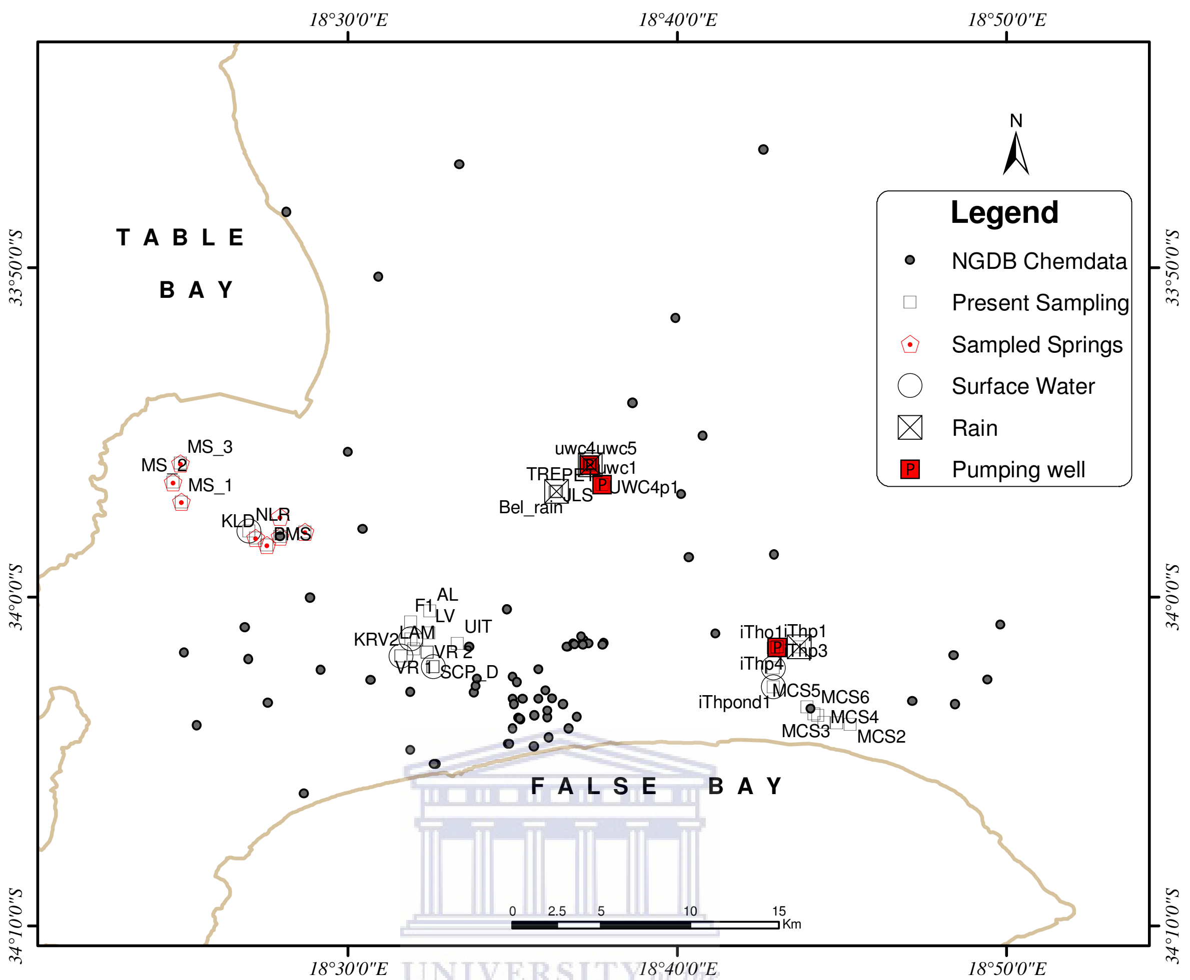



Figure 46: Location of selected NGDB monitoring wells with chemical data and the sampled wells, springs and surface water in the current study. (Note that some of the wells are located close to each other and therefore plot as clusters or one point. The letter abbreviations on the map represent wells, springs, rain and surface water with their chemical data presented in appendix 6.2).

### *6.3.1 Statistical analyses of data*

Statistical analysis for the interpretation of large data sets is common in hydrochemical studies (Ashley & Lloyd 1978). Relationships between various chemical parameters were identified using statistical methods, specifically correlation matrices and descriptive statistics in SPSS version 14. Correlations among the analysed physico-chemical parameters are presented in Table 20. Water temperatures, pH, barium, fluorite and nitrate did not show meaningful correlation with most of the measured parameters. $HCO_3$ showed the next lowest correlations with other parameters but correlated to Ca (0.67). The EC and Cl were highly positively correlated with most of the other ions (except for $HCO_3$, F, $NO_3$, and Ba), which indicates that these ions are derived from the same source with a limited composition range.

Furthermore, the study area shows three main clusters: 1) Na, Cl, and Mg concentrations have strong mutual correlations (>0.98) and Ca and $SO_4$ are correlated with this group (>0.69); 2) Fe, Na, Ca, and Mg concentrations are strongly mutually correlated (>0.80), Fe, and Mn are also mutually correlated (0.72) and correlated to Na, Mg, and Cl (>0.67); and 3) $HCO_3$ and Ca have a mutual correlation of (0.67) but $HCO_3$ show weak correlation to the other groups of ions. These clusters form the basis for discussing the sources of the solutes in groundwater of the study area.

A wide range of values and great standard deviations occur for most parameters measured. In particular, concentrations of Na and Cl have ranges of 3-2,285 and 7-5,121 ppm, respectively. Concentrations of Ca, Mg and $SO_4$ also showed large variations with ranges of 2-366, 1-321 and 0-846 ppm, respectively. $HCO_3$ has a range of 0.1-753 while $NO_3$ showed the variation (0-248). These wide distributions indicate that chemical composition is affected by multiple processes, including seawater mixing. Especially the predominance of Na and Cl indicates strong saline water impact. Of the Cl concentrations in groundwater, 21.2% exceeded the WHO drinking water standard (250 ppm). Substantial amounts of $HCO_3$ and Ca reflect contribution by water-rock interaction (Hem 1985, Park et al. 2005). Figure 47 shows the distribution of some of the major ions in groundwater samples from the study area. The most abnormal distribution was observed for K and $NO_3$ concentrations, with very low values. Na and Cl also show some high density distribution of concentrations (<200 ppm), showing that a high percentage of the samples have NaCl values below the WHO limits (85.5% samples below 250 ppm Na while 79% are below 250 $mgl^{-1}$ Cl).

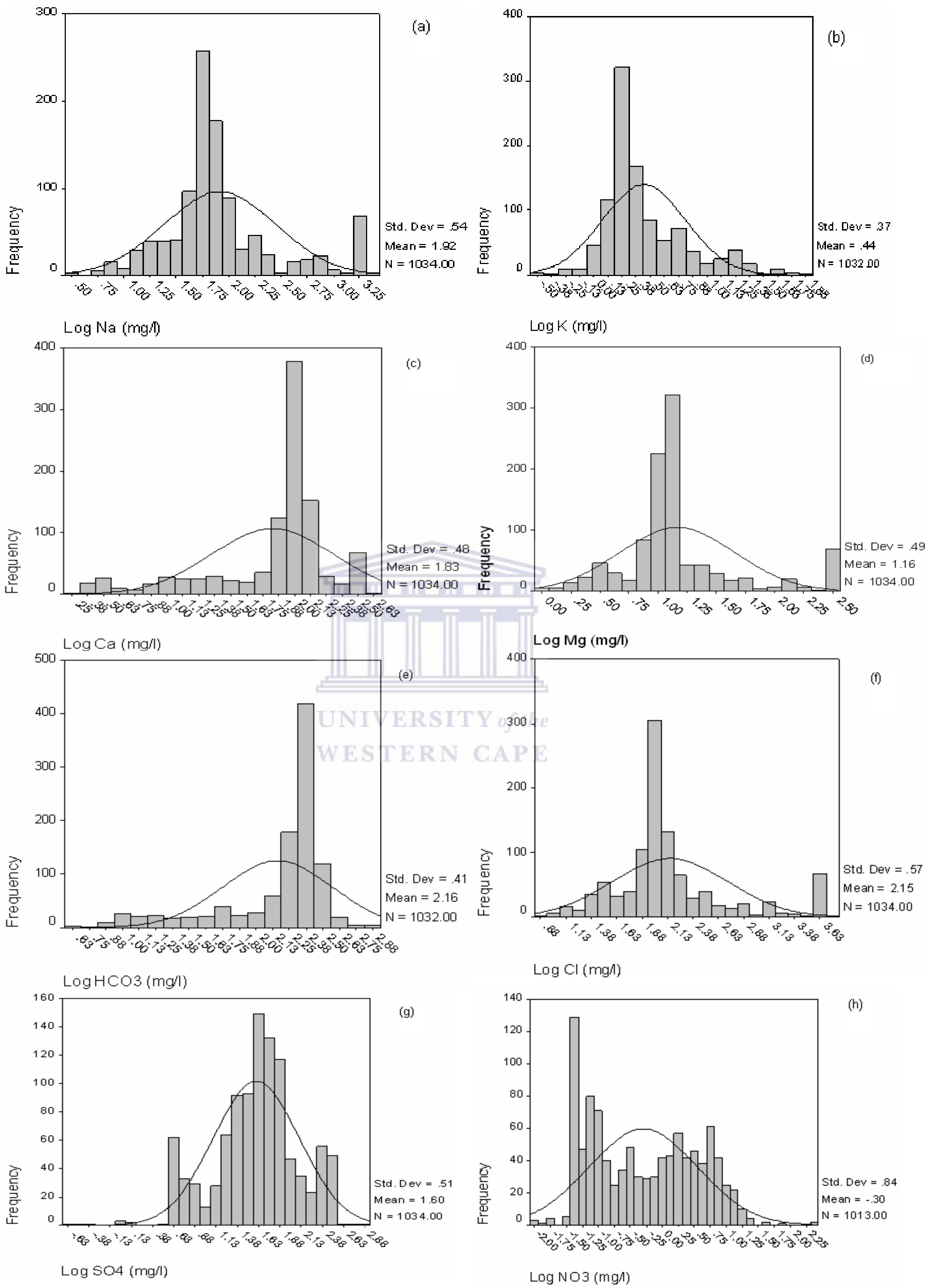



Figure 47: Distribution of some of the major ions in groundwater samples from the study area

Following the methods of Lepeltier (1969) adopted by Sinclair (1974), Park et al. (2002) and Lee & Song (2006), the cumulative frequency curves for two parameters (Cl and $HCO_3$) were used to differentiate 'anomalous' values from 'background' values. The chloride may represent effects of salinisation (or seawater mixing) while bicarbonate is indicative of water-rock interaction, respectively. The threshold values were calculated as 327 ppm for Cl and 133.8 ppm for $HCO_3$ (Figure 48a, b). Based on the thresholds values, groundwater in the sandy aquifer can be divided into four classes (figure 48c):

(1) 59.7% are dominantly influenced by the water-rock interaction;

(2) 30.6% of the groundwater samples show negligible effects by salinisation or water-rock interaction processes.

(3) 7.3% were affected by both water-rock interaction and salinisation; and

(4) 2.4% of the groundwater samples are dominantly affected by the salinisation process;

### *6.3.2 Chemical characteristics of the groundwater*

#### *6.3.2.1 Major ion chemistry*

The major ion chemistry of groundwater is useful for determining solute sources and for describing groundwater evolution. In the last two decades major ion chemistry has been employed in determining solute sources and for the evaluation of groundwater evolution (e.g. Edmunds et al. 1982, Arad & Evans 1987, Herczeg et al. 1991, 1993, Macumber 1991, 1992, Weaver & Bahr 1991, Acworth & Jankowski 1993, Kimblin 1995, Weaver et al. 1995, Elliot et al. 1999, Edmunds & Smedley 2000, Herczeg & Edmunds 2000).



Water chemistry within the Cape Flats aquifer is different from the bedrock aquifers, although within the aquifer, salinity varies greatly. Total dissolved solids (TDS) of the samples from wells screened in the Cape Flat sands are generally low (except iThemba pumping well) compared to those in the Malmesbury bedrock aquifer. Mean values of TDS for Cape Flats and Malmesbury aquifers are respectively 1229 and 1788 ppm. Generally, groundwater in Cape Town area range in TDS as follows: Cape granite aquifer (48-314 ppm); Malmesbury aquifer (264-3367 ppm); the Cape Flats aquifer (67-4314 ppm). The concentrations of calcium and bicarbonate ions in the groundwater are highest in the southern coast, especially around Mitchells Plain and lowest inland towards the west coast and the eastern borders of the Cape Flats. The concentration of calcium ranges between 1.7 and 366 ppm, whereas that of bicarbonate varies between 0.1 and 753 ppm. Bicarbonate concentration of groundwater from the granitic aquifer was the lowest (median: 19.3), in exception of well MP 61.

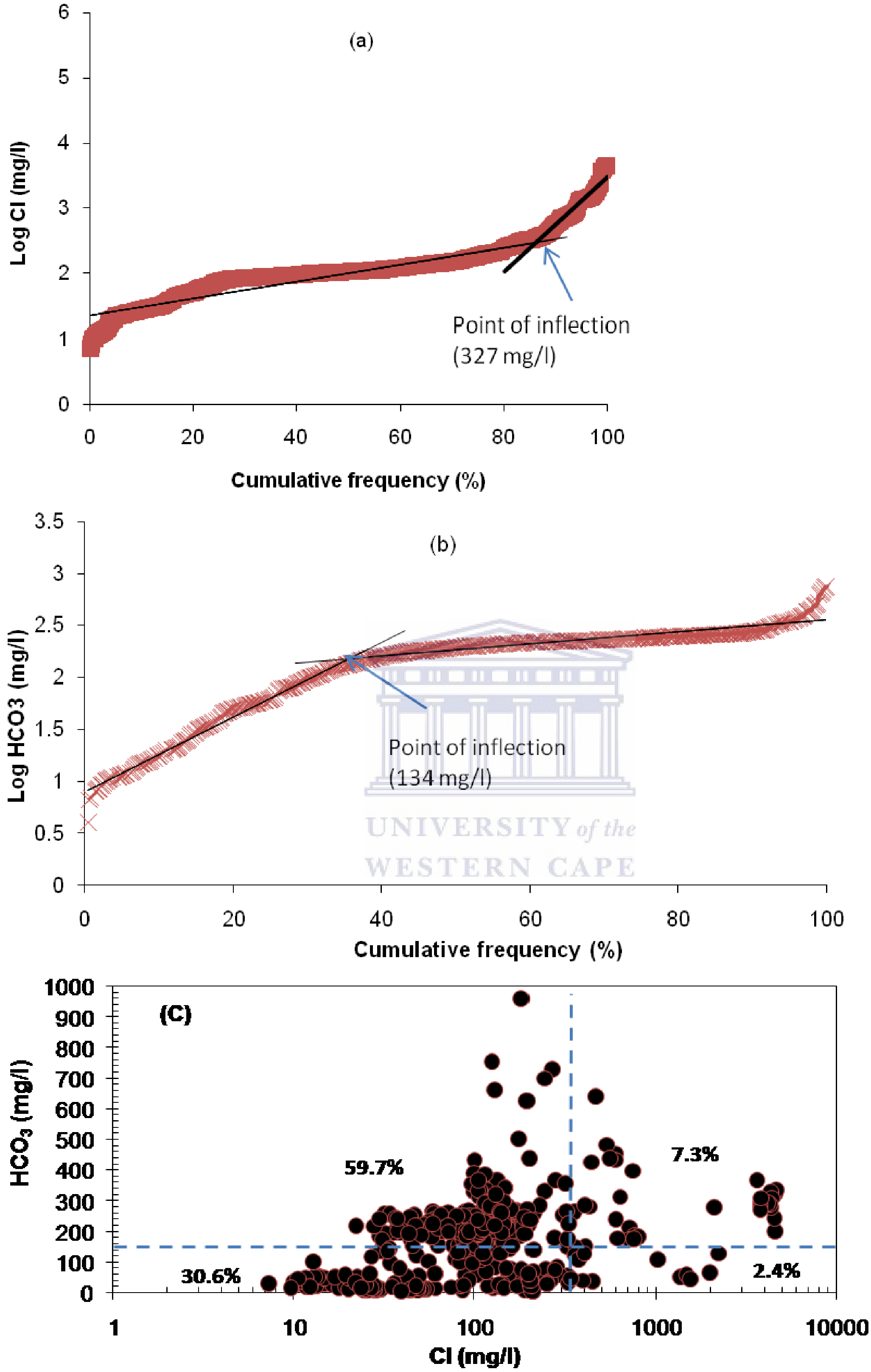



Figure 48: Cumulative frequency curves for (a) Cl and (b) $HCO_3$. The inflection points are calculated based on Sinclair (1974) and demonstrated by Park et al (2002); Lee & Song (2006). Estimated threshold values have been used to differentiate background from anomalous values. Based on the threshold values, classification of four groundwater types is also shown in (c).

The magnesium content range between 1 and 321.3 ppm and it increases along the coastline, especially in the western coast of the Cape Flats between Bloubergstrand southwards, towards the Table Mountain.

The iron content of some groundwater is above the WHO limit of 1 ppm for potable drinking waters but it is site specific reflecting the variability in chemical composition of the sediments in the aquifer. The concentration range of iron in groundwater of the study area is between 0 and 32.3 ppm. The highest iron concentrations are reflected in the groundwater samples from iThemba pumping well. During the four pumping tests conducted a total of 73 samples were analysed for chemical constituents. More than 99.9% of this showed iron concentration <10 ppm. Apart from this, a few sample of boreholes also showed high Fe concentrations. For example, the June 1986 sampling of boreholes BA018 and BA020 (in Mitchells' Plain) were 22.9 and 16.9 ppm Fe respectively. Groundwater samples from the bedrock aquifers (i.e. Malmesbury and Cape granite) are all lower than 1 ppm Fe content.

Iron is usually derived from oxidation of pyrite, which also lowers the pH of groundwater, but there are no occurrences of pyrite in this area and the pH range is 6-8. What was noticed during field sampling was that the wells had metal casing, but the extent to which this has influenced the chemistry of the water could not be determined. However, the high concentration of iron may be due to redox conditions in the aquifer and in certain cases the concentrations are thought to be related to the corrosion of the borehole casing. Historically, the site of iThemba Labs' natural environment was disturbed during construction. An old stream channel was diverted and buried during the construction of the site. The buried stream channel is located few metres away from the boreholes.



**6.4 Hydrochemical characterisation**

The chemical character of groundwater within the study area is discussed in this section. Table 20 shows the compositional distribution and variation of the different groundwater samples in the study area. The classification of water types based on TDS (ppm) and the distribution of the groundwater samples according to the aquifers is as shown in the Table. In summary, 81.5% of samples within the Cape Flats sand, 100% within the Cape Granite and 50% within the Malmesbury Shale aquifers are fresh water samples with less than 1,000 ppm total dissolved solids. No brackish or saline water was found within the Cape Granite, but

10.8% of the samples in the Cape Flats sand and 50% within the Malmesbury Shale reflect brackish with TDS up to 18,000 ppm. It is indicative that saltwater, or hypersaline water with TDS >40,000 ppm, was found in the Cape Flats sand only, in 68 or 4 samples, respectively - no such strong saltwater influence was found in the other two aquifers.

Schoeller plots are generally useful to identify groundwater with similar ionic ratios and concentrations, comparing them to groundwater with different chemical character (Guler et al. 2002). For classification of the groundwater types in different aquifers of the study area, the major ions sodium, potassium, calcium, magnesium, chloride, bicarbonate, sulphate and nitrate were plotted on a Schoeller diagram to illustrate the ionic composition of the different waters.

The variability of major ions is related to factors such as the lithologies of the aquifers, groundwater mixing, the impact of farming activities and salinisation. The three classes of groundwater sampled from wells tapping the Cape Flats, Cape granite and Malmesbury aquifers were used to plot the average equivalent concentration of the major ions and ionic combinations in the Schoeller diagram to show how the Cape Flats aquifer compares with neighbouring aquifers in the study area. Although the focus of this work is on the Cape Flats aquifer, the Cape granite and the Malmesbury aquifers borders and underlies the Cape Flats in the east and west. In most cases, the boreholes sampled and located on the Cape Flats are screened in the Malmesbury, which extensively underlies the Cape Flats sands. The pumping tests conducted in the study area have wells yielding water from the Malmesbury aquifer in places, so it is possible to investigate interconnectivity or interactions of the aquifers. However, the degree of mixing is not obvious as wells with multi-screens are not properly logged. The Cape granite shows the lowest ionic concentration. The concentration of alkaline earth elements in this aquifer is low compared to the other aquifers.

Table 20: Water types and distribution of groundwater samples in the study area

| **TDS (ppm)** | **Classification of water type** | **Distribution of groundwater samples** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Cape Flats** | **%** | **Cape Granite** | **%** | **Malmesbury Bedrock** | **%** |
| <1,000 | Fresh water | 758 | 81.5 | 60 | 100 | 30 | 50 |
| 5,000 - 18,000 | Brackish water | 100 | 10.8 | - | - | 30 | 50 |
| 18,000 - 40,000 | Saltwater | 68 | 7.3 | - | - | - | - |
| >40,000 | Hypersaline | 4 | 0.4 | - | - | - | - |

Samples from the Cape Flats aquifer were further subdivided into groups (1-5) in order to illustrate the distinction in composition of the groundwater from the individual boreholes and sites of sampling (Table 21). The average equivalent concentrations of groundwater from the Cape Granite and Malmesbury bedrock aquifers plotted for comparison. In these groups, average concentrations between selected ions and ionic combinations respectively occur more or less in the same ratio and display similar pattern. However, the absolute ionic concentrations differ between these groups. The number of samples in each group is listed in Table 21.

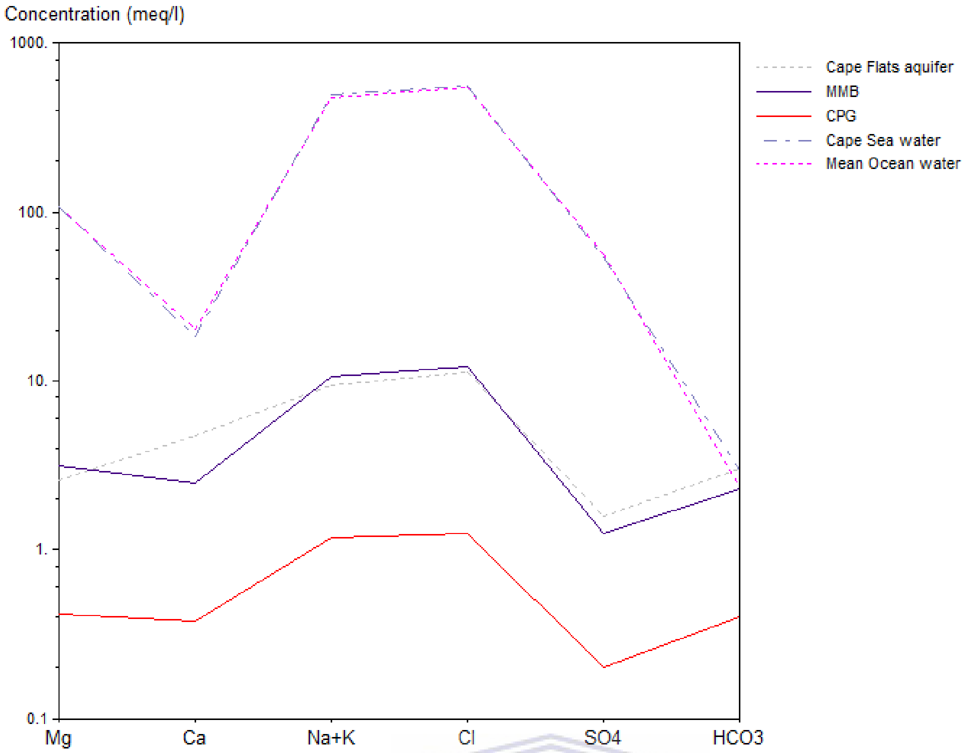
Table 21: Hydrochemical facies classification within the study area

| Group | Chemical Type Water | Description/Regime | No. Wells | No. Samples |
|---|---|---|---|---|
| 1 | Ca-$HCO_3$ | Sand aquifer: Belhar-UWC-Otery | 10 | 57 |
| 2 | Ca-Na-Cl-$HCO_3$ | Sand aquifer: Mitchels Plain-Philippi | 22 | 85 |
| 3 | Ca-Na-$HCO_3$-Cl | Sand aquifer: MitchellsPlain-Philippi-Macassar | 47 | 496 |
| 4 | Na-Ca-Cl-$HCO_3$ | Sand aquifer: Mitchells Plain-Bellville-Macassar | 31 | 106 |
| 5 | Na-Cl | Sand aquifer: Faure-Helderberg-Lakeside | 52 | 216 |
| 6 | Na-Ca-Cl-$HCO_3$/ Na-Mg-Cl-$HCO_3$ | Cape Granite: fractured bedrock | 7 | 60 |
| 7 | Na-Mg-Cl | Weathered Malmesbury Bedrock | 5 | 30 |

Although various hydrochemical facies were observed, Na-Cl and Ca-$HCO_3$ types were dominant. As the Cape Flats groundwater travels through the unconfined recharge areas towards semi-confined coastal discharge zones it may have evolved through Ca-$HCO_3$-Cl type via Ca-Na-Cl-$HCO_3$ type to Na-Cl type; or from Ca-Na-$HCO_3$-Cl type directly to Na-Cl type or through Na-Ca-Cl-$HCO_3$ to Na-Cl. These patterns give good indication that the various groundwater chemistries are changed by cation exchange reaction, as well as simple mixing in certain proportions (Richter et al. 1993; Appelo and Postma 1999; Jeen et al. 2001). The semi-logarithmic Schoeller plots in figure 49 shows that in both the Cape Flats and Malmesbury bedrock groundwaters the dominant hydrochemical facies is Na-Cl, with Mg>Ca and $HCO_3$>>$SO_4$. Significant proportions of the groundwaters showed Na-Cl type.

The average equivalent concentration of the major ions of the three aquifers: a) the Cape Flats, b) Cape Granite, and c) Malmesbury Shale are plotted in the Schoeller diagram (Figure 50). The equivalent concentrations of the elements shown compare well within the three aquifers as indicated by the similar pattern on the semi-logarithmic plots. This indicates most of the waters have similar origin. It is obvious that the Cape Flats and Malmesbury Shale are very similar in composition and in concentration as well. Apparently, the Cape Granite (through which some of the boreholes are screened) shows the lowest ionic concentration whereas the Malmesbury Shale and the Cape Flats have average concentration 10-times higher. The alkaline metals are highest within the Malmesbury Shale, whereas the earth-alkaline metals and nitrates are higher within the Capes Flats sands.

It is very difficult to find any significant criterion in the chemical solutions of the groundwater for distinction of the various aquifer types. For classification of the chemical groundwater types in the Cape Flats aquifer, the major ions sodium, potassium, calcium, magnesium, chloride, bicarbonate, sulphate and nitrate were plotted on a Schoeller diagram to illustrate the ionic composition. Typical classification of hydrochemical facies for the groundwater of the Cape Flats is shown in figure 50. The five groups of groundwater samples formed to plot the average equivalent concentration of the major ions and ionic combinations are illustrated in this figure. In these five groups, average concentrations between selected ions and ionic combinations respectively occur more or less in the same ratio and display similar pattern. However, the absolute ionic concentration differs between the groups. Group 1 shows altogether the lowest ionic concentration. The concentration of alkali elements in this group is very low compared to the other groups (although it seems to measure up with other groups in the alkaline earth elements composition). Group 5, show in all ionic concentrations except calcium and bicarbonate, the highest values. This group is shown to be predominantly Na-Cl type as illustrated in figure 51.



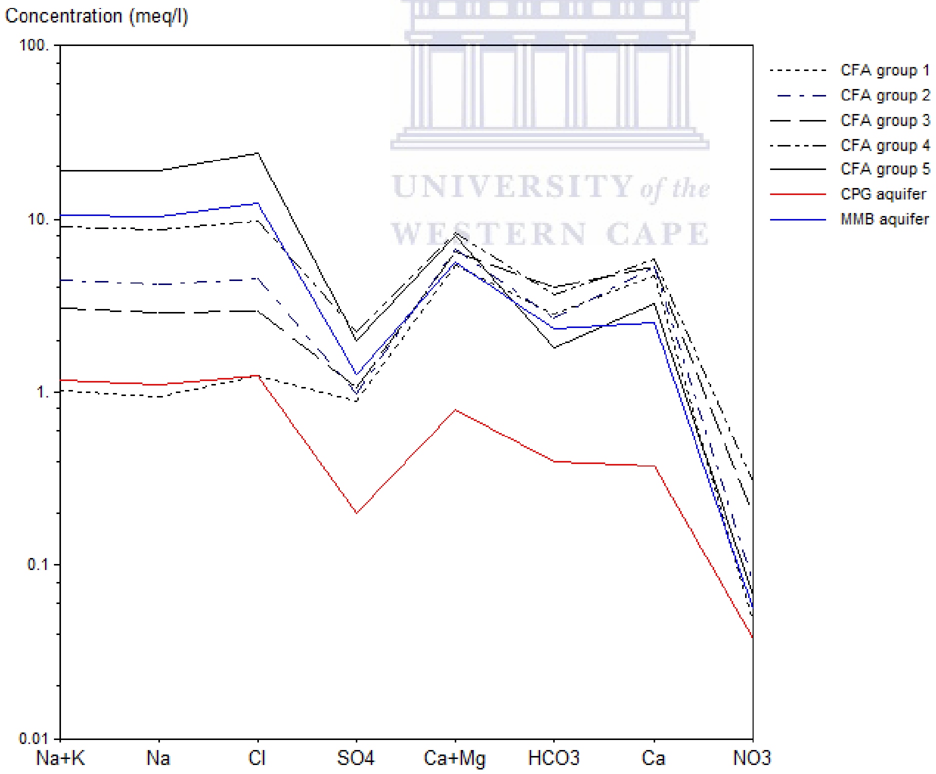






Figure 49 (**top**): Average equivalent concentrations of major ions and ionic combinations in the three aquifers in the area around Cape Town (Symbols: MMB is Malmesbury Shale aquifer; CPG is Cape Granite Aquifer. A plot of the nearby seawater sample (from Saldanha Bay, North-western coastal border of the study area) is used for comparison.
Figure 50 (**bottom**): Average equivalent concentrations of major ions and ionic combinations based on the groups 1-5 within Cape Flats Aquifer (Cape Granite and Malmesbury Shale aquifers are included for comparison)

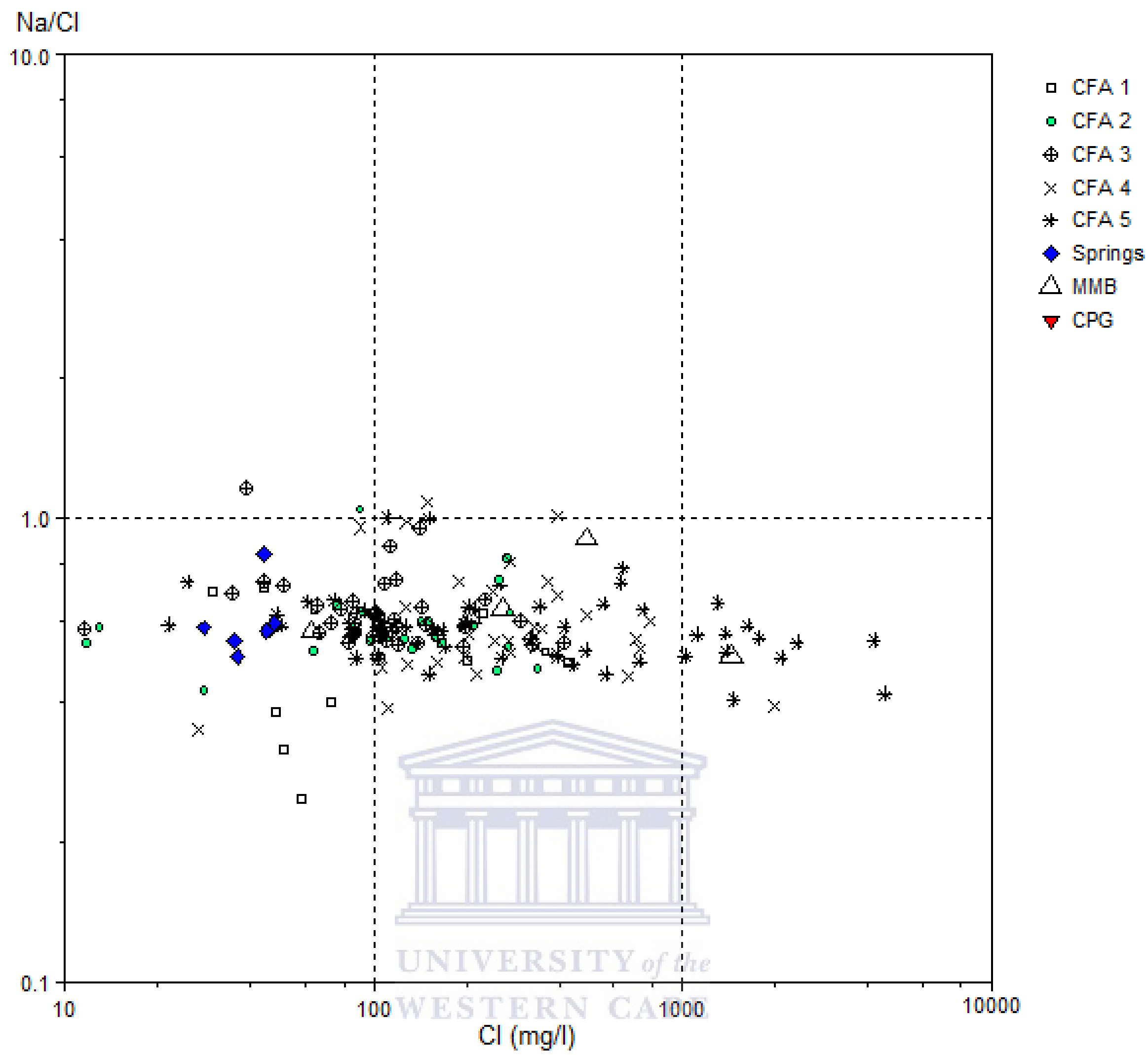



Figure 51: Scatter plot of Na/Cl versus Cl in groundwaters of the study area (symbols as explained in figures 49 and 50)

The hydrochemical composition can further be distinguished plotting the average values in a Piper diagram as in Figure 52. In the left cations triangle (figure 53), the Cape Flats groups 1-5 spread across from group 1 with Ca being dominant towards the right side where in group 5 the alkaline metals Na and K dominate the composition. However, as shown here, also Cape Granite as well as the Malmesbury Shale aquifer plots here in the right lower corner, indicating mainly Mg being in lower proportions, below 20 meq/l%. In the right-hand anionic triangle the situation is very similar, again showing a development from the Cape Flats group 1 with a high proportion of bicarbonate towards the right and a very high proportion of chloride, >80meq/l%, in group 5. The water of the Malmesbury Shale aquifer plots close to group 5 while Cape Granite water touches group 4 in the Na+K/Na-Cl end of the plot. Again, here the sulphate content is in general low, as indicated by value mainly <20 meq/l%.

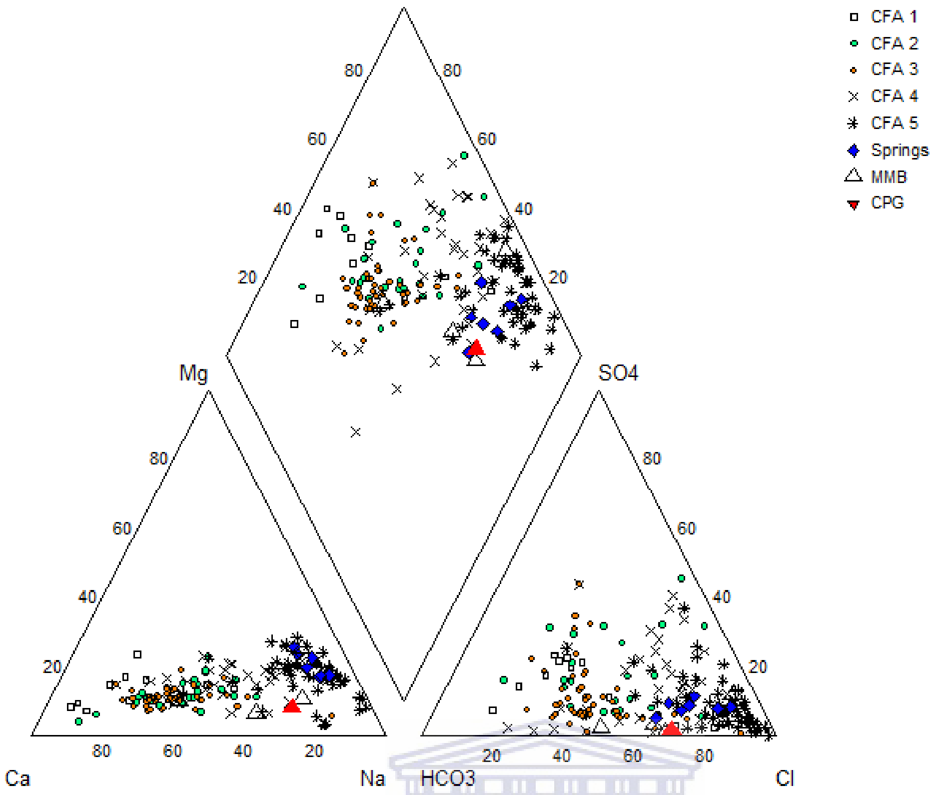



Figure 52: Piper diagram of the Cape Flats Aquifer (CFA) groups 1-5, compared to Cape Granite and Malmesbury Shale aquifer (based on average concentrations meq/l in %) Note: MMB represents Malmesbury Shale aquifer; CPG represents Cape Granite aquifer.)



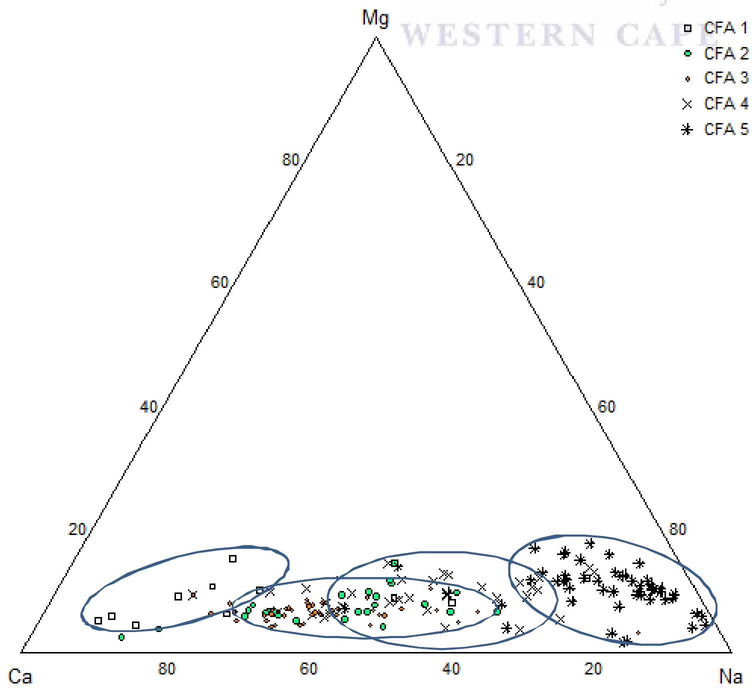



Figure 53: Cation triangle plot of groundwater samples from the Cape Flats aquifer (group 1-5)

An attempt was made to closely compare the chemical character of groundwater along the coastline and further inland. However, because monitoring data were not consistent and sampling was over different periods; and as such it is not easy to define a trend in groundwater chemistry. Notwithstanding, data from wells along the coastline especially in the coastal sector between Muizenberg and Macassar were compared to those farther inland, in the northern suburbs (Bellville and Potsdam).

Wells tapping the Cape Flats aquifer in these areas show slightly different groundwater chemistry: Potsdam (TDS range: 576-778 ppm); Bellville (TDS range: 310-914 ppm), except in the area around the Bellville Waste Disposal Site with higher values (1024-2240 ppm). Furthermore, in the Philippi area (inland) many of the wells screened in the Cape Flats sand are under the influence of agricultural activities (dominant in the area), showing range of TDS between 1198 and 4320 ppm.

River and stream water monitoring by the city of Cape Town Catchment Monitoring unit has shown intense pollution in the catchment. The extent of pollution due to leakage of river/stream water into the Cape Flats aquifer system is yet to be fully quantified. However, the sources of pollution are more likely to be waste water discharge into the streams and rivers, since most of the industrial activities and dense population are located on the Cape Flats (Adelana & Xu 2006).



### 6.5 Hydrogeochemical relations of groundwater

Hydrogeochemical relations of groundwater in the study area are illustrated in figure 54. In $HCO_3^- + CO_3^{2-}$ versus $Cl^- + SO_4^{2-}$ diagram (figure 54a). Most groundwater samples tend towards the $HCO_3^- + CO_3^{2-}$ rather than towards $Cl^- + SO_4^{2-}$ of the plot. The plot suggests that groundwaters are characterized by $HCO_3^- + CO_3^{2-} > Cl^- + SO_4^{2-}$. In order to describe the relation between $Na^++K^+$ and $Cl^-$, a $Na^++K^+$ versus $Cl^-$ plot was done as illustrated in Figure 54b. Some groundwater samples fall above the theoretical line (1:1), suggesting that the waters are dominated by alkalis ($Na^+$ and $K^+$). This excess alkalis, with respect to those associated with $Cl^-$ (from seawater), may be ascribed to silicate weathering (Stallard & Edmond 1983). Significantly, the excess alkalis are accompanied by an excess of $HCO_3^-$ over $Cl^-$ in the groundwaters (Figure 54c), indicating that most groundwaters should be characterized by $Na^+$-$HCO_3^-$ facies. However, this is not the case, as Na-Cl and Ca-$HCO_3$ dominate due to possible ion exchange.

Some groundwater samples collected from boreholes close to the sea (see Section 6.4) show high concentrations of $Cl^-$ and $Na^+$; suggesting that they may be influenced by seawater. $Cl^-/Na^+$ ratios higher than the seawater value suggest that seawater intrusion is accompanied by $Na^+$–$Ca^{2+}$ exchange, which is a common occurrence in coastal areas (Appelo and Willemsen 1987; Appelo et al. 1990, 1993; Appelo 1994). These waters show higher TDS values compared to other waters. The general relation of Na-Cl in the groundwaters of the study area is illustrated in figures 55 and 56. While Na-Cl reflects a defined pattern $Cl+SO_4$ versus Na+K is much dispersed.

The groundwater of the study area (as shown from the hydrochemical relations) displayed chemical characteristics, which may be governed by chemical weathering of the rocks, salinisation, locally accompanied by ion-exchange, and anthropogenic activities. Because of the high concentrations of $Na^+$, $SO_4^{2-}$, $Cl^-$, (and in certain instances, $NO_3^-$ and $F^-$) in some groundwater there are hydrochemical relations which cannot be explained through the water-rock interaction alone, other processes attempted are discussed in Section 6.6.

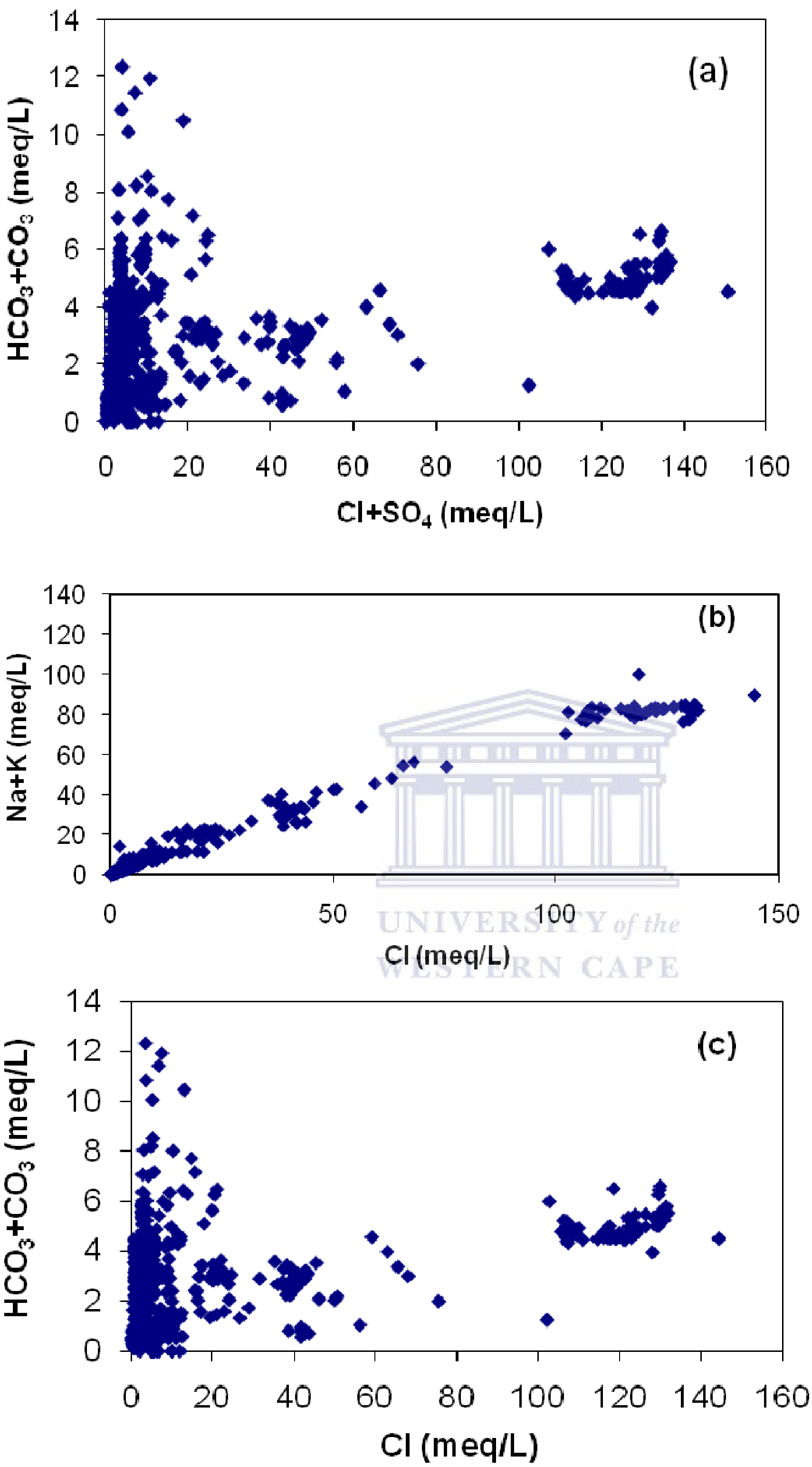
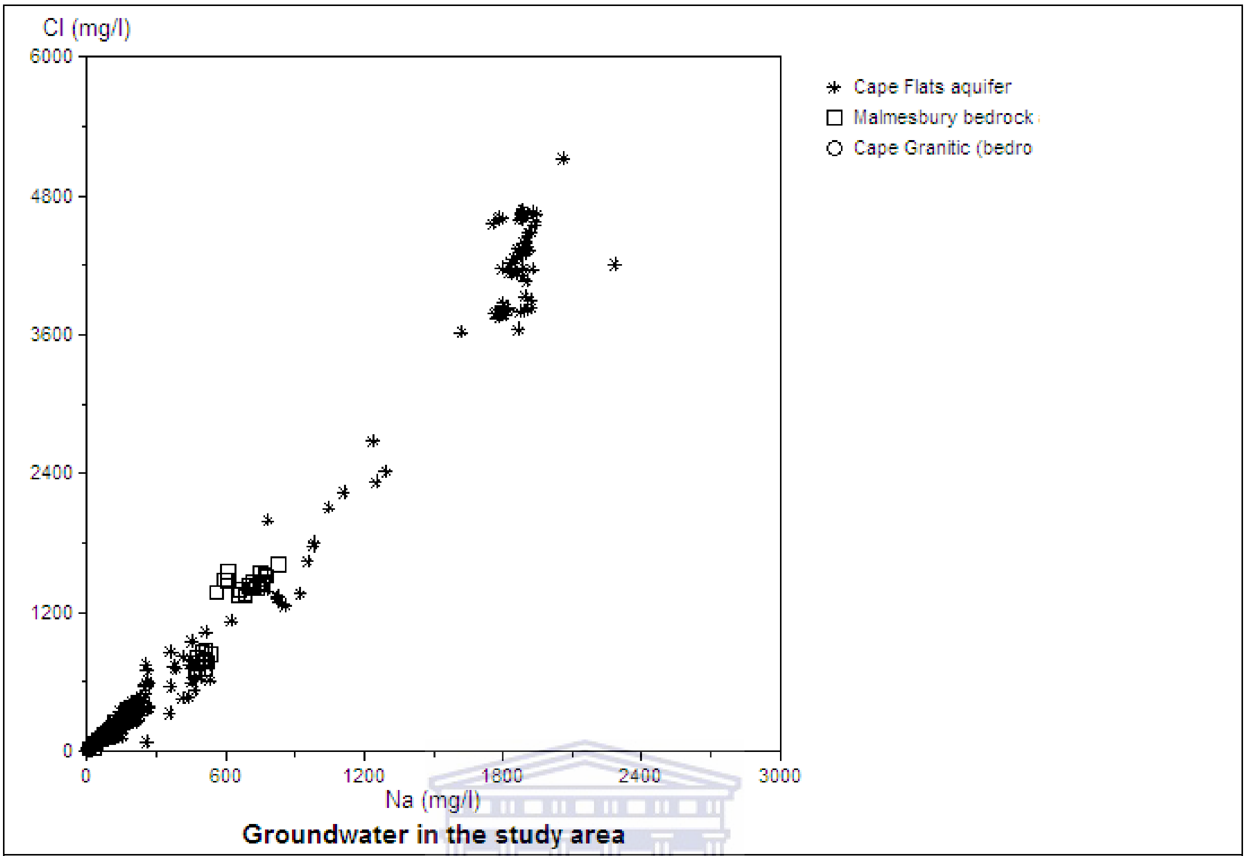





Figure 54: Relation of (**a**) $HCO_3^- + CO_3^{2-}$ with $Cl^- + SO_4^{2-}$, (**b**) $Na^+ + K^+$ with $Cl^-$ and (**c**) $HCO_3^- + CO_3^{2-}$ with $Cl^-$ in the study area.



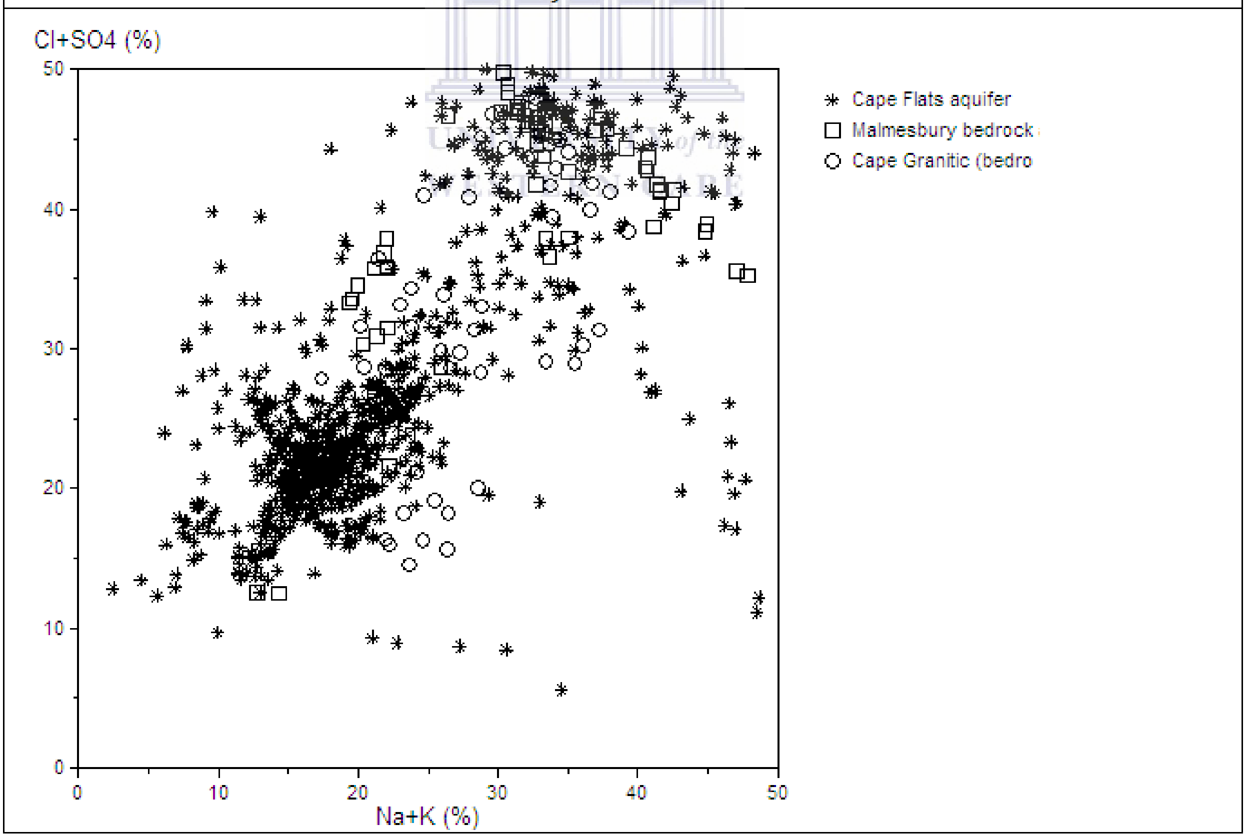




Figure 55 (top): Plot of Cl versus Na in the main aquifer types
Figure 56(bottom): Plot of Cl+$SO_4$ versus Na+Cl in the main aquifer types

## 6.6 Hydrochemical evolution

Na and Cl concentrations have strong mutual correlation (as shown in 6.4). Despite the strong correlation between the concentrations of these ions there is some variation in their ratios as well as in relation to other cations and molar ratios, as shown in Figure 57(a-g). Molar Na/Cl ratios ranged from as high as 1.95 to 0.17, with many between 0.6 and 1.2 (Figure 57a). The high Na/Cl ratios of the freshest groundwater are probably controlled by water–rock interaction, for example, albite weathering by

$$\underset{\text{(albite)}}{2NaAlSi_3O_8} + 9H_2O + 2H_2CO_3 \rightarrow \underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4} + 2Na^+ + 2HCO_3^- + 4H_4SiO_4$$

(Reaction 6.1)

Reaction 6.1 also produces kaolinite, which is common in the weathered rocks. Samples with Na/Cl ratios of 0.8–0.99 are probably due to evaporation of rainfall which has a Na/Cl ratio of 0.88±0.1 (in the study area). Samples with low Na/Cl ratios are probably the result of Na loss or exchange onto soils and clays. The high $HCO_3$/Cl ratios (up to 2.55, in the fresh groundwater, Figure 57b) are due to the weathering of feldspars (as illustrated in Reaction 6.1 above), which may occur during the initial stages of water rock interaction.



The Ca and Mg data seem to offer some explanation (figure 57c-e). These cations may be derived by dissolution of silicate minerals (e.g., plagioclase feldspar, chlorite, or biotite), and/or cation exchange of Na for Ca and Mg on clay minerals. The data further imply that calcite, dolomite, and gypsum dissolution does have a measure of control on Ca or Mg abundances, while dissolution of K-feldspar may be the major source of K. This is probably the case around Mitchells' Plain, very close to the coastline, where Ca is the dominant cation. There is the possibility that the groundwater rich in sodium ions ($Na^+$), as a result of seawater interaction, invades organic peat layers rich in calcium ($Ca^{2+}$). In this case, the sodium ions with a valency of (+1) replace the calcium with a valency of (+2). The reaction showing the cation exchange for the peaty layer is as follows:

$$2Na^+ + Ca - Peat_2 \rightarrow 2Na - Peat + Ca^{2+} \qquad (6.2)$$

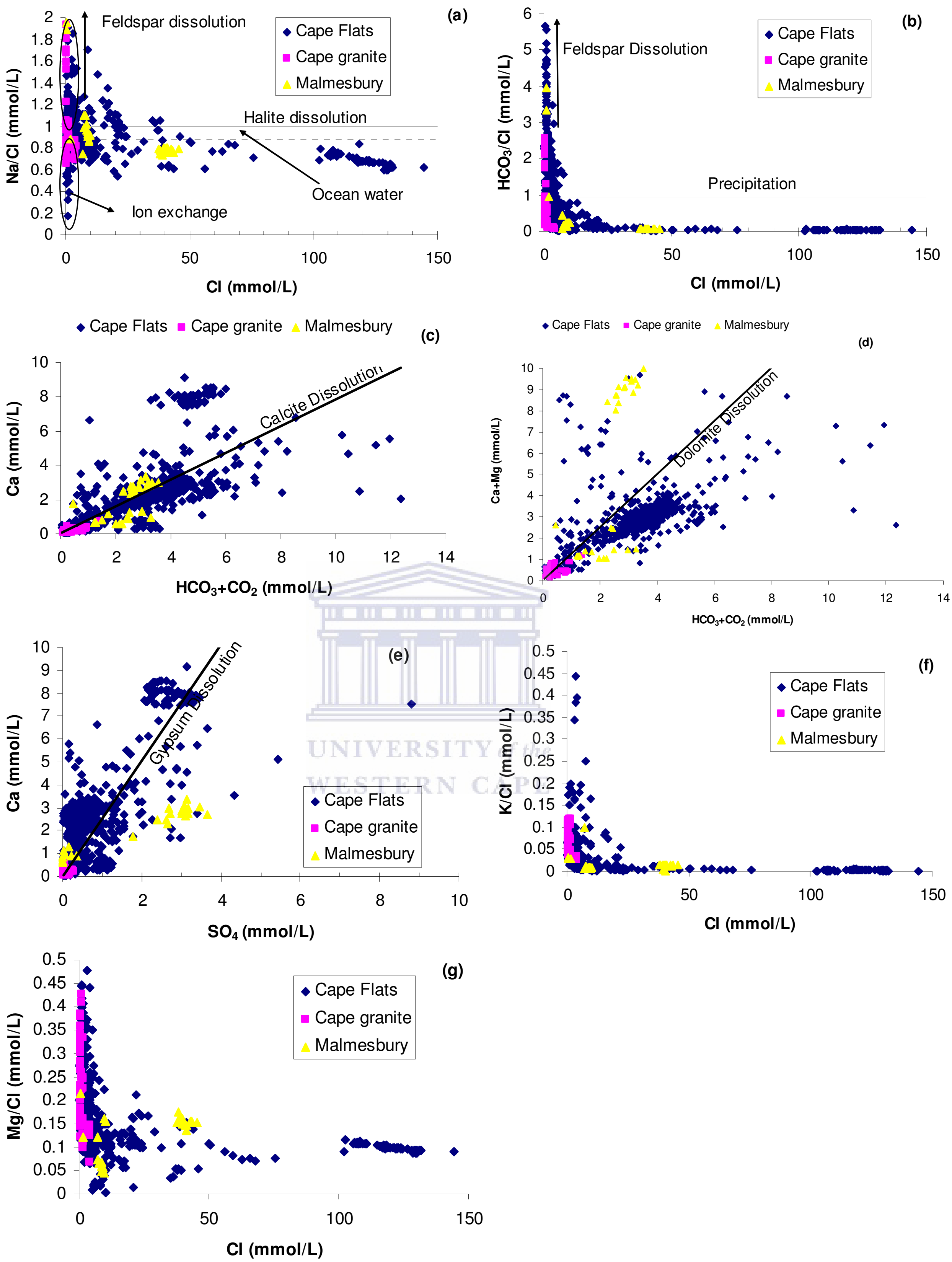





Figure 57 (a-g): Molar ratios for groundwater in the study area

As shown in Table 22 and Figs. 57(c-e), there is a good correlation between Ca and Mg (and total dissolved inorganic carbon, if measured) may have indicated some level of carbonate dissolution, as one of the major processes controlling the Ca and Mg contents of the Cape Flats groundwater in the study area.

Sulphate content of groundwater in the study is lowest in the Cape granite (<1 mmol/L) and relatively high in all groundwater samples from the Malmesbury (up to 7.3 mmol/L). Samples from the Cape Flats aquifer are low but >1 mmol/L in many sampled wells. The low sulphate contents (<1 mmol/L), low $SO_4$/Ca ratios of the Cape granite (which represents the freshest groundwater in this area); likewise imply that gypsum dissolution does not control Ca concentrations in this aquifer.

As discussed above, exchange of Ca and Mg for Na occur but not likely to be a dominant process in most of the Cape Flats groundwater. This is in accordance with the argument presented in Vandoolaeghe (1989). Concentrations of K are weakly correlated with Na (Table 22), yet K/Cl vs. Cl trends (Figure 57f) are similar to those of Na/Cl versus Cl and Mg/Cl versus Cl (Figure 57 a, g). Following the method in Petrides & Cartwright (2006), an analogous reaction to Reaction (6.1) may be written for K-feldspar that would explain the relatively high K/Cl ratios of the freshest waters. K concentrations may also be governed by reactions between the clay minerals as K is preferentially sorbed onto clays relative to Na due to its smaller ionic radius (Hem 1985, Petrides & Cartwright 2006). The lower potassium than sodium content may also be due to greater resistance to weathering of the former and is used up in the formation of clay minerals.

**Table 22: Correlation coefficients of selected parameters (values in meq/L)**

| | Na | Ca | Mg | Cl | K | Fe | Mn | $HCO_3$ | $NO_3$ | $SO_4$ | pH | EC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Na | 1.00 | 0.74 | 0.98 | 0.99 | 0.33 | 0.87 | 0.67 | 0.27 | -0.03 | 0.70 | -0.28 | 0.99 |
| Ca | | 1.00 | 0.77 | 0.75 | 0.30 | 0.80 | 0.53 | 0.67 | 0.11 | 0.72 | -0.08 | 0.81 |
| Mg | | | 1.00 | 0.99 | 0.35 | 0.87 | 0.67 | 0.28 | -0.01 | 0.74 | -0.30 | 0.98 |
| Cl | | | | 1.00 | 0.31 | 0.87 | 0.67 | 0.26 | -0.04 | 0.69 | -0.30 | 0.99 |
| K | | | | | 1.00 | 0.27 | 0.22 | 0.23 | 0.15 | 0.43 | -0.13 | 0.34 |
| Fe | | | | | | 1.00 | 0.72 | 0.34 | -0.20 | 0.64 | -0.51 | 0.88 |
| Mn | | | | | | | 1.00 | 0.15 | 0.02 | 0.43 | -0.49 | 0.66 |
| $HCO_3$ | | | | | | | | 1.00 | 0.14 | 0.34 | -0.42 | 0.08 |
| $NO_3$ | | | | | | | | | 1.00 | 0.28 | 0.30 | 0.35 |
| $SO_4$ | | | | | | | | | | 1.00 | 0.07 | 0.29 |
| pH | | | | | | | | | | | 1.00 | 0.72 |
| EC | | | | | | | | | | | | 1.00 |

Note: EC = Electrical conductivity (µS/cm)

## 6.7 Investigations of seawater intrusion

The theory of salt water interface and the level of seawater encroachment in the Cape Flats aquifer has been investigated and discussed by Gerber (1981). The maximum extent of seawater intrusion into the Cape Flats aquifer then was estimated to be approximately 1,000 m from the coastline. There are no studies since then to show any further inland seawater movement. In this study an attempt is made to investigate influence of seawater (if any) using the hydrochemical data from boreholes.

From the reviewed literature, the levels of Cl and EC are most simply indicative of salinization or seawater intrusion (Mercado 1985; Larabi et al. 2000; El Moujabber et al. 2006; Lee & Song 2006). The EC values of groundwater in the study area ranged from 9.2 to 4320 µS/cm. Field and monitoring data show also that generally groundwater salinization increases following the groundwater flow southeastwards. Figure 58 illustrates the electrical conductivity areal distribution in the Cape Flats. Samples from the granitic aquifer (at the eastern boundary of the Cape Flats) generally showed the lowest EC (< 60 µS/cm). The relations of Cl and EC with water levels and well depths are not shown as (in most cases) the wells monitored for chemistry and not necessarily monitored for water level. In figure 59 the EC (µS/cm) is plotted as function of the location distance (km) to the sea. About 16% of the samples from the Cape Flats Aquifer exceed the threshold value (190 µS/cm), which differentiates geogenic background from anomalous values. Values above the threshold may indicate saline water encroachment, when close to the coast, and/or anthropogenic contamination, least especially for locations inland.



The highest EC levels, towards 10 000 µS/cm, are reached within a distance of 8 km from the sea (figure 59a). Further inland the values decline and are mainly below the threshold value.
In figure 59(b) the Cl concentrations (in ppm) are plotted as function of the location distance (km) to the sea. In this plot, however, about 14% of the 128 boreholes (within a distance of <10 km from the sea) exceed the threshold value of 327 ppm. Again the highest values are found are found within this distance. About 5 boreholes (further inland, beyond the 10 km distance) with relatively higher values above the threshold value may indicate other sources of salinisation.

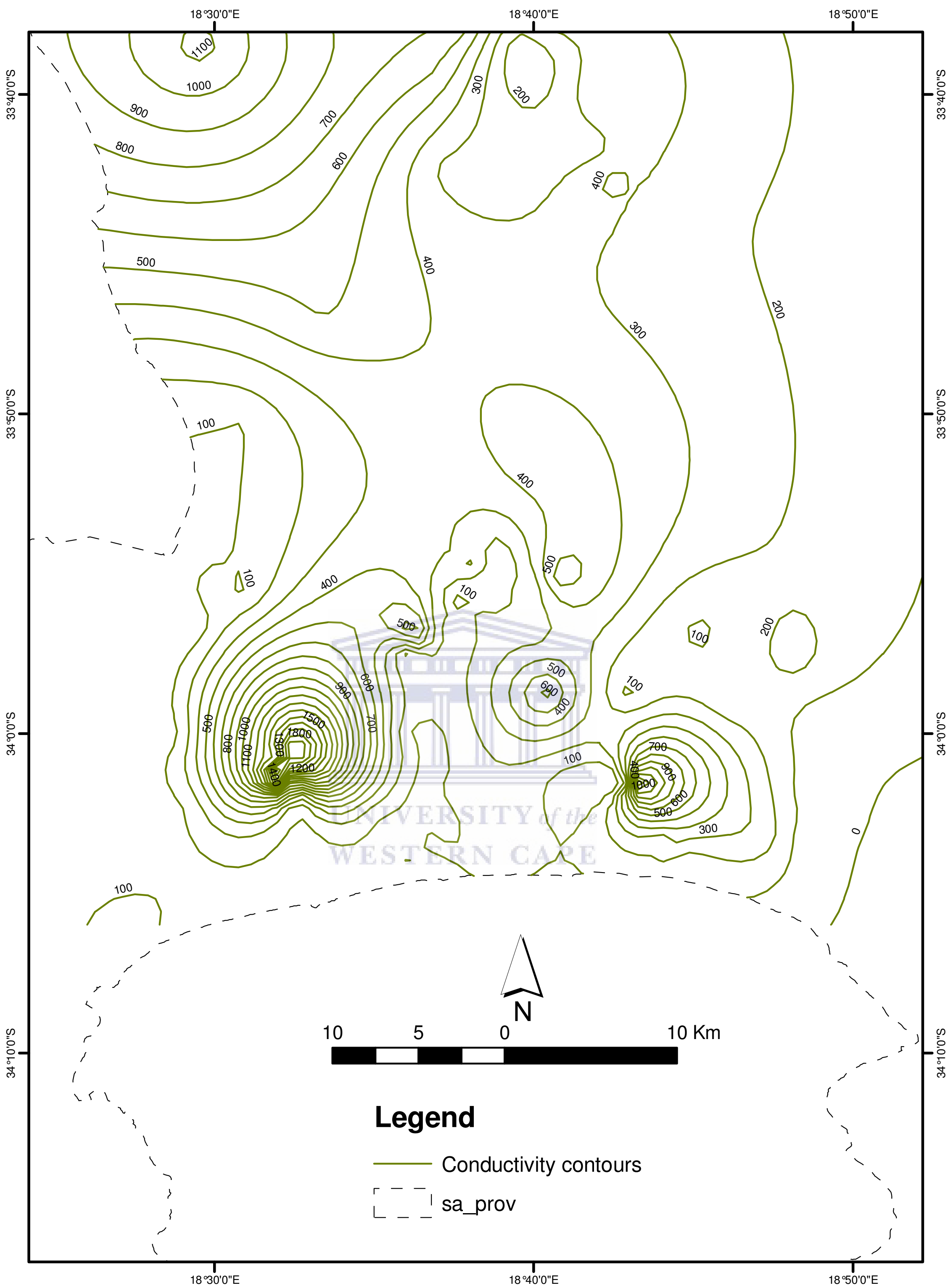



Figure 58: Areal distribution map of the electrical conductivity in the Cape Flats

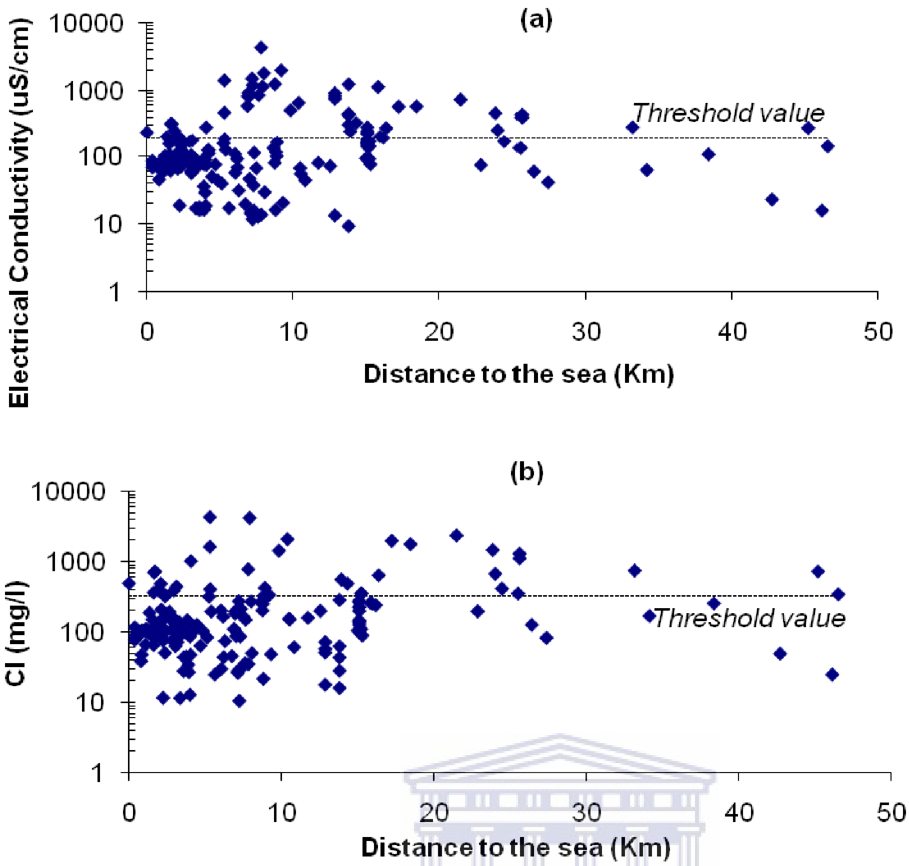



Figure 59 (a, b): Electrical conductivity (µS/cm) and chloride concentration (ppm) as function of the location distance (km) to the sea



In the last decade the effects of seawater encroachment into fresh water have also been investigated using ionic ratios (Petalas & Diamantis 1999; Sanchez Martos et al. 1999, 2002; Vengosh et al. 2002; El Moujabber et al. 2006; Lee & Song 2006; Petrides & Cartwright 2006). Figure 60 shows molar ratios of Na/Cl and $SO_4$/Cl versus Cl concentrations in groundwater of the study area. Generally, conservative seawater-fresh water mixing is expected to show a linear increase in Na and Cl (Lee & Song 2006, Sanchez et al. 1999) as well as Na/Cl values. Ratio of values of groundwater less than the seawater ratio 0.86 indicate that fresh groundwaters have been influenced by the saline water. The range of Na/Cl ratios is from 0.1 to 77 and about 5% were below the seawater ratio and exceeded the threshold value for chloride (Figure 60a). Values close to or clustering around the seawater (ratio) line may indicate recent simple mixing of groundwater with seawater (Mercado 1985; Lee & Song 2006). The effects of anthropogenic contamination (e.g. fertiliser application) may be reflected as very high Na/Cl ratios in groundwater (Lee & Song 2006; Jones et al.1999). High Na/Cl ratios have been used in the past to indicate anthropogenic contamination with chemical fertilizers, which often are leached from the soil into the groundwater. Similarly, using the same classification, figure 60(b) shows the variations in the molar ratios of $SO_4/Cl$ against Cl concentrations. In this figure molar ratios ranged between 0.003 and 22.5 while 6.9% of the groundwater samples are less than seawater value of 0.1 indicating some level of seawater contamination.

Other useful ionic ratios indicating seawater influence are Br/Cl and $Cl/(HCO_3+CO_3)$. Br is not in the historic data and could not be measured in recent sampling due to lack of laboratory capabilities. However, the range of $Cl/(HCO_3+CO_3)$ is between 0.16 and 53 and shows a positive linear relation with Cl concentrations (Figure 60c), indicating simple mixing of fresh water with saline water. The classification based on the methods of Revelle (1941), Todd (1980), Lee & Song (2006), and Petrides & Cartwright (2006) show that $Cl/(HCO_3+CO_3$ ratios <0.5 are for "unaffected", 0.5-6.6 for "slightly/moderately affected", >6.6 for "strongly affected" by seawater.

The ratio $Cl/(HCO_3+CO_3)$ shows 4.8% of the samples are below the seawater ratio in figure 60c and are classified as strongly influenced while another 3.8% are slightly/moderately affected by sea water.



In addition to geochemical data, salinization could also be evaluated by annual EC logging. Figure 61 shows results of vertical EC loggings at three selected monitoring wells in the study area. Generally a large increase of EC with depth was observed for UWC4 and 5 and iThemba labs borehole (b,c).

It is obvious from the discussions above and from earlier models (Gerber 1981, Vandoolaeghe 1989) that seawater intrusion into the Cape Flats aquifer is not an issue to raise alarm in the medium- to long-term. However, "cyclic" salt may have a definite influence due to proximity to the sea.

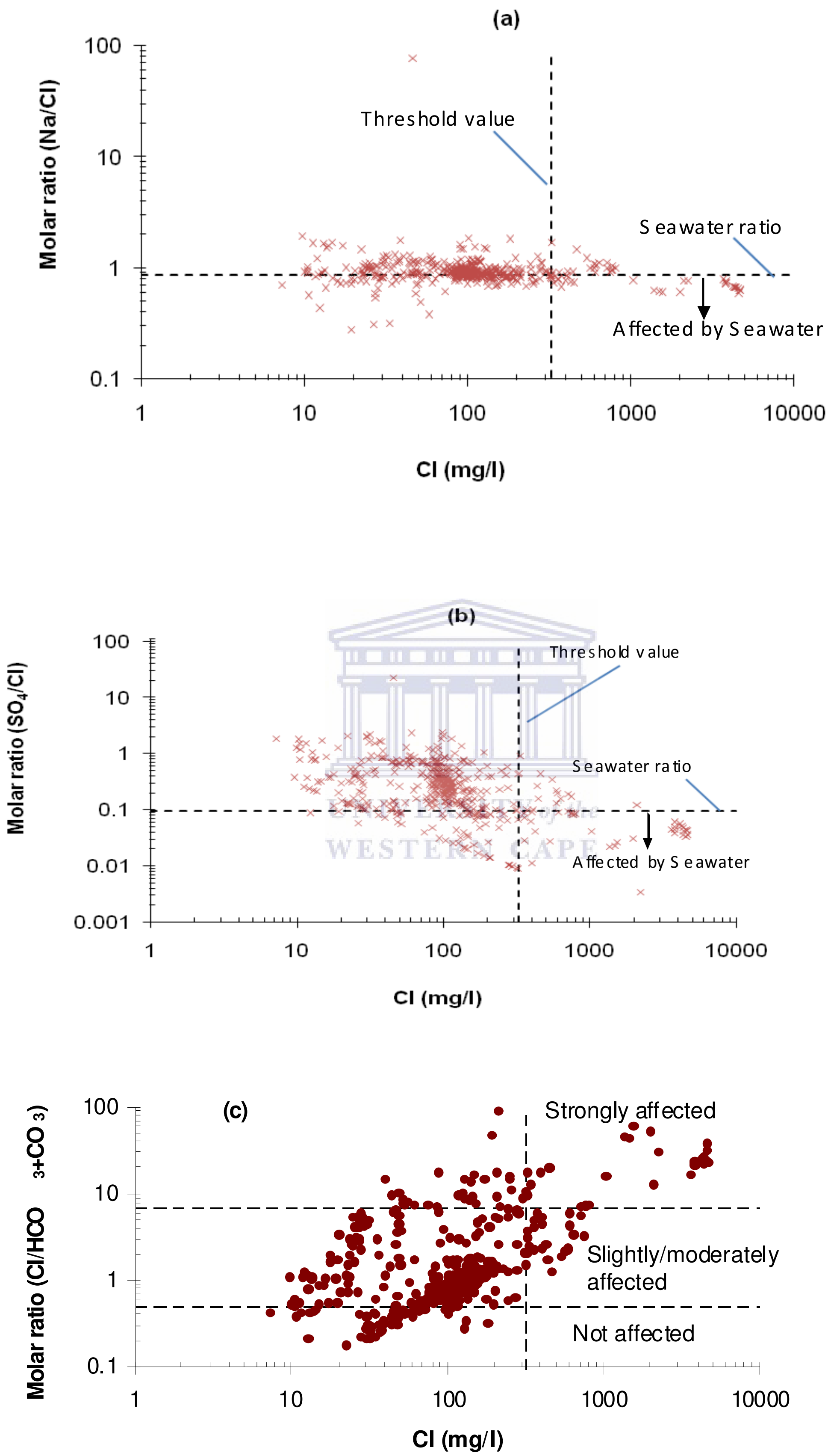



Figure 60: Molar ratios: (a), (b) Na/Cl and $SO_4$/Cl versus Cl concentration and (c) Cl/($HCO_3$+$CO_3$) versus Cl concentration

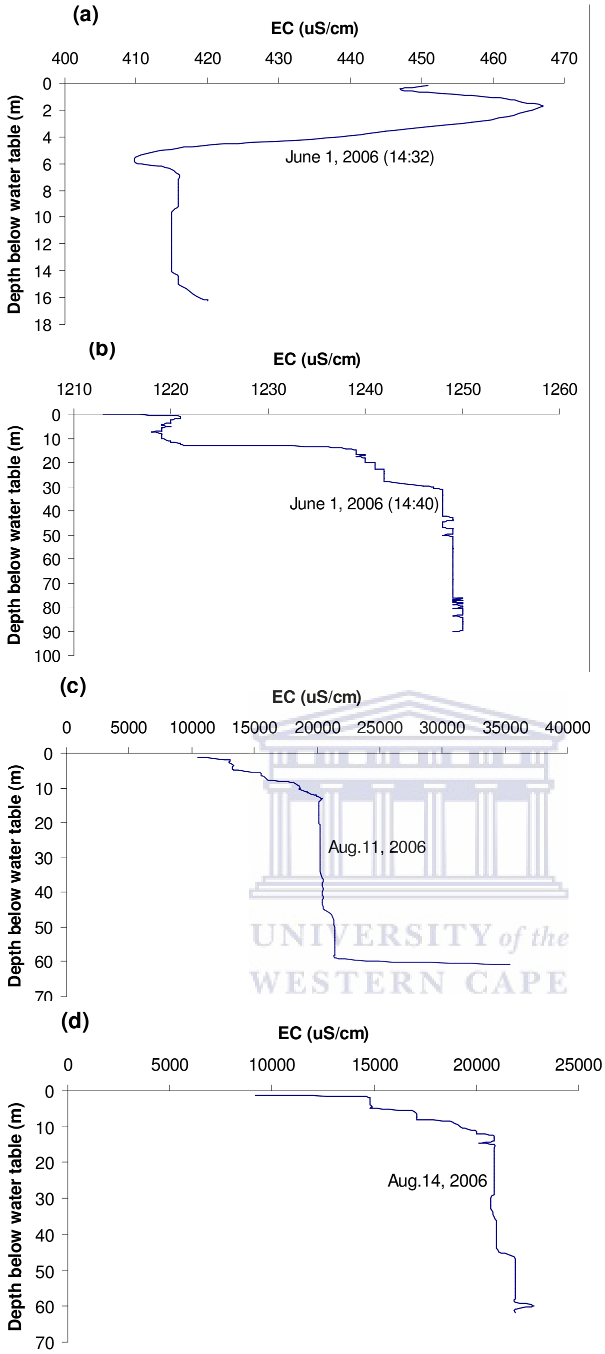





Figure 61: Vertical EC profiles at iThemba and UWC monitoring wells: (a) UWC4 test-hole about 22 m depth screened within the Cape Flats aquifer; (b) UWC5 test-hole 105 m deep and screened in the bedrock aquifer; (c) and (d) are iThemba borehole 61 m depth (tapping the Cape Flats aquifer) before and after pumping respectively.

### 6.8 Surface water chemistry

Surface water/rivers sampled in this study have TDS of 98-1113 (mean 766 ppm). The TDS within surface waters sampled within the study area is, in most cases, lower than in groundwater (average TDS: 766 ppm) in exception of the two polluted ponds at iThemba, where dissolved solids range between 952 and 1113 ppm during the four sampling episodes. Newlands reservoir showed the least TDS (98 ppm). Obviously, this is raw water transported from the Berg River and stored in the reservoir to be used for the City water supply (this water is only chlorinated and piped into the City supply mains). The average equivalent concentration of the major ions and ionic combinations in sampled surface waters of the study area are shown in figure 62 and the piper plot in figure 63.

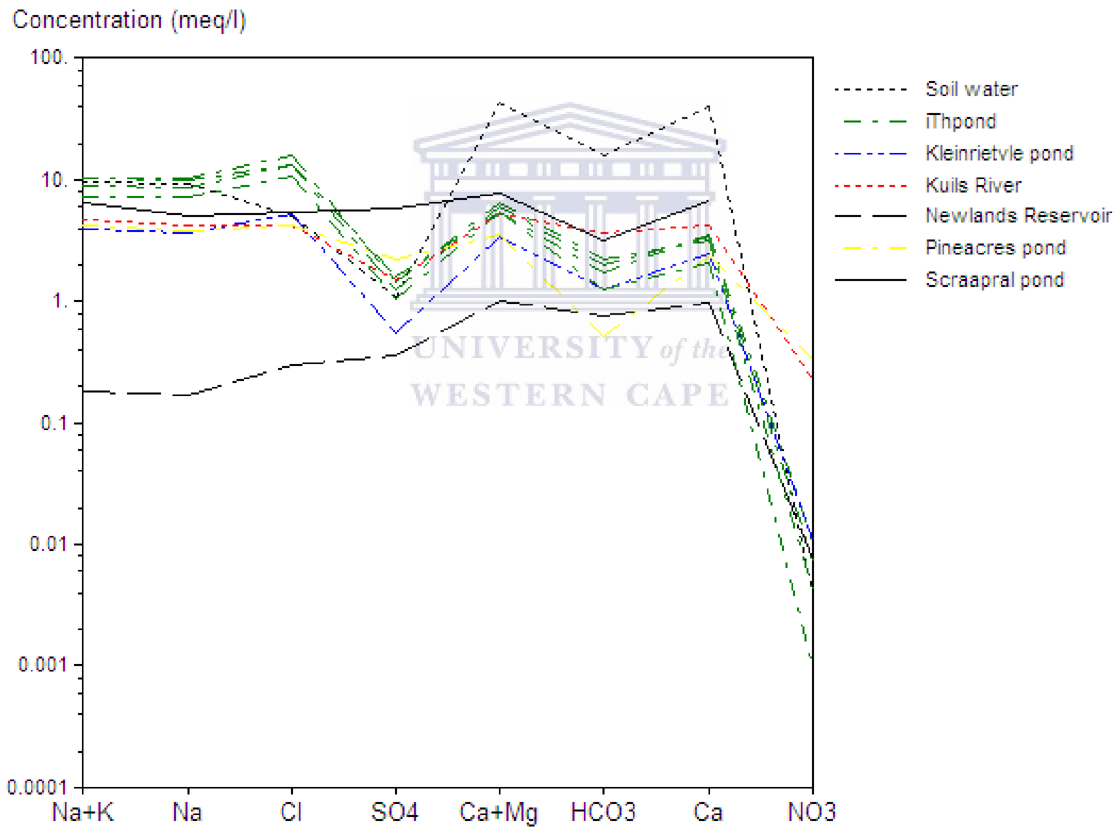



Figure 62: Average equivalent concentration of the major ions and ionic combinations in sampled surface waters of the study area (included soil water showed similar pattern)

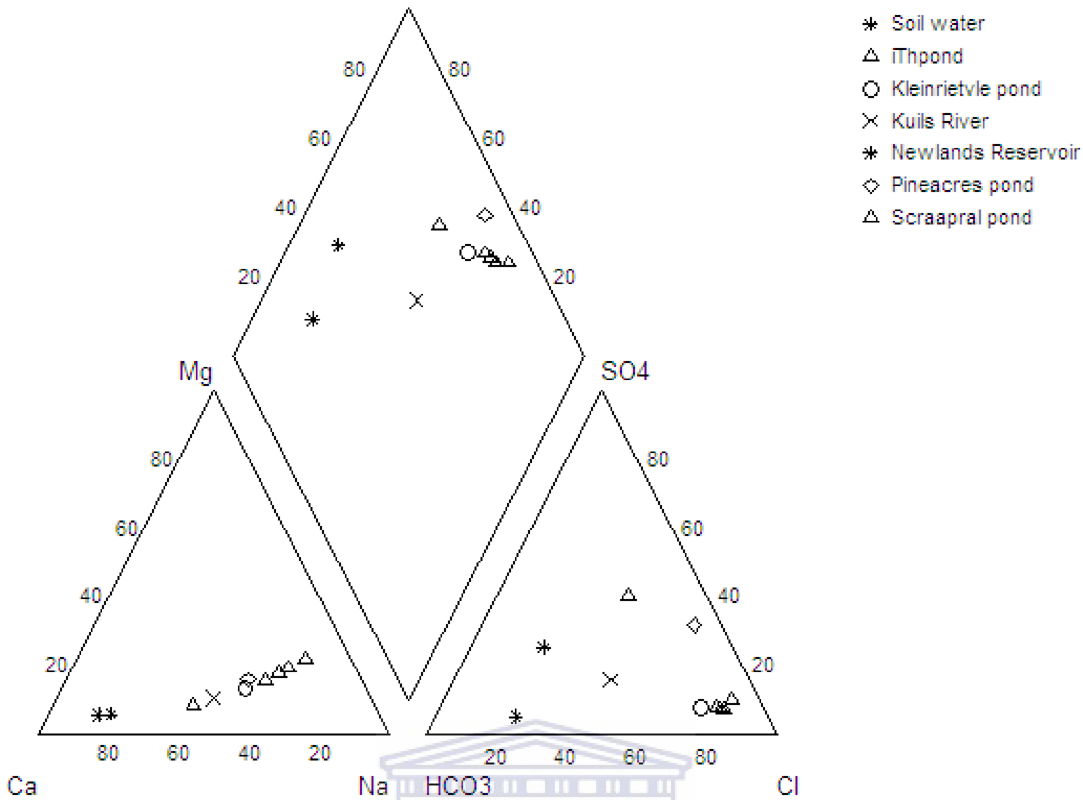



Figure 63: Piper plots of the surface water chemistry in the study area



Spring waters have TDS of 67-125 ppm with a mean of 81.4 ppm while rainwater ranges from 3.2-67 ppm (mean: 32.1 ppm). Elemental ratios and isotopic compositions (i.e., anions, cations, and stable isotopes) are also similar to that of groundwater. The average equivalent concentration of the major ions and ionic combinations in sampled springs during 2006 sampling campaign is plotted in figure 64 while the piper diagram in figure 65. The water chemistry analyses at the selected springs show low ion concentrations, indicating that the groundwater circulation through the basin is rapid. The only exception is the Newlands reservoir that showed a more depleted value for stable isotopes ($\delta^{18}O$: -4.78 ‰ and $\delta^{2}H$: -24.67 ‰). The reason for this is possibly the long distance of transport in pipeline, subjecting the water to less evaporation effect. Other surface waters have stable isotope range between -9.64 to -4.1 ‰ for deuterium and between -2.3 to -1.22 ‰ for oxygen-18.

Rainfall samples were taken in 3 sites, viz: Belhar, UWC, and iThemba. The average equivalent concentration of the major ions and ionic combinations in rainwater are plotted in figure 66 and piper plot is shown in figure 67.

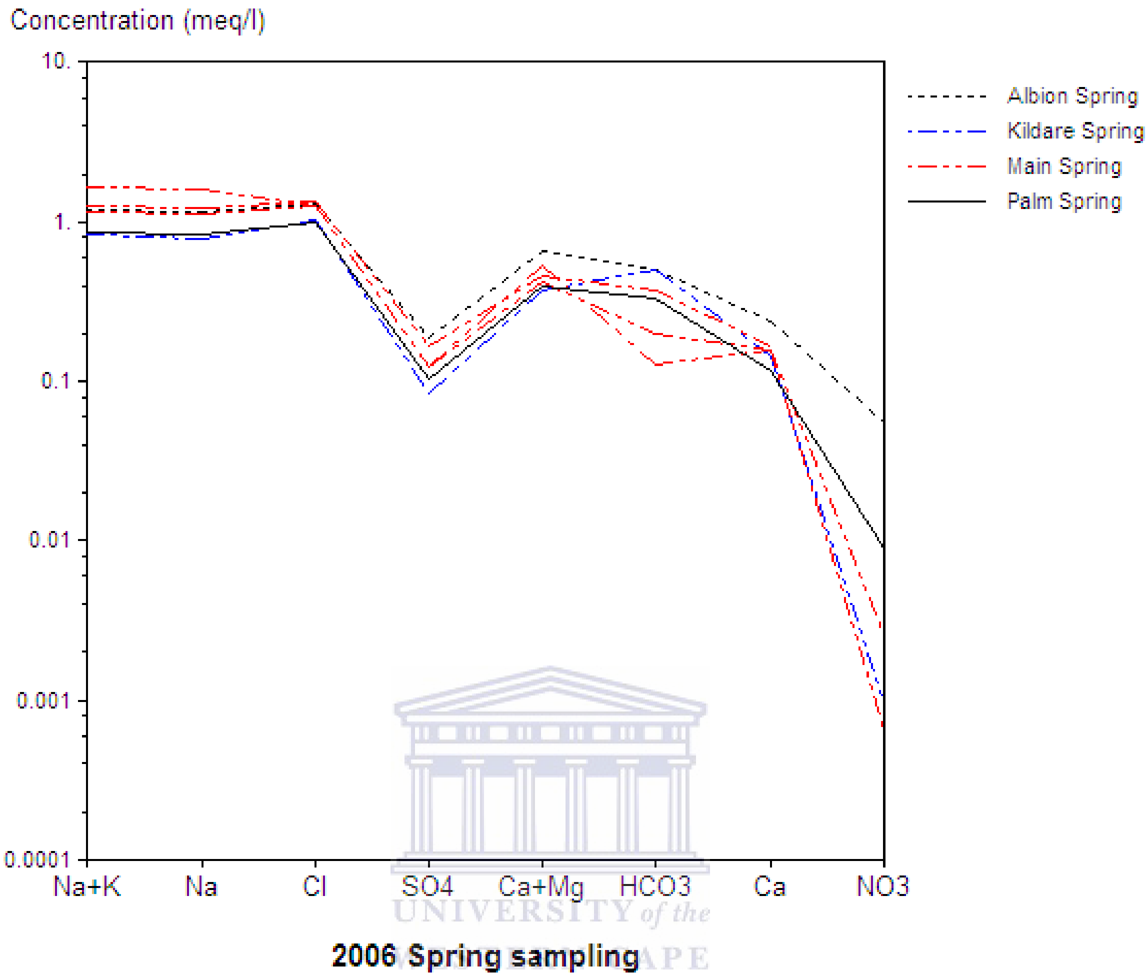



Figure 64: Average equivalent concentration of the major ions and ionic combinations in sampled springs during 2006 sampling campaign

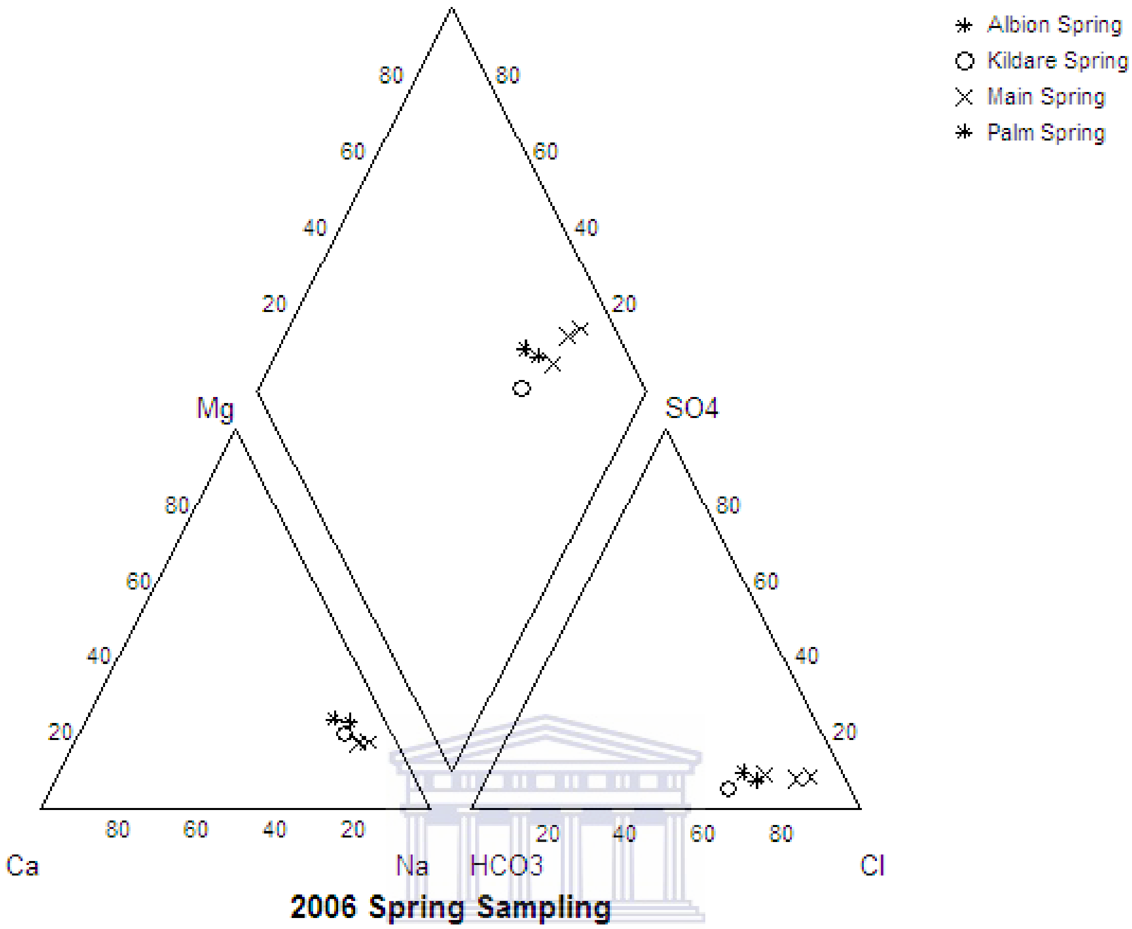





Figure 65: Piper plots of the spring-water chemistry in the study area

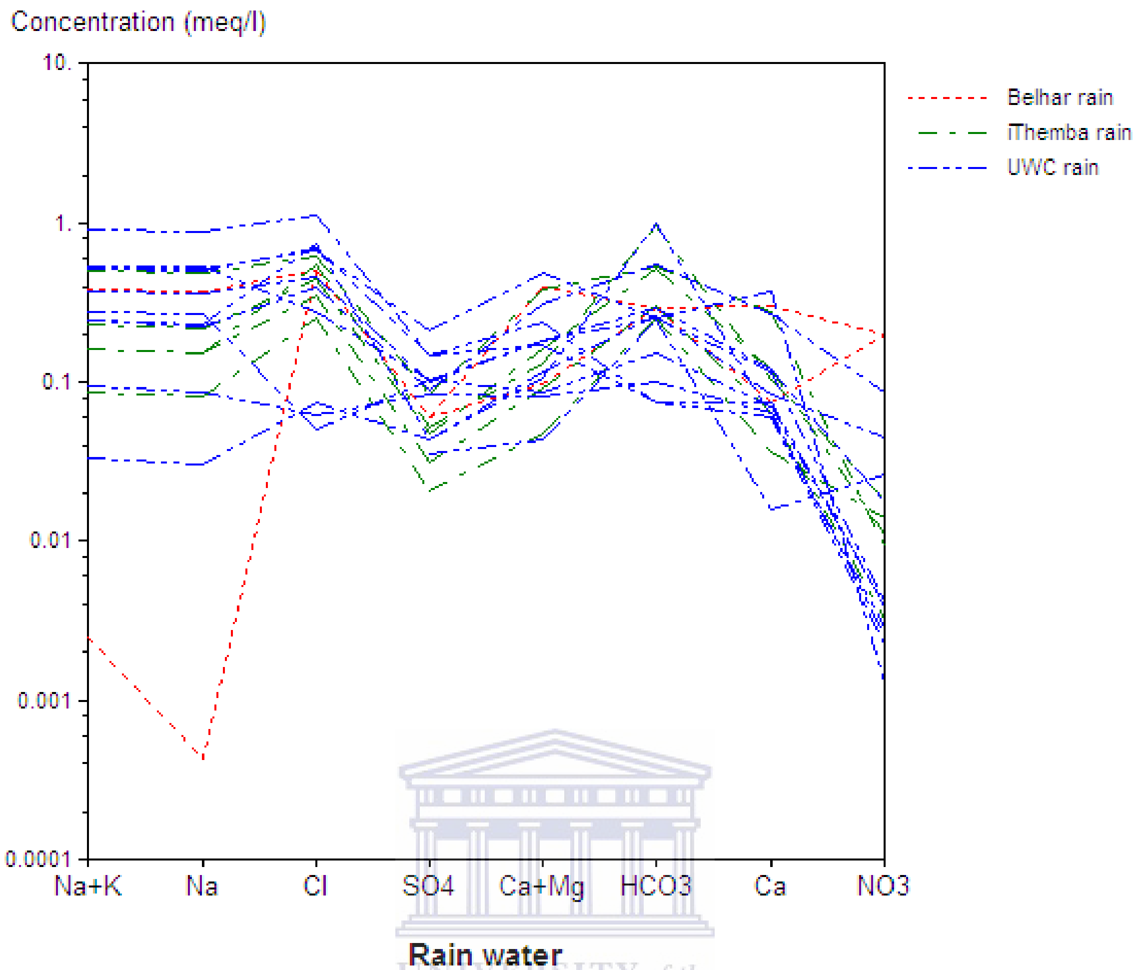





Figure 66: Average equivalent concentration of the major ions and ionic combinations in rainwater (2005-2006 sampling)

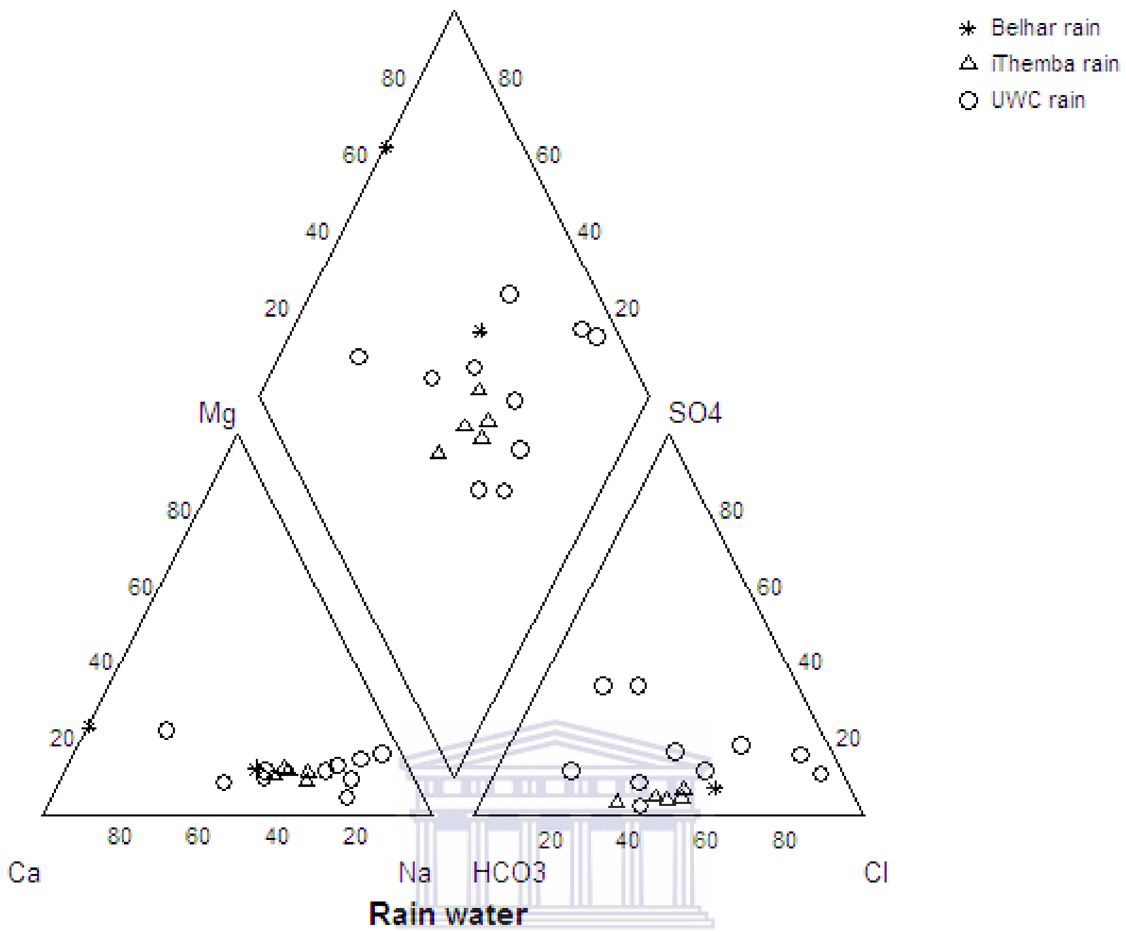



Figure 67: Piper plots of rainwater in the study area (2005-2006 sampling)



### 6.9 Groundwater quality

High salinity (Cl) and concentrations of nitrate ($NO_3$) in some parts of the aquifer are the major groundwater quality problems.

#### *6.9.1 Chloride (salinity)*

Salinity in coastal aquifer is most often described by the Cl concentration in groundwater; although Wright & Conrad (1995) used the total dissolved solids (TDS) to delineate zones of high salinity in the Cape Flats. There is no intensive exploitation of groundwater in the Cape Flats in the past 30–40 years to warrant disturbance of the natural equilibrium between fresh water and saline water. Therefore, salinity and quality problems are mostly anthropogenic, although salinity increase along the False Bay mentioned and has resulted in increasing salinity in most areas along the periphery of the coastline (Giljam & Waldron 2002). However, the extent of the encroachment inland is yet to be determined. Depending on the location and hydrochemical processes, the rate of salinization may be gradual or sudden. Observed data show that 78 percent of the Cape Flats aquifer's resources contain groundwater that meets the WHO water standard for Cl (250 ppm), primarily in the north and along the dune sand in areas of the southwest (Adelana et al. in prep). The other 22 percent showed higher Cl concentration sometimes up to 5000 ppm. Of note is the pumping well at iThemba labs, which was monitored consistently over a period. Four sets of samples have been collected for groundwater chemistry during different pumping tests (August 2006, November 2006, January 2007, and March 2007). During these four sampling and pumping episodes, Cl concentration ranges from 1396-5121 ppm (mean value: 4193 ppm). The source of Cl may be (1) seawater intrusion where it possibly extends inland (although the distance of this site to the coast is approximately 5.3 km) in the northwestern and the southern coast into the Cape Flats. However, the data so far (as explained in section6.7) does not seem to support encroachment of salt water into the Cape Flats aquifer. The elevated concentration of Na and Cl may be due to anthropogenic activities. There are a number of polluting influences in the Cape Flats which may be contributing to the degrading quality of groundwater. These include the several waste disposal sites, industrial effluents, farming activities and the effects of informal settlements.



### *6.9.2 Nitrate ($NO_3$) and phosphate ($PO_4$)*

Most municipal wells in the Cape show nitrate levels ($NO_3$-N) within acceptable limits except wells around Ottery/Philippi/Mitchell's Plain, which are mostly in excess of the drinking water standard of 10 ppm (as $NO_3$-N) or 50 ppm (as $NO_3$). These are mostly agricultural wells influenced by the active farming activities in this area. The average concentration of $NO_3^-$ and $PO_4^-$ are 2.65 (Standarddeviation 11.0 ppm $NO_3$-N) and 0.10 ppm, respectively. These values are less than the South African water quality guideline[*][1] values of 6 ppm $NO_3$-N and 0.35 ppm for phosphate and much less than maximum permissible values of 10 ppm for nitrate (as $NO_3$-N) and 6.1 ppm for phosphate.

In the worst affected areas (urban-agricultural areas), the $NO_3$-N concentrations are increasing, at rates of up to 5 ppm per year (see figure 68b). Figure 68 shows six of the boreholes under the regional groundwater quality monitoring of wells in the Cape Town area. Similar pattern is shown by the concentrations of $SO_4$ and Cl, indicating increasing tendencies of pollution trend (figure 68b-c). The main sources of $NO_3$ in these areas are fertilizers and domestic sewage effluents. The quantities of sewage that percolate to the water table on an annual basis through effluent discharge and septic tanks may be significant, and should be estimated in further studies.

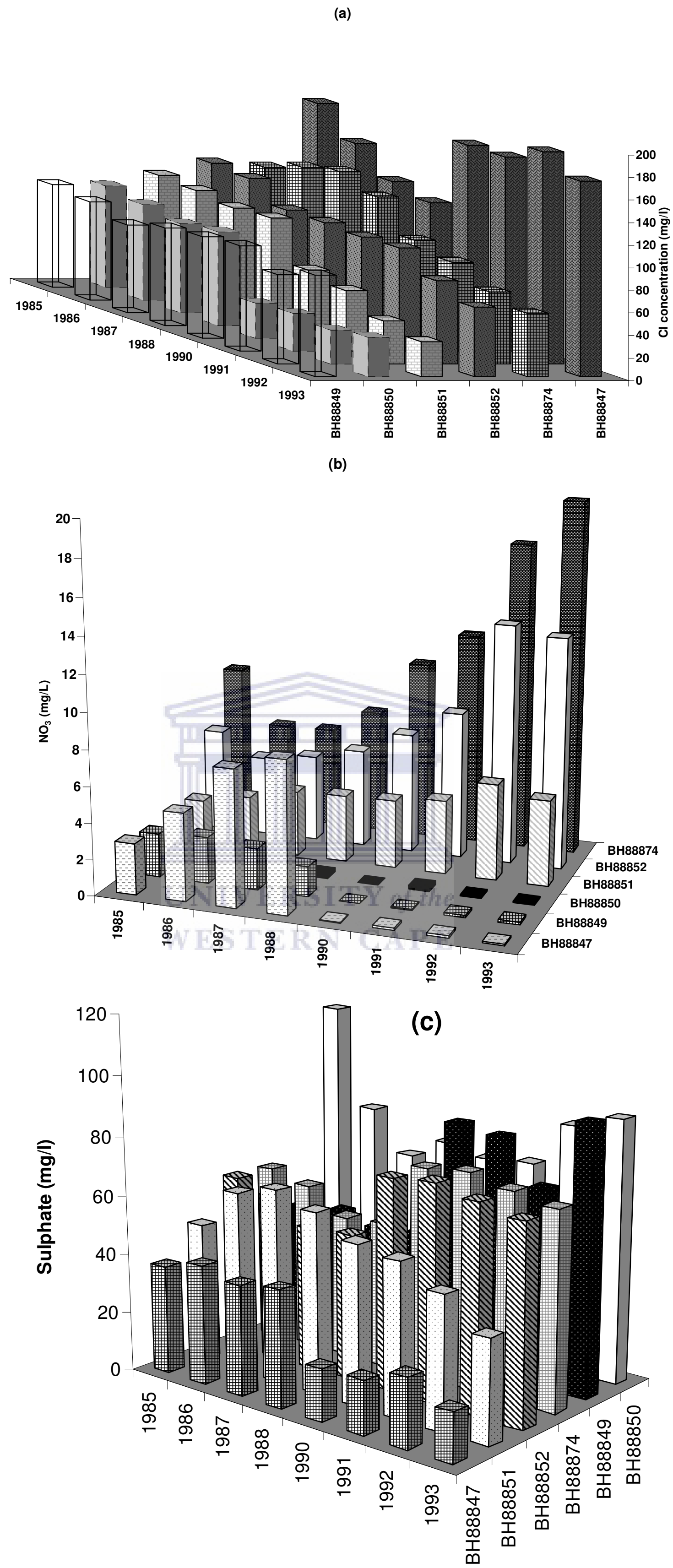



Figure 68: Yearly distribution of pollution indicators (Cl, $NO_3$, $SO_4$) in selected monitoring wells on the Cape Flats

In contrast to salinity, groundwater flowing from the east has relatively low $NO_3$ levels. Contrarily, the six shallow boreholes in Macassar showed the highest concentration of nitrate (up to 248 ppm as $NO_3$-N). This is because the wells are mostly sunk by the side of the household vegetable gardens, where fertilisers and animal manure used are washed into the groundwater through the soil zone. The relatively high concentrations of nitrate and phosphate in parts of the Cape Flats water are due to the agricultural activities and use of fertilizers in the capture zone. Agricultural activities are extensive in the northeast catchment of Macassar. This may be comparable to the intensive vegetable farming in the capture zone of the Cape Flats aquifer around Philippi/Ottery area, where >70% of vegetable production in the Western Cape are derived, and as such a good source of livelihood and income for this community dwellers. The current application rate of fertilizers has not been quantified but higher than twofold of what it was in the 1980s. Presently, there is no prescribed fertilizer application rate by the government as it is in other parts of the world. Moreover, there is home-prepared animal manure or composted sludge, which includes phosphate-rich and nitrate-rich types of compounds.

Nitrate is considered as a secondary constituent in groundwater (Todd 1980) and has been the subject of numerous research studies in Southern Africa during the past two decades (Tredoux & Kirchner 1985, Tredoux 1993, Tredoux et al. 2001, Tredoux & Talma 2006). Nitrate concentration of 10 ppm or greater may be regarded as a probable indication of contamination (Hounslow 1995) and concentrations above 8.5 ppm are in the category of low-level contamination according to Hallberg's (1989) classification. Nevertheless, nitrate concentration reached 248 ppm in the study area (as it is in northern parts of South Africa, south-eastern parts of Botswana and Namibia (Tredoux & Talma 2006). As high nitrate concentrations in drinking water are the cause of methaemoglobinaemia and can aggravate other diseases like hypertension, certain cancers, some birth defects, and spontaneous abortion (Spalding and Exner 1993), attention must be paid to the nitrate levels in water from parts of the Cape Flats at the present level and in the event of a possible increase in the future. The average worldwide concentration of $PO_4^-$-P in groundwater is 0.02 ppm and the maximum permissible level in drinking water is 6.1 ppm.

## 6.10 Stable isotopes

In the Cape Flats, Henzen (1973) and Gerber (1981) suggested that groundwater was recharged by rainwater infiltration. However, the recharge process was not well understood and the groundwater residence time was unknown due to the sparse hydrogeological data. Naturally occurring stable ($^{2}H$, $^{18}O$) and radiogenic ($^{3}H$, $^{14}C$) isotopes in water have been used over the last 50 years to address problems related to the recharge and the residence time of groundwater (e.g. Fontes 1980; Gonfiantini 1986; Clark & Fritz 1997). In this section the purpose is to identify sources of recharge, to localize recharge areas and to determine the groundwater residence time by employing isotopic measurements.

The corresponding development and management of the groundwater resources in this area require detailed and reliable information on the origin and the natural recharge rate of groundwater; as sustainable water management is vital for maintaining the ecologic system in spite of an increasing demand for water supply. Stable isotope analysis for ($\delta^{2}H$, $\delta^{18}O$) was conducted on groundwater samples from the Cape Flats and Malmesbury weathered aquifers respectively. No sampling of groundwater from the Cape granite aquifer was done due to lack of accessibility and cost. Samples were collected during the winter 2005 and 2006, following some significant rain events, and some sampling was carried out in summer 2006. Samples include rainwater (9), springs (6) and surface water (4). Data were from the sampling conducted in May 2005 (end of summer/beginning of winter) and in the period August/September 2006 (end of winter). Other data are from published reports. The sampling and analytical techniques as well as the laboratories involved have been discussed in Section 6.3. Table 190.1 shows the summary of isotopic composition of samples from the study area.



### *6.10.1 Stable isotopes in precipitation*

Isotopes in precipitation have been measured monthly for samples collected in Cape Town Airport (33° 59' S 18° 36' E, altitude 42 m asl) by the International Atomic Energy Agency (IAEA) since 1961. However, the record is partially incomplete. Cape Town has a winter rainfall (May-August: >50 mm/month) with low temperatures (<15°C); and relatively dry summer (November-April: 10-40 mm/month) with higher temperatures (>20°C). The weighted mean values of $\delta^{18}O$ and $\delta D$ are −3.3 and −12.6‰, respectively (Global Network of Isotopes in Precipitation Database, *2004*). Similarly, rainwater samples were collected at University of Cape Town (UCT) and measured for stable isotopes $^{18}O$ and $^{2}H$ from 1995-

1997 (Harris et al. 1999). The weighted monthly mean of $\delta^{18}O$ and $\delta D$ are -3.74 and -11.9‰. The plot of $\delta D$ and $\delta^{18}O$ for meteoric water in Cape Town is shown in Figure 69.

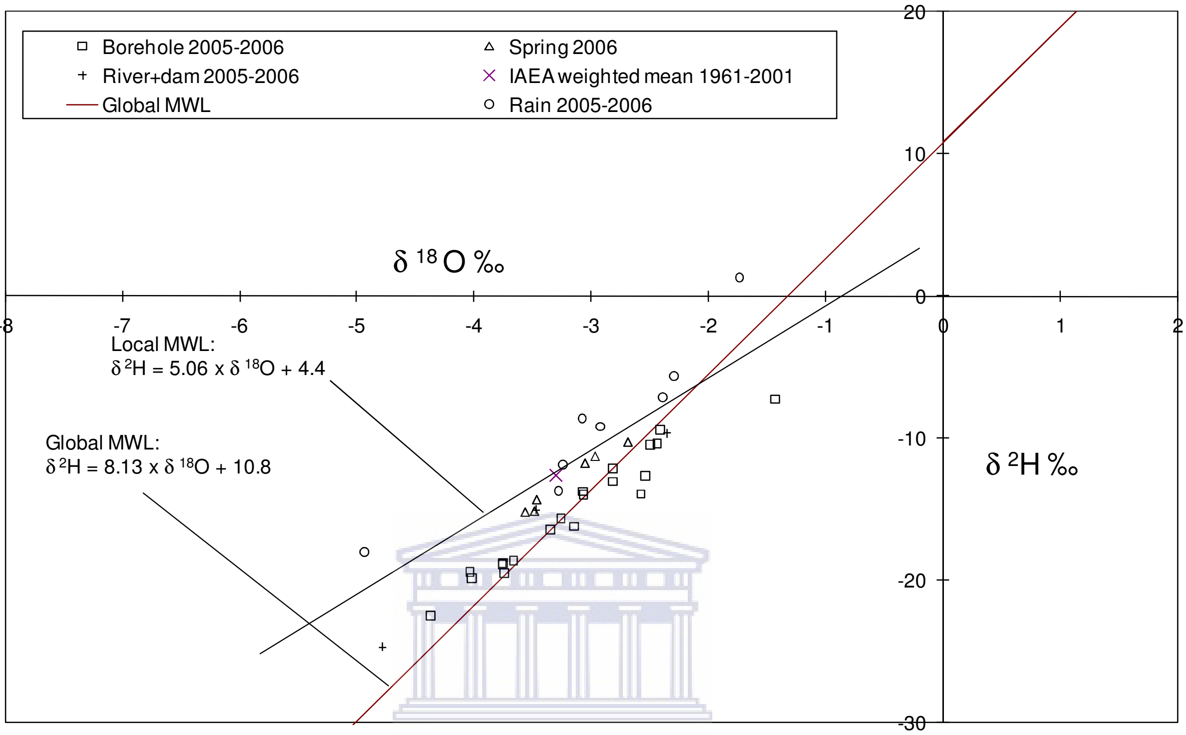



Figure 69: Correlation of $\delta\,^{2}H$ (D) against $\delta\,^{18}O$ of modern rain at Cape Town Airport. Global Meteoric Water Line (GMWL) and Local Meteoric Water Line are plotted for comparison.

The weighted yearly means of local precipitation, as well as the long-term average from 1961-2001, plot almost all *above* the GMWL following the relation 2H = 5.06 × $\delta\,^{18}O$ + 4.4. Both slope and D-excess are significantly lower as compared to the Global MWL. The lower slope is affected by secondary evaporation during rainfall, as evaporation lines tend to have a slope close to 4. The fact that the samples plot above the GMWL can be explained by a low humidity of the air where the first rain will be strongly depleted and the precipitation will plot well above the GMWL (Clark & Fritz 1997). The d-excess calculated from the weighted average values is 13.8 thus indicating a relatively lower humidity. In fact the average relative humidity for Cape Town calculated from available climatic data for a period 1956-2005 (values at 08:00, 14:00 and 20:00) result in a value of 71.5 %, whereas the GMWL requires value of above 85 %. The mean $\delta^{18}O$ values of monthly rain samples collected from University of Cape Town by Harris et al. (1999) is significantly lower than that at the Cape

Town Airport; while the weighted annual values for δD are almost identical (within analytical errors discussed in Section 6.3). However, all these data plot around the Global Meteoric Water Line (Rozanski et al. 1993) and showed relatively higher deuterium excess, d (calculated from the equation defined by Dansgaard, 1964).

Table 23: Summary of isotopic compositions in the study area

| Area | n | Mean $\delta^{18}O$ (‰) | Mean δD (‰) | Mean d-excess (‰) |
|---|---|---|---|---|
| Rain water in the Cape Flats area | 9 | -3.5 | -14.4 | 14.5 |
| Springs | 6 | -3.2 | -13.0 | 13.3 |
| Springs[2] | 12 | -3.6 | -13.1 | 16.6 |
| Surface water in the mountain area[2] | 5 | -3.1 | -9.9 | 15.2 |
| Surface water in the Cape Flats area | 4 | -3.5 | -16.4 | 12.5 |
| Cape Flats aquifer | 16 | -3.1 | -14.9 | 10.3 |
| Cape Flats aquifer[1] | 6 | -2.1 | -10.2 | 6.6 |
| Cape Flats aquifer[2] | 12 | -3.4 | -15.3 | 12.8 |
| Culemborg-Black River aquifer[2] | 18 | -2.5 | -9.2 | 11.2 |
| Malmesbury bedrock | 4 | -3.4 | -16.1 | 12.0 |

[1]Saayman et al. 2000
[2]Harris et al. 1999

### *6.10.2 Stable isotopes in surface water*

Surface water in the study area showed slightly distinct isotopic composition that allowed separation into the surface water in the mountain area and surface water on the coastal plain sand (Cape Flats) area. The Liesbeek River (in the mountain area) has values mostly falling within the group of rainwater, above the GMWL while the Eerste River (on the Cape Flats) plots at the edge of the springs and groundwater samples (figure 70). For the stable isotope composition of the Liesbeek River, Harris et al. (1999) found that the mean $\delta^{18}O$ values increase along the river course, based on the monthly samples collected at two points with different altitude (from 1995-1997). The samples of the Liesbeek River from Kirstenbosch changes in isotopic composition as it flow towards the sea (Harris et al. 1999).

Six samples of the current study were collected from springs at the foot of the mountain (30-120 m asl) in the western recharge area in May 2006. These samples had isotopic values of which were similar to those of recent rainwater in the area. The $\delta^{18}O$ and δD values for these samples ranged from −3.6 to −2.7‰ and −15.0 to −10.3‰, respectively (Table 7.5) and with the mean $\delta^{18}O$ value of -3.2‰ (*n*=6). The mean $\delta^{18}O$ value of surface water, which was located at the outlet of the mountain valleys, was −3.1‰ (Harris et al. 1999). This mean value was more negative than the mean value of precipitation in the Cape Flats area (UWC and iThemba rain samples). It is the representative for the precipitation in the Table Mountain area. The d-excess from the river samples in the basin ranged between +12.5 and +14.2‰. This indicated that evaporation is probably occurring in ponds, reservoirs and dams in the study area. The relationship between δD and $\delta^{18}O$ of water samples in Table 23 was plotted with the local meteoric water line (LMWL) and global meteoric water line (GMWL) in Figure 69. Samples may be from recent local precipitation and are less subject to evaporation than other samples in the area. The other samples (Eerste River, ponds or reservoir) collected in the area plotted to the right of the LMWL and show that the river is has been subjected to evaporation at the time of sampling, being slightly enriched with $\delta^{18}O$ and δD. However, the sample from the Newlands reservoir is the most depleted in stable isotopes. This is expected as the water is sourced (piped down) from the Berg River, located >300 km NE of Cape Town and from a higher elevation.

### *6.10.3 Stable isotopes in groundwater*

Groundwater from the Cape Flats aquifer was characterized by relatively lower $\delta^{18}O$ and δD values. The $^{18}O$ and $^{2}H$ data vary between –4.4 and –1.4‰, and –22.5 and –7.2‰ VSMOW, respectively. The corresponding average values are –3.1‰ and –14.9‰. The mean isotopic concentration of the rainwater from which the groundwater was derived suggests that the mean $^{18}O$ of rainfall events resulting in recharge is about –3.35‰ VSMOW (IAEA 2004). Three samples (MCS1, UWC2, iThbh1) from current study on the Cape Flats, showed relatively lower $\delta^{18}O$ and δD values. This value corresponds to the most isotopically depleted groundwater samples, and represents therefore the largest rainfall events in the area during sampling period. The most enriched groundwater (–1.4‰) probably represents shorter rainfall events. Figure 70 shows the correlation of $\delta\ ^{2}H$ (D) against $\delta^{18}O$ of the recent groundwater sampling (2005-2006), along with springs, rain and surface water in Cape Town area. The Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL) are plotted for comparison (Rozanski et al. 1993, IAEA 2004).

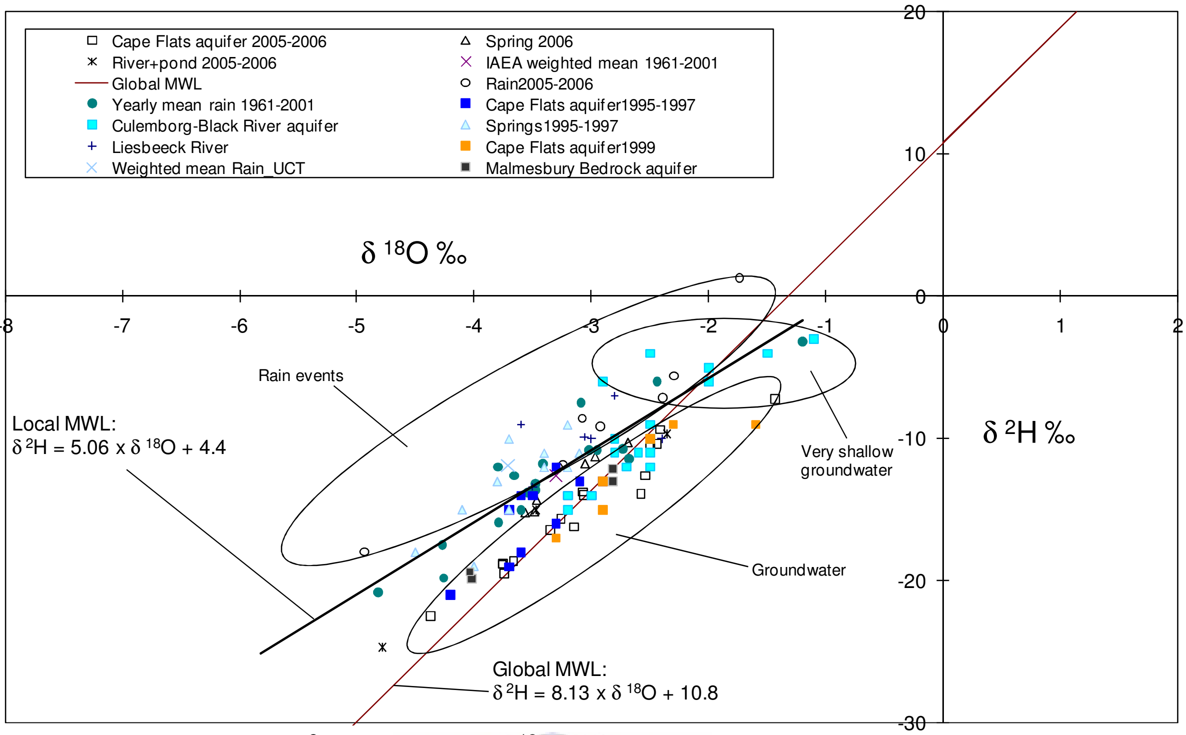



Figure 70: Correlation of $\delta^2$H (D) against $\delta$ $^{18}$O of groundwater, springs, rainwater and riverwater in Cape Town area sampled during 2005/2006. The Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL) are plotted for comparison.

### *6.10.4 Discussion*

In figure 70 the 38 samples collected during 2005 and 2006 are plotted. 20 samples are from boreholes, 9 samples represent recent precipitation events 6 were collected from springs, and 3 are representing surface water, 1 river and 2 local ponds. In order to discuss this exclusively data from previous work (included in Table 19) are also plotted.

Table 23 in section 6.10.1 summarised the average isotopic composition for the different types of water analysed in the study area since 1995. Seasonal variations in these waters are not so distinct, even in previous studies (Harris et al. 1999; Saayman et al. 2000) and as such it was not investigated here. However, Harris et al. (1999) reported seasonal variation in water from treatment plants contributing to Cape Town's mains water supply. The $\delta$ $^2$H and $\delta$ $^{18}$O values of treated water were found to be higher in April than September (Harris et al. 1999). The seasonal difference may be caused by a combination of seasonal changes in isotope composition of ambient meteoric water and evaporation from reservoirs. The differences in isotope composition which are of the order of 9‰ ($\delta$ $^2$H) and 1.6‰ ($\delta$ $^{18}$O) should enable mains water to be distinguished from groundwater, but would not allow reliable estimates to be made of the proportion of mains water contributing to a particular borehole. According to

Harris, there is also a degree of seasonal variation in O- and H-isotope ratio of the Culemborg-Black River aquifer samples but less isotope distinction between mains water and the shallow groundwater in the Culemborg area, but there is evidence that in summer, mixing with sea-water occurs. This may be related to evapo-transpiration and/or recharge by rain-water because these samples were from shallow boreholes (3-5 m depth). The Culemborg-Black River aquifer is a freshwater aquifer created by reclamation of land immediately to the east of the Cape Town CBD with the water table at an average depth of 0 to 3 m (a.s.l.) and groundwater flow towards the Table Bay (Harris et al. 1999; HKS 1995). Groundwater from the Culemborg area is said to be locally influenced by the existing and historic drainage patterns of the Black and Salt Rivers (HKS, 1995).

*6.10.4.1 Rainwater samples:*

The rainwater samples can be considered as one group as they are plotting well above the Global MWL, above the IAEA weighted average (1961-2001) and also mainly above the Local MWL (see figure 69). As discussed before, the plotting above the GMWL is an indication of a lower humidity during evaporation from the sea, humidity lower than 80%, as compared to a humidity 86/87% leading to the GMWL (Clark & Fritz 1997). Most of the rain in the greater Cape Town region falls in the winter months (June to September), with temperatures less than 10°C in the early mornings. During the summer months, however, rainfall is very low and temperatures higher, resulting in "temperature effects" (e.g. Dansgaard, 1964). At the University of Cape Town, on the slopes of Table Mountain rain-water has, on average, a higher deuterium excess than the rain-water falling on Cape Town International Airport in the Cape Flats region (Harris et al. 1999).

*6.10.4.2 Spring samples and groundwater samples:*

The spring water samples are representing groundwater flowing out at the intersection of the groundwater table with the land surface. Thus they also represent groundwater. The samples in figure 70 scatter closely around the IAEA weighted average of the years 1961-2001 just below the Local MWL, thus indicating also a high proportion of relatively recent precipitation events. They also plot all above the samples from boreholes, which generally tap lower zones from the aquifer, though the position of the screens is not known in most cases. This is in agreement with the data discussed in Harris et al. 1999, where spring-waters form an array which is enriched in deuterium relative to the global meteoric water line, whereas the Cape Flats groundwaters plot closer to the global meteoric water line. This was attributed to the difference in isotope composition of ambient rain-water. However, the more isotopically depleted values from the boreholes indicate a possible groundwater formation during slightly cooler and more humid periods in the recent past (some decades, or even centuries ago). As no data on C-14 or tritium is available, the age of the groundwater samples remains unknown.

To further discuss this, the regional distribution of deuterium values in groundwater is illustrated in figure 71. It can be seen in the figure that groundwater in the mountain area, have a similar deuterium excess to the springs but slightly different from groundwater that flows inland, south-eastwards to the sea. The reasons for the difference between the Cape Flats and the Table Mountain/reservoir signature presumably relate to differences in microclimate caused by physiography.

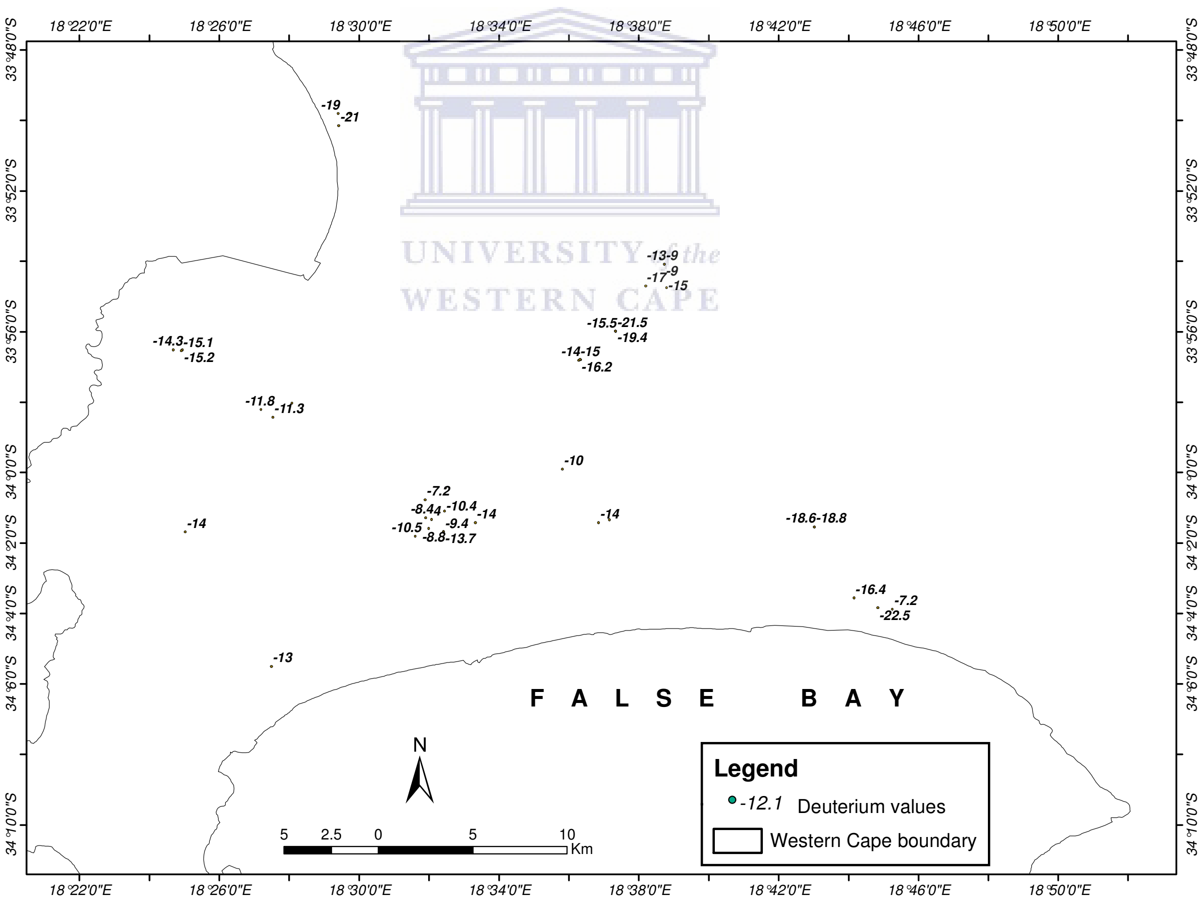



Figure 71: Map showing the regional distribution of δ $^2$H in Cape Flats groundwater.

There is no clear difference between the northern and southern suburbs except that the wells closest to the northwest and southeast coast were the more depleted than those inland. The deuterium values (-19.4 and -21.5‰) at the centre of the map represents the composition of groundwater from the Malmesbury Bedrock aquifer (UWC5 screened at 92.85 m bsl; depth greater than the Cape Flats aquifer); all others are from the Cape Flats (depth within 60 m below mean sea level). Also, springs and groundwater in the western end have similar isotopic composition (deuterium values).

**6.11 Summary**

A study of the hydrogeochemical evaluation of groundwater in the Cape Flats aquifer carried out was described in this chapter. The objective was identifying the geochemical processes and their relation with groundwater quality as well as to get an insight into the hydrochemical characteristics and factors controlling groundwater chemistry in the aquifer. Salinity and nitrate contamination are potential threats in the area, which draws attention considering the proposal to use this water for municipal drinking supply. Various graphical plots and statistical analyses were carried out using chemical data to deduce a hydrochemical evaluation of the aquifer system based on ionic constituents, water types, hydrochemical facies and factors controlling groundwater quality. The prevailing hydrochemical processes operating in the study area are simple dissolution, mixing, weathering processes of silicate, and ion exchange. The study further highlights the descriptive capabilities of conventional and multivariate techniques and major ion geochemistry as useful tools in the evaluation of this groundwater resource.

The naturally occurring stable ($^{2}H$, $^{18}O$) isotopes and hydrochemical data in Cape Town area have used to address problems related to recharge processes and the quality of groundwater in order to better inform water managers and the public on the need to develop the aquifer. The chemical analyses of long-term observational data on groundwater chemistry of the aquifers revealed the need for continuous groundwater monitoring to better inform policy on potential impacts and future development consequences. The main features on the evolution of groundwater in the Cape Flats aquifer, as well in other nearby aquifers of Cape Town, are determined by natural hydrogeological conditions and human impacts. Apart from the shallow nature of the water table and general low relief of the Cape Flats, the rate of population increase and industrial development make the aquifer more vulnerable to pollution from hum impacts.

# CHAPTER 7: FRAMEWORK FOR GROUNDWATER PROTECTION

## 7.1 Assessment of aquifer pollution vulnerability

In the last three decades, the number and diversity of potential groundwater pollutants, particularly from the application of chemical fertilisers, pesticides, and herbicides have increased making pollution assessment become the subject of groundwater investigations in urban and agricultural areas (Foster 1987, Civita 1994, Vrba & Zaporozec 1994, Foster et al. 2002). Solution to contamination issues in the form of remediation can be very expensive and technically demanding.

Therefore, aquifer vulnerability mapping has now become a method for representing spatially and semi-quantitatively, the relative susceptibility of aquifers to contamination from surface sources. The assessment of vulnerability is based on the environmental characteristics of a landscape that facilitate or impede contamination (Bekesi & McConchie 2002), and represents the "likelihood of a contaminant to reach a specified position in the groundwater system after introduction at the surface" (National Research Council 1993, Van Stempvoort et al. 1993).

There is the need for groundwater vulnerability assessment considering the rate of population growth and land use practices in Cape Town area. The City of Cape Town has been considering options to develop alternate water supply sources and exploring the possibilities of developing the Cape Flats aquifer. Since the work of Gerber (1981) and Vandoolaeghe (1989), there seems to be no move to develop the aquifer. There has been a concern on pollution in the Cape Flats because of increased agricultural practises (particularly the application of chemical fertilisers and manure) and population growth in the informal settlement areas. Mowever, the area targeted for the abstraction wellfield is surrounded by many polluting influences such as waste disposal sites and industrial estates.

Therefore, the need to have more information and increased understanding about the aquifer's vulnerability to pollution from the surface cannot be over-emphasised. Chapter 6 of this thesis has increased the understanding on the quality of groundwater in this area and the aquifer's hydrochemical characteristics from historic and current data. A large area of informal settlements is above the aquifer, uncertainties and diversity of opinions exist as to the extent to which these could limit the utilisation of the Cape Flats aquifer. Saayman et al. (2007) have done a complete overview of several existing methods on groundwater vulnerability assessment in order to determine the approach most adaptable to the Western Cape setting. No previous studies have investigated the pollution vulnerability of this aquifer or any part of the city of Cape Town.

The intention of this study is to present two methods of vulnerability mapping to assess the Cape Flats aquifer and delineate areas of high or low vulnerabilities to pollution. This chapter, therefore, summarises the results of the preliminary vulnerability assessments on the Cape Flats aquifer using common and readily adaptable methods. Generally, the prediction of groundwater pollution is very complex when evaluating large areas, because a great deal of information is needed to represent the process, the variability of natural and anthropogenic factors (Bekesi & McConchie 2002; Piscopo 2001). The relationship between pollutant sources and the characteristics of the water infiltrating through the ground surface are important (Zuquette et al. 2008). The prediction of groundwater pollution can be made using several approaches under seven different classification methods: hydrogeological environment/setting; index methods, analogue methods; parametric system methods; mathematical methods, statistical methods and combined methods (Zuquette et al. 2008).

## 7.2 Review of some existing aquifer vulnerability assessment methods

There are several methods for predicting vulnerability of aquifers to pollution or contaminant load. Many of these methods were developed and used to solve specific problems or in anticipation of future problems relating to groundwater and the environment (Barber et al.1993, NRC 1993, Vrba & Zaporozec 1994). Two widely used point count system vulnerability methods are the DRASTIC developed by the United States EPA (Aller et al. 1987) and SINTACS (Civita 1994). A third method, which is not much in use, is the ISIS (Civita and De Regibus 1995). The three methods summarized above are too generic with the knowledge of too many input parameters required. More recent methodologies have been developed with ease of application and more specifically to represent aquifer vulnerability in karst landscapes (Goldscheider 2002, 2003). Others are Gogu et al. (2003), Daly et al. 2002; Zwahlen (2003), and Ravbar and Goldscheider (2009).

The various methods require different levels of data. Generally, the more complex and detailed methods require more complex and detailed knowledge of the system being assessed. Some of the parameters require specific organizations and procedure to obtain, which is lacking in most developing countries. Some of the methods were developed for contaminated sites or to address specific environmental issues. There is the need to develop a method that accommodates the limited data in the area.

### 7.3 The method and parameter used for vulnerability assessment in the present study

A simple point count index method using a driller's well log and field measurements, developed (following the DRASTIC and SINTACS procedures), was found readily applicable in the Cape Flats, with limited and sometimes inconsistent data. This method has been applied to map and evaluate the vulnerability of a coastal plain aquifer to surface and near surface contamination in the coast of southeastern Nigeria (Edet 2004). The input parameters with the acronym CALOD include clay layer thickness (C), aquifer media character (A), lateritic layer thickness (L), overlying layer character (O) and the depth to groundwater level (D). The CALOD approach is slightly modified to the local hydrogeological setting of the Cape Flats and data availability. Therefore, in the Cape Flats the input parameters adopted after the CALOD are clay layer thickness (C), aquifer media character (A), calcrete/calcareous layer thickness (L), the overlying layer character (O) and the depth to groundwater level (D).

Therefore the CALOD vulnerability potential index (CALOD index) is computed as the sum of the products of weights and ratings assigned to each of the input parameters depending on the likelihood for contaminants reaching the water table. The CALOD index, divided into four classes (Edet 2004), has been modified in this study into five classes like most other common methods. In order to compare the results obtained with the more common methods, it was necessary to define a standard classification, in which the assess vulnerability can range from minimum to maximum predisposition of groundwater to suffer contamination originating from the surface or shallow anthropogenic activities. Therefore, the CALOD classification (vulnerability potential index) adapted in this study are as follows: (i) Low (<20); (ii) Low-Medium (20-45); (iii) Medium-High (45-60); (iv) High (60-70) and (v) Very High (>70). The data used in this study were compiled from water development agencies and drilling companies' reports in the Western Cape alongside with the data from the Department of Water Affairs (DWAF) and CSIR database.

***Clay layer thickness (C)***

The soil in the Cape Flats area is predominantly yellow, red or brown. It is clayey and quite frequently contains small nodules of calcrete (ferricrete and silcrete in some other places) and fragments of vein quartz, in addition to a variable quantity of sand grains. This is also reflected in the lithology of the area as shown in the borehole (observation and production well) logs. In the Cape Flats, clay layers of varied thickness occur and at different levels with respect to the ground surface. Such clay layers (aquitard) act as protective cover for water-bearing media. Thus, the thicker the clay layer, the less likely the aquifer can be contaminated, as it would take the contaminant a longer time to reach the aquifer in comparison to a thin clay layer. From the borehole data considered presently in the area, the thickness of the layer ranges from less than 0 to 42 m (Table 24). An earlier study and closer examination reveals that the Witzand and Springfontein Formations do possess some degree of heterogeneity and anisotropy due to the vertical and lateral grain size gradation and the occurrence of sandy clay and clayey sand lens (Theron et al. 1992). Where Witzand and Springfontein sediments form the aquifer, it is generally unconfined to semi-confined. Wherever calcareous clay and calcrete layers of the Wolfgat Formation dominate as the superficial sediments, the Bredasdorp aquifer is semi-confined in nature. The Wolfrat sediments therefore act as an aquitard.



***Aquifer media characteristics (A)***

Generally aquifer materials should be porous and have high permeability. However, the degree of permeability varies with the type of materials an aquifer is made of. Therefore the character (composition) of aquifer is significant in assessing the rates at which contaminants travel through it. The aquifer media generally refers to the consolidated or unconsolidated rock, which serves as the water-bearing unit. These water-bearing units are characterized by intercalations of silt and clay. Bearing in mind the heterogeneity of these units, a quantification of the aquifer referred to as the aquifer media number (A), was carried out as $R_c \times R_t$ where $R_c$ and $R_t$ are the ratings for aquifer composition and thickness (Tables 24, 25, 26). This is because a thick sand unit is likely to be less contaminated compared to a thin gravel unit. Thus, the higher the aquifer media number, the higher the pollution potential at each point and vice versa as shown in the tables.

Table 24: The rating for the composition of aquifer and the overlying layers

| **Thickness (m)** | | **Rating** | **Vulnerability classes** |
|---|---|---|---|
| *Aquifer media* | *Overlying media* | | |
| <25.0 | | 5 | Very high |
| 25.0–50.0 | 10.0–20.0 | 4 | High |
| 50.0–75.0 | 20.0–30.0 | 3 | Medium |
| 75.0–100.0 | 30.0–40.0 | 2 | Low |
| >100.0 | >40.0 | 1 | Very low |

Table 25: The rating for thickness of aquifer and the overlying layers

| **Composition** | **Rating** | **Vulnerability classes** |
|---|---|---|
| Gravels; Sand, coarse-gravelly, coarse calcrete, calcareous, Shelly-gravelly | 5 | Very high |
| Sands, silty, fine, medium, coarse, calcrete | 4 | High |
| Sands, clayey, fine, silty, medium, coarse | 3 | Medium |
| Sands, clayey, fine, silty, medium, | 2 | Low |
| Sands, clayey, fine, silty / Clay, sandy | 1 | Very low |

Table 26: The rating for evaluation scale for aquifer and the overlying layers

| **Total number** | **Vulnerability classes** |
|---|---|
| >20.0 | Very high |
| 15.0–20.0 | High |
| 10.0–15.0 | Medium |
| 5.0–10.0 | Low |
| <5.0 | Very low |



***Calcareous layer thickness (L)***

One peculiarity of the Cape Flats is the occurrence of calcrete and calcareous layer, which lies above the unsaturated zone but below the soil layer where present. The composition of this layer is yellowish-reddish-brownish silty, sandy clay with low permeability. This is also reflected in the lithology of the area as shown in the borehole (observation and production well) logs and the geological cross-sections. Thus the thicker the layer, the better the contaminant attenuation capacity as the texture and permeability are uniform. The thickness of this layer varies between 0 and 25 m.

***Overlying media characteristics (O)***

The overlying media represents the unsaturated extension of the aquifer media. In the study area, the unsaturated layer is sandwiched between the aquifer media and the calcareous layer. The layer, in most cases, is composed of the same materials as the aquifer. Therefore, the character of this layer was quantified following the method used for the aquifer media. The overlying layer number (O) is thus the product of $R_o$ and $R_t$, where $R_o$ and $R_t$ are the ratings for composition and thickness respectively. Data from lithologic logs show the thickness of this layer to be in the range 0 to 22.3 m, while the aquifer thickness varied from 9 to 60 m (see Table 27). This difference in thickness forms the basis for different ranges applied for thickness rating presented in Tables 24, 25, and 26, respectively, for the aquifer media and overlying layer.

***Depth-to-water level (D)***

The depth-to-water level is defined as the distance from the ground surface to the water level. The depth-to-water level is important as it determines the depth of material through which a contaminant travels before reaching the aquifer. It is assumed that the deeper the water level, the greater the chance for attenuation to occur, as deep water levels infer longer contaminant travel time. The recorded depth-to-water level in the study area ranged from less than 1 to 37 m (Table 27). The locations of the boreholes are shown in figure 72.

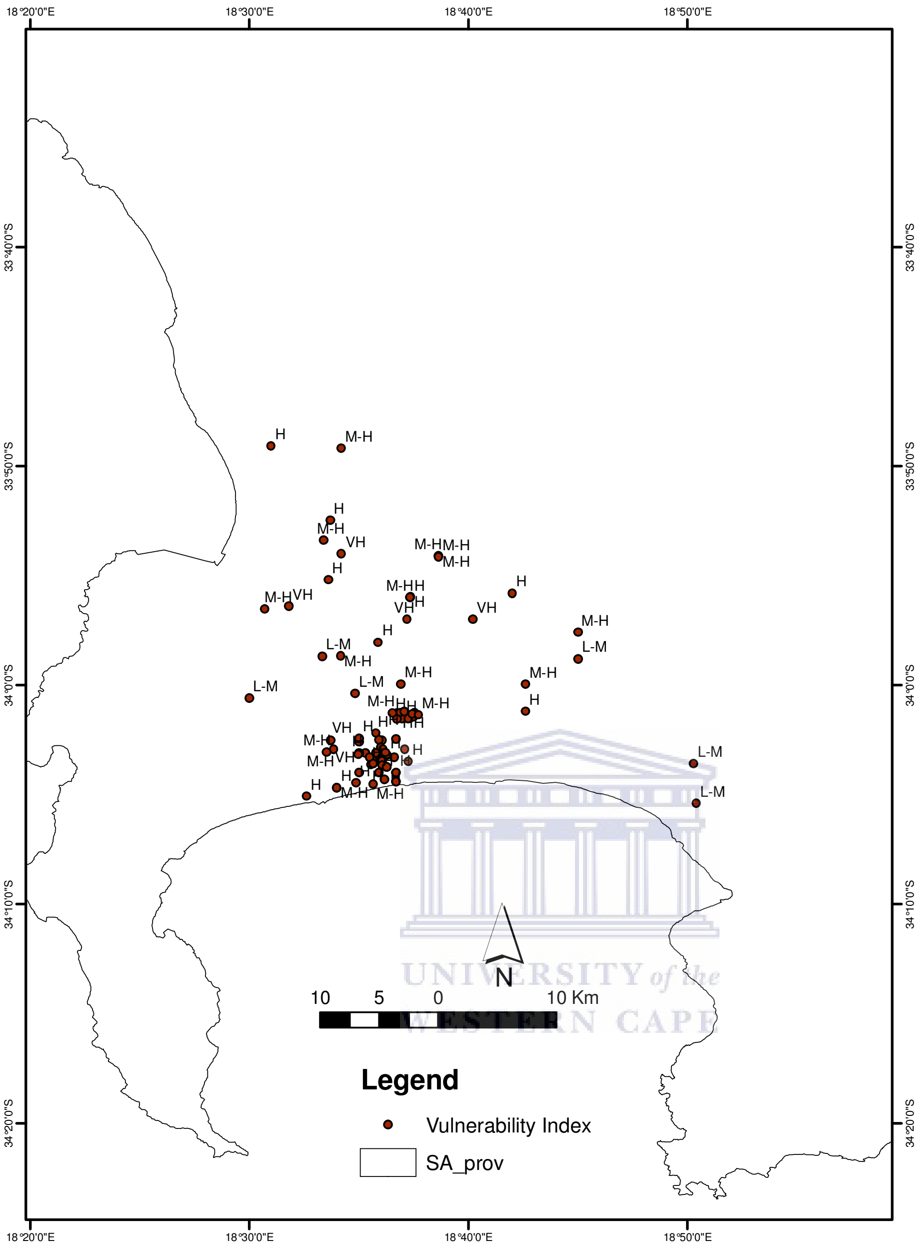




Figure 72: Location of boreholes used for the CALOD index in the study area with the vulnerability index indicated (Note that letter symbols indicate degree of vulnerability: L-M = Low-Medium, M-H = Medium-High, H = High, VH = Very High)

Table 27: Order of relative importance of the CALOD parameters

| **Parameter** | **Code** | **Unit** | **Weight** |
|---|---|---|---|
| Clayey layer thickness | C | m | 1 |
| Overlying layer character | O | no | 2 |
| Calcrete and calcareous layer thickness | L | m | 3 |
| Aquifer character | A | no | 4 |
| Depth-to-water level | D | m | 5 |

Table 28: Weight and rating for CALOD parameters

| Parameter | Code | Unit | Weight | Rating 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| | | | | Very low | Low | Medium | High | Very high |
| Clay layer thickness | C | m | 1 | >8.0 | 4.0–8.0 | 2.0–4.0 | 1.0–2.0 | <1.0 |
| Aquifer character | A | no | 4 | <3.0 | 3.0–6.0 | 6.0–9.0 | 9.0–12.0 | >12.0 |
| Calcrete and calcareous layer thickness | L | m | 3 | >10.0 | 7.5–10.0 | 5.0–7.5 | 2.5–5.0 | <2.5 |
| Overlying layer character | O | no | 2 | <5.0 | 5.0–10.0 | 10.0–15.0 | 15.0–20.0 | >20.0 |
| Depth-to-water level | D | m | 5 | >40.0 | 20.0–40.0 | 10.0–20.0 | 5.0–10.0 | <5.0 |

## 7.4 The CALOD index ($I_{CALOD}$)

The CALOD vulnerability potential index for each cell was computed as:

$$L_{CALOD} = C_W C_R + A_W A_R + L_W L_R + O_W O_R + D_W D_R \qquad 7.1.5$$

where w=weight and r=rating for the different CALOD parameters.

The computed CALOD index values are divided into five classes in this study (as opposed to four classes in Edet 2004) to accommodate “very high” vulnerability index. The classes are: low (<20), low-medium (20–45), medium-high (45–60), high (60-70), very high (>70) (Table 29), to assess the vulnerability of the aquifer as summarized in Table 29 full details presented in Appendix 7.1.



Table 29: Modified CALOD vulnerability potential class

| Class | CALOD Index | Vulnerability level | Symbol |
|---|---|---|---|
| 1 | <20.0 | Low | L |
| 2 | 20.0–45.0 | Low-medium | LM |
| 3 | 45.0–60.0 | Medium-high | MH |
| 4 | 60.0-70.0 | High | H |
| 5 | >70 | Very high | VH |

Note: Vulnerability potential refers to the degree or potential for contamination (pollution potential Edet 2004, Gogy et al. 2003)

### 7.5 CALOD vulnerability potential map

The computed CALOD index values ($I_{CALOD}$) for each borehole data point was used to produce a vulnerability potential map shown in Figure 73. The resulting map indicates that the highest potential area for contamination. The resulting map indicates that the study area generally have medium-high pollution potential. The highest potential area for contamination is along a stretch from the central part of the model area to the northwest with $I_{CALOD}$ values ranging from 60-76. In the exception of a small strip of high vulnerability potential index in the southwestern corner, the northern and southern ends of the study area are essentially medium-high (46-60), and low-medium values (42-44) existing only in the southeastern corner. There are no parts of the present study area with $I_{CALOD}$ potential less than 40 (i.e. the low class of vulnerability potential index are not represented) indicating a generally moderate to high vulnerability potential for this area. A very small area (<10%) is classified under the very high pollution potential index (figure 74).

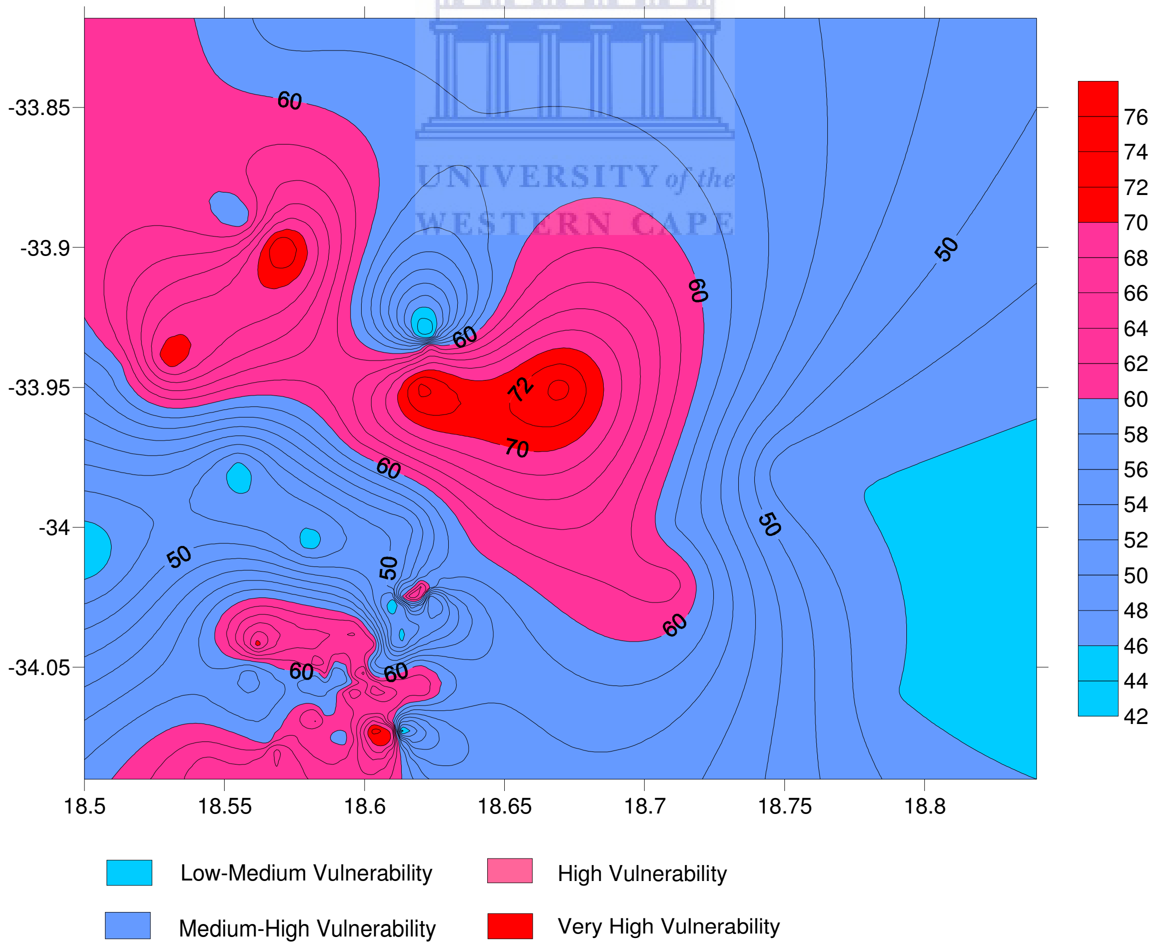




Figure 73 (a): Vulnerability potential index map for the parts of Cape Flats (based on the CALOD index value of boreholes in figure 72, modified from Adelana & Xu 2005)

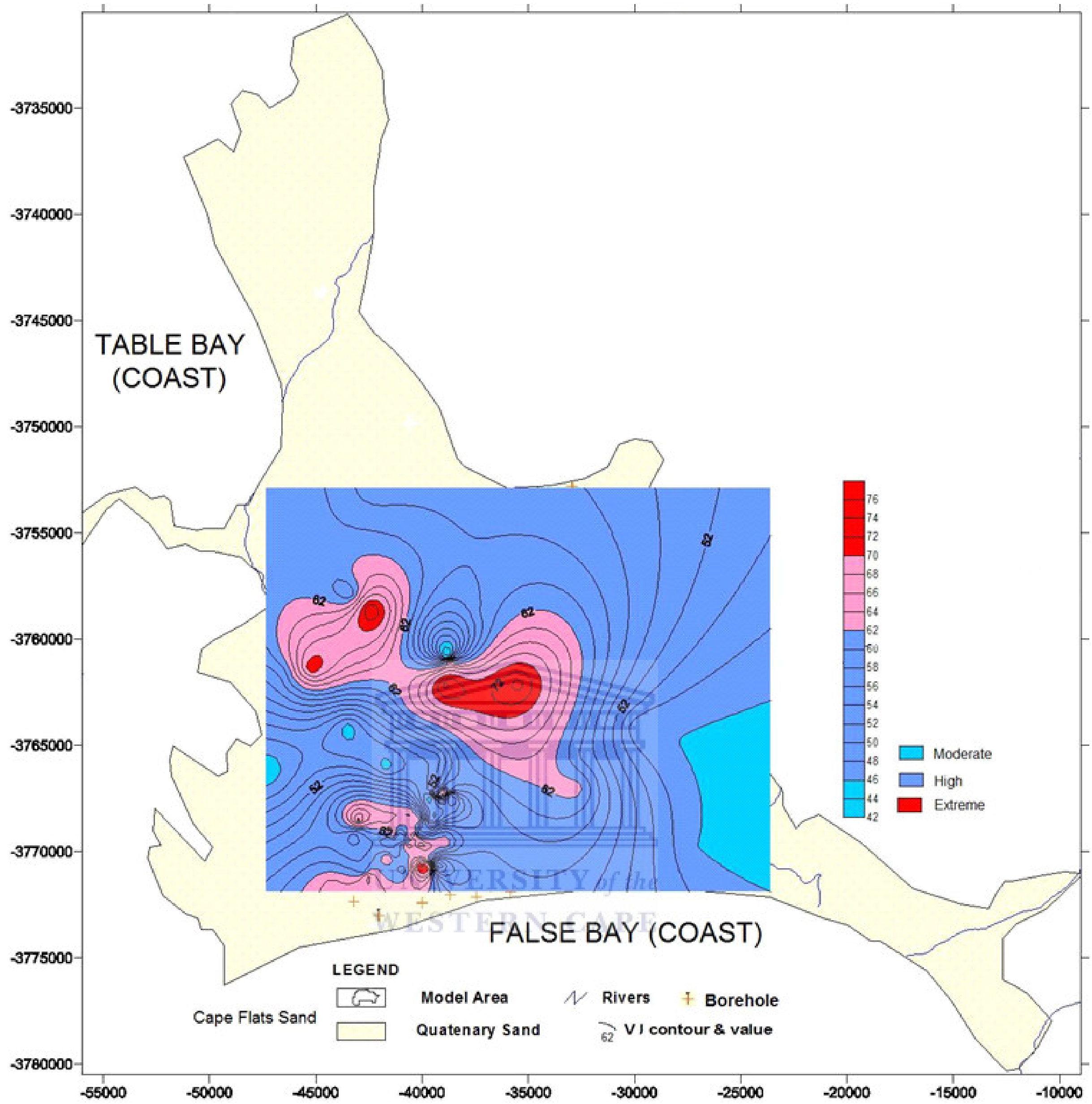



Figure 73(b): CALOD vulnerability index contour superimposed on the Cape Flats sand illustrating area of data availability and the coast at the extreme south.

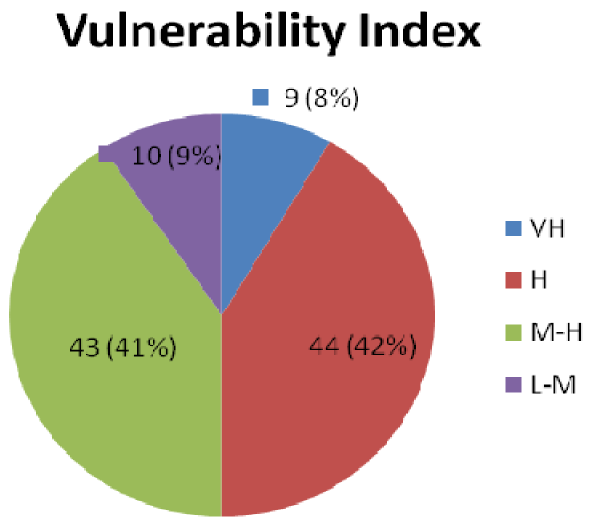



Figure 74: Distribution of vulnerability index for the study area (Note: Letter abbreviations are as explained in Table 29: L-M, low-medium; M-H, medium-high; H, high and VH, very high; the numbers in the pie chart indicates number and percentages of total investigated sites with Vulnerability level indicated in Table 29)



### 7.6 CALOD and GOD methods

The adaptation and application of the CALOD method to the Cape Flats was based on similar geological setting (Coastal Plain Sands) and the limited data for the more common methods (DRASTIC and SINTACS). The required amount of data for the DRASTIC and SINTACS methods are reduced and the assessment scheme simplified into the readily available parameters. The result of this vulnerability assessment is compared with GOD method; one of the most frequently used methods of aquifer pollution vulnerability assessment (Foster 1987). The GOD method uses fewer parameters than the DRASTIC and SINTACS, although two of these parameters (G and D) also depend on the lithology. In this Chapter, both of the CALOD and the GOD methods were applied to the Cape Flats aquifer and the results compared and analyzed.

#### *7.6.1 The GOD method of aquifer pollution vulnerability assessment*

The GOD method of aquifer pollution vulnerability assessment has been used extensively in Latin America and the Caribbean as well as in Europe (Foster et al. 2002, Vias et al. 2005, Debernardi et al. 2008, Polemio et al. 2009) because of its simplicity of concept and application. Two basic factors are considered to determine aquifer pollution vulnerability with the GOD method:

(1) The level of hydraulic inaccessibility of the saturated zone of the aquifer;

(2) The contaminant attenuation capacity of the strata overlying the saturated aquifers.

These are, however, not directly measurable and depends in turn on combination of other parameters (Foster et al. 2002). Foster (1987) and Foster & Hirata (1988) characterizes aquifer pollution vulnerability on the basis of the following (generally available or readily determined) variables using the acronym "G-O-D" vulnerability index:

Groundwater occurrence /groundwater hydraulic confinement; in the aquifer under considerations (G),

Overall lithology of the aquifer/overlying strata (vadose zone); in terms of lithological character (O),

Depth to groundwater table (D).

The range of values for each rating of the GOD parameters is short, varying from 0 (minimum vulnerability) to 1 (maximum vulnerability). The final vulnerability index is obtained as follows:

$$VI = G\ O\ D \qquad 7.1.6$$

The value of the index VI was computed and five vulnerability classes are differentiated by the method (Table 30). The results of the method applied to the study area using the same set of borehole information is presented in figure 75.

Table 30: Vulnerability parameters and rating values for GOD method (incorporating soil material; Foster 1987, Puez 1999)

| **Component of vulnerability** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| G (groundwater occurrence/degree of confinement) | Range | None | overflowing | confined | Semi-confined | | Unconfined (covered) | unconfined |
| | Rating | | 0 | 0.2 | 0.4 | | 0.6 | 1 |
| O (overall lithology of aquifer) | Range | Lacustrine /estuarine clays | Residual soils | Alluvial silts, loess | Aeolian sands | Alluvial sands | Alluvial fan gravels | Unconsolidated sediment |
| | | Non-shrinking clay | Silty clay | silt | Silty sand | Shrinking clay | Coarse sand & gravel | Thin/absent |
| | Rating | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| D (depth to groundwater) | Range | 0-2 | 2-5 | 5-10 | 10-20 | 20-50 | 50-100 | >100 |
| | Rating | 1 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 |

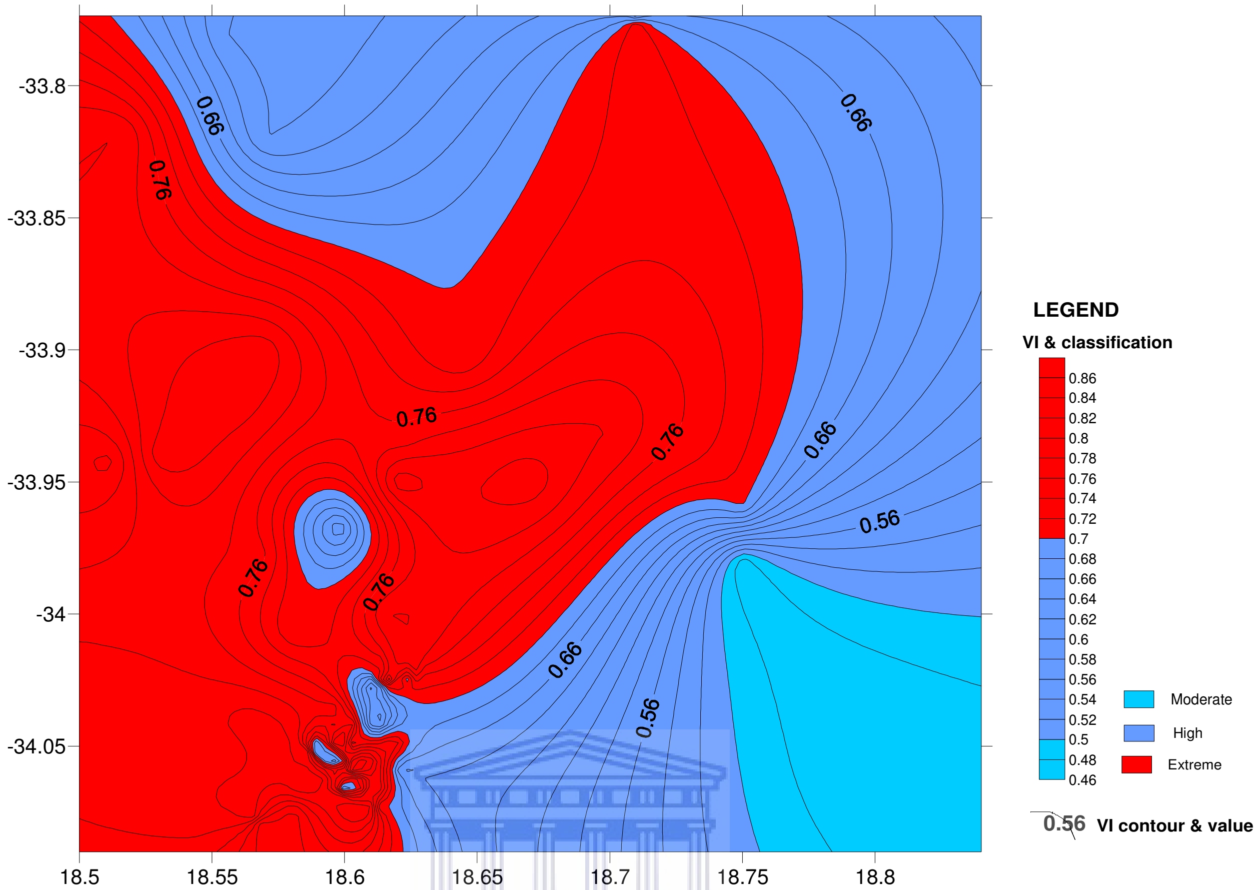



Figure 75 (a): Groundwater vulnerability map of study area using the GOD (based on the GOD pollution index values of boreholes in figure 72)

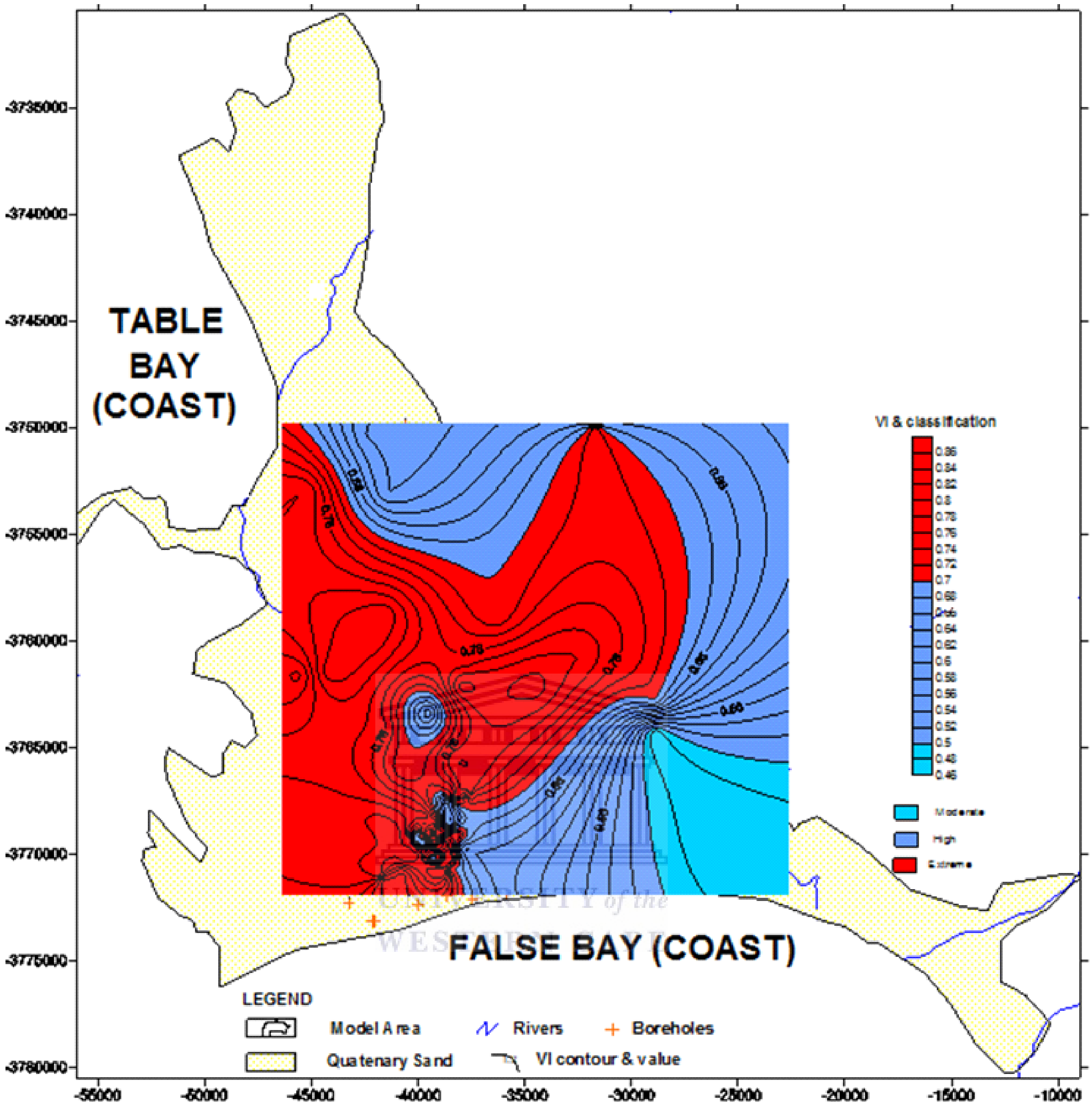



Figure 75(b): GOD vulnerability index contour superimposed on the Cape Flats sand area. The coastline is the southern boundary.

*7.6.2 Comparison of the two methods*

Figure 76 shows the aquifer pollution vulnerability results derived both from CALOD and GOD methods on a comparative plot. It demonstrates that generally the vulnerability variation of the sample sites from the two methods is similar and applicable to the study area: the aquifer pollution vulnerability is comparatively high in the GOD classification for nearly all of the central part of the model area while the area of high pollution potential is narrowed down in the CALOD classification (as shown in Figure 73). While some inconsistency occurs, for BA10 and DC232, the vulnerability is relatively low from CALOD method but high from the GOD method. Moreover from GOD method, boreholes (BA 14-32) and (BA80-88) have the same index values (as depicted in the straight line\constant in figure 76), which indicate the same pollution vulnerability potential. But from CALOD method, their relative membership degree values are different which shows that their vulnerability differs from each other.

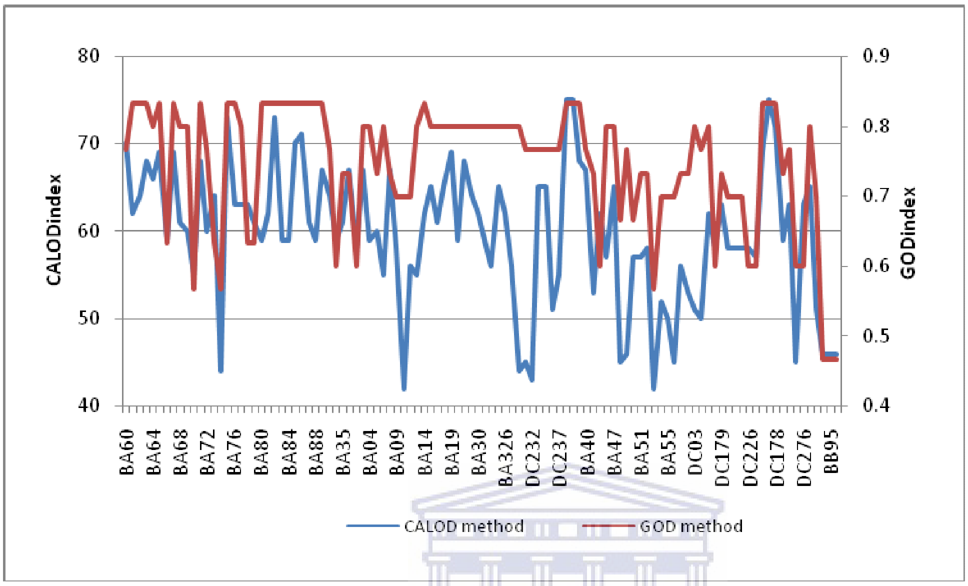



Figure 76: Comparison of aquifer pollution vulnerability results of CALOD and GOD methods



The variations in vulnerability between the sites are due differences in the depth of the water table and corresponding variations in lithology. The GOD method seemed to over-estimate the vulnerability and to provide a high sensitivity to spatial variation of key hydrogeological parameters. This is contrary to the “low” and “moderate” degree of vulnerability observed in karst and carbonate rocks respectively using the GOD method (Polemio et al. 2009, Vias et al. 2005, Coniello et al. 1997, Civita and De Regibus 1995). This further indicate that the GOD method may be more applicable in Quaternary sands, alluvial and Lacustrine deposits as demonstrated in the several studies in Latin America and the Caribbean (Foster et al. 2002, Puez 1999, Hirata et al. 1997, 1991, Chilton et al. 1990). The analysis of the obtained maps (see figures 73 and 74) shows that the areas of high vulnerability to pollution (index value from 61-76 on the CALOD and 0.70-0.86 on the GOD) predominate in the central part of the model area. These cover about 35% of the area underlain by the Cape Flats aquifer. The areas, where vulnerability is higher than average (i.e. high, very high and extreme under the two classifications), together covers almost half of the aquifer as shown by the area with available

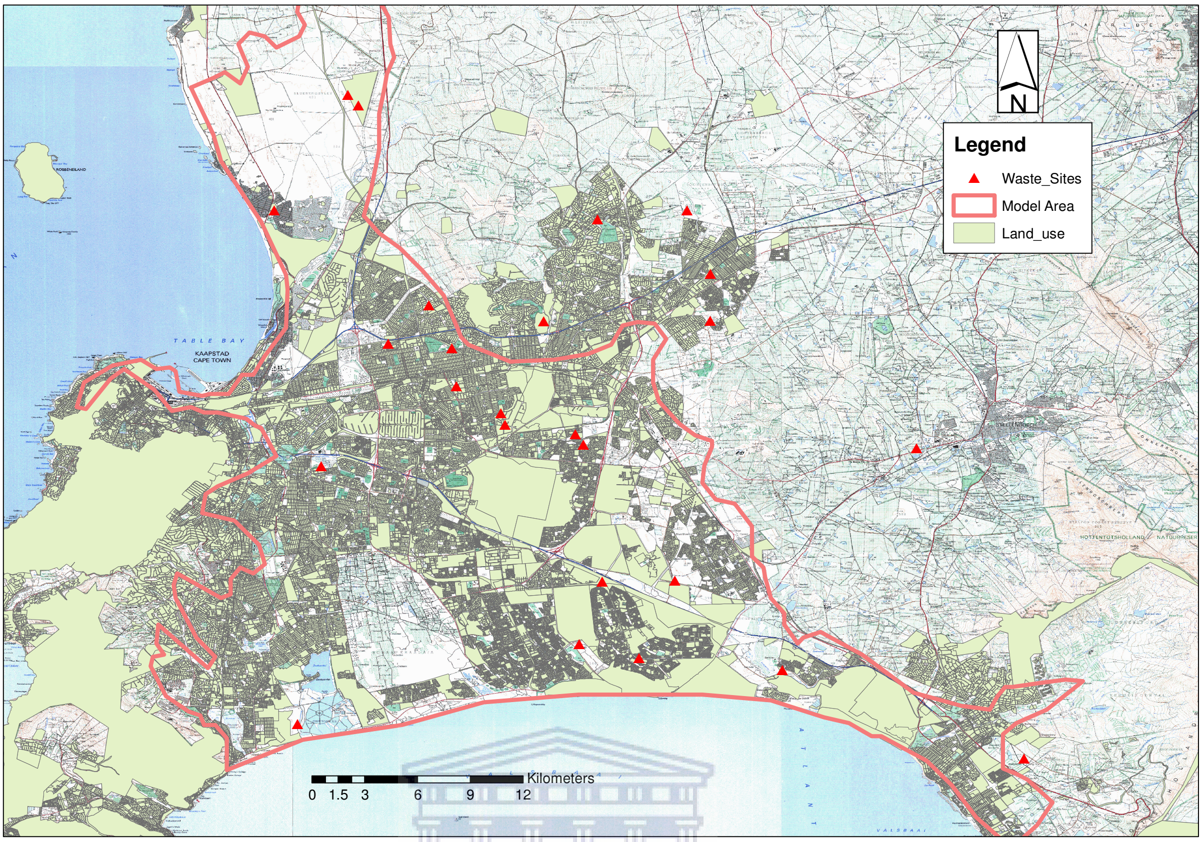



Figure 77: Model area superimposed on land use pattern (Source of background landuse map: CCT 2006)

## 7.7 Validation and sensitivity analysis

The conceptual basis and proposed method have shown that vulnerability maps can serve as the initial step for protection zoning and land use restrictions. On this basis, a vulnerability map should be reliable to a reasonable degree, and that can only be checked by validating it. There seems to be no commonly accepted method of validation but various techniques have been used in the past (Ravbar & Goldscheider 2009, Neukum et al. 2008, Andreo et al. 2006, Perrin et al. 2004, Gogu et al. 2003, Daly et al. 2002). The approaches used by these authors range from hydrographs, chemographs, bacteriological analyses, water balances, numerical simulations and tracer techniques, all of which have certain limitations.

A sensitivity analysis, as carried out in this study, helped to validate and evaluate the consistency of the analytical results and forms the basis for proper evaluation of vulnerability maps. Using sensitivity analysis, a more reliable interpretation of the vulnerability index has been achieved in vulnerability mapping (e.g. Pathak et al. 2009). Sensitivity analysis has been carried out in this study in order to evaluate the sensitivity of each CALOD parameter to the overall vulnerability index which was used to generate the map such that subjectivity can be reduced to certain extent as demonstrated in the work of Pathak et al. (2009). Pathak et al. (2009) computed the relevant variation index in order to assess the magnitude of the variation created by the removal of one parameter. Each parameter contributes with an effective weight to the vulnerability index. Several of such analyses have been applied in the assessment of aquifer vulnerability in different overlay techniques. For example, Lodwik et al. (1990) stated the map removal sensitivity measure that represents the sensitivity associated with removing one or more parameters or map overlay as follows:

$$S_i = \{V_i/N - V_{xi}/n\} \qquad (7.1.7)$$

This expression is used in the present study to approach sensitivity of the CALOD parameters, where,

$S_i$ is sensitivity (for $i$th unique condition site associated with the removal of one parameter $X$,

$V_i$ is vulnerability index computed on its $i$th site,

$V_{xi}$ is vulnerability index of the $i$th site excluding one CALOD parameter,

$N$ is the number of parameters used to compute vulnerability index in equation (7.1.5),

$n$ number of parameters used for the sensitivity analysis.

The results of the sensitivity analysis are summarized in Table 31 showing the behaviour of aquifer vulnerability to different values of the vulnerability parameters and input data.

The sensitivity analysis was carried out by computing the relevant variation index in order to assess the magnitude of the variation created by the removal of one parameter. This was used to compute the variation created by the removal of one DRASTIC parameter (Pathak et al. 2009), following the map-removal sensitivity measure described in Lodwik et al. (1990). This variation index measures the effect of the removal of each parameter and its value can be positive or negative, depending on the vulnerability index. The following expression is used in the present study for computation of variation index of the removal of one CALOD parameter:

$$Var_i = \{(V_i - V_{xi})/ V_i \}*100 \qquad (7.1.7)$$

where $Var_i$ is the variation index of the removal parameter

$V_i - V_{xi}$ are vulnerability index computed using CALOD relationship in 7.15 on the *i*th site or sub-area and vulnerability index of the *i*th area excluding one map layer or parameter respectively. Variation index directly depends upon the weighting system. Each parameter contributes with an effective weight to the vulnerability index. This effective weight can be computed for each borehole site as follows:



$$W_{xi} = (X_{ix}.X_{vi})/V_i * 100 \qquad (7.1.8)$$

Where $X_{ix}$ and $X_{vi}$ are the rating values and the weights for the parameter $X$ assigned on site respectively and $V_i$ is the vulnerability index calculated in equation 7.1.5 in the site area. The computed effective weighting factor and statistical analysis of effective weight are presented in Table 32.

Table 31: Statistical analysis on the sensitivity to removing one parameter

| Parameter | Minimum value | Maximum value | Mean | Standard deviation |
|---|---|---|---|---|
| **C** | -3.10 | -0.90 | -1.95 | 0.43 |
| **A** | -0.65 | 2.45 | 1.36 | 0.67 |
| **L** | -2.40 | 1.10 | -0.33 | 0.98 |
| **O** | -2.85 | 0.40 | -0.78 | 0.74 |
| **D** | -0.40 | 4.05 | 1.71 | 1.14 |

Table 32: Assigned weighting factor and statistics on effective weighting system

| Parameter | Assigned weight | Assigned weight (%) | Variation index ($\approx W_{xi}$) | Calculated effective weight ($X_{vi}$) | Calculated effective weight (%) |
|---|---|---|---|---|---|
| **C** | 1 | 6.67 | 0.57 | 1.04 | 6.96 |
| **A** | 4 | 26.67 | 0.39 | 4.38 | 29.21 |
| **L** | 3 | 20.00 | 0.28 | 2.62 | 17.47 |
| **O** | 2 | 13.33 | 0.23 | 2.26 | 15.11 |
| **D** | 5 | 33.33 | 0.12 | 4.69 | 31.32 |



## 7.8 Discussion and Conclusion

DRASTIC-type parametric system (CALOD) and the GOD methods, used in this research for the natural (intrinsic) vulnerability assessment based mainly on hydrogeological and geological evaluation, give reliable and clear information on a relative degree of groundwater protection. The vulnerability index of the Cape Flats indicates that this rich groundwater resource area is highly susceptible and has inherent capacity to become contaminated. If contamination and polluting influences are common, contaminants could reach the groundwater in this area within a very short time.

The resulting range of aquifer pollution potential index values (42 to 76) was used to produce the vulnerability maps in figure 74. This was compared with the GOD method (a more commonly used method) and the vulnerability index varies produced the map in figure 75. Low indexes represent aquifer that is better protected from contaminant leaching by the natural environment. On the other hand, a high pollution potential index indicates the capacity of the hydrogeologic environment to readily transport contaminants into the groundwater. The methods adopted to produce the vulnerability index for the Cape Flats was limited by the availability of data. The CALOD and GOD methods use less parameters and readily available geologic and hydrogeologic data. This methodology can be easily and effectively applied to similar and already modeled aquifer. Good knowledge of the geology and hydrogeology of given area is a condition to produce a reliable vulnerability map. It is also necessary to verify the vulnerability assessment. This verification is often based on data concerning groundwater quality and isotopic investigations.

In this study, a sensitivity analysis was carried out to validate and evaluate the consistency of the analytical results and forms the basis for proper evaluation of vulnerability maps. Using the results of the sensitivity analysis, a more reliable interpretation of the vulnerability index has been achieved. Table 31 shows the statistical analysis of the results indicating the most sensitive to contamination is parameter D (groundwater depth). This is followed, in the order of sensitivity, by parameters A, L, O and C. The highest value is associated with the depth to groundwater table (4.05) while clay layer shows the lowest sensitive value (-0.9).

The results of the variation index computed for each CALOD parameter, using eq. 7.1.7, indicate parameter D has the highest variation index (0.57) followed by parameter A with variation index (0.39), L (0.28), O (0.23) and C (0.12), respectively. This variation index measures the effect of the removal of each parameter. Variation index directly depends on the weighting system (Pathak et al. 2009). The effective weight factor calculated for each parameter shown in Table 32 further confirms that parameter D dominates the vulnerability index with average weight of 31.3% as against the theoretical assigned weight of 33.3%. The presence of shallow groundwater table in the most part of the study area increases the weight on parameter D. The real weight and the theoretical assigned weight for the parameter (C), the least on the weighting score, show a close agreement of values and percentages. The calculated weights of parameters A (29.2%) and O (15.1%) are respectively higher than the theoretical weights (i.e. 26.7% and 13.3%).

The depth-to-water level is important as it determines the depth of material through which a contaminant travels before reaching the aquifer. It is assumed that the deeper the water level, the greater the chance for attenuation to occur, as deep water levels infer longer contaminant travel time. Hence, as the depth-to-water level decrease, the risk of contamination increases. Also, the CALOD index value is computed with aquifer media character which means that areas with high permeability materials and small thickness are more likely to be contaminated compared to areas with low permeability but of same thickness. However, the thicker the layer, the lower the risk of contamination of the aquifer from pollution influences from the surface. Naturally vulnerable areas are more sensitive zones where the soils, subsoil and bedrock do not provide adequate protection and the potential exists for rapid transfer of pollutants to groundwater. Areas of concerns are, for example, recharge zones of shallow aquifers (Gogu & Dassargues 2000).

The fact that many of the calculated weights are not equal to the theoretical weights assigned in CALOD method is a confirmation that weight factors are strongly related to the value of single parameter in the context of value chosen for the other parameters. Similar conclusion was drawn from the sensitivity analysis to evaluate the influence of single parameters on aquifer vulnerability assessment using the DRASTIC method (Pathak et al. 2009). Calculating effective weights therefore is useful in order that CALOD method may become more scientifically and practically applicable to addressing local hydrogeological conditions. On the contrary, the usage of sophisticated and data-intensive methods may be more legitimate only where more data, time, finance and technical resources are readily available.

The discussed groundwater vulnerability map can be a useful preliminary tool for the planning of groundwater development in the Cape Flats. Based on this vulnerability map it is possible to point out priority areas taking into account location of different forms of a land use. Comparing the vulnerability map and land use map it is possible to identify the areas where there is significant risk of groundwater contamination and higher impact of human activities. The presented method of vulnerability mapping can be tested to cover the entire area underlain by the Cape Flats aquifer (when more data become available) as well as on the other aquifers (Malmesbury and the TMG) to give a balance picture of groundwater in the area around the City of Cape Town.

## CHAPTER 8: SUMMARY AND CONCLUSIONS

### 8.1 Summary of results and discussions

The limited availability of water resources and an ever increasing demand for water are major issues facing Water Services in the City of Cape Town. This problem demands a carefully planned and executed solution; thus making the work on water supply even more complex and challenging. This is the main reason that led to the general strategy on augmentation plans for using surface water (by construction of more dams and reservoirs on the local streams) with groundwater options. The problem of water supply in the City of Cape Town has been on since 2001 due to decreasing dam levels as a consequence of the 3 years of below average rainfall between 1998 and 2000. This study was initiated to improve knowledge of the hydrogeological situation in the Cape Flats in order to proffer solutions and make relevant suggestions based on the utilisation of groundwater, particularly from the Cape Flats aquifer.

The inventory of water resources in the Western Cape has been reviewed with particular reference to groundwater situation in Cape Town area. The groundwater situation reveals there are three significant aquifers within the Cape Town Municipality: the Newlands aquifer, the Atlantis aquifer and the Cape Flats aquifer. The most prominent and the less developed of these, the Cape Flats aquifer has been identified as a potential source to be fully utilized to augment the City's water supply. The envisaged initial quantity for extraction was estimated at $18 \times 10^6$ $m^3$/year.



Groundwater resource investigation has systematically analysed hydrogeological characteristics through pumping tests of the Cape Flats aquifer in order to identify parameters like transmissivity, specific yield and storage coefficient; and to develop relationship between abstraction well reaction and the aquifer. Information available indicated a conceptual model with an unconfined sand aquifer, grading into semi-confined conditions in some places where lenses of clay and peat exist, and underlain by the impervious shaly bedrock aquifer (Malmesbury Formation). These findings and the recharge estimates from this study will enable a more reliable numerical modeling recommended for further studies.

A number of techniques commonly used for recharge estimation in arid and semi-arid areas have been applied and evaluated to the Cape Flats semi-arid conditions. These conditions are characterized by a flat sandy subsurface, with intense urbanization which restricted vegetative cover to Nature Reserves, and average rainfall of 600 mm/a. The commonly applied methods of recharge estimation in Southern Africa have been reviewed in order to get techniques applicable to this study area. Generally usable methods for unconfined aquifers were discussed and the detailed procedures for each of the techniques have been discussed along with the results of this study in chapter 5. The estimation of recharge from simple relationships between precipitation and recharge provided estimates similar to those of water level methods as shown in Table 13 but values are believed to be exaggerated. Estimated recharge values from the water balance method are low, because only the vertical movement of water in the represented soil types is considered by the model; horizontal movement is neglected. The direct rainfall-relationships show exaggerated values of annual recharge rates but are found to be readily usable. Chloride mass balance (CMB) method gave recharge rates of 5-8 percent of estimates of mean annual precipitation, MAP, at Cape Town.

A chemical and physical characterization of groundwater in the study area has been carried out and described in chapter 6. This characterization has been based on the based on historic data and sampling during the current study (2005-2007). In particular, concentrations of Na and Cl have ranges of 3.3-2,285 and 7.0-5,121 ppm, respectively. Concentrations of Ca, Mg and $SO_4$ also showed large variations with ranges of 1.7-366, 1-321 and 0.0-846 ppm, respectively. $HCO_3$ has a range of 0.1-753 while $NO_3$ showed the least variation (0-248). These wide distributions indicate the possibility that chemical composition may be affected by multiple processes, including seawater mixing. There is a relative predominance of Na and Cl indicating influences of saline water due to the proximity to the sea. About 21% of the samples exceeded the WHO drinking water standard for Cl. Many of the groundwater samples analyzed also show high $HCO_3$ and Ca reflecting contributions by water-rock interaction.

Na and Cl concentrations have strong mutual correlation. Despite the strong correlation between the concentrations of these ions there is some variation in their ratios as well as in relation to other cations and molar ratios. Molar Na/Cl ratios ranged from as high as 1.95 to 0.17, with many between 0.6 and 1.2. The high Na/Cl ratios of the 'freshest' groundwater are probably controlled by water–rock interaction. Exchange of Ca and Mg for Na may occur but is unlikely to be a dominant process at the low salinities (TDS <800 ppm) in most of the Cape Flats groundwater. Although different chemical water types were observed, Na-Cl and Ca-$HCO_3$ were dominant. As the Cape Flats groundwater travels away from unconfined recharge areas towards semi-confined coastal discharge zones it may have evolved through Ca-$HCO_3$-

Cl type via Ca-Na-Cl-$HCO_3$ type to Na-Cl type; or from Ca-Na-$HCO_3$-Cl type directly to Na-Cl type or through Na-Ca-Cl-$HCO_3$ to Na-Cl. These patterns give good indication that the various groundwater chemistries are changed by cation exchange reaction, as well as simple mixing in certain proportions.

High Cl and $NO_3$ concentrations of nitrate in some parts of the aquifer are the major groundwater quality problems. In the urban-agricultural areas, the $NO_3$-N concentrations are increasing, in some cases rapidly; similar pattern is shown by the concentrations $SO_4$ and Cl, indicating increasing pollution trend. The main sources of $NO_3$ in these areas are fertilizers and domestic sewage effluents. The quantities of sewage that percolate to the water table on an annual basis through effluent discharge and septic tanks may be significant, and should be estimated in further studies.

The stable ($^2$H, $^{18}$O) isotopesof water molecules have been widely used to address problems related to the recharge and the residence time of groundwater. Groundwater from the Cape Flats aquifer was characterized by relatively lower $\delta^{18}$O and δD values. The $^{18}$O and $^2$H data vary between –4.4 and –1.4‰, and –22.5 and –7.2‰ VSMOW, respectively. The corresponding average values are –3.1‰ and –14.9‰. The mean isotopic concentration of the rainwater from which the groundwater was derived suggests that the mean $^{18}$O of rainfall events resulting in recharge is about –3.35‰ VSMOW.

Generally, groundwater under the entire Cape Flats is considered vulnerable. The vulnerability assessment carried out covering the greater part of the Cape Flats (where data is available) has shown that some areas may be more vulnerable than the others. The Cape Flats aquifer underlying most of the southern and central suburbs, towards Cape Town CBD has been classified as medium to high on the vulnerability index. The isolated portions on the map area indicated from high to very high on the vulnerability scale may require adequate protection measures. A sensitivity analysis carried out to validate the consistency of the analytical results forms the basis for evaluation of the vulnerability map. Using the results of the sensitivity analysis, vulnerability assessment (map) can be extended to cover the entire area of the Cape Flats sand extending towards its border with other aquifers. This would be necessary in order to allow complete groundwater protection strategies.

## 8.2 Implications for groundwater management and outlook

Obviously, the Cape Flats aquifer is highly vulnerable to pollution because of its lithological units; vulnerable to drought because of the decreasing (fluctuating) rainfall pattern and consequently recharge. The legal emphasis, therefore, is on protection for use and not necessarily protection at the cost of use. The South African National Water Act requires that water quality demand by end users be maintained, not necessarily the pristine quality of the aquifer. One of the prerequisites for the rational groundwater management and exploitation is defining quantity and quality of water resources, by analyzing the water budget and performing water quality analyses. Therefore, certain activities, which are most probable to cause pollution to aquifer, will need to be regulated in vulnerable areas of the Cape Flats. Setting the stage for participatory groundwater protection in the Cape Flats would be essential to water resource management in the region.

Implication from the analysis of results from this study is that abstraction of groundwater from the Cape Flats aquifer may not have any large impact on river flow. The evidence provided in this research that the Cape Flats aquifer does not contribute largely to river flow raises the question of other groundwater sinks, which could not be fully answered. Groundwater modeling proved that sub-surface flow leaving the basin within the aquifer is only moderate. A rough estimate of run-off within the aquifer suggests that it is even an order of magnitude smaller. While it is evident from previous work (e.g. Gerber 1976, 1981, Vandoolaeghe 1989) that hydraulic properties are highly variable in space, the location and characteristics of fracture zone of high conductivity within the Malmesbury are not known, so that they cannot be adequately included into a groundwater model at present. Additional field investigations to improve the knowledge of hydraulic properties are therefore necessary to further develop the groundwater model. Desirable further investigations can be summarized:

- The identification of the aquifer geometry (variability of the weathered zone, location of fracture zones within the underlying bedrock aquifer);
- long-term pumping test along the coast (regolith and alluvial aquifer) to properly define the fresh-salt water wedge;
- improvement on the assessment of surface and ground water run-off;
- Continuation and extension of groundwater hydrograph recording at high temporal resolution.

Annual groundwater use in the Cape Town area is currently less than 5% of the calculated groundwater recharge. Neither groundwater recharge nor a potential reduction of river flow by groundwater abstraction is therefore limiting a further development of groundwater resources on a regional scale. Since water shortage exists and water restricitions still enforced while the population is growing, the development and full utilization of this aquifer is desirable. Currently groundwater is used for irrigation farming and mostly wetting of lawns and household gardens. The actual extent of these use have not been quantified; this is highly desirable for future groundwater management.

Finally, the role of groundwater resources for water supply in the city of Cape Town cannot be over-emphasized as the need will grow considerably over the next decades. This research underlines that the development of the Cape Flats aquifer is sustainable from a geo-scientific point of view. The recharge estimates, conditions of recharge and aquifer storage capacity would support the development of the aquifer.  Due to its cost and time efficiency and the relevance of water resources planning, the chloride mass balance seems especially useful; it is recommended that detailed chloride profiling of the unsaturated and saturated zone be carried out. This will provide accurate recharge estimates for effective groundwater management, should the development of the aquifer proceed. Water balance and groundwater models can serve as a useful tool to simulate the impact of climate change on groundwater resources in the study area. However, they urgently need to be completed by continuous monitoring, and at least monthly, recording of groundwater hydrographs which are required for validation.



### 8.3 Conclusions

Previous studies on the use of groundwater from the Cape Flats have been developed on an *ad hoc* basis and few data were available. This research study considered a completeapproach to the evaluation of the Cape Flats aquifer from a description of the geology to simple conceptual hydrogeological model, with many aquifer properties such as transmissivity and storage coefficient having to be estimated from recent pumping tests and historic pumping test data.  The results have improved understanding of the Cape Flats aquifer, and have confirmed that the need for integrated management of both surface and groundwater may be urgent, considering the vulnerability of the aquifer to surface pollution and human impacts. There is a need for more complete information/data to carry out reliable flow modeling or improve the initial knowledge on models in the area.

In summary, the study has produced increased understanding on the hydraulic behaviour, recharge and hydrochemical characteristics of the Cape Flats aquifer. The overall appraisal of the groundwater system confirms the importance of conjunctive use of surface and groundwater in water management in order to solve the existing water supply problem.

# 9. REFERENCES


Acworth RI, Jankowski J (1993) Hydrogeochemical zonation of groundwater in the Botany Sands Aquifer, Sydney. Australia Geol Geophys 14:193–199.

Adams B, Foster S (1992) Land-surface zoning for groundwater protection. Journal IWEM, No.6, June.

Adams B, Baker JA, MacDonald DMJ (1992) Consideration in the implementation of groundwater protection policy, Proc. International workshop on groundwater and the environment, Beijing, August.

Adelana SMA, Olasehinde PI (2003) High nitrate in water supply in Nigeria: implications for human health. Water Resources 14(1):1-11.

Adelana SMA, Xu Y (2005) Vulnerability assessment in the Cape Flats Aquifer, South Africa. Proc. AVR05, 21-23 September, Parma, Italy.

Adelana SMA, Xu Y (2006) Contamination and protection of the Cape Flats Aquifer, South Africa. In: Xu Y & Usher B (eds) Groundwater pollution in Africa, London: Taylor & Francis, 265-277.

Adelana SMA, Xu Y, Adams S (2006a) Identifying sources and mechanism of groundwater recharge in the Cape Flats, South Africa: Implications for sustainable resource management. Proc. XXXIV Congress of the International Association of Hydrogeologists (IAH), Beijing, China, 9-13 October 2006.

Adelana SMA, Olasehinde PI, Vrbka P (2006b) A quantitative estimation of groundwater recharge in parts of Sokoto Basin, Nigeria. Journal Environmental Hydrology, 14(5): 1-17.

Adelana SMA, Tamiru A, Nkhuwa DCW, Tindimugaya C, Oga MS (2008) Urban groundwater management and protection in sub-Saharan Africa. In S.M.A. Adelana & A.M. MacDonald (eds), Applied groundwater studies in Africa, London: Taylor & Francis, 231-260.

Akiti TT (1982) Nitrate levels in some granitic aquifers from Ghana. Proc. Intern. Symp. on Impact of Agricultural Activities on Groundwater, IAH Mem. XVI, Part1, pp 87-98.

Allen RG, Pereira S, Raes D, Smith M (1998) Crop evapotranspiration: Guidelines for computing water requirements. Irrigation and Drainage Paper 56. FAO, Rome.

Allen RG, Tasurmi M, Morse AT, Trezza R (2005) A Landsat-based energy balance and evapotranspiration model in Western US Water Rights Regulation and Planning, Journal of Irrigation and Drainage Systems, 19, 3–4, 251–268.

Aller L, Bennet T, Lehr JH, Petty RJ, Hackett G (1987) DRASTIC: a standardised system for evaluating groundwater pollution potentials using hydrogeological settings. EPA/600/2–87/035, US Environmental Protect

Alley WM (1984) On the treatment of evapotranspiration, soil moisture accounting, and aquifer recharge in monthly water balance models. Water Resour Res 20(8):1137–1149.
Alley W.M., ed. (1993) Regional Groundwater Quality. Van Nostrand Reinhold: New York, USA.

Allison GB (1988) A review of some of the physical, chemical and isotopic techniques for estimating groundwater recharge. In: I. Simmers (eds.), Estimation of natural groundwater recharge. NATO ASI Series, Reidel, Dordrecht, pp. 49-72.

Allison GB, Hughes MW (1978) The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. Aust J Soil Res 16:181–195.

Allison GB, Gee GW, Tyler SW (1994) Vadose-zone techniques for estimating groundwater recharge in arid and semi-arid regions. Soil Sci. Soc. Am., 58:6-14.

Anurage TS, Ruiz L, Mohan Kumar MS, Sekhar M, Lerjnse A (2006) Estimating groundwater recharge using land use and soil data: A case study in South India. Agricultural water management 84:65-76.

Andreo B, Goldscheider N, Vadillo I, Vías JM, Neukum C, Sinreich M, Jiménez P, Brechenmacher J, Carrasco F, Hötzl H, Perles JM, Zwahlen F (2006) Karst groundwater protection: first application of a Pan-European approach to vulnerability, hazard and risk mapping in the Sierra de Líbar (southern Spain). Sci Total Environ 357:54–73.

Appelo CAJ (1994) Some calculations on multicomponent transport with cation exchange in aquifers. Ground Water 32:968–975

Appelo CAJ, Willemsen A (1987) Geochemical calculations and observations on salt-water intrusions, I, a combined geochemical/mixing cell model. J Hydrol 94:313–330.

Apello CAJ, Postma D (1999) Geochemistry, groundwater and pollution. Brookfield, Balkema, Rotterdam.

Appelo CAJ, Willemsen A, Beckman HE, Griffioen J (1990) Geochemical calculations and observations on salt-water intrusions, II, validation of a geochemical model with column experiments. J Hydrol 120:225–250.

Arad A, Evans R (1987) The hydrogeology, hydrochemistry and environmental isotopes of the Campaspe River aquifer system, north-central Victoria, Australia. J Hydrol 95:63–86.

Ashley RP, Lloyd JW (1978) An example of the use of factor analysis and cluster analysis in groundwater chemistry interpretation. J Hydrol 39:355–364.

Ball JM, Stow JG (2000) Pollution plume migration: Coastal Park landfill. Proc. Wastecon 2000, Institute of Waste Management Sommerset West, South Africa, September.

Ball J & Associates (2003) Coastal Park sanitary landfill. Water monitoring reports No. XXI submitted to the City of Cape Town.

Ball JM, Novella PH (2003) Coastal Park landfill: leachate plume migration and attenuation. City of Cape Town Waste Management Department report, Cape Town.

Ball JM, Blight GE, Vorster K (1995) Leachate pollution in seasonal water deficit are`a. Proc. 5th In-ternational Landfill Symposium, Cagliari, Sardinia.

Barber C, Bates LE, Barron R, Allison H (1993) Assessment of the relative vulnerability of groundwater to pollution: a review and background paper for the conference workshop on vulnerability assessment, AGSO 14 (2/3), pp 147-154.

Barber C, Otto CJ, Bates LE, Taylor KJ (1996) Evaluation of the relationship between land-use changes and groundwater quality in a water supply catchment, using GIS technology: The Gwelup wellfield, Western Australia. Hydrogeology J 4:6-19.

Barwis JH, Tankard AJ (1983) Pleistocene shoreline deposition and sea level history at Swartklip, South Africa. Journal of Sedimentary Petrology, 53, p.1282-1294.

Bastiaanssen WGM, Noordman EJM, Pelgrum H, Davids G, Thoreson BP, Allen RG (2005) SEBAL model with remotely sensed data to improve water resources management under actual field conditions, Journal of Irrigation and Drainage Engineering, 131, 1, 85–93.

Beekman HE, Xu Y (2003) Review of groundwater recharge estimation in arid and semi-arid southern Africa. In: Xu Y & Beekman HE (eds) Groundwater recharge estimation in Southern Africa, UNESCO IHP Series No. 64, 3-18.

Bekesi G (1998) Aquifer vulnerability assessment for the Manawatu region. PhD. Dissertation, School of Earth Sciences, Victoria University of Wellington, New Zealand.

Bekesi G, McConchie J (2002) The use of aquifer-media characteristics to model vulnerability to contamination, Manawatu region, New Zealand. Hydrogeology Journal 10:322-331.

Bekker S, van Zyl B (1998) Baseline study on Urbanization in the Cape Metropolitan Area, Cape Town

Bertram WE (1989) Geohidrologiese Opname in die Philippi-landbougebied Kaapse Vlakte. Technical Report GH3595, Directorate Geohydrology, Department of Water Affairs.

Birch GF (1968) Some eustatic shorelines along the False Bay coasts. B.Sc (Honours) project, Geology Department, University of Cape Town (unpublished).

Bredenkamp DB (1990) Quantitative estimation of groundwater recharge by means of a simple rainfall-recharge relationship. In: D.N.Lerner, A.S. Issar & I. Simmers (eds.) Groundwater Recharge, IAH Memoir 8:247-256.

Bredenkamp DB (2000) Groundwater monitoring: A critical evaluation of groundwater monitoring in groundwater resources evaluation and management. Water Research Commission Report No. 838/1/00.

Bredenkamp DB (2004) Situation analysis for preparation of institutional arrangements of groundwater management. Part 3: WRC Contract 1324, Geohydrolological assessment, Water Research Commission, Pretoria.

Bredenkamp DB, Botha LJ, Van Rensburg HJ (1995) Manual on quantitative estimation of groundwater recharge and aquifer storativity. Rep TT 73/95. Water Research Commission, Pretoria, 419pp.

Bredenkamp DB, Vogel JC, Wiegmans FE, Xu Y, Janse van Rensburg H (2007) Use of natural isotopes and groundwater quality for improved estimation of recharge and flow in dolomitic aquifers. WRC Report No. KV 177/07.

Bromley J, Edmunds WM, Fellmann E (1997) Estimation of rainfall inputs and direct recharge to the deep unsaturated zone of southern Niger using chloride profile method. J. Hydrol. 188-189 (1-4):139-154.

Burger AJ, Coertze JA (1973) Radiometric age measurements on rocks from Southern Africa to the end of 1971. Bulletin Geological Survey of South Africa, 58.

Calder IR, Wright IR, Murdyarso D (1986) A study of evaporation from tropical rainforest – West Java. Journal of hydrology 89:13-31.

Cape Metropolitan Council, CMC (1998a) Towards an Integrated Metropolitan Environmental Policy (IMEP) for the Cape Metropolitan Area: Summary of the proposed principles and stages of the policy formulation process, October 1998.

Cape Metropolitan Council, CMC (1998b) Directorate: Water and Waste Annual Report, July 1997-June 1998.

Cape Metropolitan Council, CMC (1999a) Map of Catchments in the Cape Metropolitan Area, Catchment Management Department, Directorate of Water and Waste, Cape Town.

Cape Metropolitan Council, CMC (1999b) A Socio-Economic Profile of the Cape Metropolitan Area, An analysis of the 10% sample of the 1996 Census, Development Information Centre.

Carter RC, Rushton KR, Eilers VHM, Hassan M (2002) Modeling in groundwater modeling, with limited data, Plausibility as a measure of model reliability. Proc. 4th Int Conf on calibration and reliability, Prague, Czech Republic, pp 328-330.

Cartwright I, Weaver TR, Fifield LK (2006a) Cl/Br ratios and environmental isotopes as indicators of recharge variability and groundwater flow: an example from the southeast Murray Basin, Australia. Chem Geol 231:38-56.

Cartwright I, Weaver TR, Stone D, Reid M (2006b) Constraining modern and historical recharge from bore hydrographs, 3H, 14C, and chloride concentrations: applications to understanding processes in dryland salinity areas, Murray Basin, Australia. Appl Geochem 19:1233-1254.

Catchment, Stormwater and River Management (CSRM) 2004 Annual Report for 2003/2004.

Cavé L, King P, Tredoux G (1996) Atlantis groundwater management review 1995/6. Report No. ENV/S-C96070, Environmentek, CSIR, Stellenbosch.

Central Statistical Service (1996) 1995 October Household Survey, Western Cape Province, Statistical release P0317.1.

Central Statistical Service (1997) Census '96: Preliminary estimates of the size of the population of South Africa, Pretoria.

Centre for Scientific and International Research (CSIR) 1982 The geology of the False Bay with special emphasis on the modern sediments. Report submitted to the Department of environmental Affairs. Report C/SEA 8253, CSIR, Stellenbosch.

Centre for Scientific and International Research (CSIR) 2000 Modeling of the Cape Flats aquifer, CSIR Report, Stellenbosch.

Chilton PJ, Vlugman AA, Foster SSD (1990) A groundwater pollution risk assessment for public water supply sources in Barbados. American Water Resources Association International Conference on Tropical Hydrology and Caribbean Water Resources 279-289, San Juan de Puerto Rico.

Christiansen and Awadzi (2000) Water balance in a moist semi-desidous forest of Ghana. West African Journal of Applied Ecology, Vol. 1, pp 11-20.

City of Cape Town CCT (1997) Draft Water Services Development Plan 1996/97, February 1997.

City of Cape Town CCT (2001) Water resources and water resource planning. Water Services Development Plan, December 2001, City of Cape Town.

City of Cape Town, CCT (2006) Annual Report 2005/2006. Cape Town, 219p.

Civita M (1994) Vulnerability maps of aquifers subjected to pollution: theory and practice (In Italian). Pitagora Editrice, Bologna.

Civita M, De Regibus C (1995) Sperimentazione di alcune metodologie per la valutazione della vulnerabilita degli aquiferi. Q Geol Appl Pitagora, Bologna, 3:63-71.

Clark ID, Fritz P (1997) Environmental isotopes in hydrogeology. Lewis, New York, pp 328.

Clark ID, Fritz P, Quinn OP, Rippon P, Nash H, Bin Ghalib el Said B (1987) Modern and fossil groundwater in an arid environment. A look at the hydrogeology of Southern Oman. In: Use of stable isotopes in water resources development, IAEA Symposium 299, March 1987, Vienna, pp 167–187.

Clarke R., Lawrence A. and Foster S. (1996) Groundwater - a Threatened Resource. UNEP Environment Library 15.

Cleaver G, Brown LR, Bredenkamp GJ, Smart MC, Rautenbach CJ, de W (2003) Assessment of environmental impacts of groundwater abstraction from TMG aquifers on ecosystems in the Kammanaise Nature Reserve and environs. WRC Report No. 1115/1/03, Water Research Commission, Pretoria.

CMC 1998 Cape Metropolitan Council Water Department, Annual Report, 1998.

CMC 1999 Cape Metropolitan Council Water Department, Annual Report, 1999.

Cole DI, Viljoen JHA (2001) Building sand potential of the greater Cape Town area. Bulletin 129, Council for Geoscience.

Coniello A, Ducci D, Napolitano P (1997) Comparison between parametric methods to evaluate aquifer pollution vulnerability using GIS: an example in the Piana Campana, Southern Italy. In: Marinos PG, Koukis GC, Tsiabaos GC, Stounaras GC (eds), Engineering geology and the environment, Balkema, Rotterdam, 1721-1726.

Conrad J, Nel J, Wentzel J (2004) The challenges and implications of assessing groundwater recharge: A case study – northern Sandveld, Western Cape, South Africa. Water SA, Vol. 30 No. 5 (Special edition), 75-81.

Cook PG, Herczeg AL (2002) Groundwater chemical methods for recharge studies. CSIRO Land and Water Series Edition (edited by Lu Zhang), CSIRO Publishing, Australia.

Cook PG, Walker GR, Jolly ID (1989) Spatial variability of groundwater recharge in a semi-arid region. J. Hydrol., 111: 195-212.

Cook PG, Hatton TJ, Pidsley D, Herczeg AL, Held A, O'Grady A, Eamus D (1998) water balance of a tropical woodland ecosystem, Northern Australia: a combination of micro-metereological, soil physical and groundwater chemical approaches. Journal of Hydrology 210: 1961-1977.

Coplen TB (1988) Normalisation of oxygen and hydrogen isotope data. Chem Geol 72:293–297.

Cox ME, Hillier J, Foster L, Ellis R (1996) Effects of rapidly urbanizing environments on groundwater, Brisbane, Queensland, Australia. Hydrogeology Journal, Vol. 4, No. 1, 30-47.

Craig H (1961) Standard for reporting concentrations of deuterium and oxygen-18 in natural water. Science 133:1702–1703.

Craig H, Gordon L (1965) Deuterium and oxygen-18 in the ocean and marine atmosphere. In: Tongiori E. (eds), Stable isotopes in oceanographic studies and paleotemperatures. Spoleto, 9-130.

Custodio E (2002) Coastal aquifers as important natural hydrogeological structures. In: Bocanegra E., Martinez D and Massone H. (eds.) Groundwater and Human Development, Mar de Plata, Argentina, pp.1905 - 1918.

Custodio E, Llamas MR (1983) Hidrología subterránea. Ediciones Omega, Barcelona. 2 vols: 1- 2350. Sec. 13: Relaciones agua dulce-agua salada en regiones costeras. 13: 1313-1389.

Custodio E, Bruggeman GA (1987) Saltwater problems in coastal aquifers. Studies and Reports in Hydrology 45, UNESCO Press. Paris: 1-596.

Daansgard W (1964) Stable isotopes in precipitation. Tellus 16:436–468.

Dahan O, Ronit N, Eilon MA, Brian B, Noam W (2000) On fracture structure and preferential flow in unsaturated chalk. Groundwater 38(3):444–451.

Daly D, Dassargues A, Drew D, Dunne S, Goldscheider N, Neale S, Popescu IC, Zwahlen F (2002) Main concepts of the "European approach" to karst-groundwater-vulnerability assessment and mapping. Hydrogeol J 10:340–345.

Darling WG, Edmunds WM, Smedley P (1997) Isotopic evidence for paleogroundwaters in the British Isles. Appl Geochem 12:813–829.

Davies O (1973) Pleistocene shorelines in the Western Cape and South West Africa. Annals Natal Museum, 21, p. 719-765.

Davis SN, De Wiest RJM (1976) Hydrogeology. John Wiley, New York, 322p.

De Beer JH (1983) Geophysical studies in the Southern Cape Province, and models of the lithosphere in the Cape Fold Belt. In: Sohnge APG & Halbich IW (eds), Geodaynamics of the Cape Fold Belt. Special Publication Geological Society of South Africa, 12, p. 57-64.

De Beer JH, Van Zul JSV, Goughi DI (1982) The Southern Cape Conductive Belt: its composition, origin and tectonic significance. Tectonophysics, 83, p. 205-225.

Debernardi L, De Luca DA, Lasagna M (2008) Correlation between nitrate concentration in groundwater and parameters affecting aquifer intrinsic vulnerability. Environ Geol 55:539-558.

De la Cruz MA, Du Plessis A (1981) The geology of Saldanha Bay. Bulletin Geological Survey of South Africa, 70.

Delin GN, Healy RW, Lorenz DW, Nimmo JR (2007) Comparison of local- and regional-scale estimates of ground-water recharge in Minnesota, USA. Journal of Hydrology. Vol 334, pp 231-249.

De Vries JJ, Simmers I (2002) Groundwater recharge: an overview of processes and challenges. Hydrogeol J 10(1):5–17.

Department of Water Affairs and Forestry, DWAF (1994) Minimum Requirements for the Establishment of a Waste Disposal Site, DWAF, Pretoria.

Department of Water Affairs and Forestry, DWAF(1999) Water resources protection policy implementation, resource Directed measures for protection of water resources, Integrated Manual, Report No. N/28/99.

Dingle RV, Lord AR, Hendey OB (1979) New sections in the Varswater Formation (Neogene) of Langebaan Road, Southwestern Cape, South Africa. Annals South African Museum, 78(8), p.81-92.

Dingle RV, Siesser WG, Newton AR (1983) Mesozoic and Tertiary geology of Southern Africa. Balkema, Rotterdam.

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy, Official Journal of European Communities L 327, 22.12.2000.

Domenico PA, Schwartz FW (1998) Physical and chemical hydrogeology (Chapter 17), 2nd edn. John Wiley & Sons, Inc. New York, 506pp

Dripps W, Bradbury K (2007) A simple daily soil-water balance model for estimating the spatial and temporal distribution of groundwater recharge in temperate humid areas. Hydrogeology Journal, Volume 15, Number 3, pp. 433-444.

Duvenhage AWA, Meyer R, de Raath CJ (1993) A geo-electrical survey in the Oudtshoorn area to identify potential drilling targets for groundwater. CSIR Division of Earth, Marine and Atmospheric Science & Technology, Report No. EMAP-C-93042.

Eaton TT (1995) Estimating groundwater recharge using a modified soil-water budget method. In: Proc AWRA Wisconsin Nineteenth Annual Conf, Abstracts, AWRA, Middleburg, VA, USA, p 18.

Eaton AD, Clesceri LS, Greenberg AE (1995) Standard methods for the examination of water and waste water, (19th edn). American Public Health Association, Washington, DC.

Edet EA (2004) Vulnerability evaluation of a coastal plain sand aquifer with a case example from Calabar, southeastern Nigeria. Env. Geol. 10.1007/s00254-004-0969-9.

Edmunds WM (1995) Characterisation of groundwaters in the semi-arid and arid zones using minor elements. In: H. Nash & G.J.H. McCall (eds), Groundwater Quality: 19-30, London, Chapman & Hall.

Edmunds WM, Gaye CB (1997) High nitrate baseline concentrations in groundwaters from the Sahel. J. Environ. Quality 26:1231-1239.

Edmunds WM and Smedley PL (2000) Residence time indicators in groundwater: the East Midlands Triassic sandstone aquifer. Applied Geochemistry 15: 737-752.

Edmunds WM, Carrillo JJ, Cardona A (2002) Geochemical evolution of groundwater beneath Mexico City. J Hydrol 258:1–24.

Eilers VHM, Carter RC, Rushton KR (2007) A single layer soil water balance model for estimating deep drainage (potential recharge): An application to cropped land in semi-arid North-east Nigeria. Geoderma Volume 140, Issues 1-2, pp 119-131.

Eiswirth M, Hotzl H (1994) Groundwater contamination by leaky sewer systems. Water, Down, Under, National Conference of Institution of Engineers, Adelaide, Australia, November 1994, 111-114.

El Moujabber M, Bou Samra B, Darwish T, Atallah T (2006) Comparison of different indicators for groundwater contamination by seawater intrusion on the Lebanese coast. Water Resour Manage 20:161–180.

Engelbrecht JFP (1998) Groundwater pollution from cemeteries. Proc. Biennial Conference, 4-7 May. Cape Town: The Waste Institute of Southern Africa.

Essery CI, Wilcock DN (1990) Checks on the measurement of potential evapotranspiration using water balance data and independent measures of groundwater recharge. Journal of Hydrology, 120: 51-64.

Evers S, Lerner DN (1998) How uncertain is our estimate of a wellhead protection zone? Ground Water, Vol.36, No.1.

Faillat JP (1990) Origin desnitrates dans les nappes de fissures de la zone tropicale humide. Exemple de la Cote d'Ivoire. J. Hydrol. 113: 231-264.

Fetter CW (1994) Applied hydrogeology, 3rd edn, Merril, Columbus, 691p.

Fleming BW (1977) Distribution of recent sediments in Saldanha Bay and Langebaan Lagoon. Transactions Royal Society of South Africa, 42(3/4), p. 317-340.

Fontes JC (1980) Environmental isotopes in ground water hydrology. In: Fritz P, Fontes J Ch (eds) Handbook of environmental isotope geochemistry, vol 1. Elsevier, Amsterdam, pp 75–140.

Foster SSD (1987) Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: Duijvenbooden W van, Waegeningh HG van (eds) TNO Committee on Hydrological Research, The Hague. Vulnerability of soil and groundwater to pollutants, Proceedings and Information 38:69–86.

Foster SSD, Hirata R (1988) Groundwater pollution risk assessment: a methodology using available data. WHO-PAHO/HPE-CEPIS Technical Manual, Lima, Peru.

Foster SSD, Morris BL (1994) Effects of urbanization on groundwater recharge. In: Williamson WB (eds) Groundwater problems in urban areas, Proc. ICE Conference, London, June 1993, Thomas Telford, 43-63.

Foster SSD, Lawrence AR, Morris BL (1996) Groundwater resources beneath rapidly urbanizing cities-implications and priorities for water supply management. In Report of the Habitat II Conference, Beijing, China, March 1996, 356-365.

Foster SSD, Lawrence A, Morris BL (1998) Groundwater in urban development: assessing management needs and formulating policy strategies. World Bank Technical Paper No. 390, Washington, D.C., USA.

Foster S, Chilton J, Moench M, Cardy F, Schiffler M (2000) Groundwater in Rural Development: Facing the Challenges of Supply and Resource Sustainability. World Bank Technical Paper 463: Washington D.C., USA.

Foster S, Hirata R, Gomes D, D'Elia M, Paris M (2002) Groundwater quality protection: a guide for Water Utilities, Municipal Authorities and Environmental Agencies. World Bank Publication, Washington, D.C., USA.

Fraser L, Weaver J (2000) Cape Flats Aquifer: Bulk water for Cape Town now. CSIR report ENV/S-C 2000-119, Stellenbosch.

Freeze AR, Cherry JA (1994), Groundwater. 3rd edition, Prenticehall, New York

Fuller AO, Lamming PJ (1967) The hydraulic equivalence of Quartz and Zircon in coastal deposits from the south-western districts of the Cape Province, and its application as an environmental indicator. South African Journal Sci., 63, 10:521-526.

Gat JR (1980) The isotopes of hydrogen and oxygen in precipitation. In: Fritz P, Fontes J-Ch (eds) Handbook of environmental isotope geochemistry, Vol 1, The terrestrial environment. Elsevier, Amsterdam, pp 21–47.

Gatehouse RP (1955) Some raised shorelines. Transactions Royal Society of South Africa, 58, p. 255-263.

Gerber A (1976) An investigation into the hydraulic characteristics of the groundwater source in the Cape Flats. Unpublished M.Sc. thesis, University of the Orange Free State, Bloemfontein.

Gerber A (1980) Final report on geohydrology of the sand deposits in the Cape Flats. Project 620/9839/7, Report by NIWR (CSIR), Pretoria.

Gerber A (1981) A digital model of groundwater flow in the Cape Flats. CSIR Contract Report C WAT 46, Pretoria.

Gerhart JM (1986) Groundwater recharge and its effect on nitrate concentrations beneath a manured field in Pennsylvania. Ground Water 24:383-389.

Geyh MA, Backhaus G (1979) Hydrodynamic aspects of carbon-14 groundwater dating. Isotope Hydrol V II, IAEA, Vienna: pp 631–643.

Giljam R, Waldron H (2002) The effect of the Cape Flats aquifer on the water quality of the False Bay. Proc. Western Cape Conference: Tales of a hidden treasure, September 16, Somerset West.

Gogu RC, Dassargues A (2000) Current trends and future challenges in groundwater vulnerability assessment overlay and index methods. Environ Geol 39(6):549–560.

Gogu RC, Hallet V, Dassargues A (2003) Comparison of aquifer vulnerability assessment techniques: application to the Neblon River basin (Belgium). Environ Geol 44(8):881–892.

Goldscheider N (2002) Hydrogeology and vulnerability of karst systems: examples from the Northern Alps and Swabian Alb. PhD Thesis, Schr Angew Geol Karlsruhe, Karlsruhe.

Goldscheider N (2003) Karst groundwater vulnerability mapping: application of a new method in the Swabian Alb, Germany. Hydrogeology Journal Online first, 10.1007/s10040-003-0291-3.

Gonfiantini R (1986) Environmental isotopes in lake studies. In: Fritz P, Fontes J Ch (eds) Handbook of environmental isotope geochemistry, vol 1. Elsevier, Amsterdam, pp 113–168.

Gowda PH, Senay GB, Howell TA, Marek TH (2009) Lysimetric Evaluation of Simplified Surface Energy Balance Approach in the Texas High Plains. Applied Engineering in Agriculture. 25(5): 665-669.

Gresse PG, Theron JM (1992) Geology of Worcester area. Explanation Sheet 3318, Geological Survey of South Africa.

Grischek T, Nestler W, Piechniczck D, Fischer T (1996) Urban groundwater in Dresden, Germany. Hydrogeology J 4:48-63.

Grobicki A (2000) Integrated catchment management in an urban context of the Great and Little Lotus Rivers, Cape Town, WRC Report No. 864/1/01.

Guler C, Thyne GD, McCray JE, Turner AK (2002) Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. Hydrogeology journal, 10: 455-474.

Hague A (2003) Estimating actual areal evapotranspiration from potential evapotranspiration using physical models based on complementary relationships and meteorological data. Bull Eng Geol Env, 62:57-63.

Harris C, Oom BM, Diamond RE (1999) A preliminary investigation of the oxygen and hydrogen isotope hydrology of the greater Cape Town area and an assessment of the potential for using stable isotopes as tracers. Water SA, 25, 1:15-24.

Hartnady CJH (1969) Structural analysis of some pre-Cape Formations in Western Province. Bulletin Precambrian Research Unit, University of Cape Town, 6, p. 1-70.

Hartnady CJH (1987) Tectonostratigraphic terrane analysis and Southern African crustal evolution. Proc. & abstracts of the Alex I. du Toit golden jubilee conference on tectonographic terrane analysis, Precambrian Research Unit, Cape Town, p. 4-14.

Hartnady CJH, Rogers J (1990) The scenery and geology of the Cape Peninsula. Guidebook Geocongress '90, Geological Society, South Africa.

Haughton SH (1933) Geology of Cape Town and adjoining country: Explanation of Sheet 247 (Cape Town), Geological Survey of South Africa.

Haughton SH (1969) Geological history of Southern Africa. Geological Society of South Africa, Cape Town, p. 1-529.

Healy RW, Cook PG (2002) Using groundwater levels to estimate recharge. Hydrogeol. J. 10:91–109.

Hem JD (1985) Study and interpretation of the chemical characteristics of natural water. (3rd edn) US Geol. Surv. Water Supply Paper 2254:263.

Hem JD (1991) Study and interpretation of the chemical characteristics of natural water. US Geological Survey Water Supply Paper 2254, Scientific Publishers, India

Hendey QB (1981a) Palaeoecology of the Late Tertiary fossil occurrences in ‘E’ quarry, Langebaanweg, South Africa, and a reinterpretation of their geological context: Anals South African Museum, 84(1).

Hendey QB (1981b) The geological succession of Langebaanweg, Cape Province and global events of the Late Tertiary. South African Journal of Science, 77, p.33-38.

Hendey QB (1983) Cenozoic geology and paleogeography of the fynbos region in Fynbos palaeoecology: A preliminary synthesis. Report of the South African National Scientific Programme, 75, p. 35-60.

Hendey QB, Dingle RV (1983) Onshore sedimentary phosphate deposits in South Western Africa. Technical Report Joint Geological Survey/University of Cape Town Marine Geoscience Unit, 14, p.27-40.

Hendrix JMH, Walker GR (1997) Recharge from precipitation. In: I. Simmers (eds.), Recharge of phreatic aquifers in semi-arid areas. IAH, Wallingford.



Henzen M (1973) The reclamation, storage and abstraction of purified sewage effluents in the Cape Peninsula (in Afrikaans). D.Sc. Thesis, University of the Orange Free State, Bloemfontein.

Herczeg AL, Edmunds WM (2000) Inorganic ions as tracers. In: P.G. Cook & Herczeg (eds), Environmental Tracers in Subsurface Hydrology: 31-77, Boston, Kluwer.

Herczeg AL, Simpson HJ, Mazor E (1993) Transport of soluble salts in a large semiarid basin; River Murray, Australia. J Hydrol 144:59–84.

Herczeg AL, Torgersen T, Chivas AR, Habermehl MA (1991) Geochemistry of ground waters from the Great Artesian Basin, Australia. J Hydrol 126:225–245.

Hess TM, Counsell C (2000) A water balance simulation model for teaching and learning - WaSim. Paper presented at the ICID British Section Irrigation and Drainage Research Day, 29 March 2000. HR Wallingford.

Hess T, Counsell C (2001) WaSim User Manual. HR Wallingford and Cranfield University, Silsoe, 48p.

Hill RS, Theron JN (1981) Silica sand of the Cape Flats. Bull. 69, Department of Mineral and Energy Affairs, Geological Survey of South Africa, 45p.

Hill MC, Banta ER, Harbaugh AW and Anderman ER (2000), MODFLOW-2000, The U.S. Geological Survey modular ground-water model - User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs, U. S. Geological Survey, Open-file report 00-184.

Hirata R, Bastos C, Rocha G (1997) Mappa de vulnerabildade das aguas subterraneas no Estado de Sao Paulo. Instituto Geologico, Companhia de Saneamemo Ambiental, Departamento de Agaias e EnergiaElietrica. Sao Paulo, Brasil, 2 vol.

Hirata R, Bostos C, Rocha G, Gomes G, Iritani M (1991) Groundwater pollution risk and vulnerability map of Sao Paulo State, Brasil. Water Science and Technology 24(11):159-169.

Hiscock KM (2005) Hydrogeology: Principles and practice, Blackwell Publ. Co. USA, 389pp.

Hoefs J (1997) Stable isotope geochemistry, 4th edn. Springer, Berlin Heidelberg New York.

Houston JFT (1990) Rainfall-runoff-recharge relationship in the sediment rocks of Zimbabwe. In: D.N. Lerner, A.S. Issar and I. Simmers (eds.), Groundwater Recharge, IAH, 8: 271-283.

Howard KWF, Lloyd JW (1979) The sensitivity of parameters in the Pen evaporation equations and direct recharge balance. Journal of Hydrology 41:329-344.

Inland Waters Management Team (1994) Cape Town City Council, City Engineer Report. City Engineer's Department, Cape Town.

INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA) (2004) Station 6881600 "Malan" (Cape Town) South Africa, Global Network of Isotopes in Precipitation (GNIP), http://www.iaea.or.at/programs/ri/gnip/gnipmain.htm

International Association of Hydrogeologists (IAH) 2004. Changing land-use to "farm" high quality groundwater. A comment . IAH newsletter, September 2004.

Issar A, Gat J (1981) Environmental isotopes as tool in hydrogeological research in an arid basin. Groundwater 19(5):490–494.

Jankowski J, Schofield S (2001) Trace elements as an indicator of redox processes in a fractured aquifer system, Ballimore, Central New South Wales, Australia. In: K.P. Seiler & S. Wohnlich (eds), New Appraches to Characterizing Groundwater Flow, 971-975, Swets & Zeitlinger, Lisse.

Jansen T (1967) Ondorsoek van glassandafsettings op die Kaap Vlakte en Planknek, Potgietersrus. Reprint Geological Survey of South Africa (unpublished).

Jeffaras & Green (Pty) Ltd (2002) Water resource and supply option study: Area south of Clevelly. Draft Report submitted to the City of Cape Town.

Jia H (2007) Groundwater resource evaluation of the TMG aquifer systems. PhD Dissertation, University of the Western Cape.

Jolly ID, Cook PG, Allison GB, Hughes MW (1989) Simultaneous water and solute movement through an unsaturated soil following an increase in recharge. J Hydrol 111:391–396.

Juodkazis V, Arustiene J, Klimas A, Marcinonis A (2003) Organic matter in fresh groundwater of Lithuania. Vilnius University Publishing House, Vilnius, Lithuania.

Kan A, Xu Y, Usher B (2004) Hydrogeochemical Analysis Model (HAM) in excel: A overview of input, equations and use. Institute for Groundwater Studies, University of the Free State, Bloemfontein.

Karanth KR (1991) Impact of human activities on hydrogeological environment. J Geol Soc India 38:195–206

Kendall C, McDonnel JJ (1998) Isotope tracers in catchment hydrology. Elsevier, Amsterdam.

Kollarits S, Kuschnig G, Veselic M, Pavicic A, Soccorso C, Aurighi M (2006) Decision-support systems for groundwater protection: innovative tools for resource management. Environ Geol 49: 840-848.

Kotze JC (2000) Modeling of groundwater flow in the Table Mountain Sandstone fractured aquifer in the Little Karoo region of South Africa. WRC Project Report No. K5/729, Water Research Commission, Pretoria.

Kotze JC (2001) Towards a management for groundwater exploitation in the Table Mountain Sandstone fractured aquifer. WRC Report No. 729/1/02, Water Research Commission, Pretoria.



Kotze JC (2002) Hydrogeology of the Table Mountain Sandstone aquifer – Klein Karoo. PhD Thesis, University of the Free State, Bloemfointen (unpublished).

Kovacs G (1987) Estimation of average areal evapotranspiration proposal to modify Morton's model based on the complementary character of actual and potential evapotranspiration. J Hydrol 95:227-240.

Kovar K, Krasny J (1995) Groundwater Quality: Remediation and Protection. IAHS Publication 225: IAHS Press: Wallingford, UK.

Krige AV (1927) An examination of the Tertiary and Quaternary changes of seal level in South Africa, with special stress on the evidence in favour of a recent world-wide sinking of ocean level. Annals University of Stellenbosch, 5, Series A (1), p. 1-81.

Krusemann GP, de Ridder NA (1994) Analysis and evaluation of pumping test data. International Institute for Land Reclamation and Improvement (ILRI), Wageningen.

Lamming PJ (1962) Geology of Hout Bay area. B.Sc. (Honours) project, Geology Department, University of Cape Town (unpublished).

Lamming PJ (1999) Environmental Management Programme Report. Prepared for Brakkefontein Properties (Pty) Ltd., May 1999.

Langelier WF, Ludwig HF (1942) Graphic method for indicating the mineral character of natural water. J Am Water Works Assoc 34:335–352.

Lautz LK (2008) Estimating groundwater evapotranspiration rates using diurnal water-table fluctuations in a semi-arid riparian zone. Hydrogeol. J. 16: 483-497.

Lee JY, Song SH (2006) Evaluation of groundwater quality in coastal areas: implications for sustainable agriculture. Environ Geol 10.1007/s00254-006-0560-2

Le Meur R, Zhang L (1990) Evaluation of three evapotranspiration models in terms of their applicability to an arid region. J Hydrol 114:395-411

Lerner DN (1986) Leaking pipes recharge groundwater. Ground Water, 26 (5): 654-662.

Lerner DN (1989) Groundwater recharge in urban areas. Atmospheric Environment 24(1), 29-33.

Lerner DN (1992) Borehole catchments and time-of-travel zones in aquifers with recharge. Water Resources Research, 28:2621-2628.

Lerner DN (1997) too much or too little: Recharge in urban areas. In: Chilton et al. (eds), Groundwater in the urban environment: Problems, Processes and Management: Rotterddam, Balkema, 41-47.

Lerner DN (2002) Identifying and quantifying urban recharge: a review. Hydrology Journal 10: 143-152.

Lerner DN (2004) Urban groundwater pollution. AA Balkema, Lisse.

Lerner DN, Barret MH (1996) Urban groundwater issues in the United Kingdom. Hydrogeology J, 4, 80-89.

Lerner DN, Kumar PB (1991) Defining the catchment of a borehole in an unconsolidated valley aquifer with limited data. Quarterly Journal of Engineering Geol 24, No.3:323-337.

Lerner DN, Issar AS, Simmers I (1990) Groundwater recharge – A guide to understanding and estimating natural recharge. International contributions to Hydrogeology (IAH), Verlag Heinz Heise, Germany, Vol.8, 345pp.

Levin M, Gat JR, Issar A (1980) Precipitation, flood, and groundwaters of the Negev Highlands: an isotopic study of dessert hydrology. In: IAEA arid zone hydrology: investigations with isotopic techniques, pp 3–23.

Levyns MR (1964) Migrations and origins of the Cape Flora. Trans. Royal Soc. South Africa, 37, 2:85-107.

Li L, Barry DA, Stagnitti F, Parlange JY, Jeng DS (2000) Beach water table fluctuations due to spring–neap tides: moving boundary effects. Advances in Water Resources, Volume 23, Issue 8, pp 817-824.

Linsley RK, Kohler MA, Paulhus JLH (1975) Hydrology for engineers, New York: McGraw-Hill.

Lodwik WA, Monson W, Svobodu L (1990) Attribute error and sensitivity analysis of maps of map operation in geographical information systems – suitability analysis. Int. Journal of Geographical Information Systems 4:403-428.

Lorentz SA, Hughes GO, Schulze RE (2003) Techniques for estimating groundwater recharge at different scales in Southern Africa. In: Xu Y. & Beekma H.E. (eds) Groundwater recharge estimation in Southern Africa.

Low AB, Scott LB (1983) Flowering plants of the Cape Flats Nature Reserve. University of the Western Cape Publication, Bellville.

Lu J, Sun G, McNulty SG, Amatya DM. (2005) A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. J Am Water Resour Assoc 41:621–33.

Magerman M, Knight RS, Kippie I, Weitz W (1999) Flowering plants of the Cape Flats Nature Reserve: An illustrated interactive guide. Botany Department, University of the Western Cape (internet version: http://hypnea.botany.uwc.ac.za/capediv/index.html).

Malan JA (1987) The Bredasdorp Group in the area between Gansbaai and Mossel Bay. South African Journal of Science 83, pp. 506-507.

Marloth R (1913-1932) The flora of South Africa. Vol. 1-4, Darters, Cape Town.

Mazor E, Verhagen BT (1983) Dissolved ions, stable isotopes and radioactive isotopes and noble gases in thermal waters of South Africa, J Hydrol 63:315–329.

McCarthy T, Rubidge B (2005) The story of Earth and Life: A Southern African perspective on a 4.6-billion-year journey, Struik Publishers, Cape Town.

McLear LGA (1995) A note on the potential of the Cape Flats aquifer unit to supply groundwater for domestic use in the Cape Town Metropolitan area. Technical Report No. GH 3868, DWAF, Cape Town.

McVicar CN (1991) Soil Classification, a toxonomic system for South Africa: Memoirs of the Agricultural Natural Resources of South Africa No.15, Department of Agricultural Development, Pretoria.

Meerkotter M (2003) Heavy metals and vegetable farming in Cape Town. Unpublished M.Sc. Thesis, University of the Western Cape, 147pp.

Mehlomakulu M. (2000) The influence of urban development on the water chemistry of the Cape Flats aquifer. Unpublished M.Sc. thesis, University of Cape Town, 95pp.

Meinzer OE, Sterns ND (1929) A study of groundwater in the Pomperaug Basin, Connecticut, with special reference to intake and discharge. US Geol. Surv. Water-Supply Paper 597B: 73-146.

Mercado A (1985) The use of hydrogeochemical patterns in carbonate sand and sandstone aquifers to identify intrusion and flushing of saline waters. Ground Water 23:635–645.

Merlivat L, Jouzel J (1979) Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation. J. Geophys. Res., 84: 5029-5033.

Meyer PS (2001) An explanation of the 1:500 000 hydrogeological map of Cape Town 3317. Department of Water Affairs & Forestry, 59pp.

Meyer R (2005) Analysis of groundwater level time series and the relation to rainfall and recharge. WRC Report No. 1323/1/05, Water Research Commission, Pretoria.

Mogheir Y, Singh VP (2002) Specification of information needs for groundwater resources management and planning in developing country: Gaza Strip case study. In: Sherif MM, Singh VP, Al-Rashed M (eds) Proceedings Water Resources Management in Arid Regions Conference (2) 3–20.

Mogheir Y, Singh VP, de Lima JLMP (2006) Spatial assessment and redesign of a groundwater quality monitoring network using entropy theory, Gaza Strip, Palestine. Hydrogeology J 14:700-712.

Mook WG (2005) Introduction to Isotope Hydrology - Stable and Radioactive Isotopes of Hydrogen, Oxygen and Carbon. International Contributions to Hydrogeology 25, International Association of Hydrogeologists, Lisse, Balkema.

Morris DA, Johnson AI (1967) Summary of hydrologic and physical properties of rock and soil materials as analysed by the Hydrologic Laboratory of US Geological Survey – 1948-1960. U.S. Geological Survey Water Supply Paper 1839-D.

Morton FI (1983) Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. J Hydrol 66:1-76.

Morton FI (1978) Estimating evapotranspiration from potential evaporation: practicality of an iconoclastic approach. J Hydrol 38:1-32.

National Research Council (NRC) 1993. Groundwater vulnerability assessment: Predicting relative contamination potential under Conditions of uncertainty. Committee on techniques for assessing groundwater vulnerability, Water Science &Technology Board, Commission on Geosciences, Environment, and Resources, National Academy of Sciences, 204p.

Neukum C, Hötzl H, Himmelsbach T (2008) Validation of vulnerability mapping methods by field investigations and numerical modelling. Hydrogeol J 16(4):641–658.

Ninham Shand (1994) Western Cape System Analysis: Study overview. Ninham Shand Consulting Engineers Report (unpublished).

Norman N, Whitfield G (2006) Geological journeys, Chapter 2, Struik Publishers, Cape Town.

Pandit A (2004) Coastal Aquifer Management: Monitoring, Modeling and Case Studies. J. Environ. Qual. 33:2390-2391.

Panteleit B, Kessels W, Kantor W, Schulz HD (2001) Geochemical characteristics of salinization-zones in the Coastal Aquifer Test Field (CAT-Field) in North-Germany. 1st International Conference on Saltwater Intrusion and Coastal Aquifers-monitoring, modeling, and management. Essaouira, Morocco, April 23-25, 2001.

Parker RJ (1968) Eustatic shorelines of Saldanha Bay. B.Sc (Honours) project, Geology Department, University of Cape Town (unpublished).

Park SC, Yun ST, Chae GT, Yoo IS, Shin KS, Heo CH, Lee SK (2005) Regional hydrochemical study on salinization of coastal aquifers, western coastal area of South Korea. J Hydrol 313:182–194.

Parsons R (2009) Is Groenvlei really fed by groundwater discharged from the TMG Aquifer? Water SA (Online) vol.35 no.5, Pretoria.

Parsons R, Taljard M (2000) Assessment of the impact of the Zandvliet Wastewater Treatment Works on groundwater. Biennial Conference, Sun City, 28 May – 1 June, Water Institute of South Africa.

Pathak DR, Hiratsuka A, Awata I, Chen L (2009) Groundwater vulnerability assessment in shallow aquifer of Kathamandu Valley using GIS-based DRASTIC model. Environ Geol 57:1569-1578.

Pawar NJ, Shaikh IJ (1995) Nitrate pollution of groundwaters from basaltic aquifers–Deccan trap hydrologic province, India. Environ Geol 25:197–204.

Perrin J, Pochon A, Jeannin PY, Zwahlen F (2004) Vulnerability assessment in karstic areas: validation by field experiments. Environ Geol 46:237–245.

Petalas CP, Diamantis IB (1999) Origin and distribution of saline groundwaters in the upper Miocene aquifer system, coastal Rhodope area, northeastern Greece. Hydrogeol J 7:305–316.

Petrides B, Cartwright I (2006) The hydrogeology and hydrogeochemistry of the Barwon Downs Graben aquifer, southwestern Victoria, Australia. Hydrogeology J 14:809-826.

Piscopo G (2001) Groundwater Vulnerability Map: Explanatory Notes, Center of Natural Resources, Department of Land and Water Conservation, New South Wales, Australia, 14 p.

Polemio M, Casarano D, Limoni PP (2009) Karstic aquifer vulnerability assessment methods and results at a test site (Apulia, southern Italy). Nat. Hazards Earth Syst. Sci., 9, 1461-1470.

Price M, Reed DW (1989) The influence of mains leakage and urban drainage on groundwater levels beneath conurbations in the UK. Proc. Inst. Civil Engineers, 86(1), 31-39.

Puez G (1999) Evaluacion de la vulnerabilidad a la contaminacion de las aguas subterraneas en el valle del Cauca. Informe Ejecutivo. CorpoRegional del Valle del Cauca, Columbia.

Ravbar N, Goldscheider N (2009) Comparative application of four methods of groundwater vulnerability mapping in a Slovene karst catchment. Hydrogeology Journal 17: 725-733.

Rehm BW, Moran SR, Groenewold GH (1982) Natural groundwater recharge in an upland area of central North Dakota, USA. Journal of Hydrology 59:293-314.

Reilly TE, Goodman AS (1985) Quantitative analysis of saltwater-freshwater relationships in groundwater systems: a historical perspective. J. Hydrology, 80: 125-160.

Revelle R (1941) Criteria for recognition of sea water in groundwaters. Trans Am Geophys Union 22:593–597.

Reynders AG, Lynch SD (1993) Compilation of a National-scale Groundwater Vulnerability Map of South Africa. In: Proc. Second Biennial Groundwater Convention, "Africa Needs Groundwater", Groundwater Division of the Geological Survey of South Africa, Johannesburg, Sept. 1993.

Roets W (2008) Groundwater Dependence of Aquatic Ecosystems Associated with the TMG Aquifer. Unpublished Ph.D. Thesis, University of the Western Cape, Cape Town, South Africa.

Rogers J (1980) First report on the Cenozoic sediments between Cape Town and Saldanha. Open-file Report Geological Survey of South Africa, 136.

Rogers J (1982) Lithostratigraphy of Cenozoic sediments between Cape Town and Elans Bay, Palaeoecology Africa, 15, p.121-137.

Rogers J (1983) Lithostratigraphy of Cenozoic sediments on the coastal plain between Cape Town and Saldanha. Technical Report Joint Geological Survey/University of Cape Town Marine Geoscience Unit, 14, p.87-103.

Rozanski K, Araguás-Araguás L, Gonfiantini R (1993) Isotopic patterns in modern global precipitation. In: Climate Change in Continental Isotopic Records, Geophysical Monograph 78, American Geophysical Union, 1-36.

Rozanski K, Sonntag C, Munnich KO (1982) Factors controlling stable isotope of European precipitation. Tellus 34:142–150.

Saayman IC (1999) Case study on the chemical characteristics of a pollution plume and a determination of its direction of movement at the Bellville Waste Site, Cape Town, South Africa. Unpublished M.Sc. Thesis, Royal Institute of Technology, (KTH), Stockholm.

Saayman IC, Adams S, Harris C (2000) Examples of O- and H- isotopes to identify surface water pollution in groundwater. In: Sililo et al. (eds.) Groundwater: Past Achievements and Future Challenges, AA Balkema, Rotterdam, pp 599-603.

Saayman IC, Beekman HE, Adams S, Campbell RB, Conrad J, Fey MV, Jovanovic N, Thomas A, Usher BH (2007) Assessment of Aquifer Vulnerability in South Africa. WRC Report No. 1432/1/07, 97p.

Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10:18–39.

Schalke HJW (1973) The upper Quaternary of the Cape Flats area, Cape Province, South Africa. Scripta Geol. 15, pp1-37.

Selaolo ET (1998) Tracer studies and groundwater recharge assessment in the eastern fringe of the Botswana Kalahari. PhD dissertation, Vrije universiteit, Amsterdam.

Sharma ML, Hughes MW (1985) Groundwater recharge estimation using chloride, deuterium, and oxygen-18 profiles in deep coastal sands of western Australia. J. Hydrol. 81:93-109.

Simmers I (1988) Estimation of natural groundwater recharge. NATO ASI series C 222, Reidel, Dordrecht.

Sophocleous MA (1991) Combining the soil water balance and water level fluctuation methods to estimate natural groundwater recharge: Practical aspects. J. Hydrology 124:229-241.

Sophocleous MA (2004) Groundwater recharge and water budgets of the Kansas High Plains and related aquifers. Kansas Geol. Surv. Bull. 249:1–102.

Sophocleous MA, Perry CA (1985) Experimental studies in natural groundwater recharge dynamics: the analysis of observed recharge events. J Hydrology 81(3/4):297-332.

Sililo OTN, Saayman IC, Fey MV (2001) Groundwater vulnerability to pollution in urban catchments. WRC Report No. 1008/1/01.



Sukhija BS, Nagabhushanam P, Reddy DV (1996) Groundwater recharge in semi-arid regions of India: an overview of results obtained using tracers. Hydrogeol J 4(3):50–71.

Sukhija BS, Reddy DV, Nagabhushanam P, Bhattacharya SK, Jani RA, Kumar D (2006) Characterization of recharge processes and groundwater flow mechanisms in weathered-fractured granite of Hyderabad (India) using isotopes. HJ 14:663-674.

Stoy PC, Katul GG, Siqueira MBS, Juang J-Y, Novick KA, McCarthy HR, Oishi AC, Uebelherr JM, Kim H-S, Oren R. 2006. Separating the effects of climate and vegetation on evapotranspiration along a successional chronosequence in the southeastern US. Glob Change Biol 12:2115–35.

Swanson SK (1996) A comparison of two methods used to estimate groundwater recharge in Dane County, Wisconsin. MSc Thesis, University of Wisconsin, Madison, USA.

Su H, McCabe MF, Wood EF, Su Z, Prueger J (2005) Modeling evapotranspiration during SMACEX, comparing two approaches for local and regional scale prediction, Journal of Hydrometeorology, 6, 910–22.

Tankard AJ (1974) Varswater Formation of the Langebaanweg-Saldanha area, Cape Province. Transactions Geological Society of South Africa, 77, p. 265-283.

Tankard AJ (1975) The marine Neogene Saldanha Formation. Transactions Geological Society of South Africa, 78, p. 257-264.

Tankard AJ, Jackson MPA, Eriksson KA, Hobday DK, Hunter DR, Minter WEL (1982) Crustal evolution of Southern Africa. Sringer-Verlag, New York.

Theron JN (1966) Glass-sand deposits in the Cape Flats. Reprints Geological Survey of South Africa (unpublished).

Theron JN (1974) Geological sheet 3418BA, Strandfontein (1:50 000): Geological Survey, South Africa (Open file).

Theron JN (1984) The geology of Cape Town and environs: Explanation of Sheets 3318CD, 3318DC, 3418AB, 3418Ad, 3418BA. Geological Survey of South Africa.

Theron, JN, Gresse PG, Siegfried HP, Rogers J (1992) The geology of the Cape Town area. Explanation on Sheet 3318, Geological Survey, South Africa, 140p.

Thornthwaite CW (1948) Instructions and tables for computing potential evapotranspiration and the water balance, Publications in Climatology, 10 (3):183–311.

Timmerman LRA (1985) Preliminary report on the Geohydrology of the Grootwater Primary Aquifer unit between Yzerfontein and the Modder River. Gh Report # 3372, Geohydrology, Cape Town.

Timmerman LRA (1986) Sandveld Region: Possibilities for the Development of a Groundwater Supply Scheme from a Primary Aquifer Northwest of Graafwater. Report Gh3471, Geohydrology, Cape.

Timmerman LRA (1987) Calculation of groundwater recharge by means of the Penman Formula for evapotranspiration. Technical Report GH 3557, Directorate of Geohydrology, Department of Water Affairs. lgium (unpublished).

Timmerman LRA (1988) Regional hydrogeological study of the lower Berg River area, Cape Province, South Africa. PhD thesis, Geology Department, State University Ghent, Belgium (unpublished).

Todd DK (1980) Ground water hydrology. Wiley , New York.

Traut MJ, Stow JG (1999) Coastal Park landfill site groundwater quality monitoring-Report 1, Sci-entific Services Dept., Directorate of Water and Waste, Cape Town City Council.

Traut MJ, Stow JG (2001) Groundwater quality monitoring: Coastal landfill Site. Report No.2, CMC Administration, Cape Town.

Tredoux G (1984) The groundwater pollution hazard in the Cape Flats. J. Water Poll. Cont. Vol.83, No. 4, pp 473-483.

Tredoux G (1993) A preliminary investigation of the nitrate content of groundwater and limitation of the nitrate input. Report to the Water Research Commission Report No. 368/1/93.

Tredoux G, Kirchner J (1985) The occurrence of nitrate in groundwater in South West Africa/Namibia. Paper presented at conference: *Nitrates in Water* (Paris), 12p.

Tredoux G, Talma AS (2006) Nitrate in southern Africa. In: Xu & Usher (eds), Groundwater Pollution in Africa, Taylor & Francis, London: 12-35.

Tredoux G, Engelbrecht JFP, Tama AS (2001) Nitrate in groundwater in Southern Africa. In: New Approaches Characterizing Groundwater Flow, K.P. Seiler and S. Wohnlich (Eds.). Swets & Zeitlinger, Lisse, pp. 663-666.

United States Environmental Protection Agency (USEPA). 1987: Case studies of proposed groundwater classification guidelines. Office Groundwater Protection and Office Policy Analysis. Washington, D.C.

Usher BH, Pretorius JA, Dennis I, Jovanovic N, Clarke S, Titus R, Xu Y (2004) Identification and prioritisation of groundwater contaminants and sources in South Africa's urban catchments. WRC Report No. 1326/1/04.

Vandoolaeghe MAC (1989) The Cape Flats groundwater development pilot abstraction scheme. Technical Report No. GH3655, Directorate Geohydrology, DWAF, Cape Town.

Vandoolaeghe MAC (1990) The Cape Flats aquifer. Technical Report No. GH3687, Directorate Geohydrology, DWAF, Cape Town.

Van Dam JC (1997) Seawater intrusion in coastal aquifers: guidelines for study, monitoring and control. FAO Water Reports 11, Roma: 1-152.

Van Stempvoort D, Ewert L, Wassenaar L (1993) Aquifer vulnerability index (AVI): A GIS compatible method for groundwater vulnerability mapping. Can. Water Res. Journ. 18:25-37.

van Zyl GN (1995) Population study for the Cape Metropolitan Region, 1995, unpublished.

Vengosh A, Gill J, Davisson ML, Hudson GB (2002) A multi-isotope (B, Sr, O, H, and C) and age dating ($^{3}H$-$^{3}He$ and $^{14}C$) study of groundwater from Salinas Valley, California: hydrochemistry, dynamics, and contamination processes. Water Resour Res 38:9-1–9-17.

Vias JM, Andreo B, Perles MJ, Carrasco F (2005) A comparative study of four schemes for groundwater vulnerability mapping in a dioffuse flow carbonate aquifer under Mediterranean climatic conditions. Environ Geol 47: 586-595.

Visser HN, Schoch AE (1973) The geology and mineral resources of the Saldanha Bay area. Memoir Geological Survey of South Africa, 63, p.1-150.

Vogel JC (1970) Carbon-14 dating of groundwater. Isotope Hydrol 1970 IAEA, Vienna: 225–240.

Vrba J, Zaporozec A (eds). 1994. Guidebook on mapping groundwater vulnerability. International Contributions to Hydrogeology, Vol. 16, International Asssociation of Hydrogeologists, Heise, Hannover.

Walker F (1952) The geology of Cape Peninsula. In: Cape Peninsula. Maskew Miller Ltd., Cape Town: 1-13.

Walker F (1956) The dolerites of the Cape Peninsula. Transactions Geological Society of South Africa, 59, p. 77-92.

Walker GR, Jolly ID, Cook PG (1991) A new chloride leaching approach to the estimation of diffuse recharge following a change in land use. J. Hydrol., 128: 49-67.

Walker GR, Cook PG, Gilfedder M (2002) Recharge/discharge determination. In Fundamentals of Groundwater Science, Technology and Management Vol. 2 – Technology, Australian Groundwater School.

Walter H, Leith H (1960) Klimadiagram. VEB Gustav Fischer Verlag, Jena.

Water Framework Directive (2006) Common implementation strategy, Guidance No. 15, Guidance on groundwater monitoring, European Communities.

Waterloo Hydrogeologic Inc. (1999) AquaChem version 3.7 for Windows: Aqueous Geochemical Analysis, Plotting and Modeling. Waterloo Hydrogeologic Inc. Software notes, Canada.

Weaver JMC, Tworeck WC (1988) Hydrogeological investigation of leachate attenuation at the Bellville South Solid Waste Disposal Site. Report to the Foundation for Research Development, CSIR.

Weaver JMC, Talma AS, Cave LC (1999) Geochemistry and isotopes for resource evaluation in the fractured rock aquifers of the TMG, WRC Report No. 481/1/99, Water Research Commission, Pretoria.

Wilson WE, Moore JE (1998) Glossary of hydrology. American Geological Institute, Virginia, 248p.

Wood WW, Rainwater KA, Thompson DB (1997) Quantifying macropore recharge: examples from a semi—arid area. Groundwater 35:1097–1106.

Woodborne MW (1983) Bathymetry, solid geology and Quaternary sedimentology of Table Bay. Technical report Joint Geological Survey/University of Cape Town, Marine Geoscience Unit, 14, p. 266-277.

Woodborne MW (1982) Sediment distribution and the correlation between lithofacies and associated seismic reflection signatures on Table Bay. B.Sc. (Honours) project, Geology Department, University of Cape Town (unpublished).

Wright W, Conrad J (1995) The Cape Flats Aquifer: Current status. CSIR report 11/95, Stellenbosch.

Wu Y (2005) Groundwater recharge estimation in TMG aquifer systems with a case study of Kammanassaie area. PhD Dissertation, University of the Western Cape.

Wu Y, Xu Y (2004) Recharge estimation with mixing model of chloride mass balance in Vermaaks River Valley, South Africa (extended abstract). Understanding Groundwater Flow from Local to Regional scales, XXXIII IAH Congress & ALHSUD Congress, Zacatecas, Mexico.

Xinping Z, Lide T, Jingmiao L (2005) Fractionation mechanism of stable isotope in evaporating water body. Journal of Geographical Sciences, Volume 15, Number 3, pp. 375-384.

Xu Y, Beekman HE (eds), 2003. Groundwater recharge estimation in Southern Africa. UNESCO IHP Series No. 64, UNESCO Paris. ISBN 92-9220-000-3.

Xu Y, van Tonder GJ (2001) Estimation of recharge using a revised CRB method. Water SA, Vol. 27, No.3: 15-23.

Xu Y, Wu Y, Titus R (2002) Influence of the Vermaaks Wellfield abstraction on groundwater levels and streams in vicinity. Report prepared for the Department of Water Affairs, Bellville (unpublished).

Xu Y, Wu Y, Duah A (2007) Groundwater recharge estimation of the TMG Aquifer Systems with case studies. WRC Report No. 1329/1/07.

Xu Y, Colvin C, van Tonder GJ, Hughes S, le Maitre D, Zhang J, Mafanya T, Braune E (2002b) Towards the resource directed measures: groundwater component. WRC Report No. 1090-2/1/03.



Yang Y, Lerner DN, Barret MH, Tellam JH (1999) Quantification of groundwater recharge in the city of Nottingham. Env. Geol. 38(3), 183-198.

Zhang S, Howard K, Otto C, Ritchie V, Solilo OTN, Appleyard S (2004) Sources, types, characteristics and investigation of urban groundwater pollutants. In: Lerner DN (eds.) Urban groundwater pollution, AA Balkema, Lisse, pp 53-107.

Zhu C, Winterle JR, Love EI (2003) Late Pleistocene and Holocene groundwater recharge from the chloride mass balance method and chlorine-36 data. Water Resour Res 39(7):1182.

Zuquette LV, Palma JB, Pejon OJ (2008) Methodology to assess groundwater pollution conditions (current and pre-disposition) in the São Carlos and Ribeirão Preto regions, Brazil. Bulletin of Engineering Geology and the Environment, 10.1007/s10064-008-0173-y.

Zwahlen F (ed) (2003) Vulnerability and risk mapping for the protection of carbonate (Karstic) aquifers. Final report COST action 620. European Commission, Directorate-General for Research, Brussels, 297 pp.

SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| *CCT* | City of CapeTown |
| *CMC* | Cape Metropolitan Council |
| *CSIR* | Centre for Scientific and International Research |
| *DWAF* | Department of water Affairs and Forestry |
| GMWL | Global Meteoric Water Line |
| *LMWL* | Local Meteoric Water Line |
| *meq* | Milli-equivalent |
| *UWC* | University of the Western Cape |
| *VSMOW* | Vienna Standard Mean Ocean Water |
| $g$ | Gravitational acceleration, $L^2/T$ |
| $h$ | Hydraulic head, L |
| $\boldsymbol{K}$ | Hydraulic conductivity, L/T |
| $n$ | Porosity |
| $Q_0$ | Constant well pumping rate, $L^3/T$ |
| $Q(t)$ | Well pumping-injection rate by volume, $L^3/T$ |
| $r$ | Radial distance from the pumping well, L |
| $r_{max}$ | Radial distance for maximum values of $u_j$ and $v_j$, L |
| $r_w$ | Radius of the pumping well, L |
| $R_{s,\ reg}$ | solar radiation at the regional location [MJ $m^{-2}$ $day^{-1}$], |
| $R_{a,\ reg}$ | Extra-terrestrial radiation at the regional location [MJ $m^{-2}$ $day^{-1}$]. |
| $R_a$ | extraterrestrial radiation [MJ $m^{-2}$ $d^{-1}$], $T_{min}$ |
| $T_{max}$ | maximum air temperature [°C], |
| $T_{min}$ | minimum air temperature [°C], |
| $k_{Rs}$ | adjustment coefficient (0.16.. 0.19) [$°C^{-0.5}$]. |
| $R_n$ | is the net radiation |
| G | is the soil heat flux |
| $(e_s - e_a)$ | represents the vapour pressure deficit of the air |
| $c_p$ | represents the slope of the saturation vapour pressure temperature relationship |
| $\gamma$ | psychrometric constant, |

| | |
|---|---|
| $r_s$ - $r_a$ | the (bulk) surface and aerodynamic resistances |
| $S_s$ | Specific storage |
| $t^*$ | $(=tK/S_s r^2)$ dimensionless time |
| $T$ | $(=bK)$ transmissivity, $L^3/T$ |
| $T_p$ | Pumping-injection period, 1/T |
| δ | delta |
| *d-excess* | Deuterium excess |
| ‰ | Part per thousand |
| $^2H$ or (D) | Deuterium or Hydrogen isotope |
| $^{18}O$ | Oxygen isotope |

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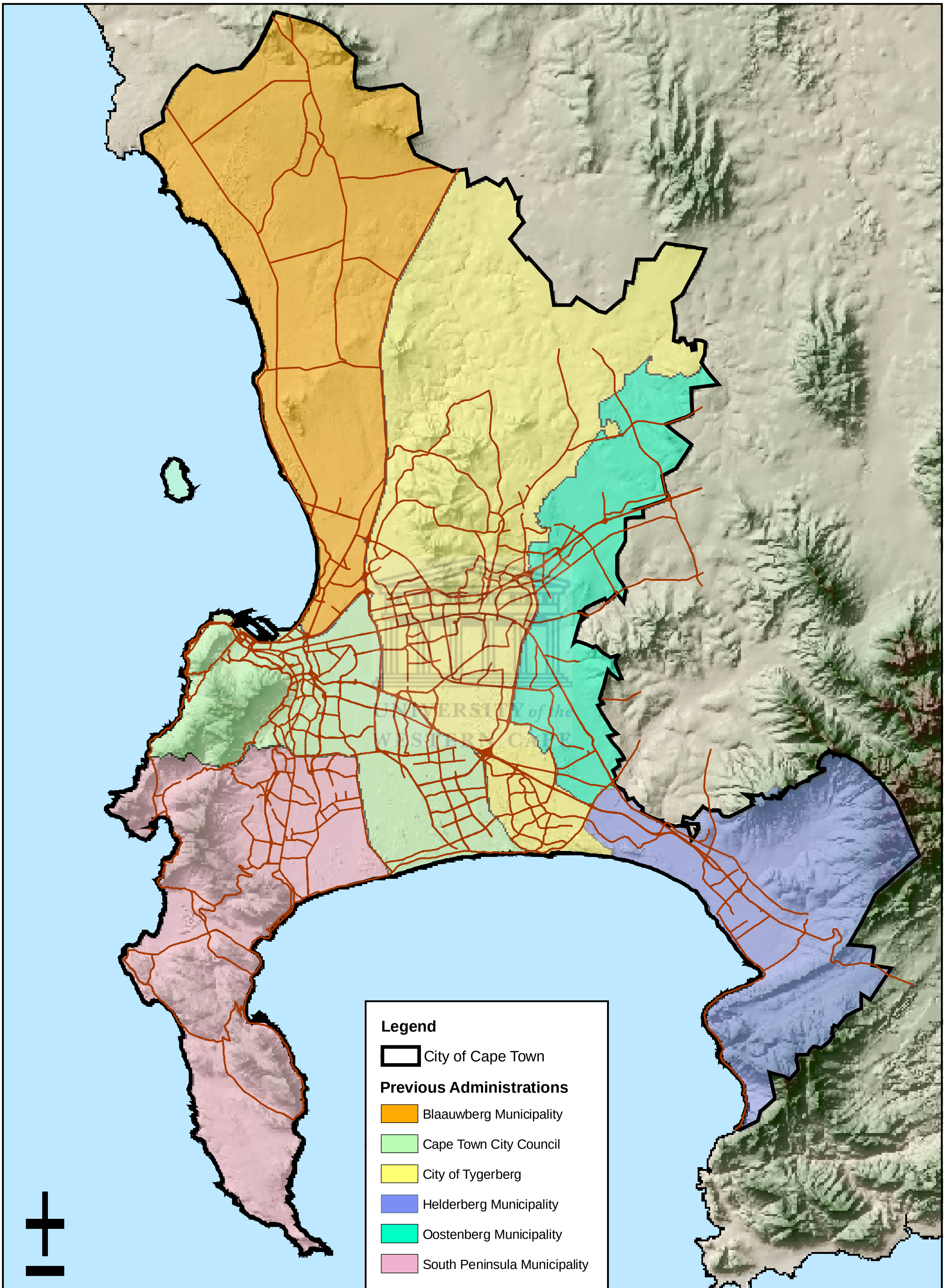
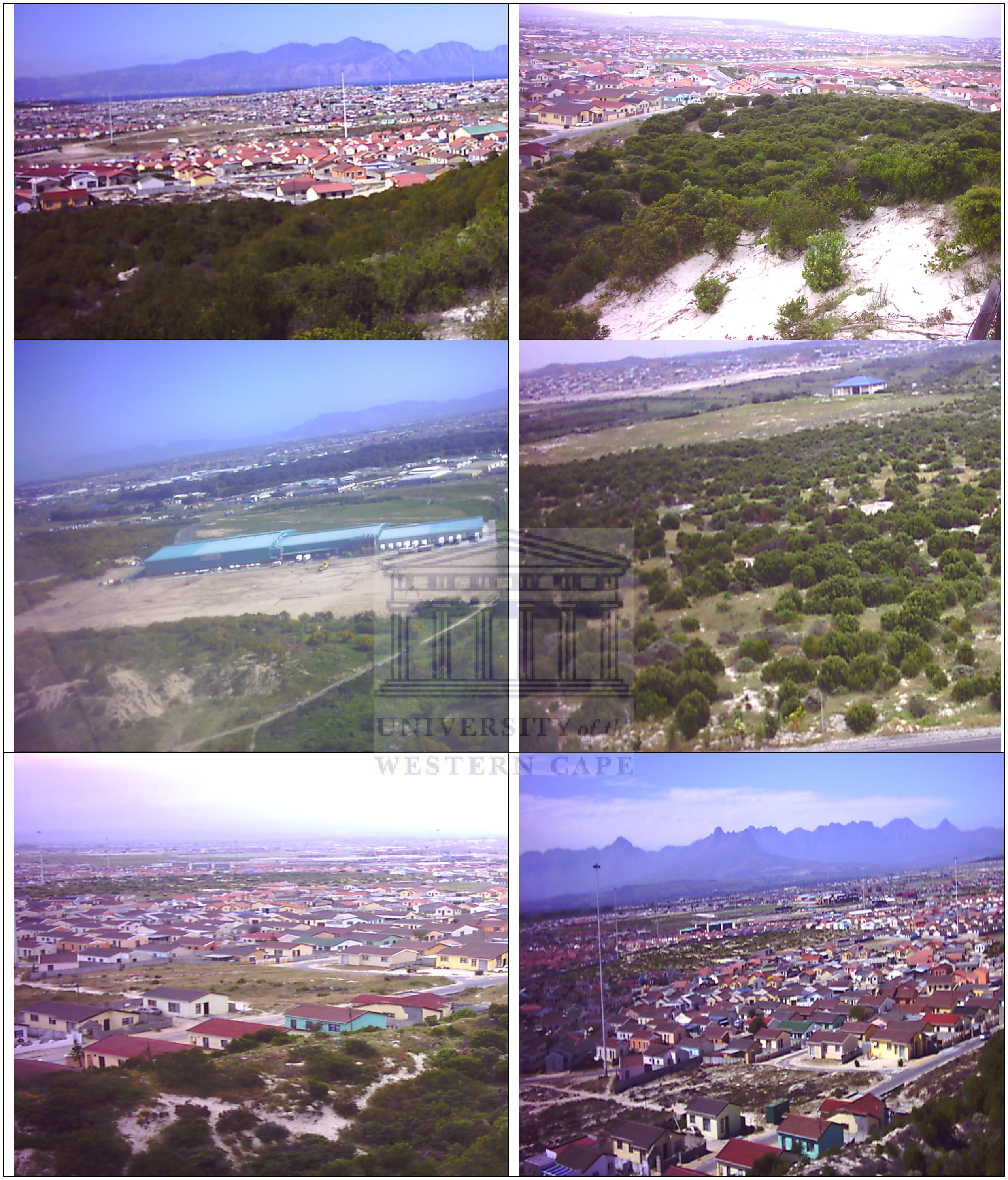
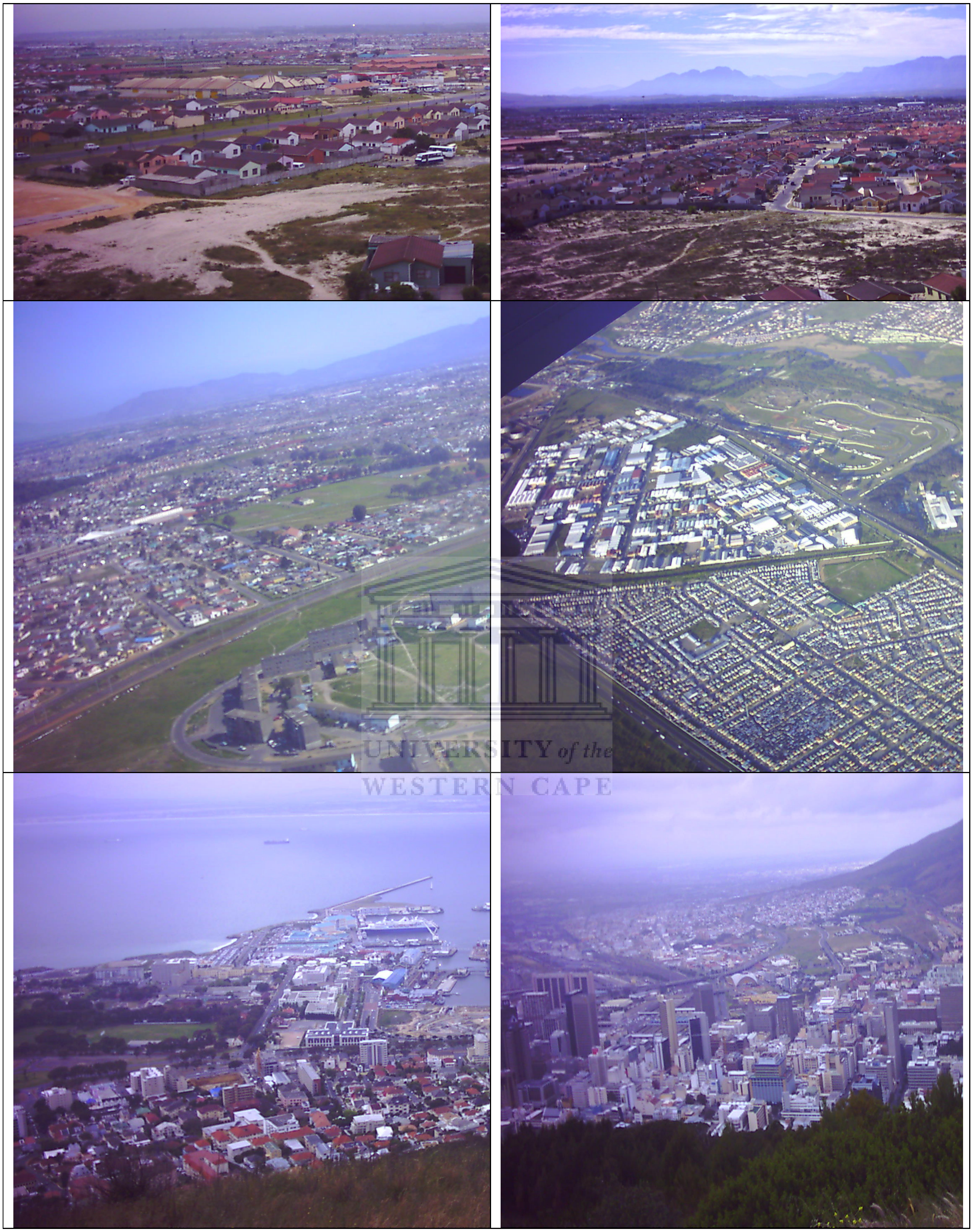



Produced by Strategic Development Information and GIS, June 2007

**City of Cape Town showing the previous Administrations**

**Appendix 2.1: Pictures of vegetation and land surface area open to recharge flux from rain**



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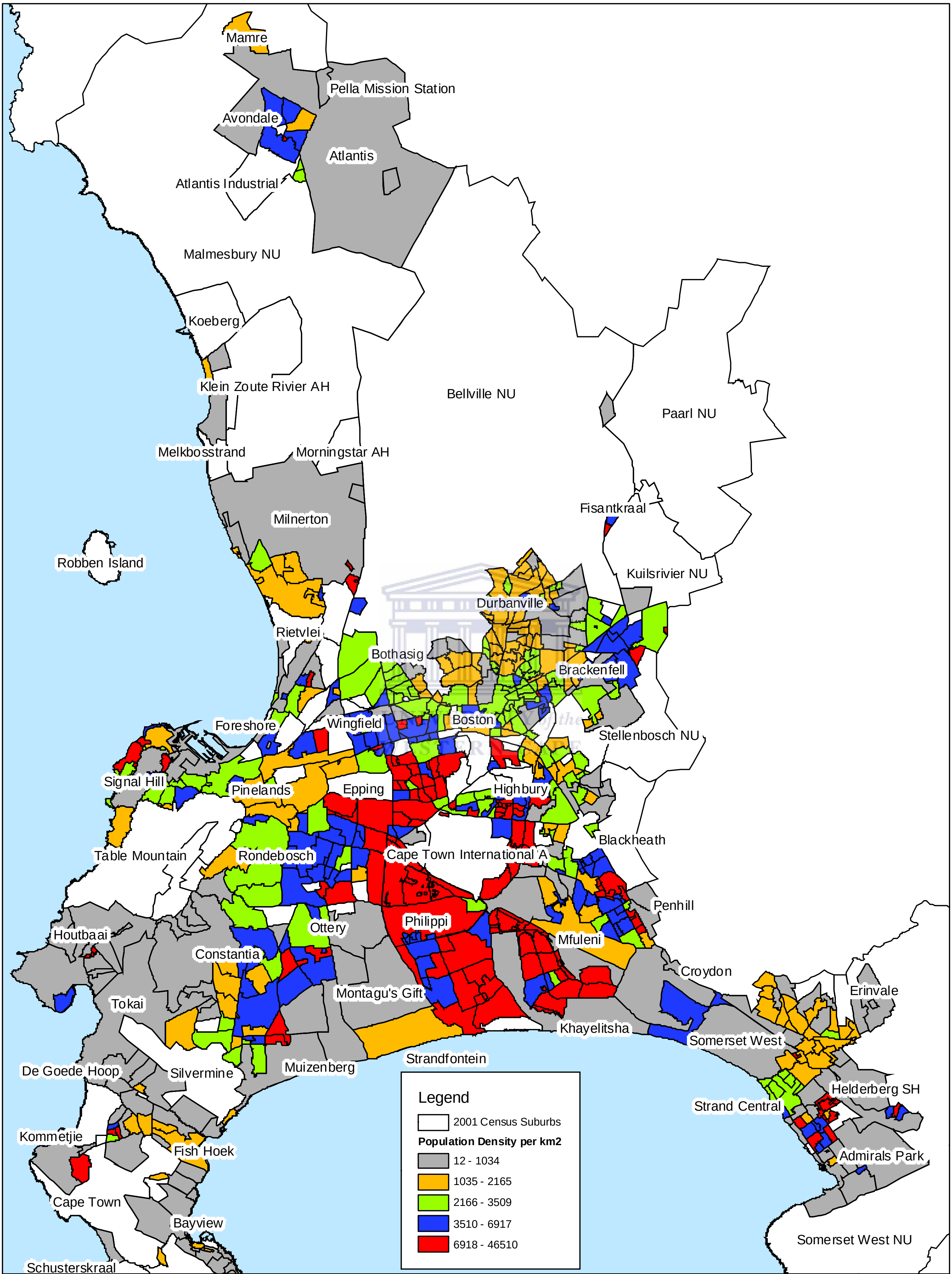



Produced by Strategic Development
Information and GIS, March 2006
Data extracted from 2001 Census, SSA

**2001 Population Density per km2 by Suburb**

THIS CITY WORKS FOR YOU

Appendix 4.1: Monthly Average of Daily Rain (mm) Data for station - CAPE TOWN

| Year | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1841 | | | | 41.1 | 82.5 | 99.1 | 31.2 | 60.5 | 37.8 | 93.5 | 26.5 | 30.2 | 502.4 |
| 1842 | 22.7 | 4.7 | 17.3 | 24.9 | 94.8 | 176.3 | 43.8 | 118.8 | 79.9 | 30.3 | 33.8 | 20.3 | 667.6 |
| 1843 | 0.2 | 37.7 | 8.4 | 78.7 | 73.2 | 174.5 | 62.4 | 59.8 | 33.1 | 5.9 | 94.0 | 2.1 | 630.0 |
| 1844 | 11.6 | 48.2 | 13.9 | 79.3 | 8.8 | 104.2 | 73.1 | 66.1 | 32.8 | 9.3 | 20.6 | 9.0 | 476.9 |
| 1845 | 80.9 | 7.5 | 17.4 | 22.5 | 95.4 | 63.2 | 48.2 | 95.1 | 68.3 | 9.5 | 11.0 | 11.6 | 530.6 |
| 1846 | 61.4 | 24.6 | 12.3 | 27.6 | 227.0 | 52.7 | 18.7 | 39.4 | 56.0 | 8.3 | 27.4 | 10.3 | 565.7 |
| 1847 | 15.7 | 2.0 | 4.2 | 85.6 | 58.8 | 70.0 | 44.9 | 153.1 | 37.5 | 32.6 | 36.0 | 27.7 | 568.1 |
| 1848 | 1.2 | 48.9 | 16.3 | 53.8 | 86.8 | 133.4 | 88.8 | 62.8 | 59.3 | 5.6 | 22.7 | 17.0 | 596.6 |
| 1849 | 6.4 | 11.7 | 12.5 | 14.8 | 170.9 | 88.7 | 110.4 | 75.9 | 58.6 | 15.3 | 23.7 | 36.6 | 625.5 |
| 1850 | 52.8 | 5.0 | 40.6 | 111.2 | 64.8 | 172.5 | 99.3 | 91.1 | 68.6 | 87.2 | 47.2 | 10.5 | 850.8 |
| 1851 | 6.6 | 0.9 | 3.8 | 24.8 | 75.8 | 173.4 | 97.8 | 15.1 | 35.5 | 53.4 | 15.1 | 15.3 | 517.5 |
| 1852 | 3.3 | 7.0 | 38.3 | 30.2 | 112.3 | 41.9 | 102.1 | 118.3 | 61.3 | 22.5 | 29.3 | 8.4 | 574.9 |
| 1853 | 25.7 | 12.2 | 52.1 | 31.2 | 71.1 | 100.9 | 109.2 | 79.9 | 38.0 | 33.6 | 2.1 | 4.4 | 560.4 |
| 1854 | 8.2 | 16.0 | 36.9 | 29.0 | 58.6 | 76.0 | 71.9 | 86.0 | 73.7 | 29.2 | 18.7 | 9.4 | 513.6 |
| 1855 | 8.8 | 4.3 | 26.2 | 40.1 | 78.7 | 113.6 | 68.7 | 133.5 | 124.1 | 16.5 | 3.2 | 0.3 | 618.0 |
| 1856 | 9.4 | 9.1 | 30.3 | 12.3 | 100.0 | 82.3 | 79.5 | 80.5 | 44.2 | 33.2 | 35.9 | 40.5 | 557.2 |
| 1857 | 4.6 | 12.8 | 2.7 | 64.2 | 70.5 | 115.6 | 78.0 | 111.4 | 45.2 | 33.1 | 6.6 | 31.2 | 575.9 |
| 1858 | 31.0 | 25.0 | 21.0 | 67.1 | 19.3 | 75.7 | 108.6 | 142.3 | 68.4 | 18.6 | 28.4 | 11.3 | 616.7 |
| 1859 | 46.3 | 24.5 | 26.7 | 19.8 | 175.9 | 138.6 | 165.8 | 124.2 | 81.8 | 61.1 | 65.6 | 5.4 | 935.7 |
| 1860 | 21.6 | 26.5 | 16.2 | 30.2 | 167.3 | 126.2 | 125.2 | 23.5 | 127.4 | 53.0 | 6.0 | 17.2 | 740.3 |
| 1861 | 20.3 | 1.7 | 22.1 | 40.3 | 109.5 | 193.3 | 109.2 | 48.6 | 64.7 | 2.7 | 32.7 | 1.3 | 646.4 |
| 1862 | 5.8 | 5.9 | 9.5 | 23.8 | 31.6 | 274.0 | 159.8 | 103.3 | 57.1 | 90.1 | 40.3 | 0.0 | 801.2 |
| 1863 | 5.1 | 17.1 | 74.2 | 65.1 | 136.6 | 81.4 | 60.3 | 68.1 | 43.6 | 68.9 | 23.4 | 8.2 | 652.0 |
| 1864 | 13.7 | 0.3 | 7.3 | 25.7 | 70.6 | 111.0 | 68.2 | 55.4 | 50.5 | 49.8 | 24.8 | 3.1 | 480.4 |
| 1865 | 7.6 | 3.5 | 9.9 | 47.0 | 98.6 | 23.9 | 124.9 | 42.5 | 16.6 | 78.9 | 14.5 | 6.9 | 474.8 |
| 1866 | 0.8 | 78.9 | 4.7 | 38.2 | 19.4 | 143.9 | 60.6 | 57.8 | 36.5 | 25.4 | 10.1 | 12.2 | 488.5 |
| 1867 | 10.0 | 27.0 | 26.8 | 62.0 | 77.3 | 90.0 | 110.2 | 34.8 | 36.7 | 89.5 | 5.4 | 14.0 | 583.7 |
| 1868 | 18.0 | 26.3 | 11.8 | 55.0 | 47.5 | 85.3 | 67.3 | 17.7 | 23.0 | 68.8 | 60.5 | 25.5 | 506.7 |
| 1869 | 4.4 | 1.7 | 14.1 | 47.7 | 204.6 | 241.9 | 77.9 | 104.6 | 30.0 | 26.1 | 32.8 | 35.9 | 821.7 |
| 1870 | 18.3 | 1.8 | 4.0 | 34.7 | 110.8 | 133.2 | 171.4 | 112.8 | 33.4 | 44.9 | 11.3 | 37.1 | 713.7 |
| 1871 | 8.1 | 4.3 | 24.7 | 37.6 | 78.9 | 97.8 | 76.0 | 89.6 | 29.5 | 18.7 | 18.4 | 27.7 | 511.3 |
| 1872 | 18.3 | 14.7 | 35.4 | 6.2 | 173.6 | 117.9 | 60.8 | 194.9 | 53.9 | 23.9 | 27.6 | 17.9 | 745.1 |
| 1873 | 7.3 | 5.5 | 14.2 | 55.9 | 100.1 | 126.8 | 82.5 | 102.6 | 27.4 | 21.5 | 16.3 | 44.4 | 604.5 |
| 1874 | 2.0 | 1.4 | 37.7 | 122.0 | 49.9 | 79.3 | 118.3 | 95.7 | 39.8 | 52.5 | 65.7 | 2.1 | 666.4 |
| 1875 | 0.0 | 35.0 | 15.4 | 34.3 | 44.9 | 144.2 | 29.1 | 104.0 | 97.5 | 53.9 | 32.9 | 58.8 | 650.0 |
| 1876 | 2.7 | 0.0 | 57.1 | 28.0 | 77.8 | 87.5 | 88.9 | 154.3 | 47.2 | 28.5 | 32.9 | 66.7 | 671.6 |
| 1877 | 18.4 | 41.0 | 14.0 | 90.7 | 344.8 | 69.4 | 32.2 | 93.1 | 41.0 | 45.0 | 76.5 | 40.7 | 906.8 |
| 1878 | 21.4 | 31.0 | 39.7 | 33.9 | 191.0 | 207.9 | 194.3 | 127.8 | 68.3 | 80.4 | 25.1 | 0.0 | 1020.8 |
| 1880 | 47.7 | 12.7 | 26.7 | 43.3 | 32.0 | 41.8 | 67.1 | 85.5 | 61.5 | 5.3 | 12.5 | 14.0 | 450.1 |
| 1881 | 9.1 | 2.8 | 23.0 | 90.5 | 174.8 | 82.9 | 71.8 | 89.8 | 31.2 | 27.0 | 36.7 | 10.3 | 649.9 |
| 1882 | 2.8 | 4.8 | 112.5 | 50.7 | 70.8 | 83.8 | 160.8 | 62.8 | 54.2 | 78.2 | 11.0 | 77.7 | 770.1 |
| 1883 | 31.6 | 10.4 | 27.7 | 60.2 | 148.0 | 126.1 | 138.3 | 108.8 | 80.4 | 60.6 | 1.6 | 21.0 | 814.7 |
| 1884 | 10.2 | 23.0 | 14.8 | 58.3 | 58.5 | 121.9 | 119.7 | 29.6 | 126.4 | 88.1 | 66.5 | 1.8 | 718.8 |
| 1885 | 10.7 | 53.8 | 29.1 | 48.8 | 94.8 | 157.0 | 52.4 | 107.4 | 39.1 | 46.4 | 42.0 | 27.1 | 708.6 |
| 1886 | 5.9 | 0.0 | 84.6 | 16.7 | 61.1 | 195.1 | 61.8 | 98.4 | 63.5 | 90.9 | 7.5 | 20.2 | 705.7 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1887 | 96.2 | 12.7 | 47.1 | 54.1 | 101.8 | 70.7 | 73.8 | 101.0 | 22.3 | 72.3 | 19.5 | 20.8 | 692.3 |
| 1888 | 4.2 | 0.4 | 18.0 | 92.2 | 217.4 | 247.5 | 95.4 | 73.8 | 72.0 | 13.2 | 36.0 | 29.6 | 899.7 |
| 1889 | 2.0 | 31.1 | 37.8 | 130.1 | 136.1 | 86.8 | 83.9 | 126.9 | 86.1 | 15.2 | 12.6 | 36.0 | 784.6 |
| 1890 | 11.2 | 32.3 | 4.8 | 54.5 | 150.5 | 18.0 | 162.3 | 92.4 | 53.5 | 37.7 | 35.8 | 16.2 | 669.2 |
| 1891 | 5.2 | 25.7 | 9.8 | 74.7 | 196.1 | 80.3 | 186.7 | 76.6 | 81.4 | 7.1 | 6.3 | 19.9 | 769.8 |
| 1892 | 21.9 | 4.2 | 44.3 | 53.5 | 105.3 | 289.7 | 157.2 | 143.2 | 63.7 | 27.3 | 50.6 | 76.8 | 1037.7 |
| 1893 | 1.6 | 9.8 | 3.4 | 51.0 | 63.3 | 117.1 | 57.1 | 139.2 | 94.8 | 51.0 | 5.8 | 1.1 | 595.2 |
| 1894 | 0.8 | 25.1 | 11.5 | 25.8 | 63.3 | 107.6 | 78.7 | 80.4 | 28.7 | 43.3 | 32.1 | 3.3 | 500.6 |
| 1895 | 16.4 | 0.0 | 18.2 | 77.5 | 96.0 | 91.6 | 41.8 | 63.6 | 95.0 | 50.0 | 23.7 | 14.6 | 588.4 |
| 1896 | 24.6 | 13.0 | 42.8 | 16.0 | 67.2 | 97.7 | 63.3 | 68.1 | 33.6 | 22.9 | 20.6 | 0.8 | 470.6 |
| 1897 | 9.9 | 22.1 | 19.5 | 25.4 | 46.7 | 46.6 | 127.5 | 71.2 | 63.1 | 46.9 | 17.7 | 14.1 | 510.7 |
| 1898 | 34.2 | 23.3 | 28.1 | 85.6 | 102.9 | 84.7 | 155.7 | 33.9 | 80.4 | 63.8 | 26.9 | 11.1 | 730.6 |
| 1899 | 20.3 | 5.5 | 10.8 | 37.4 | 88.4 | 51.0 | 108.0 | 224.5 | 33.9 | 58.4 | 8.1 | 33.0 | 679.3 |
| 1900 | 10.2 | 22.3 | 16.7 | 36.9 | 83.2 | 39.8 | 121.0 | 70.2 | 36.1 | 65.0 | 21.3 | 17.1 | 539.8 |
| 1901 | 129.2 | 16.3 | 8.5 | 18.9 | 165.6 | 34.8 | 129.8 | 14.8 | 50.7 | 20.4 | 56.8 | 7.8 | 653.6 |
| 1902 | 14.9 | 13.3 | 22.8 | 63.7 | 108.7 | 117.7 | 116.5 | 98.5 | 151.9 | 119.7 | 21.6 | 7.3 | 856.6 |
| 1903 | 46.0 | 5.6 | 33.9 | 55.2 | 131.0 | 172.2 | 63.1 | 81.8 | 58.1 | 94.7 | 6.4 | 11.3 | 759.3 |
| 1904 | 8.6 | 2.3 | 10.2 | 150.6 | 85.6 | 166.4 | 62.7 | 117.9 | 63.0 | 71.9 | 30.6 | 39.2 | 809.0 |
| 1905 | 15.3 | 15.0 | 25.4 | 1.3 | 115.0 | 337.8 | 62.7 | 77.6 | 40.4 | 36.2 | 22.4 | 17.1 | 766.2 |
| 1906 | 9.9 | 1.1 | 18.5 | 51.3 | 92.6 | 68.2 | 46.3 | 72.8 | 25.3 | 32.7 | 13.8 | 82.1 | 514.6 |
| 1907 | 14.5 | 5.8 | 20.8 | 49.1 | 159.5 | 50.9 | 35.1 | 37.7 | 43.2 | 30.5 | 20.8 | 38.3 | 506.2 |
| 1908 | 24.8 | 8.3 | 11.7 | 124.7 | 31.4 | 147.9 | 67.7 | 77.0 | 44.9 | 51.7 | 26.2 | 11.0 | 627.3 |
| 1909 | 14.7 | 1.7 | 77.0 | 9.0 | 48.9 | 44.7 | 61.9 | 185.9 | 19.8 | 58.5 | 12.7 | 75.3 | 610.1 |
| 1910 | 0.2 | 9.9 | 32.0 | 29.2 | 111.3 | 69.9 | 109.0 | 74.2 | 34.9 | 37.3 | 37.3 | 1.6 | 546.8 |
| 1911 | 16.0 | 12.9 | 6.7 | 45.1 | 132.0 | 115.0 | 102.8 | 58.8 | 116.6 | 24.5 | 30.2 | 35.1 | 695.7 |
| 1912 | 4.3 | 8.8 | 19.5 | 84.1 | 69.0 | 60.7 | 55.4 | 89.6 | 106.9 | 23.4 | 36.6 | 1.5 | 559.8 |
| 1913 | 9.7 | 21.2 | 2.9 | 60.2 | 62.2 | 84.9 | 101.8 | 95.6 | 49.6 | 38.1 | 44.6 | 38.8 | 609.6 |
| 1914 | 61.4 | 8.3 | 8.4 | 41.4 | 63.0 | 100.7 | 109.1 | 111.3 | 77.4 | 14.1 | 27.5 | 13.0 | 635.6 |
| 1915 | 0.1 | 0.0 | 46.2 | 71.4 | 49.2 | 150.6 | 169.9 | 52.0 | 64.7 | 12.9 | 30.6 | 12.7 | 660.3 |
| 1916 | 10.9 | 10.1 | 13.2 | 25.2 | 74.4 | 105.1 | 82.5 | 130.0 | 46.2 | 19.3 | 9.3 | 12.3 | 538.5 |
| 1917 | 19.6 | 0.9 | 12.3 | 27.9 | 108.7 | 97.6 | 218.5 | 54.7 | 43.7 | 28.0 | 19.9 | 11.7 | 643.5 |
| 1918 | 1.3 | 12.1 | 22.9 | 26.1 | 117.4 | 122.1 | 93.0 | 5.5 | 47.1 | 43.8 | 55.6 | 21.8 | 568.7 |
| 1919 | 24.7 | 39.7 | 3.3 | 43.4 | 38.3 | 75.9 | 96.5 | 55.7 | 90.0 | 8.2 | 17.2 | 4.8 | 497.7 |
| 1920 | 7.3 | 7.3 | 4.1 | 19.3 | 87.1 | 138.8 | 131.6 | 81.0 | 92.8 | 53.8 | 19.5 | 42.4 | 685.0 |
| 1921 | 19.5 | 34.4 | 7.2 | 38.2 | 8.7 | 201.3 | 108.0 | 102.6 | 73.1 | 30.7 | 13.0 | 19.3 | 656.0 |
| 1922 | 42.1 | 22.1 | 14.5 | 28.4 | 43.5 | 106.2 | 59.4 | 94.2 | 22.1 | 37.8 | 11.1 | 4.1 | 485.5 |
| 1923 | 13.5 | 4.1 | 17.8 | 68.9 | 136.1 | 139.5 | 95.0 | 80.7 | 46.9 | 19.1 | 81.3 | 5.2 | 708.1 |
| 1924 | 6.6 | 0.2 | 18.7 | 22.3 | 48.9 | 121.1 | 39.6 | 100.4 | 34.9 | 45.7 | 38.4 | 1.1 | 477.9 |
| 1925 | 14.9 | 5.1 | 0.4 | 12.2 | 37.1 | 236.8 | 101.5 | 39.6 | 34.9 | 82.5 | 48.6 | 6.3 | 619.9 |
| 1926 | 7.6 | 21.3 | 5.5 | 18.3 | 92.0 | 44.0 | 111.6 | 76.1 | 46.1 | 67.4 | 11.5 | 1.4 | 502.8 |
| 1927 | 4.4 | 33.2 | 8.5 | 34.4 | 76.0 | 43.1 | 44.3 | 129.1 | 18.5 | 19.5 | 38.5 | 32.5 | 482.0 |
| 1928 | 13.7 | 10.5 | 14.5 | 17.7 | 9.2 | 110.6 | 39.5 | 57.8 | 80.4 | 22.1 | 22.4 | 24.8 | 423.2 |
| 1929 | 0.0 | 11.6 | 12.5 | 82.4 | 59.1 | 72.4 | 98.6 | 49.1 | 46.4 | 14.6 | 15.1 | 34.6 | 496.4 |
| 1930 | 19.3 | 27.7 | 11.8 | 23.4 | 7.8 | 16.6 | 67.3 | 62.3 | 130.5 | 14.8 | 26.1 | 11.3 | 418.9 |
| 1931 | 0.0 | 32.6 | 0.1 | 97.4 | 51.6 | 30.0 | 39.3 | 100.8 | 57.1 | 54.6 | 3.2 | 18.2 | 484.9 |
| 1932 | 11.4 | 51.3 | 19.0 | 8.6 | 126.9 | 121.7 | 65.5 | 71.5 | 56.9 | 21.2 | 8.7 | 41.1 | 603.8 |
| 1933 | 43.7 | 6.9 | 9.6 | 1.4 | 49.1 | 118.6 | 92.9 | 60.4 | 18.7 | 27.5 | 10.9 | 1.7 | 441.4 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1934 | 13.7 | 11.7 | 24.6 | 4.1 | 111.1 | 45.7 | 75.3 | 85.1 | 54.0 | 53.7 | 11.5 | 5.4 | 495.9 |
| 1935 | 8.6 | 5.6 | 20.4 | 32.5 | 14.8 | 8.0 | 15.3 | 10.1 | 53.5 | 24.7 | 27.9 | 8.0 | 229.4 |
| 1936 | 54.1 | 9.1 | 30.9 | 13.2 | 68.6 | 72.9 | 73.4 | 83.3 | 64.9 | 25.1 | 5.6 | 31.4 | 532.5 |
| 1937 | 29.7 | 7.1 | 47.1 | 55.0 | 87.5 | 206.0 | 151.4 | 35.4 | 43.3 | 28.8 | 27.6 | 0.8 | 719.7 |
| 1938 | 24.6 | 7.0 | 17.2 | 80.2 | 121.7 | 50.7 | 69.5 | 71.0 | 85.0 | 61.5 | 24.2 | 30.8 | 643.4 |
| 1939 | 0.3 | 41.2 | 10.2 | 38.9 | 101.7 | 49.2 | 91.4 | 69.0 | 30.3 | 7.7 | 31.2 | 16.6 | 487.7 |
| 1940 | 4.4 | 44.3 | 28.5 | 97.7 | 88.9 | 127.0 | 68.0 | 27.9 | 51.8 | 40.0 | 29.5 | 13.1 | 621.1 |
| 1941 | 25.6 | 12.8 | 38.2 | 135.6 | 151.3 | 115.3 | 95.4 | 66.5 | 98.7 | 53.5 | 16.4 | 29.8 | 839.1 |
| 1942 | 18.1 | 4.4 | 13.5 | 49.4 | 152.1 | 196.8 | 66.2 | 94.8 | 52.5 | 33.1 | 6.1 | 9.6 | 696.6 |
| 1943 | 43.2 | 13.3 | 24.8 | 56.4 | 86.2 | 56.2 | 87.1 | 93.3 | 45.3 | 44.8 | 20.9 | 4.0 | 575.5 |
| 1944 | 50.8 | 5.3 | 5.4 | 43.3 | 119.4 | 214.5 | 135.7 | 123.8 | 81.0 | 50.7 | 25.7 | 33.1 | 888.7 |
| 1945 | 0.8 | 1.1 | 5.1 | 43.5 | 177.9 | 166.7 | 95.2 | 87.0 | 5.5 | 33.6 | 4.6 | 171.2 | 792.2 |
| 1946 | 13.9 | 17.7 | 30.0 | 57.8 | 89.9 | 42.5 | 82.9 | 83.5 | 146.2 | 25.5 | 11.3 | 17.4 | 618.6 |
| 1947 | 13.3 | 2.1 | 65.0 | 30.1 | 88.3 | 45.0 | 196.5 | 48.0 | 35.5 | 0.0 | 5.6 | 9.2 | 538.6 |
| 1948 | 35.1 | 3.4 | 40.3 | 48.2 | 102.7 | 73.4 | 134.3 | 50.9 | 68.5 | 41.0 | 8.3 | 20.6 | 626.7 |
| 1949 | 15.5 | 5.0 | 6.2 | 65.3 | 41.6 | 67.7 | 100.3 | 95.6 | 63.6 | 26.4 | 31.7 | 11.1 | 530.0 |
| 1950 | 6.8 | 3.1 | 8.9 | 117.5 | 60.5 | 50.2 | 234.7 | 42.0 | 99.2 | 31.3 | 42.7 | 18.1 | 715.0 |
| 1951 | 32.5 | 2.4 | 17.0 | 152.4 | 51.6 | 179.2 | 97.9 | 44.2 | 66.4 | 30.5 | 49.1 | 0.8 | 724.0 |
| 1952 | 1.3 | 10.9 | 21.1 | 46.2 | 76.5 | 65.0 | 86.6 | 144.4 | 121.0 | 18.9 | 47.1 | 10.8 | 649.8 |
| 1953 | 2.0 | 4.4 | 9.0 | 162.8 | 145.3 | 53.2 | 100.2 | 54.3 | 19.4 | 29.5 | 27.4 | 10.1 | 617.6 |
| 1954 | 11.4 | 16.4 | 12.4 | 51.5 | 263.1 | 82.9 | 191.7 | 95.0 | 42.9 | 34.6 | 13.8 | 21.6 | 837.3 |
| 1955 | 0.2 | 70.0 | 12.5 | 56.8 | 16.1 | 48.3 | 126.0 | 141.7 | 29.2 | 44.7 | 36.9 | 25.9 | 608.3 |
| 1956 | 10.1 | 7.3 | 19.6 | 39.2 | 146.1 | 140.1 | 129.3 | 117.5 | 28.4 | 51.3 | 4.0 | 42.5 | 735.4 |
| 1957 | 5.4 | 31.4 | 32.7 | 21.2 | 145.8 | 115.2 | 152.7 | 183.4 | 37.7 | 123.0 | 7.8 | 0.4 | 856.7 |
| 1958 | 8.2 | 62.2 | 14.3 | 61.1 | 117.4 | 46.4 | 16.1 | 95.8 | 23.3 | 25.7 | 18.6 | 0.0 | 489.1 |
| 1959 | 17.7 | 13.6 | 35.5 | 132.2 | 192.7 | 20.7 | 32.8 | 78.1 | 38.4 | 33.4 | 6.2 | 25.5 | 626.8 |
| 1960 | 5.8 | 8.9 | 30.1 | 30.5 | 82.5 | 172.9 | 32.3 | 21.0 | 18.0 | 5.5 | 1.6 | 18.3 | 427.4 |
| 1961 | 34.5 | 6.6 | 40.9 | 6.6 | 44.2 | 126.3 | 46.0 | 72.4 | 97.1 | 20.6 | 0.3 | 13.8 | 509.3 |
| 1962 | 2.8 | 39.6 | 68.4 | 77.8 | 0.0 | 221.5 | 64.2 | 74.0 | 34.5 | 112.6 | 17.2 | 2.6 | 715.2 |
| 1963 | 69.2 | 0.7 | 5.3 | 8.6 | 22.3 | 77.9 | 108.4 | 81.3 | 26.7 | 12.4 | 40.7 | 16.6 | 470.1 |
| 1964 | 2.5 | 28.1 | 1.9 | 16.4 | 39.7 | 113.5 | 70.6 | 87.6 | 36.6 | 49.3 | 30.4 | 2.7 | 479.3 |
| 1965 | 25.4 | 25.9 | 50.5 | 57.4 | 74.1 | 47.5 | 68.3 | 77.3 | 16.4 | 40.0 | 7.0 | 33.7 | 523.5 |
| 1966 | 8.9 | 36.0 | 66.5 | 37.3 | 66.6 | 48.8 | 115.5 | 108.1 | 43.6 | 12.7 | 33.4 | 15.8 | 593.2 |
| 1967 | 21.8 | 0.0 | 10.0 | 79.0 | 48.9 | 130.1 | 63.7 | 39.0 | 26.9 | 36.0 | 41.8 | 2.8 | 500.0 |
| 1968 | 33.0 | 6.3 | 0.0 | 54.3 | 110.8 | 171.3 | 103.4 | 64.5 | 9.7 | 68.7 | 2.2 | 25.6 | 649.8 |
| 1969 | 35.0 | 6.7 | 19.6 | 48.2 | 14.5 | 114.9 | 47.5 | 68.1 | 51.5 | 45.0 | 7.8 | 5.8 | 464.6 |
| 1970 | 10.1 | 18.1 | 3.8 | 7.0 | 132.9 | 122.4 | 114.4 | 100.0 | 56.4 | 58.4 | 12.1 | 34.8 | 670.4 |
| 1971 | 9.5 | 0.0 | 6.6 | 20.0 | 56.4 | 57.6 | 86.9 | 82.6 | 76.8 | 24.0 | 4.3 | 12.8 | 437.5 |
| 1972 | 19.7 | 10.3 | 15.7 | 55.2 | 78.5 | 65.6 | 56.7 | 69.4 | 42.3 | 15.2 | 0.0 | 34.6 | 463.2 |
| 1973 | 1.3 | 0.3 | 9.1 | 5.8 | 42.9 | 31.6 | 84.4 | 71.7 | 46.6 | 13.2 | 13.7 | 27.2 | 347.8 |
| 1974 | 20.2 | 6.2 | 7.4 | 18.6 | 132.8 | 184.3 | 49.2 | 230.1 | 48.6 | 52.0 | 36.0 | 10.7 | 796.1 |
| 1975 | 24.2 | 2.1 | 7.8 | 51.1 | 194.0 | 53.1 | 153.2 | 57.9 | 4.0 | 40.1 | 32.2 | 3.5 | 623.2 |
| 1976 | 0.0 | 3.2 | 114.4 | 50.7 | 63.3 | 173.2 | 53.9 | 71.8 | 54.1 | 8.2 | 64.0 | 52.0 | 708.8 |
| 1977 | 14.9 | 67.2 | 10.1 | 64.2 | 128.1 | 177.3 | 123.1 | 112.7 | 47.7 | 13.1 | 16.4 | 20.6 | 795.4 |
| 1978 | 13.6 | 28.4 | 13.7 | 65.0 | 45.9 | 23.1 | 27.2 | 107.5 | 57.2 | 39.1 | 6.0 | 16.8 | 443.5 |
| 1979 | 22.3 | 22.5 | 8.2 | 5.5 | 80.4 | 79.8 | 53.4 | 22.8 | 29.6 | 135.0 | 8.1 | 0.4 | 468.0 |
| 1980 | 14.0 | 20.5 | 0.1 | 60.7 | 100.8 | 90.6 | 20.7 | 210.1 | 37.6 | 26.5 | 57.1 | 19.6 | 658.3 |

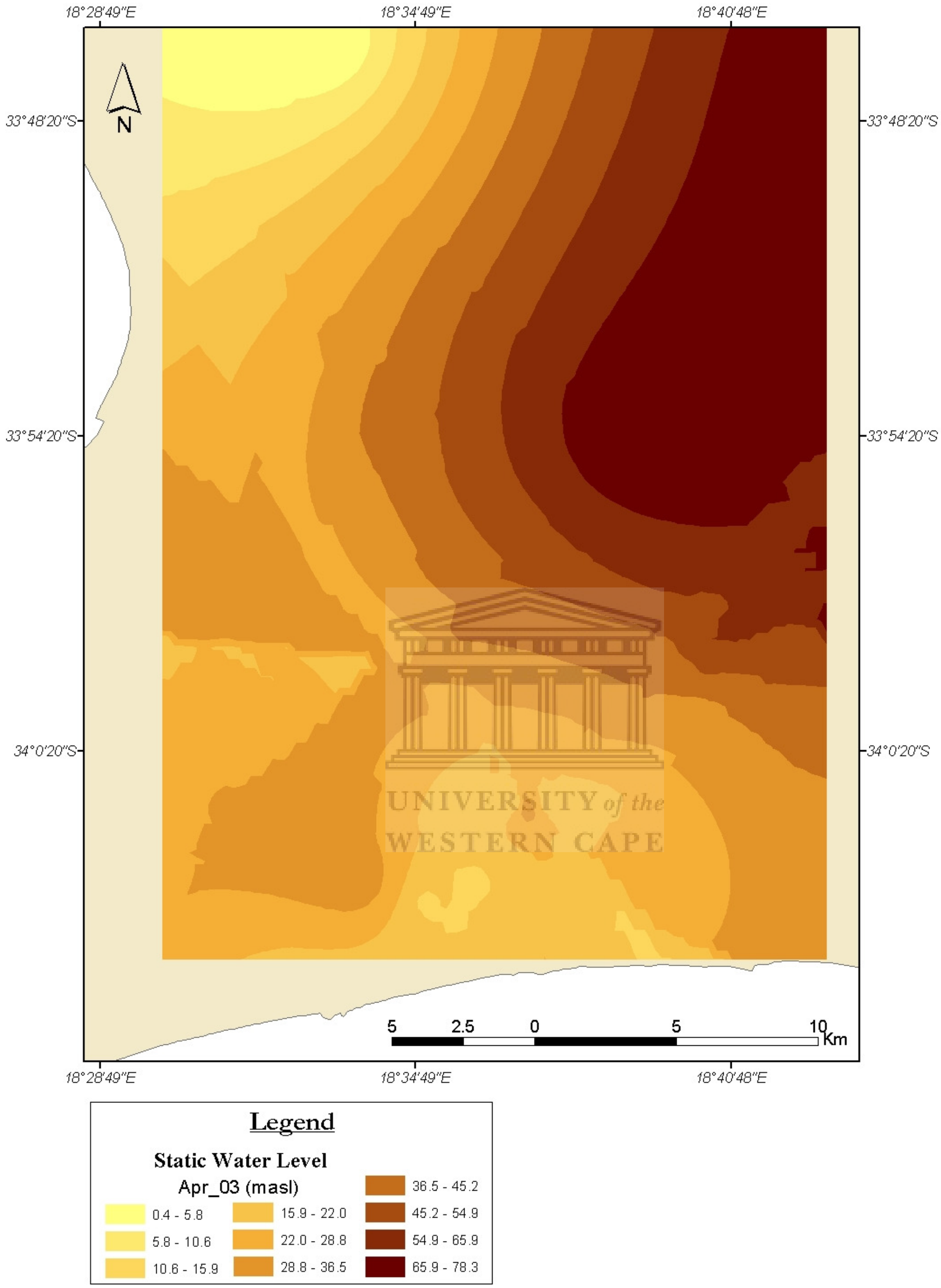
| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1981 | 62.4 | 0.0 | 46.1 | 55.7 | 20.9 | 125.7 | 129.7 | 96.9 | 73.5 | 8.4 | 15.1 | 29.1 | 663.5 |
| 1982 | 27.3 | 3.6 | 5.1 | 38.3 | 41.9 | 75.5 | 134.3 | 87.9 | 13.5 | 26.2 | 27.8 | 27.3 | 508.7 |
| 1983 | 2.7 | 27.3 | 56.4 | 8.4 | 115.0 | 180.2 | 92.2 | 45.1 | 39.4 | 15.3 | 6.0 | 8.2 | 596.2 |
| 1984 | 4.3 | 5.6 | 20.2 | 36.4 | 128.5 | 31.1 | 76.9 | 42.6 | 100.2 | 54.9 | 0.8 | 54.0 | 555.5 |
| 1985 | 24.5 | 20.4 | 79.9 | 62.6 | 47.0 | 128.1 | 119.1 | 94.1 | 38.9 | 6.0 | 3.3 | 3.5 | 627.4 |
| 1986 | 12.5 | 8.1 | 30.3 | 61.2 | 45.8 | 174.1 | 134.0 | 136.7 | 36.4 | 32.7 | 18.9 | 8.5 | 699.2 |
| 1987 | 74.9 | 11.8 | 19.3 | 48.4 | 93.0 | 113.4 | 186.3 | 149.7 | 58.7 | 8.9 | 20.3 | 38.9 | 823.6 |
| 1988 | 0.0 | | 15.4 | 41.8 | 64.4 | 31.0 | 87.1 | 114.8 | 44.8 | 40.5 | 11.5 | 1.5 | 452.8 |
| 1989 | 0.0 | 36.5 | 85.6 | 82.4 | 132.6 | 69.3 | 167.5 | 143.3 | 110.2 | 50.3 | 32.6 | 3.4 | 913.7 |
| 1990 | 43.4 | 62.4 | 0.0 | 142.9 | 86.9 | 114.3 | 157.7 | 36.7 | 24.3 | 5.1 | 16.7 | 16.3 | 706.7 |
| 1991 | 3.3 | 19.8 | 7.1 | 17.7 | 69.7 | 110.1 | 190.4 | 35.4 | 84.4 | 50.6 | 10.4 | 6.7 | 605.6 |
| 1992 | 0.0 | 34.7 | 10.2 | 98.4 | 85.5 | 133.8 | 71.6 | 42.4 | 73.1 | 62.3 | 10.8 | 16.9 | 639.7 |
| 1993 | 9.9 | 49.1 | 5.3 | 172.5 | 198.1 | 82.5 | 117.7 | 82.0 | 10.5 | 2.0 | 5.6 | 33.7 | 768.9 |
| 1994 | 17.0 | 2.2 | 8.7 | 34.5 | 52.4 | 248.5 | 75.8 | 35.3 | 32.4 | 16.5 | 6.2 | 0.0 | 529.5 |
| 1995 | 41.4 | 0.8 | 0.4 | 27.7 | 71.5 | 102.9 | 125.9 | 78.6 | 3.8 | 30.2 | 2.5 | 14.8 | 500.5 |
| 1996 | 0.0 | 29.6 | 27.6 | 41.1 | 37.1 | 105.9 | 119.8 | 88.1 | 91.2 | 51.4 | 36.2 | 27.2 | 655.2 |
| 1997 | 8.3 | 5.6 | 0.1 | 57.2 | 69.1 | 100.9 | 27.0 | 107.1 | 8.1 | 22.1 | 80.2 | 5.2 | 490.9 |
| 1998 | 11.3 | 0.0 | 17.8 | 47.6 | 145.0 | 71.6 | 96.8 | 50.0 | 27.8 | 22.1 | 60.3 | 50.5 | 600.8 |
| 1999 | 0.1 | 1.5 | 0.0 | 71.9 | 33.3 | 65.6 | 36.9 | 98.1 | 112.4 | 0.2 | 20.3 | 0.0 | 440.3 |
| 2000 | 13.7 | 0.0 | 6.0 | 10.2 | 30.9 | 83.2 | 67.9 | 56.4 | 58.7 | 8.5 | 9.2 | 0.5 | 345.2 |
| 2001 | 15.0 | 14.3 | 0.0 | 36.5 | 112.4 | 81.5 | 222.3 | 134.5 | 111.5 | 40.1 | 12.5 | 3.0 | 783.6 |
| 2002 | 49.7 | 14.5 | 3.5 | 38.8 | 70.4 | 105.3 | 100.0 | 57.8 | 20.0 | 38.8 | 20.5 | 5.0 | 524.3 |
| 2003 | 3.1 | 10.6 | 38.5 | 14.3 | 33.5 | 33.0 | 46.9 | 146.1 | 66.3 | 19.2 | 1.0 | 11.8 | 424.3 |
| 2004 | 9.8 | 0.6 | 12.9 | 90.0 | 12.2 | 75.3 | 76.5 | 195.5 | 43.0 | 126.0 | 4.0 | 2.7 | 648.5 |
| 2005 | 30.7 | 1.5 | 3.8 | 97.9 | 134.7 | 105.6 | 43.6 | 157.3 | 29.7 | 13.5 | 20.1 | 1.2 | 639.6 |
| 2006 | 0.0 | 13.0 | 4.7 | 30.1 | 121.8 | 34.0 | 71.4 | 56.2 | 20 | 37.2 | 37.7 | 10 | 436.1 |
| 2007 | 0.5 | 27.3 | 18.6 | 65.6 | 96.0 | 123.4 | 151.5 | 101.5 | 18.2 | 18.7 | 40.8 | 18.5 | 680.6 |
| 2008 | 6.8 | 13.9 | 5.2 | 15.2 | 51.4 | 63.2 | 182.4 | 79.6 | 138 | 12.4 | 53.1 | 7.8 | 628.8 |
| 2009 | 1.4 | 3.6 | 0.8 | 24.0 | 64.4 | 108.4 | 88.4 | 52.0 | 60.2 | 31.6 | 86.2 | 4.4 | 525.4 |
| **Maximum:** | **129.2** | **78.9** | **114.4** | **172.5** | **344.8** | **337.8** | **234.7** | **230.1** | **151.9** | **135.0** | **94.0** | **171.2** | **1037.7** |
| **Minimum:** | **0.0** | **0.0** | **0.0** | **1.3** | **0.0** | **8.0** | **15.3** | **5.5** | **3.8** | **0.0** | **0.0** | **0.0** | **229.4** |
| **Range:** | **129.2** | **78.9** | **114.4** | **171.2** | **344.8** | **329.8** | **219.4** | **224.6** | **148.1** | **135.0** | **94.0** | **171.2** | **808.3** |
| **Median:** | **11.4** | **10.5** | **15.4** | **44.3** | **82.5** | **99.9** | **87.8** | **81.2** | **47.2** | **32.7** | **20.6** | **14.0** | **617.8** |
| **Mean:** | **17.5** | **15.6** | **21.6** | **50.3** | **90.8** | **106.2** | **94.2** | **86.0** | **54.5** | **38.2** | **24.5** | **19.2** | **618.2** |
| **Std.dev.** | **19.4** | **15.8** | **20.6** | **33.7** | **53.2** | **58.2** | **44.8** | **40.9** | **29.9** | **26.4** | **18.7** | **20.4** | **134.3** |

Appendix 4.2: Average Daily Temperature (˚C) Data for station - CAPE TOWN Measured at 08:00

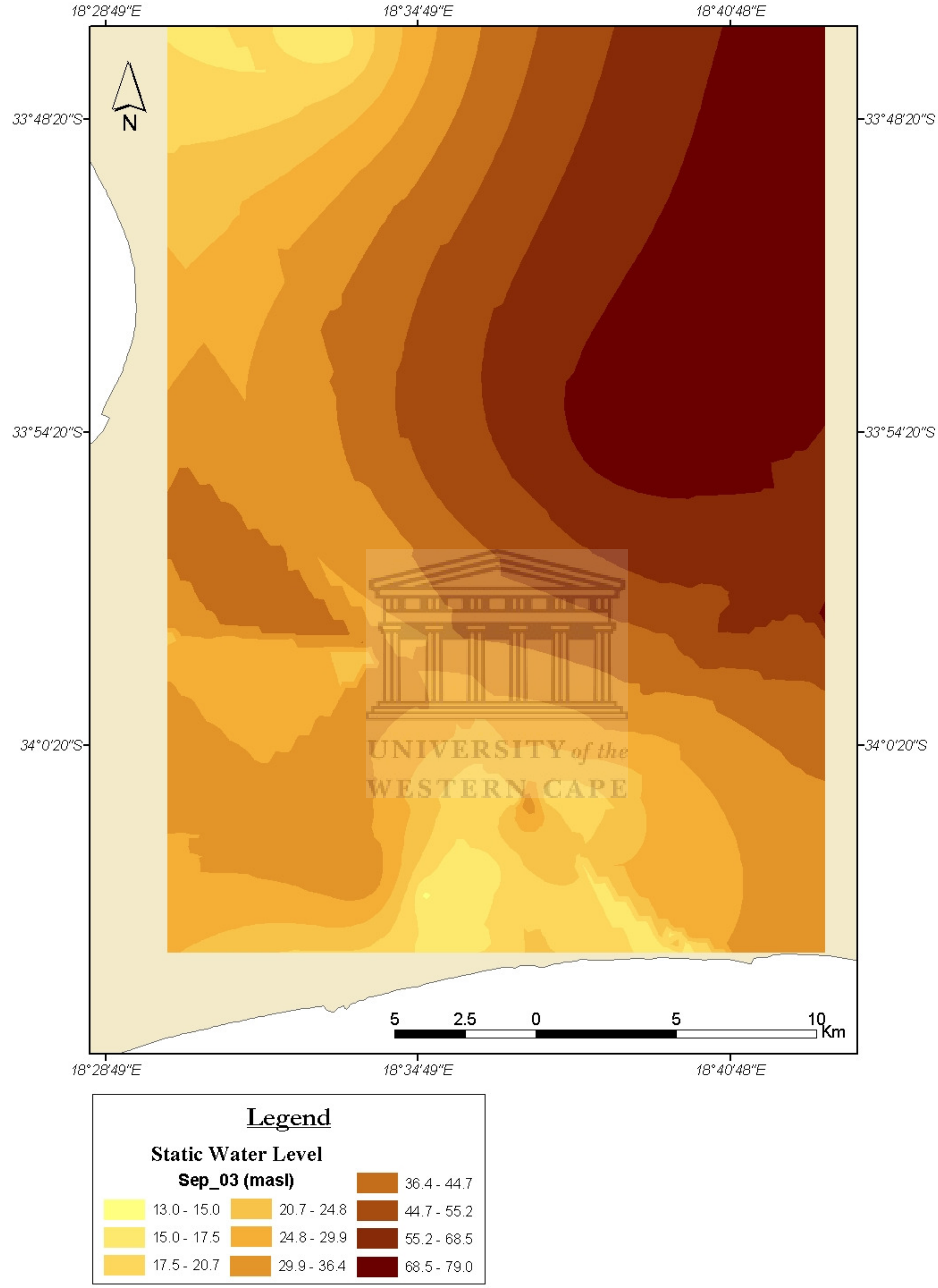
| Year | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | Annual mean T(℃) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1933 | 21.4 | 21.2 | 19.0 | 19.2 | 14.4 | 11.9 | 12.0 | 12.3 | 14.9 | 17.2 | 19.6 | 22.4 | 17.1 |
| 1934 | 22.2 | 22.5 | 20.1 | 19.5 | 15.8 | 15.4 | 12.3 | 12.6 | 15.4 | 17.3 | 20.1 | 21.3 | 17.8 |
| 1935 | 22.1 | 22.6 | 19.4 | 18.4 | 15.1 | 13.2 | 12.3 | 14.5 | 13.7 | 17.0 | 19.1 | 20.4 | 17.3 |
| 1936 | 19.4 | 19.7 | 21.2 | 18.3 | 13.3 | 14.1 | 13.6 | 14.1 | 15.7 | 16.5 | 19.4 | 19.9 | 17.1 |
| 1937 | 21.8 | 22.3 | 20.6 | 18.1 | 14.6 | 13.3 | 12.5 | 14.2 | 15.1 | 17.1 | 19.1 | 21.2 | 17.5 |
| 1938 | 21.1 | 20.9 | 20.5 | 17.6 | 15.4 | 14.9 | 13.8 | 12.9 | 14.3 | 16.1 | 18.2 | 19.7 | 17.1 |
| 1939 | 21.8 | 21.4 | 20.6 | 17.1 | 16.5 | 15.3 | 14.2 | 13.5 | 15.7 | 17.6 | 19.8 | 21.1 | 17.9 |
| 1940 | 22.3 | 22.4 | 19.7 | 16.9 | 14.8 | 13.7 | 14.0 | 14.7 | 13.7 | 18.0 | 18.1 | 20.5 | 17.4 |
| 1941 | 22.2 | 21.1 | 20.6 | 16.7 | 14.5 | 13.2 | 13.2 | 14.6 | 14.1 | 16.7 | 18.0 | 20.0 | 17.1 |
| 1942 | 21.4 | 22.1 | 20.7 | 19.5 | 15.7 | 13.2 | 12.7 | 12.7 | 14.3 | 17.1 | 20.0 | 20.3 | 17.4 |
| 1943 | 20.4 | 19.9 | 21.2 | 17.6 | 14.3 | 13.0 | 11.6 | 12.9 | 14.1 | 16.1 | 18.4 | 21.4 | 16.7 |
| 1944 | 21.9 | 22.6 | 20.8 | 18.2 | 15.4 | 13.3 | 13.0 | 12.8 | 14.7 | 16.9 | 17.8 | 19.2 | 17.2 |
| 1945 | 21.1 | 22.3 | 21.4 | 19.4 | 15.8 | 13.8 | 11.9 | 12.9 | 16.4 | 16.3 | 19.8 | 19.2 | 17.5 |
| 1946 | 20.8 | 21.4 | 19.7 | 17.8 | 15.3 | 13.1 | 11.7 | 14.1 | 13.9 | 16.7 | 18.9 | 20.4 | 17.0 |
| 1947 | 21.1 | 22.9 | 21.2 | 17.3 | 15.1 | 12.5 | 12.3 | 13.3 | 15.3 | 16.6 | 19.6 | 20.7 | 17.3 |
| 1948 | 21.8 | 22.3 | 20.0 | 18.4 | 16.3 | 12.3 | 12.2 | 13.2 | 13.7 | 16.6 | 19.2 | 20.2 | 17.2 |
| 1949 | 21.7 | 22.5 | 21.8 | 17.5 | 15.6 | 15.7 | 12.8 | 13.7 | 14.9 | 17.1 | 18.4 | 20.3 | 17.6 |
| 1950 | 21.7 | 20.8 | 20.4 | 16.7 | 16.0 | 13.5 | 12.3 | 14.6 | 14.5 | 17.5 | 18.3 | 19.4 | 17.1 |
| 1951 | 20.5 | 21.3 | 19.9 | 17.6 | 16.2 | 14.5 | 12.6 | 13.9 | 13.3 | 15.6 | 17.5 | 20.1 | 16.9 |
| 1952 | 21.7 | 23.0 | 19.4 | 18.3 | 14.5 | 13.4 | 12.4 | 13.4 | 15.2 | 16.8 | 19.6 | 20.0 | 17.3 |
| 1953 | 22.8 | 22.4 | 21.6 | 16.5 | 15.3 | 13.7 | 12.5 | 13.4 | 16.3 | 17.1 | 19.0 | 20.1 | 17.5 |
| 1954 | 21.4 | 21.5 | 20.9 | 17.5 | 14.8 | 14.1 | 11.2 | 13.2 | 14.4 | 16.1 | 18.6 | 20.0 | 17.0 |
| 1955 | 22.2 | 20.6 | 21.0 | 16.9 | 16.0 | 13.5 | 12.8 | 12.3 | 13.4 | 15.4 | 17.9 | 18.7 | 16.7 |
| 1956 | 22.1 | 19.9 | 20.0 | 16.7 | 14.0 | 12.7 | 12.9 | 12.7 | 15.3 | 16.2 | 20.1 | 20.5 | 16.9 |
| 1957 | 22.2 | 21.2 | 20.3 | 17.2 | 15.1 | 13.5 | 13.4 | 13.3 | 14.8 | 14.6 | 17.8 | 21.4 | 17.0 |
| 1958 | 21.7 | 20.4 | 20.3 | 17.6 | 14.4 | 12.4 | 13.7 | 14.0 | 14.7 | 16.9 | 18.3 | 22.1 | 17.2 |
| 1959 | 20.8 | 22.3 | 20.0 | 16.9 | 14.6 | 13.9 | 13.1 | 14.3 | 15.6 | 16.6 | 19.3 | 20.4 | 17.3 |
| 1960 | 22.0 | 22.3 | 19.8 | 17.9 | 15.2 | 14.5 | 12.9 | 13.8 | 16.4 | 17.7 | 21.0 | 21.8 | 17.9 |
| 1961 | 21.9 | 22.1 | 21.9 | 19.4 | 15.4 | 14.9 | 14.8 | 14.3 | 14.7 | 15.5 | 19.9 | 20.6 | 17.9 |
| 1962 | 21.8 | 21.5 | 20.6 | 18.6 | 16.5 | 14.0 | 13.4 | 13.9 | 15.0 | 16.9 | 18.0 | 20.9 | 17.6 |
| 1963 | 23.3 | 21.6 | 21.6 | 17.9 | 16.4 | 14.8 | 13.1 | 14.0 | 16.3 | 18.4 | 20.8 | 21.7 | 18.3 |
| 1964 | 22.5 | 21.2 | 21.4 | 18.8 | 16.8 | 13.4 | 13.3 | 13.3 | 14.3 | 16.8 | 18.2 | 21.3 | 17.6 |
| 1965 | 21.4 | 21.3 | 20.1 | 18.6 | 15.4 | 12.9 | 13.7 | 14.0 | 16.3 | 17.5 | 18.6 | 19.0 | 17.4 |
| 1966 | 21.1 | 19.8 | 19.8 | 19.6 | 16.0 | 14.5 | 12.7 | 14.2 | 15.5 | 17.5 | 19.1 | 21.0 | 17.5 |
| 1967 | 20.4 | 22.0 | 20.6 | 17.5 | 15.2 | 12.8 | 13.0 | 13.4 | 15.9 | 17.1 | 19.5 | 21.4 | 17.4 |
| 1968 | 20.4 | 20.6 | 21.7 | 18.7 | 15.7 | 13.6 | 12.5 | 12.8 | 15.6 | 16.3 | 19.5 | 20.4 | 17.3 |
| 1969 | 21.4 | 22.1 | 21.6 | 17.5 | 15.2 | 13.3 | 13.4 | 14.5 | 14.5 | 16.9 | 18.5 | 20.8 | 17.5 |
| 1970 | 21.5 | 21.4 | 21.2 | 19.4 | 15.1 | 13.4 | 11.9 | 12.8 | 14.1 | 18.0 | 17.7 | 18.6 | 17.1 |
| 1971 | 20.8 | 22.1 | 20.7 | 17.8 | 15.8 | 13.4 | 12.9 | 13.0 | 13.4 | 17.3 | 18.8 | 20.8 | 17.2 |
| 1972 | 22.3 | 22.4 | 21.2 | 18.2 | 16.1 | 13.9 | 13.8 | 13.2 | 15.6 | 18.4 | 21.2 | 19.7 | 18.0 |
| 1973 | 21.6 | 23.4 | 21.3 | 20.4 | 16.1 | 14.9 | 14.0 | 13.6 | 14.2 | 18.3 | 20.1 | 21.3 | 18.3 |
| 1974 | 22.3 | 23.2 | 21.6 | 20.1 | 16.1 | 15.2 | 13.6 | 13.4 | 14.6 | 16.1 | 19.3 | 20.9 | 18.0 |
| 1975 | 21.7 | 22.8 | 21.2 | 18.3 | 16.2 | 15.1 | 13.5 | 13.3 | 16.6 | 16.5 | 18.7 | 20.7 | 17.8 |
| 1976 | 23.1 | 21.9 | 20.6 | 19.1 | 17.5 | 14.3 | 13.4 | 13.5 | 15.2 | 17.3 | 16.4 | 19.7 | 17.6 |
| 1977 | 21.1 | 22.6 | 21.0 | 19.2 | 14.7 | 14.6 | 12.7 | 13.8 | 15.0 | 16.3 | 20.0 | 21.0 | 17.6 |
| 1978 | 22.2 | 21.7 | 21.2 | 19.2 | 15.0 | 14.3 | 15.2 | 13.2 | 15.9 | 16.0 | 20.1 | 21.3 | 17.9 |
| 1979 | 21.8 | 22.4 | 20.3 | 19.3 | 17.4 | 14.1 | 14.1 | 14.8 | 14.8 | 16.3 | 19.5 | 22.3 | 18.1 |
| 1980 | 22.3 | 21.9 | 22.0 | 18.1 | 15.6 | 14.7 | 14.9 | 15.2 | 16.7 | 17.1 | 18.0 | 20.2 | 18.0 |
| 1981 | 21.0 | 22.0 | 21.2 | 19.3 | 17.1 | 12.8 | 12.3 | 13.4 | 14.4 | 18.8 | 19.4 | 20.9 | 17.7 |
| 1982 | 21.8 | 21.3 | 20.6 | 18.3 | 15.8 | 13.0 | 13.4 | 13.7 | 16.5 | 18.2 | 18.3 | 19.5 | 17.5 |
| 1983 | 22.0 | 20.9 | 20.3 | 20.1 | 15.5 | 13.7 | 13.1 | 13.6 | 14.0 | 17.8 | 19.3 | 21.3 | 17.6 |
| 1984 | 22.6 | 22.4 | 21.8 | 19.2 | 15.7 | 14.8 | 14.3 | 14.1 | 15.3 | 16.7 | 20.4 | 19.8 | 18.1 |
| 1985 | 22.1 | 22.3 | 20.2 | 18.1 | 16.6 | 14.8 | 13.3 | 14.5 | 15.6 | 17.9 | 21.8 | 20.7 | 18.1 |
| 1986 | 22.4 | 22.3 | 20.2 | 18.9 | 17.1 | 14.2 | 13.5 | 14.9 | 16.3 | 17.8 | 19.2 | 20.3 | 18.1 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1987 | 21.1 | 21.0 | 21.4 | 18.2 | 16.4 | 14.6 | 13.7 | 14.2 | 15.4 | 17.6 | 18.3 | 19.9 | 17.6 |
| 1988 | 21.0 | 22.8 | 20.4 | 17.2 | 16.6 | 13.2 | 14.1 | 14.6 | 15.2 | 16.9 | 19.2 | 21.2 | 17.7 |
| 1989 | 22.2 | 21.8 | 20.1 | 18.7 | 15.5 | 14.2 | 13.0 | 13.9 | 14.9 | 16.1 | 19.4 | 20.8 | 17.5 |
| 1990 | 21.9 | 21.8 | 21.0 | 17.8 | 15.9 | 12.9 | 12.3 | 13.8 | 15.6 | 17.0 | 18.6 | 20.7 | 17.4 |
| 1991 | 21.9 | 21.2 | 22.0 | 19.4 | 17.6 | 14.0 | 13.6 | 13.0 | 15.3 | 17.7 | 19.0 | 21.0 | 18.0 |
| 1992 | 22.9 | 22.0 | 21.3 | 18.2 | 15.0 | 13.5 | 13.5 | 13.9 | 14.9 | 16.9 | 19.5 | 21.1 | 17.7 |
| 1993 | 22.6 | 21.8 | 21.8 | 18.0 | 15.5 | 14.3 | 14.9 | 14.7 | 15.9 | 18.1 | 20.1 | 20.9 | 18.2 |
| 1994 | 22.5 | 22.5 | 21.2 | 18.9 | 15.3 | 13.9 | 13.2 | 14.6 | 16.1 | 19.1 | 20.2 | 22.2 | 18.3 |
| 1995 | 22.4 | 23.1 | 22.2 | 18.2 | 17.3 | 14.5 | 12.3 | 14.3 | 16.2 | 16.8 | 19.9 | 21.9 | 18.2 |
| 1996 | 22.5 | 22.2 | 20.0 | 19.5 | 16.9 | 14.3 | 13.1 | 13.6 | 14.7 | 17.1 | 17.9 | 20.9 | 17.7 |
| 1997 | 21.6 | 21.6 | 20.8 | 18.1 | 16.6 | 13.1 | 14.6 | 14.4 | 17.6 | 19.9 | 19.0 | 19.9 | 18.1 |
| 1998 | 21.3 | 23.6 | 20.9 | 19.2 | 16.2 | 14.7 | 13.9 | 14.9 | 15.8 | 18.1 | 19.5 | 21.8 | 18.3 |
| 1999 | 23.0 | 22.4 | 22.7 | 19.4 | 16.9 | 15.4 | 14.3 | 15.4 | 15.0 | 19.8 | 20.1 | 24.0 | 19.0 |
| 2000 | 23.1 | 23.3 | 21.4 | 19.0 | 17.0 | 15.6 | 15.3 | 15.6 | 15.4 | 18.6 | 20.9 | 21.3 | 18.8 |
| 2001 | 22.5 | 22.7 | 20.9 | 18.7 | 16.5 | 14.3 | 14.4 | 14.4 | 15.7 | 18.8 | 21.1 | 22.2 | 18.5 |
| 2002 | 21.7 | 23.5 | 22.1 | 19.1 | 15.8 | 13.1 | 13.4 | 14.6 | 17.5 | 17.3 | 18.6 | 22.1 | 18.2 |
| 2003 | 22.4 | 22.7 | 22.0 | 20.0 | 17.1 | 14.8 | 14.6 | 12.8 | 15.6 | 18.4 | 19.9 | 20.6 | 18.4 |
| 2004 | 22.3 | 22.9 | 20.5 | 18.7 | 18.2 | 15.3 | 14.5 | 14.3 | 16.1 | 18.1 | 21.2 | 22.8 | 18.7 |
| 2005 | 22.8 | 22.8 | 22.2 | 18.6 | 16.4 | 13.9 | 15.8 | 13.1 | 14.5 | 15.8 | 19.0 | 19.8 | 17.9 |
| 2006 | 23.2 | 23.3 | 20.6 | 18.5 | 15.5 | 14.8 | 13.1 | 13.7 | 14.5 | 15.8 | 19.0 | 19.8 | 17.6 |
| 2007 | 22.9 | 21.3 | 20.4 | 18.4 | 15.4 | 13.0 | 12.3 | 13.0 | 14.5 | 15.8 | 19.0 | 19.8 | 17.1 |
| 2008 | 26.5 | 26.6 | 26.6 | 24.1 | 21.4 | 17.7 | 16.7 | 18.3 | 18.1 | 22.0 | 23.2 | 25.5 | 22.2 |
| 2009 | 26.2 | 28.1 | 26.9 | 23.9 | 20.3 | 18.6 | 19.7 | 18.7 | 19.1 | 23 | 24.1 | 24.9 | 22.8 |
| **Maximum:** | **23.3** | **23.6** | **22.7** | **20.4** | **18.2** | **15.7** | **15.8** | **15.6** | **17.6** | **19.9** | **21.8** | **24.0** | **24.0** |
| **Minimum:** | **19.4** | **19.7** | **19.0** | **16.5** | **13.3** | **11.9** | **11.2** | **12.3** | **13.3** | **14.6** | **16.4** | **18.6** | **18.6** |
| **Range:** | **3.9** | **3.9** | **3.7** | **3.9** | **5.0** | **3.8** | **4.6** | **3.3** | **4.3** | **5.3** | **5.4** | **5.5** | **5.5** |
| **Median:** | **21.8** | **22.1** | **20.8** | **18.3** | **15.7** | **13.9** | **13.2** | **13.7** | **15.1** | **17.0** | **19.2** | **20.7** | **20.7** |
| **Mean:** | **21.8** | **21.9** | **20.8** | **18.4** | **15.8** | **13.9** | **13.2** | **13.7** | **15.1** | **17.1** | **19.2** | **20.7** | **20.7** |
| **Std.dev.** | **0.7** | **0.9** | **0.8** | **0.9** | **0.9** | **0.9** | **0.9** | **0.7** | **0.9** | **1.0** | **1.0** | **1.0** | **1.0** |

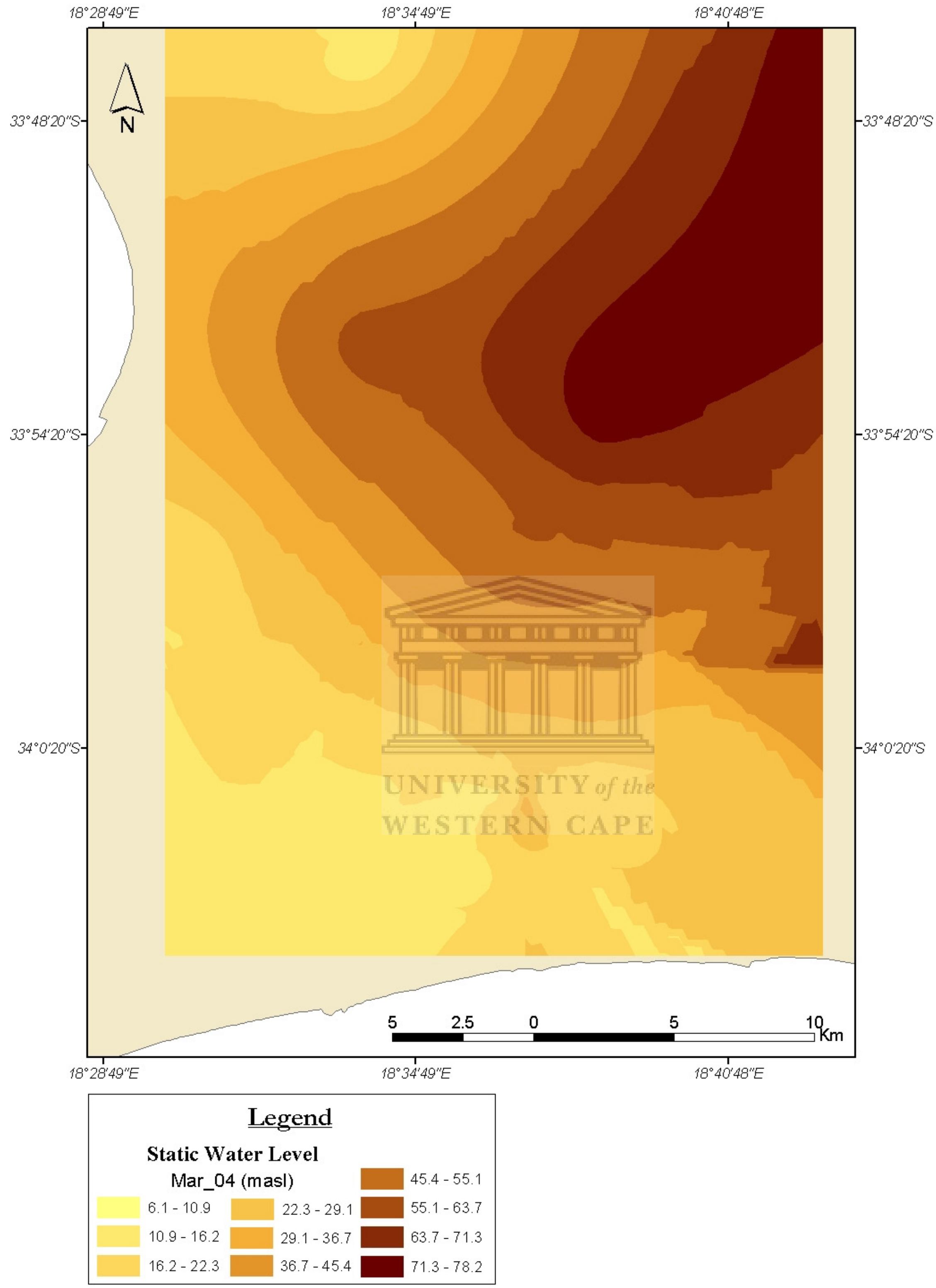
Appendix 4.3a: Water level contour maps monitoring data (April 2003)



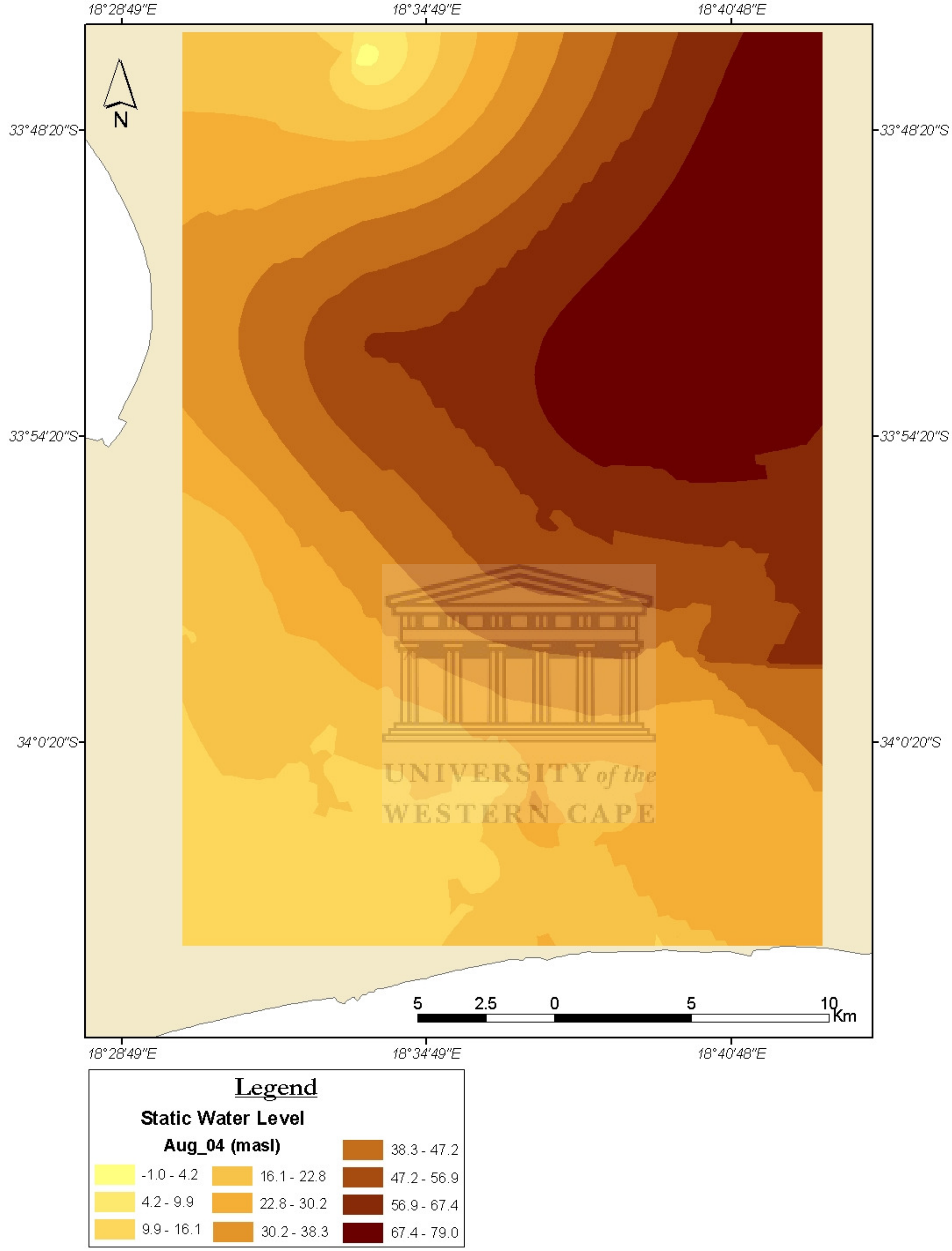
Appendix 4.3b: Water level contour maps monitoring data (September 2003)



Appendix 4.3c: Water level contour maps monitoring data (March 2004)



Appendix 4.3d: Water level contour maps monitoring data (August 2004)



**Appendix 4.4a: Climate paparmeters & calculations of daily Eto**

**DAILY $ET_O$ PENMAN-MONTEITH DATA Staion: Cape Town (South Africa)**

**Altitude: 42 m Lat. 33.97°S Long. 18.60°E**

| **Year:2000** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 15.8 | 28.4 | 58 | 338 | 11.4 | 28.4 | 6.62 |
| February | 16.9 | 27.5 | 64 | 381 | 11.2 | 26.3 | 5.98 |
| March | 15.7 | 26 | 68 | 348 | 9.9 | 21.4 | 4.69 |
| April | 11.8 | 24.1 | 70 | 248 | 8.7 | 16.3 | 3.23 |
| May | 10.3 | 21.2 | 74 | 215 | 6.4 | 11 | 1.98 |
| June | 9.4 | 20.3 | 73 | 216 | 6.3 | 9.4 | 1.86 |
| July | 8.1 | 17.9 | 74 | 228 | 6.6 | 10.2 | 1.71 |
| August | 9.8 | 19 | 77 | 243 | 7.2 | 13.3 | 2.17 |
| September | 9 | 18.7 | 72 | 243 | 7.5 | 16.9 | 2.87 |
| October | 10.4 | 22.5 | 61 | 313 | 10 | 23.6 | 4.79 |
| November | 13.9 | 24.7 | 64 | 278 | 9.9 | 25.5 | 5.22 |
| December | 15.3 | 24.4 | 61 | 362 | 10.9 | 27.9 | 5.92 |
| **Average** | 12.2 | 22.9 | 68 | 285 | 8.8 | 19.2 | 3.92 |

| **Year:2001** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 15.5 | 26.3 | 58 | 9 | 11.6 | 15.7 | 1.47 |
| February | 16 | 28 | 60 | 8 | 10.8 | 17.8 | 2.31 |
| March | 13.8 | 25.6 | 67 | 8 | 9.9 | 20.1 | 3.05 |
| April | 12.4 | 22.6 | 71 | 10 | 7.4 | 19.4 | 3.13 |
| May | 10.5 | 20.6 | 69 | 6 | 6.9 | 20 | 3.19 |
| June | 8.6 | 18.1 | 72 | 7 | 6.2 | 19.4 | 2.98 |
| July | 8.3 | 17.9 | 71 | 7 | 5.3 | 17.8 | 2.7 |
| August | 9.3 | 17 | 74 | 7 | 5.7 | 17.4 | 2.52 |
| September | 10.2 | 18.9 | 73 | 7 | 7.3 | 17.6 | 2.36 |
| October | 12.9 | 21.8 | 71 | 8 | 7.4 | 14.8 | 1.86 |
| November | 14.8 | 24.6 | 65 | 11 | 10.7 | 15.4 | 1.56 |
| December | 15.8 | 25.9 | 64 | 10 | 11.4 | 14.5 | 1.28 |
| **Average** | 12.3 | 22.3 | 68 | 8 | 8.4 | 17.5 | 2.37 |

| **Year:2002** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 15.6 | 25.4 | 65 | 12 | 11.2 | 15.3 | 1.55 |
| February | 16 | 28.3 | 64 | 13 | 10.8 | 17.8 | 2.39 |
| March | 15 | 26.9 | 73 | 17 | 9.6 | 19.7 | 3.2 |
| April | 12.2 | 23.5 | 77 | 10 | 7.4 | 19.4 | 3.24 |
| May | 9.8 | 19.6 | 77 | 7 | 5.7 | 18.3 | 2.97 |
| June | 7.8 | 16.5 | 79 | 6 | 5.6 | 18.5 | 2.79 |
| July | 7.2 | 16.8 | 80 | 13 | 6.3 | 19.3 | 2.8 |
| August | 7.1 | 18.8 | 74 | 22 | 7.6 | 20.1 | 2.84 |
| September | 10.4 | 21.3 | 76 | 13 | 8.3 | 18.9 | 2.66 |
| October | 10.6 | 21.2 | 67 | 6 | 9.9 | 17.7 | 2.07 |
| November | 11.3 | 22.8 | 63 | 8 | 10.8 | 15.5 | 1.35 |
| December | 16.3 | 26.6 | 66 | 10 | 11 | 14.2 | 1.29 |
| **Average** | 11.6 | 22.3 | 72 | 11 | 8.7 | 17.9 | 2.43 |

| **Year:2003** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 16.5 | 26.5 | 64 | 15 | 11.7 | 15.8 | 1.62 |
| February | 16.7 | 27.3 | 68 | 15 | 11 | 18 | 2.47 |
| March | 16 | 25.7 | 74 | 13 | 9.1 | 19.1 | 3.06 |
| April | 13.6 | 24.3 | 76 | 13 | 7.9 | 20.1 | 3.39 |
| May | 10.3 | 21.2 | 78 | 10 | 7.3 | 20.6 | 3.37 |
| June | 6.2 | 19.5 | 74 | 12 | 7.7 | 21.6 | 3.27 |
| July | 6.8 | 18 | 73 | 12 | 6.9 | 20.1 | 2.97 |
| August | 6.7 | 16.8 | 77 | 12 | 6.2 | 18.1 | 2.53 |
| September | 9.5 | 18.9 | 74 | 12 | 7.4 | 17.7 | 2.35 |
| October | 11.5 | 23.2 | 65 | 16 | 8.3 | 15.8 | 1.99 |
| November | 13.4 | 24.7 | 60 | 19 | 11 | 15.7 | 1.59 |
| December | 14.5 | 24.4 | 61 | 15 | 10.5 | 13.7 | 1.17 |
| **Average** | 11.8 | 22.5 | 70 | 14 | 8.8 | 18 | 2.48 |

| **Year:2004** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 17 | 27.6 | 63 | 20 | 11.3 | 15.4 | 1.72 |
| February | 16.8 | 27.3 | 67 | 20 | 10.6 | 17.6 | 2.51 |
| March | 13.2 | 24.5 | 64 | 18 | 9.7 | 19.9 | 2.99 |
| April | 12.3 | 22.8 | 74 | 16 | 6.7 | 18.4 | 3.03 |
| May | 10.7 | 21.3 | 80 | 4 | 7 | 20.2 | 3.29 |
| June | 8.2 | 19.2 | 78 | 5 | 6.2 | 19.4 | 3.05 |
| July | 6.1 | 18.7 | 77 | 3 | 7.6 | 21.2 | 3.09 |
| August | 8.6 | 17.7 | 82 | 4 | 6.4 | 18.4 | 2.64 |
| September | 9.3 | 20.7 | 73 | 25 | 9.3 | 20.2 | 2.76 |
| October | 11.7 | 21.4 | 69 | 16 | 9.1 | 16.8 | 2.03 |
| November | 15.1 | 24.6 | 65 | 12 | 11.2 | 15.9 | 1.57 |
| December | 16.3 | 26.5 | 61 | 12 | 11.4 | 14.5 | 1.27 |
| **Average** | 12.1 | 22.7 | 71 | 13 | 8.9 | 18.1 | 2.5 |

| **Year:2005** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 17 | 27.3 | 62 | 16 | 11.3 | 15.4 | 1.63 |
| February | 16.9 | 27.2 | 67 | 14 | 11.1 | 18.1 | 2.48 |
| March | 15 | 26.3 | 69 | 13 | 9.4 | 19.5 | 3.09 |
| April | 12.1 | 23.3 | 78 | 12 | 7.7 | 19.8 | 3.28 |
| May | 10.4 | 19.2 | 81 | 8 | 5.2 | 17.5 | 2.88 |
| June | 7 | 17.2 | 84 | 9 | 5.6 | 18.5 | 2.79 |
| July | 7.8 | 19.7 | 78 | 8 | 6.9 | 20.1 | 3.08 |
| August | 7.4 | 15.9 | 83 | 8 | 5.6 | 17.2 | 2.44 |
| September | 9.5 | 19.5 | 77 | 10 | 8.1 | 18.6 | 2.5 |
| October | 9.7 | 21.8 | 68 | 13 | 9 | 16.6 | 1.97 |
| November | 13.4 | 24.6 | 63 | 15 | 10.1 | 14.8 | 1.5 |
| December | 14.6 | 25 | 59 | 14 | 11.8 | 14.9 | 1.18 |
| **Average** | 11.7 | 22.3 | 72 | 12 | 8.5 | 17.6 | 2.4 |

| **Year:2006** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 16.9 | 27.7 | 64 | 19 | 12 | 16.1 | 1.74 |
| February | 16.5 | 27.7 | 70 | 20 | 10.8 | 17.8 | 2.55 |
| March | 14.1 | 25.4 | 65 | 14 | 10.2 | 20.5 | 3.12 |
| April | 12 | 22.8 | 75 | 19 | 8 | 20.2 | 3.3 |
| May | 9.3 | 19.9 | 77 | 10 | 5.7 | 18.3 | 2.93 |
| June | 8.1 | 20.1 | 76 | 11 | 7.3 | 21 | 3.27 |
| July | 8.7 | 16.9 | 83 | 14 | 5.1 | 17.5 | 2.68 |
| August | 7.9 | 17.7 | 77 | 6 | 6.8 | 18.9 | 2.67 |
| September | 10.3 | 20.9 | 72 | 6 | 8 | 18.5 | 2.53 |
| October | 11.3 | 22.4 | 69 | 14 | 9.4 | 17.1 | 2.1 |
| November | 13.9 | 24.6 | 65 | 19 | 10.6 | 15.3 | 1.6 |
| December | 15.4 | 25 | 61 | 7 | 10.9 | 14.1 | 1.13 |
| **Average** | 12 | 22.6 | 71 | 13 | 8.7 | 17.9 | 2.47 |

| **Year:2007** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 17.6 | 28.2 | 64 | 9 | 11.7 | 15.8 | 1.71 |
| February | 16.2 | 26.4 | 68 | 8 | 10.7 | 17.7 | 2.37 |
| March | 14.2 | 26.5 | 69 | 8 | 10.2 | 20.5 | 3.14 |
| April | 12.8 | 24 | 75 | 10 | 8 | 20.2 | 3.36 |
| May | 9.7 | 21.1 | 80 | 6 | 7.2 | 20.5 | 3.31 |
| June | 8.1 | 17.9 | 80 | 7 | 5.5 | 18.4 | 2.86 |
| July | 6.9 | 17.6 | 77 | 7 | 6.7 | 19.9 | 2.9 |
| August | 8.2 | 17.8 | 77 | 7 | 6.2 | 18.1 | 2.59 |
| September | 9.2 | 19.8 | 72 | 7 | 7.9 | 18.3 | 2.44 |
| October | 12.1 | 23.3 | 64 | 8 | 9.7 | 17.4 | 2.12 |
| November | 12.8 | 22.2 | 67 | 11 | 9.4 | 14.1 | 1.39 |
| December | 15.7 | 26.3 | 65 | 10 | 11 | 14.2 | 1.21 |
| **Average** | 12 | 22.6 | 72 | 8 | 8.7 | 17.9 | 2.45 |

| **Year:2008** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 16.8 | 26.5 | 67 | 15 | 11.5 | 15.6 | 1.68 |
| February | 16.9 | 26.6 | 73 | 15 | 10 | 16.9 | 2.39 |
| March | 14.8 | 26.6 | 69 | 13 | 10.7 | 21.1 | 3.28 |
| April | 12.2 | 24.1 | 73 | 13 | 8.9 | 21.5 | 3.48 |
| May | 12.9 | 21.4 | 80 | 10 | 5.1 | 17.4 | 3.01 |
| June | 9.8 | 17.7 | 80 | 12 | 5.1 | 17.8 | 2.86 |
| July | 7.5 | 16.7 | 83 | 12 | 5.7 | 18.4 | 2.73 |
| August | 7.7 | 18.3 | 77 | 12 | 7.6 | 20.1 | 2.86 |
| September | 7.6 | 18.1 | 74 | 12 | 7 | 17.2 | 2.26 |
| October | 11 | 22 | 69 | 16 | 10 | 17.8 | 2.11 |
| November | 14 | 23.2 | 68 | 19 | 10.2 | 14.9 | 1.53 |
| December | 16 | 25.5 | 67 | 15 | 10.9 | 14.1 | 1.3 |
| **Average** | 12.3 | 22.2 | 73 | 14 | 8.6 | 17.7 | 2.46 |

| **Year:2009** | *Min Temp* | *Max Temp* | *Humidity* | *Wind* | *Sun* | *Rad* | *ETo* |
|---|---|---|---|---|---|---|---|
| Month | *°C* | *°C* | *%* | *km/day* | *hours* | *MJ/m²/day* | *mm/day* |
| January | 16.4 | 26.2 | 66 | 16 | 11.7 | 15.8 | 1.64 |
| February | 17 | 28.1 | 63 | 14 | 11.1 | 18.1 | 2.45 |
| March | 15.7 | 26.9 | 71 | 13 | 9.6 | 19.7 | 3.18 |
| April | 13.2 | 23.9 | 76 | 12 | 6.8 | 18.6 | 3.17 |
| May | 10.6 | 20.3 | 82 | 8 | 6 | 18.7 | 3.07 |
| June | 9.5 | 18.6 | 79 | 9 | 5.4 | 18.2 | 2.89 |
| July | 7.7 | 19.7 | 72 | 8 | 6.8 | 20 | 3.04 |
| August | 8.7 | 18.7 | 76 | 8 | 6.6 | 18.7 | 2.74 |
| September | 9.8 | 19.1 | 73 | 10 | 6.8 | 16.9 | 2.3 |
| October | 12.5 | 23 | 69 | 13 | 9.5 | 17.2 | 2.14 |
| November | 14.1 | 24.1 | 65 | 15 | 9.9 | 14.6 | 1.53 |
| December | 15.2 | 24.9 | 65 | 14 | 11.4 | 14.5 | 1.27 |
| **Average** | 12.5 | 22.8 | 71 | 12 | 8.5 | 17.6 | 2.45 |

**Appendix 4.4b: Calculated PET and AET values for Cape Town (2000-2009)**

**AET (mm)**

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000 | 82.12 | 0.00 | 11.45 | 11.48 | 17.53 | 55.52 | 49.72 | 55.03 | 68.77 | 16.52 | 6.80 | 5.20 | 380.13 |
| 2001 | 9.00 | 4.70 | 2.50 | 33.59 | 46.02 | 42.84 | 55.30 | 64.40 | 87.70 | 68.35 | 19.30 | 6.40 | 440.10 |
| 2002 | 54.38 | 15.78 | 9.30 | 22.10 | 33.56 | 37.20 | 43.30 | 66.80 | 80.10 | 45.39 | 22.26 | 15.79 | 445.96 |
| 2003 | 2.40 | 8.40 | 33.49 | 19.60 | 26.48 | 26.68 | 33.12 | 53.25 | 70.97 | 35.74 | 7.06 | 22.23 | 339.42 |
| 2004 | 5.80 | 0.20 | 9.20 | 45.12 | 13.41 | 31.86 | 43.55 | 56.80 | 81.65 | 65.19 | 8.09 | 9.20 | 370.08 |
| 2005 | 20.00 | 5.96 | 8.70 | 46.85 | 44.13 | 33.80 | 49.40 | 50.20 | 83.00 | 45.64 | 19.85 | 1.36 | 408.89 |
| 2006 | 0.00 | 13.00 | 4.70 | 17.34 | 38.35 | 46.10 | 43.50 | 61.90 | 71.60 | 27.34 | 46.46 | 10.00 | 380.30 |
| 2007 | 0.50 | 25.73 | 18.10 | 22.24 | 44.75 | 46.96 | 47.20 | 60.70 | 90.06 | 35.07 | 40.25 | 19.06 | 450.62 |
| 2008 | 6.80 | 13.90 | 5.20 | 15.20 | 23.94 | 41.89 | 41.70 | 60.60 | 80.20 | 97.11 | 48.02 | 7.81 | 442.37 |
| 2009 | 1.40 | 3.60 | 0.80 | 15.79 | 33.97 | 42.20 | 55.00 | 66.70 | 74.84 | 40.55 | 56.68 | 5.28 | 396.80 |
| **Mean** | **18.24** | **9.13** | **10.34** | **24.93** | **32.21** | **40.50** | **46.18** | **59.64** | **78.89** | **47.69** | **27.48** | **10.23** | |

**Rain (mm)**

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000 | 16.10 | 0.00 | 12.90 | 13.80 | 62.30 | 92.60 | 46.30 | 46.20 | 66.60 | 6.60 | 6.80 | 5.90 | 376.10 |
| 2001 | 8.30 | 4.70 | 2.50 | 39.40 | 80.60 | 62.30 | 207.80 | 97.30 | 47.00 | 26.30 | 12.70 | 6.40 | 595.30 |
| 2002 | 60.90 | 14.90 | 9.30 | 28.00 | 71.90 | 76.40 | 98.20 | 65.70 | 26.10 | 32.50 | 22.00 | 15.90 | 521.80 |
| 2003 | 2.40 | 8.40 | 47.60 | 11.90 | 37.10 | 25.00 | 33.40 | 100.30 | 63.90 | 19.20 | 5.80 | 21.10 | 376.10 |
| 2004 | 5.80 | 0.20 | 9.20 | 63.10 | 3.90 | 91.10 | 64.70 | 169.70 | 25.10 | 98.90 | 3.40 | 9.20 | 544.30 |
| 2005 | 24.50 | 2.00 | 8.70 | 95.30 | 77.70 | 90.20 | 64.60 | 89.60 | 29.70 | 13.50 | 20.10 | 1.20 | 517.10 |
| 2006 | 0.00 | 13.00 | 4.70 | 30.10 | 121.80 | 34.00 | 71.40 | 56.20 | 20.00 | 37.20 | 37.70 | 10.00 | 436.10 |
| 2007 | 0.50 | 27.30 | 18.60 | 65.60 | 96.00 | 123.40 | 151.50 | 101.50 | 18.20 | 18.70 | 40.80 | 18.50 | 680.60 |
| 2008 | 6.80 | 13.90 | 5.20 | 15.20 | 51.40 | 63.20 | 182.40 | 79.60 | 137.80 | 12.40 | 53.10 | 7.80 | 628.80 |
| 2009 | 1.40 | 3.60 | 0.80 | 24.00 | 64.40 | 108.40 | 88.40 | 52.00 | 60.20 | 31.60 | 86.20 | 4.40 | 525.40 |
| **Mean** | **12.67** | **8.80** | **11.95** | **38.64** | **66.71** | **76.66** | **100.87** | **85.81** | **49.46** | **29.69** | **28.86** | **10.04** | |

**PET_Monthly daily ave (mm)**

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000 | 6.63 | 5.98 | 4.69 | 3.23 | 1.98 | 1.86 | 1.71 | 2.17 | 2.87 | 4.79 | 5.22 | 5.92 | 47.04 |
| 2001 | 6.25 | 6.12 | 4.44 | 4.44 | 2.17 | 1.58 | 1.78 | 2.08 | 2.92 | 3.84 | 5.45 | 6.02 | 47.09 |
| 2002 | 5.74 | 5.61 | 4.16 | 2.66 | 1.76 | 1.23 | 1.40 | 2.14 | 3.07 | 4.25 | 5.22 | 5.96 | 43.20 |
| 2003 | 6.17 | 5.39 | 4.16 | 2.87 | 1.80 | 1.38 | 1.70 | 1.85 | 2.76 | 4.27 | 5.60 | 5.91 | 43.84 |
| 2004 | 6.41 | 5.72 | 4.48 | 2.70 | 1.79 | 1.40 | 1.43 | 1.83 | 3.18 | 4.03 | 5.49 | 6.37 | 44.82 |
| 2005 | 6.42 | 5.68 | 4.50 | 2.74 | 1.66 | 1.12 | 1.59 | 1.62 | 2.76 | 4.03 | 5.38 | 6.43 | 43.94 |
| 2006 | 6.56 | 5.52 | 4.66 | 2.96 | 1.70 | 1.52 | 1.39 | 1.99 | 3.13 | 4.22 | 5.50 | 5.99 | 45.15 |
| 2007 | 6.26 | 5.53 | 4.41 | 2.97 | 1.72 | 1.55 | 1.53 | 1.96 | 3.11 | 4.47 | 5.19 | 5.92 | 44.63 |
| 2008 | 6.06 | 5.14 | 4.60 | 3.07 | 1.96 | 1.46 | 1.33 | 1.96 | 2.66 | 4.28 | 5.06 | 5.83 | 43.42 |
| 2009 | 6.06 | 5.98 | 4.52 | 2.92 | 1.74 | 1.40 | 1.77 | 2.15 | 2.89 | 4.45 | 5.29 | 5.80 | 44.97 |
| **Mean** | **6.26** | **5.67** | **4.46** | **3.05** | **1.83** | **1.45** | **1.56** | **1.98** | **2.94** | **4.26** | **5.34** | **6.02** | |

**PET_ave_montly (mm)**

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000 | 212.02 | 167.39 | 145.45 | 96.91 | 61.47 | 55.65 | 52.87 | 67.34 | 86.11 | 148.41 | 156.63 | 183.38 | 1433.63 |
| 2001 | 193.63 | 171.24 | 137.76 | 137.76 | 67.27 | 45.93 | 55.21 | 64.47 | 87.56 | 119.07 | 163.41 | 186.57 | 1429.88 |
| 2002 | 178.01 | 157.05 | 128.93 | 79.73 | 54.71 | 37.01 | 43.30 | 66.49 | 92.14 | 131.66 | 156.52 | 184.74 | 1310.29 |
| 2003 | 191.13 | 150.91 | 129.03 | 86.05 | 55.67 | 41.38 | 52.63 | 57.27 | 82.68 | 132.31 | 168.07 | 183.28 | 1330.41 |
| 2004 | 198.86 | 160.12 | 138.91 | 80.90 | 55.46 | 41.94 | 44.22 | 56.62 | 95.44 | 125.03 | 164.59 | 197.33 | 1359.42 |
| 2005 | 199.11 | 159.02 | 139.49 | 82.14 | 51.47 | 33.62 | 49.35 | 50.21 | 82.84 | 124.94 | 161.48 | 199.37 | 1333.04 |
| 2006 | 203.41 | 154.62 | 144.54 | 88.66 | 52.72 | 45.69 | 43.17 | 61.84 | 93.78 | 130.83 | 164.92 | 185.74 | 1369.92 |
| 2007 | 193.99 | 154.92 | 136.56 | 89.05 | 53.43 | 46.60 | 47.36 | 60.61 | 93.42 | 138.65 | 155.80 | 183.64 | 1354.03 |
| 2008 | 187.88 | 143.85 | 142.71 | 92.12 | 60.83 | 43.73 | 41.30 | 58.87 | 79.93 | 132.63 | 151.80 | 180.88 | 1316.53 |
| 2009 | 188.01 | 167.38 | 140.02 | 87.54 | 54.06 | 42.11 | 54.74 | 66.68 | 86.74 | 137.96 | 158.66 | 179.77 | 1363.67 |
| **Mean** | **194.60** | **158.65** | **138.34** | **92.09** | **56.71** | **43.37** | **48.42** | **61.04** | **88.06** | **132.15** | **160.19** | **186.47** | 1360.08 |

Appendix 4.5: Water Balance Table for Cape Town (2000-2009)

| | | Method | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | Rainfall (mm) | Rainfall (WMO) gauging | 376.1 | 595.3 | 521.8 | 376.1 | 544.3 | 517.1 | 436.1 | 680.6 | 628.8 | 525.4 |
| B | PET (mm) | CROPWAT 8 (FAO-56 Penman-Monteith eq.) | 1433.6 | 1429.9 | 1310.3 | 1330.4 | 1359.4 | 1333.0 | 1369.9 | 1354.0 | 1316.5 | 1363.7 |
| C | AET (mm) | WaSim (Water balance eq.) | 380.1 | 440.1 | 446.0 | 339.4 | 370.1 | 408.9 | 380.3 | 450.6 | 442.4 | 396.8 |
| D | Runoff (mm) | WaSim (Water balance eq.) | 60.4 | 134.4 | 70.9 | 39.1 | 162.2 | 99.0 | 55.8 | 192.6 | 158.5 | 128.6 |
| E | Deep percolation (mm) | WaSim (Water balance eq.) | 0.0 | 5.6 | 8.0 | 4.3 | 4.8 | 7.5 | 5.6 | 19.9 | 26.9 | 14.7 |
| F | Relative transpiration (%) | WaSim (Water balance eq.) | 27.4 | 32.3 | 35.2 | 27.7 | 28.0 | 31.7 | 29.4 | 33.9 | 34.5 | 29.7 |
| G | Change in soil or groundwater storage | A-C-D | -64.4 | 20.8 | 4.9 | -2.4 | 12.0 | 9.2 | 0.0 | 37.4 | 27.9 | 0.0 |
| H | Groundwater recharge which becomes baseflow | E-G | 64.4 | -15.2 | 3.1 | 6.7 | -7.2 | -1.7 | 5.6 | -17.5 | -1.1 | 14.7 |
| I | Total change in soil and groundwater storage | G+H | 0.0 | 5.6 | 8.0 | 4.3 | 4.8 | 7.5 | 5.6 | 19.9 | 26.9 | 14.7 |

**Appendix 4.6.1: Pumping test3 @ iThembaLabs - 09/01/2007 to 12/01/2007**

**Pumping started at 11.10 am on 09/01/2007 and stopped at 11.32 am on 12/01/2007**

**Comapany: UWC** **Conductor: Segun** **Date: 09/01/2007**

**Constant discharge for borehole:** ***1.1 L/s*** **Pump type: Submersible**

**Borehole depth:__62__m; S.WL:__1.92___m; pump inlet depth:_28.5 m**

| Constant discharge | | | | Recovery | | | Remark |
|---|---|---|---|---|---|---|---|
| **T (min.)** | **SWL(m)** | **awdown (** | **Q(l/s.)** | **T (min.)** | **SWL (m)** | **al drawdown (m)** | |
| **0** | 1.92 | 0.00 | | 0 | 5.49 | 3.57 | |
| 0.5 | 3.30 | 1.38 | | 0.5 | 4.34 | 2.42 | |
| 1 | 3.60 | 1.68 | | 1 | 4.11 | 2.19 | |
| 1.5 | 3.81 | 1.89 | | 1.5 | 3.96 | 2.04 | |
| 2 | 3.89 | 1.97 | | 2 | 3.85 | 1.93 | |
| 2.5 | 3.99 | 2.07 | | 2.5 | 3.76 | 1.84 | |
| 3 | 4.06 | 2.14 | | 3 | 3.70 | 1.78 | |
| 4 | 4.13 | 2.21 | | 4 | 3.67 | 1.75 | |
| 5 | 4.22 | 2.30 | | 5 | 3.60 | 1.68 | |
| 6 | 4.30 | 2.38 | | 6 | 3.55 | 1.63 | |
| 7 | 4.36 | 2.44 | | 7 | 3.48 | 1.56 | |
| 8 | 4.42 | 2.50 | | 8 | 3.45 | 1.53 | |
| 9 | 4.46 | 2.54 | | 9 | 3.41 | 1.49 | |
| 10 | 4.50 | 2.58 | | 10 | 3.38 | 1.46 | |
| 11 | 4.54 | 2.62 | | 11 | 3.36 | 1.44 | |
| 14 | 4.57 | 2.65 | | 12 | 3.33 | 1.41 | |
| 15 | 4.63 | 2.71 | | 15 | 3.24 | 1.32 | |
| 20 | 4.75 | 2.83 | | 20 | 3.15 | 1.23 | |
| 25 | 4.81 | 2.89 | | 25 | 3.07 | 1.15 | |
| 30 | 4.87 | 2.95 | | 30 | 3.02 | 1.10 | |
| 35 | 4.91 | 2.99 | | 35 | 2.97 | 1.05 | |
| 40 | 4.96 | 3.04 | | 40 | 2.93 | 1.01 | |
| 45 | 5.00 | 3.08 | | 45 | 2.88 | 0.96 | |
| 50 | 5.02 | 3.10 | | 50 | 2.86 | 0.94 | |
| 55 | 5.05 | 3.13 | | 55 | 2.84 | 0.92 | |
| 60 | 5.08 | 3.16 | | 60 | 2.81 | 0.89 | |
| 70 | 5.11 | 3.19 | | 70 | 2.77 | 0.85 | |
| 80 | 5.15 | 3.23 | | 80 | 2.74 | 0.82 | |
| 90 | 5.17 | 3.25 | | 90 | 2.71 | 0.79 | |
| 100 | 5.20 | 3.28 | | 100 | 2.67 | 0.75 | |
| 110 | 5.22 | 3.30 | | 110 | 2.66 | 0.74 | |
| 120 | 5.23 | 3.31 | | 120 | 2.64 | 0.72 | |
| 140 | 5.26 | 3.34 | | 140 | 2.61 | 0.69 | |
| 160 | 5.27 | 3.35 | | 160 | 2.58 | 0.66 | |
| 180 | 5.30 | 3.38 | | 180 | 2.56 | 0.64 | |
| 210 | 5.32 | 3.40 | | 210 | 2.53 | 0.61 | |
| 240 | 5.33 | 3.41 | | 240 | 2.51 | 0.59 | |
| 270 | 5.34 | 3.42 | | 270 | 2.49 | 0.57 | |
| 300 | 5.35 | 3.43 | | 330 | 2.47 | 0.55 | |
| 330 | 5.35 | 3.43 | | 420 | 2.45 | 0.53 | |
| 360 | 5.36 | 3.44 | | 480 | 2.43 | 0.51 | |
| 420 | 5.37 | 3.45 | | 540 | 2.43 | 0.51 | |
| 480 | 5.37 | 3.45 | | 600 | 2.42 | 0.50 | |
| 540 | 5.37 | 3.45 | | 660 | 2.42 | 0.50 | |
| 600 | 5.39 | 3.47 | | 1140 | 2.36 | 0.44 | |
| 660 | 5.39 | 3.47 | | 1800 | 2.32 | 0.40 | |
| 720 | 5.39 | 3.47 | | 2580 | 2.30 | 0.38 | |
| 780 | 5.40 | 3.48 | | 4140 | 2.30 | 0.38 | |
| 840 | 5.40 | 3.48 | | 4320 | 2.30 | 0.38 | |
| 900 | 5.40 | 3.48 | | 4620 | 2.30 | 0.38 | |
| 1000 | 5.40 | 3.48 | | 5640 | 2.33 | 0.41 | |
| 1100 | 5.40 | 3.48 | | 7020 | 2.32 | 0.40 | |
| 1200 | 5.41 | 3.49 | | 8460 | 2.35 | 0.43 | |
| 1300 | 5.40 | 3.48 | | 8735 | 2.34 | 0.42 | |
| 1400 | 5.41 | 3.49 | | | | | |
| 2700 | 5.44 | 3.52 | | | | | |
| 2800 | 5.45 | 3.53 | | | | | |
| 2900 | 5.45 | 3.53 | | | | | |
| 3000 | 5.45 | 3.53 | | | | | |
| 3100 | 5.45 | 3.53 | | | | | |
| 3200 | 5.45 | 3.53 | | | | | |
| 3400 | 5.45 | 3.53 | | | | | |
| 4000 | 5.48 | 3.56 | | | | | |
| 4200 | 5.48 | 3.56 | | | | | |

**Appendix 4.6.2: Pumping test data**

**Pumping test 4 @ iThembaLabs - 09/03/07 to 12/03/07**

**Pumping started at 10 am on 09/01/2007 and stopped at 09.52 am on 12/01/20**

**Comapany: UWC** **Conductor: Segun** **Date: 09/03/2007**

**Constant discharge for borehole: *1.1 L/s*** **Pump type: Submersible, motorised**

**Borehole depth:__62__m; S.WL:__2.53___m; pump inlet depth:_28.5 m**

| tant discharge | | | | Recovery | | | Remark |
|---|---|---|---|---|---|---|---|
| T (min.) | SWL(m) | awdown ( | Q(l/s.) | T (min.) | SWL (m) | al drawdown (m) | |
| **0** | 2.53 | 0.00 | | 0 | 5.49 | 3.57 | |
| 0.5 | 3.70 | 1.17 | | 0.5 | 4.34 | 2.42 | |
| 1 | 3.90 | 1.37 | | 1 | 4.11 | 2.19 | |
| 1.5 | 4.07 | 1.54 | | 1.5 | 3.96 | 2.04 | |
| 2 | 4.23 | 1.70 | | 2 | 3.85 | 1.93 | |
| 2.5 | 4.30 | 1.77 | | 2.5 | 3.76 | 1.84 | |
| 3 | 4.34 | 1.81 | | 3 | 3.70 | 1.78 | |
| 4 | 4.40 | 1.87 | | 4 | 3.67 | 1.75 | |
| 5 | 4.50 | 1.97 | | 5 | 3.60 | 1.68 | |
| 6 | 4.60 | 2.07 | | 6 | 3.55 | 1.63 | |
| 7 | 4.70 | 2.17 | | 7 | 3.48 | 1.56 | |
| 8 | 4.71 | 2.18 | | 8 | 3.45 | 1.53 | |
| 9 | 4.73 | 2.20 | | 9 | 3.41 | 1.49 | |
| 10 | 4.78 | 2.25 | | 10 | 3.38 | 1.46 | |
| 12 | 4.82 | 2.29 | | 11 | 3.36 | 1.44 | |
| 15 | 4.88 | 2.35 | | 12 | 3.33 | 1.41 | |
| 20 | 4.96 | 2.43 | | 15 | 3.24 | 1.32 | |
| 25 | 5.05 | 2.52 | | 20 | 3.15 | 1.23 | |
| 30 | 5.10 | 2.57 | | 25 | 3.07 | 1.15 | |
| 35 | 5.15 | 2.62 | | 30 | 3.02 | 1.10 | |
| 40 | 5.20 | 2.67 | | 35 | 2.97 | 1.05 | |
| 45 | 5.23 | 2.70 | | 40 | 2.93 | 1.01 | |
| 50 | 5.26 | 2.73 | | 45 | 2.88 | 0.96 | |
| 55 | 5.30 | 2.77 | | 50 | 2.86 | 0.94 | |
| 60 | 5.35 | 2.82 | | 55 | 2.84 | 0.92 | |
| 80 | 5.39 | 2.86 | | 60 | 2.81 | 0.89 | |
| 100 | 5.41 | 2.88 | | 70 | 2.77 | 0.85 | |
| 120 | 5.45 | 2.92 | | 80 | 2.74 | 0.82 | |
| 140 | 5.48 | 2.95 | | 90 | 2.71 | 0.79 | |
| 160 | 5.50 | 2.97 | | 100 | 2.67 | 0.75 | |
| 180 | 5.52 | 2.99 | | 110 | 2.66 | 0.74 | |
| 210 | 5.54 | 3.01 | | 120 | 2.64 | 0.72 | |
| 270 | 5.58 | 3.05 | | 140 | 2.61 | 0.69 | |
| 330 | 5.57 | 3.04 | | 160 | 2.58 | 0.66 | |
| 390 | 5.58 | 3.05 | | 180 | 2.56 | 0.64 | |
| 450 | 5.60 | 3.07 | | 210 | 2.53 | 0.61 | |
| 510 | 5.61 | 3.08 | | 240 | 2.51 | 0.59 | |
| 570 | 5.64 | 3.11 | | 270 | 2.49 | 0.57 | |
| 630 | 5.64 | 3.11 | | 330 | 2.47 | 0.55 | |
| 690 | 5.64 | 3.11 | | 420 | 2.45 | 0.53 | |
| 750 | 5.64 | 3.11 | | 480 | 2.43 | 0.51 | |
| 810 | 5.64 | 3.11 | | 540 | 2.43 | 0.51 | |
| 870 | 5.64 | 3.11 | | 600 | 2.42 | 0.50 | |
| 930 | 5.65 | 3.12 | | 660 | 2.42 | 0.50 | |
| 990 | 5.65 | 3.12 | | 1140 | 2.36 | 0.44 | |
| 1050 | 5.65 | 3.12 | | 1800 | 2.32 | 0.40 | |
| 1150 | 5.66 | 3.13 | | 2580 | 2.30 | 0.38 | |
| 1250 | 5.67 | 3.14 | | 4140 | 2.30 | 0.38 | |
| 1350 | 5.68 | 3.15 | | 4320 | 2.30 | 0.38 | |
| 1450 | 5.68 | 3.15 | | 4620 | 2.30 | 0.38 | |
| 1550 | 5.68 | 3.15 | | 5640 | 2.33 | 0.41 | |
| 1650 | 5.69 | 3.16 | | 7020 | 2.32 | 0.40 | |
| 1750 | 5.67 | 3.14 | | 8460 | 2.35 | 0.43 | |
| 1850 | 5.67 | 3.14 | | 8735 | 2.34 | 0.42 | |
| 1950 | 5.69 | 3.16 | | | | | |
| 2050 | 5.70 | 3.17 | | | | | |
| 2150 | 5.70 | 3.17 | | | | | |
| 2250 | 5.70 | 3.17 | | | | | |
| 2350 | 5.70 | 3.17 | | | | | |
| 2450 | 5.70 | 3.17 | | | | | |
| 2550 | 5.70 | 3.17 | | | | | |
| 2650 | 5.70 | 3.17 | | | | | |
| 2750 | 5.72 | 3.19 | | | | | |
| 2850 | 5.72 | 3.19 | | | | | |
| 2950 | 5.72 | 3.19 | | | | | |
| 3050 | 5.73 | 3.20 | | | | | |
| 3150 | 5.72 | 3.19 | | | | | |
| 3250 | 5.73 | 3.20 | | | | | |
| 3350 | 5.72 | 3.19 | | | | | |
| 3450 | 5.73 | 3.20 | | | | | |
| 3950 | 5.70 | 3.17 | | | | | |
| 4050 | 5.70 | 3.17 | | | | | |

**Appendix 4.7: Aquifer parameters**

**A: Step drawdown test data: yields and specific drawdowns**

| BH No. | Pump intake (m) | Step I | | Step II | | Step III | | Step IV | | Step V | | Step VI | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q (Kl/d) | ∑s (m) | Q (Kl/d) | ∑s (m) | Q (Kl/d) | ∑s (m) | Q (Kl/d) | ∑s (m) | Q (Kl/d) | ∑s (m) | Q (Kl/d) | ∑s (m) |
| G32963 | | 487.6 | 2.45 | 712.3 | 3.49 | 888.3 | 4.35 | 1045 | 5.03 | 1293.4 | 6.3 | - | - |
| G32965 | 18 | 483.8 | 3.35 | 704.2 | 4.78 | 893.7 | 6.14 | 1283 | 8.68 | 1845.5 | 12.6 | - | - |
| G32966 | 24 | 490.7 | 3.55 | 621.2 | 4.61 | 1005.6 | 7.34 | 1128 | 8.31 | 1367.7 | 10.6 | - | - |
| G32967 | 27 | 537.1 | 2.45 | 757.3 | 3.48 | 1010 | 4.48 | 1539 | 6.61 | 2290.4 | 9.47 | 2970.7 | 12.84 |
| G32968 | 30 | 508.9 | 1.87 | 775.4 | 2.23 | 1111.9 | 3.71 | 1810 | 6.5 | 3168.2 | 11 | - | - |
| G32969 | 24 | 365 | 4 | 509.7 | 5.84 | 657.5 | 7.87 | 792.2 | 10.52 | 1005.6 | 14.8 | - | - |
| G32978 | 33 | 529.6 | 1.94 | 788.8 | 2.93 | 1111.9 | 4.16 | 1540 | 5.8 | 2270.6 | 8.64 | 3116.4 | 13.66 |
| G32979 | 18 | 478.2 | 2.02 | 688.6 | 2.9 | 1061.8 | 4.54 | 1473 | 6.31 | 2185 | 9.55 | - | - |
| G32981 | 33 | 533.9 | 2.86 | 766.3 | 4.13 | 1057.9 | 5.7 | 1509 | 7.91 | 2290.4 | 11.6 | 3665 | 15.42 |

**B: Constant discharge rate test data**

| BH No. | Depth of pumping intake (m) | Yield | | RWL | Max drawdown (m) |
|---|---|---|---|---|---|
| | | L/s | Kl/d | | |
| G32963 | 20 | 13.7 | 1187 | 3.94 | 5.83 |
| G32965 | 18 | 20.1 | 1735 | 4.25 | 12.28 |
| G32966 | 24 | 12.9 | 1115 | 5.71 | 8.83 |
| G32967 | 27 | 22.9 | 1980 | 7.28 | 8.78 |
| G32968 | 30 | 32.8 | 2838 | 7.36 | 10.28 |
| G32969 | 24 | 10.2 | 879 | 6.12 | 12.52 |
| G32978 | 33 | 22.5 | 2023 | 5.9 | 7.78 |
| G32979 | 18 | 25.8 | 2231 | 4.77 | 9.77 |
| G32981 | 33 | 14 | 1187 | 5.29 | 11.88 |
| Total | | | | 174.9 | 15176 |

**C: Hydraulic parameters estimated from constant discharge rate tests (Vandoolaeghe 1989)**

| BH No. | T (m2/d) | Aquifer Thickness (m) | k (m/d) |
|---|---|---|---|
| G32963 | 133.8 | 32 | 4.2 |
| G32965 | 116 | 28 | 4.1 |
| G32966 | 76.5 | 19 | 4 |
| G32967 | 106.5 | 21 | 5.1 |
| G32968 | 117.6 | 27 | 4.3 |
| G32969 | 27.8 | 19 | 1.4 |
| G32978 | 203.8 | 32 | 6.3 |
| G32979 | 115.6 | 32 | 3.6 |

Appendix 4.8: Estimation of k values using different interpretation methods

| Method-> | HURR 1966 | HÖLTING 1984 | BOGOMOLOW 1958 | ZANGAR 1958 | LOGAN (in Kruseman & de Ridder 1994) | Average |
|---|---|---|---|---|---|---|
| Parameter-> | k | k | k | k | k | k |
| Unit-> | m/day | m/day | m/day | m/day | m/day | m/day |
| iThemba (Test 3) (REC 1. SEGMNT) | 0.38 | 0.46 | 3.37 | 12.96 | 26.78 | 8.79 |
| iThemba (Test 2) | 0.29 | 0.49 | 3.63 | 13.82 | 0.86 | 3.82 |
| iThemba (Test 1) | 0.34 | 0.62 | 4.67 | 17.28 | 1.12 | 4.81 |
| Obs. well to iThemba (REC 1. SEGMNT) | 0.42 | 17.28 | 103.68 | 432.00 | 25.06 | 115.69 |
| UWC BH4 | 0.14 | 1.64 | 3.46 | 24.19 | 1.90 | 6.27 |
| Obs. well to UWC BH4 | 0.10 | 12.96 | 16.42 | 406.08 | 9.50 | 89.01 |
| Maximal value | 0.42 | 17.28 | 103.68 | 432.00 | 26.78 | 116.03 |
| Minimal value | 0.10 | 0.46 | 3.37 | 12.96 | 0.86 | 3.55 |
| Average value | 0.28 | 5.62 | 23.33 | 146.88 | 11.23 | 37.47 |
| Median value | 0.31 | 1.12 | 4.15 | 20.74 | 5.79 | 6.42 |
| UWC BH5 (REC 1. SEGMNT) | 0.16 | 0.50 | 2.51 | 5.44 | 1.38 | 2.00 |
| Obs. well to UWC BH5 (REC 1. SEGMNT) | 0.10 | 1.04 | 4.92 | 17.28 | 2.33 | 5.13 |
| Maximal value | 0.42 | 17.28 | 103.68 | 432.00 | 26.78 | 116.03 |
| Minimal value | 0.10 | 0.46 | 2.51 | 5.44 | 0.86 | 1.87 |
| Average value | 0.26 | 5.90 | 29.30 | 150.49 | 10.73 | 39.34 |
| Median value | 0.29 | 1.12 | 4.67 | 20.74 | 5.79 | 6.52 |

**Appendix 5.1: Yearly estimates of recharge from rainfall in Cape Town (1933-2009)**

| YEAR | Mean Annual rainfall,P (in mm/a) | Mean Annual temp.,T (in ℃) | R.E = ( 0.35*(Ry-360)) (in mm/a) after Bredenkamp 1990 | Recharge (% of rain) | r = 50.8 (p/25.4 - 15)^0.4 (in mm/a) after Sinha & Sharma 1988 | Recharge (% of rain) |
|---|---|---|---|---|---|---|
| 1933 | **441.40** | 17.11 | 28.5 | 6.5 | 48.3 | 10.9 |
| 1934 | **495.90** | 17.84 | 47.6 | 9.6 | 91.9 | 18.5 |
| 1935 | **229.40** | 17.28 | | | | |
| 1936 | **532.50** | 17.08 | 60.4 | 11.3 | 121.2 | 22.8 |
| 1937 | **719.70** | 17.46 | 125.9 | 17.5 | 271.0 | 37.6 |
| 1938 | **643.40** | 17.09 | 99.2 | 15.4 | 209.9 | 32.6 |
| 1939 | **487.70** | 17.86 | 44.7 | 9.2 | 85.4 | 17.5 |
| 1940 | **621.10** | 17.38 | 91.4 | 14.7 | 192.1 | 30.9 |
| 1941 | **839.10** | 17.07 | 167.7 | 20.0 | 366.5 | 43.7 |
| 1942 | **696.60** | 17.44 | 117.8 | 16.9 | 252.5 | 36.2 |
| 1943 | **575.50** | 16.70 | 75.4 | 13.1 | 155.6 | 27.0 |
| 1944 | **888.70** | 17.19 | 185.0 | 20.8 | 406.2 | 45.7 |
| 1945 | **792.20** | 17.50 | 151.3 | 19.1 | 329.0 | 41.5 |
| 1946 | **618.60** | 16.95 | 90.5 | 14.6 | 190.1 | 30.7 |
| 1947 | **538.60** | 17.31 | 62.5 | 11.6 | 126.1 | 23.4 |
| 1948 | **626.70** | 17.15 | 93.3 | 14.9 | 196.6 | 31.4 |
| 1949 | **530.00** | 17.64 | 59.5 | 11.2 | 119.2 | 22.5 |
| 1950 | **715.00** | 17.12 | 124.3 | 17.4 | 267.2 | 37.4 |
| 1951 | **724.00** | 16.89 | 127.4 | 17.6 | 274.4 | 37.9 |
| 1952 | **649.80** | 17.28 | 101.4 | 15.6 | 215.0 | 33.1 |
| 1953 | **617.60** | 17.53 | 90.2 | 14.6 | 189.3 | 30.6 |
| 1954 | **837.30** | 16.96 | 167.1 | 20.0 | 365.0 | 43.6 |
| 1955 | **608.30** | 16.69 | 86.9 | 14.3 | 181.8 | 29.9 |
| 1956 | **735.40** | 16.91 | 131.4 | 17.9 | 283.5 | 38.6 |
| 1957 | **856.70** | 17.05 | 173.8 | 20.3 | 380.6 | 44.4 |
| 1958 | **489.10** | 17.18 | 45.2 | 9.2 | 86.5 | 17.7 |
| 1959 | **626.80** | 17.28 | 93.4 | 14.9 | 196.6 | 31.4 |
| 1960 | **427.40** | 17.91 | 23.6 | 5.5 | 37.1 | 8.7 |
| 1961 | **509.30** | 17.92 | 52.3 | 10.3 | 102.6 | 20.2 |
| 1962 | **715.20** | 17.57 | 124.3 | 17.4 | 267.4 | 37.4 |
| 1963 | **470.10** | 18.30 | 38.5 | 8.2 | 71.3 | 15.2 |
| 1964 | **479.30** | 17.58 | 41.8 | 8.7 | 78.6 | 16.4 |
| 1965 | **523.50** | 17.36 | 57.2 | 10.9 | 114.0 | 21.8 |
| 1966 | **593.20** | 17.54 | 81.6 | 13.8 | 169.8 | 28.6 |
| 1967 | **500.00** | 17.38 | 49.0 | 9.8 | 95.2 | 19.0 |
| 1968 | **610.50** | 17.29 | 87.7 | 14.4 | 183.6 | 30.1 |
| 1969 | **464.60** | 17.46 | 36.6 | 7.9 | 66.9 | 14.4 |
| 1970 | **670.40** | 17.07 | 108.6 | 16.2 | 231.5 | 34.5 |
| 1971 | **437.50** | 17.21 | 27.1 | 6.2 | 45.2 | 10.3 |
| 1972 | **463.20** | 17.97 | 36.1 | 7.8 | 65.8 | 14.2 |
| 1973 | **347.80** | 18.25 | | | | |
| 1974 | **796.10** | 18.02 | 152.6 | 19.2 | 332.1 | 41.7 |
| 1975 | **623.20** | 17.85 | 92.1 | 14.8 | 193.8 | 31.1 |
| 1976 | **708.80** | 17.64 | 122.1 | 17.2 | 262.2 | 37.0 |
| 1977 | **795.40** | 17.63 | 152.4 | 19.2 | 331.5 | 41.7 |
| 1978 | **443.50** | 17.92 | 29.2 | 6.6 | 50.0 | 11.3 |
| 1979 | **467.60** | 18.07 | 37.7 | 8.1 | 69.3 | 14.8 |
| 1980 | **638.60** | 18.04 | 97.5 | 15.3 | 206.1 | 32.3 |
| 1981 | **663.50** | 17.69 | 106.2 | 16.0 | 226.0 | 34.1 |
| 1982 | **508.70** | 17.51 | 52.0 | 10.2 | 102.2 | 20.1 |
| 1983 | **596.20** | 17.61 | 82.7 | 13.9 | 172.2 | 28.9 |
| 1984 | **501.50** | 18.07 | 49.5 | 9.9 | 96.4 | 19.2 |
| 1985 | **627.40** | 18.13 | 93.6 | 14.9 | 197.1 | 31.4 |
| 1986 | **699.20** | 18.05 | 118.7 | 17.0 | 254.6 | 36.4 |
| 1987 | **823.60** | 17.63 | 162.3 | 19.7 | 354.1 | 43.0 |
| 1988 | **452.80** | 17.67 | 32.5 | 7.2 | 57.4 | 12.7 |
| 1989 | **913.70** | 17.53 | 193.8 | 21.2 | 426.2 | 46.6 |
| 1990 | **706.70** | 17.42 | 121.3 | 17.2 | 260.6 | 36.9 |
| 1991 | **605.60** | 17.95 | 86.0 | 14.2 | 179.7 | 29.7 |
| 1992 | **639.70** | 17.69 | 97.9 | 15.3 | 207.0 | 32.4 |
| 1993 | **768.90** | 18.20 | 143.1 | 18.6 | 310.3 | 40.4 |
| 1994 | **529.50** | 18.28 | 59.3 | 11.2 | 118.8 | 22.4 |
| 1995 | **401.20** | 18.23 | 14.4 | 3.6 | 16.2 | 4.0 |
| 1996 | **655.20** | 17.70 | 103.3 | 15.8 | 219.4 | 33.5 |
| 1997 | **490.90** | 18.08 | 45.8 | 9.3 | 87.9 | 17.9 |
| 1998 | **600.80** | 18.30 | 84.3 | 14.0 | 175.8 | 29.3 |
| 1999 | **440.30** | 19.00 | 28.1 | 6.4 | 47.4 | 10.8 |
| 2000 | **345.20** | 18.85 | | | | |
| 2001 | **783.60** | 18.50 | 148.3 | 18.9 | 322.1 | 41.1 |
| 2002 | **524.30** | 18.21 | 57.5 | 11.0 | 114.6 | 21.9 |
| 2003 | 424.30 | 18.38 | 22.5 | 5.3 | 34.6 | 8.2 |
| 2004 | 648.50 | 18.73 | 101.0 | 15.6 | 214.0 | 33.0 |
| 2005 | 575.10 | 12.11 | 75.3 | 13.1 | 155.3 | 27.0 |
| 2006 | 436.10 | 17.63 | 26.6 | 6.1 | 44.1 | 10.1 |
| 2007 | 680.60 | 17.14 | 112.2 | 16.5 | 239.7 | 35.2 |
| 2008 | 628.80 | 17.28 | 94.1 | 15.0 | 198.2 | 31.5 |
| 2009 | 525.4 | 17.66 | 57.9 | 11.0 | 115.5 | 22.0 |
| **Max** | 913.70 | 19.00 | 193.80 | 21.21 | 426.16 | 46.64 |
| **Min** | 229.40 | 12.11 | 14.42 | 3.59 | 16.16 | 4.03 |
| **Range** | 684.30 | 6.89 | 179.38 | 17.62 | 410.00 | 42.61 |
| **Mean** | **597.66** | **17.56** | **87.30** | **13.42** | **182.74** | **27.81** |
| **Median** | 608.30 | 17.58 | 88.92 | 14.48 | 186.44 | 30.36 |
| **St. Dev** | 138.57 | 0.80 | 44.64 | 4.46 | 102.03 | 10.79 |

Appendix 6.1 Statistics of physical and chemical parameters of groundwater samples from the Cape Flats aquifer (historic data & recent sampling)

| | Min | Max | Average | St. Dev. | Dev. Coeff | Var% | No. of samples |
|---|---|---|---|---|---|---|---|
| pH | 4.8 | 9.1 | 6.9 | 6.1 | 88.4 | 47 | 1053 |
| T(Wa) | 17.2 | 25.4 | 19.9 | 1.5 | 7.5 | 32 | 130 |
| Cond | 48.4 | 10370.0 | 1178.9 | 1825.4 | 154.8 | 100 | 1020 |
| SIO2 | 0.0 | 25.5 | 5.1 | 3.2 | 61.8 | 100 | 876 |
| Na | 3.3 | 2285.8 | 229.9 | 471.0 | 204.8 | 100 | 1051 |
| Ca | 1.7 | 366.0 | 101.2 | 75.3 | 74.4 | 100 | 1051 |
| Mg | 1.0 | 321.3 | 36.3 | 72.2 | 199.0 | 100 | 1048 |
| Cl | 7.0 | 5121.1 | 466.8 | 1064.2 | 228.0 | 100 | 1051 |
| SO4 | 0.0 | 846.6 | 70.0 | 82.1 | 117.2 | 100 | 1051 |
| HCO3 | 0.1 | 753.0 | 190.7 | 102.6 | 53.8 | 100 | 1040 |
| NO3 | 0.0 | 248.4 | 2.7 | 10.9 | 409.1 | 100 | 1046 |
| NH4 | 0.0 | 173.0 | 1.4 | 9.8 | 676.3 | 100 | 1019 |
| PO4 | 0.0 | 11.4 | 0.1 | 0.6 | 692.0 | 100 | 1034 |
| F | 0.0 | 3.1 | 0.2 | 0.2 | 106.2 | 100 | 1019 |
| Fe | 0.0 | 30.3 | 2.9 | 5.9 | 201.5 | 100 | 607 |
| Mn | 0.0 | 2.3 | 0.1 | 0.2 | 246.5 | 100 | 598 |
| Ba | 0.0 | 2.0 | 0.1 | 0.2 | 315.1 | 100 | 477 |
| Sr | 0.0 | 5.8 | 1.4 | 0.8 | 55.4 | 100 | 504 |
| Cu | 0.0 | 2.7 | 0.0 | 0.1 | 772.8 | 100 | 573 |
| Zn | 0.0 | 1.3 | 0.0 | 0.1 | 323.6 | 100 | 545 |
| Ni | 0.0 | 0.1 | 0.0 | 0.0 | 56.4 | 100 | 517 |
| Rb | 0.0 | 0.0 | 0.0 | 0.0 | 46.1 | 67 | 10 |
| B | 0.0 | 3.8 | 0.1 | 0.2 | 165.0 | 100 | 558 |
| Al | 0.0 | 1.3 | 0.8 | 0.4 | 51.8 | 100 | 478 |
| As | 0.0 | 1.0 | 0.1 | 0.1 | 61.3 | 100 | 495 |
| Be | 0.0 | 728.0 | 1.9 | 37.4 | 1943.1 | 100 | 378 |
| Cd | 0.0 | 0.0 | 0.0 | 0.0 | 62.7 | 100 | 513 |
| Co | 0.0 | 0.2 | 0.0 | 0.0 | 53.6 | 99 | 380 |
| Cr | 0.0 | 0.1 | 0.0 | 0.0 | 89.9 | 100 | 498 |
| Hg | 0.0 | 14.0 | 0.1 | 0.8 | 1530.5 | 100 | 334 |
| Mo | 0.0 | 0.1 | 0.0 | 0.0 | 106.9 | 100 | 455 |
| Pb | 0.0 | 0.9 | 0.1 | 0.1 | 123.3 | 100 | 541 |
| Li | 0.0 | 0.0 | 0.0 | 0.0 | 104.6 | 100 | 10 |
| Sr | 0.0 | 5.8 | 1.4 | 0.8 | 55.4 | 100 | 504 |
| P | 0.0 | 3.3 | 0.2 | 0.6 | 292.3 | 100 | 35 |
| H2S | 0.0 | 11.4 | 0.7 | 1.8 | 276.9 | 100 | 39 |
| V | 0.0 | 0.0 | 0.0 | 0.0 | 210.8 | 100 | 10 |
| Zr | 0.0 | 1.4 | 0.0 | 0.1 | 293.5 | 99 | 355 |

**Appendix 7.1: CALOD vulnerability input data for the Cape Flats**

| BH_NO | Latitude | Longitude | Head | Depth | Calrete | CL | OL | SA | AT | AM | Weighting | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BA60 | -34.059842 | 18.594444 | 20 | 3 | 0 | 4 | 9 | 30 | 21 | Sfmg | 5 | 5 |
| BA61 | -34.047500 | 18.600000 | 20 | 3 | 8 | 0 | 11 | 30 | 19 | Shrcg | 5 | 5 |
| BA62 | -34.051547 | 18.596389 | 20 | 3 | 9 | 0 | 8 | 31 | 23 | Srhcg | 5 | 5 |
| BA63 | -34.051389 | 18.601389 | 20 | 2 | 4 | 0 | 5 | 26 | 21 | Sfmg | 5 | 5 |
| BA64 | -34.058333 | 18.598611 | 40 | 7 | 0 | 0 | 0 | 29 | 29 | Sfm | 3 | 4 |
| BA65 | -34.059722 | 18.594444 | 20 | 3 | 0 | 0 | 7 | 29 | 22 | Shcg | 5 | 5 |
| BA66 | -34.053333 | 18.596389 | 20 | 2 | 18 | 0 | 2 | 22 | 20 | Srg | 4 | 5 |
| BA67 | -34.057500 | 18.601111 | 20 | 3 | 0 | 0 | 7 | 25 | 18 | Sfmg | 5 | 5 |
| BA68 | -34.060833 | 18.601111 | 40 | 6 | 3 | 0 | 5 | 29 | 24 | Sfmgr | 5 | 5 |
| BA69 | -34.051667 | 18.596389 | 40 | 7 | 6 | 0 | 12 | 32 | 20 | Shcg | 4 | 5 |
| BA70 | -34.051667 | 18.588333 | 40 | 1 | 10 | 8 | 22 | 32 | 10 | Shfmy | 3 | 5 |
| BA71 | -34.041944 | 18.601111 | 20 | 3 | 4 | 0 | 9 | 23 | 14 | Sfmg | 5 | 5 |
| BA72 | -34.048611 | 18.618333 | 20 | 3 | 9 | 3 | 5 | 28 | 23 | Srhmy | 3 | 5 |
| BA73 | -34.058333 | 18.621111 | 40 | 4 | 10 | 0 | 2 | 21 | 19 | Srg | 4 | 5 |
| BA74 | -34.041111 | 18.611667 | 40 | 4 | 21 | 7 | 7 | 26 | 19 | Sry | 2 | 5 |
| BA75 | -34.071667 | 18.602778 | 40 | 4 | 0 | 0 | 0 | 24 | 24 | Gs | 5 | 5 |
| BA76 | -34.055000 | 18.610000 | 20 | 4 | 11 | 0 | 0 | 18 | 18 | Srg | 4 | 5 |
| BA77 | -34.043333 | 18.583333 | 10 | 6 | 4 | 0 | 4 | 21 | 17 | Shrcg | 5 | 5 |
| BA78 | -34.066667 | 18.598611 | 20 | 3 | 11 | 0 | 9 | 30 | 21 | Srg | 4 | 5 |
| BA79 | -34.057500 | 18.594444 | 20 | 3 | 16 | 0 | 6 | 30 | 24 | Srg | 4 | 5 |
| BA80 | -34.048890 | 18.564170 | 40 | 2 | 16 | 0 | 8 | 28 | 20 | Srg | 4 | 5 |
| BA81 | -34.060556 | 18.592500 | 40 | 2 | 3 | 0 | 6 | 33 | 27 | Sfm | 3 | 4 |
| BA82 | -34.073611 | 18.611667 | 40 | 1 | 0 | 0 | 10 | 22 | 12 | Gs | 5 | 5 |
| BA83 | -34.078056 | 18.566667 | 40 | 2 | 14 | 0 | 6 | 29 | 23 | Srg | 4 | 5 |
| BA84 | -34.066667 | 18.583333 | 40 | 3 | 12 | 0 | 0 | 29 | 29 | Sfm | 3 | 4 |
| BA85 | -34.051667 | 18.583333 | 40 | 4 | 4 | 0 | 10 | 33 | 23 | Shcg | 5 | 5 |
| BA86 | -34.041940 | 18.561670 | 40 | 3 | 1 | 0 | 10 | 25 | 15 | Sfmg | 5 | 5 |
| BA87 | -34.066667 | 18.611667 | 40 | 1 | 13 | 0 | 2 | 24 | 22 | Grs | 5 | 5 |
| BA88 | -34.053333 | 18.604444 | 40 | 3 | 11 | 0 | 6 | 25 | 19 | Srhm | 5 | 5 |
| BA31 | -34.066670 | 18.583330 | 60 | 4 | 0 | 0 | 0 | 7 | 11 | S | 5 | 5 |
| BA32 | -34.060010 | 18.594440 | 60 | 5 | 0 | 6 | 0 | 26 | 21 | S | 5 | 5 |
| BA34 | -34.062230 | 18.604440 | 60 | | 0 | 17 | 0 | 33 | 28 | S | 3 | 4 |
| BA35 | -34.041660 | 18.598610 | 60 | 4 | 0 | 1 | 0 | 17 | 13 | S | 5 | 5 |
| BA36 | -34.078060 | 18.566670 | 60 | 6 | 0 | 11 | 0 | 31 | 37 | Scy | 3 | 4 |
| BA37 | -34.057500 | 18.601110 | 60 | 6 | 0 | 42 | 0 | 54 | 60 | Sy | 3 | 3 |
| BA02 | -34.047500 | 18.600000 | 10 | 8 | 4 | 0 | 0 | 17 | 24 | Sy | 3 | 5 |
| BA04 | -34.051670 | 18.588330 | 25 | 19 | 3 | 0 | 0 | 39 | 57 | Syr | 2 | 3 |
| BA05 | -34.074450 | 18.581110 | 15 | 14 | 0 | 3 | 0 | 7 | 21 | Sr | 2 | 5 |
| BA06 | -34.051160 | 18.558850 | 16 | 16 | 7 | 0 | 0 | 6 | 22 | Syr | 2 | 5 |
| BA07 | -34.051670 | 18.596390 | 12 | 8 | 0 | 5 | 0 | 22 | 30 | Ssc | 4 | 4 |
| BA09 | -34.048610 | 18.601670 | 11 | 27 | 0 | 2 | 0 | -2 | 25 | Sg | 5 | 5 |
| BA11 | -34.073610 | 18.611670 | 30 | 27 | 5 | 3 | 5 | 11 | 37 | Sr | 2 | 4 |
| BA12 | -34.055000 | 18.591660 | 25 | 23 | 4 | 1 | 0 | -2 | 21 | Scgr | 4 | 5 |
| BA13 | -34.066700 | 18.611670 | 21 | 19 | 2 | 0 | 2 | 16 | 34 | Sr | 2 | 4 |
| BA14 | -34.051670 | 18.583330 | 4 | 2 | 8 | 0 | 0 | 22 | 24 | Sr | 2 | 5 |
| BA15 | -34.040550 | 18.583330 | 16 | 16 | 2 | 0 | 0 | 20 | 35 | Srg | 4 | 4 |
| BA17 | -34.060830 | 18.601110 | 14 | 14 | 1 | 0 | 0 | 16 | 30 | Sf | 3 | 4 |
| BA18 | -34.036660 | 18.596390 | 17 | 11 | 2 | 0 | 0 | 12 | 23 | Sy | 3 | 5 |
| BA19 | -34.062220 | 18.604440 | 13 | 9 | 2 | 1 | 0 | 22 | 31 | Srg | 4 | 4 |
| BA20 | -34.060000 | 18.594440 | 11 | 8 | 3 | 0 | 0 | 20 | 28 | Sr | 2 | 4 |
| BA23 | -34.021950 | 18.619450 | 10 | 7 | 2 | 2 | 0 | 25 | 32 | Sryg | 4 | 4 |
| BA25 | -34.053330 | 18.604440 | 10 | 9 | 5 | 0 | 0 | 15 | 25 | Srg | 4 | 5 |
| BA30 | -34.066670 | 18.598610 | 14 | 10 | 2 | 0 | 0 | 24 | 34 | Sr | 2 | 4 |
| BA322 | -34.075560 | 18.594170 | 22 | 10 | 7 | 0 | 0 | 39 | 49 | Srg | 4 | 4 |
| BA323 | -34.052780 | 18.582780 | 9 | 6 | 6 | 0 | 0 | 22 | 28 | Sr | 2 | 4 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BA325 | -34.084720 | 18.543610 | 8 | 6 | 0 | 1 | 0 | 20 | 26 | Sy | 3 | 4 |
| BA326 | -34.021940 | 18.616670 | 11 | 9 | 2 | 0 | 0 | 21 | 30 | Sr | 2 | 4 |
| BA327 | -34.020000 | 18.618000 | 18 | 14 | 2 | 1 | 0 | 22 | 36 | Sfr | 2 | 4 |
| BA03 | -34.010000 | 18.500000 | 19 | 18 | 12 | 1 | 0 | 31 | 49 | Sr | 2 | 4 |
| DC231 | -33.932720 | 18.622840 | 22 | 18 | 12 | 0 | 0 | 23 | 41 | Sr | 2 | 4 |
| DC232 | -33.932910 | 18.622520 | 21 | 18 | 13 | 0 | 2 | 32 | 50 | Sr | 2 | 4 |
| DC234 | -33.933200 | 18.622550 | 17 | 10 | 2 | 0 | 0 | 26 | 36 | Srg | 4 | 4 |
| DC235 | -33.933110 | 18.622470 | 14 | 12 | 0 | 0 | 0 | 19 | 31 | Sg | 5 | 4 |
| DC236 | -33.933040 | 18.622250 | 15 | 13 | 5 | 0 | 0 | 35 | 48 | Sr | 2 | 4 |
| DC237 | -33.933300 | 18.622180 | 19 | 16 | 7 | 0 | 0 | 40 | 56 | Srg | 4 | 3 |
| BA08 | -33.950000 | 18.620000 | 4 | 2 | 0 | 0 | 0 | 20 | 22 | Sg | 5 | 5 |
| BA10 | -33.900000 | 18.570000 | 4 | 1 | 0 | 0 | 0 | 24 | 26 | Sg | 5 | 4 |
| BA39 | -34.023890 | 18.613890 | 5 | 2 | 3 | 0 | 0 | 24 | 26 | Sf | 3 | 4 |
| BA40 | -34.023060 | 18.613330 | 3 | 2 | 7 | 2 | 0 | 32 | 35 | Ssg | 5 | 4 |
| BA41 | -34.021390 | 18.612220 | 22 | 14 | 2 | 0 | 0 | 37 | 51 | Sr | 2 | 3 |
| BA45 | -34.024170 | 18.622230 | 19 | 15 | 0 | 7 | 0 | 19 | 34 | Scg | 4 | 4 |
| BA46 | -34.021110 | 18.625840 | 18 | 13 | 2 | 0 | 0 | 24 | 37 | Sr | 2 | 4 |
| BA47 | -34.025280 | 18.616390 | 17 | 11 | 0 | 0 | 0 | 17 | 28 | Sg | 5 | 4 |
| BA48 | -34.025000 | 18.622500 | 25 | 10 | 20 | 0 | 0 | 33 | 43 | Sr | 2 | 4 |
| BA49 | -34.024170 | 18.625000 | 32 | 29 | 5 | 0 | 0 | -3 | 27 | Sr | 2 | 4 |
| BA50 | -34.021110 | 18.615000 | 13 | 10 | 12 | 1 | 0 | 11 | 21 | Shy | 3 | 5 |
| BA51 | -34.025560 | 18.621110 | 13 | 10 | 10 | 0 | 0 | 16 | 26 | Shy | 3 | 4 |
| BA52 | -34.021950 | 18.623890 | 11 | 10 | 5 | 2 | 0 | 15 | 25 | Shy | 3 | 4 |
| BA53 | -34.025840 | 18.612220 | 35 | 29 | 25 | 2 | 0 | -9 | 20 | ry | 2 | 5 |
| BA54 | -34.020280 | 18.618060 | 32 | 27 | 7 | 2 | 0 | 6 | 33 | Srcg | 4 | 4 |
| BA55 | -34.021390 | 18.608890 | 36 | 32 | 5 | 0 | 0 | -10 | 21 | Sr | 2 | 5 |
| BA58 | -34.006400 | 18.580560 | 37 | 37 | 10 | 3 | 0 | -4 | 34 | Sryg | 3 | 4 |
| BA59 | -34.022780 | 18.628610 | 16 | 14 | 4 | 2 | 0 | 18 | 33 | Src | 3 | 4 |
| BA01 | -34.051390 | 18.603330 | 16 | 14 | 5 | 2 | 0 | 18 | 32 | Scy | 3 | 4 |
| CD51 | -33.808350 | 18.375000 | 23 | 11 | 20 | 5 | 0 | 28 | 39 | Sy | 3 | 4 |
| CD52 | -33.808330 | 18.375030 | 23 | 19 | 3 | 0 | 0 | 15 | 33 | Srg | 4 | 4 |
| DC03 | -33.999310 | 18.615290 | 28 | 20 | 8 | 0 | 0 | 10 | 31 | Srg | 4 | 4 |
| DC04 | -33.977780 | 18.569450 | 33 | 27 | 5 | 0 | 0 | -4 | 23 | Sr | 2 | 5 |
| DC161 | -33.818060 | 18.516670 | 18 | 14 | 4 | 0 | 0 | 33 | 47 | Srg | 4 | 4 |
| DC177 | -33.781110 | 18.556390 | 20 | 16 | 2 | 8 | 0 | 20 | 36 | Sry | 3 | 4 |
| DC179 | -33.774440 | 18.710280 | 16 | 15 | 2 | 2 | 0 | -7 | 9 | Sry | 3 | 5 |
| DC182 | -33.901760 | 18.643920 | 24 | 23 | 0 | 3 | 0 | -13 | 10 | Sy | 3 | 5 |
| DC183 | -33.901760 | 18.643890 | 22 | 21 | 0 | 2 | 0 | -12 | 9 | Sy | 3 | 5 |
| DC184 | -33.902480 | 18.644080 | 22 | 23 | 0 | 2 | 0 | -6 | 17 | Sy | 3 | 5 |
| DC226 | -33.773610 | 18.710280 | 22 | 18 | 0 | 8 | 0 | 13 | 31 | Scy | 3 | 4 |
| DC175 | -33.820000 | 18.570000 | 18 | 18 | 0 | 15 | 0 | 23 | 41 | Scf | 3 | 4 |
| DC176 | -33.920000 | 18.560000 | 7 | 1 | 5 | 0 | 0 | 21 | 23 | Srg | 4 | 5 |
| DC180 | -33.950000 | 18.670000 | 26 | 2 | 0 | 0 | 0 | 39 | 42 | S | 4 | 4 |
| DC178 | -33.940000 | 18.530000 | 11 | 2 | 3 | 0 | 0 | 24 | 25 | Srg | 4 | 4 |
| DC237 | -33.942220 | 18.511940 | 19 | 16 | 5 | 0 | 0 | 10 | 26 | Sryg | 4 | 4 |
| DC239 | -33.874710 | 18.561430 | 10 | 2 | 4 | 1 | 0 | 30 | 32 | Scrg | 2 | 4 |
| DC241 | -33.780950 | 18.555350 | 18 | 17 | 8 | 4 | 0 | 22 | 39 | Srh | 2 | 4 |
| DC276 | -33.967500 | 18.598060 | 18 | 14 | 2 | 3 | 0 | 7 | 20 | Sry | 3 | 5 |
| DC185 | -33.930000 | 18.700000 | 19 | 17 | 0 | 0 | 0 | 11 | 28 | S | 4 | 4 |
| DC186 | -33.960000 | 18.750000 | 34 | 32 | 3 | 2 | 0 | -17 | 15 | Src | 3 | 4 |
| BB94 | -33.980000 | 18.750000 | 22 | 11 | 22 | 6 | 0 | 41 | 52 | Shy | 3 | 3 |
| BB95 | -34.060000 | 18.790000 | 22 | 12 | 20 | 5 | 0 | 41 | 52 | Shcy | 3 | 3 |
| BB96 | -34.090000 | 18.840000 | 21 | 11 | 18 | 5 | 0 | 38 | 50 | Shcy | 3 | 4 |

*G* Gravel, *S* Sand, *C* Clay, *g* gravelly, *h shelly, r calcrete/calcareous, s* sandy, *y* clayey, *c* coarse, *m* medium, *f* fine/silty

V.H = Very High, H = High, M = Medium, L = Low, V.L = Very Low, VI = Vulnerability Index

CA = calcrete, CL = clayey layer, OL = overlying layer, SA = saturated aquifer thickness, AT

| AC | Rating | | OL | $C_R$ | $C_wC_R$ | $A_R$ | $A_wA_R$ | $L_R$ | $L_wL_R$ | $O_R$ | $O_wO_R$ | $D_R$ | $D_RD_w$ | I_CALOD | VI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25 | 4 | 5 | 20 | 2 | 2 | 5 | 20 | 5 | 15 | 4 | 8 | 5 | 25 | 70 | H |
| 25 | 3 | 4 | 12 | 5 | 5 | 5 | 20 | 2 | 6 | 3 | 6 | 5 | 25 | 62 | H |
| 25 | 4 | 5 | 20 | 5 | 5 | 5 | 20 | 2 | 6 | 4 | 8 | 5 | 25 | 64 | H |
| 25 | 3 | 5 | 15 | 5 | 5 | 5 | 20 | 4 | 12 | 3 | 6 | 5 | 25 | 68 | H |
| 12 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 5 | 15 | 5 | 10 | 4 | 20 | 66 | H |
| 25 | 1 | 5 | 5 | 5 | 5 | 5 | 20 | 5 | 15 | 2 | 4 | 5 | 25 | 69 | H |
| 20 | 3 | 5 | 15 | 5 | 5 | 5 | 20 | 1 | 3 | 3 | 6 | 5 | 25 | 59 | M-H |
| 25 | 1 | 5 | 5 | 5 | 5 | 5 | 20 | 5 | 15 | 2 | 4 | 5 | 25 | 69 | H |
| 25 | 1 | 5 | 5 | 5 | 5 | 5 | 20 | 4 | 12 | 2 | 4 | 4 | 20 | 61 | H |
| 20 | 3 | 4 | 12 | 5 | 5 | 5 | 20 | 3 | 9 | 3 | 6 | 4 | 20 | 60 | M-H |
| 15 | 1 | 3 | 3 | 2 | 2 | 5 | 20 | 2 | 6 | 1 | 2 | 5 | 25 | 55 | M-H |
| 25 | 3 | 5 | 15 | 5 | 5 | 5 | 20 | 4 | 12 | 3 | 6 | 5 | 25 | 68 | H |
| 15 | 2 | 5 | 10 | 3 | 3 | 5 | 20 | 2 | 6 | 3 | 6 | 5 | 25 | 60 | M-H |
| 20 | 4 | 5 | 20 | 5 | 5 | 5 | 20 | 2 | 6 | 4 | 8 | 5 | 25 | 64 | H |
| 5 | 2 | 5 | 10 | 2 | 2 | 2 | 8 | 1 | 3 | 3 | 6 | 5 | 25 | 44 | M-H |
| 25 | 4 | 5 | 20 | 5 | 5 | 5 | 20 | 5 | 15 | 4 | 8 | 5 | 25 | 73 | H |
| 20 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 1 | 3 | 5 | 10 | 5 | 25 | 63 | H |
| 25 | 2 | 5 | 10 | 5 | 5 | 5 | 20 | 4 | 12 | 3 | 6 | 4 | 20 | 63 | H |
| 20 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 1 | 3 | 5 | 10 | 5 | 25 | 63 | H |
| 20 | 4 | 5 | 20 | 5 | 5 | 5 | 20 | 1 | 3 | 4 | 8 | 5 | 25 | 61 | H |
| 20 | 3 | 5 | 15 | 5 | 5 | 5 | 20 | 1 | 3 | 3 | 6 | 5 | 25 | 59 | M-H |
| 12 | 1 | 5 | 5 | 5 | 5 | 4 | 16 | 4 | 12 | 2 | 4 | 5 | 25 | 62 | H |
| 25 | 5 | 4 | 20 | 5 | 5 | 5 | 20 | 5 | 15 | 4 | 8 | 5 | 25 | 73 | H |
| 20 | 2 | 5 | 10 | 5 | 5 | 5 | 20 | 1 | 3 | 3 | 6 | 5 | 25 | 59 | M-H |
| 12 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 1 | 3 | 5 | 10 | 5 | 25 | 59 | M-H |
| 25 | 4 | 4 | 16 | 5 | 5 | 5 | 20 | 4 | 12 | 4 | 8 | 5 | 25 | 70 | H |
| 25 | 3 | 4 | 12 | 5 | 5 | 5 | 20 | 5 | 15 | 3 | 6 | 5 | 25 | 71 | H |
| 25 | 4 | 5 | 20 | 5 | 5 | 5 | 20 | 1 | 3 | 4 | 8 | 5 | 25 | 61 | H |
| 25 | 3 | 5 | 15 | 5 | 5 | 5 | 20 | 1 | 3 | 3 | 6 | 5 | 25 | 59 | M-H |
| 25 | 0 | 5 | 0 | 5 | 5 | 5 | 20 | 5 | 15 | 1 | 2 | 5 | 25 | 67 | H |
| 25 | 0 | 5 | 0 | 2 | 2 | 5 | 20 | 5 | 15 | 1 | 2 | 5 | 25 | 64 | H |
| 12 | 0 | 5 | 0 | 1 | 1 | 4 | 16 | 5 | 15 | 1 | 2 | 5 | 25 | 59 | M-H |
| 25 | 0 | 5 | 0 | 4 | 4 | 5 | 20 | 5 | 15 | 1 | 2 | 4 | 20 | 61 | H |
| 12 | 5 | 5 | 25 | 1 | 1 | 4 | 16 | 5 | 15 | 5 | 10 | 5 | 25 | 67 | H |
| 9 | 5 | 5 | 25 | 1 | 1 | 3 | 12 | 5 | 15 | 5 | 10 | 4 | 20 | 58 | M-H |
| 15 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 4 | 12 | 5 | 10 | 4 | 20 | 67 | H |
| 6 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 4 | 12 | 5 | 10 | 4 | 20 | 59 | M-H |
| 10 | 5 | 5 | 25 | 4 | 4 | 4 | 16 | 5 | 15 | 5 | 10 | 3 | 15 | 60 | H |
| 10 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 3 | 9 | 5 | 10 | 3 | 15 | 55 | M-H |
| 16 | 5 | 5 | 25 | 2 | 2 | 5 | 20 | 5 | 15 | 5 | 10 | 4 | 20 | 67 | H |
| 25 | 5 | 5 | 25 | 3 | 3 | 5 | 20 | 5 | 15 | 5 | 10 | 2 | 10 | 58 | M-H |
| 8 | 4 | 5 | 20 | 3 | 3 | 3 | 12 | 3 | 9 | 4 | 8 | 2 | 10 | 42 | M-H |
| 20 | 5 | 5 | 25 | 4 | 4 | 5 | 20 | 4 | 12 | 5 | 10 | 2 | 10 | 56 | M-H |
| 8 | 4 | 5 | 20 | 5 | 5 | 3 | 12 | 5 | 15 | 4 | 8 | 3 | 15 | 55 | M-H |
| 10 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 2 | 6 | 5 | 10 | 5 | 25 | 62 | H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 5 | 15 | 5 | 10 | 3 | 15 | 65 | H |
| 12 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 5 | 15 | 5 | 10 | 3 | 15 | 61 | H |
| 15 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 5 | 15 | 5 | 10 | 3 | 15 | 65 | H |
| 16 | 5 | 5 | 25 | 4 | 4 | 5 | 20 | 5 | 15 | 5 | 10 | 4 | 20 | 69 | H |
| 8 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 4 | 12 | 5 | 10 | 4 | 20 | 59 | M-H |
| 16 | 5 | 5 | 25 | 3 | 3 | 5 | 20 | 5 | 15 | 5 | 10 | 4 | 20 | 68 | H |
| 20 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 3 | 9 | 5 | 10 | 4 | 20 | 64 | H |
| 8 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 5 | 15 | 5 | 10 | 4 | 20 | 62 | H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 3 | 9 | 5 | 10 | 3 | 15 | 59 | M-H |
| 8 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 3 | 9 | 5 | 10 | 4 | 20 | 56 | M-H |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 5 | 5 | 25 | 4 | 4 | 4 | 16 | 5 | 15 | 5 | 10 | 4 | 20 | 65 | H |
| 8 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 5 | 15 | 5 | 10 | 4 | 20 | 62 | H |
| 8 | 5 | 5 | 25 | 4 | 4 | 3 | 12 | 5 | 15 | 5 | 10 | 3 | 15 | 56 | M-H |
| 8 | 5 | 5 | 25 | 4 | 4 | 3 | 12 | 1 | 3 | 5 | 10 | 3 | 15 | 44 | M-H |
| 8 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 1 | 3 | 5 | 10 | 3 | 15 | 45 | M-H |
| 8 | 4 | 5 | 20 | 5 | 5 | 3 | 12 | 1 | 3 | 4 | 8 | 3 | 15 | 43 | M-H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 5 | 15 | 5 | 10 | 3 | 15 | 65 | H |
| 20 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 5 | 15 | 5 | 10 | 3 | 15 | 65 | H |
| 8 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 3 | 9 | 5 | 10 | 3 | 15 | 51 | M-H |
| 12 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 3 | 9 | 5 | 10 | 3 | 15 | 55 | M-H |
| 25 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 5 | 15 | 5 | 10 | 5 | 25 | 75 | H |
| 20 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 5 | 15 | 5 | 10 | 5 | 25 | 75 | H |
| 12 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 4 | 12 | 5 | 10 | 5 | 25 | 68 | H |
| 20 | 5 | 5 | 25 | 3 | 3 | 5 | 20 | 3 | 9 | 5 | 10 | 5 | 25 | 67 | H |
| 6 | 5 | 5 | 25 | 5 | 5 | 2 | 8 | 5 | 15 | 5 | 10 | 3 | 15 | 53 | M-H |
| 16 | 5 | 5 | 25 | 2 | 2 | 5 | 20 | 5 | 15 | 5 | 10 | 3 | 15 | 62 | H |
| 8 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 5 | 15 | 5 | 10 | 3 | 15 | 57 | M-H |
| 20 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 5 | 15 | 5 | 10 | 3 | 15 | 65 | H |
| 8 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 1 | 3 | 5 | 10 | 3 | 15 | 45 | M-H |
| 8 | 5 | 5 | 25 | 5 | 5 | 3 | 12 | 3 | 9 | 5 | 10 | 2 | 10 | 46 | M-H |
| 15 | 5 | 5 | 25 | 4 | 4 | 5 | 20 | 1 | 3 | 5 | 10 | 4 | 20 | 57 | M-H |
| 12 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 2 | 6 | 5 | 10 | 4 | 20 | 57 | M-H |
| 12 | 5 | 5 | 25 | 3 | 3 | 4 | 16 | 3 | 9 | 5 | 10 | 4 | 20 | 58 | M-H |
| 10 | 5 | 5 | 25 | 3 | 3 | 4 | 16 | 1 | 3 | 5 | 10 | 2 | 10 | 42 | M-H |
| 16 | 5 | 5 | 25 | 3 | 3 | 5 | 20 | 3 | 9 | 5 | 10 | 2 | 10 | 52 | M-H |
| 10 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 3 | 9 | 5 | 10 | 2 | 10 | 50 | M-H |
| 12 | 5 | 5 | 25 | 3 | 3 | 4 | 16 | 2 | 6 | 5 | 10 | 2 | 10 | 45 | M-H |
| 12 | 5 | 5 | 25 | 3 | 3 | 4 | 16 | 4 | 12 | 5 | 10 | 3 | 15 | 56 | M-H |
| 12 | 5 | 5 | 25 | 3 | 3 | 4 | 16 | 3 | 9 | 5 | 10 | 3 | 15 | 53 | M-H |
| 12 | 5 | 5 | 25 | 2 | 2 | 4 | 16 | 1 | 3 | 5 | 10 | 3 | 15 | 46 | M-H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 4 | 12 | 5 | 10 | 3 | 15 | 62 | H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 2 | 6 | 5 | 10 | 2 | 10 | 51 | M-H |
| 10 | 5 | 5 | 25 | 5 | 5 | 4 | 16 | 3 | 9 | 5 | 10 | 2 | 10 | 50 | M-H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 4 | 12 | 5 | 10 | 3 | 15 | 62 | H |
| 12 | 5 | 5 | 25 | 2 | 2 | 4 | 16 | 5 | 15 | 5 | 10 | 3 | 15 | 58 | M-H |
| 15 | 5 | 5 | 25 | 3 | 3 | 5 | 20 | 5 | 15 | 5 | 10 | 3 | 15 | 63 | H |
| 15 | 5 | 5 | 25 | 3 | 3 | 5 | 20 | 5 | 15 | 5 | 10 | 2 | 10 | 58 | M-H |
| 15 | 5 | 5 | 25 | 3 | 3 | 5 | 20 | 5 | 15 | 5 | 10 | 2 | 10 | 58 | M-H |
| 15 | 5 | 5 | 25 | 3 | 3 | 5 | 20 | 5 | 15 | 5 | 10 | 2 | 10 | 58 | M-H |
| 12 | 5 | 5 | 25 | 2 | 2 | 4 | 16 | 5 | 15 | 5 | 10 | 3 | 15 | 58 | M-H |
| 12 | 5 | 5 | 25 | 1 | 1 | 4 | 16 | 5 | 15 | 5 | 10 | 3 | 15 | 57 | M-H |
| 20 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 3 | 9 | 5 | 10 | 5 | 25 | 69 | H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 5 | 15 | 5 | 10 | 5 | 25 | 75 | H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 4 | 12 | 5 | 10 | 5 | 25 | 72 | H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 3 | 9 | 5 | 10 | 3 | 15 | 59 | M-H |
| 8 | 5 | 5 | 25 | 4 | 4 | 3 | 12 | 4 | 12 | 5 | 10 | 5 | 25 | 63 | H |
| 8 | 5 | 5 | 25 | 2 | 2 | 3 | 12 | 2 | 6 | 5 | 10 | 3 | 15 | 45 | M-H |
| 15 | 5 | 5 | 25 | 3 | 3 | 5 | 20 | 5 | 15 | 5 | 10 | 3 | 15 | 63 | H |
| 16 | 5 | 5 | 25 | 5 | 5 | 5 | 20 | 5 | 15 | 5 | 10 | 3 | 15 | 65 | H |
| 12 | 5 | 5 | 25 | 3 | 3 | 4 | 16 | 4 | 12 | 5 | 10 | 2 | 10 | 51 | M-H |
| 9 | 5 | 5 | 25 | 2 | 2 | 4 | 16 | 1 | 3 | 5 | 10 | 3 | 15 | 46 | M-H |
| 9 | 5 | 5 | 25 | 2 | 2 | 4 | 16 | 1 | 3 | 5 | 10 | 3 | 15 | 46 | M-H |
| 12 | 5 | 5 | 25 | 2 | 2 | 4 | 16 | 1 | 3 | 5 | 10 | 3 | 15 | 46 | M-H |