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Changes in Groundwater Level Dynamics in Aquifer Systems – Implications for Resource Management in a Semi-Arid Climate

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1. Introduction

Groundwater has long been and continues to serve as a reliable source of water for a variety of purposes, including industrial and domestic uses and irrigation. The use of generally high-quality groundwater for irrigation dwarfs all other uses (Burke, 2002); and there are a number of aspects of water quality that have to be managed in such circumstance (e.g salinity, Sodium Absorption Ratio, nutrients, depending on the circumstances of the irrigation). As such there is the need to understand the various implications for use in the management of groundwater resources.

Effective management of groundwater is highly dependent on appropriate reliable and up-to-date information (Adelana, 2009) as may be contained in a groundwater database (GDB). According to FAO (2003a), there are currently thousands of local and personal databases storing key technical and licensing data in a very unsatisfactory manner (mostly in terms of usable formats). Hence, the hard evidence required for the assessment of global trends in groundwater depletion and aquifer degradation is still lacking. It is therefore difficult to assess the extent to which global food production could be at risk from either over-abstraction or from groundwater quality deterioration.

A study on groundwater and food security conducted by FAO (2003a) revealed that compiling reliable groundwater-level and abstraction data (to determine depletion rates) was fraught with problems of coverage, consistency and reliability. Therefore obtaining reliable time-series data on groundwater levels in specific aquifers in many countries may be key to assessing global trend and invariably future impact on food security. The complete lack of a GDB is seriously constraining the formulation and implementation of effective groundwater management policies in many countries. This reinstates the importance of consistency and reliability of groundwater level monitoring for effective groundwater management. In order to ensure sustainable management groundwater level responses must be considered in relation to climate changes and in response to increased agricultural food production.

In the context of varying climatic conditions and frequent lower than average annual rainfall, observed groundwater responses vary and subsequently reduce recharge, stream flow, and the water balance. For example, over the last ten years, decrease in rainfall amount

and rain intensity has been the major factor responsible for the declining groundwater levels across northern Victoria in SE Australia (Reid, 2010; Reid et al., 2007). The prolonged effects are expected to contribute a negative impact on water security, agricultural production and the ecosystem. However, under conditions of reduced groundwater use (with recycled water or inter-catchment water transfer), the impacts of irrigated agriculture on the hydrodynamics of shallow aquifer systems and the quality of the groundwater will also need to be fully quantified. Such impacts have been witnessed in other groundwater systems across Australia (Giambastiani et al., 2009; Kelly et al., 2009; McLean & Jankoski, 2002; McLean et al., 2000; Schaffer & Pigois, 2009) and elsewhere in the world (Abidin et al., 2001; Adelana et al., 2006a, 2006b; Chai et al., 2004; Hotta et al., 2010; Lopez-Quiroz et al. 2009).

This study demonstrates the importance of consistent groundwater level monitoring in relation to (and its implications on) effective and sustainable resource management as well as improved the understanding of climate impacts on groundwater levels. Two case examples are selected from areas at different level of groundwater monitoring, used to illustrate impact of climate variability as well as the importance of reliable and consistent groundwater monitoring database.

2. Background

Water use in both study areas (the Werribee Plains, Western Melbourne metropolitan, South-east Australia (Figure 1) and the Cape Flats, Cape Town metropolitan area, South Africa (Figure 2)) supports year-round irrigation, and is one of conjunctive use, including a channel network fed by releases from reservoirs and recycled water, respectively, and supplementary groundwater extractions. This represents two long established irrigation districts: the Werribee Irrigation District (WID) and the Cape Flats farming areas, both known for their market gardens. At a national scale, the WID is major suppliers of lettuce, cabbage, broccoli and cauliflower (SRWA, 2009), while the Cape Flats, especially the Greater Philippi horticultural area, is an important source of Cape Town's fresh produce (such as lettuce, onions, fresh fruit, bananas, potatoes) and which, at the regional scale produces 70-80% of vegetable sold in the Greater City of Cape Town (Rabe 1992, CCT 2010). For the two areas, the location, the highly productive soils and intensive cropping capability allow for diverse production and all-year-round supply. Moreover the close proximity of the two farming areas to fast growing commercial centres (Melbourne and Cape Town, respectively) provide market advantages and increases the value of the land for urban development.

Active groundwater management of the system in the Werribee Plains was initiated in 1998, at which time a safe yield of 2,400 ML/yr was estimated, compared to the sum of licensed groundwater extraction about 6,000 ML/yr. The installation of meters on all licensed bores occurred in 2004. A 25% restriction in licensed volume was in place (SKM, 2004) and this has since been regularly reviewed. Southern Rural Water Authority (SRWA) is the responsible agency for the management of groundwater resources in this district. Until recently, irrigators have been able to consistently rely on approximately 10,000 ML of water rights from SRWA's water distribution system (predominantly concrete-lined channels) and 5,000 ML of groundwater licences in the underlying shallow Groundwater Management Area (Rodda & Kent, 2004). In the Cape Flats, the Department of Water Affairs (DWA) is responsible for permits, licensing and metering. All information regarding registered

groundwater users and licensed volumes are encoded onto WARMS (Water use And Registration Management System section of DWA) database. In practise, the farmers in the Cape Town area irrigate their crops, particularly during the dry summer months and intensely in drier years. As at December 2006, the highest single registered volume was 699.15 ML/yr (Adelana, 2011). From WARMS record in 2006, there were 211 bores used for agriculture, 25 for industry and two for water supply within the City of Cape Town municipality (although a number of unregistered household bores may exist). The City of Cape Town has water restriction and management plan in place since 2002.

In the WID, expected threats to the aquifer include seawater intrusion from the coastline and estuarine portion of the Werribee River, inter-aquifer transfer of saline groundwater, and water level-induced bore failure. Reduced rainfall conditions exacerbate these threats by reduced recharge from both rainfall and channel leakage, increased estuarine length of the Werribee River, and an increased dependency on groundwater (SRWA, 2009). In the Cape Flats aquifer the maximum extent of seawater intrusion into the Cape Flats aquifer has been estimated to be approximately 1,000 m from the coastline (Gerber 1981), although recent studies (Adelana, 2011; Adelana & Xu, 2006) did not confirm inland saltwater movement. Nevertheless, surface water in the Cape Flats is known to be contaminated from various sources (Usher et al., 2004; Adelana & Xu, 2006) and the potential treat to groundwater identified (Adelana & Xu, 2006).

Within the WID, the highest percentage of groundwater extraction is from the Werribee deltaic sediments. Regions of the deltaic aquifer adjacent to the coastline and estuary have exhibited depressed watertable conditions, with hydraulic heads falling below mean sea level and/or at lowest recorded levels. These regions are also exhibiting rising groundwater salinity, particularly in deeper piezometers (SRWA, 2009). In the Western Cape, agricultural sector is one of the largest users of water resources; but rapid economic development and population growth is also generating increased pressure on water supplies. For example, the growth in urban water demand in the Greater Cape Town Metropolitan Area was projected to increase from 243 million m³ in 1990 to 456 million m³ in 2010; whereas for irrigation water demand the increase is from 56 million m³ in 1991 to 193 million m³ in 2010 (Ninham Shand, 1994). Over 60 % of the annual urban demand and 90 % of the irrigation demand occurs in summer (Adelana, 2011).

3. Study approach

In order to investigate varying climatic conditions and the impact of frequent lower than average annual rainfall on observed groundwater levels the long-term climate data are analysed and compared for both study areas. In the long-term, rainfall, minimum and maximum temperatures are related to climate variability. The climate data obtained were analysed and statistically interpreted. Long-term data are from the South African Weather Service (Station: Cape Town Observatory/Airport) and Bureau of Meteorology (BOM with station in Laverton near Werribee).

The groundwater databases of the Department of Primary Industries (DPI) and Department of Sustainability and Environment (DSE) Groundwater Management System (GMS) were examined to select representative bores tapping the Werribee Delta aquifer. Also, from the National Groundwater Database (NGDB) managed by DWA, a few bores screened in the

Cape Flats aquifer were selected. These bores were investigated by evaluating the groundwater levels and salinity (specifically the electrical conductivity) within shallow aquifers. The criteria for selection were continuous groundwater level record (minimum of 10 years record, with minimal interruptions or errors) and screened within the respective aquifers under this study.

The time-series groundwater data at selected locations within Cape Town area were compared with those of bore network data in the Werribee Plain. The analysis of this data was undertaken using Hydrograph Analysis: Rainfall and Time Trends (HARTT), a statistical tool that analyses groundwater data using the effect of long-term rainfall patterns, determined by accumulative residual techniques (Ferdowsian et al., 2001). This method can differentiate between the effect of rainfall fluctuations and the underlying trend of groundwater level over time. Rainfall is represented as an accumulation of deviations from average rainfall, and the lag between rainfall and its impact on groundwater is explicitly represented. HARTT produces a fitted curve through the groundwater level readings.

According to Ferdowsian et al. (2001), two variables are used to produce this line:

Rainfall variable (X_1); accumulative monthly residual rainfall (AMRR, mm), or accumulative annual residual rainfall (AARR, mm).

Time trend (X_2) (1,2,3 days...from first reading)

At any point along the fitted curve, the following equation holds:

$$Y = c + aX_1(\text{rainfall}) + bX_2(\text{time trend}) \quad (1)$$

Where:

c is the intercept.

a and b are coefficients calculated in the multiple regression analysis.

Y is the water level depth at a point along the fitted curve.

So, to calculate the effect of rainfall, the following equation is used:

$$Y' = aX_1(\text{rainfall}) \quad (2)$$

And to calculate the underlying trend, the following equation is used:

$$Y'' = c + bX_2(\text{time trend}) \quad (3)$$

The R^2 value (the coefficient of determination) is the degree of fit of the calculated curve compared to the recorded water levels (a value of 1 is a perfect fit; the degree of fit becomes less with decreasing values below 1). The p-value indicates the level of significance of each variable. If the p-value is less than 0.05, then the variable is significant. If it is less than 0.01, then it is highly significant. If the trend is not significant (as determined by R^2) then the rate of rise or fall is not reliable. And if the rainfall variable is not significant then the reliability of the effect and the delay period (in the hydrograph response to effective rainfall) is low (Ferdowsian et al., 2001).

The method improves the estimation of time trends and allows for better interpretation of treatment effects on groundwater levels. The advantage and limitation of this method over other techniques of hydrograph analyses have been highlighted in Cheng et al. (2011).

Access to several unpublished reports has also yielded valuable information. A general overview of the study area is presented with the description of geology and hydrogeological settings in order to first understand the groundwater system in both areas.

4. Description of the study area

The vegetable growing Werribee Irrigation District (WID) lies on Melbourne’s rapidly-developing western urban fringe underlain by shallow Delta aquifer. The name of the management area for the Werribee Delta aquifer is the Deutgam Water Supply Protection Area (WSPA). The aquifer is linked to both Port Phillip Bay and the tidal extent of the Werribee River (SRWA, 2009). Deutgam WSPA is located around the Werribee South irrigation area (Figure 1). On the other hand, the fresh fruits and vegetable farm area in Cape Town is located on the Cape Flats, especially the Phillipi-Mitchells Plain Irrigation area. A large portion of the area around Cape Town is the sand-covered coastal plain (Cape Flats) shown in figure 2. The City of Cape Town Management Area (CMA) 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 (Schalke, 1973; Theron et al., 1992). The greater portion of the entire sand cover of the Western Cape are been considered in this study, particularly the south-western part of the City of Cape Town and the north-western end (Atlantis), where basic data and bore information are available.

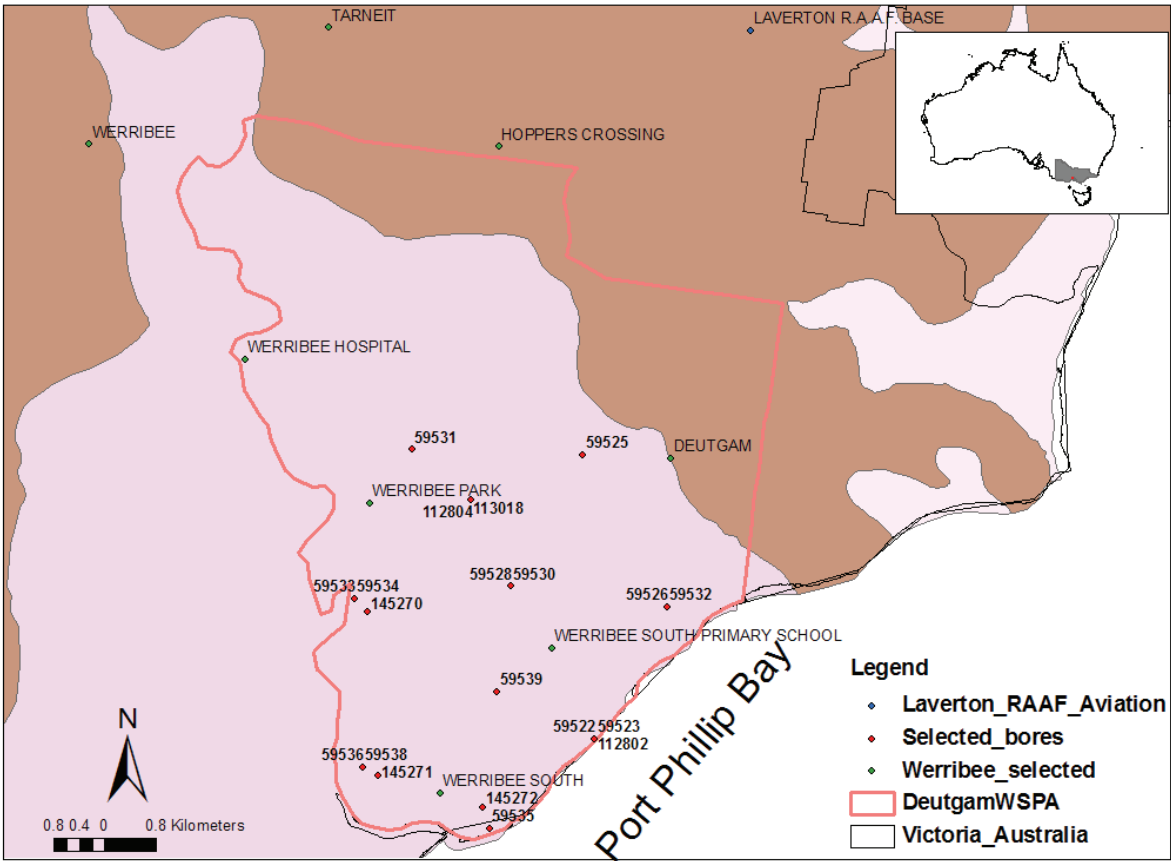


Fig. 1. Location of the Werribee Plains and Deutgam WSPA, western fringe of Melbourne. Inset: Deutgam WSPA (red spot) in Victoria (grey shade) within map of Australia

4.1 Geology and hydrogeology

4.1.1 The Cape Flats

A study of the geological units show the oldest rock in Cape Town and suburbs are the meta-sediments of the pre-Cambrian Malmesbury Group, which occupy the coastal plain between Saldanha and False Bay in the west, to the first mountain ranges in the east (Meyer, 2001). Several erosional windows to this Group are exposed in mainly fault-controlled valleys further to the east and south. Natural 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 (Schalke, 1973; Theron et al., 1992). 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.

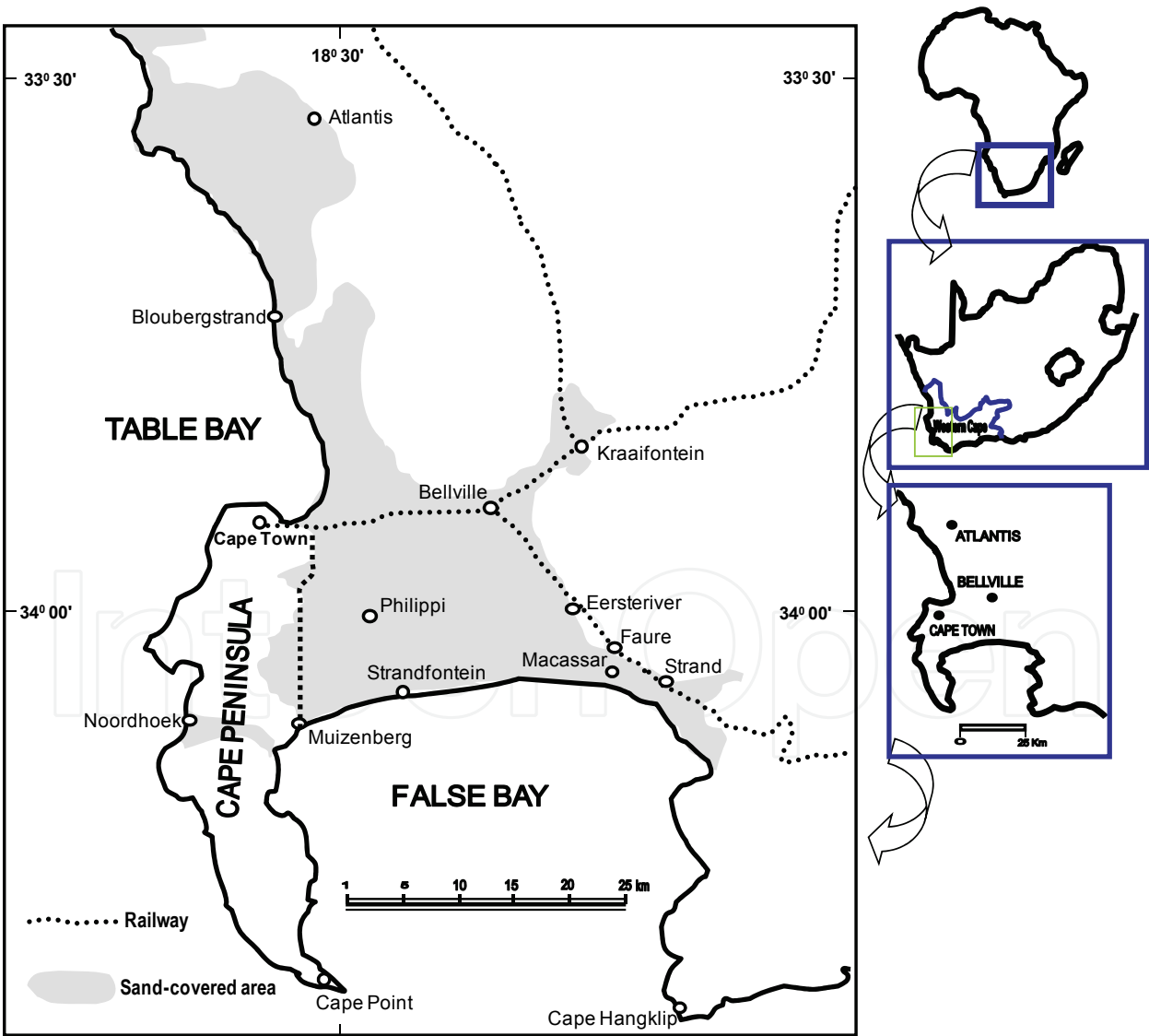


Fig. 2. Location of the Cape Flats sand in the Western Cape, South Africa (Adelana et al., 2010)

According to Meyer (2001) bore yield (from about 497 boreholes in the Sandveld Group) indicates that 41% of boreholes yield 0.5L/s and less while 30% yields 2L/s and more. Transmissivity values range from 32.5-619m²/d (from recent pumping test data in Adelana, 2011), but typical values between 200 and 350 m²/d were recorded in Gerber (1981). A detailed description of the hydrogeology of the different geological units is documented in Meyer (2001). The net groundwater recharge to the Cape Flats aquifer in the south-western Cape varies between 15% and 47% of mean annual precipitation (Adelana, 2011). The general aquifer configuration and flow direction in the Cape Flats has been presented as indicating flow from western and south-eastern to the coast. A conceptual model of the aquifer has been developed to indicate all flow is regionally unconfined and two-dimensional with negligible vertical components, although inter-bedded clay and peat layers produce semi-confined conditions in places (Adelana et al., 2010).

4.1.2 The Werribee Plains

The Deutgam WSPA includes all geological units to 40m below the natural surface, encompassing the shallow Werribee Delta sediments (DWSPACC, 2002). An alluvial deposit up to 20 m thick has accumulated in the gorge of the Werribee River. This gorge is the major terrain feature of the Werribee Plains with its alluvial deposit known to be gravelly at the base and fines upwards to become clayey at the surface (Condon, 1951). According to this work and more recent studies (Holdgate et al., 2001, 2002; Holdgate & Gallagher, 2003), the alluvial terraces on the valley floor provide evidence of Pleistocene and Holocene sea level changes. This alluvium, eroded by rejuvenated streams, was deposited (in Late Quaternary times) along the base of the Werribee River. There are prominent intra-volcanic sands within the Newer Volcanics (along the Werribee Plains) while the Older Volcanics were picked in few bores between coal-bearing sediments of the Werribee Formation (Holdgate et al., 2001). In general, the Werribee Formation is disconformably overlain by marine sandstone and mudstone/marlstone (Taylor, 1963 as cited in Holdgate et al., 2002; Holdgate & Gallagher, 2003). Across the Werribee Plains these exceed 120 m in thickness (Holdgate et al., 2001).

The groundwater system used in the Werribee South is called the Werribee Delta aquifer. The Werribee Delta sediments consist of sand and gravel lenses situated within clays and silts. The variable nature of the deltaic sediments resulted in a wide variation in aquifer parameters (SKM, 2002). According to SKM (1998), within the coarser sand horizons the hydraulic conductivity ranges from 10 to 15m/day, with a specific yield of 0.01 to 0.2 but the overall hydraulic conductivity of the aquifer is less than 5m/day with representative specific yield in order of 0.04. Typical bore yields for the Werribee Delta aquifer system are generally less than 5L/s, however yields up to 15L/s have been recorded (SKM, 2002). The selected bores for this study were screened in the Werribee Delta aquifer system, which are mostly sandy or silty clay material at shallow depths but with significant sand and gravel seams at a relatively deeper depth. The Werribee Delta aquifer system is unconfined to semi-confined and groundwater depth varied between 4-7m below ground surface. Recharge to the aquifer system is predominantly from direct rainfall infiltration and surplus irrigation water (SKM, 2002) as well as leakage from the ageing concrete-lined channels (Rodda & Kent, 2004).

4.2 Climate

The study areas (Cape Flats and Werribee Plains) are both under Mediterranean climate. Climate is temperate with warm dry summers and maximum rainfall occurring during winter/spring respectively. Historical average annual rainfall (1913-2009) varies from 1100 mm/yr in the upper north-west of the Werribee catchment to 540mm/yr near Werribee (SRWA, 2009). Historical data (1841-2009) showed there is a variable rainfall gradient in the Greater Cape Town area; rainfall is largely controlled by topography – between 500 mm and 1700 mm on the Cape Peninsula, to 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 Western Cape region (Adelana, 2011). To the north of the Western Cape, this climate regime grades into semi-desert whereas to the south-east coast the climate becomes less seasonal and tends towards sub-tropical. Drier summer conditions and lower winter temperatures tend to inhibit some plants’ growth.

Therefore, rainfall, minimum and maximum temperatures were analysed and compared to show climate variability over the years, and to identify/assess its impact on groundwater levels. Figure 3 show the annual/seasonal rainfall variation in the study areas. There is a similar pattern in the fluctuation of observed annual rainfall being less than the long-term average in many years. Long-term or historical climatic conditions indicate that on average, annual rainfall in the Werribee for the period 1950-1979 exceeded that for the period 1980-2009, with the period 1997-2009 being one of considerably lower than average annual rainfall. For example, during 2004/05, rainfall in the Werribee River catchment was approximately equal to the long-term average; whereas rainfall was about 60% of long term average for 2005/06, although inflows were only 21% of the long term average (SRWA, 2006). Consequently, storage levels fell from an average 34% at the start of the year to 16% at the end of the year and irrigators and diverters in the Werribee system were allocated 80% of their water entitlement (SRWA, 2006).

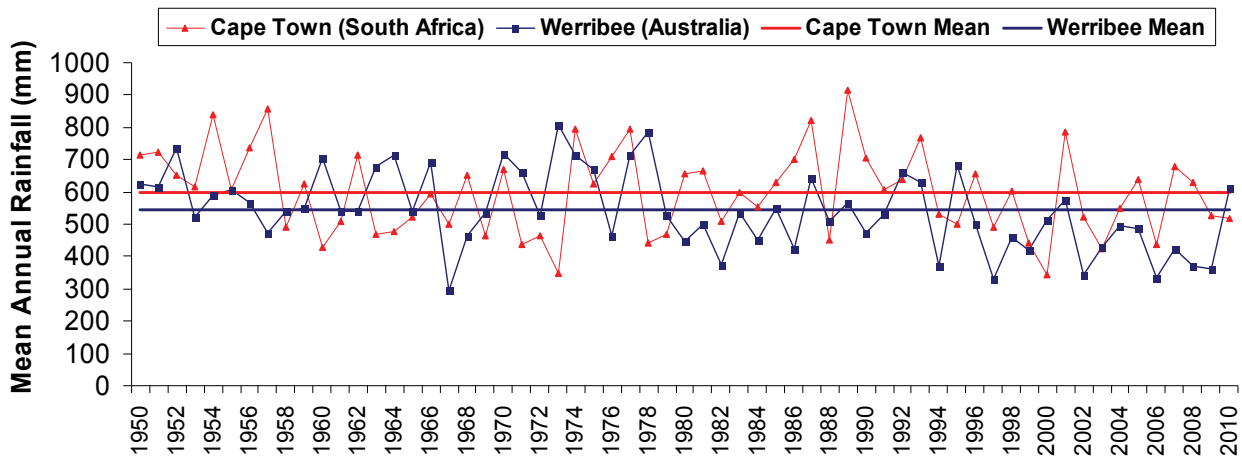


Fig. 3. Annual mean of rainfall in the study areas 1950-2010 (Station: Cape Town Airport and Laverton RAAF Base)

In the Cape Flats from 1958 the trend in rainfall showed continuous decrease up till 1974; 1982-1985 was also a dry period with total average rainfall below annual mean. Since then there has been much fluctuation in the pattern of rainfall in the Cape Town area. This was shown to be comparable to older records (1921-1941) of relatively dry periods; for example

1935 recorded the least annual rainfall (229.4 mm/yr) (Adelana, 2011). A similar situation is observed from 1999-2003, with the exception of year 2001 that showed a relatively wetter record (i.e.784 mm/yr). Based on available information going as far back as the 1960s, Cape Town enters into a drought cycle (i.e. a lower than average rainfall pattern) on average every 6 years (Cape Water Solutions, 2010). The last of such a cycle was in 2003 and 2004 with dry winter and nearly 200mm less than long-term mean of annual rainfall. The consequences include lower dam levels and the imposition of water restrictions.

Seasonal patterns in the Cape Town area show a marked winter rainfall incidence, with June/July typically the wettest month. The general climatic trend throughout the study area

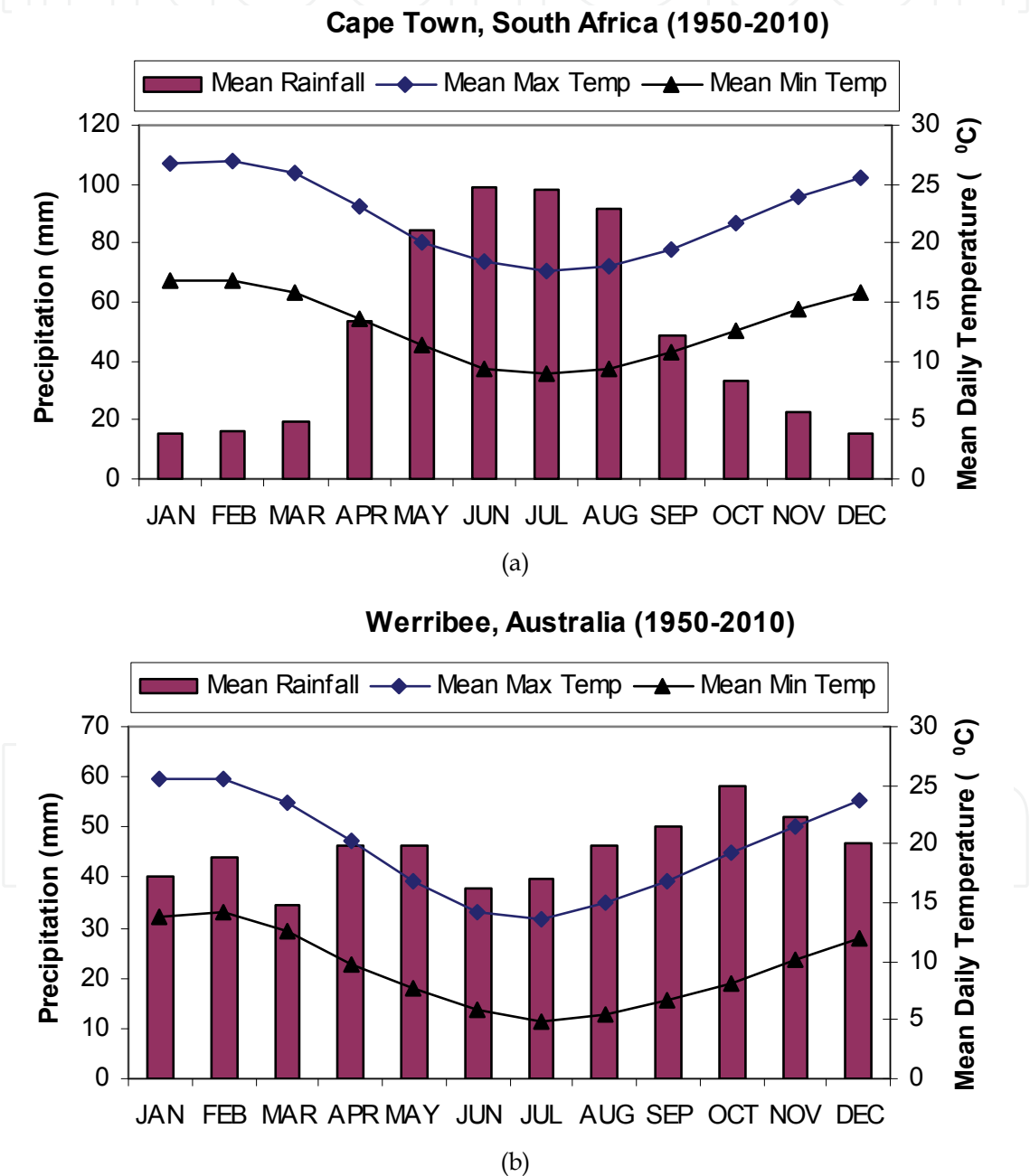


Fig. 4. (a) Cape Town mean monthly rainfall with maximum and minimum temperature. (b) Werribee mean monthly rainfall with maximum and minimum temperature

is a gradual increase in rainfall and a reduction in temperatures moving from north to south. Mean annual rainfall (1950-2010) has a long-term average of 597 mm. There is a dry period with less than 20 mm rainfall per month from November to March (Figure 4a); the mean annual temperature is moderate, approximately 17 °C. In the Werribee Plains, rainfall variability throughout a typical year does not exhibit a clear seasonal bias like the Cape Flats but fairly distributed, with average monthly rainfall ranging from 36 mm/month (March) to 59 mm/month (October) (Figure 4b).

5. Groundwater level response

The results of the HARTT analysis for the selected bores are summarised into a Table in Appendix I. The groundwater trends determined in this analysis are comparable for both the Werribee Plain Delta aquifer and the Cape Flats aquifer. There is little or no delay in response to rainfall events. Although most of the bores showed a generally slight decline, few bores have a rising trend yet the rise is much less than 20 cm/yr. Most of the bores screened in the Werribee Delta aquifer have groundwater trend ranging -3 to 4 cm/yr (in exception of B112802 with more positive trend, 12 cm/yr). All of these bores showed no delayed response and a quick rise in response to the wet year 2010 (after lower than average rainfall from 2007-2009) (Appendix II a-d). The selected bores in the Werribee mostly showed the lowest groundwater levels (i.e. highest drawdown) in late 2003 and early 2004 except B59536 whose highest drawdown was in February 2007 (Appendix II d).

The groundwater trend of bores within the Cape Flats aquifer ranges from -8 to 8 cm/yr (except BA232 with more positive trend, 14 cm/yr; which is within the Philippi allotment portion). The bores on the Cape Flats showed marked seasonal fluctuations and a more slightly downward trend in comparison to the Werribee bores (see Table in Appendix I). The Cape Flats bores are examples of good data records with missing gaps (Appendix II e-j). Most of the bores selected along the south coast on the Cape Flats also showed no delayed response except BA002 (Appendix II e). Although there are no lithologic logs for most of these bores, there are reports of occurrence of thick lenses of clay within the Cape Flats sand aquifer (Adelana, 2011; Gerber, 1976) that may contribute to delayed response of bores to rainfall events.

There are no significant negative trends (groundwater trend all < -9 cm/yr) in both study area, even though a few bores were also selected from the intensively irrigated Atlantis area of Western Cape. Examples of bores from the Cape Flats sand in north-western Cape (Atlantis) showing influence of pumping in the 1990s are presented in Appendix II (k-n) with summary table in Appendix I). The Cape Flats aquifer in the Atlantis area has been under the Managed Aquifer Recharge (MAR) program since the last 20 years. Although the extent to which this has influenced the response of the bores is not known since the data are not accessible, it is expected to contribute to a more positive trend. Irrigation is intense in the Werribee area but the conjunctive groundwater use (with surface water, recycle water) may have been responsible for no significant negative trend.

However, the Philippi-Mitchells Plain bores are still more negative relative to both Atlantis and Werribee Irrigation districts even though both have longer history of groundwater use for irrigation. This may be in response to groundwater usage. It was estimated that

approximately 13 million m³ are abstracted from the Cape Flats aquifer by commercial farmers in the Philippi area of Cape Town (Colvin & Saayman, 2007), and an additional 5 million m³ are abstracted by the City of Cape Town administration to irrigate sports fields at Strandfontein and Mitchell's Plain (Wright & Conrad, 1995). Moreover, another 20 million m³ was abstracted from wellfields in the southern part of the aquifer during the Pilot Abstraction Scheme to understudy the Cape Flats aquifer response to stress conditions (Gerber, 1981; Vandoolaeghe, 1989).

The bores examined across the Werribee Plain showed declines in groundwater levels occurring from 1996 to 1999, 2003 to 2004 and in late 2006 to early 2007. This tends to follow the downward trend in the frequency and amount of rainfall and is consistent with the general groundwater trend observed across Victoria during this period (Hekmeijer et al., 2008; Reid, 2010). The groundwater level drawdown of Werribee Delta aquifer shows that during the early 1990s seasonal drawdown was less than 0.5 m but in 1996, the seasonal fall increased up to 2 m. This indicates more use of groundwater for irrigation due to the lack of supply from the Werribee River. Therefore, the seasonal fluctuations are mostly influenced by rainfall and usage; however, some observation bores show seasonal fluctuation that is believed to align with the pattern of channel deliveries (i.e. due to enhanced channel leakage) and groundwater pumping (SKM, 2009a, 2009b).

The observed groundwater trends and behaviour in the South African example (i.e. bores screened in the Cape Flats aquifer) are equally consistent with the fluctuations in rainfall pattern. It is obvious that the groundwater level falls due to less rain and possibly higher use from production bores, while rainfall recharge and recovery take place in wetter times when there is conversely less pumping. Some of the Cape Flats bores in Atlantis showed a marked response to pumping influences and have recorded higher groundwater level changes within short time. For example, WP167 with groundwater level decline of 3.5 m from August 1993-June 1995 and continuous decrease into the early 2000s. WP184 also show declines of 5.5m (September 1994-April 1995) and 4.8 m (October 1999-August 2000). Such high declines have influenced spring flows and base flow, and hence, the implications on groundwater management. Therefore, the groundwater declines are discussed in the context of groundwater resource sustainability and its implications on water security and resource management plans, including consideration of water conservation measures or conjunctive water use.

6. Salinity

The analysis of groundwater trends is critical in the study of salinity risk and the effectiveness of preventative measures. The majority of DPI bores were installed in response to reports of saline discharge outbreaks in the 1980s and 1990s (Clark & Harvey, 2008). Salinity has impacts on the social, economic and environmental values in any catchment. Therefore, groundwater monitoring co-ordinated by DPI and DSE provides an important tool in the understanding, measurement and management of salinity across the state of Victoria. Hence it is currently been reviewed and prioritised based on key assets in the state (Reid et al., 2011).

In both WID and the Cape Flats, salinity (as measured by electrical conductivity (EC) of groundwater or total dissolved solids (TDS)) revealed the varying quality of groundwater

by comparing historic data with recent measurements. The groundwater salinity monitoring in the Werribee Plains commenced in 2002 while in the Cape Flats regular monitoring began in 1979. Groundwater salinity in the Werribee Plains varies from 1000 to 6000 mg/L TDS, and this (according to Leonard, 1979; SKM, 2002) represents the best quality water in the aquifer

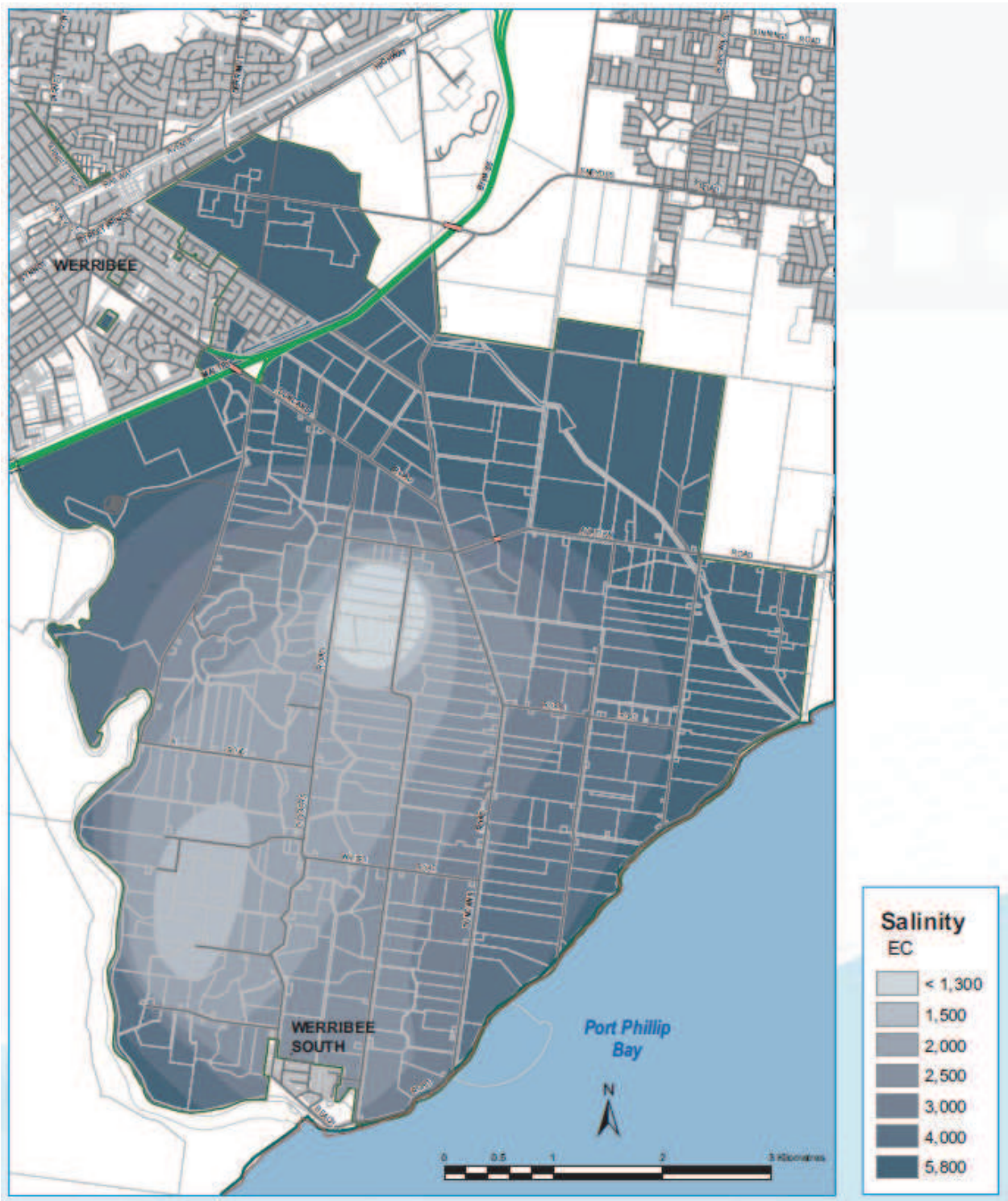


Fig. 5. The spatial distribution of salinity (i.e. variation of EC) across the WID (after SRWA, 2009)

systems in the area. The spatial distribution of salinity (i.e. variation of EC in $\mu\text{S}/\text{cm}$) across the WID is shown in Figure 5. This distribution showed the northern and eastern parts of the districts as relatively higher in salinity than the central-southern part. The highest groundwater salinity was recorded in bore B145273, located closest to the coastline (although the bore is not screened in the Werribee Delta aquifer). This is most probably primary salinity and does not coincide with any of the state's key asset areas (Reid et al., 2011). Nevertheless, under the Southern Rural Water plan on the WID, the key driver of groundwater management is to avoid drawing down the aquifer to the point where seawater intrusion takes place. The source of the salinity in the Werribee Delta has been traced to more saline adjacent aquifers or seawater intrusion (although studies to confirm this are on-going). Several studies in line with the management strategy have therefore been in place since the last 10 years (SRWA, 2004, 2006, 2009).

Total dissolved solids of the samples from bores screened in the Cape Flat sands are generally low compared to those of other aquifers in the area (Adelana, 2011). This salinity values varied from 67-4314 mg/L. The EC values of groundwater from the Cape Flats aquifer ranged from 9.2 to 4320 $\mu\text{S}/\text{cm}$. Field and monitoring data (Adelana, 2011) showed also that generally groundwater salinity increases following the groundwater flow direction, south-eastwards. Figure 6 illustrates the electrical conductivity areal distribution in the Cape Flats. The relations of chloride and EC with groundwater levels and well depths are not shown (in most cases) because the wells monitored for salinity are not necessarily used for groundwater level observations.

7. Resource management implications

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. For example, the higher than average rainfall in the 2010/2011 season across Victoria (all reflected in the hydrograph analysis) may have influence on water use decisions and water restrictions. However, sustainable groundwater management decisions would require long-term monitoring and projections. Such long-term data covering all key elements of the hydrological cycle including groundwater fluctuations and water-level trends are essential as a basis for management and for evaluating the implications of changes in use.

Long-term monitoring using a number of observation bores has demonstrated that water levels have both declined and recovered over time and in the aquifer investigated. There has been full recovery of the aquifer over the past wet months (2010-2011), and this has been much more than what the recovery would have been over a normal wet year in Victoria. However, this is no cover against management measures except such higher than average rainfall becomes consistent over a longer period of time. Such monitoring data will be 'handy' information to support decision-making and demonstrate the impacts of climate on level changes in relation to resource management. Water level and quality data has been used a number of times in Victoria and (at least three occasions within the last 7 years) in Cape Town to change the extent of groundwater abstraction in order to support sustainable management.

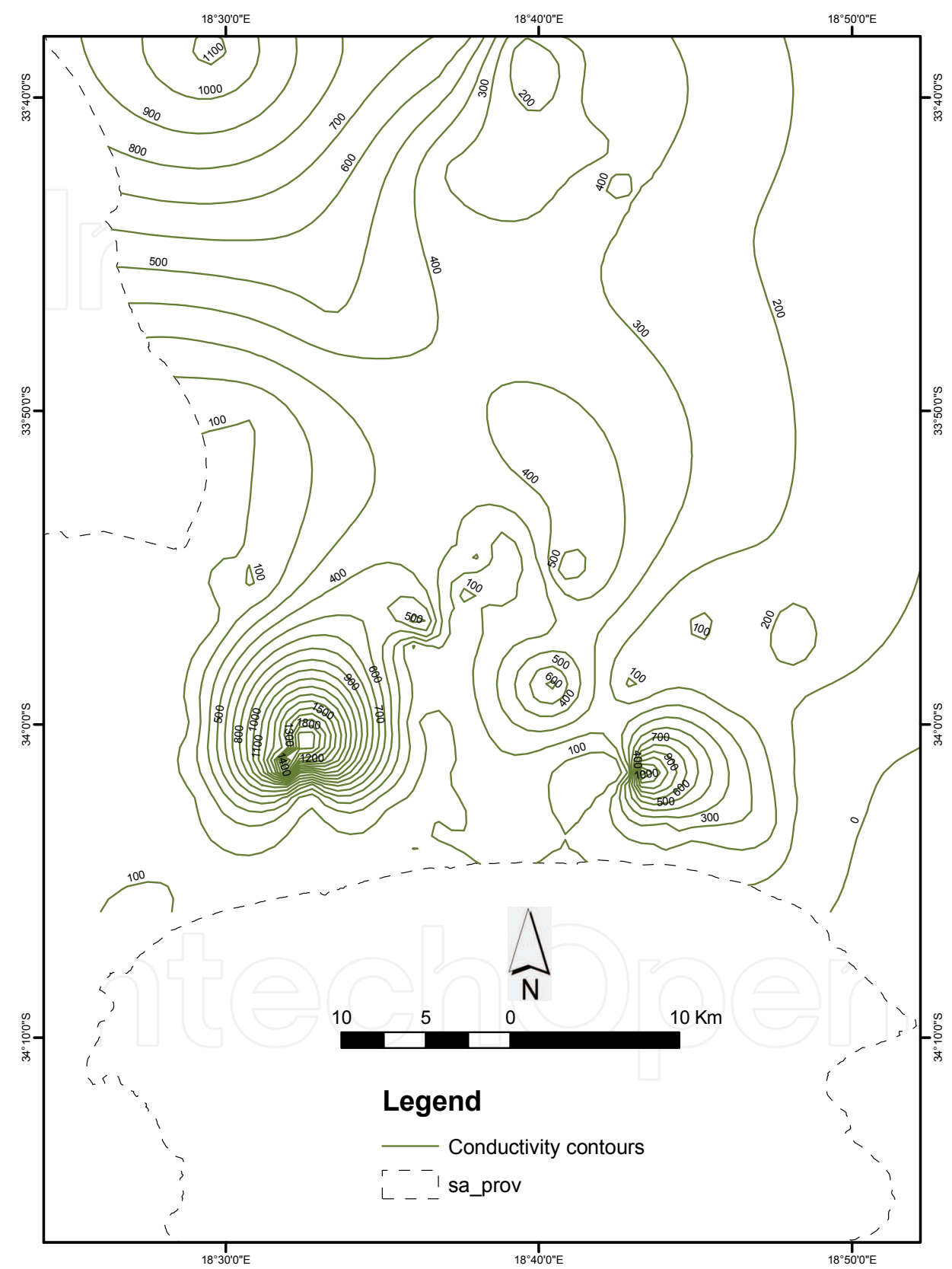


Fig. 6. Areal distribution map of electrical conductivity (in $\mu\text{S/cm}$) in the Cape Flats (Adelana et al., 2010)

In 1998, new groundwater management arrangements were put in place to maximise development opportunities in the Werribee Irrigation District, yet ensure that groundwater resources are managed in a sustainable way. Management arrangements include Groundwater Management Areas (GMAs); Groundwater Supply Protection Areas (GSPAs); and Groundwater Management Plans (SRWA, 2006). Water restrictions have since been in place and at different stages of restriction, they are periodically reviewed. For example, in March 2011, Southern Rural Water announced a substantial boost in groundwater allocation for landowners in the Deutgam Water Supply Protection Area based around Werribee. A full ban on groundwater use in Werribee was introduced in 2006 because of the threat of seawater intrusion into the groundwater through aquifer from Port Phillip Bay (SRWA, 2006). SRWA announced a partial lifting to 25% allocation in early January 2011, and recommended to the Minister a lifting to 75% after careful monitoring showed the aquifer is continuing to improve (SRWA, 2011). More than average mean rainfall over the last 12 months has seen groundwater levels rising and salinity levels improving. All bores can now be used for stock and domestic purposes.

Currently the Department of Water Affairs (Cape Town regional office) is capacity-constrained, which limits its ability to continue groundwater monitoring and the processing of licence applications (Colvin & Saayman, 2007). In such a situation, very little additional management of groundwater resources is possible. However, by the year 2012, DWA aims to complete institutional transformation with the establishment of Water User Associations (WUAs) and Catchment Management Agencies; and the licensing of all water use within another 5 years. Also, the City of Cape Town adopted an integrated approach to water management, which seeks a balance between water conservation and water demand management initiatives and conventional supply augmentation. But based on observations (Colvin & Saayman, 2007), formal government tend to focus on bulk water supply while household level bore use and development planning has not been fully integrated into water strategies.

Private (household) use of groundwater from the Cape Flats aquifer is widespread and increasing since the early 2000s when potable water tariffs increased. The immediate impact of such unregulated use was not feasible in this study due to prolonged missing gaps (mid-1990s to early 2000s) in water level data. The current gradual downward trend if projected would reflect in future bore responses as monitoring continues. To support this, the survey conducted by Colvin and Saayman (2007) revealed society's impacts on groundwater currently result from indirect drivers such as Water Demand Measure (WDM) introduced in the mid-1990s. This obviously occurs within the broader context of society supported by natural resources and a model which includes the resource base and its feedback.

Although the Department is aware of the increased private groundwater abstraction at a household level in Cape Town, this water use is covered under Schedule 1 of the National Water Act and therefore does not need to be registered with the Department. The cumulative impact of these small-scale abstractions generates concerns. Colvin and Saayman (2007) suggested that where the cumulative effect of these small-scale abstractions under Schedule 1 is too large and negative, by-laws or regulations can be promulgated – even by a municipality. Such a by-law or regulation would override the entitlements under

Schedule 1. As far as information available to date, no such by-laws or regulations have been promulgated either by DWA or the City of Cape Town.

Colvin and Saayman's (2007) survey further reveal there are concerns within government Departments (Department of Water Affairs and the Department of Agriculture) that the national land reform programme may be contributing to unsustainable resource exploitation in places. For example, some of the Cape Flats bores in Atlantis area (shown in the appendix) represent a marked response to pumping influences with a decline of 4-6 m within 1-2 years in mid-1990s and then continuous decline into the early 2000s. Such high declines may influence spring flows and base flows, and hence, have implications on groundwater resource management. Some of these monitoring bores are responding to pumping influences from the Atlantis wellfields. Bulk water supply wellfields at Atlantis have been in operation for over 20 years, supplying the satellite industrial town with water (Tredoux, 1982; Tredoux & Cave, 2002). This led to the establishment of a management scheme, known as the Atlantis Water Resource Management Scheme (AWRMS) to manage water resources in the area and to follow on the introduction of WDM in the South African Water Act 1997. The City of Cape Town also commissioned the Council for Scientific and Industrial Research (CSIR) to conduct intensive monitoring and numerical modelling of the Atlantis wellfields (Colvin & Saayman, 2007). Such information would help management of the groundwater resource.

Generally groundwater acts as the primary buffer against the impact of climate variability and spatial variability in drought. The buffering capacity of groundwater increases social resilience to drought in both urban and rural communities. However, as human development has become more susceptible to such variability, three major gaps in groundwater management were identified (FAO, 2003b): accelerated degradation of groundwater systems by over-abstraction, and effective resource depletion through quality changes (pollution, salinity), and the inability to resolve competition for groundwater between sectoral and environmental uses. Each of these has implications for sustainable development as demonstrated in this study.

Given the sensitivity of both aquifers to climate variability and pumping and the observed water quality changes noted above, it is considered necessary to uphold formal regulatory measures to avert further water level and quality decline. Effective institutional approaches need to be aware of the realities surrounding groundwater use and the inherent risks associated with development, the level of uncertainty (plus limitations in data quality) and the range of social pressures. The general lack of professional and public awareness about the sustainable use of groundwater resources will need to be continuously addressed. A more coherent planning framework should guide all scales of groundwater development and appropriate policy responses needed to prevent further degradation of the groundwater systems.

8. Conclusion

Climate (i.e. rainfall) is the primary factor influencing the fluctuation and trend of groundwater level although increased usage contributed to the drawdown especially during the dry years. The trend and seasonal fluctuation of groundwater level in the two study areas generally correlated with seasonal rainfall and linear trends were observed in a

number hydrograph of bores in the area. The bore hydrographs of the Cape Flats aquifer showed marked seasonal fluctuations and a more slightly downward trend (-8 to 14 cm/yr) in comparison to the Werribee Delta aquifer bores (-3 to 4 cm/yr).

The resulting groundwater declines invariably affect groundwater resource sustainability and by implication water security. For example, the Werribee Delta aquifer groundwater level drawdown shows that during the early 1990s seasonal drawdown was less than 0.5 m but increased up to 2 m in 1996. The decline and general downward trend indicates increased reliance on groundwater. The fall in groundwater levels coincides with salinity increases from 2,500 EC to over 6,000 EC and, consequently yielding information that the source of salinity in the Werribee Delta could be more than saline adjacent aquifers or seawater intrusion (studies to confirm this are on-going).

Groundwater level responses and behaviour in observation bores, in response to climate and pumping in productive aquifers, is an indication of homogeneity and lateral hydraulic connection within the shallow coastal aquifers investigated in this study. However, the cases involving deeper aquifers and their responses were not considered. This is because the shallow aquifers are mostly used in both study area and the hydrogeological parameters have shown higher yield of these aquifers relative to the deeper ones. It is expected that vertical hydraulic conductivity will vary with the various underlying geological materials and only if aquifer connectivity exist that pumping from one productive aquifer can induce water level change in observation bores installed in other aquifers. Therefore, a more comprehensive study investigating the impacts of level changes in shallow aquifers on underlying deeper aquifer(s) would be necessary for effective resource management in these areas.

The groundwater trends and salinity increases are discussed in the context of groundwater resource sustainability and its implications on water security and resource management plans, including consideration of water conservation measures or conjunctive water use. However, aspects relating changes in groundwater level and zones of declining groundwater head to aquifer connectivity may be necessary to improve understanding of the system and, by implication, critical to the development of sustainable management frameworks for semi-arid regions.

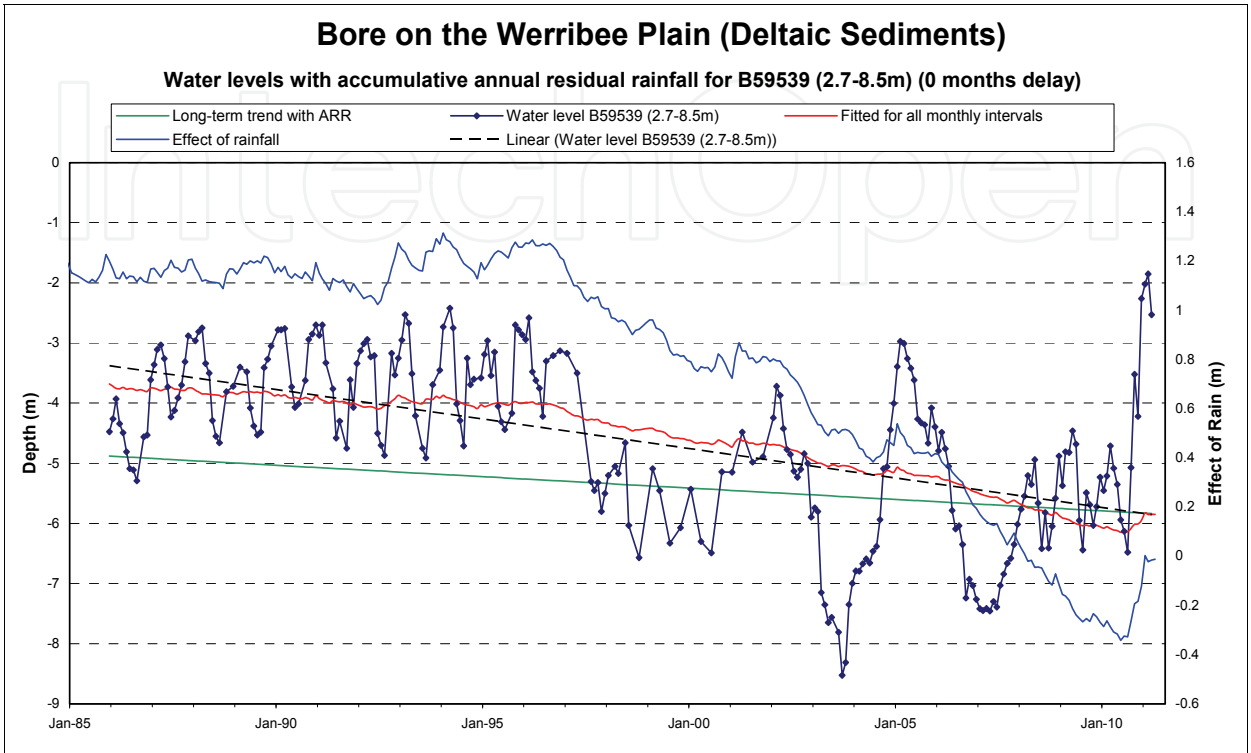
In the face of the prolonged dry period (1995-2007) and a come-back of wet years (2010/2011), current irrigation and agricultural practices need to be reviewed in the catchments to ensure groundwater sustainability and secure future agricultural viability. Groundwater level responses in bores (consistent level records in WID, coupled with the data gaps in the Cape Flats farming districts), illustrate the importance of monitoring in relation to natural/environmental responsiveness and resilience. State-wide groundwater monitoring in Victoria (Australia) and the quarterly meter reading has continued to assist management decisions. There are realities surrounding groundwater use and inherent risks associated with development, the level of uncertainty and the range of social pressures. The social views of groundwater lag behind the formal policy of a public resource. Therefore, continued support for basic data collection and groundwater evaluation is justified on both scientific and social process grounds. The water authorities in the two case studies must adequately manage and maintain interactions with key stakeholders ensuring open and transparent relationships that are based on trust to promote good governance.

¹Bore screened in the Cape Flats aquifer ²Bore screened in the Werribee Delta aquifer

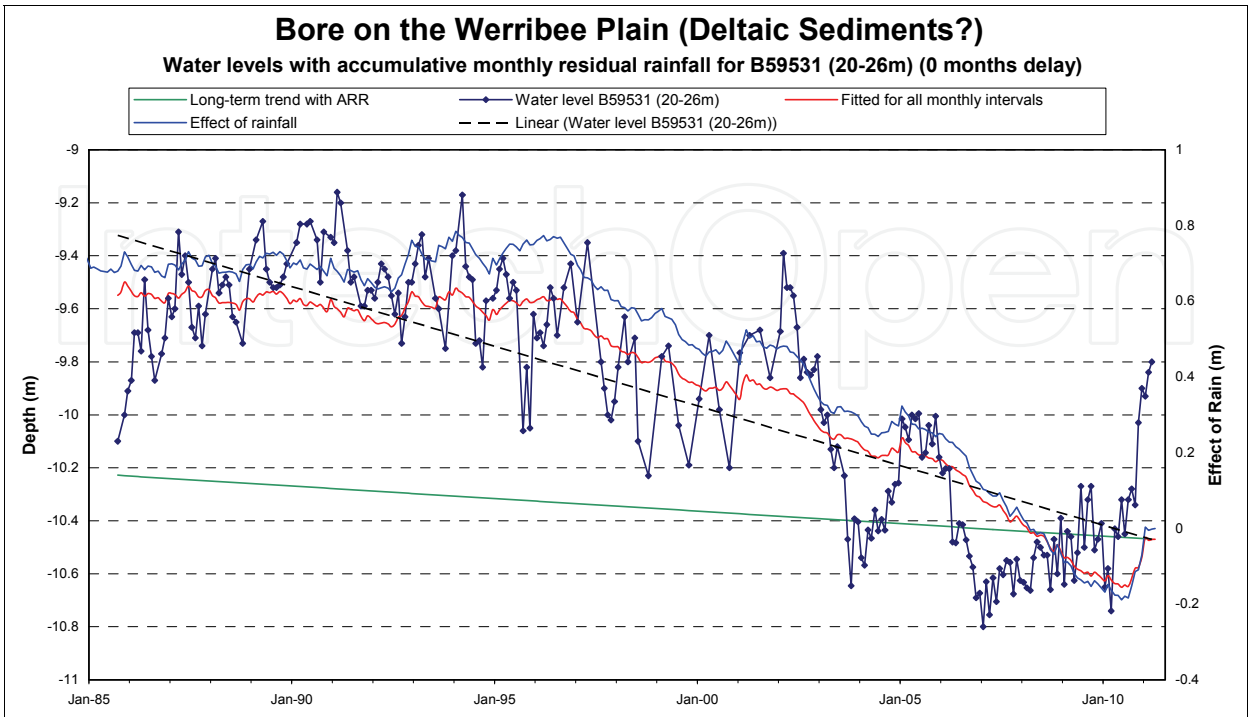
Bore	Location	Depth (m)		Best Fit Delay (months)	R ² for selected one	C	Acc. Residual Rainfall (mm)		Time (month)		Mor p (y)
		Initial	Final	AARR			value	p	value	p	
G30944	Atlanti ¹	-7.0	-6.2	3	0.54	-6.23	0.0039	0.0000	-0.0061	0.0000	
PA20	Atlanti ¹	-3.6	-3.8	1	0.45	-3.70	0.0013	0.0000	-0.0014	0.0167	
WP167	Atlanti ¹	-10.6	-11.1	2	0.68	-11.08	0.0098	0.0000	0.0007	0.7462	
WP184	Atlanti ¹	-8.2	-9.0	0	0.37	-10.42	0.0089	0.0000	0.0129	0.0003	
DC182	Bellville ¹	-2.1	-4.1	0	0.33	-5.89	0.0062	0.0000	0.0068	0.0934	
DC184	Bellville ¹	-1.8	-1.6	0	0.33	-2.14	0.0012	0.0000	0.0027	0.0001	
BA002	Philippi ¹	-6.5	-6.8	2	0.38	-6.21	0.0008	0.0000	-0.0020	0.0000	
BA076	Philippi ¹	-4.7	-4.2	0	0.69	-3.67	0.0013	0.0000	-0.0015	0.0000	
BA083	Philippi ¹	-4.6	-3.8	0	0.38	-1.78	0.0047	0.0000	-0.0075	0.0000	
BA084	Philippi ¹	-4.5	-3.9	0	0.38	-2.48	0.0035	0.0000	-0.0050	0.0000	
BA232	Philippi ¹	-2.7	-2.3	0	0.57	-3.99	0.0030	0.0000	0.0121	0.0000	
B59520	Werribee ²	-2.6	-2.2	0	0.08	-2.80	0.0001	0.0039	0.0003	0.2578	
B59521	Werribee ²	-3.1	-2.6	0	0.05	-3.17	0.0001	0.0135	0.0003	0.2419	
B59523	Werribee ²	-2.0	-1.6	0	0.53	-2.41	0.0005	0.0000	-0.0008	0.1535	
B59525	Werribee ²	-5.7	-3.8	0	0.51	-6.03	0.0013	0.0000	-0.0016	0.2216	
B59531	Werribee ²	-10.1	-9.8	0	0.74	-10.23	0.0006	0.0000	-0.0008	0.0345	
B59533	Werribee ²	-3.6	-3.2	0	0.16	-3.58	0.0001	0.0010	0.0001	0.5042	
B59536	Werribee ²	-5.9	-4.1	0	0.58	-6.69	0.0013	0.0000	-0.0028	0.0370	
B59537	Werribee ²	-2.8	-2.5	0	0.05	-3.02	0.0001	0.1641	0.0000	0.8788	
B59539	Werribee ²	-4.5	-2.5	0	0.32	-4.88	0.0009	0.0049	-0.0032	0.1043	
B112802	Werribee ²	-7.7	-6.8	0	0.60	-11.68	0.0028	0.0000	0.0105	0.0046	
B113018	Werribee ²	-3.9	-3.6	0	0.50	-5.34	0.0009	0.0000	0.0036	0.0094	

Appendix II: Some examples of HARTT analysis graphs from the selected bores in the study areas

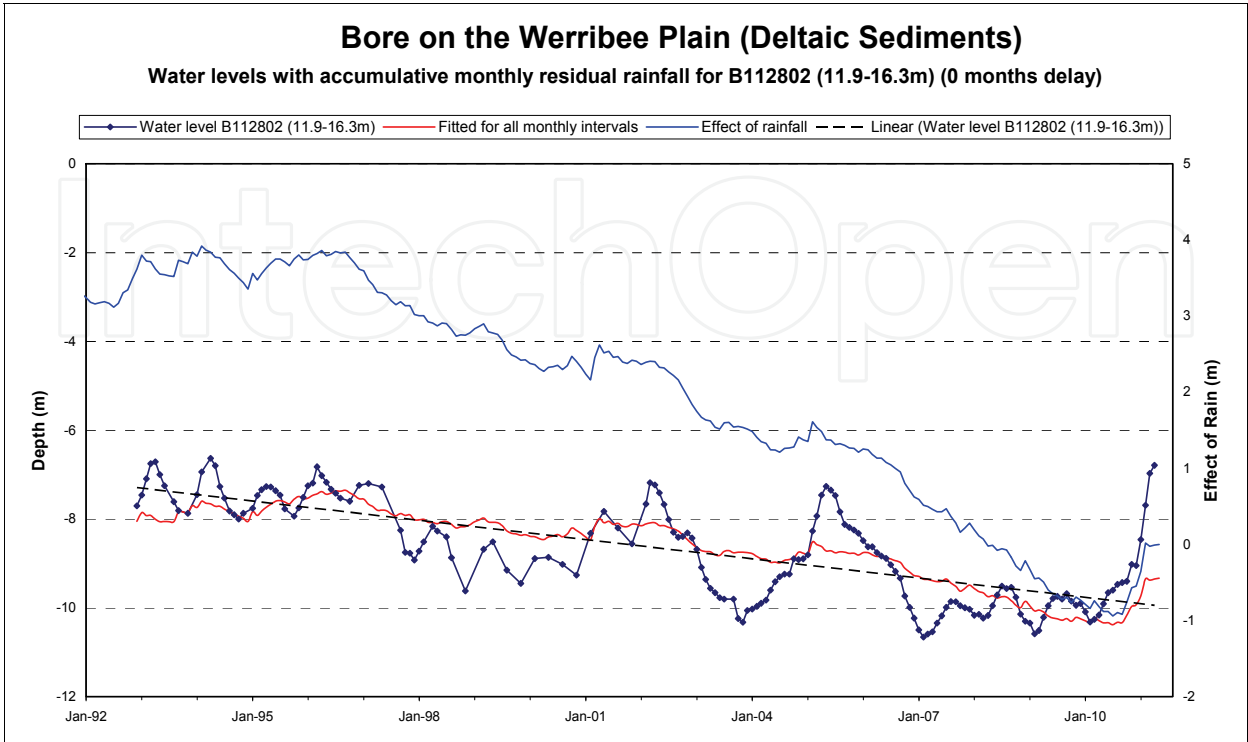
Appendix II a: HARTT analysis graph for Bore 59539 (from Werribee Plains)



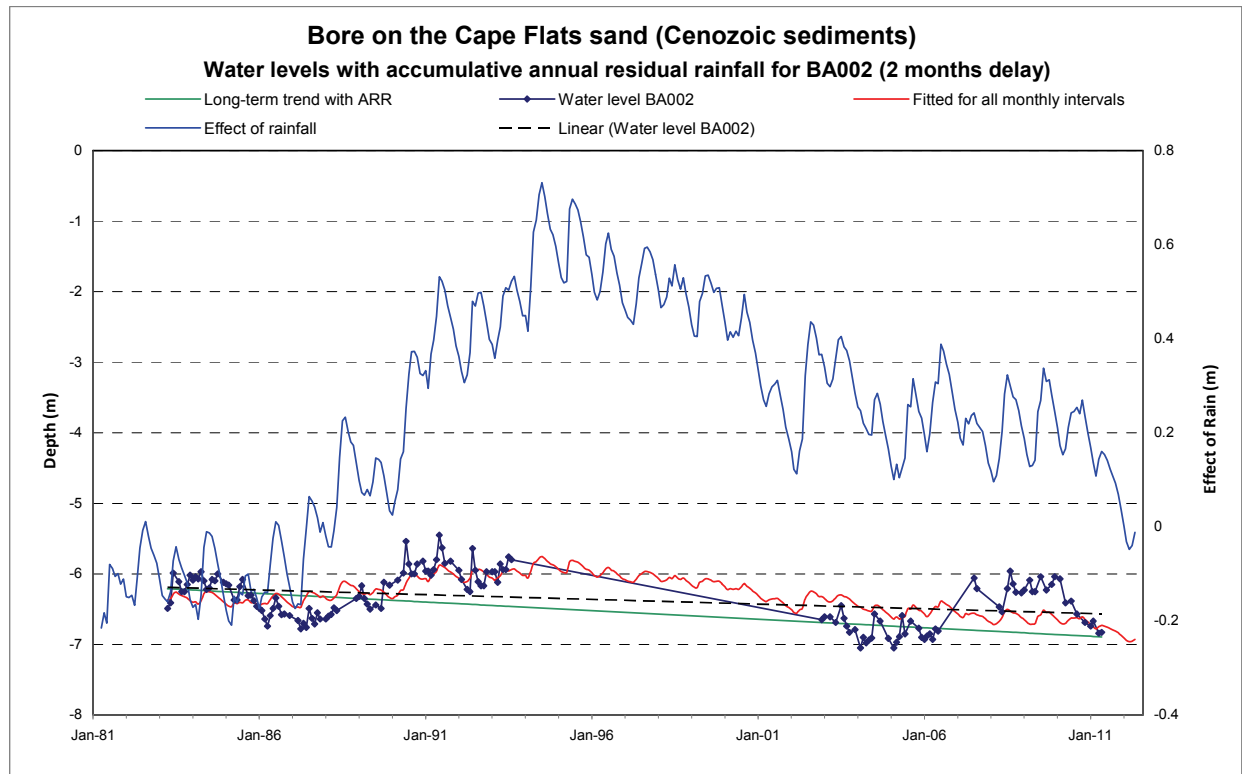
Appendix II c: HARTT analysis graph for Bore 59531 (from Werribee Plains)



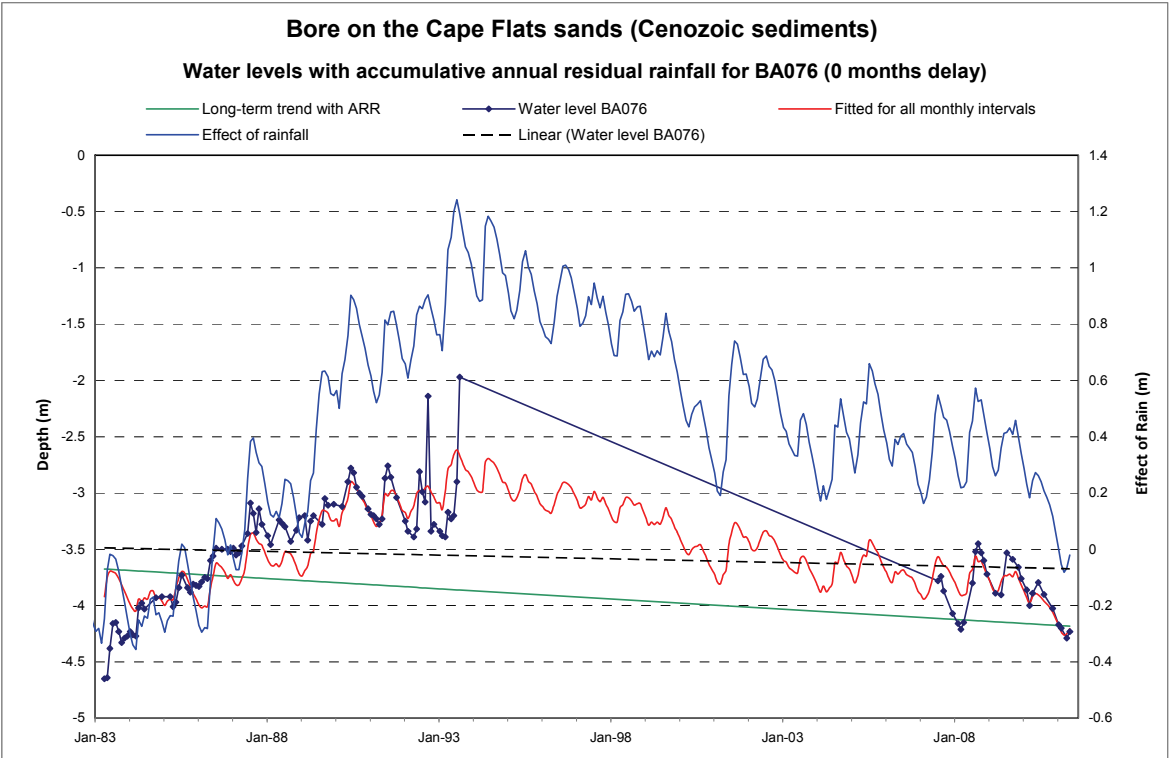
Appendix II d: HARTT analysis graph for Bore 112802 (from Werribee Plains)



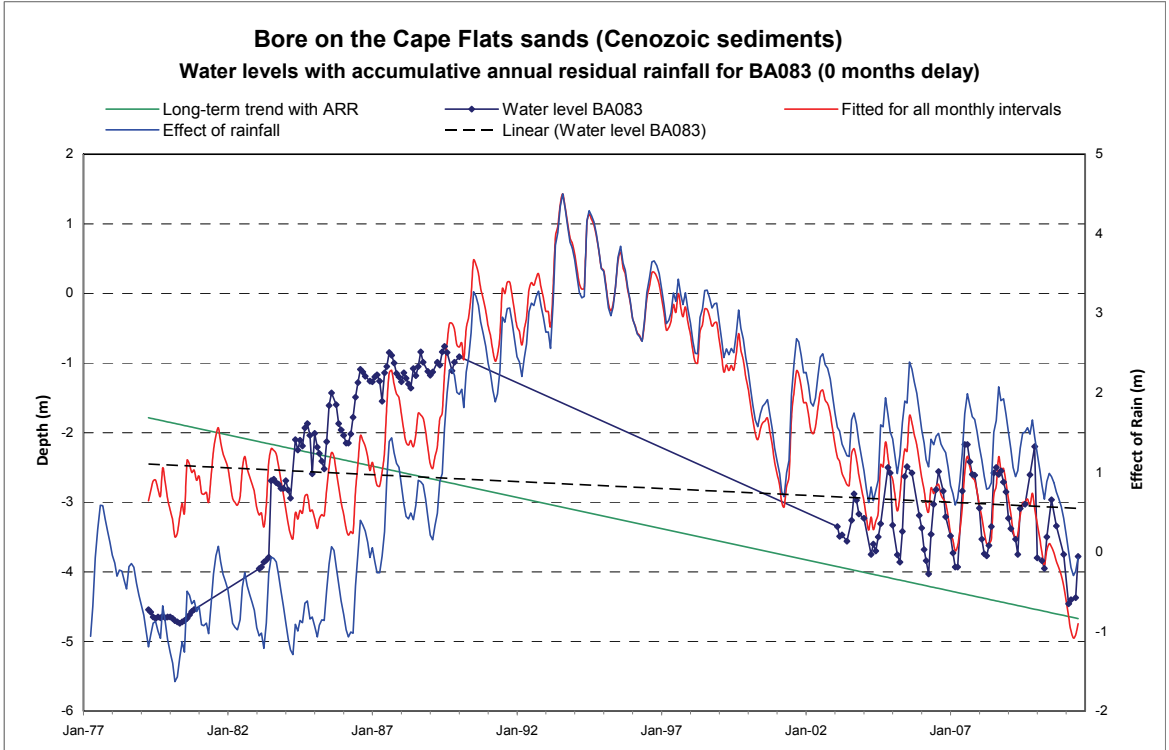
Appendix II e: HARTT analysis graph for BA002 (from Cape Flats, Philippi-Mitchells Plain)



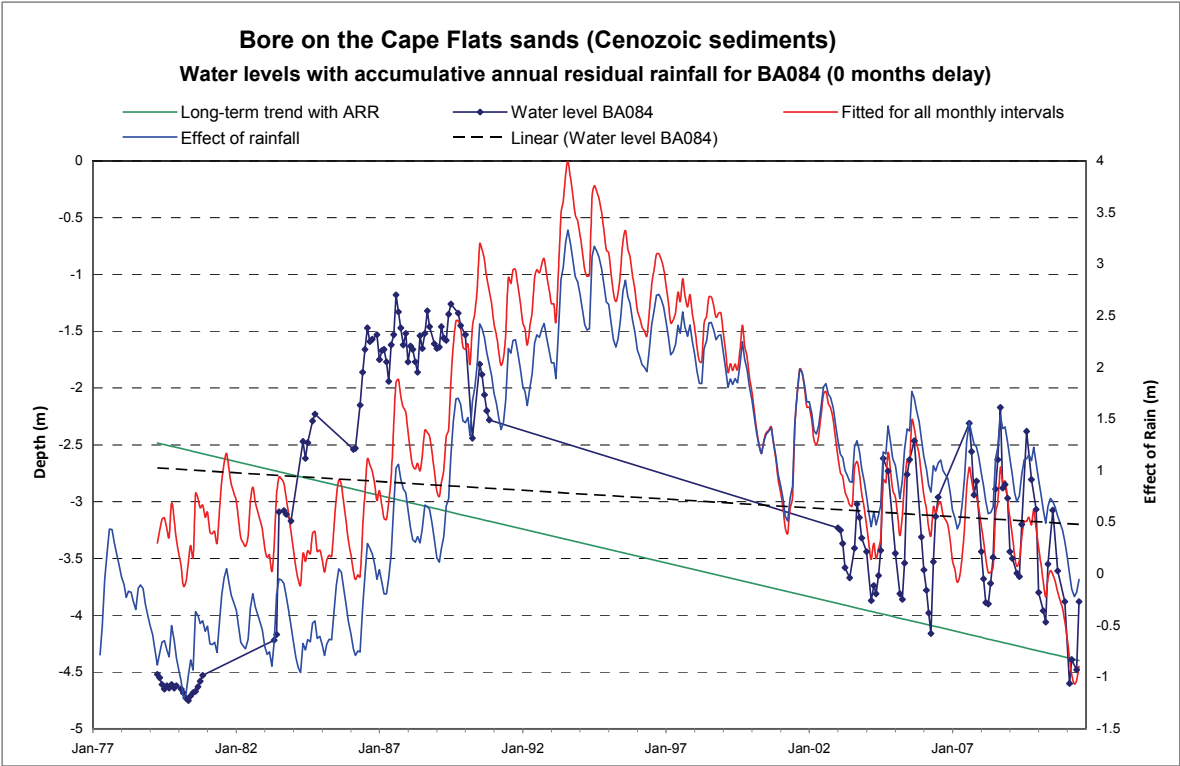
Appendix II f: HARTT analysis graph for BA076 (from Cape Flats, Philippi-Mitchells Plain)



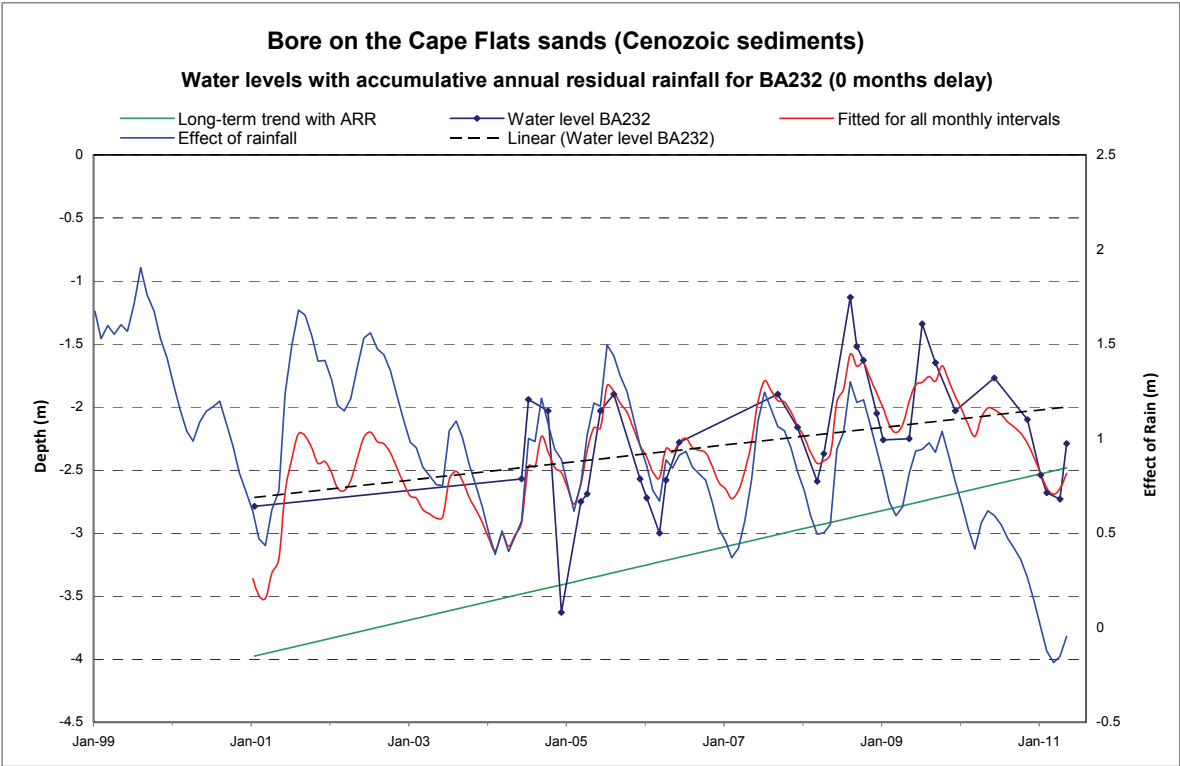
Appendix II g: HARTT analysis graph for BA083 (from Cape Flats, Philippi-Mitchells Plain)



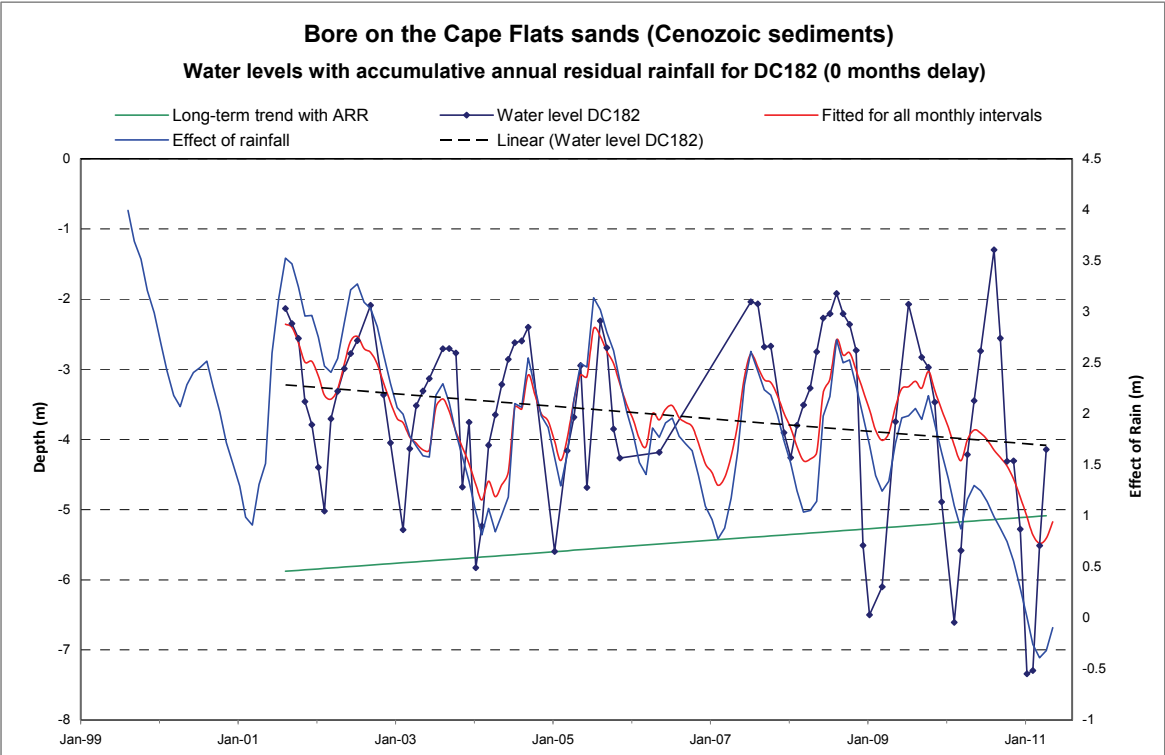
Appendix II h: HARTT analysis graph for BA084 (from Cape Flats, Philippi-Mitchells Plain)



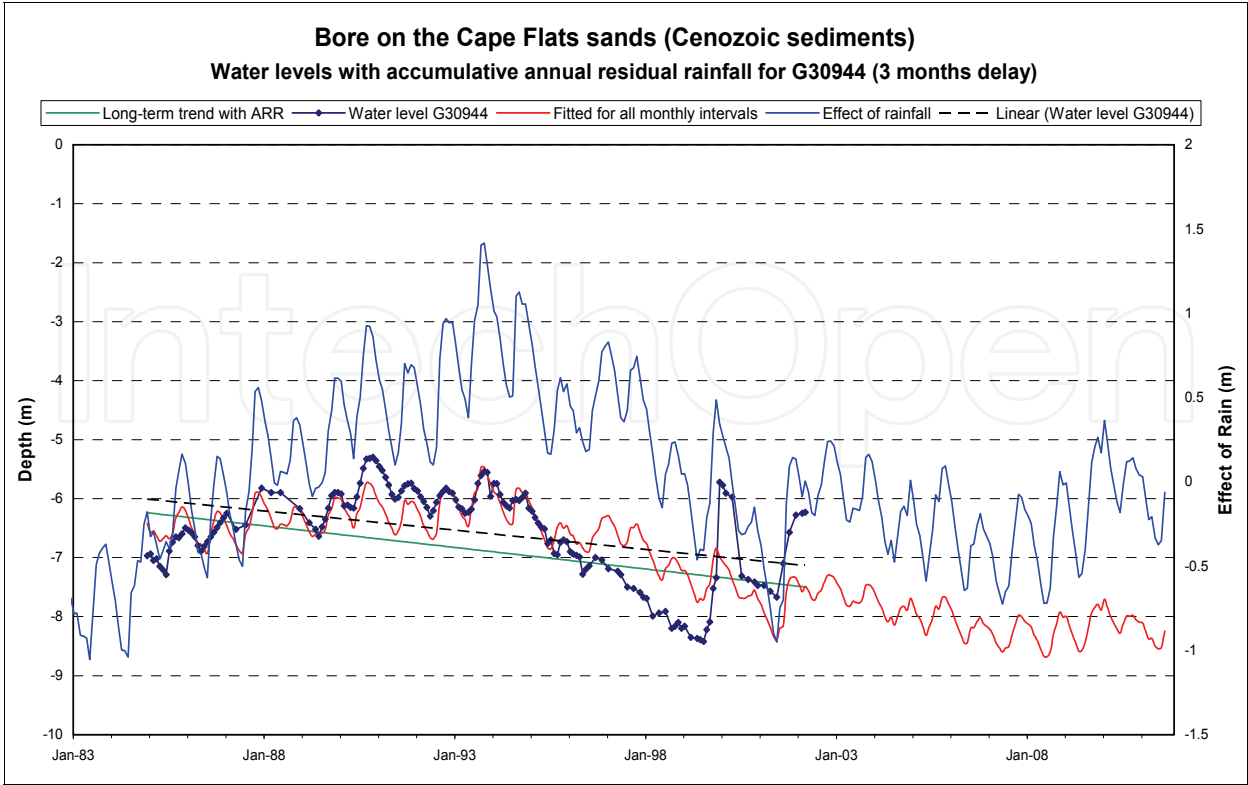
Appendix II i: HARTT analysis graph for BA232 (from Cape Flats, Philippi)



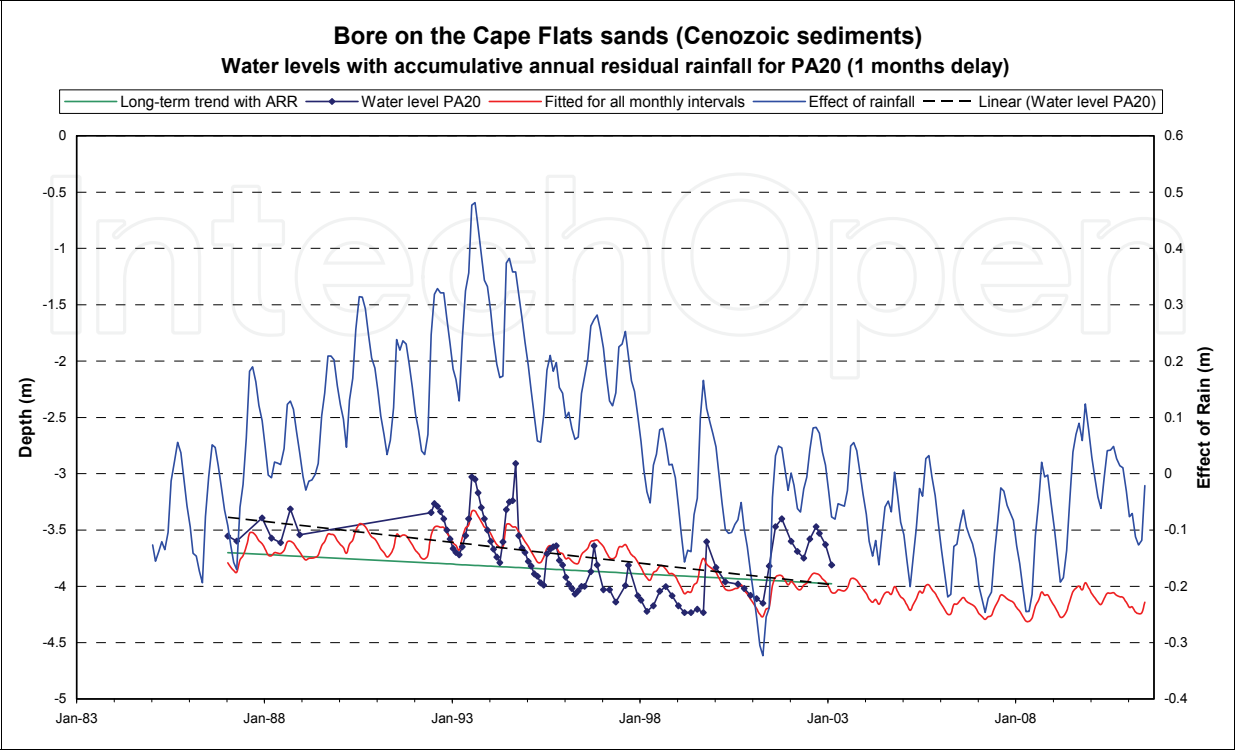
Appendix II j: HARTT analysis graph for DC182 (from Cape Flats, Bellville)



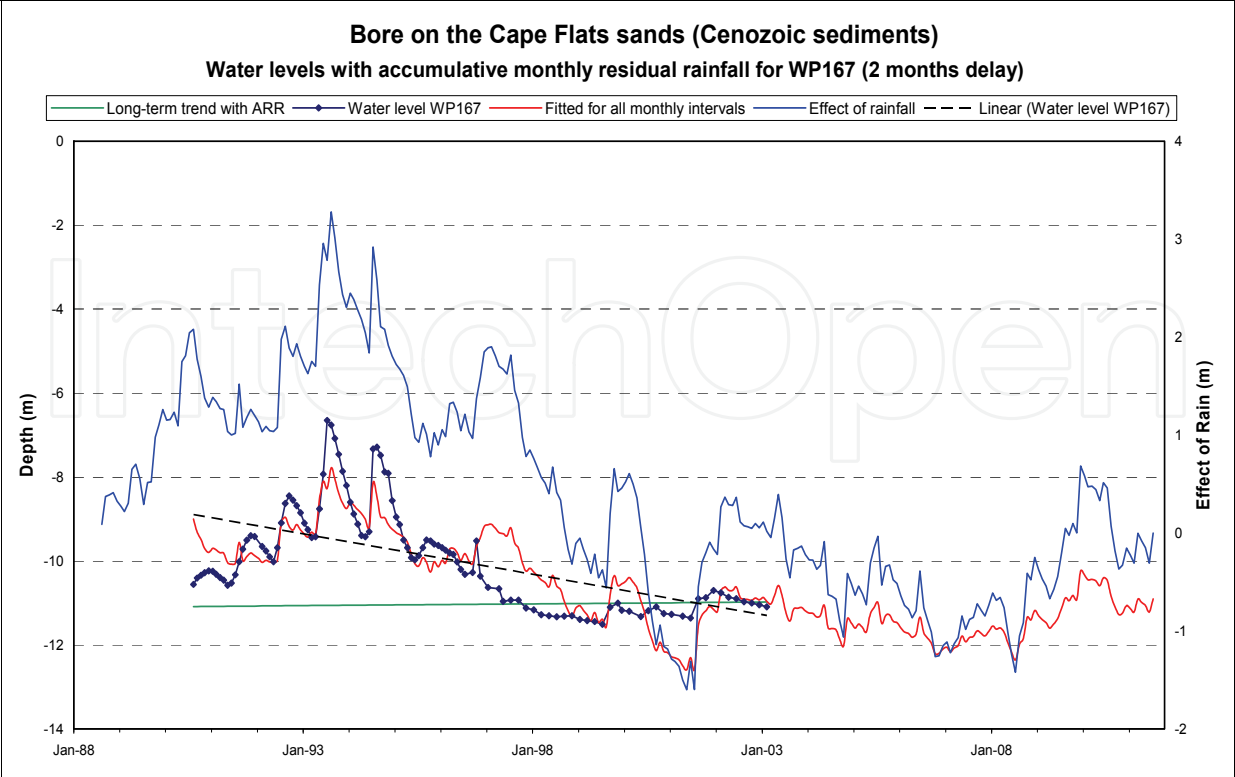
Appendix II k: HARTT analysis graph for G30944 (from Cape Flats, Atlantis)



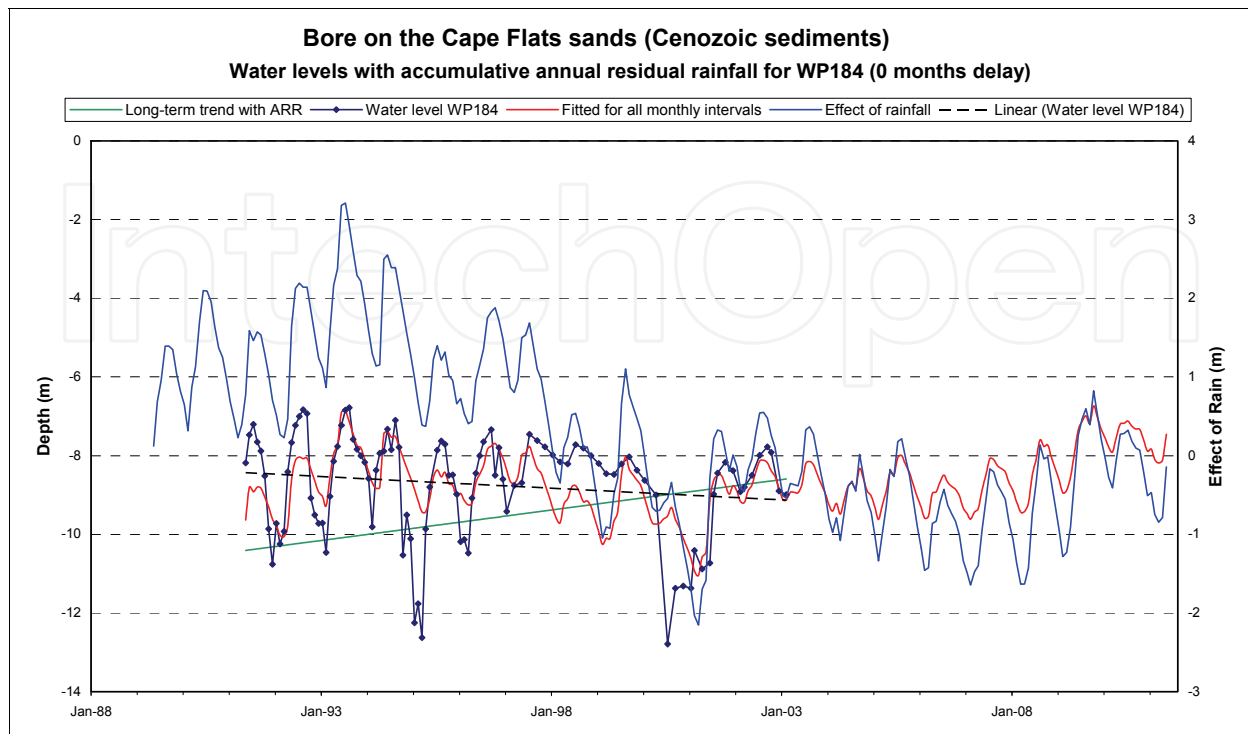
Appendix II (I): HARTT analysis graph for PA20 (from Cape Flats, Atlantis)



Appendix II (m): HARTT analysis graph for WP167 (from Cape Flats, Atlantis)



Appendix II (n): HARTT analysis graph for WP184 (from Cape Flats, Atlantis)



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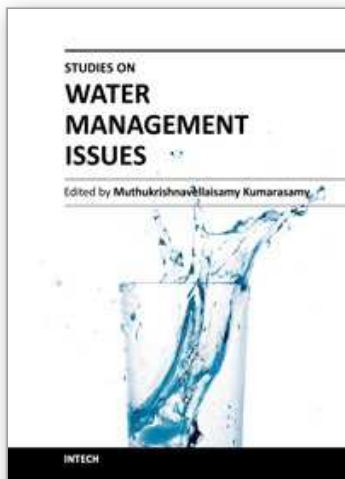
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This book shares knowledge gained through water management related research. It describes a broad range of approaches and technologies, of which have been developed and used by researchers for managing water resource problems. This multidisciplinary book covers water management issues under surface water management, groundwater management, water quality management, and water resource planning management subtopics. The main objective of this book is to enable a better understanding of these perspectives relating to water management practices. This book is expected to be useful to researchers, policy-makers, and non-governmental organizations working on water related projects in countries worldwide.

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