A Geohydrological Study of the Richards Bay Area

by

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The author of the dissertation hereby declares that the research done and reported in this dissertation is original work done by herself, and was not copied from any other source, unless referenced clearly.

water and words
easy to pour
impossible to recover

- chinese proverb

Acknowledgments

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ABSTRACT

Numerical methods such as groundwater models can play a vital role in understanding the dynamics of an aquifer provided that the input data is accurate and sufficient to represent the environmental system adequately.

The groundwater flow model used in this project requires specific information about geological features, hydraulic properties as well as recharge and evapotranspiration. All the available information has been collected and interpreted to use in the model.

There is a need to develop conceptual models of the region for the implementation of the numerical methods. The regional geology is well described in the literature, but observations on a local scale do not always conform to the regional stratigraphy. Consequently, many assumptions have been made in the construction of three conceptual models, namely a single layer model, a multi-layer model with homogeneous hydrological properties and a heterogeneous multi-layer model.

MODFLOW (McDonald and Harbaugh, 1983), a quasi three dimensional, finite difference, groundwater flow model, was used to determine the regional groundwater flow patterns in the Richards Bay area. A summary of the theory and parameterization process used in the model is presented. Considerable detail is offered for the conceptual modelling of specific processes not incorporated in the finite difference scheme of the numerical model. These include recharge and evapotranspiration.

The model domain and parameters that were used in the model as well as the calibrations are described. For the general flow pattern for the region, the groundwater divides for each catchment were determined and are presented in relation to the diverse land use sectors. The project identified the different land use sectors within the principle catchment areas of the main water resources of the region. In particular, it provided a demarcation of which parts of the Richards Bay Industrial sectors could influence the water quality of the various water bodies of the region.

UITTREKSEL

Numeriese metodes soos grondwater modelle het 'n belangrike rol te speel om akwifeer dinamika te verstaan mits daar genoeg en akkurate data is om verteeenwoordigend van die omgewing te wees.

Die grondwater vloeimodel wat in hierdie projek gebruik is, benodig spesifieke informasie oor die geologiese eienskappe, die hidroliese kenmerke asook die grondwater aanvulling en verdamping. Al die beskikbare informasie is verkry en geïnterpreteer vir gebruik in die model.

Daar bestaan 'n behoefte om konsepsionele modelle van die streek te ontwikkel sodat numeriese modelle geïmplementeer kan word. Die regionale geologie is goed beskryf in die literatuur, maar waarnemings op kleiner skaal stem nie altyd ooreen met die regionale stratigrafie nie. Gevolglik is daar baie aannames gemaak met die opstelling van drie konsepsionele modelle, naamlik 'n enkellaag model, 'n meerlaag model met homogene hidrologiese eienskappe en 'n heterogene meerlaag model.

MODFLOW (McDonald and Harbaugh, 1983), 'n kwasi-driedimensionele, eindige element grondwater vloeimodel, is gebruik om die grondwater vloeipatroon vir die Richardsbaai gebied te bepaal. 'n Opsomming van die teorie en 'n beskrywing hoe eienskappe aan die model toegeken is, word aangebied. Aansienlike detail word gewy aan die konsepsionele modellering van prosesse wat nie ingesluit is in die eindige element skema van die numeriese model nie. Dit sluit grondwater aanvulling en verdamping in.

Die model domain en eienskappe wat in die model gebruik is, sowel as die kalibrasies, word beskryf. Die algemene vloeipatroon vir die gebied het gelei tot die bepaling van die grondwater skeidslyne vir elke opvang gebied en word aangebied in verhouding tot die verskillende landgebruike. Hierdie projek het die verskillende landgebruike geïdentifiseer wat binne die opvang gebiede van die verskillende waterbronne val. Dele van die industriële gebied wat water kwaliteit van die verskillende waterbronne in die streek kan beïnvloed, is afgebaken.

1 INTRODUCTION

Environmental awareness has become a key issue worldwide. Until recently the main emphasis of conservation fell on preserving the Fauna and Flora, but in the last few years the whole concept of conservation took a much broader meaning. Many countries and big industries are being forced to recognize these changes through the implementation of ISO 9000 and ISO 14000. Modern development has an impact on the environment and is considered a threat to the environment in many cases. Foster, Morris and Chilton (1999), describes how urbanization causes changes to groundwater recharge and how this leads to the deterioration of the quality of groundwater. While future developments must continue to sustain healthy economies, ways must be sought for the protection of the environment and groundwater in particular.

In South Africa the Water Act (Act 36 of 1998) is a good example of man's concern to reserve water not only for human need, but also for the environment. The Act requires that each catchment management agency (CMA) develop a strategy for the water resources in its area, by seeking co-operation and agreement from the various stakeholders and interested persons. Protection, use, development, conservation, management and control of water resources must be considered in the development of such a strategy. There is thus a need for greater understanding of the systems and the development of appropriate tools and methods for monitoring and investigations.

Numerical modelling, as described in this thesis, creates a better understanding of groundwater systems and is a relatively inexpensive tool which should be used in conjunction with other tools and information for integrated catchment management.

Richards Bay is an industrial town that has developed very rapidly during the last two decades and is still expanding. All these developments put more demands on water supply and at the same time pose a threat to water quality.

The two lakes in the study area, namely Mzingazi and Nsezi, are used for domestic and industrial water supplies. The groundwater systems contributing to these lakes are one of the many important aspects to be considered for managing the water resources properly.

An extensive groundwater monitoring program is an ideal but expensive method for identifying and evaluating problems in the local aquifers. This would also provide an indication of the extent of any problems that may have already occurred. While this may prove to be one option for management and remediation, numerical simulation modelling on the other hand, can provide a real time indication of the impact of developments and can be used to identify potentially sensitive areas which could seriously affect the local water resources. Suitable simulation modelling programs are relatively inexpensive and can also be used as educational and management tools in the planning and development of the urban and rural sections of Richards Bay.

The simulation models considered in this study provide a means of defining the local groundwater flow lines. These simulated flow conditions are necessary for simulating contaminant transport. This would indicate those sections of the Richards Bay area which could be affected through industrial development and may be a major source of pollution to the water supply reservoirs.

1.1 AIMS and OBJECTIVES

The aim of this study is to determine the groundwater flow dynamics of the Richards Bay area in order to identify :-

- regional groundwater flow patterns
- groundwater divides for smaller scale modelling and
- establish the basis of solute transport modelling in the region by means of numerical modelling.

In order to achieve these aims, several objectives have been defined:-

1) *Develop a conceptual geological model for the area* by collecting all available geological and hydrogeological data of the area. These data together with published geological surveys will be used to construct the spatial distribution of hydrogeological features which are important for numerical modelling. This will be done in consultation with geologists who have worked in the region.

2) Use the conceptual *model to develop a numerical groundwater flow model for the area.* The conceptual model will be used to identify the appropriate stratigraphic layers to use with homogeneous or heterogeneous hydraulic features which can be incorporated in the numerical model.

3) *Establish suitable concepts* to model sensitive numerical parameters (like recharge and evapotranspiration) in the groundwater model.

4) *Calibrate the numerical simulation model and derive estimates of flow paths.*

2 GENERAL DESCRIPTION

The large primary aquifer along the Maputaland coastal plain constitutes almost a quarter of all the coastal aquifers in South Africa (Campbell, Parker-Nance and Bate, 1992). This area supports a large population, extensive agriculture, substantial mining and industrial sectors that are critically dependent on the limited water resources. The aquifers are shallow systems supporting strong interaction with the surface water bodies that are threatened by saline intrusion, overutilization and pollution.

2.1 LOCATION

The area chosen for this study is Richards Bay which lies on the north-east coast of Kwazulu-Natal (Figure 2.1). The town has developed rapidly since the nineteen seventies, when a part of the Mhlatuze estuary was reconstructed to form the deep sea harbour. Easy access to a harbour as well as a government policy of decentralization (Department of Water Affairs, 1986), resulted in the construction of several industries and subsequent development of large urban and suburban areas. Agriculture in the area consists mainly of commercial forest plantations and sugar cane farms. Several fresh water bodies are found in and around Richards Bay and these provide water for domestic and industrial use. Nearby towns of Empangeni, eSikhawini, Nseleni and KwaMbonambi are also indicated in Figure 2.1.

2.2 WATER DEMAND

South Africa can be described as a dry country. Although Kwazulu-Natal has a higher rainfall than most of the country, it is also subject to severe droughts. In 1995 water restrictions were implemented in the study area whereby industry was allowed only 90% of full allocation, domestic water supply was cut down to 60% of full demand and agriculture was cut to 30% of full allocation (Kelbe , 1996).

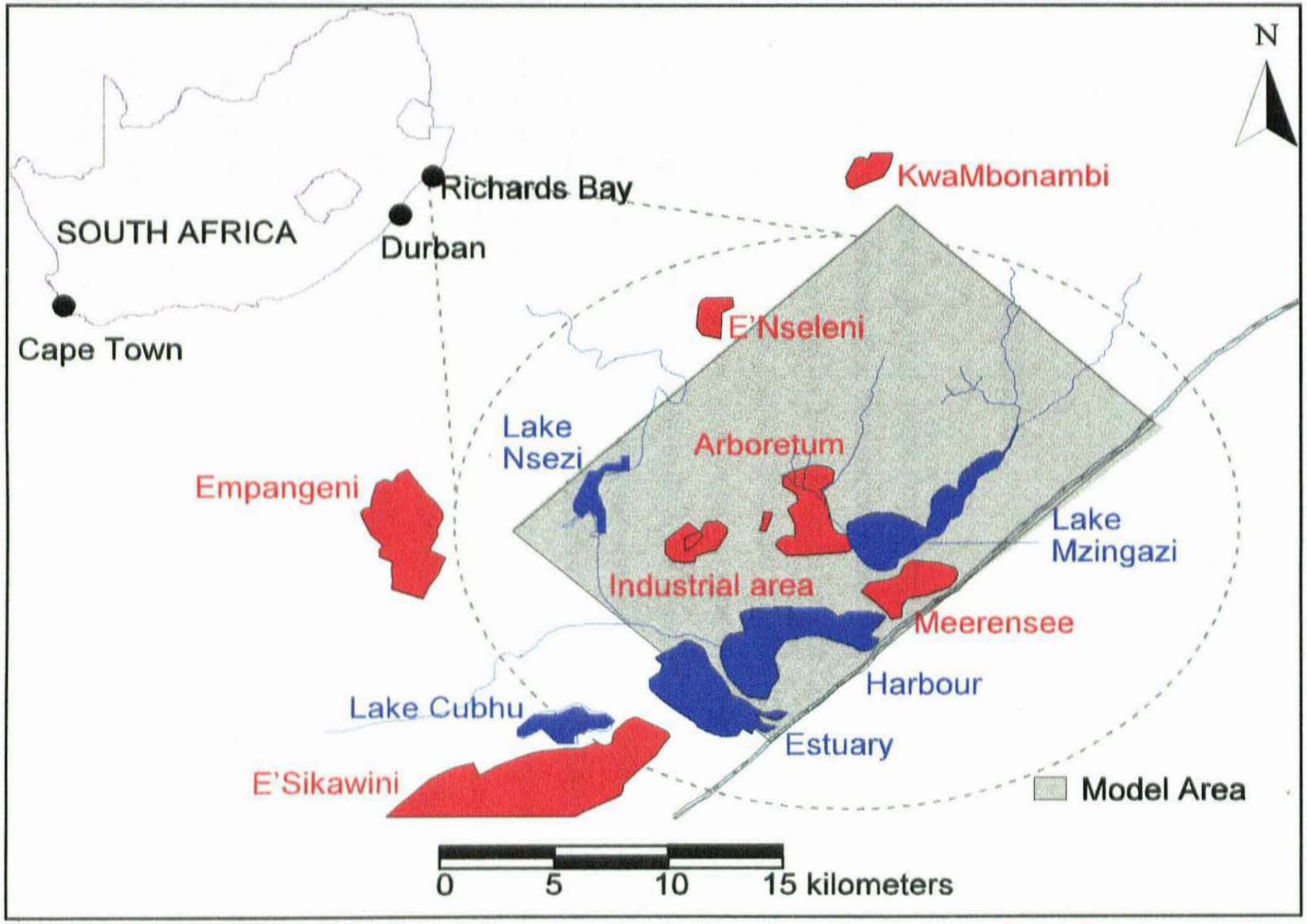

Figure 2.1 South Africa and the Richards Bay area

It is expected that the population of Richards Bay will increase at a rate of 4.2% per year with an even larger increase in water demand (Department of Water Affairs, 1986). This additional demand may have a severe impact on water resources in future times of drought and may even cause restriction on future developments in the area (Kelbe, 1996). An emergency augmentation scheme, supplying water from the Tugela river has been funded by local industry. Plans are being made to develop a full transfer scheme which will supply water to the Mhlatuze system.

2.3 WATER RESOURCES

The management of several water resources falls under the jurisdiction of Mhlatuze Water and the Richards Bay Transitional Local Council (TLC), but only those that fall within the model area (Figure 2.1) will be discussed here. They are the harbour and the two water supply lakes, namely Mzingazi and Nsezi. The catchment area between the lakes is the main urban and industrial centre of Richards Bay. This area has several natural streams, artificial drainage systems and many small wetlands. Since the soils are highly permeable, they have the potential to yield significant quantities of water (Rawlins and Kelbe, 1991). Consequently, the expansion and development of heavy industries and their support services could produce a source of contamination to the groundwater and possibly the main water resources of Richards Bay. Any potential contaminats should be identified in order to control the activities that cause them (Foster, Morris and Chilton, 1999).

2.3.1 HARBOUR

The catchment area of the Harbour hosts several industries such as aluminium smelters, a fertilizer industry, coal handling facilities and other businesses. The waste disposal site of Richards Bay also falls within the catchment area of the harbour. All of these may have an impact on the environment.

2.3.2 *LAKE NSEZI*

Lake Nsezi is the principle reservoir for water extraction by Mhlatuze Water (MW, 1997). The Empangeni TLC and many large industries are supplied with water by Mhlatuze Water from this lake (Figure 2.2). The Lake is fed from the Nseleni and Mposa Rivers whose catchment areas contain a large urban settlement at E'Nseleni (Figure 2.1). To meet the demands from industrial users, Lake Nsezi is supplemented with water from the Mhlatuze River. A total of 18,89 million m^3 of water was transferred from the pump station at the weir to the lake in 1997 (Figure 2.2). This water supply reservoir falls under the jurisdiction of Mhlatuze Water who are the bulk water suppliers for the region, including several industries and local mining houses. The Richards Bay TLC also receives some supplementary water from Lake Nsezi. Figure 2.2 gives an indication of the water allocated for the different users in the region. The lake is also maintained by some groundwater seepage from the local primary aquifer and direct recharge from rainfall.

2.3.3 *LAKE MZINGAZI*

Lake Mzingazi is the main water supply reservoir for the Richards Bay TLC and specific industries as indicated in Figure 2.2. In times of severe water shortage when extraction from Lake Mzingazi is stopped, as in the early 1990's, the Richards Bay TLC is fully reliant on Mhlatuze Water for its water requirements.

With only a small stream (Mpisisni River) feeding it, the replenishment of Lake Mzingazi is dominated by groundwater and direct recharge from rainfall (Archibald, 1997/98, Kelbe and Germishuyse, 1999).

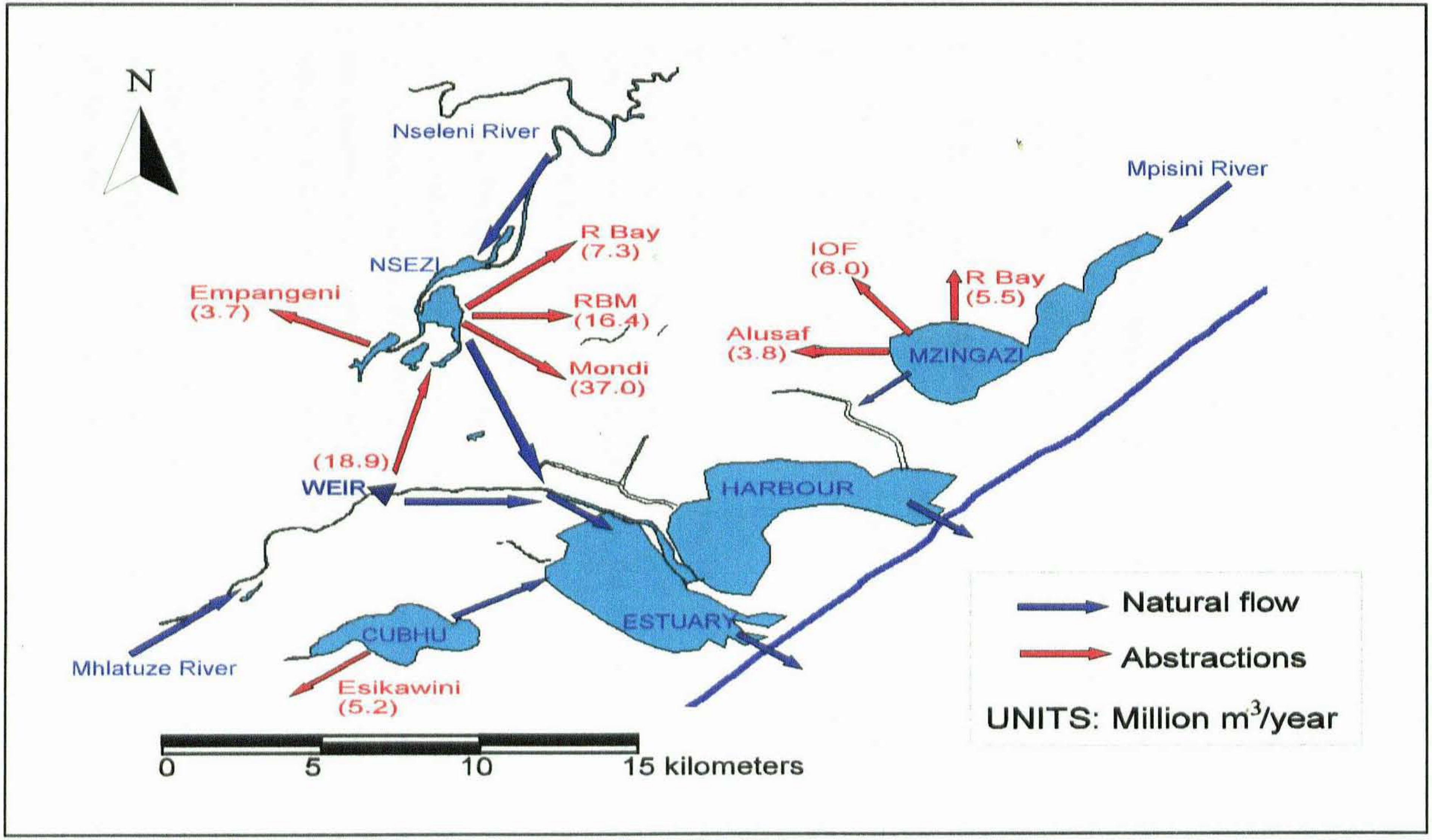

Figure 2.2 Water allocation in the Richards Bay area (adapted from Kelbe, 1996)

Extraction from Lake Mzingazi for industry and domestic use, increased from 2,5 million m^3/year in 1976 to 13,5 million m^3/year in 1996. During the drought years from 1992 to 1995, extraction dropped to 6,5 million m^3/year as a result of imposed restrictions and for three months in early 1995 extraction was stopped altogether when the lake level dropped to 1m above mean sea level (Figure 2.3).

Studies of the saline intrusion problems for Lake Mzingazi have been conducted by Simmonds (1990), Van Tonder, Botha & Muller (1986), Cyrus, Martin and Reavell (1997) and Rawlins, Kelbe and Germishuyse (1997).

2.3.4 GROUNDWATER EXTRACTION

There is no groundwater extraction in the Richards Bay area, since private boreholes are prohibited by Municipal by-laws. However, some of the industries extract groundwater as a precaution against contamination (Terblanche, 1997).

2.3.5 DRAINAGE

Most of the surface water in the industrial areas of Richards Bay flows in natural or man made channels towards the harbour (see Figure 2.5). There is also an effluent pipeline, under the control of Mhlatuze Water, for the disposal of industrial effluent which discharges out at sea.

2.3.6 WATER QUALITY OF LAKES

The deterioration of water quality has called for specific control measures in the past. These were caused by decaying vegetation and the presence of dissolved iron and manganese in the raw water of Lake Nsezi. In 1997, this required treatment of the water for taste and odour problems at the Empangeni treatment plant (Mhlatuze Water, 1997).

In the treatment of the water of Lake Mzingazi, the Richards Bay municipality had to implement additional processes to neutralize the effect of eutrophication (enrichment of water with nutrients) (Department of Water Affairs, 1986).

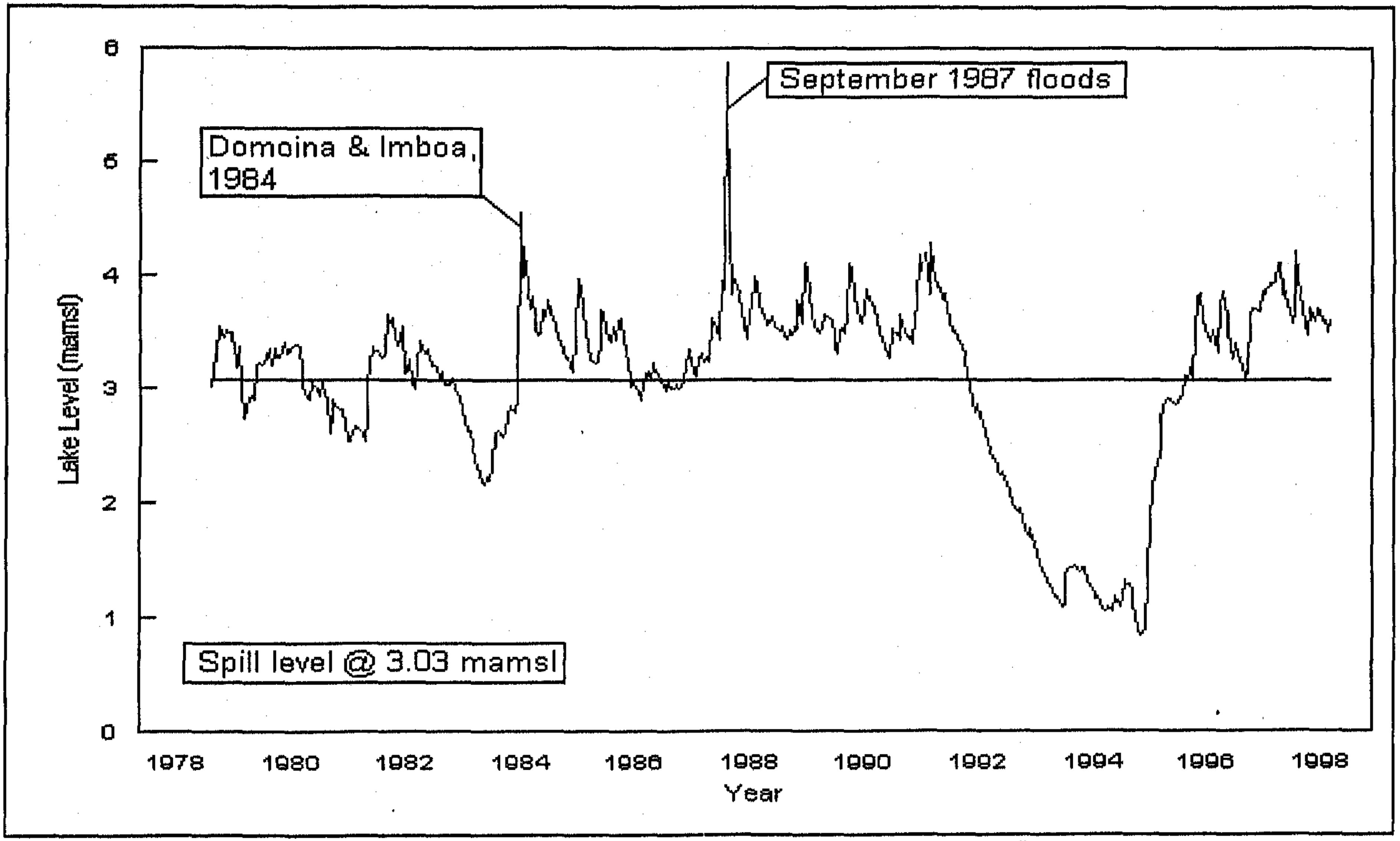

Figure 2.3 Water levels of Lake Mzingazi from 1980 to 1998 indicated as meter above mean sea level (mamsl).

The added nutrients or metals (manganese and iron) were most probably transported from elsewhere in the catchment of these lakes. Groundwater flow patterns which will be presented in this thesis may help with investigations to locate the sources of these contaminants.

2.4 CLIMATE

According to Money (1988), Zululand has a unique "humid and wet" climate in comparison to other African regions (Figure 2.4).

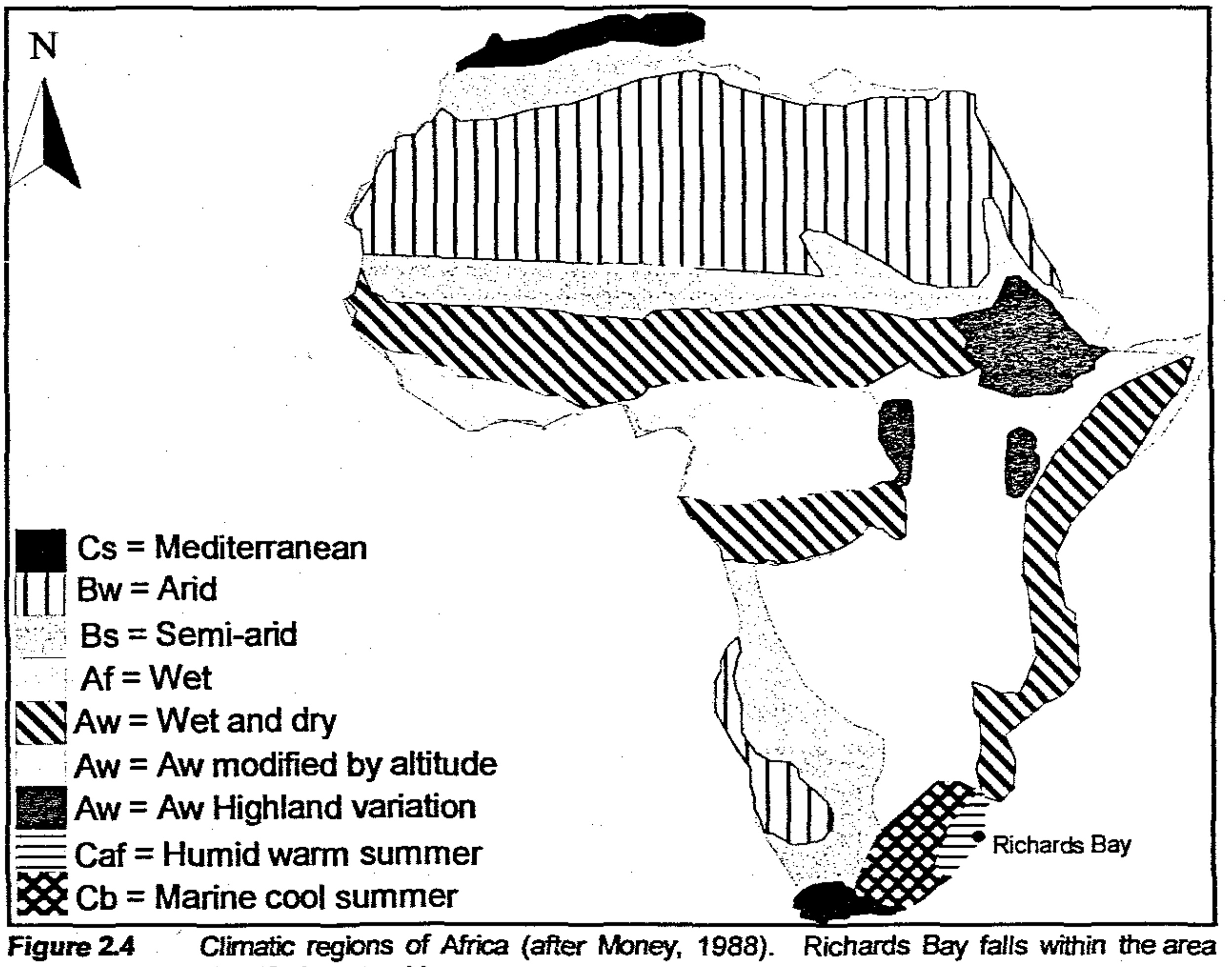

Figure 2.4 *Climatic regions of Africa (after Money, 1988).* Richards Bay falls within the area classified as Humid warm summer.

The rainfall over the north-eastern coastal region of South Africa is derived from both tropical and middle latitude systems (Garstang, Kelbe, Emmitt and London, 1987). Tropical influence is manifested in easterly waves which advect warm moist air from the Indian Ocean in association with the Inter-Tropical Convergence Zone and the Indian Ocean high pressure system. Low-level convergence in the presence of unstable atmospheric conditions produce frequent cumulus convective rainfall during the summer months. However, extreme rainfall does occur when tropical cyclones move over the area in their seasonal migrations from the equatorial zone toward the subtropics, during the later part of summer (Kelbe and Germishuyse, 1999).

Westerly waves originating in the temperate latitudes, particularly if they are linked to tropical depressions, produce widespread frontal precipitation along the entire east coast which is often preceded by thunderstorms that produce heavy localised rainfall. In conjunction with synoptic scale instability, these systems have produced extensive flooding in the region. All these extreme rainfall conditions have occurred along the east coast during the past decades.

Rainfall, temperature and evaporation are the main factors determining the recharge to the groundwater and consequently are discussed in more detail in Chapter 4 on Data and Information.

2.5 LAND-USE IN THE STUDY AREA

In calculating groundwater recharge (percolation), the runoff, evaporation and interception play a vital role. All these processes are influenced by the different land-uses in the catchment. The different developments in the study area are described in general terms in this section. Industrial areas have a predominance of impervious surfaces like roads and roofs which channel much of the rainfall through drains and canals, as surface runoff. Urban residential areas have a mixture of roads, roofs and vegetation which will allow various degrees of infiltration and interception. Agricultural and forestry areas will have relatively more interception and varying degrees of infiltration. All of these have to be taken into account in the recharge and discharge modelling.

2.5.1 INDUSTRIES AND RAILWAYS

Figure 2.5 shows the main industries in the Richards Bay area. The main railway lines and rivers are shown in Figure 2.5. The location of these industries is very important in terms of groundwater pollution and solute transport. It is well known that industries can contribute to pollution (Foster *et al*, 1999), either directly or indirectly and it is necessary to determine the groundwater flow dynamics around these sites. These flow paths may be used in future to determine the position of remediation boreholes in case of accidental spillage, or to determine the best locations for monitoring water quality.

2.5.2 URBAN AREAS AND ROADS

The urban areas have generally been developed around important water bodies and rivers (Figure 2.6). The main urban expansion is still concentrated around Lake Mzingazi with a golf course on the eastern banks of the lake. These areas of urban gardens can be important when addressing pollution. Fertilizers are often used on these urban gardens causing an addition of nitrates, phosphorus and potassium which can leach to the groundwater and eventually end up in the lake (Manahan, 1994). A high concentration of such nutrients in surface water is often the cause of *eutrophication*, which leads to excess algal growth and may eventually lead to severe deterioration of the lake water quality (Manahan, 1994). The roads, which are also shown in Figure 2.6, are important for recharge estimation, because they are impervious areas where no water from rainfall will percolate into the groundwater. Runoff from the roads is channelled off through drains and can be a major factor when modelling small scale studies.

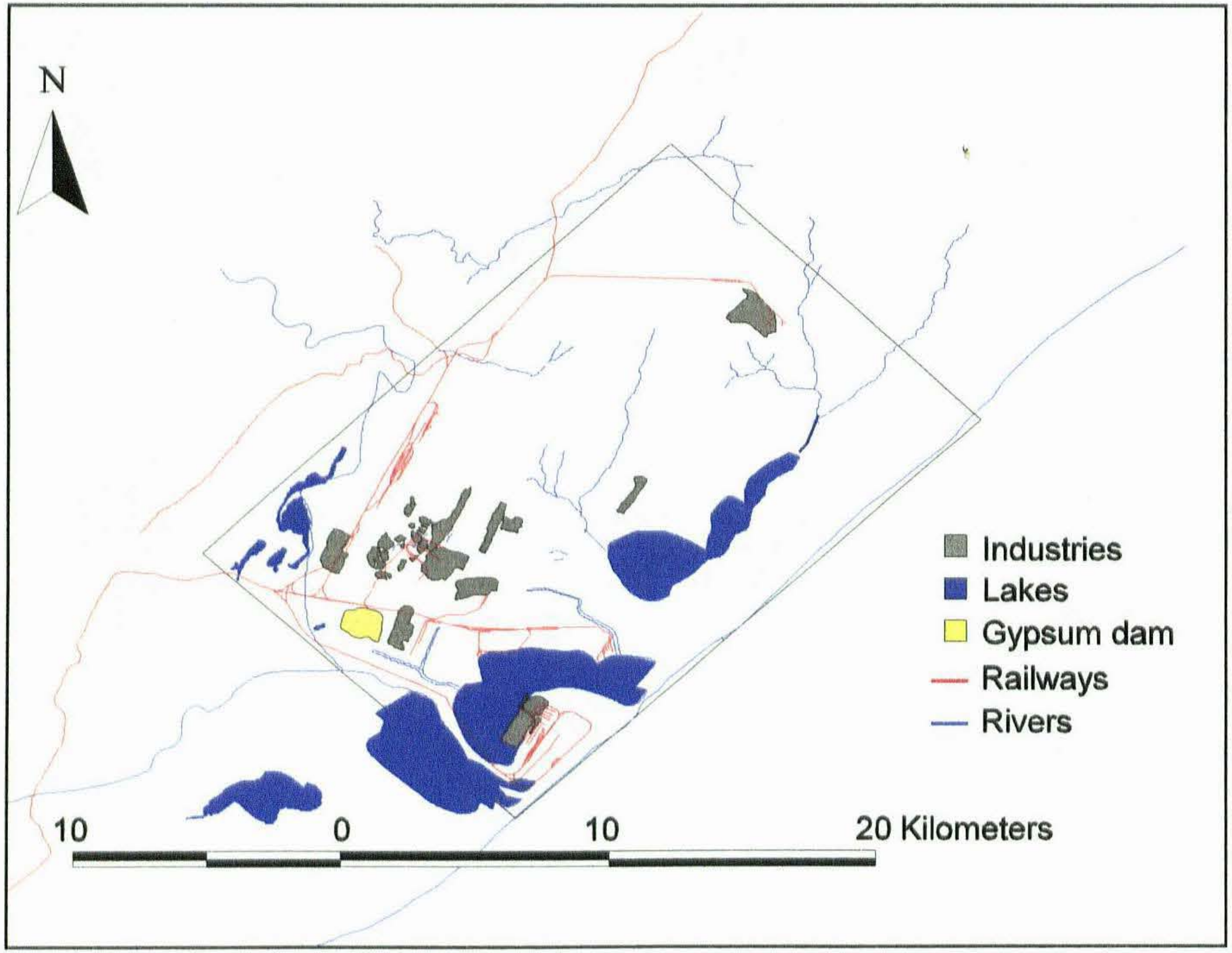

Figure 2.5 Main Industries and Railways.

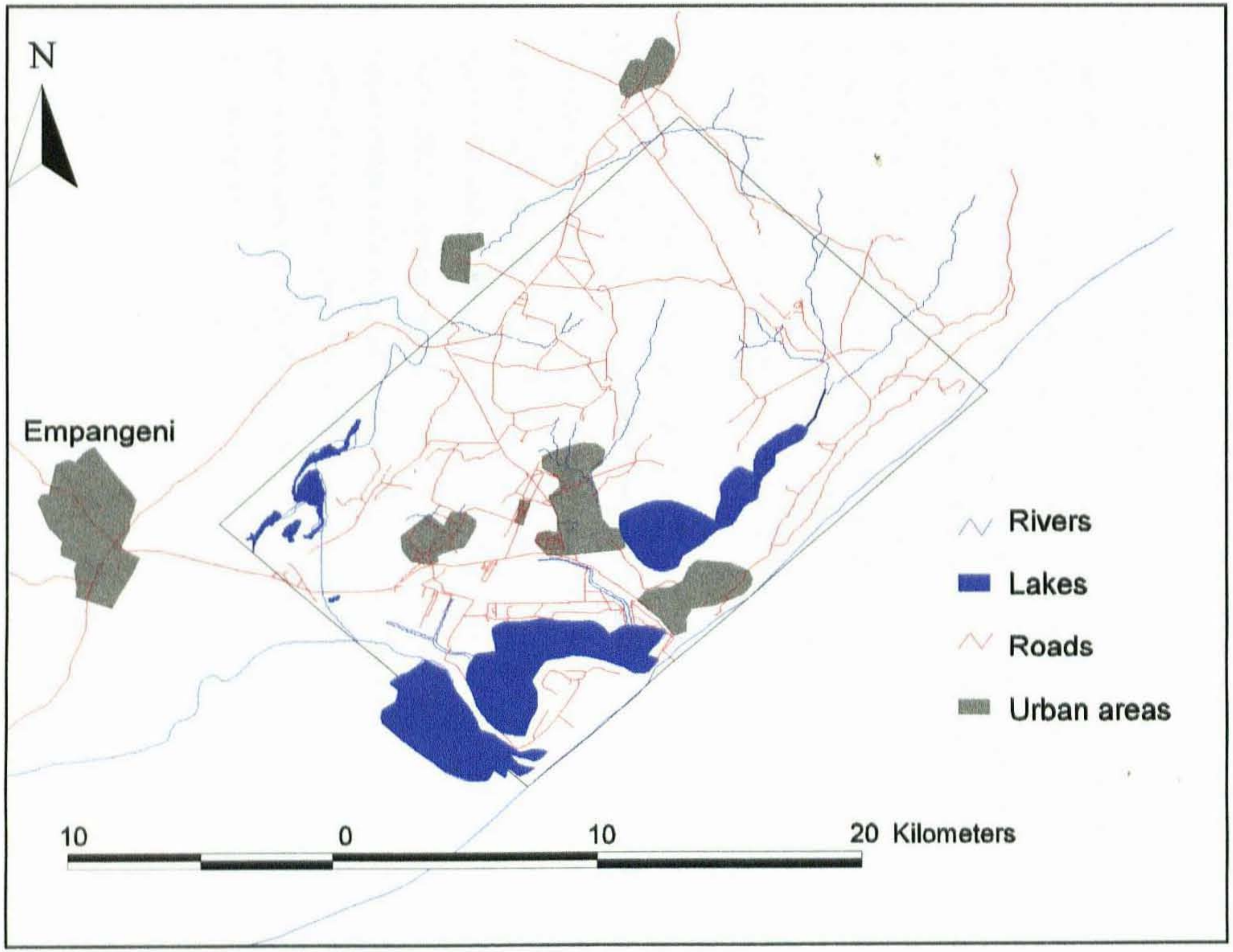

Figure 2.6 Urban Areas and Main Roads

2.5.3 *INFORMAL SETTLEMENTS*

Most of the informal settlements in the study area are situated near lake Mzingazi as shown in Figure 2.7. The Richards Bay TLC has developed an agri-village on the north western peninsular of the lake between the shore and the airport. There is also an informal peri-urban area between Lake Mzingazi and the coast and further up the coast (Figure 2.7). These informal settlements are expanding rapidly and many of them do not have any formal provision for waste control. All the surface water streams in the area feed directly into the lake and these streams may be experiencing a deterioration in water quality due to these settlements. Phosphorus is introduced to surface or groundwater from detergents used for washing (which is often done directly in the streams) and from human and animal wastes. Phosphorus has been named the main culprit in cases of excessive eutrophication (Manahan, 1994).

2.5.4 *FORESTRY AND AGRICULTURE*

Figure 2.7 shows that commercial forest plantations form a large part of the study area, most of which are planted with *Eucalyptus* species. These forests cause changes in water yield (Bosch and Hewlett, 1982) and they are therefore very important in the study of a water balance for areas with shallow water tables. The deep roots of the *Eucalyptus* species are expected to lead to high evapotranspiration from both the unsaturated zone and from the capillary zone for those deep rooting trees that are in hydraulic contact with the water table. Indigenous forests as well as swamps and grasslands are also shown in Figure 2.7. These will also be having an effect on the groundwater.

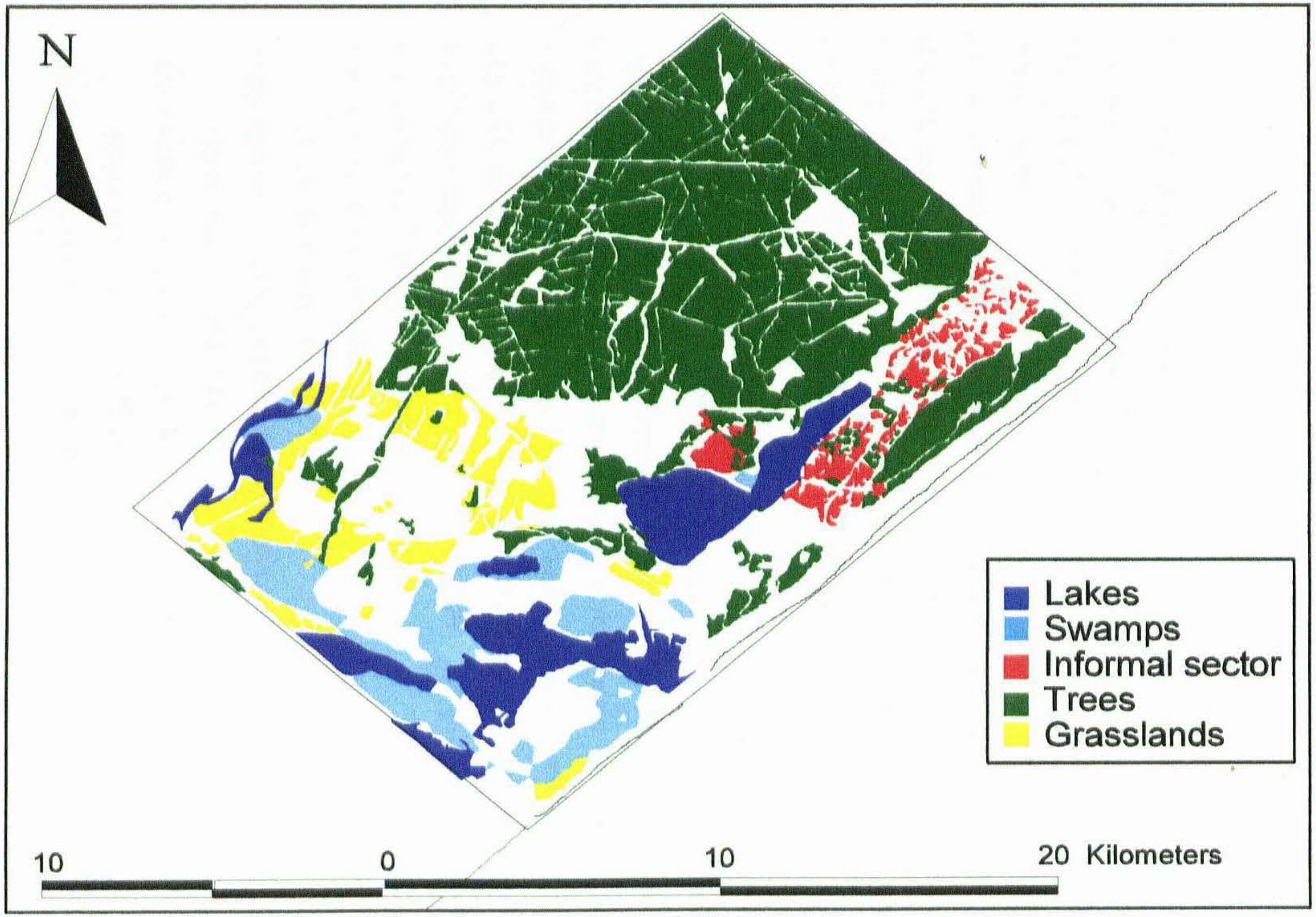

Figure 2.7 Informal Settlements, forestry areas, grassland and swamps.

3 REGIONAL GEOLOGY

A hydrological modelling study requires that all available knowledge of the geology of the area is used to create a conceptual model for the groundwater system. The formation of the conceptual model is based on this knowledge of the geology and relevant surface morphological features. This conceptual model is then used to form the basis of the numerical model. In this section, the geology is described as a series of events leading to the present system, using information from published studies of the coastal region. Each of the different formations is also discussed separately to conceive their relevance to this study.

The geological history of the Zululand coastal plains is closely linked to the rise and fall of the sea-levels (Tankard, 1976, Ramsey, 1997) (see Figure 3.1). Because of the series of related marine and terrestrial periods, the area can be classified as a transitional geological environment, with sub-environments leading to deltas or deltaic systems, beach and barrier island systems, estuarine and lagoonal systems, and tidal flats (Domenico and Schwartz, 1990). Different processes through geological time have been responsible for forming the different sedimentary formations and sub-environments. These processes are:

- Tectonism: the monoclinic folding and slip faulting as described by King (1972) and Von Weh and Anderson (1990),
- Aggregation: marine deposits from different stages of high sea-level (King, 1972, Maud, 1968, Botha, 1997),
- Degradation: drainage erosion in periods of low sea-level (King, 1972, Hattingh, Meyer and Barnes,1995, Worthington 1978) and
- Terrestrial: alluvial or wind-blown deposits (Maud, 1968, Maud and Orr, 1975).

General descriptions of the geology have been presented by Worthington (1978), Botha (1997), Hattingh, Meyer and Barnes (1995), Meyer and Godfrey (1995). The

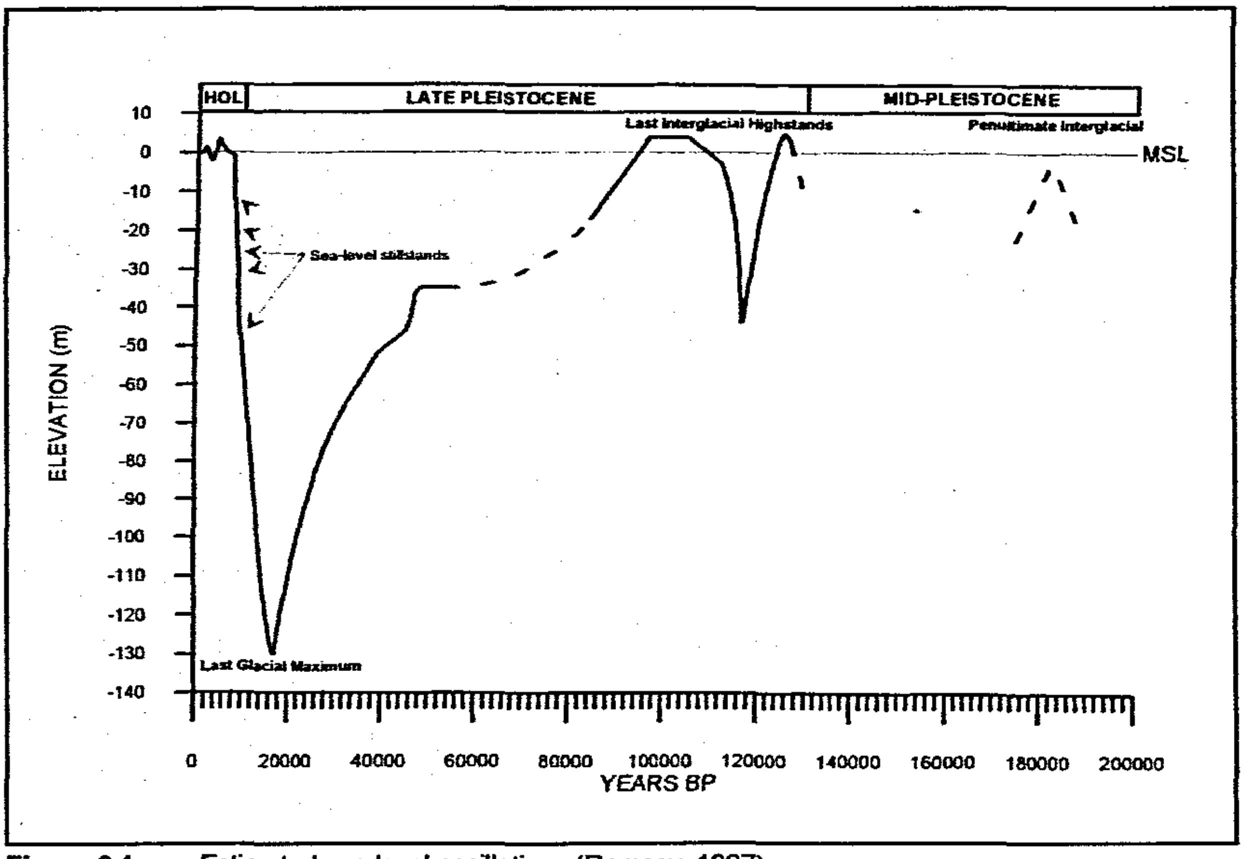

Figure 3.1 Estimated sea level oscillations (Ramsey, 1997)

study area consists primarily of late Pleistocene to Holocene sands that cover most parts of the Zululand coastal plain. The area is underlain by marine, littoral and dune deposits which Botha (1997) proposed to be grouped as the Maputaland Group. A simplified geological map indicating the western boundary of the Zululand coastal plain is shown in Figure 3.2. This boundary between the basement rocks (Precambrian) and later sedimentary units has been chosen as a boundary for the study area because it coincides with the Nseleni river which forms a hydrological boundary.

3.1 GEOLOGICAL HISTORY and SUCCESSION

Resulting from the breakup of Gondwanaland, the eastern rock formations of southern Africa were bent down and folded progressively into the monoclinic structure until they passed into the continental shelf beneath the ocean (King, 1972). This rifing was also accompanied by uplift and North-South tensional faulting which generated seaward

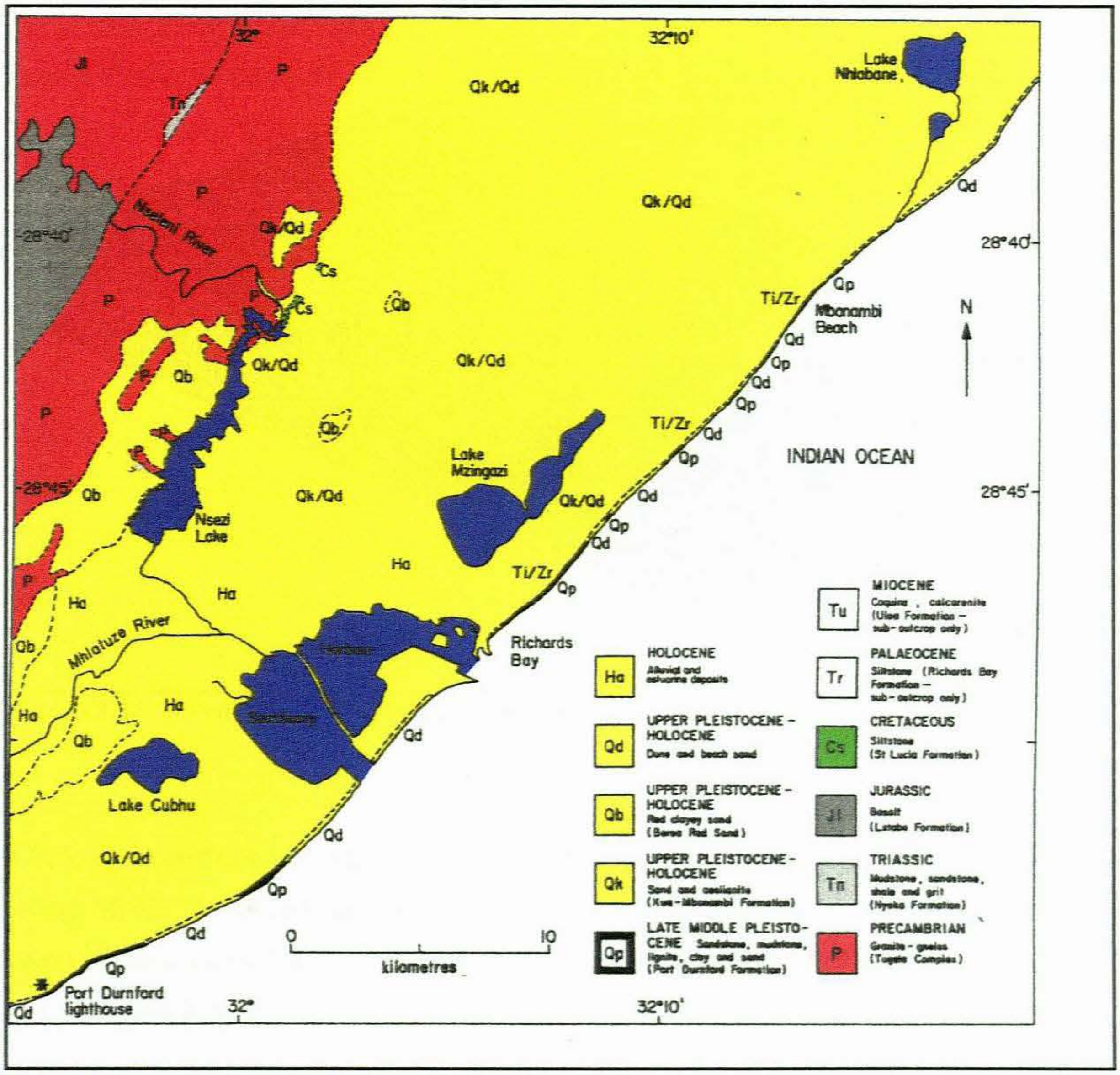

Figure 3.2 Geological map from Worthington, 1978

stepping fault blocks. A new coastline developed with a strong relief which resulted in an abundance of coarse elastic sediments (Tankard *et al*, 1982).

An era of high sea-levels during the Cretaceous age followed and induced marine transgression which caused the formation of a thick marine strata by the deposition of sediments along the coast (I in Figure 3.3). At the end of the Cretaceous age, deposition was brought to close by the worldwide eustatic regression (Tankard *et al*, 1982) and the Cretaceous sediments were exposed to surface erosion processes.

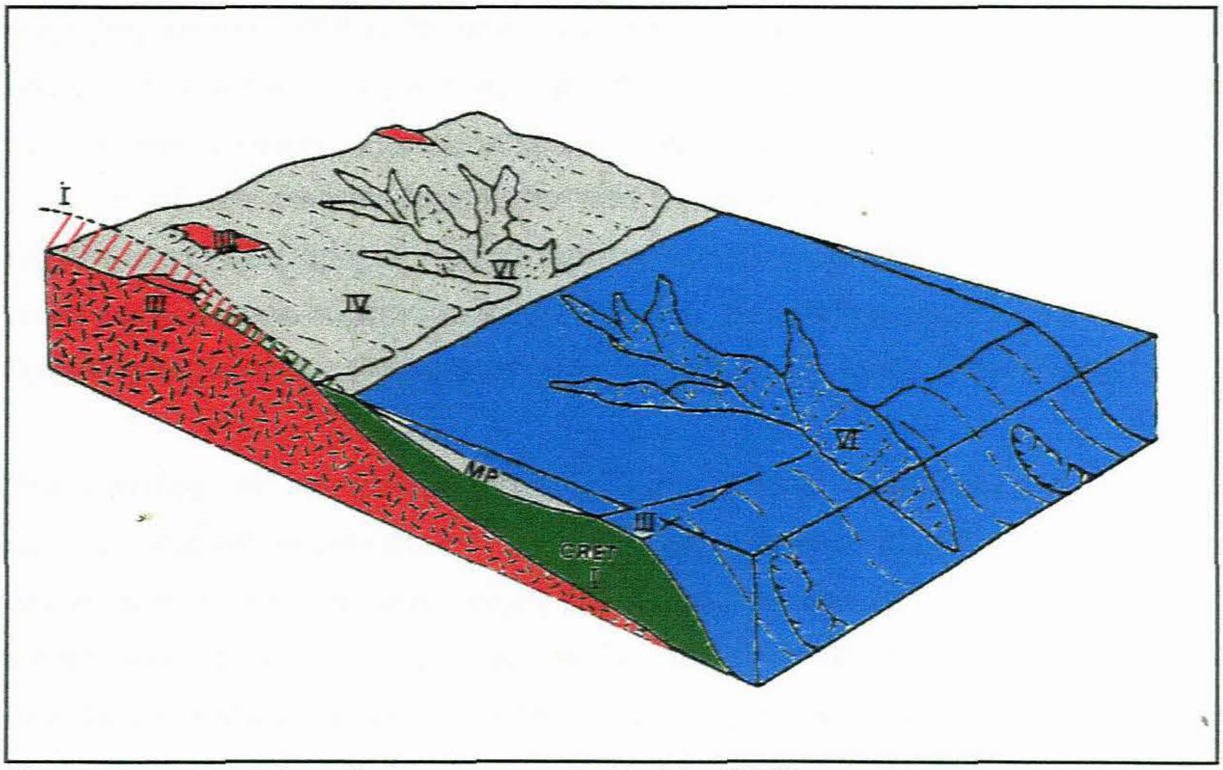

Figure 3.3 Formation of incisions as proposed by King (1972)

There is no evidence of deposits during this period of low sea-levels and it is believed (King, 1972) that coastal upliftment and drainage erosion during this period, formed deep incisions into the Cretaceous sediments in places such as the Mhlatuze mouth (VI in Figure 3.3).

The Miocene age with higher sea-levels that followed the Cretaceous, left rich fossil bearing sediments over the Cretaceous sediments on the present coastal plains.

After this short period, sea-levels dropped again due to an upheaval that elevated the interior plateau. King (1972) describes these eras of low sea-levels as periods of intermission, because they left no record in the strata of the coastal plain, but formed incisions by river flow (VI in Figure 3.3)

Then, during the Pliocene age, sea-levels rose again and soft, lime-rich sandstone was deposited on the present coastal plains. Rivers were drowned and formed lagoons when they were cut off from the sea (King, 1972). According to Tankard *et al* (1982) lagoonal deposits and the overlying peat and barrier sands as well as a coastal dune complex were exposed by coastal erosion. These deposits were first observed at Port Durnford and are conjointly called the Port Durnford formation. Maud (1968) and Hobday and Orme (1974) all suggest that the Port Durnford beds have formed during periods of sea-levels slightly higher than present. Recent investigations suggest that they were formed under freshwater lake environments (Oschadleus and Vogel, 1996).

Fluvial and aeolian sands were deposited during the late Pleistocene and Holocene periods. These more recent sands are comprised of successive units of boulder beds, old red sands, younger cover sands, coastal dunes and calcarenites of aeolian, estuarine and alluvial origin (Hobday, 1976). Hobday (1976) attributes these sands to aeolian processes which accompanied marine regressions. He also ascribes the basal coarser (estuarine or beach) deposits to a transgressive-regressive couplet. These sands have given rise to inland ridges which are believed to reflect ancient coastline positions (Hattingh *et al,* 1995). Maud (1990) reasons that the coastal dunes were formed in periods of low sea-level and more windy conditions than present.

3.2 GENERAL GEOLOGICAL STRATIGRAPHY

Several authors summarized the general (simplified) stratigraphic succession for the Zululand Coastal Plain similar to Table 3.1. They are Worthington (1978)[W], Simmonds (1990)[S], von Weh and Anderson (1990)[vWA] and Kelbe, Rawlins and Nomquphu (1995)[KRN]. This succession has been revised by Botha (1997) because some of the stratigraphic units have been poorly defined and there has been inconsistent use of some terms. Table 3.1 includes Botha's (1997)[B] refined descriptions of the different soil formations (Figure 3.4). However, his new classification has not yet been approved by the South African Committee for Stratigraphy (SACS). In this recent description, the soils previously described as the Port Durnford formation (Hobday and Orme, 1974) have now been subdivided into Kosi Bay and Port Durnford formations (Botha, 1997).

The Miocene and Pliocene deposits (previously described as the Uloa formation) are now separately described as the Umkwelani and the Uloa formations (Botha, 1997).

The stratigraphic succession as described in Table 3.1 is a general description for the Zululand coastal plains. On a smaller scale region it was not always clear from borehole information which of these formations are present in any location. An attempt has been made to identify the formations that are present in the Richards Bay area (Table 3.1).

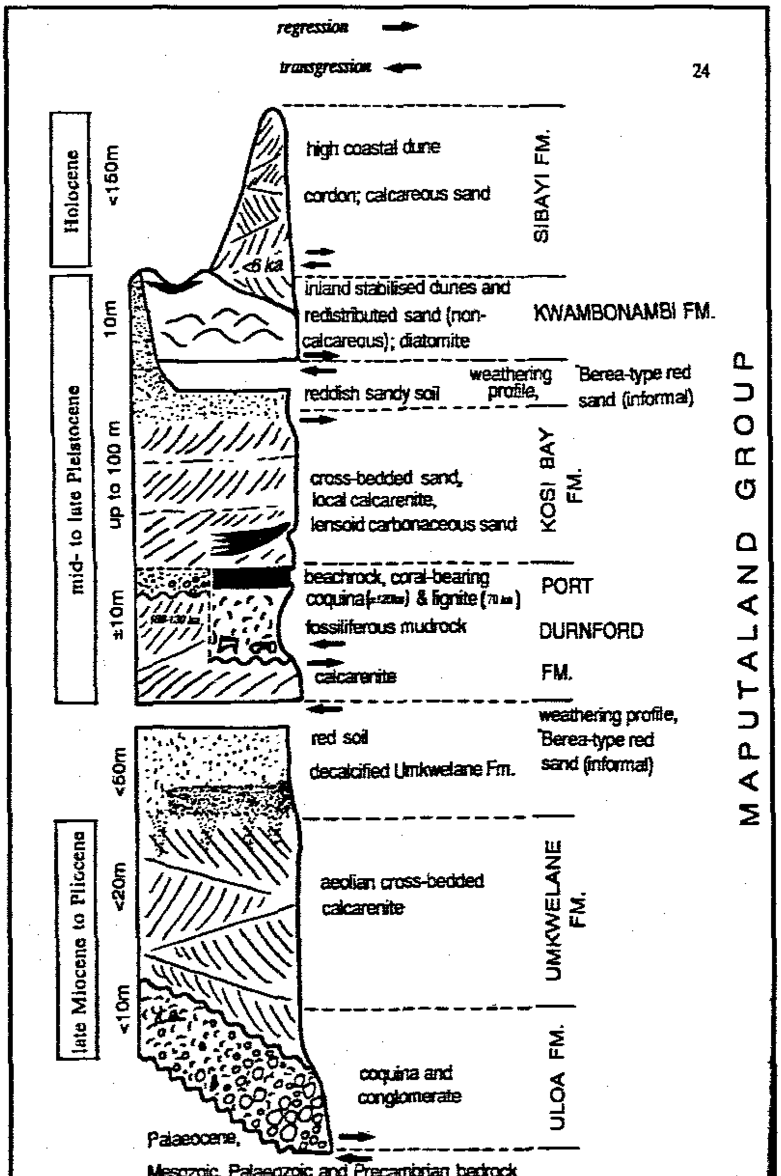

Figure 3.4 Formations as proposed by Botha (1997)

SYSTEM	SERIES	LITHOLOGY	FORMATION	R. BAY	REFERENCES
Quarternary	Holocene (0 - $1x10^4$ yrs)	Estuarine and alluvial sands, silts and clays		yes	S, W, B, KRN,vWA
	Holocene and Upper Pleistocene ($1x10^4$ - $2x10^6$yrs)	Dune and beach sand	Sibayi	yes	W, B, vWA
		Aeolianite and sand	Kwambonambi	yes	W, B, KRN
		Sand, red clayey sand	Berea Type	no	S, W, B, KRN,vWA (AGC combined the Kwambonambi and Berea types)
	Middle Pleistocene	Sandstone, mudstone, lignite, sand and clay	Port Durnford (including Kosi Bay)	yes	S, W, B, KRN,vWA
		Red soil	Berea Type	no	B
Tertiary	Pliocene and Miocene (2 - $20x10^6$ yrs)	Coquina, calcarenite	Uloa (including Umkwelane)	yes	S, W, B, KRN,vWA
	Paleocene	Siltstone	Richards Bay	yes	W, B, KRN,vWA
Cretaceous	Senonian	Siltstone	St Lucia	yes	S, W, B, KRN,vWA

Table 3.1 Stratigraphic succession of the coastal region and its existence in the Richards Bay area. References are explained on page 3-5.

3.3 GEOLOGIC UNITS OF THE RICHARDS BAY AREA

For geohydrological modelling, the thickness of the aquifers and their hydraulic properties are the principle criteria for developing the conceptual model of the geology. In the numerical model an impermeable basement rock is assumed for the lower boundary that is overlain by sedimentary deposits with varying thickness and hydraulic properties. It is necessary to identify the spatial extent of each deposit in order to form the conceptual model.

3.3.1 BASEMENT ROCKS

The basement rocks of Kwazulu-Natal are crystalline granites, gneisses and schists (King, 1972). These rocks were exposed by crustal uplift and erosion of overlying rocks. The Natal Group, consisting mostly of sandstones, are the oldest and lowest of a sequence of rock strata that overlie the basement rocks. The Karroo Supergroup covers the Natal Group with thousands of meter of sedimentary strata overcapped by volcanic lavas. These rocks dip seawards due to monoclinic folding and step faulting. King (1972) suggests that the monocline is the major structure that causes the Karroo formations to dip to elevations below sea level beyond the coastline. The monocline was described by King (1972) as a crustal downwarp to the east from a north-south axis of maximum uplift. To the east of this axis the strata bent down progressively until they passed into the continental shelf beneath the ocean.

Marine deposits formed the Cretaceous system some 50+ million years ago. The Cretaceous shore-line corresponds fairly closely to the present western margin of the Zululand coastal plain (Figure 3.2). It underlies the entire coastal plain and consists mostly of uniform siltstone with occasional thin clay lenses and thin bands of hardy limestone (Worthington, 1978). Marine fossils are present in places. A recent excavation at the Richards Bay harbour produced many examples of ammonites and shells in the black Cretaceous clays and siltstones (Figure 3.5).

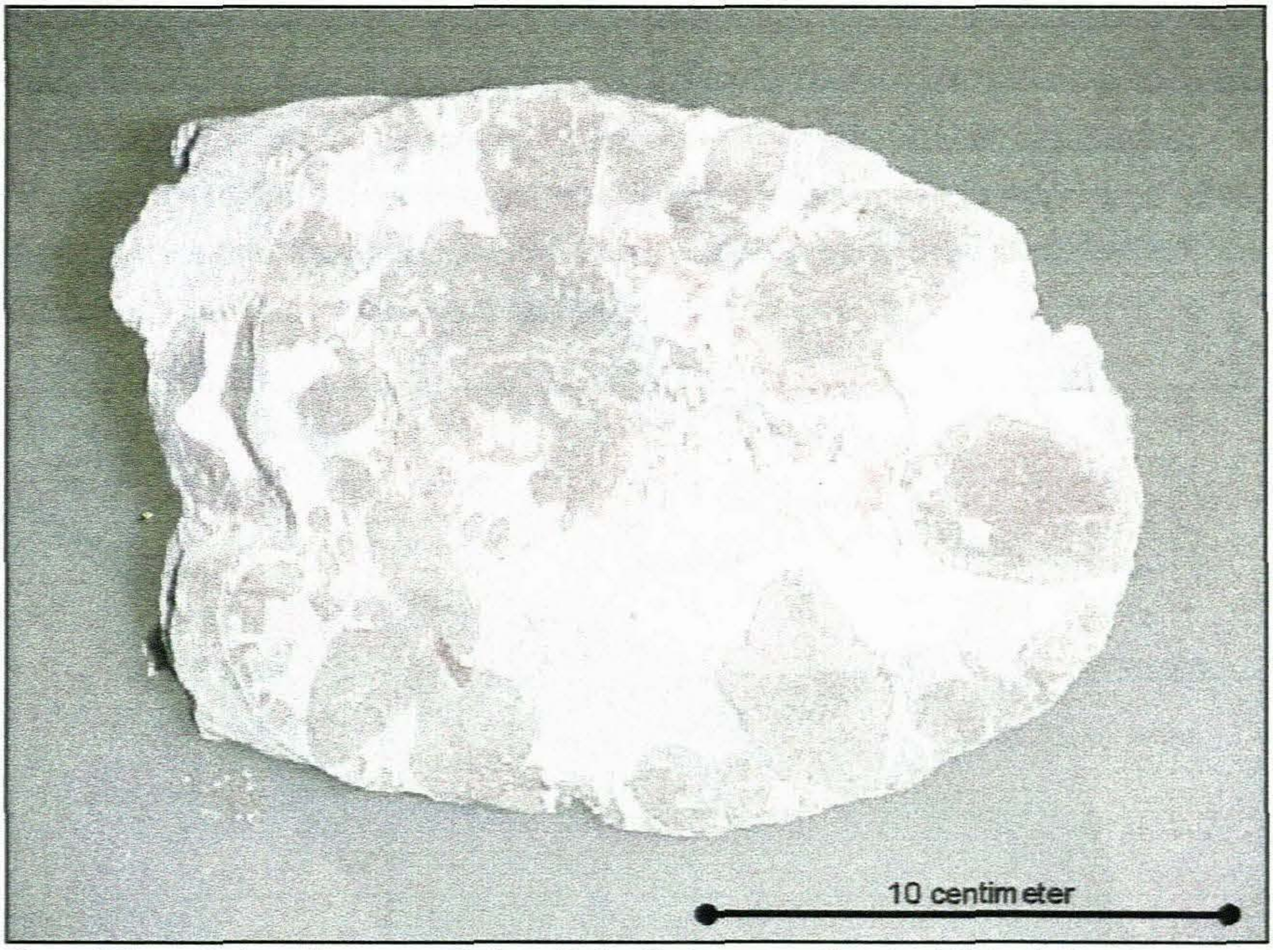

Figure 3.5 A piece of an ammonite found in the Cretaceous sediments at Richards Bay.

It is generally accepted that the Cretaceous formation is very thick under the ocean and tapers out inland towards Lake Nsezi (see Figure 3.6). Worthington (1978) estimated the thickness of the Cretaceous sediments at the present coastline to be of the order of 1000m. In the study area, the upper Cretaceous surface elevation varies from approximately -20m above mean sea level (m amsl) at the coast to between 20 and 40m amsl inland at the Nseleni river. This is a general slope of about 3 degrees dipping towards the east. However, due to erosion, there are several deep incisions in this surface. The deepest of these incisions in the study area is the Mhlatuze valley which reaches depths of -60m amsl. The elevation of the upper surface of Cretaceous sediments have been estimated from Worthington (1978) and more recent surveys (see Chapter 5).

The Cretaceous sediments and the overlying Paleocene deposits have similar hydraulic properties and identical lithology (Maud and Orr, 1975). Botha (1997) also mentions that the lithologies of the Paleocene and Cretaceous siltstones are almost identical and Worthington (1978) does not distinguish between the Paleocene siltstones and the earlier Cretaceous siltstones. Consequently, these deposits have been included with the Cretaceous deposits for the purpose of this study.

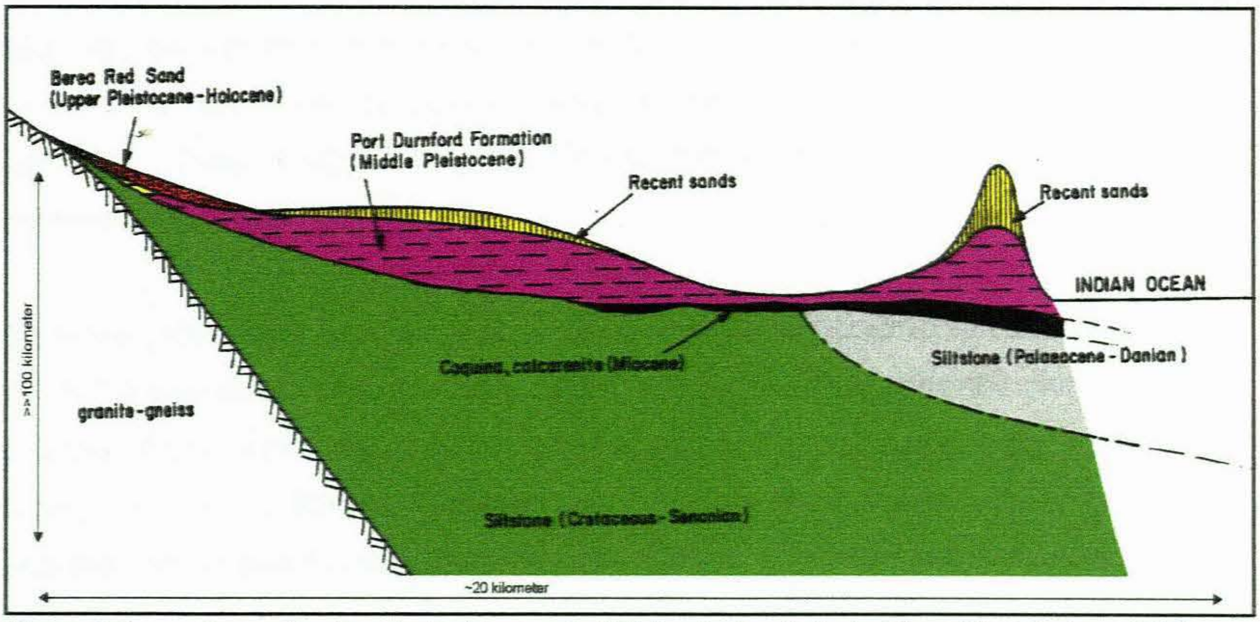

Figure 3.6 Generalized geological transect at Richards Bay (adapted from Worthington, 1978)

3.3.2 THE TERTIARY SYSTEM

• *Miocene (Uloa) to Pliocene (Umkwelane Formation)*

It has been assumed that the Cretaceous (and Paleocene) sediments form the basement of the regional aquifer. Overlying these deposits are several formations that constitute the principle aquifer of the Richards Bay area. The Miocene sediments generally form a thin layer where present in the study area. They occur at a higher elevation in areas further north (at Uloa) where some outcrops appear. This dip towards the south is presumed to be the effect of late tertiary tectonic movement or hinge faulting (Maud, 1996 - personal communications).

The sediments deposited during the Miocene and Pliocene periods comprise a hard coarse coquina of shell fragments (Uloa formation) and an aeolian cross-bedded calcarenite (termed Umkwelane formation by Botha, 1997). The latter has been interpreted as being of both Miocene age (Frankel, 1968) and Pliocene age (King,1982). This bed of calcarenite is formed from marine deposits and is South Africa's richest fossil-bearing deposit (King, 1982). Borehole data for the Richards Bay area confirms that these deposits may be up to 19m thick at some locations and entirely absent at other locations which may be less than 1km away. In their study of the coastal dunes near St. Lucia, Davies, Lynn and Partners (1992) made no mention of any Miocene or Pliocene sediments. They observed only the Port Durnford formation directly overlying the Cretaceous deposits.

Simmonds (1990) mentions the conspicuous absence of this layer in places and Maud and Orr (1975) describes it as erratically distributed. According to Worthington (1978) the absence of this layer may be the result of preferential drainage erosion. However, Hattingh, Meyer and Barnes (1995) propose that the Miocene sediments lie in confining beds that run parallel to the coast and give three possible explanations to support their theory:

- These deposits are reef relics that were left after post-Miocene erosion,
- The deposits are the result of step faulting which caused preferential erosional surfaces due to accentuated drainage lines, and
- The deposits could have formed from a combination of the other two possibilities mentioned above.

Though this may be a plausible explanation for certain areas along the coastal plain, data from the areas around Richards Bay suggest that the Miocene deposits are distributed more randomly. The random distribution of these sediments are discussed in more detail in Chapter 5.

3.3.3 QUATERNARY SYSTEM

• *Pleistocene Age (Port Durnford and Kosi Bay Formations)*

An extensive layer of quaternary deposits, collectively known as the Port Durnford formation, overlies the Miocene, Pliocene and Cretaceous sediments. This system is much more widespread than the Miocene and Pliocene deposits. It is present beneath most of the coastal barrier complex, although it seems to thin out towards the west.

The Port Durnford sediments are thought to have been deposited at sea-levels of 33-45m (Maud, 1968) or 8m (Hobday and Orme, 1974) above present sea-levels. However, Oschadleus and Vogel (1996) suggest that this formation was deposited under freshwater lake environments.

Outcrops of the Port Durnford formation are found on the beaches north of Richards Bay and near Lake Nsezi (Figure 3.2). Hobday and Orme (1974) suggest that gaps in this formation were formed by the late Pleistocene streams breaching the coastal barrier. The Port Durnford formation varies from being absent to a thickness of over 40 m (Worthington, 1978). The western boundary of this formation is believed to coincide with the western boundary of the coastal barrier complex (du Preez, 1975) as indicated in Figure 3.2.

The Port Durnford formation is not a homogeneous layer. It consists of poorly consolidated fine grained sands, clays, silts and lignite. A discontinuous lignite (peat) band subdivides it into two basic layers:

- The lower argillaceous member (deposited during periods of marine transgression) consists mostly of sands and clayey sand with marine fossils.
- The upper arenaceous member (deposited under lagoonal-shallow marine conditions) comprise cross-bedded sands. This member has subsequently been reclassified as the Kosi Bay formation by Botha (1997).

•Figure 3.7 shows a section through the Port Durnford formation 6km east-north-east of Port Durnford lighthouse which is approximately 50km south-west of Richards Bay.

3.3.4 *RECENT / COVER SANDS*

• *Holocene age (Kwambonambi and Sibayi formations)*

The entire study area is covered by a layer of unconsolidated, fluvial and aeolian sands from late Pleistocene and Holocene to recent ages. Alluvial sedimentation in the Holocene period filled many bedrock valleys close to the coast (Botha, 1997). The sands are predominantly fine-grained, but vary from unconsolidated to loosely consolidated (Worthington, 1978). The "modern" coastal dunes reach elevations of over a 100 m amsl. In some areas these dunes have been mined for heavy minerals.

These cover sands form the topographical surface of the Zululand coastal plain which is characterized by recent north-south trending coastal dune ridges formed from recent aeolian deposits. These dunes attain elevations of approximately 100 metres in the Richards Bay area. The dune ridges consist of homogeneous sand which overlies the Port Durnford formation in places. Further inland, clay lenses are thought to have formed in the valleys between these dune cordons. The high coastal dunes are believed to be very young and in some places still in the course of formation and are only stable due to their vegetation cover (Maud, 1980).

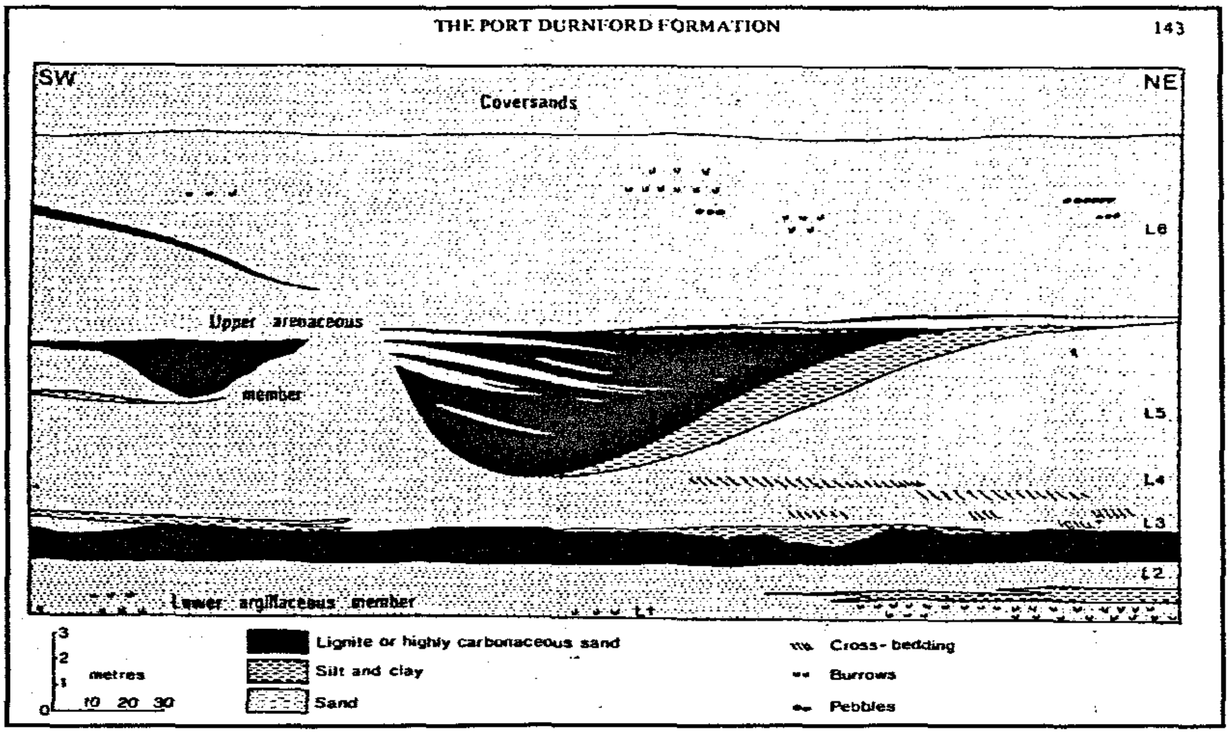

Figure 3.7 The Port Durnford Formation (after Hobday and Orme, 1974)

3.3.5 OTHER FORMATIONS

This brief discussion includes units that have been documented for the region, but have not been observed in the study area or in observations from smaller scale studies.

• *Berea Type Red Sands*

Because the red sands and clays in the region are the products of weathering that formed in different ages, Botha (1997) doubt their use as a litho-stratigraphic unit. Meyer and Godfrey (1995) pointed out that the Berea formation found in the Durban region is the weathering product of Pleictocene age calcarenite, but the red dune sands north of Mtunzini are the weathering product of much older "dune rock". Although these sands are widely documented, no evidence of the Berea formation could be found within the present study area.

• *Clay Lenses*

The presence of clay lenses in the study area is apparent when borehole data are studied. These clay lenses vary in size and are often present at many different levels. It is difficult to define the spatial extend of these lenses, because of their variability and also their absence in many places. There are indications that the area between lakes Mzingazi and Nsezi, has a clay layer (or a large clay lens) of low permeability just below the surface. These clays may or may not form part of the Port Durnford formation.

• *Older Aeolian Sands*

Davies, Lynn and Partners (1992) distinguished the older aeolian sands as a separate unit. They have also observed a sandstone member overlying the Port Durnford sediments. Others, Botha (1997), Worthington (1978) and Meyer and Godfrey (1995) add a sandstone member as part of the upper Port Durnford.

4 DATA AND INFORMATION

General descriptions, based on specific geological surveys, have been presented for the regional geology in Chapter 3. However, in order to create a conceptual model of the Richards Bay area, more specific information is required. Similarly the numerical model requires information for estimation of hydraulic properties of the layers as well as information on the boundary and initial conditions. A description of the data needed for this study is described in this section and the different sources of data are indicated.

4.1 GEOLOGICAL INFORMATION FOR RICHARDS BAY

General knowledge about the geology of the region that was described in the previous section, is very important to help with the creation of a conceptual model of the study area. Several specific studies have been undertaken in parts of the Zululand coastal plain area are described here. Geological descriptions (King, 1972, Maud, 1968, Meyer and Godfrey, 1995, and others) were mostly done on a more regional scale, while modelling studies were generally restricted to more localized areas (Kelbe and Rawlins, 1992, Kelbe, Snyman and Rawlins, 1994, Kelbe, Rawlins and Nomquphu, 1995). Some of the sites that were examined for this geological survey, are separated from the present study area by more than 100 km, but the work done in these areas is considered important in the context of this study because of the inferred similarity of geological conditions throughout the Zululand coastal plain.

Geological descriptions of the Zululand coastal plains were undertaken by King (1972 and 1982), Maud (1968 and 1980), Maud and Orr (1975), Hobday (1976), Hobday and Orme

(1974), Meyer and Godfrey (1995), du Preez (1975). Several additional studies have been conducted in the Richards Bay area and are discussed here.

4.1.1 RECENT GEOLOGICAL SURVEYS

Webb (1971 and 1972) undertook subsoil studies near Lake Nsezi and in the present industrial area of Richards Bay. His work has been considered to be very important for this study, since it covers an area where geological information is very limited. His reports contain borehole logs and interpolated data which have been used in the creation of a contoured elevation of the aquifer bottom for the study area.

Worthington's work (1978) is the most comprehensive study on the groundwater and geology of the area around Lake Mzingazi, and has been very valuable in the present study. Borehole logs and soundings as well as some of his interpolated data have been used in the construction of geological layers. The hydraulic conductivity values calculated from pumping tests have been used as initial input for the groundwater model. In 1990 Simmonds reported on saline intrusion into Lake Mzingazi. His study has provided more borehole logs from which geological information were taken, as well as water level data. He provides hydraulic conductivity values for different depths at one borehole.

More information on hydraulic conductivities for different soil types has been obtained from Davies, Lynn and Partners (1992) in their study of the geology of the eastern shores of Lake St. Lucia. Heath (1983), Shaw (1985) and Kruseman and de Ridder (1994) provided hydraulic conductivities for different soil types, which have been used as general guidelines in establishing a range of values for calibration studies.

4.1.2 RECENT GEOHYDROLOGICAL MODELLING STUDIES

Several numerical modelling studies have been done in other regions with similar geology. Kelbe and Rawlins (1992) used the program INTERSAT to model the groundwater dynamics for the eastern shores region of Lake St. Lucia. The groundwater flux into the western shores of Lake St. Lucia was modelled by Kelbe, Rawlins and Nomquphu (1995) while Kelbe, Snyman and Rawlins (1994) modelled the impact of the Sokhulu well field on groundwater of the area which is situated just north-east of the present study area. Calibrated hydraulic parameters and recharge from these studies, have been used as guidelines for setting the initial set of parameter values in the numerical modelling of Richards Bay.

4.1.3 ADDITIONAL GEOHYDROLOGICAL DATA

Many organizations and private companies in the Richards Bay area have been approached to supply information on any geological surveys, in particular any borehole logs for the region. Richards Bay Minerals (RBM), Alusaf, Mondi, the Borough of Richards Bay, Uthungulu Regional Council, Portnet and Indian Ocean Fertilizers have all supplied borehole logs. These are in addition to the many borehole logs and geological information that was obtained from the National Groundwater Data Base (NGDB) of the Department of Water Affairs and Forestry. Meyer and Godfrey (1995) also supplied the relevant borehole data used in their study of the geohydrological mapping project for the Zululand coastal plains. A map of the location of all the boreholes available is shown in Figure 4.1.

The location, surface elevation, depth to each geological formation and a code for the geological formation have been captured for each borehole provided by the donor organization and stored in the HydroCom database (Hodgon, Fourie and Lukas, 1987-1991). In some cases water level measurements and chemistry data are available and these were also captured in HydroCom. This program was chosen in order to be compatible with the National Groundwater Data Base (NGDB) which is stored in the same format.

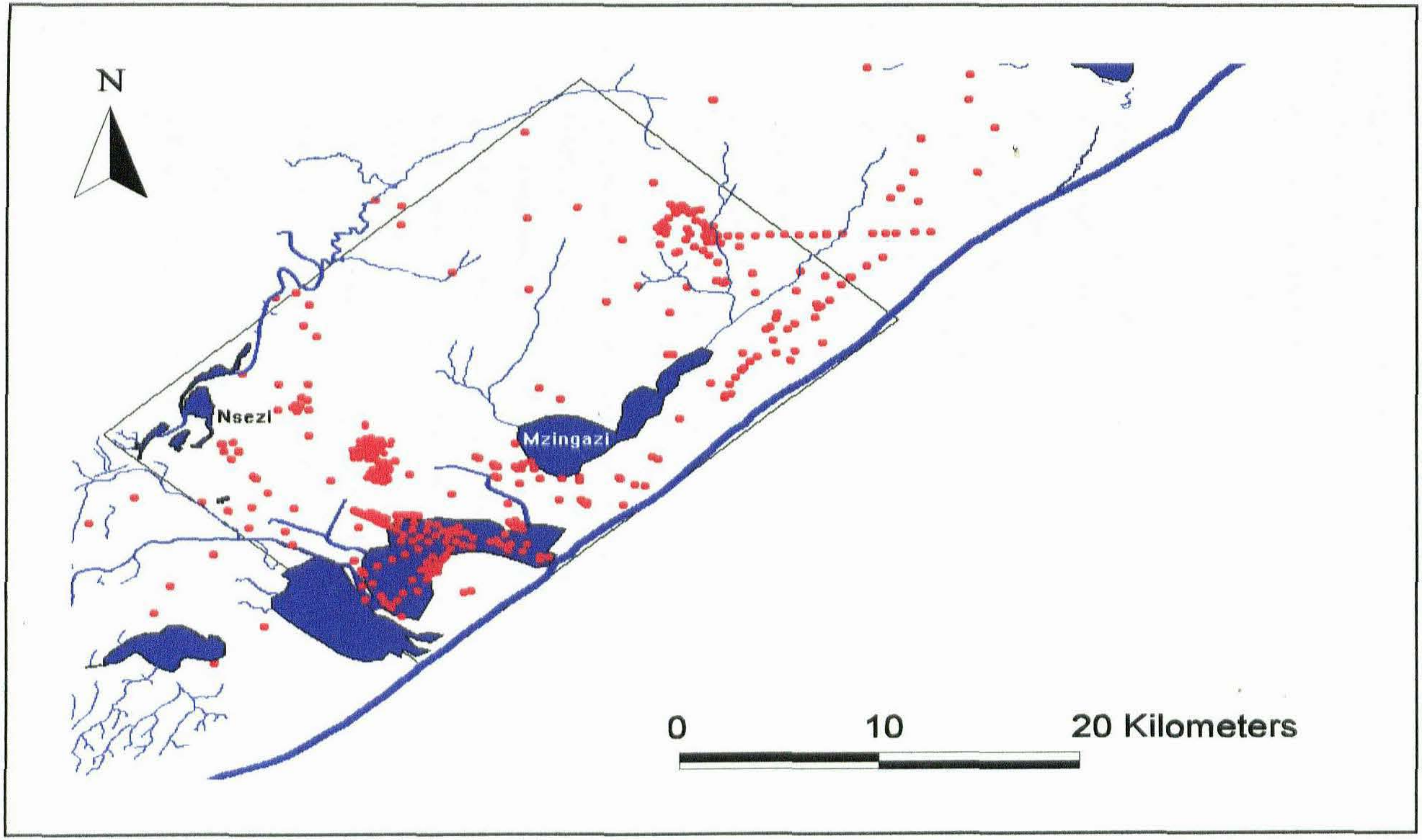

Figure 4.1 All the boreholes available in the Richards Bay area

It has been necessary to determine the reliability of the data used in the database. Several problems have been encountered with the geological logs received from different sources. Some of these problems as well as the procedures, which were followed when problems were encountered, are described here.

- Inaccurate location: Often only a farm name is indicated for the location of the borehole. In such cases the NGDB follows the policy of positioning the borehole in the middle of the farm. When more than one borehole was drilled on one farm, the database indicates all these boreholes have been located in the same spot, but the geology may be very different. These boreholes were ignored as data points for the geological interpretations, but are used to confirm interpretations e.g. the surface elevation of the Cretaceous sediments within the farm boundaries, could not be higher than measured at these boreholes

- Shallow boreholes: Many boreholes were only drilled to a shallow depth and provided no information about the older, deeper formations. These boreholes were handled as those described above.

- Geophysical soundings: Geophysical soundings have been done by Worthington (1978) using the Schlumberger method. However, in such homogeneous sands the soundings are difficult to interpret and generally the only information they provide is the depth to the Cretaceous sediments. Three of these soundings have been reinterpreted by Meyer (1996) to determine if new techniques could provide different interpretations, but in all three cases his results are the same as Worthington's initial interpretations. The information from soundings has been used in the creation of the surface elevation of the Cretaceous sediments.

- Surface elevation: Surface elevation as given on the geological logs does not always correspond to the surface elevation at similar locations inferred from ortho photo contours. The surface elevation of all the boreholes used in this study has been checked and corrected where possible.

- HydroCom codes: Data received in HydroCom format have been examined for consistency in all the different fields. Several examples were found where the *lithology code* field and the *geological unit* field of a borehole gave conflicting information. In all such cases the information from the *geological unit* field was used rather than the *lithology code*. The reason for adopting this approach was based on an understanding of how the field data is transferred to HydroCom. This is illustrated in the following example: The borehole log sheet is read by a typist at the Department of Water Affairs and Forestry. A unit on the log sheet is termed Miocene . The typist does not have any information on the lithology, but must enter a code into the *lithology code* field and may choose the wrong code. A second example is that there is no code in HydroCom for calcarenite or coquina which are often used on a borehole log sheet. Again the typist may choose a wrong code, because the *lithology code* field has to be entered in the program.

Figure 4.2 indicates all the boreholes that were useful for geological interpretations, as well as the positions of three transects through the area. Only the circled boreholes are indicated on the transects (Figures 4.3 - 4.5). The transects show the topographical surface elevation, the surface elevation of the Cretaceous and Miocene deposits as well as of the selected boreholes. In Figures 4.3 and 4.4, the variability of the soils can be seen from the borehole logs and Figure 4.5 shows the deep incision in the Cretaceous sediments near the harbour

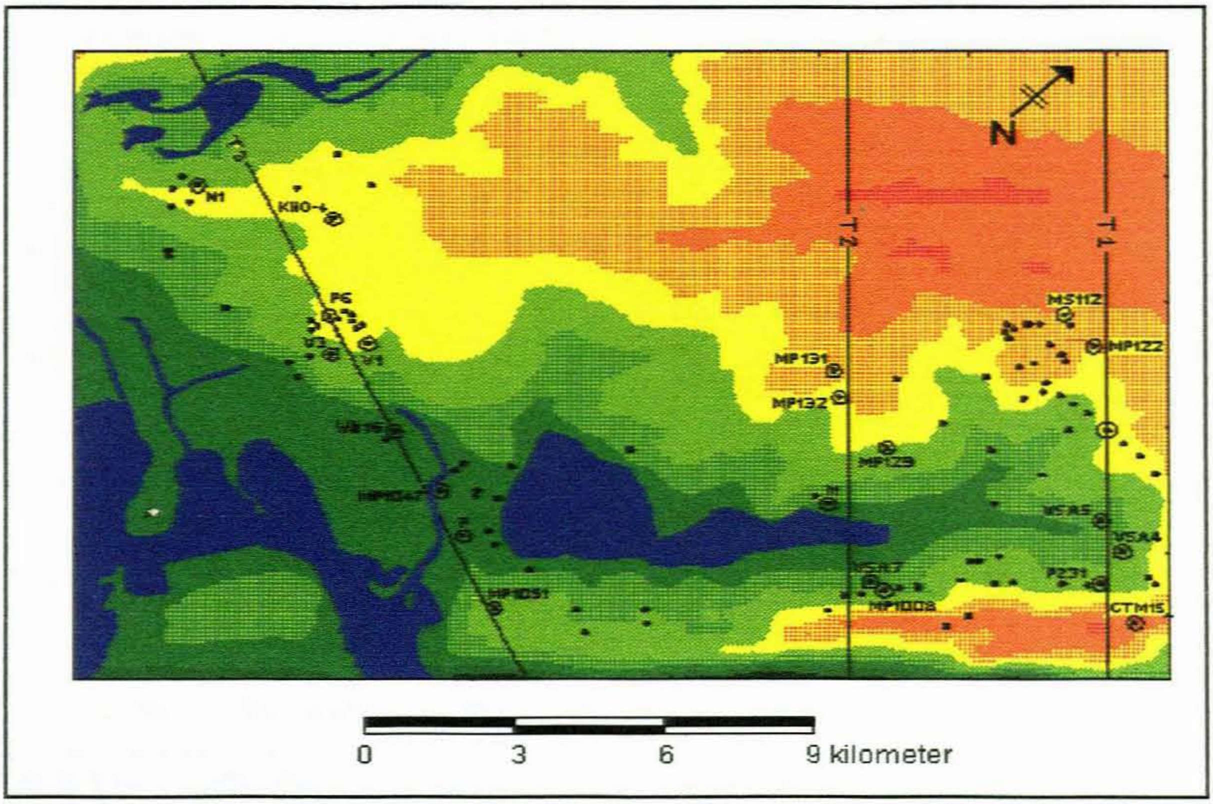

Figure 4.2 The model area with indications of the surface elevation, boreholes and positions of transects that are shown in the following figures.

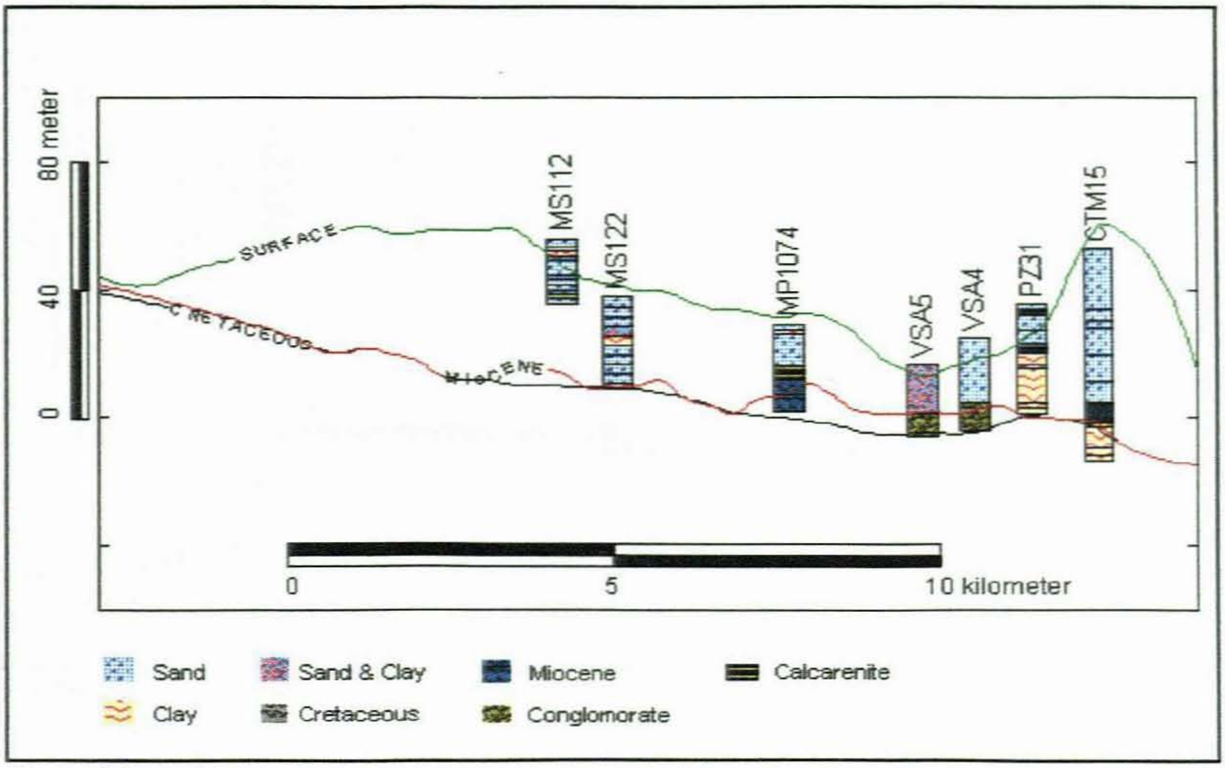

Figure 4.3 Transect 1

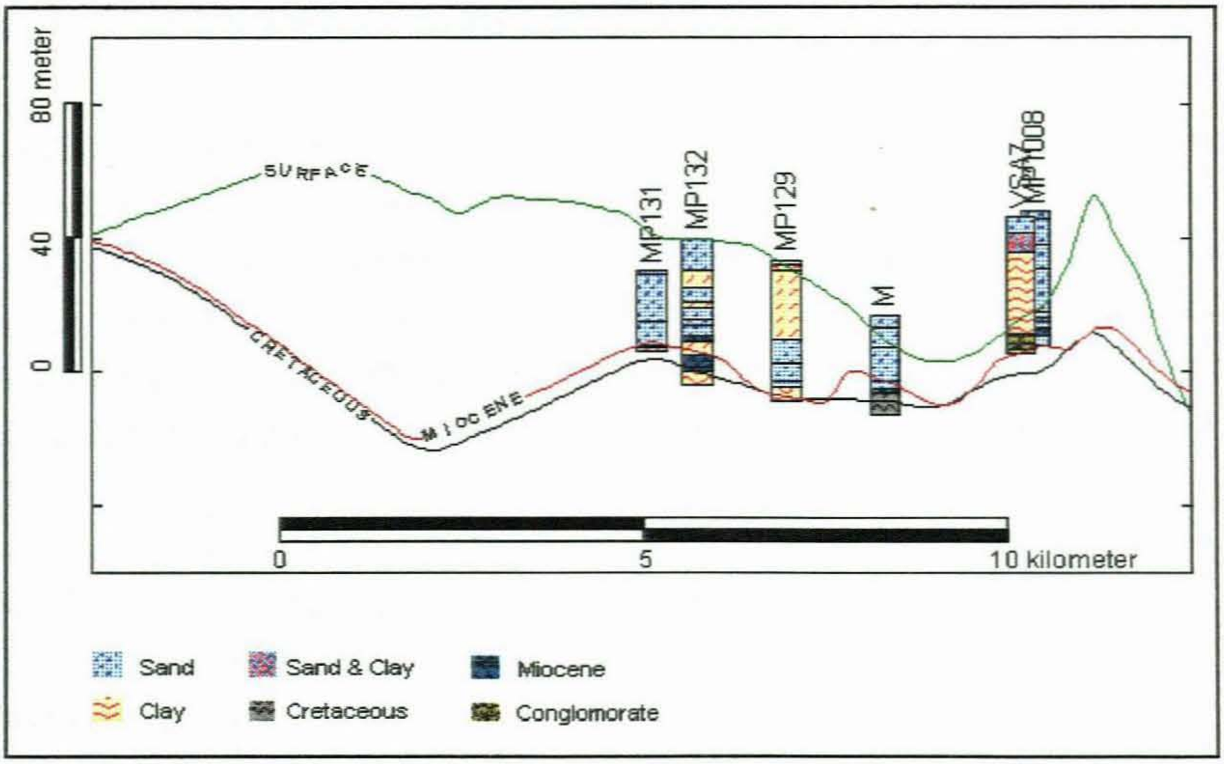

Figure 4.4 Transect 2

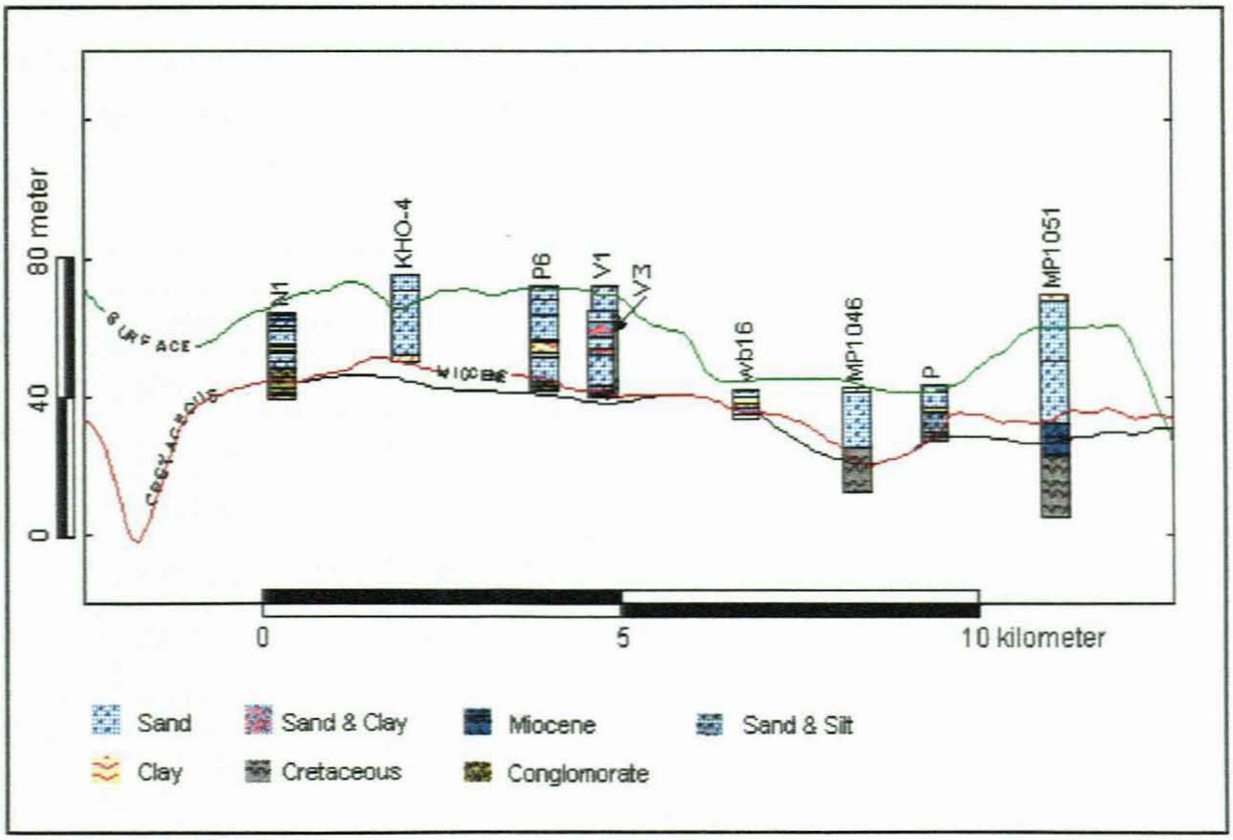

Figure 4.5 Transect 3

4.2 CLIMATE AND WEATHER DATA

Zululand has a "humid and wet" climate (Money, 1988) which is derived from the migration of tropical and middle latitude systems associated with the annual seasons. Richards Bay falls in a climate zone which can be regarded as subtropical with hot, humid summers and mild winters. It is located on the coast where the warm Mozambique current moderates the climatic variability. Several features of the climate are important in groundwater studies and these are described in this section.

4.2.1 RAINFALL

Rainfall data is of utmost importance in the determination of groundwater recharge. The method used to calculate recharge (see section 6.4) requires daily rainfall data. *For this study the Weather Bureau's daily rainfall data was extracted from the* Computing Centre for Water Research (CCWR), University of Natal. Richards Bay Minerals (RBM) supplied information for one additional rainfall station. The locations of these weather stations are indicated on the map shown in Figure 4.6 and Table 4.1 indicates the mean annual rainfall for each station as well as the first and last year of data.

Station name	MAP	Start (year)	End (year)
305037	994	1919	1995
305128	1078	1927	1993
304822	1101	1916	1987
304823	1092	1929	1993
305043	1216	1931	1978
RBM	1500	1976	1996
304735	1200	1973	1983
304736	1132	1960	1995
305017	1152	1970	1983

Table 4.1 Rainfall stations with mean annual precipitation and start and end years of data.

The RBM rainfall station was used for calculations of recharge (section 6.5), because it is the only station with a continuous data set. However, the rainfall at this station is slightly higher than at any of the other stations. The rainfall has not been adjusted, but the groundwater model was calibrated for recharge that was calculated from daily rainfall (see section 6.4). Figure 4.7 shows the mean monthly rainfall at the RBM rainfall station. The lower (red) bars indicate the mean monthly rainfall while the green bars indicate the standard deviation. The height of the combined bar is the sum of the mean and the standard deviation.

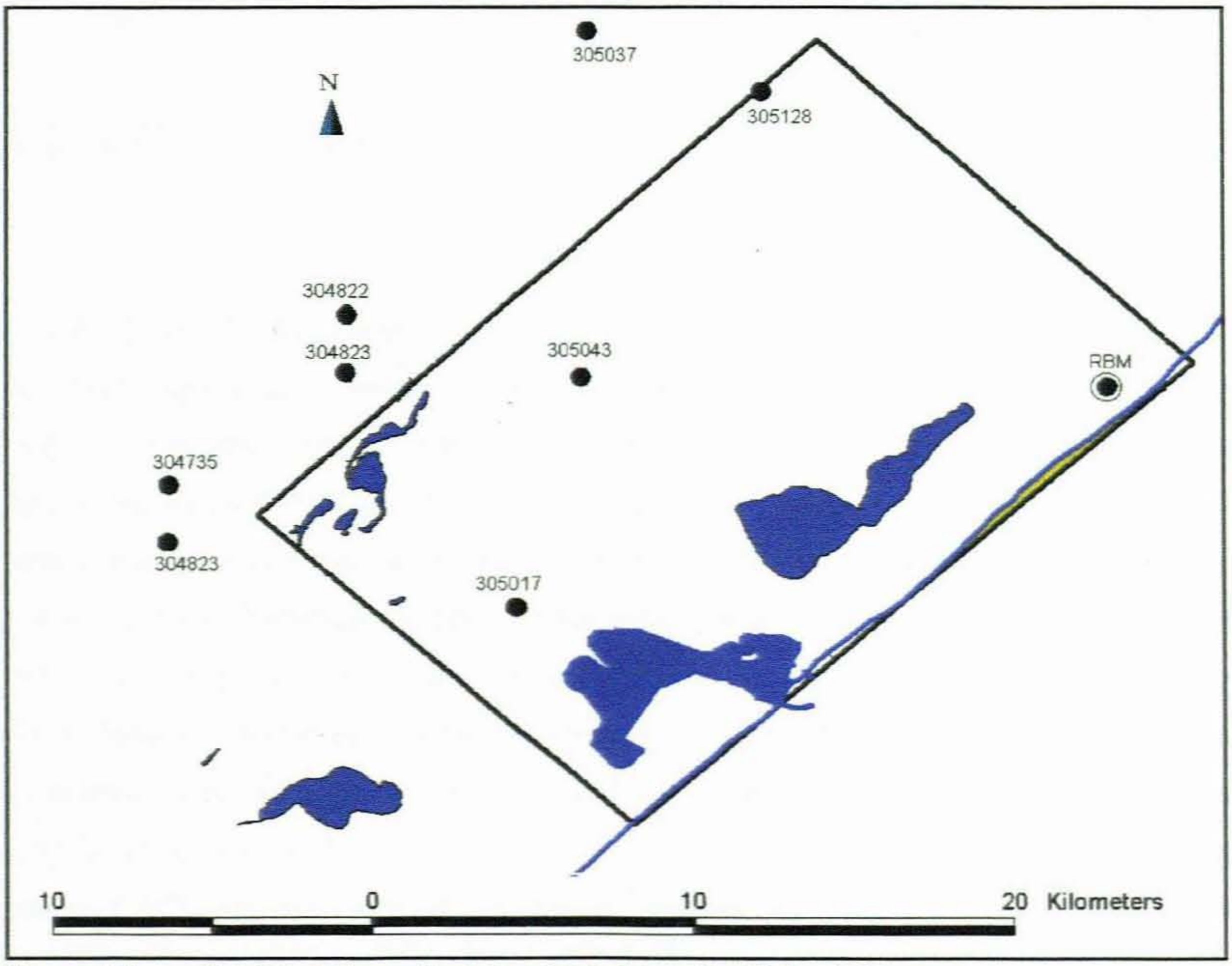

Figure 4.6 Rainfall stations with daily rainfall data in the Richards Bay area.

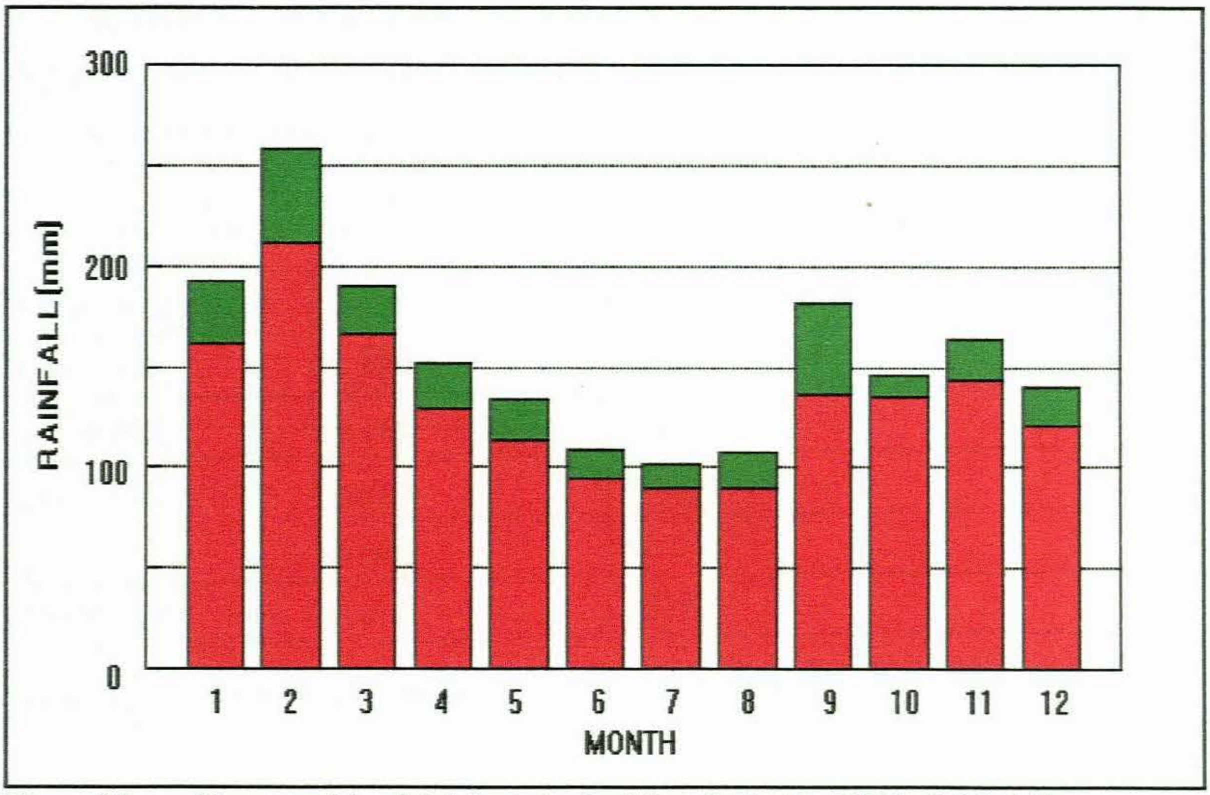

Figure 4.7 Mean monthly rainfall (and standard deviation) at the RBM rainfall station.

4.2.2 EVAPORATION AND EVAPOTRANSPIRATION

Evapotranspiration is one of the parameters used in the numerical model (section 6.3.4). It is also important to consider evapotranspiration for the calculation of groundwater recharge, since evaporation and transpiration diminish the amount of water that will reach the water table from soil moisture and also from contact with the capillary fringe. Weather conditions such as temperature, humidity, wind and radiation influence the rate of evaporation and some of these conditions will be discussed briefly in the following sections. Several studies have been presented that indicate various characteristics of the evaporation. According to Maud (1968) evaporation exceeds annual precipitation in the region. Meyer and Godfrey (1995) give an evaporation value of 1422mm/year, which is 320mm higher than their figure for rainfall. Midgley *et al* (1994) put Richards Bay in a zone of 1300 to 1400mm/year (Figure 4.8). Schultze (1982) gives the average monthly potential evapotranspiration as more than 150mm for January and less than 100mm in June and July for the Richards Bay area.

The evaporation stations in the Richards Bay area, the measured mean annual evaporation and the type of evaporation pan used are listed in Table 4.2. The location of these and other stations are shown in Figure 4.8.

Station number	Type	Mean annual evaporation (mm/yr)
W1E002	S pan	1410
W1E003	A pan	1923
W1E005	S pan	1554
	A pan	1773
W1E009	S pan	1557

Table 4.2 *The evaporation stations in the Richards Bay area*

4.2.3 TEMPERATURE

Summer temperatures are generally warm to hot and winters are mild to warm. According to Meyer and Godfrey (1995) the daily maximum, minimum and mean averages for Richards Bay are 27.7, 16.9 and 21.8 degrees Celsius respectively. The absolute maximum and minimum temperatures recorded at weather station 305168 (Richards Bay) over the period 1983 to 1995 are 39 and 6.5 degrees Celsius. Temperatures measured in 1994 at weather station 301622 which is situated at the University of Zululand some 25 km away from Richards Bay, are shown in Figure 4.9 These high temperatures have a strong influence on evaporation of the region.

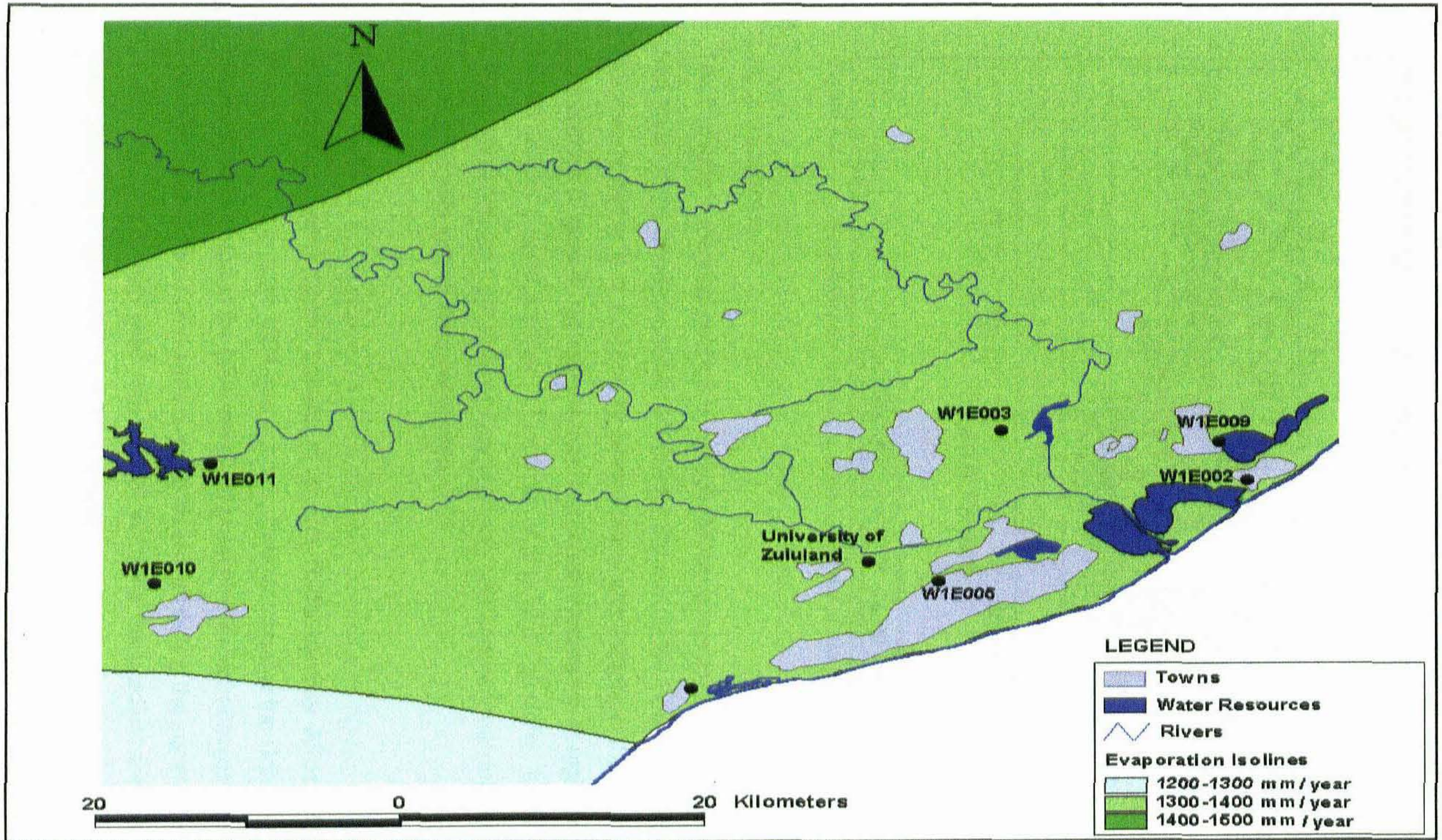

Figure 4.8 Evaporation zones from Midgley, Pitman and Middleton (1994) with the location of Evaporation stations as black dots.

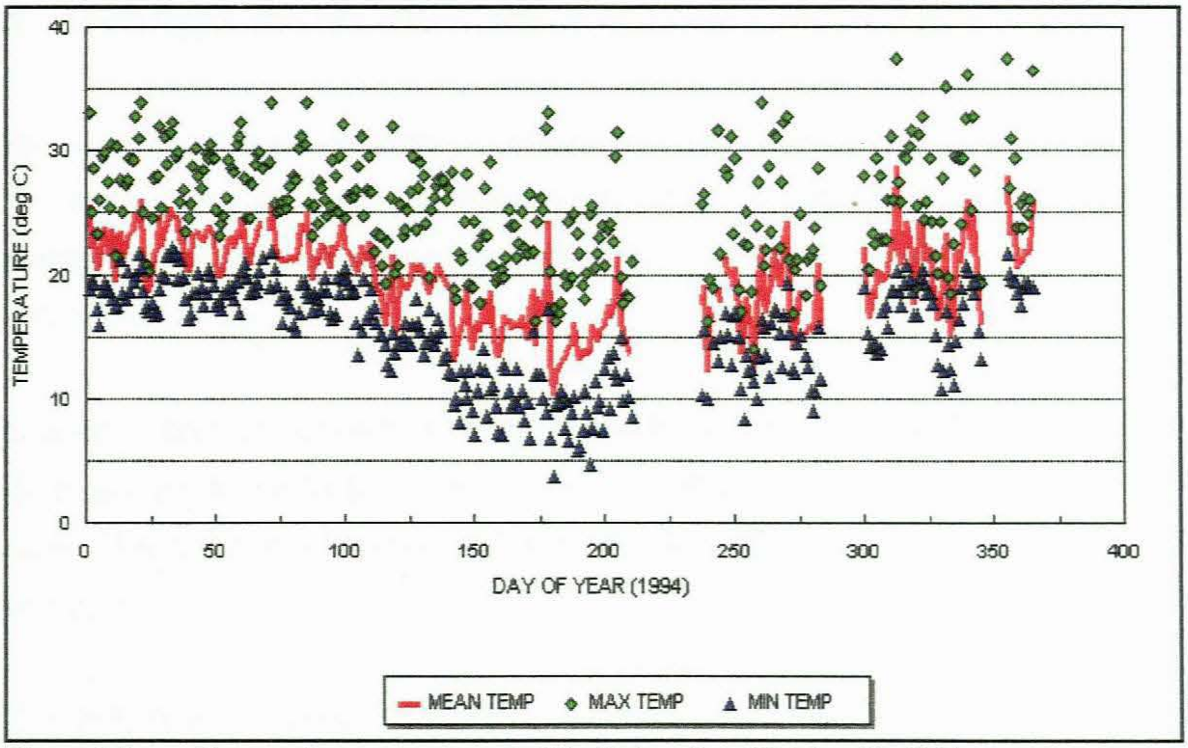

Figure 4.9 Temperature as measured at the University of Zululand in 1994.

4.2.4 HUMIDITY

The humidity in the study area is very high. Measurements at the Richards Bay airport had an average hourly humidity of 90% for the period November 1993 to June 1994. Relative humidity is a function of temperature and therefore the daily variation in temperature (Figure 4.9) suggests that the humidity increases at night and reaches its lowest levels around midday. Because of the high humidity, the high potential evaporation derived from solar energy is greatly restricted without enhanced advection associated with strong wind ventilation.

4.2.5 WIND

The average wind speed measured at the Richards Bay Airport for the period November 1993 to June 1994 was 3.3 m/s. Further inland at the University of Zululand the average wind speed for 1994 was 0.59 m/s with the maximum recorded wind speed of 2.4m/s. The highest wind speeds were measured during the summer months. There is also a strong diurnal wind regime that supports the gradient wind during the day when potential evaporation is at its greatest.

4.3 HYDRAULIC PROPERTIES

Hydraulic properties are different for the various stratigraphic units. Stratigraphic units with similar hydraulic characteristics can be grouped together as one layer in the numerical model. Representative hydraulic parameters are required in order to model the different units.

However if there is sufficient measurements to derive estimates for calibration of individual units, it may be possible to derive "calibrated" estimates for uncertain initial values. This procedure has been followed because measured data for the study area was scarce.

4.3.1 HYDRAULIC CONDUCTIVITY

Table 4.3 summarizes some of the hydraulic conductivity values (in m/day) that were found in the literature. Worthington (1978) and Simmonds (1990) conducted pumping tests at some boreholes around Lake Mzingazi. The results of their pumping tests have been used for the initial estimates of hydraulic conductivity in the model.

For the Richards Bay and the Zululand coastal plain, the hydraulic conductivities given by different authors, vary considerably. These values are summarized in Table 4.4 where all values have been converted to the same units (m/day) for comparison. Martinelli and Associates (1988) give a transmissivity value of $10m^3$/day/m for the Nhlabane area which is situated 5 km to the north of the present study area. Unfortunately the aquifer thickness was not mentioned and therefore this value has very little use in Visual MODFLOW which requires hydraulic conductivity as input.

Tables 4.3 and 4.4 should be compared with Figure 4.10 which shows how the hydraulic conductivities of different soil types overlap.

Material	Heath (1983)	Kruseman *et al* (1994)	Shaw (1985)
Fine Sand	0.5 to 200	1 to 5	12
Medium Sand		5 to 20	
Course sand		20 to 200	
Silt	0.001 to 5		0.08
Clay	10^{-7} to 10^{-3}	10^{-8} to 10^{-2}	10^{-4}
Sandstone	10^{-5} to 1	0.001 to 1	3.1
Limestone			0.94

Table 4.3 Hydraulic conductivities (in m/day) as found in the literature.

TEST METHOD	LAB	LAB	PUMPING	LAB
Material	**Davies *et al* (1992)**	**Meyer *et al* (1995)**	**Worthington (1978)**	**Simmonds (1990)**
Cover Sands	15.6 - 25.9	15.6		
Older Cover Sands	15.2			
Older Aeolian Sands	0.83 - 0.87	0.87		
Port Durnford Sands	7.46	4.3		
Port Durnford	0.11 - 0.59			
Miocene			0.5 - 34.6	$0.11 - 2^{-5}$

Table 4.4 Hydraulic conductivity values (in m/day) for the Richards Bay area as determined by different authors.

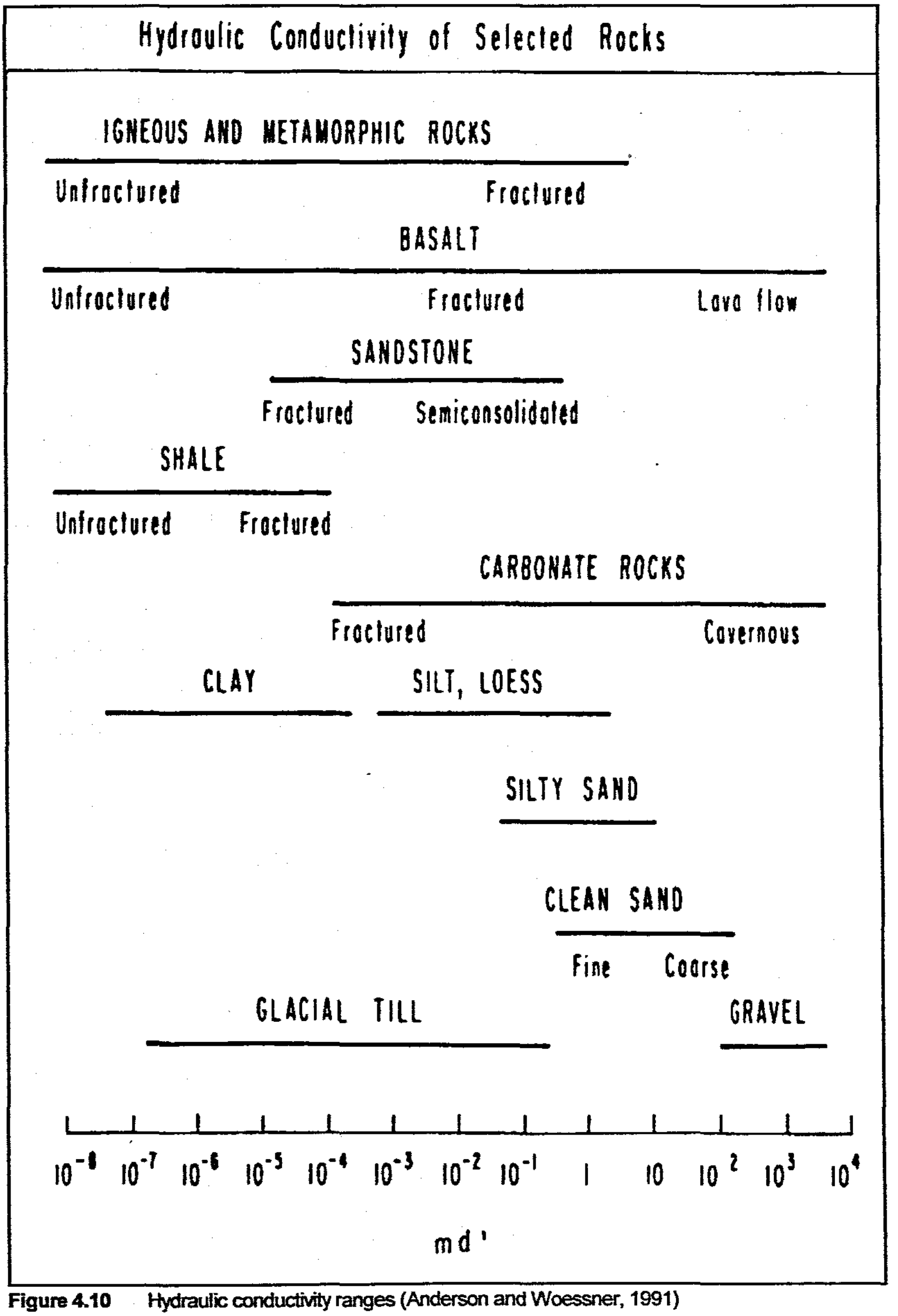

Figure 4.10 Hydraulic conductivity ranges (Anderson and Woessner, 1991)

4.3.2 STORATIVITY

Storativity is the capacity of an aquifer to transfer water to and from storage and is described by one of the storage parameters: specific storage, storage coefficient or specific yield. For unconfined aquifers the storativity is related directly to effective porosity. Very few values have been derived for porosity in the Richards Bay area. Table 4.5 indicates porosity values estimated by Davies *et al* (1992) for the eastern shores of Lake St Lucia. According to Anderson and Woessner (1991) the specific storage of sand ranges from $10^{-3}m^{-1}$ to $10^{-4}m^{-1}$.

4.4 WATER LEVELS

Field measurements of groundwater levels are very important when calibrating the flow model. Unfortunately, very few boreholes have been monitored for water levels over a long period of time in the study area. Water levels are mostly recorded only for the day when the borehole was drilled. Figure 4.11 indicates all the boreholes with some water level information. Boreholes where water levels have been monitored over a long period of time are concentrated in areas A and B shown in Figure 4.11.

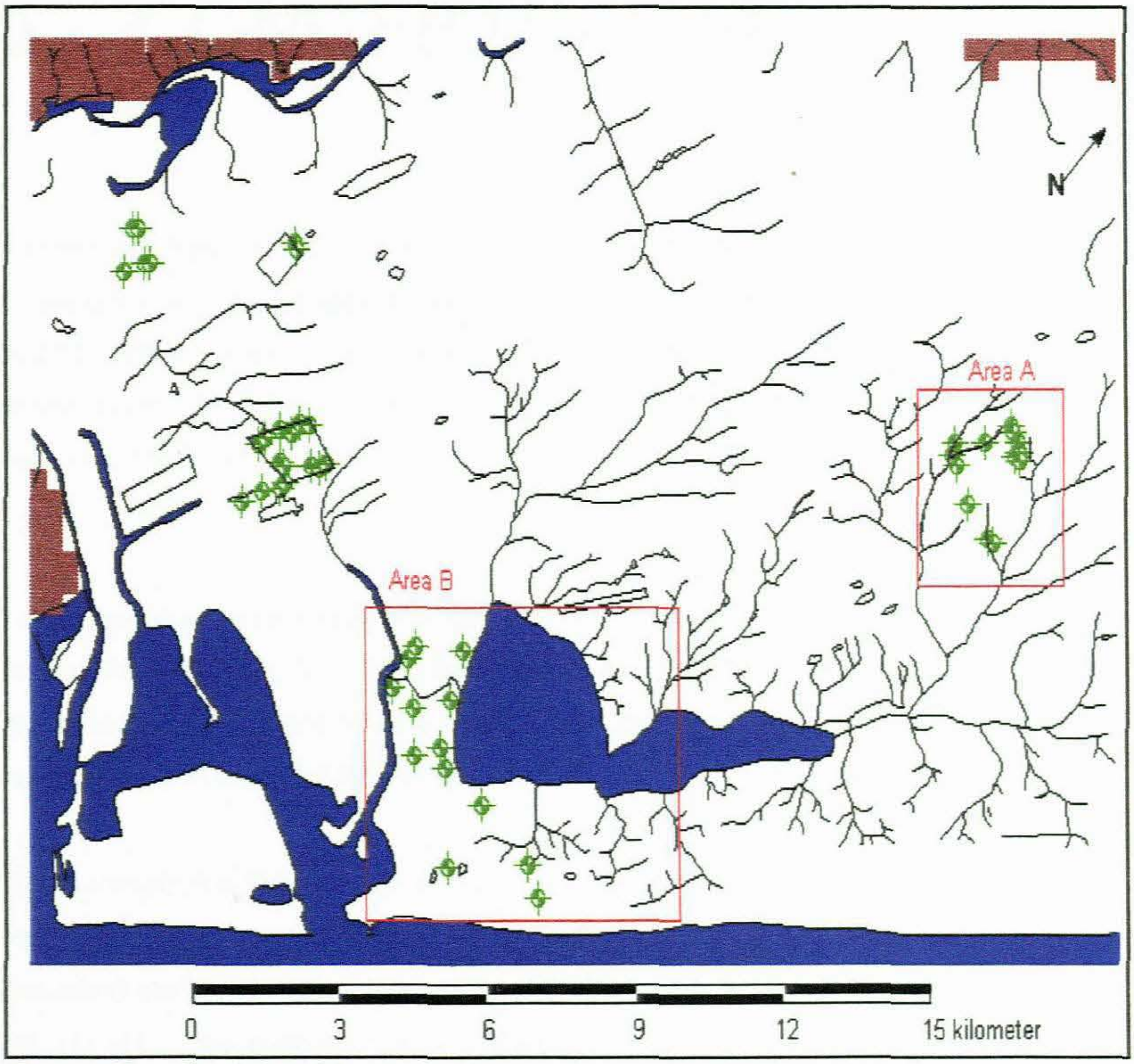

Figure 4.11 Boreholes with water level data

5 CONCEPTUAL MODEL

A simplified description of the physical features of the geology and hydraulic features is needed to conceptualize the groundwater system. This conceptual model is used to determine the design and dimensions of the numerical grid as well as the boundary conditions for the numerical model. The construction of a conceptual model forms a very important part of any modelling study, because it forms the basis of the flow model.

The conceptual model should include all the hydraulic characteristics of the study area that are important features of the flow dynamics. The construction of such a simplified model is a pragmatic approach that also contributes to a better understanding of the real system and makes analysis easier (Anderson and Woessner, 1991).

The formulation of the conceptual model involves identification and description of the natural physical boundaries of all the important aquifers which will be used for the numerical model. Numerical models require that either flux or head are specified at the boundaries. The hydrological boundaries or the different hydrostratigraphic units should also be identified in the formulation of a conceptual model. A hydrostratigraphic unit is a set of geologic units with similar hydraulic properties (Maxey, 1964) and are generally chosen to represent field conditions as a set of uniform layers.

5.1 REGIONAL BOUNDARIES

Three types of boundary conditions are distinguished, namely:

- Boundary conditions of the first kind (or Dirichlet type) have a known or constant head value. An example of such a boundary is any large surface water body where the water level remains relatively constant.

- Boundary conditions of the second kind (or Neumann type) have a constant or known flux over the boundary. Impervious boundaries are special cases of such boundaries, because the flux is zero.

- Boundary conditions of the third kind (mixed boundary conditions) are a combination of the first two conditions. They are used at semipervious (leakage) boundaries such as rivers and drains.

A rectangular model grid was selected such that the inactive area represented by the Indian Ocean was minimized. Since boundary conditions can form impenetrable barriers between aquifers, the boundaries of the rectangular model grid were chosen to coincide with the physical boundaries. The four boundaries used in this study are shown in Figure 5.1 and are defined as follow:

5.1.1 SIDE A - D

The boundary A - D coincides with the coast line (Figure 5.1) and forms a natural boundary with a mean daily water table elevation at mean sea level. This boundary was modelled as a constant head boundary (Dirichlet type) at mean sea level and tidal effects were assumed to be negligible.

5.1.2 SIDE A - B

The harbour, parts of the Mhlatuze river and the drainage from Lake Nsezi (which is part of the Mhlatuze flood plain) form another natural boundary (Figure 5.1). This sector was modelled as a constant head boundary in the harbour and a boundary of the third kind along the river sections. The river package in MODFLOW was used to model the river section of this boundary.

5.1.3 SIDE B - C

The boundary B - C in Figure 5.1 forms the interior section of the study area that is bounded by Lake Nsezi and sections of the Nseleni river. Lake Nsezi is maintained at a constant head through augmentation and consequently it was modelled as a constant head boundary. The rest of the B - C boundary was also modelled as a constant head with elevations adjusted from cell to cell to coincide with the elevation of the river.

5.1.4 SIDE C - D

This is the only side of the model area that does not conform to a natural boundary. While there are drainage lines crossing this boundary, the hydraulic gradient is small and suggest a flow towards the sea (see the cross section, Figure 4.3). Consequently, it was decided to model this boundary as a no flux boundary. This boundary is also far removed from the main area of interest and inaccuracies due to this assumption would be diminished toward the area of concern near the main industrial section of Richards Bay.

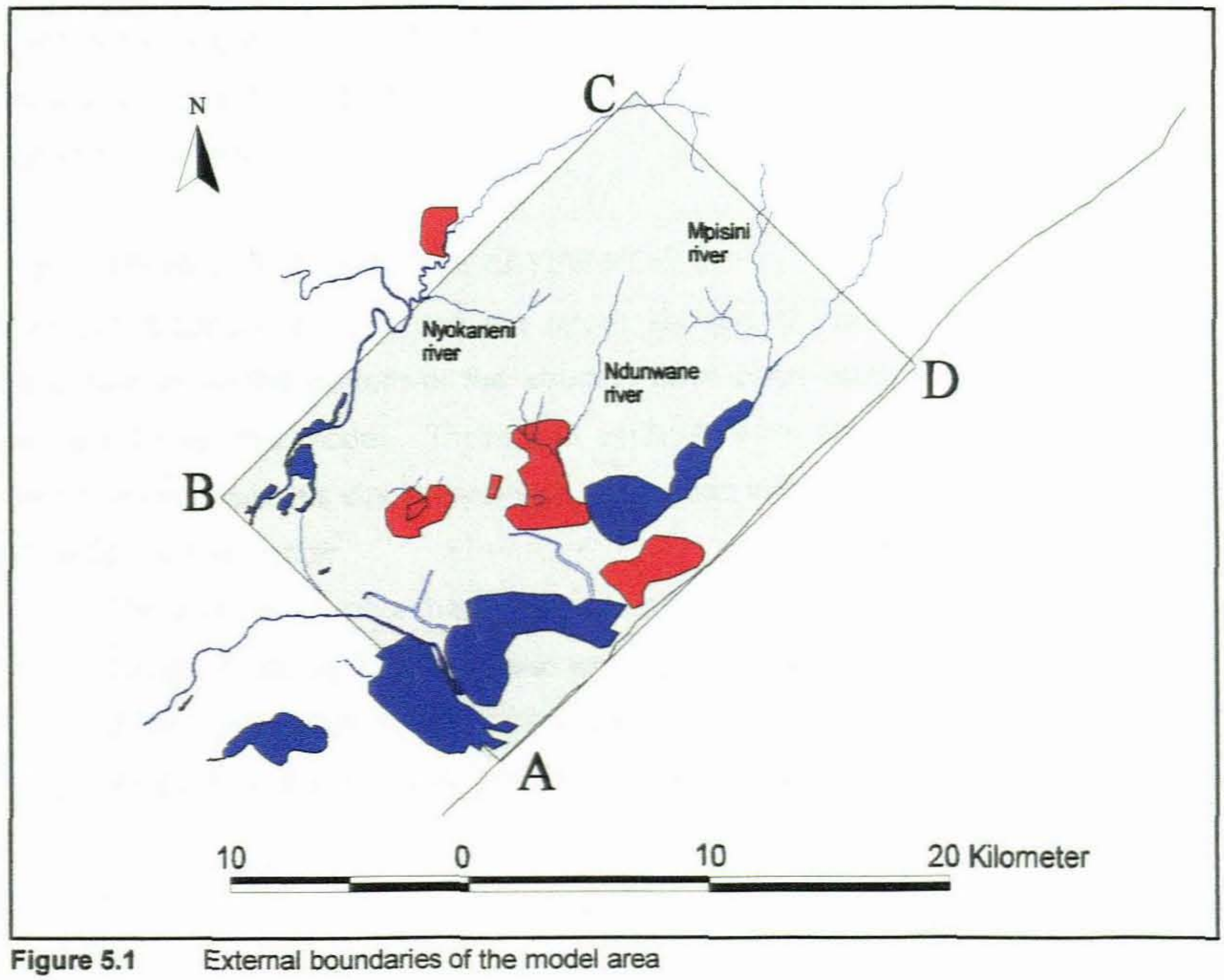

Figure 5.1 External boundaries of the model area

5.2 HORIZONTAL BOUNDARIES

The creation of a surface boundary for each layer is determined by the properties defining the layer. Three different approaches were examined in this study. The first study assumed a one layer model. This is justified on the assumption that the horizontal dimensions of the study site are much larger than the vertical dimensions and there is insufficient detailed information for further delineation of the aquifers. The second approach assumes that the hydraulic properties of each layer are homogeneous and uniform throughout each layer. When using this approach the term hydrostratigraphic unit can be used for a layer (Maxey, 1964). The third approach arbitrarily defines a fixed layer thickness and applies heterogeneous hydraulic properties across the layer. The procedures used to create the different horizontal boundaries for each of these three approaches are described below. The actual surface elevations were created by interpolating from all the points where data was available. Universal Kriging, through the program SURFER (Keckler, 1994), was used for all interpolations.

5.2.1 APPROACH 1: THE ONE LAYER MODEL

The topographical surface and the upper surface of the Cretaceous sediments (assumed to be the bottom of the aquifer) have been used to define the vertical boundaries for this model. These two surfaces were also used in the two other approaches where this single layer was subdivided into several layers.

•*Top Surface Elevation*

The surface elevation has been taken from 1:50000 topographical maps. All the contours, at 20m intervals, were digitized and interpolated in SURFER. 2970 points were used for interpolation. Figure 5.2 shows a 3D view of the topography together with the contours as they were created by SURFER.

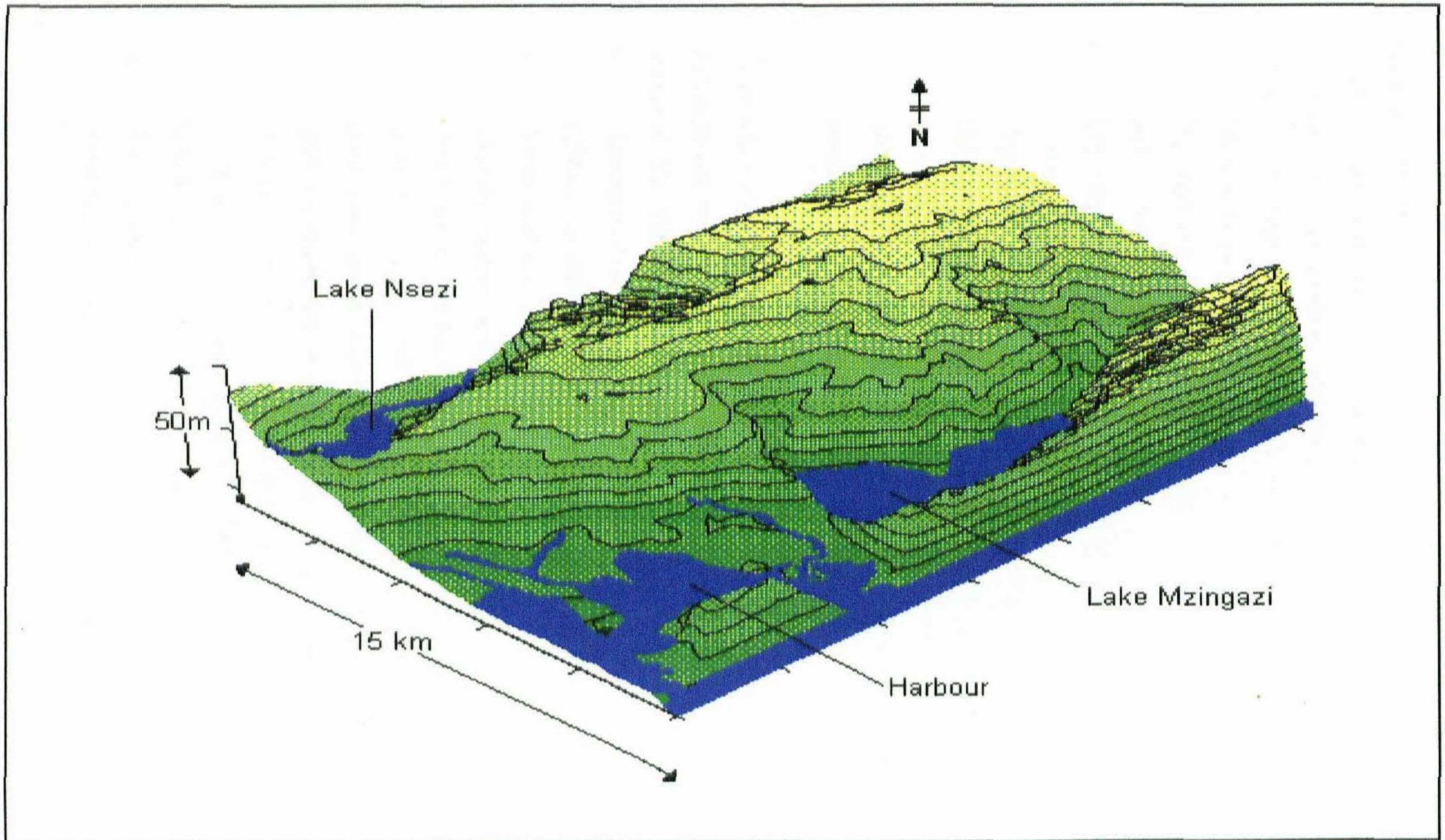

Figure 5.2 3D view of the surface elevation as interpolated from 20m contour lines (vertical axis exaggerated)

•Bottom of Aquifer

The fine grained siltstones of Cretaceous and Paleocene eras are virtually impervious (due to a high clay content) and have been assumed to define the bottom of the aquifer. This surface has been shaped by different processes:

- Tectonic movement of Miocene or later age (Maud, 1996).
- Drainage channels formed in younger geological times eroded the siltstones away in places (Worthington, 1978).
- The siltstones were deposited in two different geological eras, namely Cretaceous and Paleocene.
- The irregular surface can be seen clearly from transects through areas with a high density of boreholes (Figure 4.5). In the harbour area, differences of 5m in the upper Cretaceous elevation occur within 50m which indicates a slope of 10%. On the other side of the model area a 20m difference in elevation was measured within 1km (slope of 2%).

Great care was made to create this surface as accurately as possible using all available sources of information. The upper elevation of the siltstone deposits were obtained from the following data and information sources:

- Contours of the Cretaceous level presented by Webb (1972) for the Mhlatuze valley area, were digitized and used as a part of the data set (Figure 5.3).
- Contours of the Cretaceous level derived by Worthington (1978) were digitized and incorporated into the data set (Figure 5.3).
- Worthington's medium range soundings (Worthington 1978) were also used as extra data points. [Although borehole data are preferred to data interpolated from geophysical soundings, these medium range soundings were in good agreement with the boreholes around it and in some areas they provided the only available information. Only one of these soundings (S20 from Worthington, 1978) was ignored, because the surrounding 6 boreholes and 2 soundings had values that were at least 20m lower.]
- The elevation of the upper Cretaceous was taken from all the borehole logs that were obtained from the various sources and which went down deep enough to

intersect these deposits. The location of these boreholes are shown in Figure 5.3.

- Many of the shallow boreholes did not descend to the Cretaceous sediments and these were used to verify the created surface. Each borehole was checked to see if this new surface was at an elevation that was lower than the depth of the shallow borehole. Where this was not the case, the borehole location was added as an extra point to the data set for the Bottom of the Aquifer. It was assumed that the lowest point in each of the boreholes, was 1m above the upper Cretaceous sediments.
- The inland boundary of the Zululand coastal plain (Figure 3.2) marks the interception of the Cretaceous sediments and the basement rocks. It was assumed that the Cretaceous sediments reach the topographical surface elevation at this boundary. Where the boundary of the Zululand coastal plain was further inland than the model area, the Cretaceous surface elevation was interpolated from the boundary to the edge of the model area.
- Where the interpolated surface and the topographical surface meet, such as near the Nyokaneni river (Figure 5.1) additional data points were added around the river to "force" the upper Cretaceous elevation to be below the topographical surface. In these areas the modelled aquifer became very thin, consequently the numerical model was set to have a minimum layer thickness of 1 meter.
- In total 562 points were used to create the upper surface of the Cretaceous sediments that represents the lower boundary of the model domain.

The interpolated surface of Cretaceous and Paleocene siltstones (Figure 5.4) were personally discussed with various geologists (Maud, 1996, Rheeder, 1996, Hattingh, 1996, Meyer, 1996). This surface may be updated in future years as more information becomes available. Two important features are discernable in Figure 5.4. There is a very deep incision that coincides with the Mhlatuze river and estuary. There is also a Paleo-channel that runs through the middle of Lake Mzingazi and may have a large impact on the lake hydraulics (Kelbe and Germishuyse, 1999).

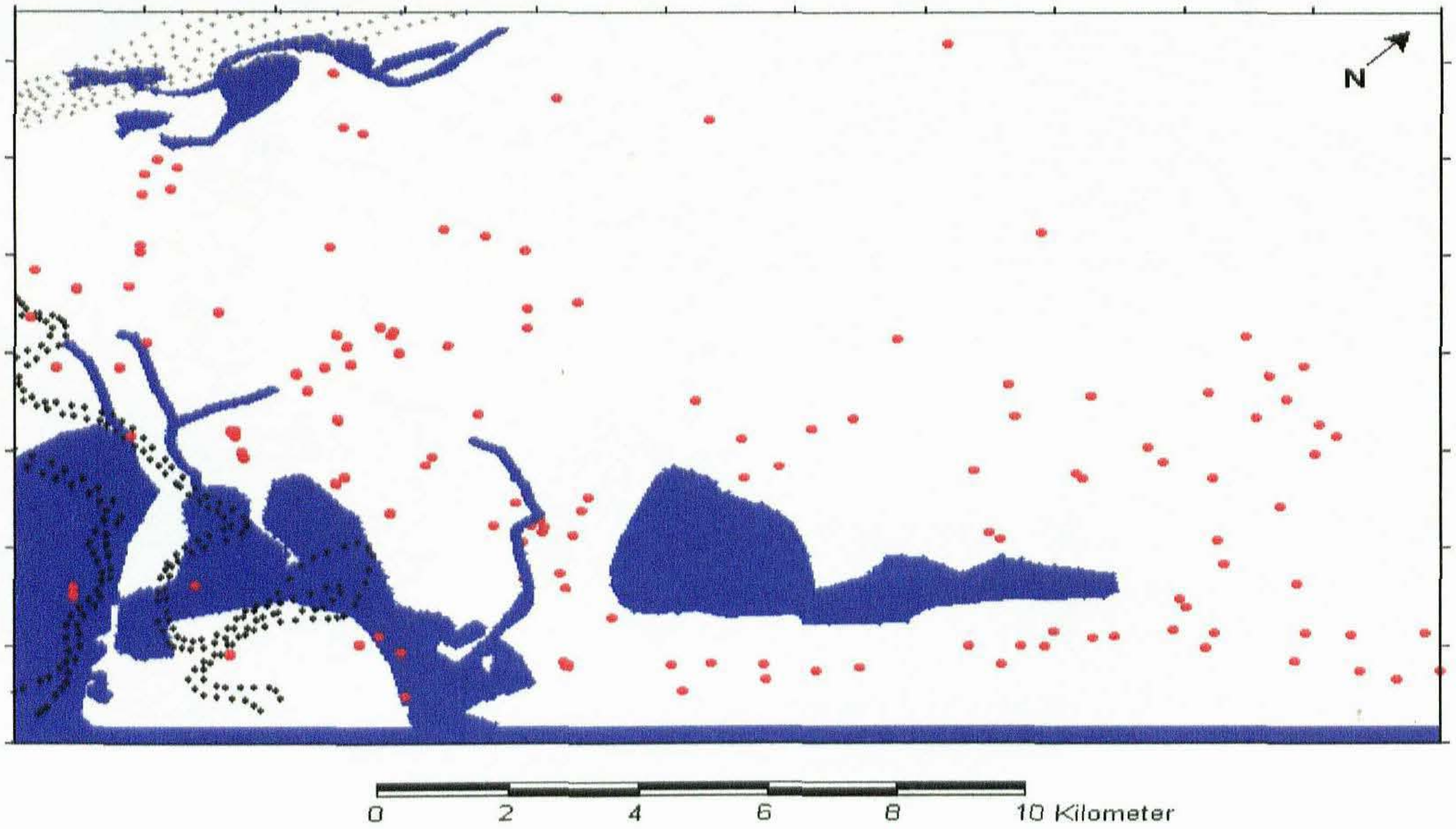

Figure 5.3 Boreholes used (red) to create the lower boundary of the aquifer. Contours (grey) are from Webb (1972). Some of the contours (black) from Worthington (1978) are also indicated.

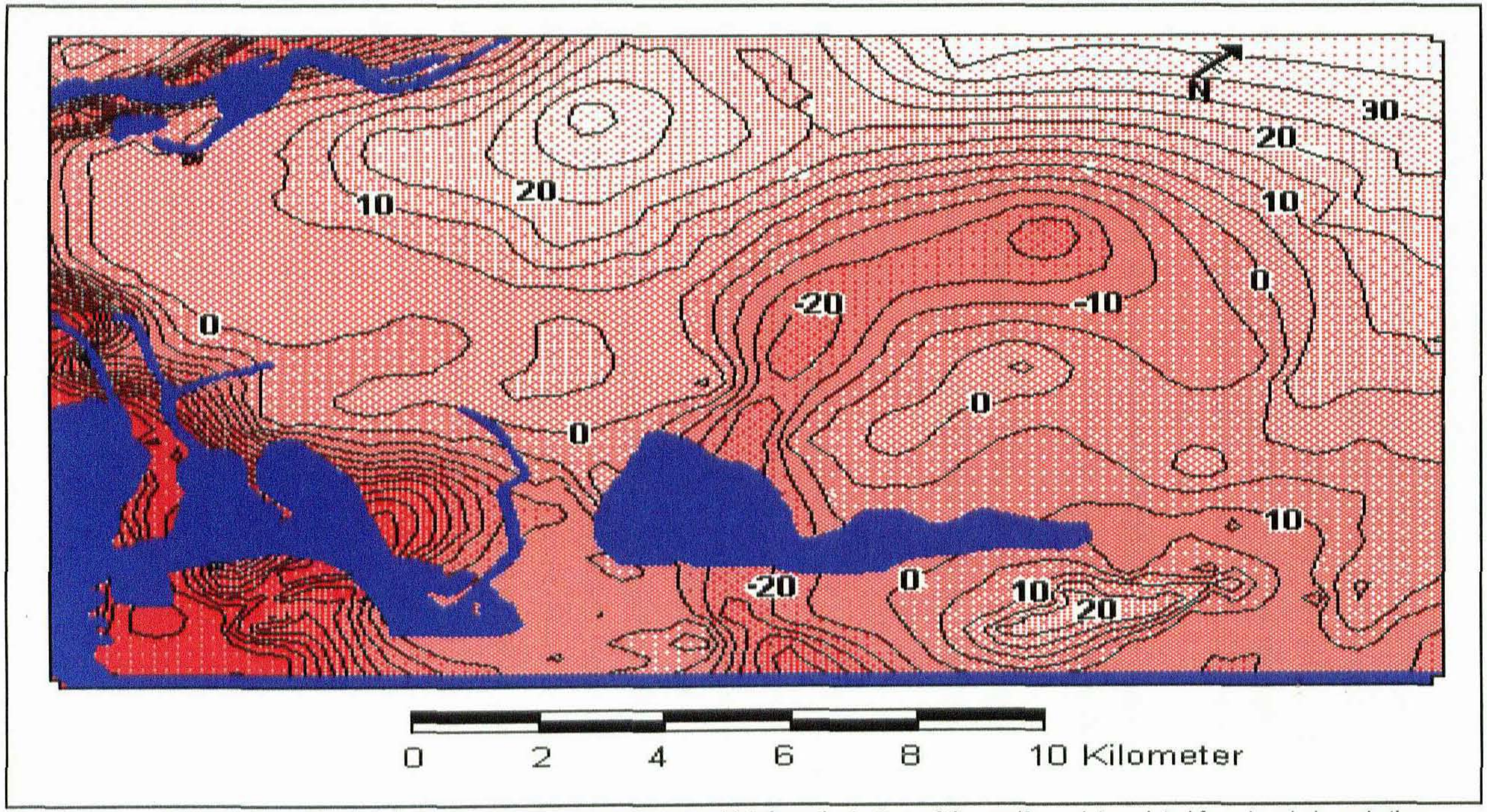

Figure 5.4 Upper surface elevation (m) of the Cretaceous sediments which form the bottom of the aquifer as interpolated from borehole and other information described in the text.

5.2.2 *APPROACH 2: HOMOGENEOUS LAYERS*

Hydrostratigraphic units were first described by Maxey (1964). A hydrostratigraphic unit represents a group of different geological features which have similar hydrogeological features. It was decided that the different geological formations of the study area could be grouped into four layers of similar hydrogeological features. The four layers chosen from the general stratigraphy and borehole information (see Figure 5.5) were:

- Layer 1: the highly permeable cover sands (Sibayi and Kwambonambi Formations),
- Layer 2: the confining argillaceous or clayey layer (Kosi Bay and Port Durnford Formations),
- Layer 3: a permeable sand layer (Umkwelani Formation), and
- Layer 4: sections of highly permeable deposits from the Miocene era (Uloa Formation).

Only the cover sands (layer 1) were considered to be present over the entire area. All the other layers are absent in certain places. The clayey deposits identified in the borehole logs, varied greatly in their spatial extent and distribution. In many borehole logs several different clay layers were indicated. This made the creation of four distinct layers a difficult task which needed careful interpolations. The procedures that were used to create a model of these layers are described below, starting from the lowest layer and working towards the top. The upper surface of a layer forms the lower surface of the layer above it and the upper surface of the top layer is the topographical surface which has been described in section 5.2.1

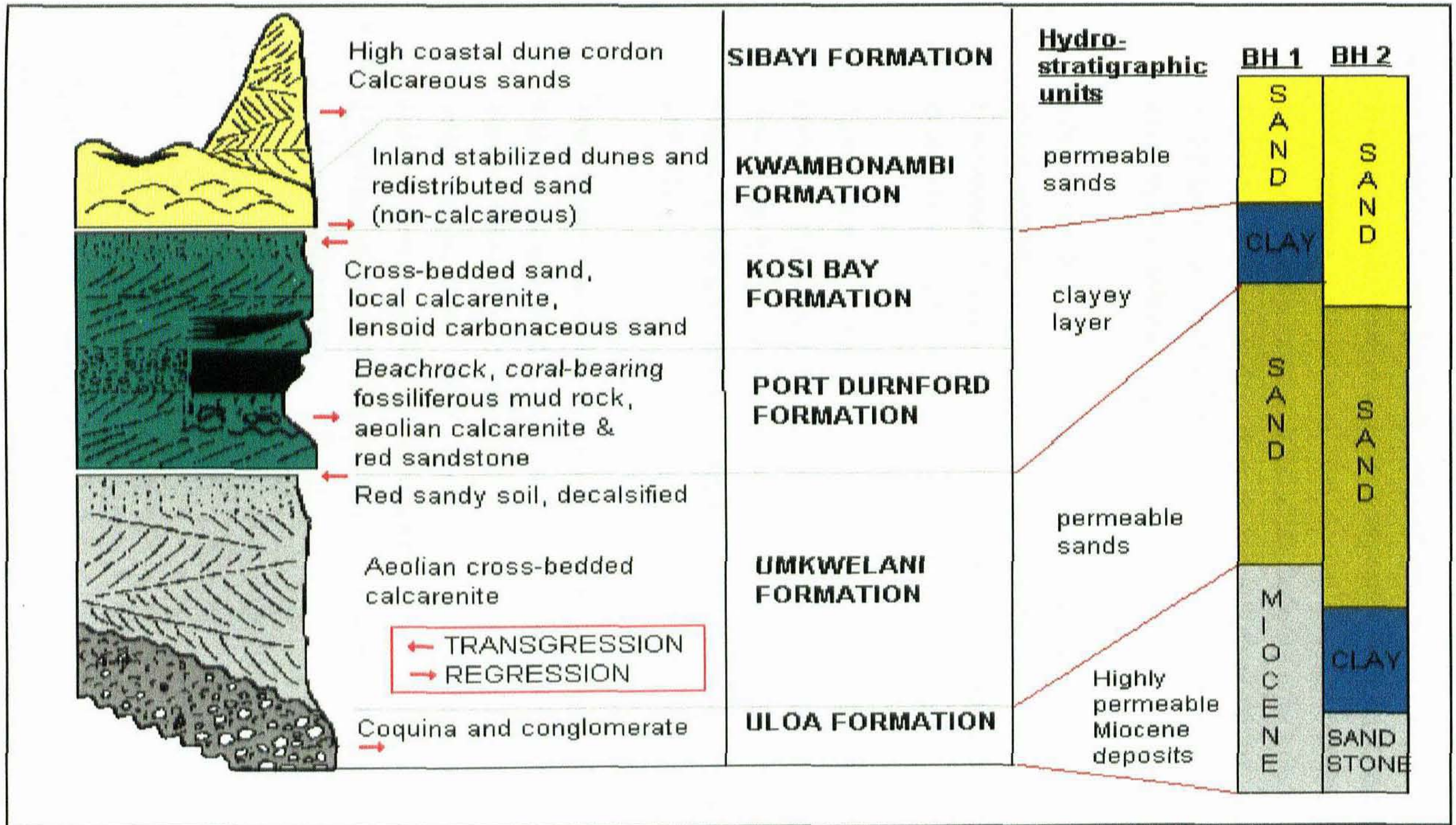

Figure 5.5 Stratigraphy as adapted from Botha (1997) and its relation to the initial conceptual model and observed borehole profiles.

•*Surface elevation of Layer Four (Miocene and Pliocene Deposits)*

The Umkwelani Formation was previously considered part of the Uloa formation and therefore most borehole logs do not distinguish between these two formations. For the purpose of this study these two units (coloured in greys in Figure 5.5) were combined to form one hydrostratigraphic unit. This layer (unit) is not continuous, but it was considered an important layer because of its relatively high permeability (Hattingh, 1996).

Where no geological data was available in the study area, particularly for the inland portion, it was assumed that the Miocene deposits are present everywhere ("?"-areas in Figure 5.6), except where rivers or streams may have eroded these deposits away.

Direct interpolation from borehole logs was found to be inappropriate in the derivation of the upper surface of this layer, because it resulted in a surface which was below the aquifer bottom for large parts of the model area. Therefore a different procedure was followed to estimate the surface elevation of this layer.

The first step was to separate the boreholes with evidence of Miocene deposits from those where the Miocene deposits were absent. These borehole locations were identified in a grid network which conformed to the one that was ultimately used in the numerical model. The study domain was represented by 66 x 45 cells and each borehole was identified with a single cell. The surface elevation of layer four (Figure 5.8) was estimated using these boreholes in a spreadsheet in the following manner:

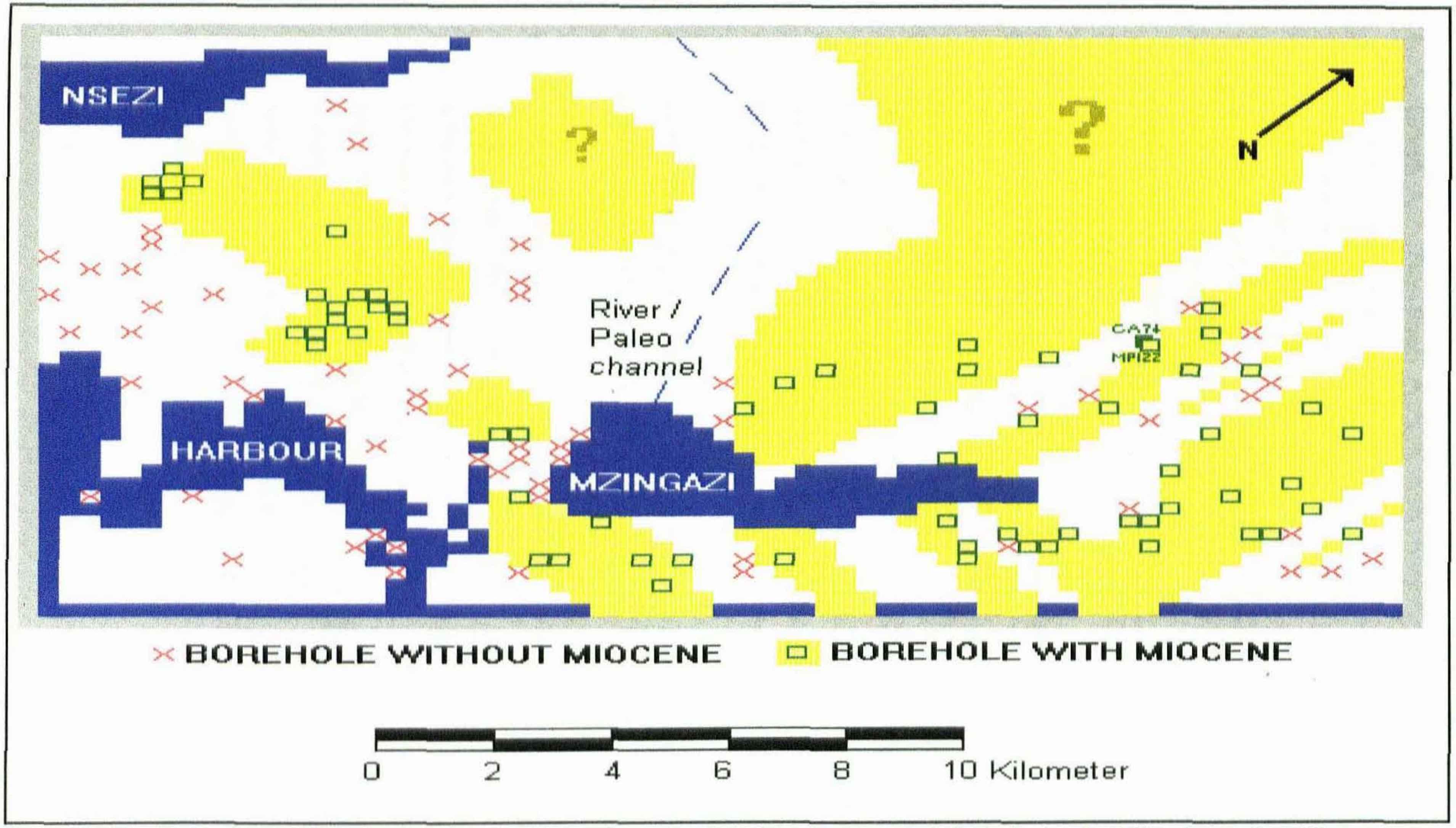

Figure 5.6 Presence of the Miocene deposits as interpolated from borehole data. Red crosses indicate the location of boreholes where Miocene deposits are absent and the green blocks indicate the location s of boreholes where Miocene deposits are found

- Sheet A: The final SURFER grid file of the bottom of the aquifer was opened in a spreadsheet so that each spreadsheet cell represented a model grid node.

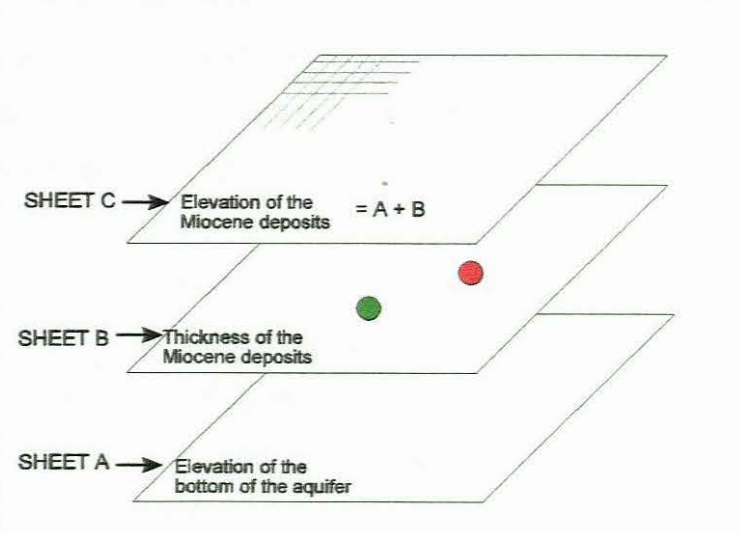

Figure 5.7 Visual representation of procedure followed on a spreadsheet

- 72 boreholes indicated the presence of Miocene deposits. The thickness of the Miocene layer in each of the 72 points, was then assigned to the nearest node point (cell) and marked in green on sheet B of the spreadsheet as shown in Figure 5.7. This sometimes resulted in more than one data point for a single cell, in which case average thicknesses were used.

- A thickness of 0 was added where the Miocene was indicated absent in the 69 points marked (X) in red in Figure 5.6.

- Sheet B: From this information the thickness was then interpolated so that it became thinner near areas with no Miocene deposits. Table 5.1 indicates the interpolation between a few boreholes and Figure 5.6 shows the results of this interpolation, the yellow areas indicating the suggested presence of Miocene deposits.

			0		0	0	0
		2		1	0	0	0
3	3	3	2	1	1	0	0
4	4	4	3	2	1	0	0
5	5	4	3	2	1	0	0
6	5	4	3	2	1	0	0

Table 5.1 Interpolation of thickness

- Refinement of the layer surface was based on the suggestions that these *Miocene deposits could be reef relics or step faults (Hattingh et al, 1995), which* were assumed to have a fairly uniform orientation. The interpolated cells were grouped subjectively along a N-S axis (Figure 5.6) .

- The possible removal of the Miocene by drainage erosion during more recent times was inferred by assuming that no Miocene deposits were present in areas associated with the erosion channels (Figure 5.6 - the white area between uncertain "?"-areas). This area includes deep Paleo-channels (compare with Figure 5.4) and present surface streams.

- <u>Sheet C:</u> The thickness of the Miocene deposits (from sheet B) was added to the Cretaceous elevation (from sheet A) for each cell. This resulted in a grid file for the upper surface elevation of the Miocene deposits.
  The resulting surface profile of the Miocene deposits is shown in Figure 5.8.

•*Surface elevation of Layers Two and Three*

Much time and effort was spent trying to create the other layers in a similar manner, but the lack of uniformity in geological logging and the very large variability in the logs made it an extremely difficult task. Several practical problems were encountered with fitting real data into this layered model. A set of rules were followed when it was not clear to which layer a specific description belonged:

a) In many boreholes only sand was observed above the Miocene (or Cretaceous) deposits and it was assumed that Layer 2 was absent in these locations. In order to create four layers for this modeling approach, the sand was divided into layers of equal thickness to form Layers 1 and 3. Layer 2 was reduced to a minimum thickness of 0.001m in these places.

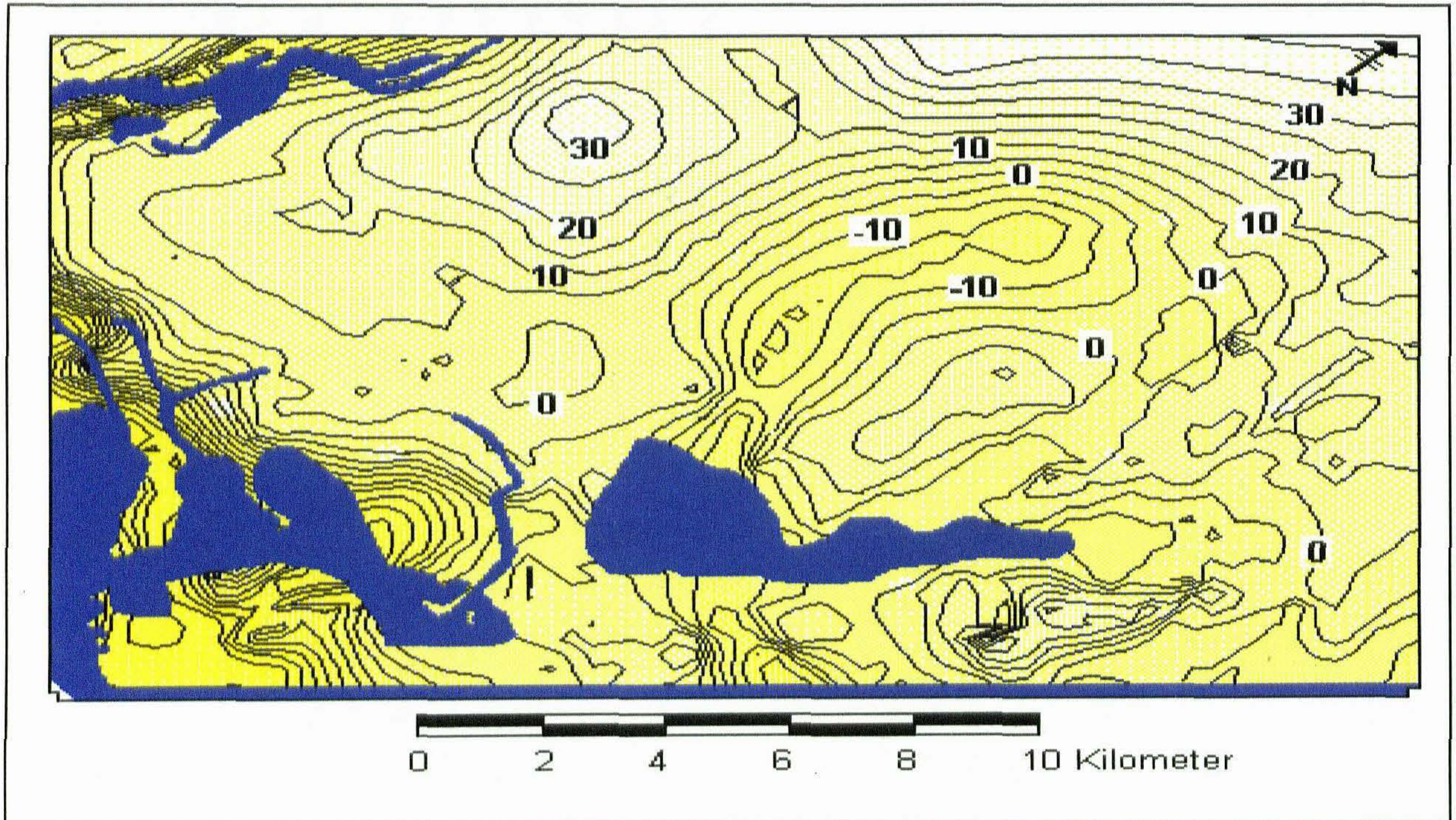

Figure 5.8 Surface profile of the upper Miocene deposits after interpolation.

b) In places where more than one clay layer was separated by sand, only one of them was assigned to Layer 2. Nearby boreholes were used to determine which clay layer was most likely to form part of a more widespread layer of clay.

c) Where there was a single clay layer situated at the surface, it was assumed that there were no cover sands at the specific location. In these locations Layer 1 was reduced to a minimum thickness of 0.001m.

SURFER was used for interpolation of layer elevations between boreholes. These interpolations were checked at each grid point to ensure that none of the layers overlapped as a result of the spatial interpolation. The upper surfaces for layers 3 and 2, after interpolation, can be seen in Figures 5.9 and 5.10 respectively.

5.2.3 APPROACH 3: HETEROGENEOUS LAYERS

Because of the difficulties with the second approach and because of the discontinuous nature of these layers, it was decided to try a different approach. This approach was to create three layers of approximately equal thickness in each vertical column and then assign a spatially variable hydraulic conductivity within each layer. For this process each borehole was studied individually in order to create the variability. Note that this method does NOT follow the more common approach of hydrostratigraphic units which leads to hydrologically uniform (homogeneous) layers.

The study area was subdivided into three layers of almost equal thickness in each vertical column. Figure 5.11 illustrates that a layer can vary in thickness, but the thickness in any point is close to a third of the thickness of the aquifer at that point.

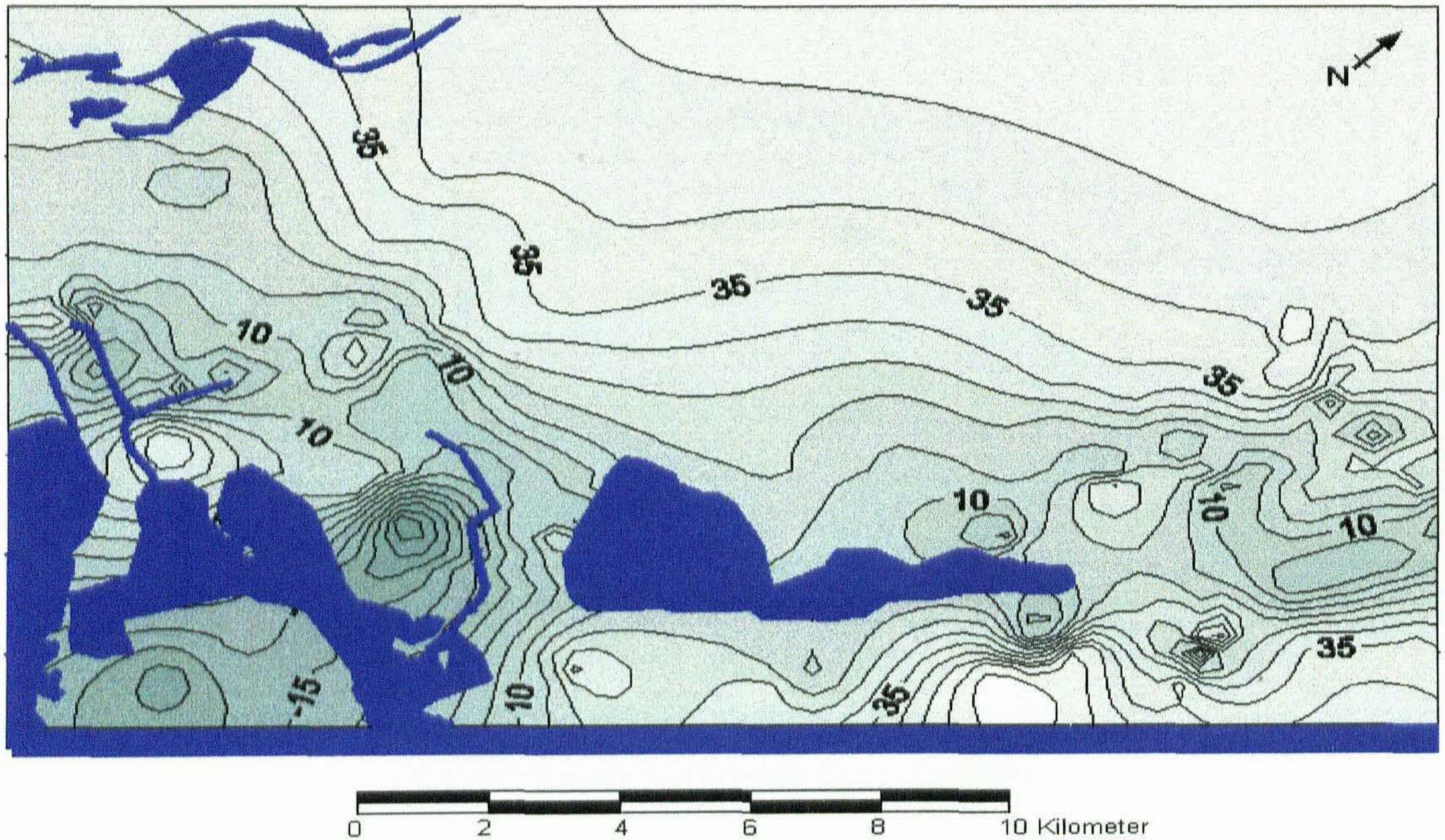

Figure 5.9 Upper surface of Layer 3

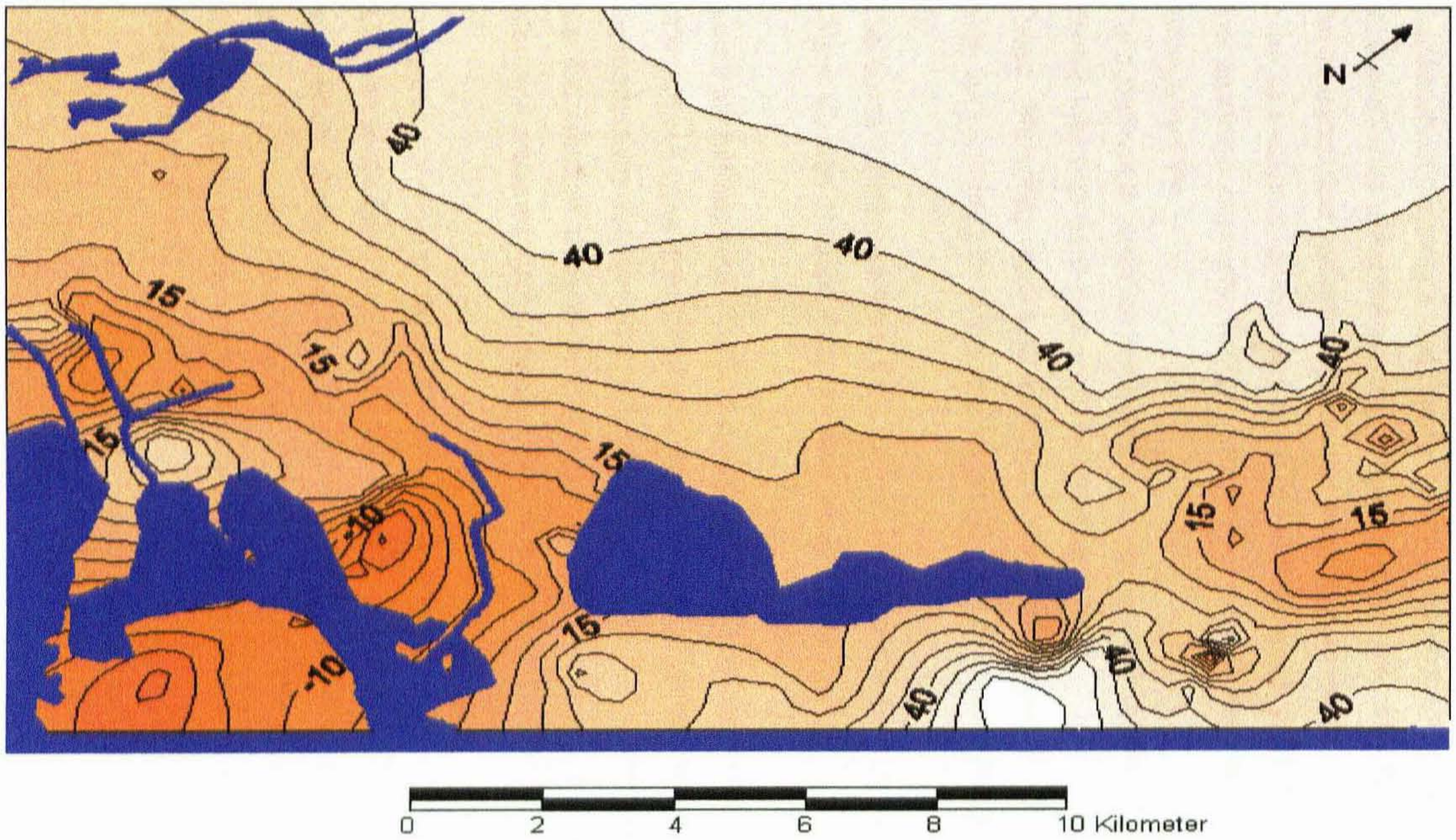

Figure 5.10 Upper surface of Layer 2

Another spreadsheet procedure (see Figure 5.12) was developed to create the elevation of each of these layers using the same grid spacing as for the other approaches:

- The topographical surface elevation was created in a spreadsheet so that each cell in the spreadsheet represented a grid cell of the numerical model.
- The aquifer bottom was created in a similar way on the second sheet of the spreadsheet file.
- The difference in elevation between the two surfaces (thickness of the aquifer) was divided into 3 for each grid point (spreadsheet cell).
- These differences were then subtracted from the topographical surface grid for each spreadsheet cell to form the bottom surface of Layer 1 (top surface of Layer 2).
- The same differences were then added to the aquifer bottom value to form the bottom surface of Layer 2 (top surface of Layer 3).

To represent the heterogeneity in hydraulic features in these layers that are represented by the different soil types present in each borehole log, a value was calculated for the hydraulic conductivity at each grid point and for each layer. The remainder of this section describes the creation of spatially variable hydraulic properties based on borehole information and assumed hydraulic properties for each formation encountered.

An example of a borehole profile (thickness and lithology) is given in the first section of Table 5.2. The second section of Table 5.2 shows the assumed ("equal") layers together with the borehole profile (depth thickness and soil type) and the assumed hydraulic conductivity for each soil type. The last column of Table 5.2 is the calculated average hydraulic conductivity for each of the layers for the borehole according to the procedure shown in Figure 5.12.

Borehole X (profile)	
Depth profile (m from top)	**Soil type**
0 - 7	Sand
7 - 12	Clay
12 - 15	Sand
15 - 22	Clay
22 - 28	Clay
28 - 30	Miocene deposits

Borehole X (subdivided profile)					
Layer	**Depth (m from top)**	**Thickness (m)**	**Soil type**	**Assumed Hydraulic conductivity (m/day)**	
1	0 - 7	7	Sand	25	20.5
	7 - 10	3	Clay	10	
2	10 - 12	2	Clay	10	14.5
	12 - 15	3	Sand	25	
	15 - 20	5	Clay	10	
3	20 - 22	2	Clay	10	13.6
	22 - 28	6	Clay	10	
	28 - 30	2	Miocene deposits	28	

Hydraulic conductivities for each layer at position X:

L1 = {(7*25)+(3*10)}/10 = 20.5 m/day
L2 = {(2*10)+(3*25)+(5*10)}/10 = 14.5 m/day
L3 = {(2*10)+(6*10)+(2*28)}/10 = 13.6 m/day

Table 5.2 Example of borehole information as used in a spreadsheet to calculate average hydraulic conductivities for pre-set layers

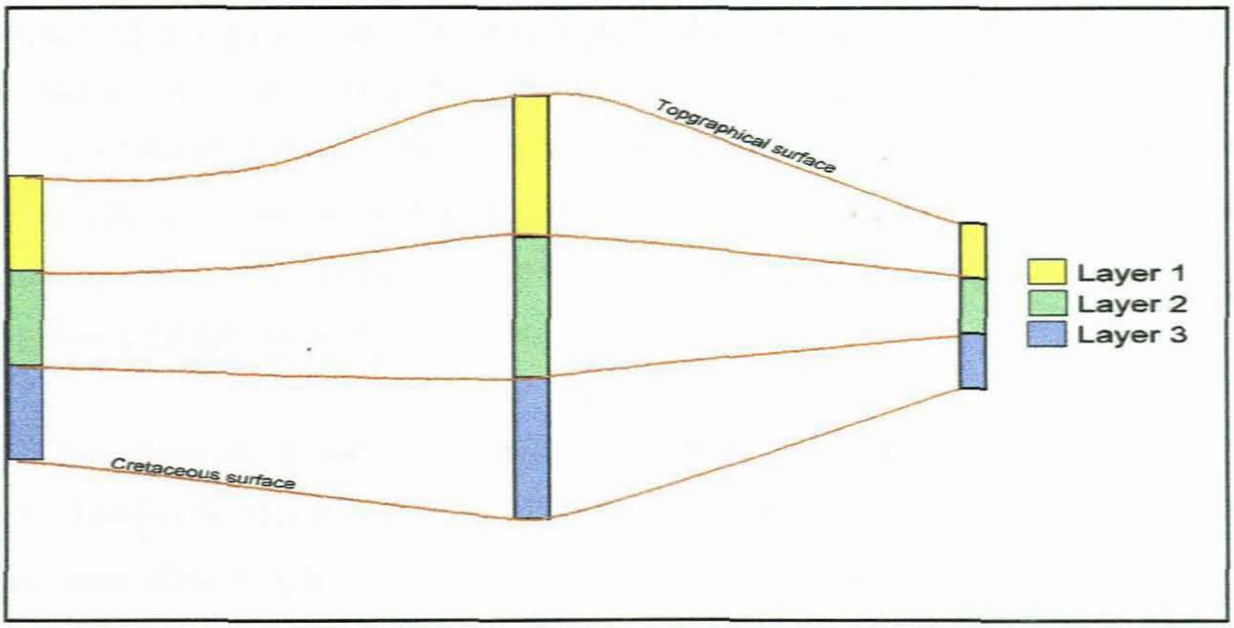

Figure 5.11 Layers with equal thickness in each vertical point

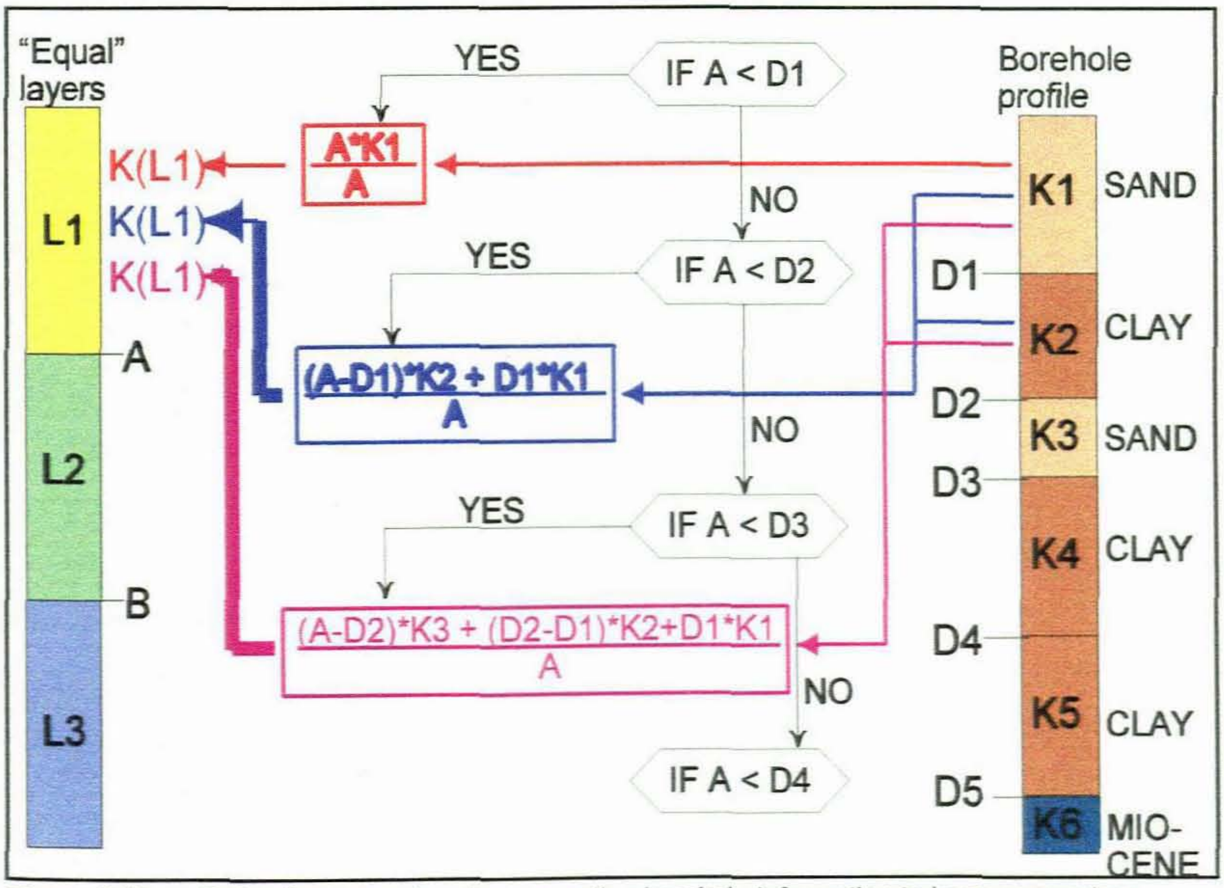

Figure 5.12 Estimation procedure for connecting borehole information to layer parameters. K=Permeability, D=Depth, L=Layer and A=Depth of layer 1.

Figure 5.12 is a diagrammatic representation of the procedure followed to calculate an average hydraulic conductivity for layer 1 for the illustrated borehole. The right hand side indicates a typical borehole log which has been categorised by hydraulic parameter K_i. On the left hand side the same profile thickness has been divided into the three equal depth layers (L_j). The procedure for deriving the hydraulic parameter $K(L_j)$ is also shown in Figure 5.12 with an example in Table 5.2.

This procedure was repeated for each layer and for all the boreholes available. The calculated hydraulic conductivity ($K(L_j)$) was assigned to the relevant borehole positions and interpolated using SURFER (Keckler, 1994), to get a spatial distribution for each layer.

6 NUMERICAL MODEL

Water resources are frequently analysed using numerical simulation models because of the extreme complexity of non-linear processes and interactions which make it difficult to adopt physical or empirical models for all but the simplest situations. There is a huge range of numerical models which have been grouped into several classes that include multi-dimensional deterministic models and stochastic models. The multi-dimensional models can be subdivided into both steady state and dynamic systems in 1- 2- or 3-dimensions.

In groundwater systems there is usually an assumption of greater uniformity and homogeneity than in surface water systems, because of the lack of information on the variability of the system. 2-Dimensional, 3-dimensional and quasi 3-dimensional models are often used to simulate flow conditions. Verwey and Botha (1992) did a comparative study of 2- and 3-dimensional models. There are numerous 3-dimensional finite difference and finite element models (see Table 6.1) which have been developed for application in field conditions. Some of these have been applied in regional studies in the Zululand region. Kelbe and Rawlins (1992), Kelbe, Rawlins and Nomquphu (1995) and Rawlins and Kelbe (1991) have used the INTERSAT model (Voorhees and Kirkner, 1987) to investigate the influence of proposed developments on groundwater systems as part of Environmental Impact Assessments in Zululand. Although there is very little difference between the numerical concepts of INTERSAT and MODFLOW (McDonald and Harbaugh, 1983), the latter was chosen for this study because it is generally recognized as the industry standard and has good support from the developers. Many researchers and/or developers have added pre-and post-processing functions for MODFLOW (see Table 6.1). One such model, Visual MODFLOW (Guiguer and Franz, 1996) has been obtained for this study and applied to model the groundwater system of the Richards Bay area. Extra modules for MODFLOW have also

FULL NAME	Type	Engine	2D / 3D
ASM	FD	ASM	2D
PLASM	FD	PLASM	2D
INTERSAT	FD	INTERSAT	Quasi 3D
Visual MODFLOW	FD	MODFLOW	Quasi 3D
Processing Modflow for Windows (PMWin)	FD	MODFLOW	Quasi 3D
Groundwater Vistas	FD	MODFLOW	Quasi 3D
ModIME	FD	MODFLOW	Quasi 3D
MS-VMS	FD	MODFLOW	Quasi 3D
Modflow Integrated Modeling Environment	FD	MODFLOW	Quasi 3D
ModelGIS	FD	MODFLOW	Quasi 3D
Groundwater Modelling System (GMS)	FE/FD	More than one	3D / Q3D
Argus Open Numerical Environment	FE/FD	More than one	3D / Q3D
FEMWATER	FE	FEMWATER	3D
AQUIFEM	FE	AQUIFEM	3D
AQUA3D	FE	AQUA3D	3D
MICRO-FEM	FE	MICROFEM	3D
AQUAMOD for Windows	FE	AQUAMOD	2D
SUTRA	FE	SUTRA	2D

Table 6.1 Groundwater models considered for application in this study

been developed to expand the functionality of the system e.g. the Lake Package that simulates lake level fluctuations by Council (1997).

This chapter presents a summary of the theoretical basis of the MODFLOW programme because an understanding is necessary for parameter estimations and the assignments of boundary conditions. The application involves the additional development of several conceptual models of some surface-groundwater interactions, such as the vertical recharge rate to represent the surface boundary conditions.

6.1 STRUCTURE OF THE MODEL

MODFLOW is designed to simulate geohydrological flow conditions in a saturated porous media and to determine the water balance of aquifer systems that include the effects of groundwater extraction. The model is capable of solving multi-layer three-dimensional problems using a variable grid network which allows for increased spatial resolutions of specific points of interest.

The MODFLOW groundwater model describes the subsurface hydraulics using the finite difference linearization approach to solve the groundwater flow equations based on the quasi three-dimensional vector volume shown in Figure 6.1. The finite difference approach upon which the MODFLOW model is based, is a combination of Darcy's Law of motion under saturated conditions and the Continuity Principle. Darcy's Law states that in an isotropic medium (cell) the specific flow rate is proportional to the negative head gradient (∇**h**).

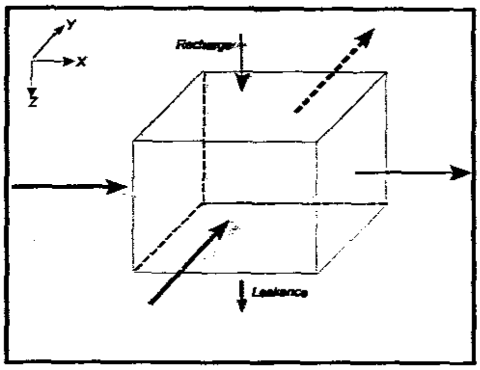

Figure 6.1 Quasi 3D vector volume (cell)

$$\overline{V} = -K\nabla h \qquad (1)$$

where

$\overline{V}$ = (V_x, V_y, V_z) is the velocity field

∇ = $\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}$, the gradient

K = hydraulic conductivity

h = head

The Continuity Principle states that the rate of change of storage at any instant in time is given by:

$$\frac{dS}{dt} = I - O \qquad (2)$$

where S = specific storage of the porous material

t = time

I = rate of inflow

O = rate of outflow

From equations (1) and (2) the flow equation can be written as:

$$\nabla(K\nabla h)-Q_v=S(\frac{\partial h}{\partial t}) \qquad \text{.................................(3)}$$

where Q_v is the sink/source term in the vertical direction.

The flow equation above can be solved analytically only under very simple idealistic conditions. The solution generally requires discretization in space and time with mathematical iteration to achieve solution convergence.

6.2 HORIZONTAL DISCRETIZATION

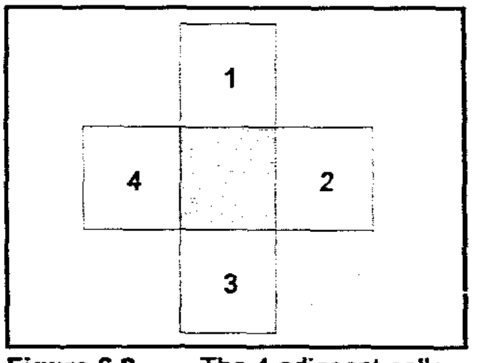

Figure 6.2 *The 4 adjacent cells from where flow is calculated for the central cell (grey)*

In a finite-difference model, the model domain is divided into a grid of rows, columns and layers which form rectangular cells. Within each cell there is a node at which the head is to be calculated. MODFLOW uses the block-centred formulation whereby the nodes are at the centre of the cells. In a one layer model, each non-border cell has four adjacent cells, this increases to six adjacent cells if there is a layer above and a layer below the central cell. For each cell Darcy's Law (equation 1) is written for flow to or from the 4 horizontally adjacent cells (Figure 6.2). Flow to and from the 2 vertically adjacent cells are calculated as a leakance (section 6.3). The sum of all these flows from adjacent cells and external sources must be equated to the rate of change in storage within the cell (equation 2).

In MODFLOW, the term $\partial h/\partial t$ is approximated over a time interval which starts at time **t** and extends backwards to time **t-Δt** (see Figure 6.3). This backward-difference approach is used because it is numerically more stable than other methods (McDonald and Harbaugh, 1983).

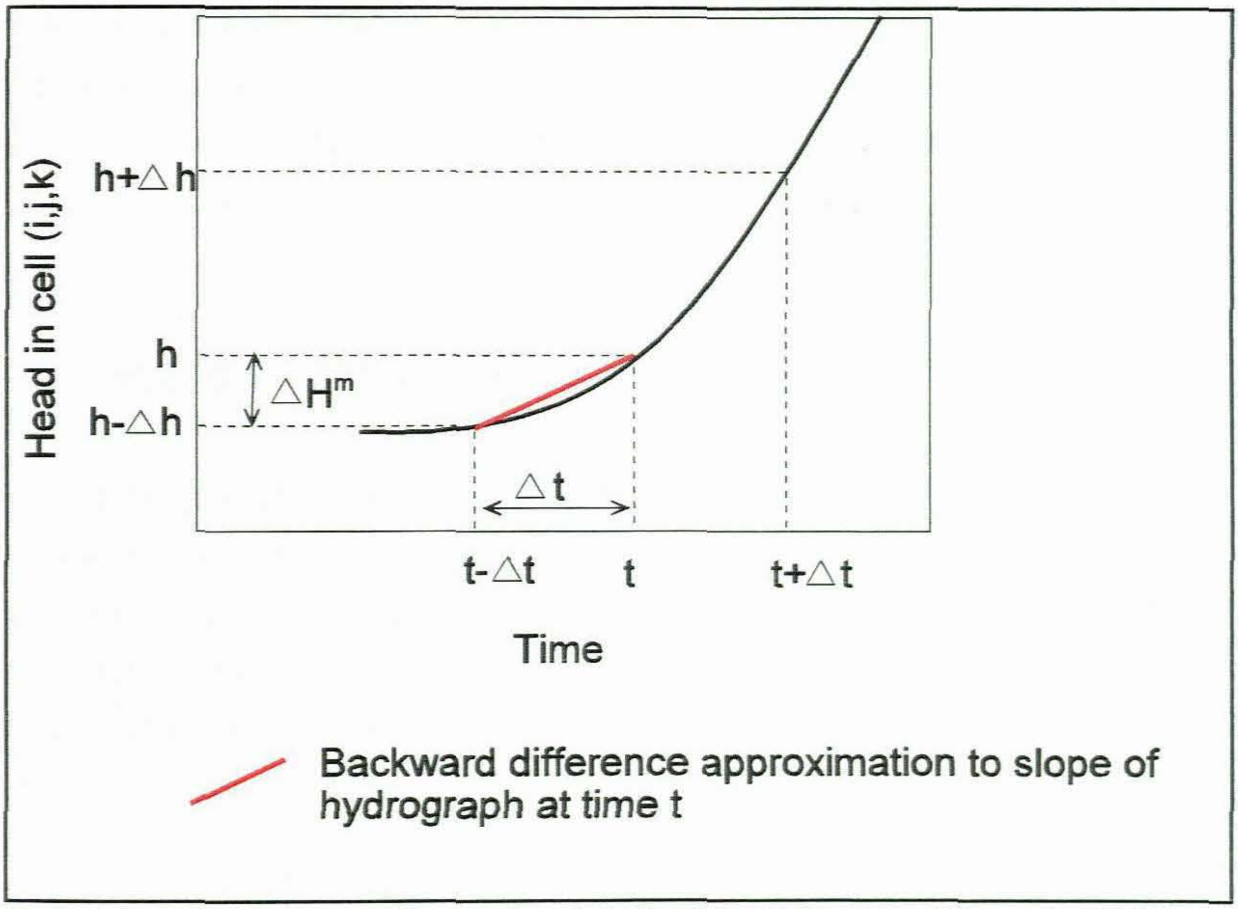

Figure 6.3 The backward-difference time derivative (after McDonald and Harbough, 1983)

The flow equation (equation 3) is written for every cell and solved simultaneously for the heads at the end of the first timestep. The Heads at the end of the timestep make up the unknowns, while the heads at the beginning of the first timestep are the user specified starting heads. Once the heads have been calculated for the end of the first timestep, the process is repeated for the next timestep. The newly calculated heads for the end of the previous timestep are used as starting heads for the next timestep.

Iterations within a timestep start by assigning a trial value for head at each node at the end of that timestep. These estimated values are altered by an iterative procedure of calculations that produce a new set of head values which are in closer agreement with the system of equations. This process is repeated by using the new set of heads as starting values. When changes between successive iterations become smaller than the head change criterion, specified by the user, the iterations stop and the head is assumed to have achieved sufficient convergence.

These equations and iterations solve for the horizontal advection. Vertical fluxes are described in equation 3 by the term $\mathbf{Q_v}$. The vertical component is added or subtracted as a linear storage term and must be determined in separate modules (packages) as specific boundary conditions.

6.3 VERTICAL DISCRETIZATION

MODFLOW consists of several packages to solve different hydrological processes representative of different boundary conditions. There may be more than one package to model a specific hydrological process and the user specifies which of these packages will be used. Table 6.2 list the normal packages which can be used in MODFLOW. The packages that are used to represent specific boundaries in this study, are discussed in more detail in the following sections

6.3.1 RIVER PACKAGE (RIV)

The river package simulates effects of flow between surface water features and the groundwater system. It can be used to simulate rivers, streams or lakes. The package assumes a vertical flux across a head gradient separated by a conducting layer. This conducting layer can be visualized as a layer of lower hydraulic conductivity which separates the surface water from the groundwater (Figure 6.4).

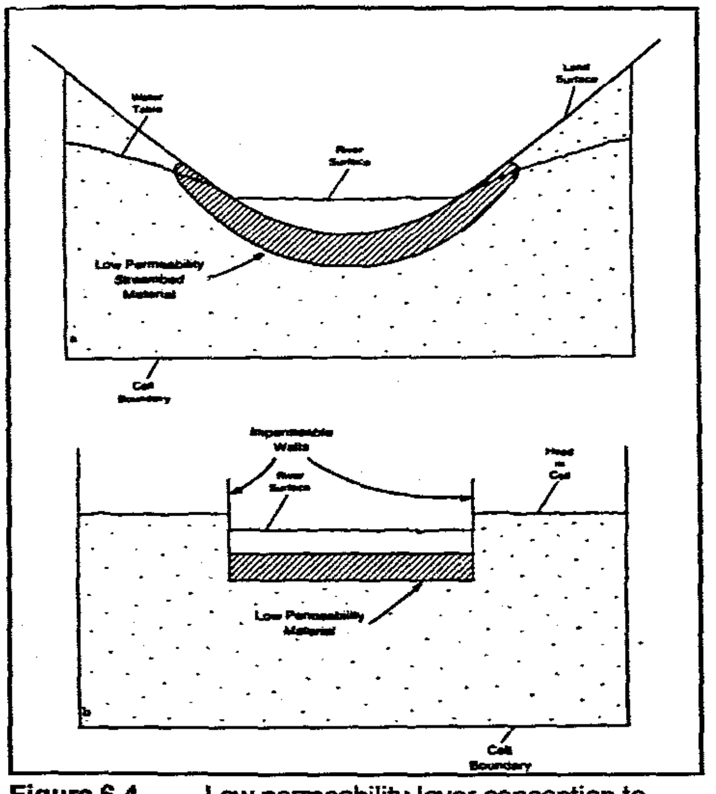

Figure 6.4 Low permeability layer conception to model rivers and drains.

The rate of conductance is dependent on the area, thickness and hydraulic conductivity of the layer between the surface water and groundwater system according to equation 4.

Package Name	Package Description
Basic	Defines and sets key model parameters such as the grid and boundaries
Block-centred Flow	Sets grid parameters and calculates the conductance between cells (i,j,k)
Numerical Iteration Solvers	
SIP	Strongly Implicit Procedure Iterative solution
SOR	Slice successive Over-Relaxation Iterative
PCG2	Preconditioned Conjugate Gradient
Modflow Packages	
Recharge (RCH)	Determines the rate of recharge to groundwater
Evapotranspiration	Determines vertical evaporation fluxes
River (RIV)	Determines flow into river nodes within cells.
Drain (DRN)	Determines flow out of drains into cells.
Well (WEL)	Specifies flow to wells
General-head boundaries (GHB)	Specifies conductance between external sources and the cell
Separate packages from other developers	
Reservoir (RES1)	Simulates large water bodies (Fenske *et al*, 1996)
Lake Package (LAK1)	Simulates fluctuating lake levels (Cheng and Anderson, 1993)
Lake Package (LAK2)	Simulates fluctuating lake levels (Council, 1997)
Stream Routing (STR)	Routes flow down a river (Prudic, 1989)

Table 6.2 *List of packages available with Modflow 96 (McDonald and Harbough, 1983)*

$$C = \frac{KLW}{M} \qquad \text{.....(4)}$$

where

C = riverbed conductance
K = hydraulic conductivity of intervening layer
L = length of river as it crosses the node
W = width of river
M = thickness of the intervening layer

Based on this conceptual model, the flow between the river and the groundwater system is given by:

$$Q = C(H_{riv} - h_{i,j,k}) \qquad \text{.....(5)}$$

where

Q = flow between the river and the aquifer
C = riverbed conductance
H_{riv} = head in the river
$h_{i,j,k}$ = head in the node of the cell underlying the river

Depending on the head gradient between the surface- and groundwater, the river can either contribute water to the groundwater system or drain water from it.

6.3.2 DRAIN PACKAGE (DRN)

The drain package uses the same assumptions as the river package but is constrained by the condition that it has no effect when the aquifer head drops below the drain elevation. In other words, when using the drain package, water can flow from the aquifer into the drain, but not from the drain into the aquifer. The drain does not occupy a cell as a whole, but assumes that the drain head prevails only locally within the cell (Figure 6.5).

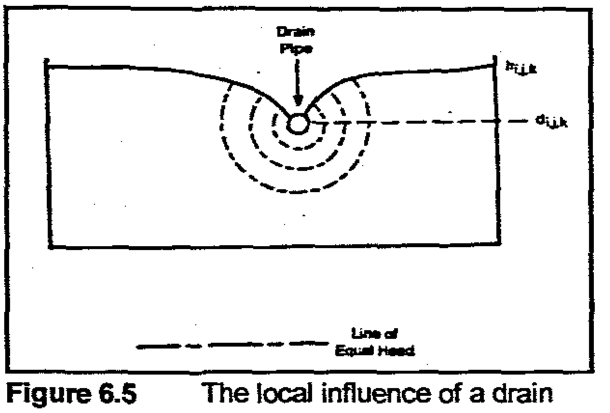

Figure 6.5 The local influence of a drain cell

6.3.3 RECHARGE PACKAGE (RCH)

This package simulates spatially distributed recharge to the groundwater system. It is calculated as a vertical flux multiplied by area of the cell and forms one component of Q_v in equation (3). In Visual MODFLOW one can specify whether the recharge must be applied to the top layer only or to the highest active cell. MODFLOW has one extra option that allows the recharge to be applied to any cell in the vertical column.

In this study the recharge is assumed to be equivalent to percolation and therefore it does not correspond directly to rainfall. Groundwater can contribute to evapotranspiration when plants are in hydraulic contact with the groundwater through the capillary fringe. Concequently, the recharge component needs to include the evapotranspiration component if the evapotranspiration process forms part of the simulation model. The calculation of the recharge component is based on a conceptual model of hydrological processes that are discussed in section 6.5

6.3.4 EVAPOTRANSPIRATION PACKAGE (EVT)

Plant transpiration and direct evaporation from the saturated zone is simulated by the evapotranspiration package. Since there are several different definitions of evaporation, it is important to identify the ones that are relevant to this study. Actual evaporation refers to the amount of water converted form the liquid phase to the vapour phase and removed from the system by atmospheric processes. This can occur at bare surfaces when liquid water is in hydraulic contact with the surface and through transpiration from within the rooting depth of the soil. The simulation is based on the

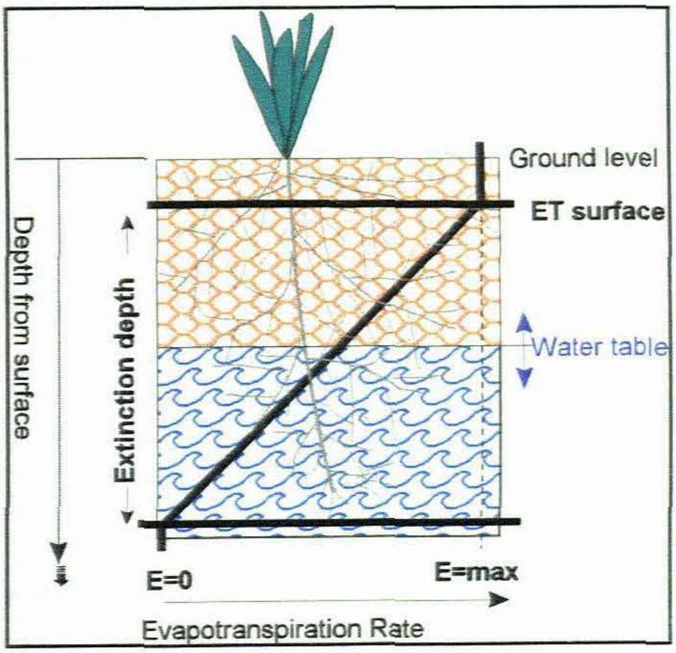

Figure 6.6 MODFLOW's evapotranspiration model

following assumptions that are illustrated in Figure 6.6:

- when the water table reaches the evapotranspiration surface, water table losses occur at a maximum rate specified by the user,
- when the water table is at or below the specified extinction depth below the evapotranspiration surface, evapotranspiration ceases
- if the water table is anywhere between the above two limits, evapotranspiration varies linearly in relation to the water table elevation.

Plant roots may penetrate several model layers and thus evapotranspiration may occur from more than one layer. However, in MODFLOW the user must specify one layer from which evapotranspiration will take place, while Visual MODFLOW assumes that evapotranspiration occurs only from the upper layer.

6.3.5 THE BLOCK CENTERED FLOW PACKAGE (BCF)

During the iteration process to solve the differential flow equation, the head is calculated for each cell in each timestep. It may happen that the head can drop below a cell bottom, in which case the cell becomes a dry cell. Once a cell becomes dry, it acts as an inactive cell and cannot hold or receive water again. McDonald *et al* (1991) upgraded the BCF package for MODFLOW to include a cell-rewetting option (BCF2). This option allows no-flow or inactive cells to be re-wetted. When the cell-rewetting option is activated, the user specifies whether a cell-rewetting factor or a cell-rewetting threshold will be used. In both cases cells may be re-wetted from the sides only, or from the sides and below. This feature is very important in aquifers where the water table may fall below the top layer in some places during drought periods.

6.4 MODELLING OF LAKES

Lakes can be modelled in many different ways depending on the purpose of the study:

- Kinzelbach (1986) implies that lakes should be modelled as constant heads, in which case pathlines will stop at the edge of the lake.

- Guiguer and Franz (1996) recommend the river package to model lakes and other surface water bodies. This option ensures that there is movement of water below the lake, which may be critical in some studies.
- Additional packages and models have been developed to model lakes. Cheng and Anderson (1993) developed a lake package (LAK1) for MODFLOW which could simulate varying lake levels. This package was upgraded (LAK2) by Council (1997) who included some of the features of another package (RES1) developed by Fenske *et al* (1996).

6.5 RECHARGE AND EVAPOTRANSPIRATION

It is important to distinguish between total recharge and net recharge. Most calculations of recharge in the literature use net recharge (Bredenkamp *et al*, 1995, Meyer and Godfrey, 1995 and Worthington, 1978). However, if the modeller plans to use the evapotranspiration package in MODFLOW, care must be taken when estimating recharge. In this case study the total recharge must be used in the recharge package, since some of that recharge will be lost to evapotranspiration. That means recharge (percolation) has to be estimated from rainfall and other surface and sub-surface processes (shown in Figure 6.7), excluding evapotranspiration from the water table.

Bredenkamp *et al* (1995) have presented many methods for groundwater recharge which relate primarily to lumped models. Meyer and Godfrey (1995) estimated recharge from rainfall using a chloride tracer and Worthington (1978) used a series of equations to calculate first runoff and then recharge from other known parameters. All these methods use net recharge. Rawlins and Kelbe (1991) have presented a simple groundwater recharge model which was based on observations of ground water response to individual daily rainfall events at St Lucia.

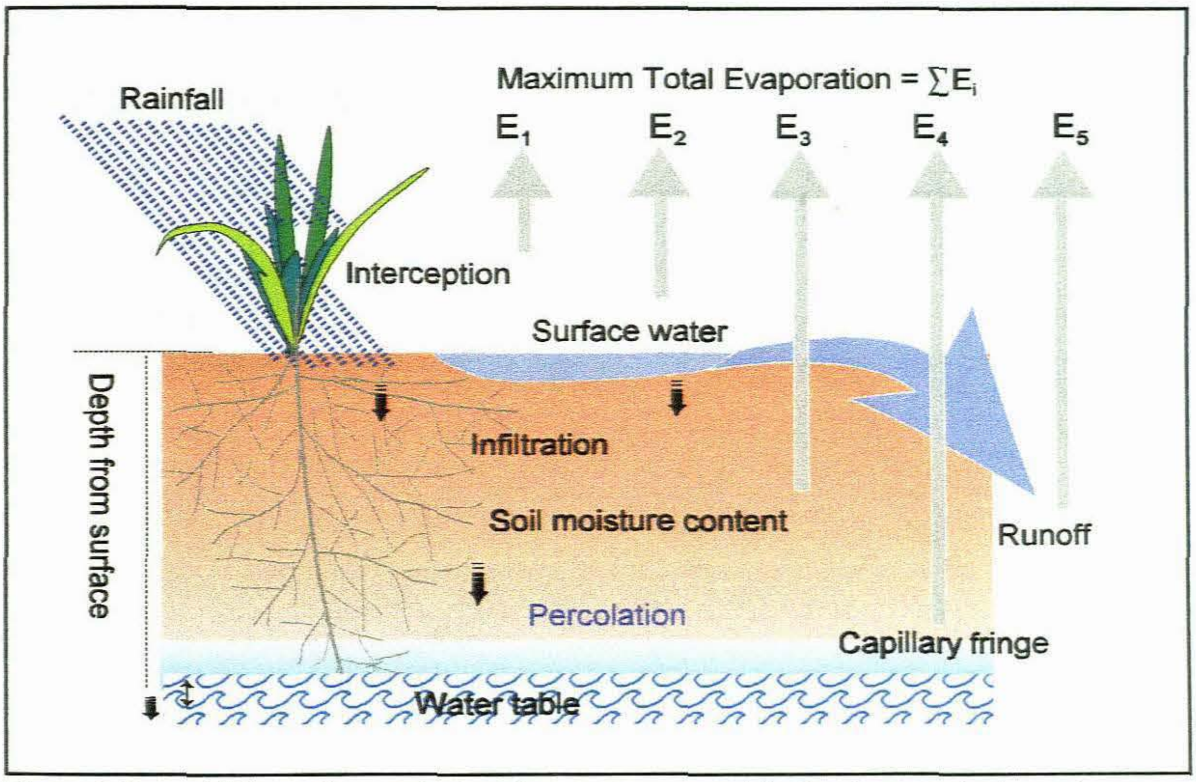

Figure 6.7 All the surface and subsurface processes contributing to groundwater recharge

Their recharge model incorporates the effects of antecedent depletion of soil moisture content by assuming that the soil moisture was depleted through evaporation at about 2mm/day. This assumes that it would take five days to deplete a rainfall infiltration of *10mm. Thus 10 mm of rainfall is required before groundwater recharge will occur.* To calculate the effective groundwater recharge on a specific day, the following assumptions (illustrated in Figure 6.8) were made:

- No rainfall on the day (R_0) means no recharge to the groundwater.
- Less than 10 mm of rainfall (R_i) proportionally weighted (w_i) over a five day period ending on the model day, will not contribute to groundwater recharge.
- More than 50 mm of rainfall proportionally weighted over the five day period, contributes to 50 mm recharge and the rest was assumed to be lost through surface runoff.
- If the total rainfall proportionally weighted over a five day period was between 10 and 50 mm, recharge was calculated by summarizing the weighted rainfall of the last five days and subtracting 10 mm which is assumed to be lost to soil and plant storage.

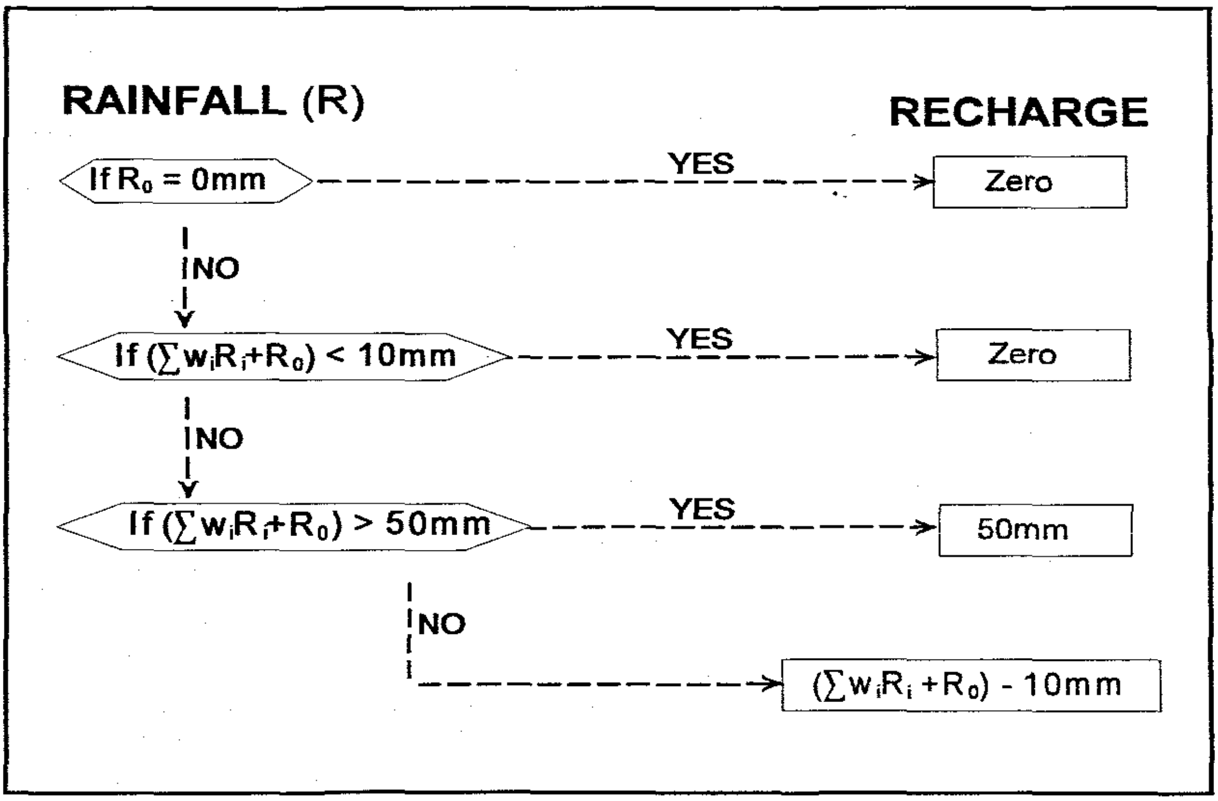

Figure 6.8 Recharge model used in this study (Rawlins and Kelbe, 1991)

Daily rainfall data from a weather station in the dunes near Lake Mzingazi was used to calculate recharge. The 20 years average annual rainfall at this weather station was 1592 mm/yr. The Rawlins and Kelbe (1991) model was applied to calculate recharge from rainfall and antecedent conditions. This produced an average recharge of 994 mm/yr which indicates that 62% of daily rain, on average, percolates into the groundwater where further evapotranspiration (E_4) occurs (see Figure 6.7). It assumes that interception and soil moisture evaporation together with the surface runoff are taken into account before recharge to the groundwater occurs. Evapotranspiration from the water table for vegetation in hydraulic contact with the water table (capillary fringe area) is accounted for in the model simulation. The evapotranspiration loss will be modelled using MODFLOW's evapotranspiration package. This concept differs considerably from the usual recharge models currently employed in other studies (Bredenkamp *et al*, 1995, Meyer and Godfrey, 1995 and Worthington, 1978) where E_4 is not included in the groundwater simulations. The model of Rawlins and Kelbe (1991) was based on a grassland area and has been adapted for other land uses as shown in Table 6.3. Recharge for grasslands was calculated for the study area by this method to give an average gross recharge of 960 mm/yr which is about 60% of the mean rainfall. For urban areas it was assumed that there is less recharge to the groundwater because surfaces like roads and roofs will contribute to more surface runoff and evaporation. Maximum evapotranspiration from the groundwater was assumed to reach potential evaporation (atmospheric demand) for Eucalyptus, but for other land uses the maximum evapotranspiration from groundwater was reduced to the values shown in Table 6.3.

	Recharge		Maximum evapo-transpiration	Extinction depth ~rooting depth
UNITS	%	mm/yr	mm/year	m
Grassland and swamps	60	960	900	1.5
Urban and Industrial	45	720	700	1.0
Informal sector	50	800	800	5.0
Eucalyptus	60	960	1100 (=potential)	15.0
Indigenous	65	1040	1000	10.0

Table 6.3 Assumed recharge and evapotranspiration values for different land uses

7 MODEL GRID and MODEL PARAMETERS

The conceptual model identified the hydraulically important features that needed to be included in the numerical model. This chapter describes how the conceptual model was incorporated into the numerical model and how the parameters were estimated and assigned to the model domain. The uncertainty of specific parameter values is also discussed in an attempt to determine the expected range of values likely to be experienced in this study. This provides considerable support when calibration studies are conducted on the model.

7.1 MODEL AREA and GRID DESIGN

Assuming that the area of primary interest is constrained by the boundary conditions already described, an area of 22 km in the X-direction and 15 km in the Y-direction was sufficient to cover the model domain. In order to reduce the number of inactive cells (Indian Ocean) in the model, the chosen grid was rotated so that the coast line coincided with the model grid. Figure 7.1 shows the main hydrological features and the chosen model grid in relation to the 1:50000 maps that cover the study area. Figure 7.2 shows the numerical grid in relation to the main hydrological features.

The river package in MODFLOW was chosen to simulate the internal boundaries associated with lake Mzingazi. Because of the considerable catchment area contributing to discharge from the Nseleni river, this feature was modelled using surface runoff models by Kelbe and Germishuyse (1998).

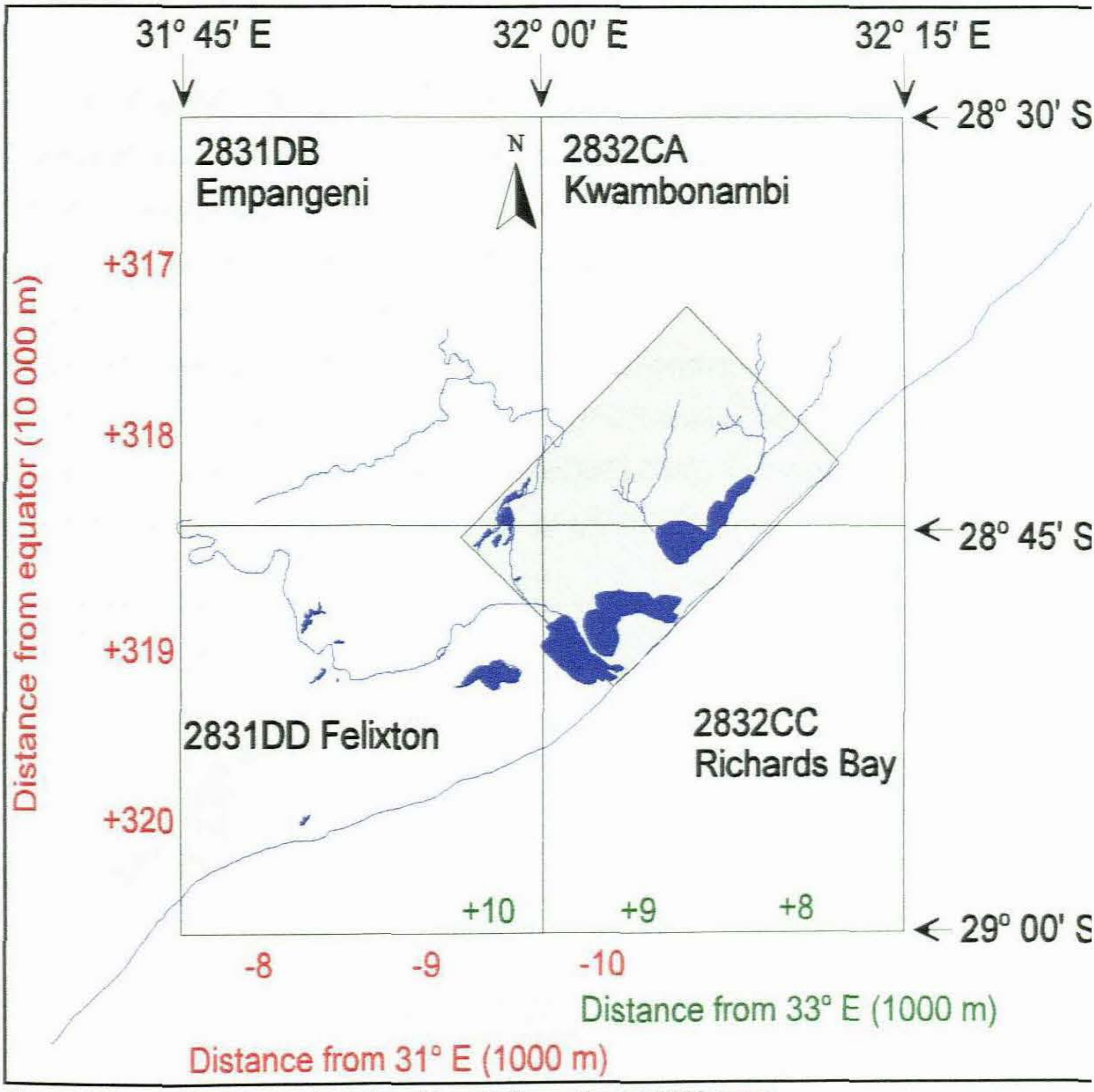

Figure 7.1 Model area (grey) and how it fits on the 1:50000 maps

7.2 TRANSFORMATION FROM CONCEPTUAL TO NUMERICAL MODEL

This section attempts to describe the practical problems in creating the numerical model based on the conceptual model and very limited data for the study area.

7.2.1 FROM MAP TO GRID

The elevation contours of the 1:50000 topographical maps were digitized using IDRISI (Eastman, 1987-1997). The digitized IDRISI files are text files listing the X and Y coordinates for each feature. These IDRISI files were converted into SURFER (Keckler, 1994) format by changing the file headers and adding elevation as a third column after the X and Y data columns. Shan and Stephens (1994) recommended that, for optimal results, the grid size used in SURFER should be exactly the same as the grid size in the numerical model (Visual MODFLOW). For this study, the same grid size was used in both SURFER and Visual MODFLOW.

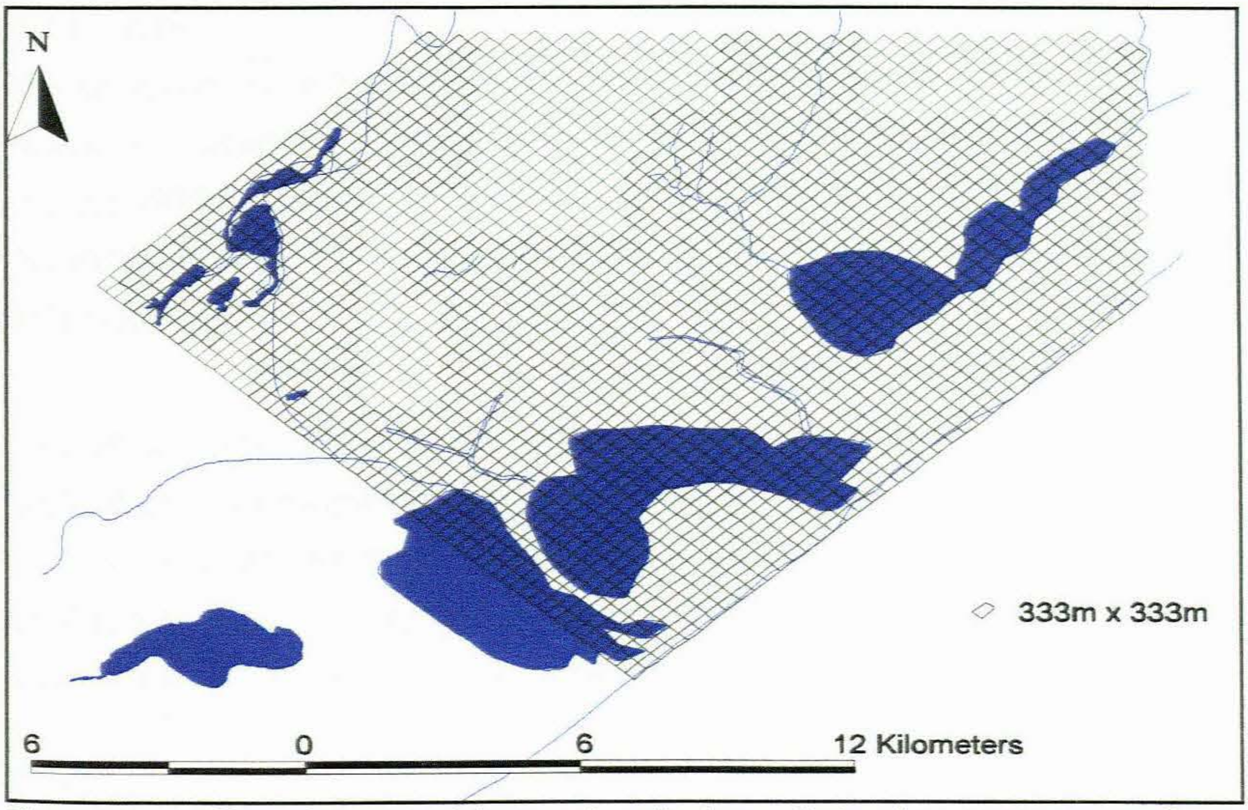

Figure 7.2 Grid overlain on model area, only partly shown. Each cell represents an area of 333m x 333m.

Since Visual MODFLOW only accepts length units in meters or feet, it was decided to digitize directly in meter from the 1:50000 topographical maps rather than using the degree system. The South African coordinate system in meters, has the origin at all the uneven longitudes. This gives the values in a westerly direction from the reference longitude as positive and the values east of the reference longitude as negative. The further away from the uneven longitudes, the larger the errors become. Since the study area is situated around the 32 degree longitude, it falls on the border of two coordinate systems where the error is largest. The two coordinate systems involved are the negative LO31 system and the positive LO33 system.

Because of these difficulties and because the grid was going to be rotated to reduce inactive cells, it was decided to rotate the maps before digitizing. A new coordinate system (in meter) with the origin of both X and Y at 0 was created with the origin near the harbour mouth. This coordinate system was used for digitizing and all numerical work in this study (see Figure 7.2).

7.2.2 LAYERS

The top and bottom surface elevation of each layer were created using SURFER as discussed in Chapter 5. One of the advantages of VisualMODFLOW was that it could import SURFER files directly into the model grid to form the boundaries between layers. For all the layers the SURFER files were created with the same grid size as that of the MODFLOW grid.

Input of parameter values into the model, was made easy by Visual MODFLOW when a DXF file of the area was imported to the model grid. A file showing lakes, the harbour and rivers was created by digitizing all these features in IDRISI and then exporting to DXF format. This DXF file was overlain on the model grid and used in specifying boundary conditions (shown as the white areas in Figure 7.3).

7.3 HYDROGEOLOGIC PARAMETERS

For the one layer model, hydraulic conductivity and storativity were considered to be homogeneous throughout the full extent of the layer. Recharge and evapotranspiration values were estimated for the five different land-uses (Table 6.3). The model area was divided into the five land-use categories as shown in Figure 7.3.

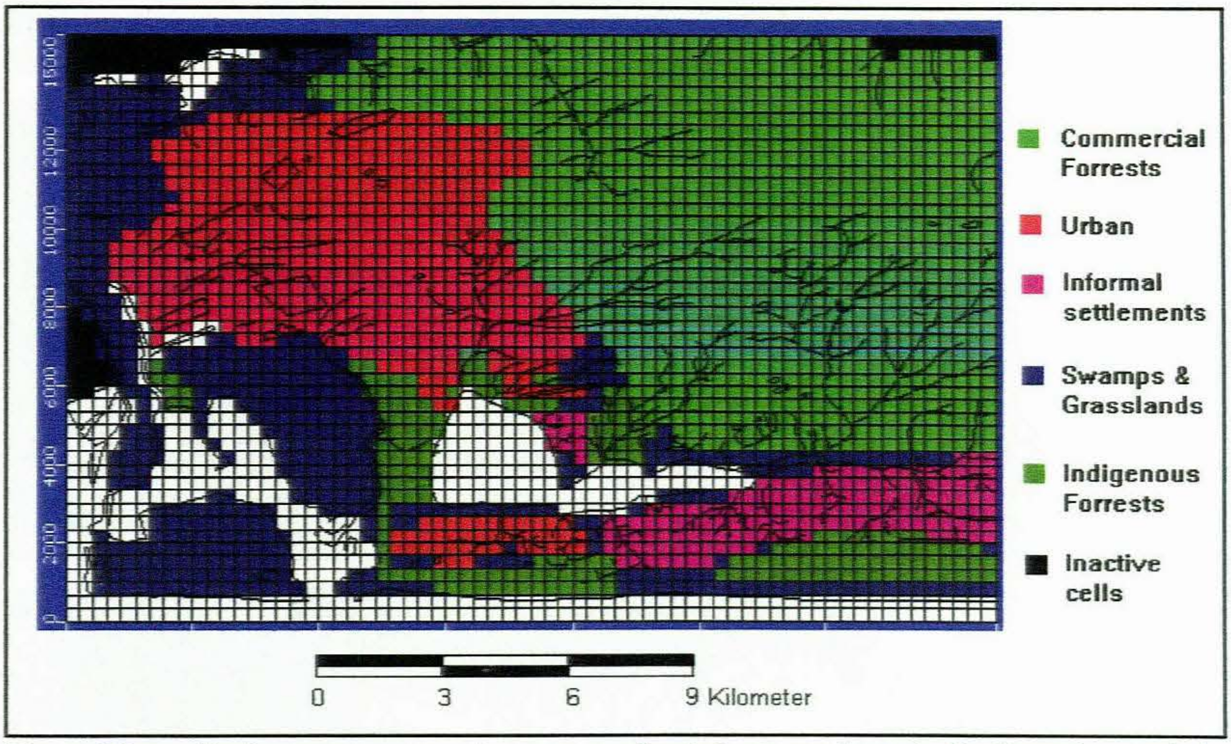

Figure 7.3 Recharge areas were chosen according to land-use shown by the five colour coded categories.

For the 3 layer model, however, variable hydraulic conductivities were used as described earlier. Figure 7.4 shows the hydraulic conductivity distribution that were derived for each layer according to the procedure described in detail in section 5.2.3.

The hydraulic conductivity is relatively high for the upper sandy layer (Layer 1), but in the lower layers (Layers 2 and 3) there are large areas with lower hydraulic conductivity which may restrict flow. These areas are indicated in black in Figure 7.4 and may redirect the flow through the local aquifer away from Lake Nsezi.

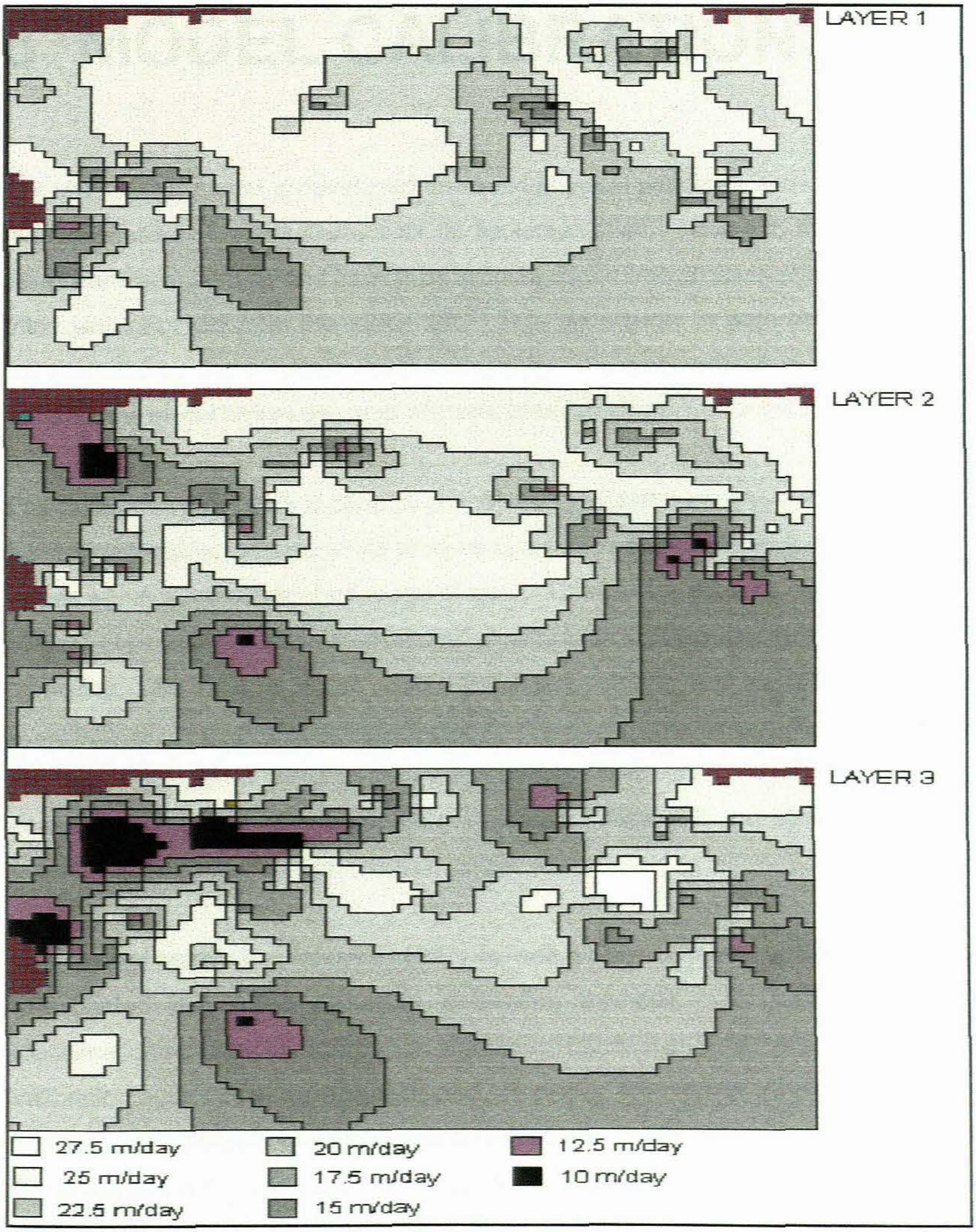

Figure 7.4 Hydraulic conductivity distribution of each layer.

8 MODEL CALIBRATION

The MODFLOW model is developed on sound physical principles and concepts that require relatively few parameters for its implementation. However, most of these parameters are unknown and have to be estimated from limited observations which are often well removed from the study site. This uncertainty in parameter values is compounded by the unknown spatial variability. Consequently, it is imperative to calibrate the model before any level of confidence can be derived in the model results.

The calibration procedure is done by changing model parameters systematically until a set of parameters is found which produce simulated heads that match the measured values within a pre-established range of error. This can be done by a trial-and-error method or by using an automated numerical calibration techniques that involve inverse modelling. An inverse model checks the head solution and adjusts parameters systematically in order to minimize an objective function. The objective function is often the sum of squared differences between measured and simulated heads. Different iterative methods (like Gauss-Newton, Levenberg-Marquardt and others) are often used to minimize the function (Häfner, 1996).

In a related study Germishuyse (1997) as well as Germishuyse and Kelbe (1997) investigated automated numerical calibration methods. By using parameter identification with the Front Limitation Algorithm (Häfner *et al*, 1996), several numerical calibration approaches were investigated. However, the numerical calibrations were shown to be no better than the trial-and-error method. Consequently, the trial-and-error method was used in this study. The procedure is based on the method of Anderson and Woessner (1991) illustrated in Figure 8.1.

To date, the calibration process has not been standardized, though the need for such methodology is recognized as an important part of quality assurance in code application (National Research Council, 1989). Anderson and Woessner (1991) give

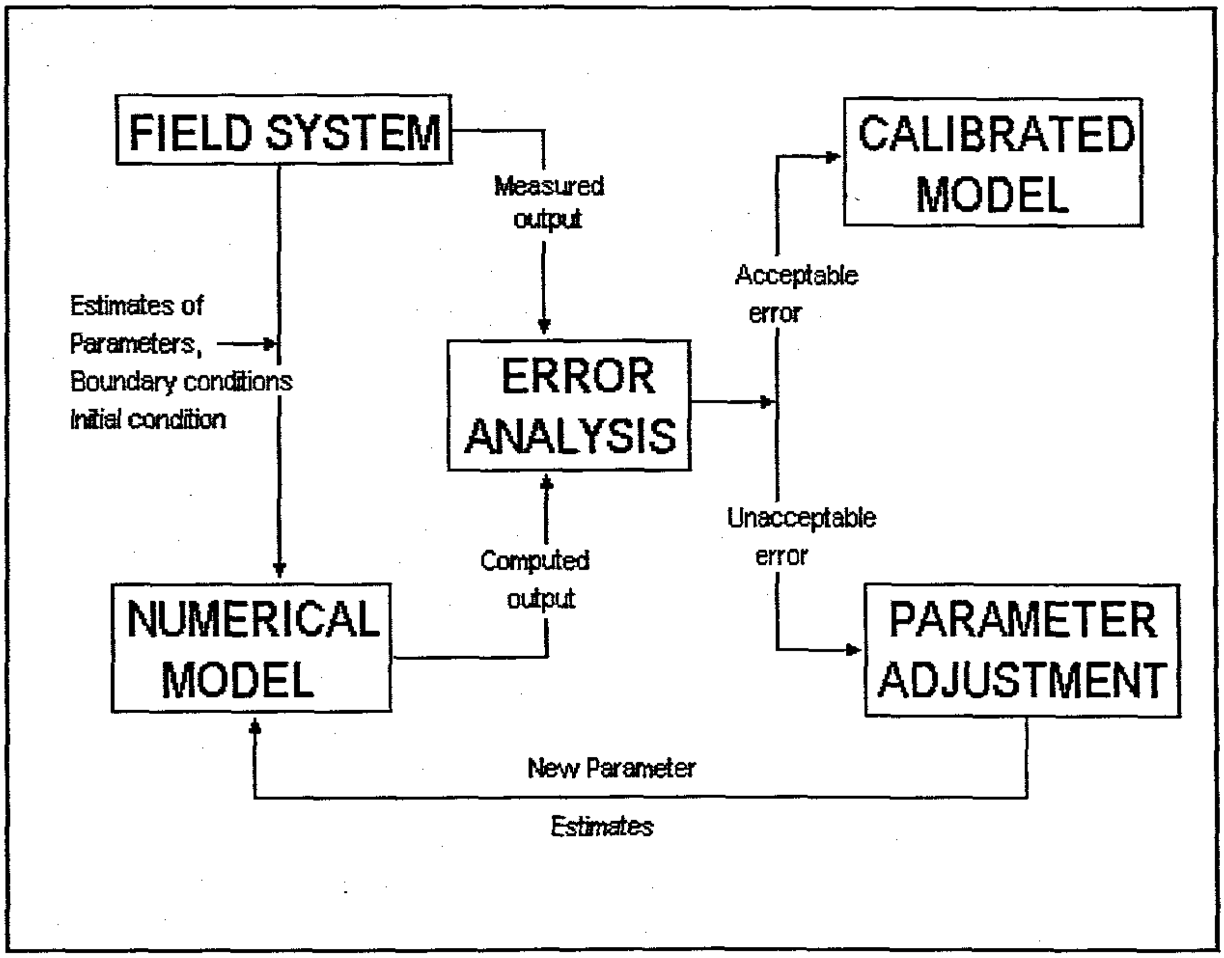

Figure 8.1 Trial-and-error calibration procedure (after Anderson and Woessner, 1991)

a method of setting calibration targets and discussing results in relation to what level of calibration could be reached.

The one layer steady state model was used for calibration purposes and the calibrated values were checked against measured values under transient conditions. Horizontal and vertical hydraulic conductivities were assumed to be the same because there was no information to the contrary.

Only two parameters, recharge and hydraulic conductivity, were used for calibration. For the purpose of calibration in the one layer model, both parameters were assumed to be homogeneous over the entire model area.

8.1 FIELD MEASURED HYDRAULIC HEAD

In order to set a calibration target, all the water level measurements available for this study was assessed. The water level measurements were few and far between and they originated from different sources. Many boreholes had an observed water level only for the day that they were drilled. Many more had no readings at all, even for the day they were drilled. Boreholes from two areas, however, had a series of water level observations . These two areas (A and B) have been indicated in Figure 4.11 and are enlarged in Figures 8.2 and 8.3 respectively. For area A (Figure 8.2) the time series of observed data stretched from 1992 to 1996, but most boreholes did not have a full series of data. For area B (Figure 8.3) the time series of observed data stretched from 1990 to 1994, which was a very dry period.

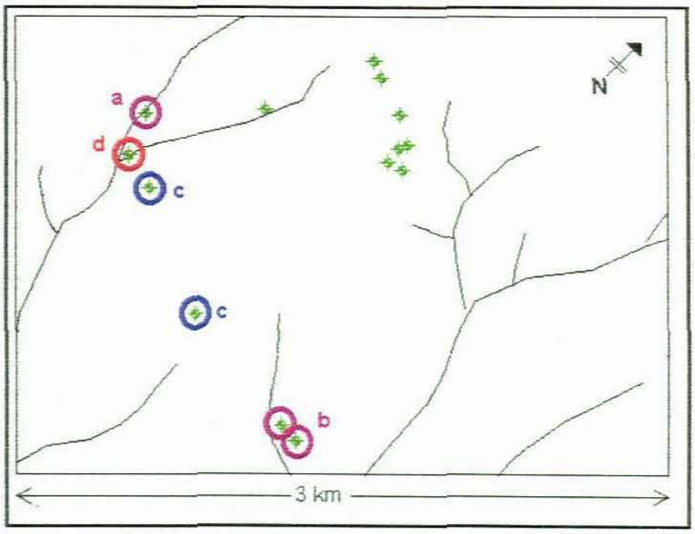

Figure 8.2 Borehole water levels. 'a' and 'b' have water levels below 30 mamsl and boreholes 'c' have water levels between 35 and 38 mamsl.

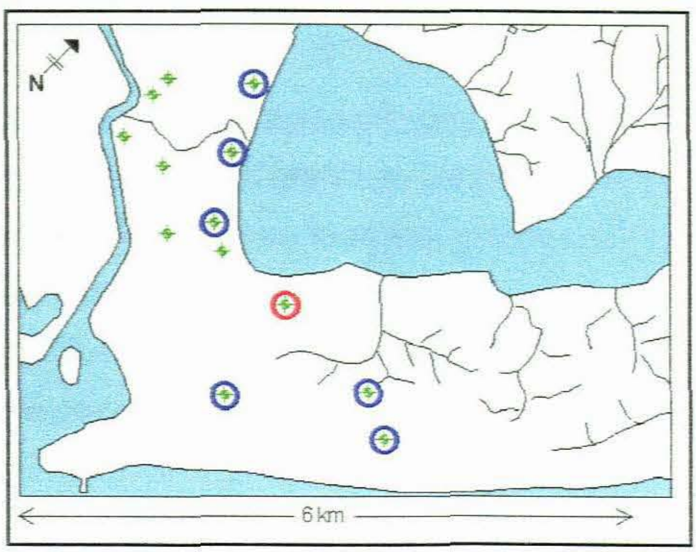

Figure 8.3 Boreholes where water levels vary more than 2 m between wet and dry periods.

Due to the limited set of observations used in the calibration, extreme care must be taken when analysing simulated versus measured data. For example where water levels were measured at the height of the drought, the simulated steady state water levels representing varied hydrological conditions, are expected to be higher than the measured level representing drought conditions.

Most of the boreholes in area A have a water level of 40 mamsl or higher. The borehole indicated 'a' in Figure 8.2 has a measured water level of 31 m amsl, the two boreholes indicated 'b' in Figure 8.2 have water levels of below 30m amsl and the water levels of the boreholes indicated 'c' in Figure 8.2 vary between 35 and 38m amsl. The water level in borehole 'd' in Figure 8.2 varies between 40 and 42m amsl.

The water level difference between the boreholes indicated by 'a' and 'd' is more than 10m. This could be due to a perched water table above a localized clay lens and must be considered when setting calibration targets.

Some of the boreholes in Figure 8.3 show extreme variations in water levels between wet and dry periods. The borehole circled in red in Figure 8.3 varies from 6.2m amsl in dry periods to 10.2m amsl in wetter periods. The boreholes circled in blue in Figure 8.3 varies more that 2m from wet to dry periods. Again, this variability must be taken into account when setting calibration targets for a steady state model.

8.2 STEADY STATE CALIBRATIONS

Due to the extreme spatial variability discussed above, it was not easy to decide what absolute difference would be acceptable to use as a calibration target (Woessner and Anderson, 1990). Since the spatial variability in measured head was greater than 10m in a small area (Figure 8.2) and the temporal variability within a borehole was up to 4m, the initial calibration target was set at a 3m difference between simulated head and observed average head. Results were compared by counting how many boreholes were within this limit of 3m.

All the calibration efforts discussed below, were done for the one layer model. The hydraulic conductivity for the region was varied between 5m/day and 25m/day, which is well within the expected range. Recharge was varied between 500mm/year and 1500m/year.

The parameters derived from the initial trial-and-error calibration study produced a recharge value of 1000 mm/year and a regional hydraulic conductivity of 10m/day when the maximum evapotranspiration rate was 1000 mm/yr.

Using these "calibrated" parameters, 37 out of the 49 boreholes (76%) were within the 3m limit that was set as a calibration target. The simulated versus the measured water levels after calibration are shown in Figure 8.4. Outliers are circled in black or red to indicate under- or over-simulated levels respectively. These outliers are also indicated on a map of the model area in Figure 8.5.

The problem areas are assumed to relate to areas where the hydraulic conductivity is very different than that of the surrounding areas. The problem is illustrated by analysing the borehole logs of the group of boreholes on the right hand side of Figure

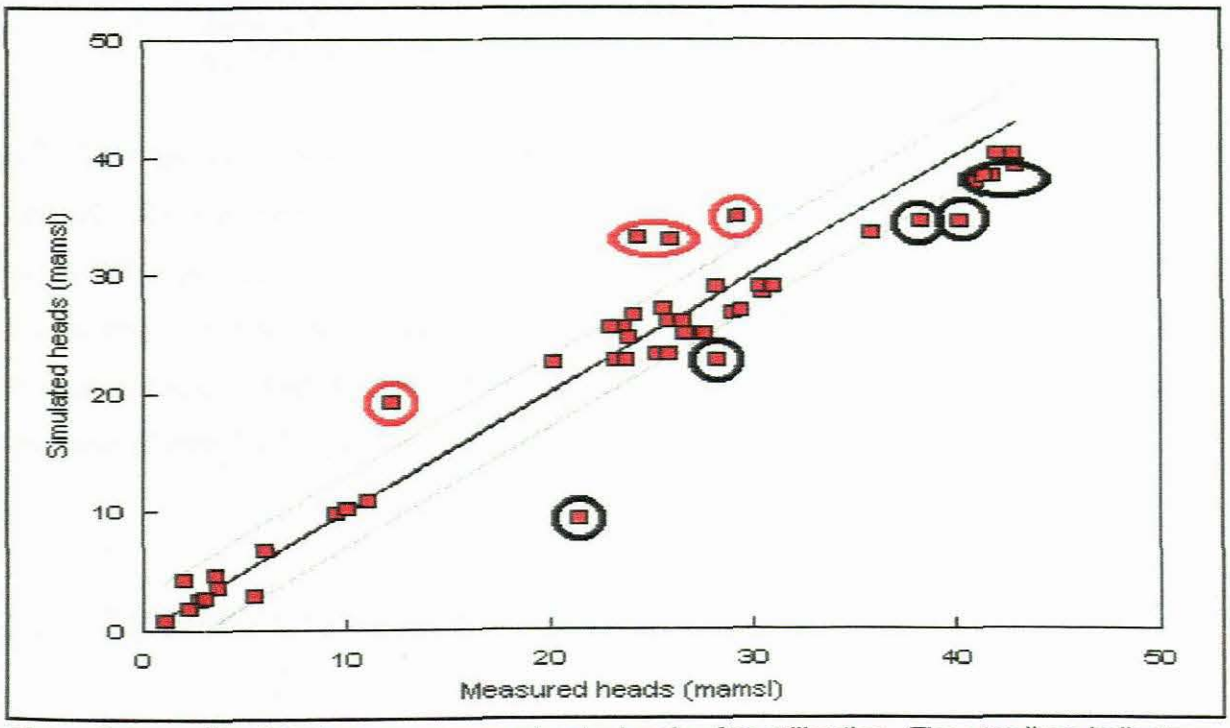

Figure 8.4 Simulated versus measured water levels after calibration. The grey lines indicate a 3m difference.

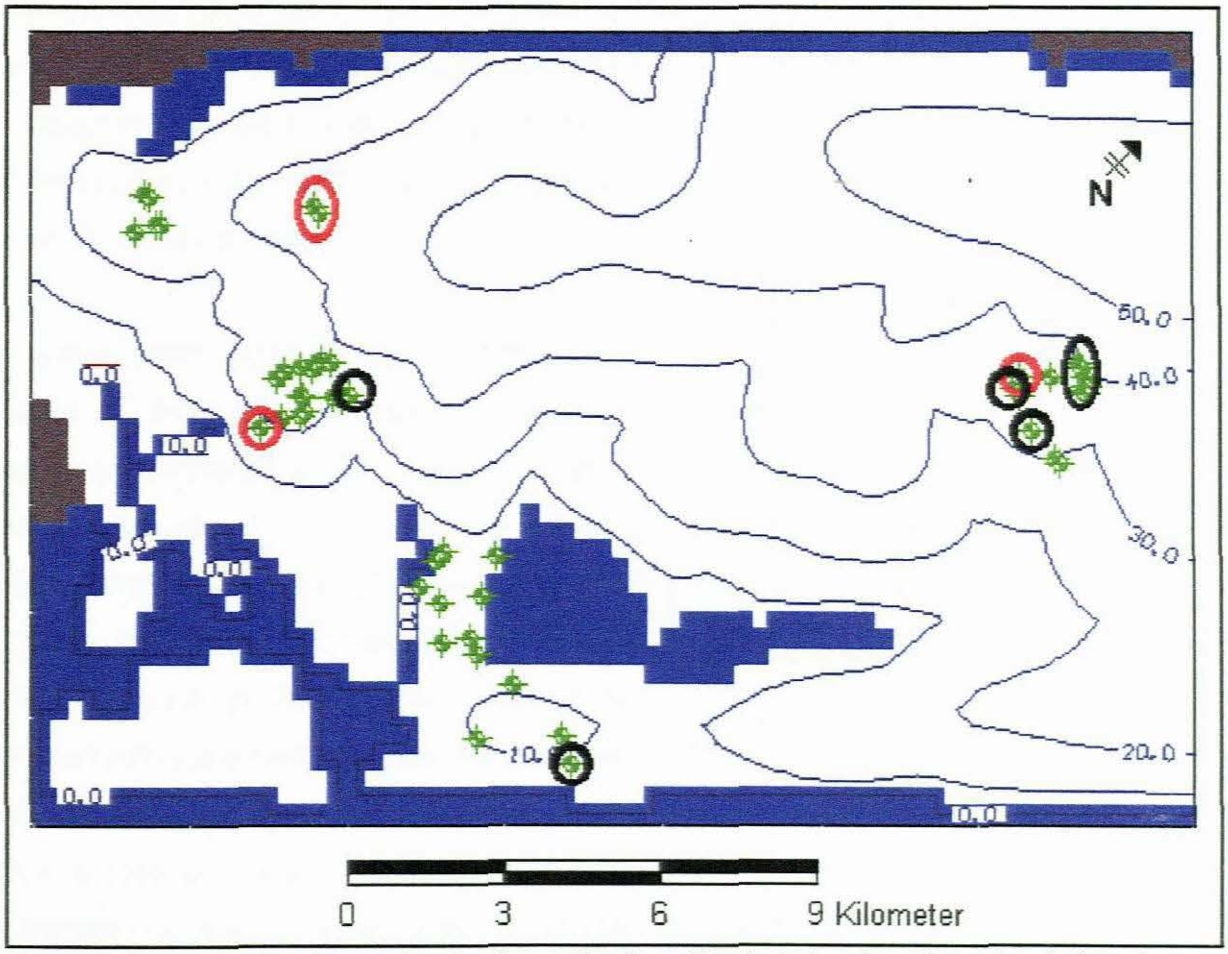

Figure 8.5 Simulated water levels after calibration. Black circles show those boreholes where the simulated head was more than 3m higher than the measured head. The red circles indicate boreholes where the simulated head was more than 3m lower than the measured head.

8.5. For the entire depth of the borehole circled in red in Figure 8.5, only sand was logged. All the boreholes of that group and circled in black in Figure 8.5 have a localised clay layer that may cause a perched water table which could be an explanation for the differences in the observed water levels. This clay layer was not included in the numerical model and may explain why the simulated water table is lower than measured for these boreholes.

8.3 TRANSIENT CALIBRATIONS

The transient model was setup from 1976 to 2002. 19 Stress periods of varying length (given in Table 8.1) were chosen to represent wet, dry and average periods. The chosen time series includes two flood events (stress periods 6 and 10) and an extreme dry period (stress periods 13 to 16).

S. Period	End Day	End Date
1	1597	15-May-80
2	1961	15-May-81
3	2511	15-Nov-82
4	2648	01-Apr-83
5	2937	15-Jan-84
6	3014	15-Apr-84
7	3654	01-Jan-86
8	4184	15-Jun-87
9	4276	15-Sep-87
10	4292	01-Oct-87
11	5737	15-Sep-91
12	5966	01-May-92
13	6269	01-Mar-93
14	6361	01-Jun-93
15	6544	01-Dec-93
16	7045	15-Apr-95
17	7122	01-Jul-95

Table 8.1 Stress Periods, Model Days and Dates for the transient model.

Steady state calibrated parameters were used in the transient model. However, average recharge and evapotranspiration was recalculated for each stress period. Simulated and measured water levels are shown in Figure 8.6. The borehole labelled MP1048 is situated in the dunes between the ocean and Lake Mzingazi and the other two boreholes are situated between the lake and the saltwater canal. These simulations indicate that the one layer model is capable of simulating natural conditions.

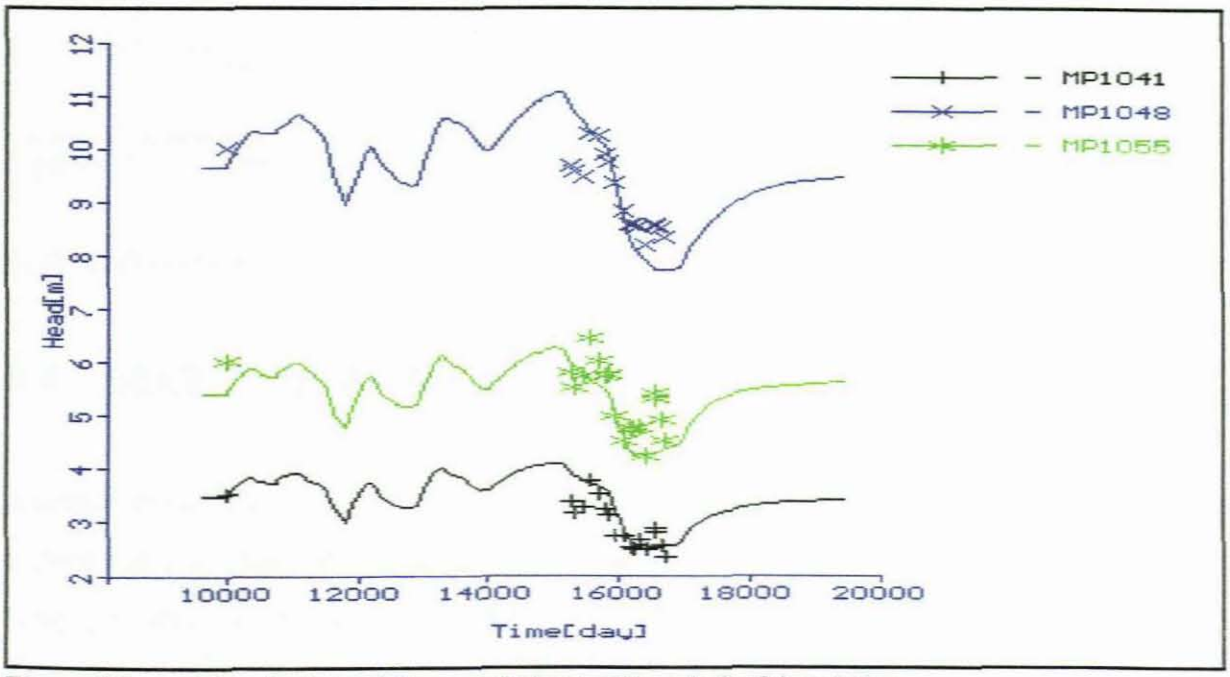

Figure 8.6 Transient simulations and observed heads for 3 boreholes.

As described in the previous chapter, a regional model cannot simulate all the small changes within an aquifer and it is expected that the simulation will deviate from the observed at some points. The simulated results do nct correspond well for two boreholes (Figure 8.7) in the northern section of the study area (overlapping red and black circles in Figure 8.5). These two borehole have very different water levels. Because they are situated very close together, the simulated values are likely to be similar and consequently, the large difference. Figure 8.7 cannot be explained as a

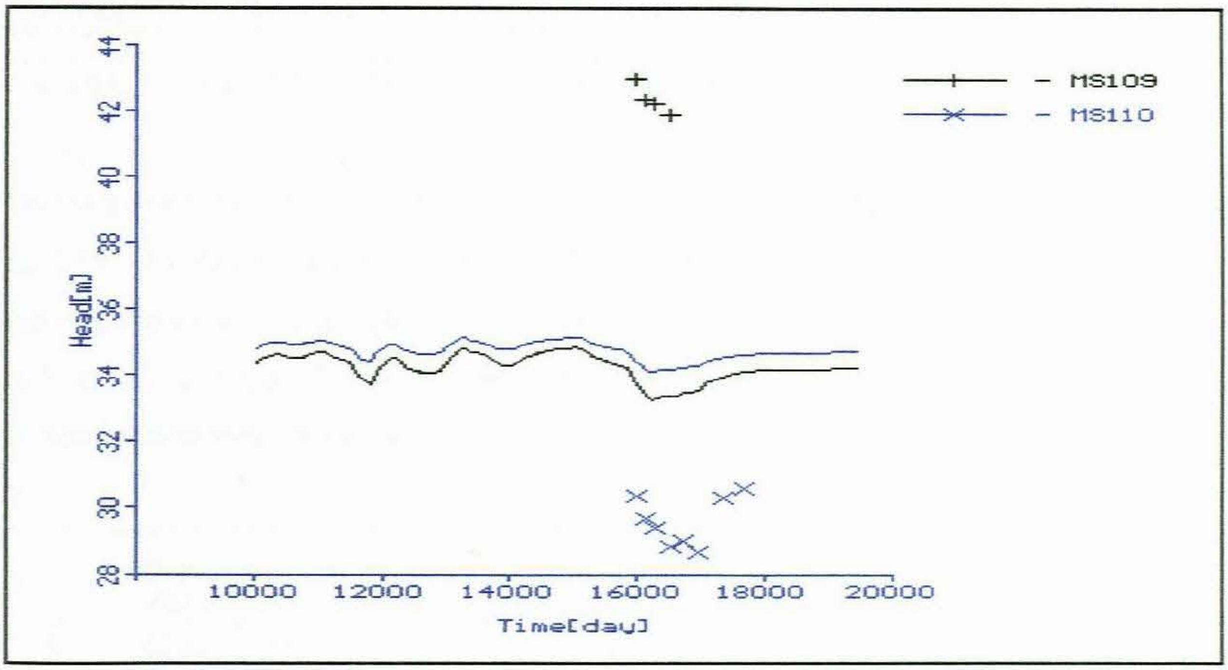

Figure 8.7 Transient simulated and measured water levels for 2 boreholes.

calibration problem.

8.4 SENSITIVITY ANALYSIS

A sensitivity analysis is done to quantify the uncertainty in the calibrated model. During a sensitivity analysis the calibrated parameters are changed systematically (one at a time) and the magnitude of simulated change is compared. Six simulation runs were done using the calibrated set of parameters with one parameter changed. The different runs are described in Table 8.2.

	RECHARGE (mm/year)	MAXIMUM EVAPOTRANSPIRATION (mm/year)	HYDRAULIC CONDUCTIVITY (m/day)
CONTROL	1000	1000	10
A (Recharge)	500	1000	10
B (Recharge)	1500	1000	10
C (Hydr.Cond)	1000	1000	5
D (Hydr.Cond)	1000	1000	15
E (Evap)	500	500	10
F (Evap)	1500	1500	10

Table 8.2 Parameters used for different sensitivity runs

The resulting change in head between the calibrated run (control) and the sensitivity runs (A - F) was quantified by averaging the water level in 49 observation points for each of the runs. The percentage change between the control run and each sensitivity run (shown in Figure 8.8) indicates that recharge is the most sensitive parameter and evapotranspiration the least.

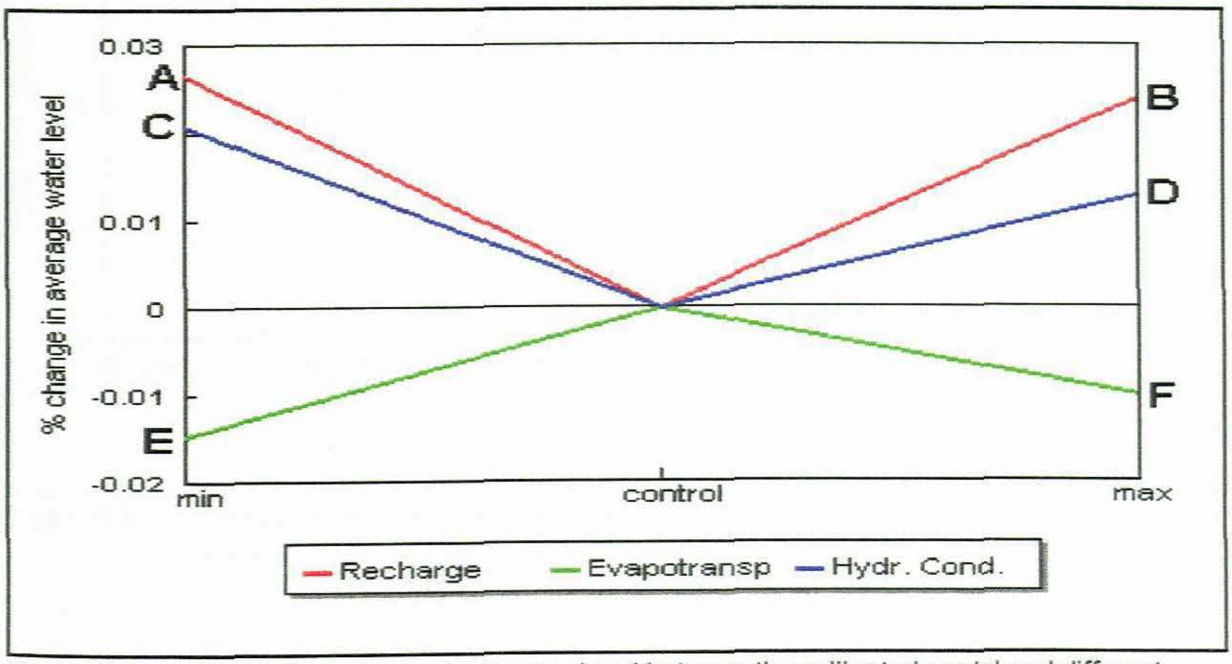

Figure 8.8 Percentage change in average head between the calibrated model and different sensitivity models.

Another way of displaying sensitivity results is to choose some observation points which had a very good agreement between measured and simulated head values for the calibrated model and plot absolute changes for each sensitivity run at each of these points (see Figure 8.9). The distribution of the five boreholes chosen are indicated in Figure 8.10. It can be seen that there is very little difference between the simulated and the measured values for the control run. For all five boreholes run A over-simulated the water table. Runs B,C and F the first borehole (MP1043) was over-simulated, while all the other boreholes were under-simulated. For runs D and E two boreholes (MP1044 and MP1045) were under-simulated, while three were over simulated.

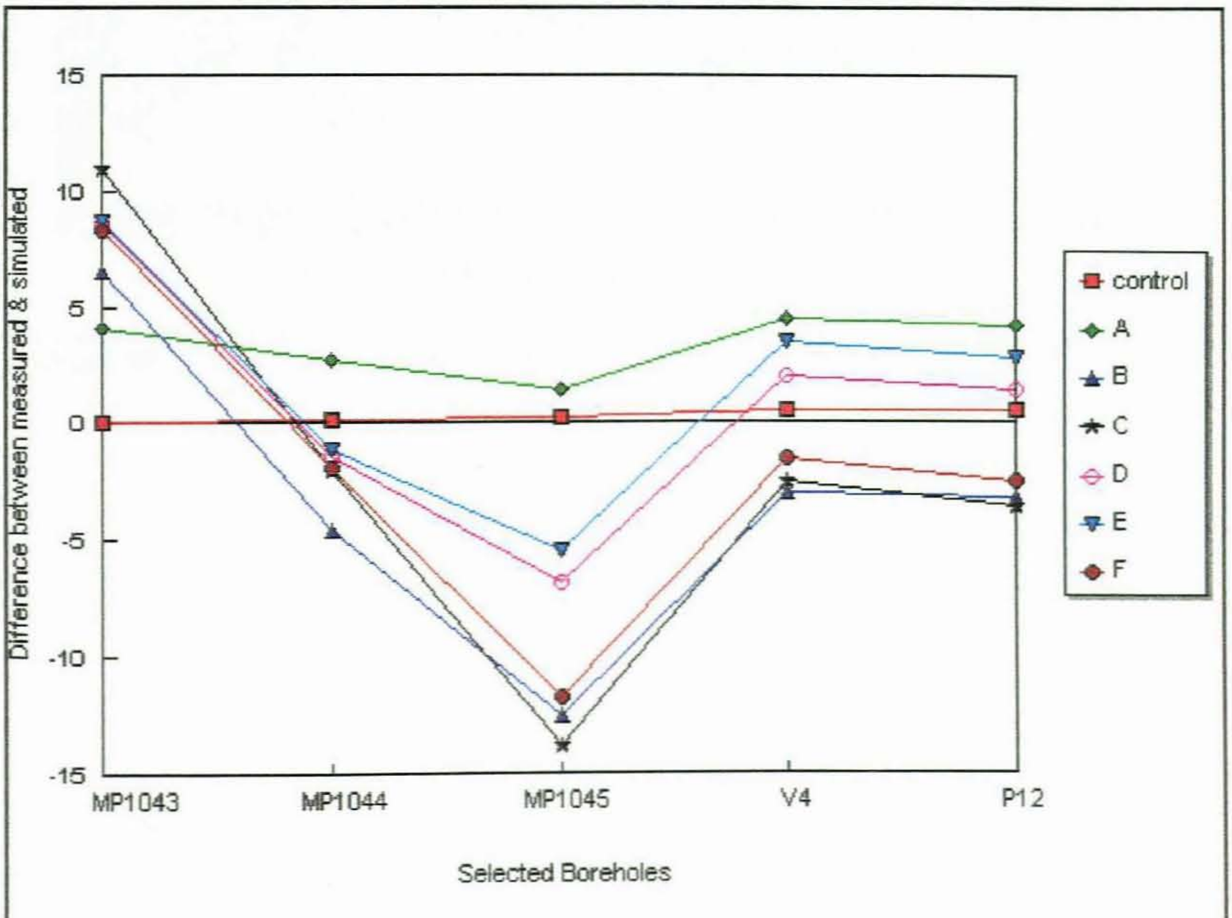

Figure 8.9 Difference between simulated and measured water levels for selected boreholes. A - F are the different sensitivity runs as indicated in Table 8.2

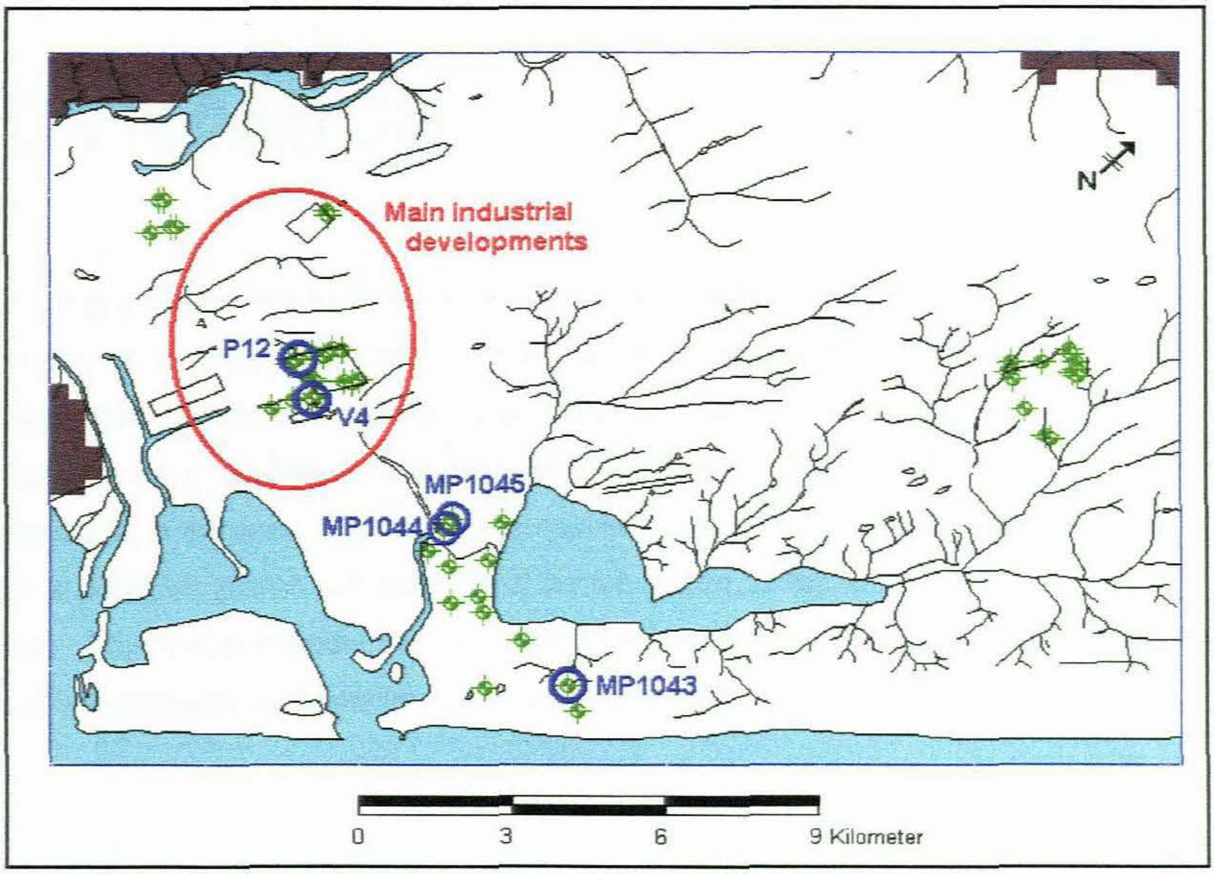

Figure 8.10 Locations of the 5 boreholes used for sensitivity analysis.

9 REGIONAL GROUNDWATER DYNAMICS

This study has provided the basis for deriving the regional groundwater flow pattern around Richards Bay. It has also been used to examine the water budget for Lake Mzingazi. The groundwater flow dynamics of the area is an important feature that helps to understand the groundwater system. It gives an indication of which areas contribute recharge to the main water resources of the area. The flow patterns can be used to indicate the general direction in which a pollution plume will travel and hence it can assist in deriving a monitoring procedure. The regional model may be used as a starting point for future, more detailed studies of specific sites and smaller scale problem areas.

9.1 THE ONE LAYER MODEL

Since the horizontal extent of the model domain is much larger than the vertical extent, a one layer model can be considered a reasonable representation of the system (Kinzelbach, 1986). This has been adopted in the initial stages of this study.

9.1.1 STEADY STATE

The one layer model has been configured to perform steady state simulations by using long term average parameters that are assumed to represent "normal" hydrological states. The steady state model has been calibrated against available observations (chapter 8) and the simulated water levels for average meteorological conditions are shown in Figure 8.5. The regional flow pattern for the study area under these average conditions is shown in Figure 9.1. The flow directions and velocities are representative of a single regional aquifer with the main surface drainage lines (rivers) included. The flow dynamics indicate that there is substantial drainage from the catchment area to the main surface water bodies which must play a role in sustaining the lake systems.

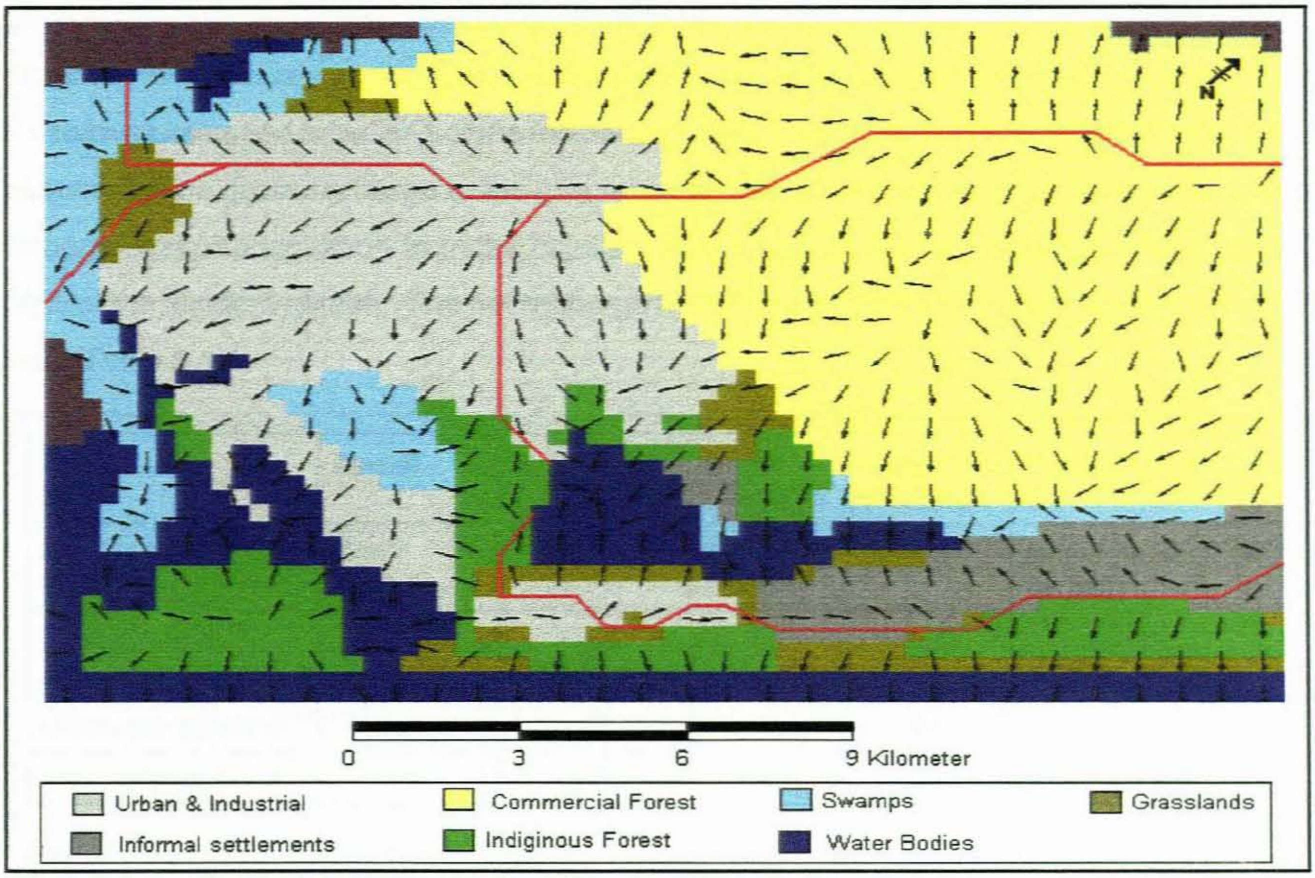

Figure 9.1 Regional flow pattern on the different land uses in the area.

9.1.2 RECHARGE

By applying the model of Rawlins and Kelbe (1991), described in previous sections, to the daily rainfall series, the recharge and other losses were calculated. These other losses include runoff and evaporation. This recharge model was originally developed and calibrated for grasslands. Other land-use types have been simulated in this study using the parameters given in Table 6.3. The relative proportion of each component is given in Table 9.1. Grasslands and swampy areas generally have 60% of the rainfall go into groundwater recharge. When the water table is less than 1.5 m (assumed rooting depth for grasslands) below the grassland surface, some of this recharge will be lost to evapotranspiration from the capillary fringe and thus reduce the net recharge. The gross and net recharge for the entire area under a specific land-use type is also given in Table 9.1. For the grasslands and urban and industrial sectors, the model indicate that ~30% of the incident rainfall goes into recharge when evaporation is taken into account.

In the urban areas it was assumed that there is much less interception (5%) than for grasslands, because of the impervious surfaces like roofs and roads. The surface runoff was assumed to be 3 times as much as that for grasslands (30% of rainfall) and the evaporation losses was assumed to be 20% of the incident rainfall. The remaining 45% of the rainfall was assumed to be gross recharge to the groundwater. Some of this recharge will be extracted through evapotranspiration from the capillary fringe so that the net recharge amounted to 30% of the incident rainfall. The net recharge from the other land-use types is considerably less (Table 9.1).

	Runoff	Evaporation	Gross Recharge	Gross Recharge	Net Recharge
UNITS	**% of rainfall**	**% of rainfall**	**% of rainfall**	**mm/yr**	**mm/yr (% of rainfall)**
Grassland and swamps	10	30	60	759	478 (31)
Urban and Industrial	30	25	45	800	471 (30)
Informal sector	15	35	50	802	239 (15)

Table 9.1 Adaptation of recharge values for different land uses after calculation for grasslands and swamps

9.1.3 FLOW PATTERN

The simulated flow pattern has been used to determine the principle water divides that separate the recharge zones for each of the primary water bodies. Within each of these recharge areas, the land use features could have a significant impact on the quantity and quality of the groundwater recharge. These impacts would propagate through the groundwater system to impact on the main wetlands.

The recharge (catchment) area for the main water resources in the Richards Bay area were delineated from the flow pattern which has been superimposed on the main land use categories in Figure 9.1. The flow direction of the regional groundwater system indicates four main regions that have a direct influence on the lakes, harbour and ocean water bodies respectively. There are few industrial sites in the recharge area for the main water supply reservoir, Lake Mzingazi. However, there are several large industrial complexes with substantial infrastructure in the catchment area of Lake Nsezi which could be a significant threat to the contamination of this system.

The principal threat of pollution to Lake Mzingazi is the urban and peri-urban (informal) development around the entire lake as well as the agricultural village on the western shores. The informal settlements cover 14% of the Mzingazi catchment within the study area. There is also a potential for significant reduction of groundwater contribution to Lake Mzingazi from the extensive afforestation of 65% of the catchment. If the afforestation reduces the recharge, then this would have a significant impact on the yield of the lake under very dry conditions.

The simulated groundwater flow into Lake Mzingazi for steady state conditions, was used to calculate a water budget for the lake. This water budget is compared (Table 9.2) to the detailed water budget done by Worthington (1978).

RECHARGE			DISCHARGE		
	This study	**Worthington (1978)**		**This study**	**Worthington (1978)**
UNITS	**10^3 m^3/day**	**10^3 m^3/day**		**10^3 m^3/day**	**10^3 m^3/day**
Rain	39 (34%)	43 (15%)	Evapotranspiration	35 (30%)	16 (6%)
Groundwater	41 (36%)	78 (28%)	Spill	43 (37%)	260 (93%)
Stream flow	35 (30%)	159 (57%)	Extraction	47 (33%)	
			Groundwater	<1	1
			Change in storage	0	3 (1%)
TOTAL	**115**	**280**	**TOTAL**	**115**	**280**

Table 9.1 Water budget for Lake Mzingazi with amounts in 1000 m^3/day (and percentage in brackets).

The groundwater recharge to the lake is almost half of that proposed by Worthington (1978), while the contribution by surface water sustaining the lake is almost a quarter of that suggested by Worthington (1978). Similar discrepancies are indicated by the discharge (and abstraction) for these two studies.

9.2 MULTILAYER MODELS

During the transient calibration study described in section 8.4, some areas were identified as problematic with poor correspondence between the simulated and observed heads. If these problems were caused by geological heterogeneity, it was thought that a multilayer model may improve the simulations in those areas. Consequently, an attempt was made to divide the aquifer into four stratigraphically similar units (described in section 5.2.2). This was a difficult task mainly caused by an insufficient data set. Hence a heterogeneous model divided into three layers with spatially distributed hydraulic conductivity for each layer (see section 5.2.3) was created. The simulation results from three different approaches are compared here. They are the homogeneous one layer model (method 1), the model with four homogeneous layers (method 2) and the model with three heterogeneous layers (method 3). Figure 9.3 shows the simulated groundwater levels from these different models.

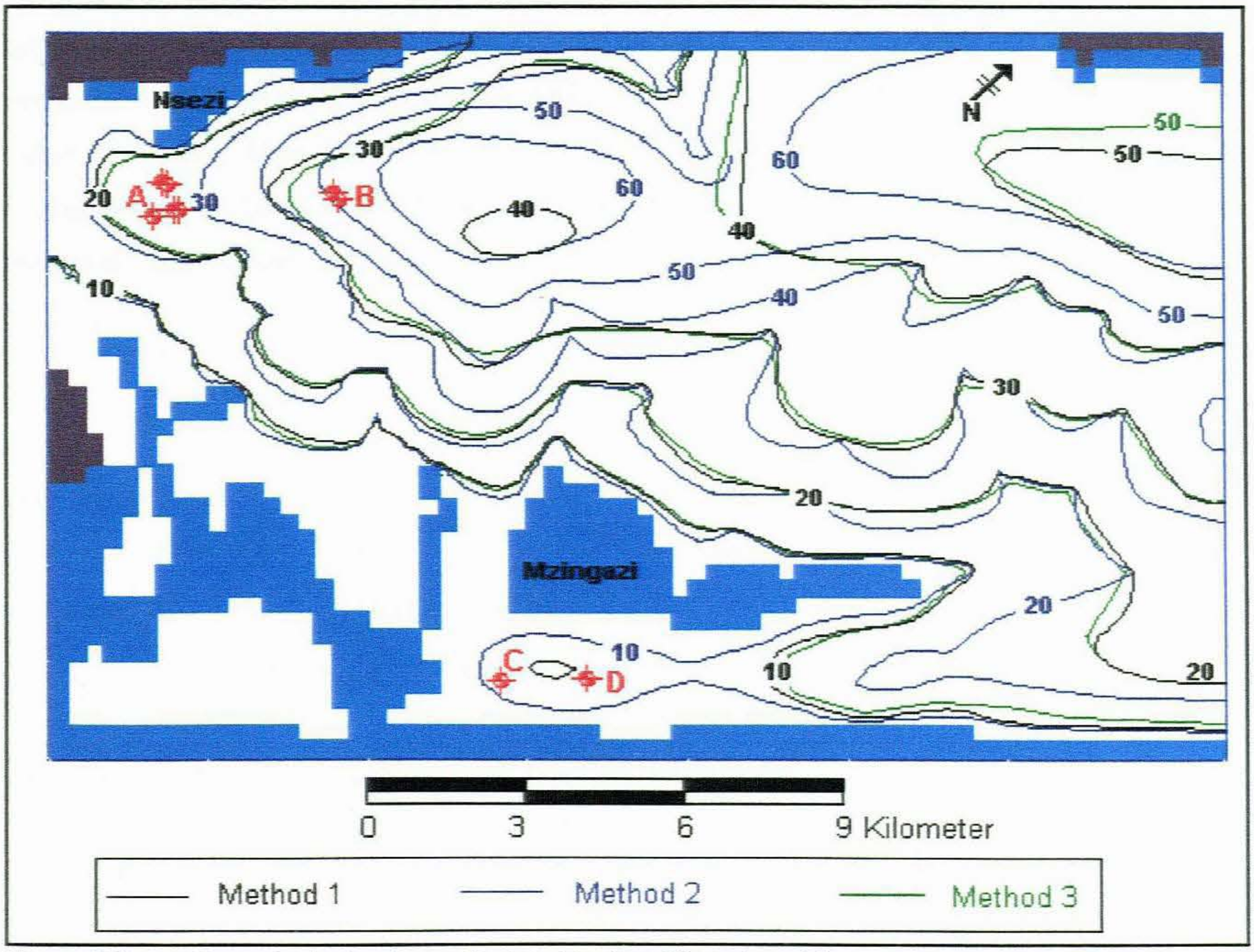

Figure 9.3 Groundwater levels as simulated by the different models.

The simulated water table elevations for all three methods are very similar, except for the region near Lake Nsezi and the region between Lake Mzingazi and the ocean. For the higher elevated water tables, there is a large difference (exceeding 20m in places) between the different simulations.

The different simulated heads between Lake Mzingazi and the Ocean indicate that the stratigraphy may be an important feature. The water level has been monitored at boreholes C and D (see Figure 9.3) and these values vary between 8.3 and 10.2m amsl for borehole C and between 9.1 and 12.2m amsl for borehole D. The simulated water table using methods 1 and 2 was acceptable in this region, but the simulated water table using method 3 was too low in this region.

There are some boreholes in the area near Lake Nsezi, but unfortunately their water levels have only been measured when the borehole was drilled and is not monitored on a regular basis. In area A (see Figure 9.3) the measured water level was between 23 and 24m amsl when the boreholes were drilled. In area B (see Figure 9.3) the measured water level was between 27 and 29m amsl when the boreholes were drilled. In both these areas the simulated water levels from method 2 was inaccurate, but the simulated water table using methods 1 and 3 was acceptable.

10 DISCUSSION and RECOMMENDATIONS

This study has produced several products that have contributed to the geohyrological knowledge of the Richards Bay area.

1) Geological surfaces

Through a detailed analysis of the available borehole data that have been acquired, captured and analysed, a map of the upper surface of the Cretaceous siltstone deposits has been constructed (Figure 5.9) This map was discussed with geologists who have worked in the region (Rheeder, 1996, Maud, 1996, Hattingh, 1996, Meyer 1996). All of them agreed that this surface was acceptable. This surface defines the principle lower boundary of the primary aquifer in the region.

Overlying the Cretaceous sediments are discontinuous layers of the Miocene deposits (Davies Lynn and Partners, 1992, Simmonds, 1990, Maud and Orr, 1975, Worthington, 1978 and Hatting, Meyer and Barnes, 1995). The lower surface is described by the Cretaceous sediments and the upper surface has been estimated (Figure 5.6) from the limited available data.

An attempt has been made to map the upper surfaces of other sedimentary layers. However, there is very low confidence in the accuracy of these surfaces because the borehole information was insufficient to allow a reasonable delineation.

2) Conceptual Models

Apart from the conceptual model of the geological features, conceptual models for recharge and evapotranspiration were refined and applied in the numerical model. Many groundwater modelers use a net recharge for groundwater studies (Bredenkamp *et al*, 1995). However, in this study a gross recharge is used together with evapotranspiration. Model results showed that the net recharge varies between 15% and 31% of rainfall depending on the land-use type. This is in the same range as the net recharge described by (Bredenkamp *et al*, 1995).

3) Numerical Model

The defined stratigraphy has been used to configure a numerical model of the area for regional groundwater studies. Calibration studies have been done and the resulting model was used too derive the regional flow patterns which indicate that most of the groundwater that originate in the industrial area of Richards Bay flows towards the harbour with a small portion flowing towards Lake Nsezi (Figure 9.1).

This model as well as the derived geological surfaces have subsequently been used for other studies of the coastal Lakes (Kelbe and Germishuyse, 1998, Germishuyse and Kelbe, 1999). The knowledge gained from this model has also been applied in the hydrological investigation of specific sites in the Richards Bay area (Kelbe and Germishuyse, 1999b).

10.1 RECOMMENDATIONS

The models examined in this project are mathematically and theoretically sound but their applications suffer from a lack of sufficient information. The lack of information in the region is a serious constraint to the use of the numerical models for other purposes such as solute transport modelling. In many cases this can be overcome through calibrations, but once again, only if there is sufficient field data. Clearly, the biggest limiting factor in numerical modelling is the availability of data and information about the system. However, one of the greatest assets of numerical modelling is that it identifies gaps in the information and the need for additional monitoring. This study has led to the establishment of a long term monitoring point in the centre of the industrial area of Richards Bay.

Groundwater flow models are critically dependent on hydrogeological data. The present extensive data base of borehole logs was conducted for geological or engineering surveys and very seldom contains specific information on the geohydrology or hydraulic properties of the aquifers. This information is even more important when solute transport modelling is considered because of the interaction between soils and particle movement. Consequently, it is strongly recommended that geological and soil surveys attempt to determine more hydraulic features of the profiles when logging the boreholes.

The rapid improvement in mass transport simulation tools needs to be matched by increased awareness in data requirements. There is a need to determine a common and reliable tracer in the regional groundwater system and establish a regular network of monitoring observation points in conjunction with other needs. In coastal regions such as Richards Bay, the potential for groundwater pollution and its potential impact on regional and local water resources needs to be carefully managed and this involves the establishment of a suitable monitoring programme.

There is a potential for contamination of the groundwater recharge areas for both Lakes Mzingazi and Nsezi and this may have serious long term detrimental impact on the water quality of the lakes. It is recommended that the local water authorities implement a programme for regional groundwater monitoring in the coastal primary aquifer.

Stream flow measurements at the inflow of lakes will provide better information on the lake water budget. This is crucial for management of water supply.

11 REFERENCES

Anderson, M.P. and Woessner, W.W. (1991) *Applied groundwater modelling - Simulation of flow and advective transport.* Academic Press Inc., San Diego

Archibald, C.G.M. (1997/8) *Protection of Lake Mzingazi from Pollution.* CSIR Status Report for 1997/1998. Prepared for Richards Bay TLC.

Australian Groundwater Consultants (1975) *Richards Bay Groundwater Investigations.* Unpublished Report to RBM.

Bosch, J.M. and Hewlett, J.D. (1982) *A Review of Cathment Experiments to Determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration.* Journal of Hydrology, Vol 55, pp 3 - 23.

Botha, G.A. (1997) *The Maputaland Group: A Provisional Lithostratigrapy for Coastal Kwazulu-Natal.* IN: Maputaland. Focus on the Quarternary Evoltion of the South-East African Coastal Plain. Edited by G.A. Botha. Council for Geoscience, Silverton.

Bredenkamp, B.D., Botha, L.J., van Tonder, G.J. and van Rensburg, H.J. (1995) *Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity.* Report prepared for Water Research Commission.

Campbell, E.E., Parker-Nance, T. and Bate, G.C. (1992) *A Compilation of Information on the Magnitude, nature and Importance of Coastal Aquifers in Southern Africa.* Water Research Commission Report No 370/1/92

Cheng, X. and Anderson, M.P. (1993) *Numerical Simulation of Ground-Water Interaction with Lakes Allowing for Fluctuating Lake Levels.* Ground Water, Vol 31, No6, pp 929 - 933.

Council, G.W. (1997) *Simulating Lake-Groundwater Interaction with MODFLOW.* Proceedings of the 1997 Georgia Water Resource s Conference, held 20 - 22 March, at The University of Georgia. Editor: K.J. Hatcher

Cyrus,D.P., Martin, T.J. and Reavell, P.E. (1997) *Salt-water intrusion from the Mzingazi River and its effects on adjacent swamp forest at Richards Bay, Zululand, South Africa.* Water SA, Vol 23, No 1,pp101 - 108.

Davies, Lynn and Partners (1992) *Landform Geomorphology and Geology.* IN: Coastal and Environmental Services. Environmental Impact Assessment. Eastern Shores of Lake St Lucia. (Kingsa/Trojan Lease Area) Specialist Reports. Volume 1: Biophysical Environment. Chapter 2.

Department of Water Affairs (1986) *Management of the Water Resources of the Republic of South Africa.* The Department of Water Affairs, Pretoria.

Domenico, P.A. and Schwartz, F.W. (1990) *Physical and Chemical Hydrology*. John Wiley and sons, Inc., New York.

du Preez, J.W. (1975) *The Geology of the Area West of Richards Bay: Explanation to sheet 2831D and 2832C.* Geological Survey Report No 244. (Unpublished)

Eastman, J.R. (1987-1997) *IDRISI Source Code.* Clark University, Worcester, USA.

Fenske, J.P., Leake, S.A. and Prudic, D.E. (1996) *Documentation of a Computer Program (RES1) to Simulate Leakage from Reservoirs Using the Modular Finite-Difference Ground-Water Flow Model (MODFLOW).* US Geological Survey Open-file Report 96-364.

Foster, S.S.D., Morris, B.L. and Chilton, P.J. (1999) *Groundwater in urban Development - a Review of Linkages and Concerns.* In: Impacts of Urban Growth on Surface Water and Groundwater Quality (Proceedings of IUGG 99 Symposium HS5, Birmingham, July 1999). IAHS Publ. No. 259, 1999.

Frankel, J.J. (1968) *Tertiary Sediments in the Lower Umfolozi River Valley, Zululand.* Transactions of the Geologicl Society of South Africa, LXXI, 135 - 145.

Garstang, M., Kelbe, B.E., Emmitt, G.D. and London, W.B. (1987) *Generation ofConvective Storms over the Escarpment of Northeastern South Africa.* Monthly Weather Review, Vol 115, No 2, P429 - 443.

Germishuyse, T. (1997) *Final Report to "Stiftung Zur Forderung Der Wissenschaflichen Schule Zunker-Busch- Luckner"*, Dresden, Germany.

Germishuyse, T. and Kelbe, B.E. (1997) *Waste Site Investigation (including Calibration studies).* Final Report to Richards Bay Minerals (confidential).

Germishuyse T. and Kelbe B.E. (1999) *Surface-groundwater modelling studies of coastal lakes on the east coast of South Africa.* Coastal Engineering and Marina Developments. Eds CA Brebbia and P Anagnostopoulos, WITpress, Southampton, Boston, UK. pp 347 -355

Guiguer, N. and Franz, T. (1996) Visual MODFLOW. *The Integrated Modeling Environment for MODFLOW and MODPATH.* Version 2.11, Waterloo Hydrogeologic Software. User manual.

Häfner, F. (1996) Personal Communications.

Hattingh, R.P. (1996) Personal Communications.

Hattingh, R.P., Meyer, R. and Barnes, J.M.T. (1995) *Impact Assessment of the Clarifier Waste Disposal Site: Implications and Proposal for A New Disposal Site.* Unpublished report to RBM.

Heath, R.C. (1983) *Basic ground-water hydrology.* US Geological Survey, Water Supply Paper 2220. As quoted by Anderson and Woessner (1991).

Hobday, D.K. (1976) *Quaternary sedimentation and development of the Lagoonal complex, Lake St Lucia, Zululand.* Ann. S. Afr. Mus., 71, 93 - 113.

Hobday, D.K. and Orme, A.R. (1974) *The Port Durnford Formation: A major Pleistocene Barrier-Lagoon Complex along the Zululand Coast.* Transactions of the Geological Society of South Africa, Vol 77, pp 141-149.

Hodgson, F., Fourie, G. and Lukas, E. (1987-1991) *HydroCom.* HydroSolutions, Inc., Bloemfontein.

Keckler, D. (1994) *SURFER for Windows.* Golden Software, Inc. Golden, Colorado.

Kelbe, B.E. (1996) *Specialist Study on the Potential Impact of the Proposed CPC Smelter Development on Water Supply and Water Quality.* CSIR, Environmental Services, Pretoria.

Kelbe, B.E. and Germishuyse, T. (1998) *Groundwater modelling of the Lakes in the Mhlatuze Catchment.* Report to Knight Piésold.

Kelbe, B.E., and Germishuyse, T. (1999) *Geohydrological Studies of the Primary Coastal Aquifer in Zululand.* Report to the Water Research Commission (K5/720) To be published

Kelbe, B.E., and Germishuyse, T. (1999b) *Hydrological investigation of Bulk Storage Facility, Richards Bay.* Report to ISCOR.

Kelbe, B.E. and Rawlins, B.K. (1992) *Hydrology.* IN: Coastal and Environmental Services. Environmental Impact Assessment. Eastern Shores of Lake St Lucia. (Kingsa/Trojan Lease Area) Specialist Reports. Volume 1: Biophysical Environment. Chapter 3.

Kelbe, B.E., Rawlins, B.K. and Nomquphu, W. (1995) *Geohydrological Modelling of Lake St. Lucia.* Report to Department of Water Affairs and Forestry.

Kelbe, B.E., Snyman N-M and Rawlins, B.K. (1994) *Geohydrological Modelling of the Sokhulu Well Field.* Hydrological Research Unit, Consultancy Report.

King, L.C. (1970) Uloa revisited. *A Review of the Essential Data From this Classic Locality, and A Statement of Tertiary History of the Zululand Coastal Area.* Transactions of the Geologicl Society of South Africa, LXXIII, 151 - 158.

King, L.C. (1972) *The Natal Monocline (first edition).* University of Natal Press, Pietermaritsburg.

King, L.C. (1982) *The Natal Monocline (second edition).* University of Natal Press, Pietermaritzburg.

Kinzelbach, W. (1986) *Groundwater modelling.* Elsevier Science Publishing Company Inc., Amsterdam.

Kruseman, G.P. and de Ridder, N.A. (1994) Analysis and Evaluation of Pumping Test Data. IRLA Publication 47, Printed in The Netherlands.

Manahan, S.E. (1994) *Environmental Chemistry.* Lewis Publishers, USA.

Martinelli and Assosiates (1988) *Development of a Groundwater Supply.* Interim Report on Phase I Investigations. Unpublished report to RBM.

Maud, R.R. (1968) *Quaternary Geomorphology and Soil Formation in Coastal Natal.* Annals of Geomorphology, 7, 155 - 199.

Maud, R.R. (1980) *The Climate and Geology of Maputaland.* In: Studies on the Ecology of Maputaland. Edited by M.N. Bruton and K.H. Cooper. Cape and Transvaal Printers.

Maud, R.R. (1990) *Sea-level Movements as Evidence of Late Quaternary Environmental Changes in Southern Africa.* Paleoecology of Africa, Vol 21, pp 27 - 34.

Maud, R.R. (1996) Personal Communications.

Maud, R.R. and Orr, W.N. (1975) *Aspects of post-Karroo geology in the Richards Bay area.* Transactions of the Geological Society of South Africa, Vol 78, pp 101-109.

Maxey, G.B. (1964) *Hydrostratigraphic units.* Journal of Hydrology, Vol 2 pp. 124 - 129.

McDonald, M.G., and Harbaugh, A.W. (1983) *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model.* US Geological Survey, Open-File Report 83-875.

McDonald, M.G., Harbaugh, A.W., Orr, B.R. and Ackerman, D.J. (1991) *A Method of Converting No-Flow Cells to Variable-Head Cells in the USGS Modular Finite-Difference Ground-Water Flow Model.* US Geological Survey, Open-File Report 91-536.

Meyer, R. (1996) Personal Communications.

Meyer, R and Godfrey, L. (1995) *Kwa-Zulu/Natal geohydrological mapping project mapping unit 7. CSIR Report No. EMAP-C-95024.* In: Characterization and mapping of the groundwater resources KwaZulu-Natal province (Department of Water Affairs and Forestry).

Mhlatuze water (1997) *Annual report.*

Midgley, D.C., Pitman, W.V. and Middleton, B.J. (1994) *Surface Water Resources of South Africa 1990.* WRC Report no 298/6.1/94.

Money, D.C. (1988) *Climate and Environmental Systems.* Unwin Hyman, London.

National Research Council (1989) *Groundwater Models: Scientific and Regulatory Applications. National* Academy Press, Washington D.C. (As quoted by Woessner and Anderson.)

Oschadleus, H.D. and Vogel, J.C. (1996) *Radiometric Date for the Port Durnford Peat and Development of Yellow-wood Forest along the South African East Coast.* South African Journal of Science, Vol 92, pp43 - 45.

Prudic, D.E. (1989) *Documentation of A Computer Program to Simulate Stream-Aquifer Relations Using A Modular, Finite-difference, Ground-water Flow Model:* U.S. Geological Survey Open-File Report 88-729, 113 p.

Ramsay. P. J. (1997) *Holocene Sea-level Changes.* IN: Maputaland. Focus on the Quarternary Evoltion of the South-East African Coastal Plain. Edited by G.A. Botha. Council for Geoscience, Silverton.

Rawlins, B.K. and Kelbe, B.E (1991) *Case study on the hydrological response of a shallow coastal aquifer to afforestation.* IN: Hydrological Basis of Ecologically Sound Management of Soil and Groundwater. (Proceedings of the Vienna Symposium, August 1991). IAHS Publ. no. 202.

Rawlins, B.K., Kelbe, B.E and Germishuyse, T. (1997). *The Potential for Saline Water Intrusion to A Coastal Lake Under Drought Conditions, Investigations at Richards Bay, Zululand.* Proceeding of the Eighth SANCIAHS Symposium, Pretoria.

Rheeder, J.W.J. (1996 - 1999) Personal Communications.

Schulze, R.E. (1982) *Agrohydrology and -climatology of Natal.* Published by Water Research Commission, Pretoria.

Shan, C. and Stephens, D.B. (1994) *Recommendations for Usage of SURFER to Gridding Model Results.* Ground Water, Vol 32, No 3. May - Jun 1994.

Shaw, E.M. (1985) *Hydrology in Practice.* Van Nostrand Reinhold Co. Inc. London.

Simmonds, A.L.E. (1990) *Investigations Into Possible Saline Intrusion At Lake Mzingazi, Richards Bay.* Department of Water Affairs, Geohydrology Report No. 3711.

Tankard, A.J. (1976) *Cenozoic Sea-Level Changes: A Discussion.* Annals of the South African Museum, 71, pp1-17.

Tankard, A.J., Jackson, M.P.A., Eriksson, K.A., Hobday, D.K., Hunter, D.R. and Minter W.E.L. (1982) *Crustal Evolution of Southern Africa.* Springer-Verlag, New York

Terblance, C. (1997) Personal Communications.

van Tonder, G.J., Botha, J.F. and Müller, J.L. (1986) *The Problem of Sea-Water Intrusion near Lake Mzingazi at Richards Bay.* Water SA, 12, 83 - 88.

Verwey, J.P. and Botha, J.F. (1992) *A Comparative Study of Two- and Three-Dimensional Groundwater Models.* Vol 1. Water Research Commission Report No 271/1/92

von Weh, M.W. and Anderson, N.J.B. (1990) *Normal Slip Faulting in the Coastal Areas of Northern Natal and Zululand, South Africa.* South African Journal of Geology, Vol 93, 574 - 582.

Voorhees, M.J. and Kirkner, R.A. (1987). *The applied groundwater flow model INTERSAT* HYDROSOFT INC. 2831 Ringling Blvd, Sarasota Florida, U.S.A.

Webb, D.L and Associates (1971) *Report to the Richards Bay Town Board on a Subsoil Exploration of the Alluvial Areas at Richards Bay.* Ref. 3161, D.L.Webb and Associates.

Webb, D.L and Associates (1972) *Report to the Richards Bay Town Board on an Investigation of Subsoil and Founding Conditions in the Proposed Industrial Areas.* Ref. 3374, D.L.Webb and Associates.

Woessner, W.W. and Anderson, M.P. (1990) *Setting Calibration Targets and Assessing Model Calibration - Room for Improvement: An Example From North America.* IN: ModelCARE90: Calibration and Reliability In Groundwater Modelling (Proceedings of the Conference Held in The Hague, September 1990). IAHS Publ. No. 195, p279 - 288.

Worthington, P.F. (1978) *Groundwater Conditions in the Zululand Coastal Plain around Richards Bay.* CSIR Report no RFIS 182.

General References used (not referred to in text)

Bear, J. and Verruijt, A. (1987) *Modelling groundwater flow and pollution.* D.Reidel publishing company Dordrecht, Holland.

Eggleston, J.R., Rojstaczer, S.A. and Peirce, J.J. (1996) *Identification of hydraulic conductivity structure in sand and gravel aquifers: Cape Cod data set.* Water Resources Research, 32, 5, 1209-1222.

Fetter, C.W. (1994) *Applied Hydrogeology.* Prentice-Hall, Inc., New Jersey

Freeze, R.A. and Cherry, J. A. (1979) *Groundwater.* Prentice-Hall, Inc., Englewood Cliffs.

Häfner, F., D.Sames and Voigt, H-D. (1992) *Warme und Stofftransport.* Springer-Verlag, Berlin.

Hattingh, R.P. (1997) *Hydrogeochemistry of the Zululand Coastal Plain.* IN: Maputaland. Focus on the Quarternary Evoltion of the South-East African Coastal Plain. Edited by G.A. Botha. Council for Geoscience, Silverton.

Hemens, J., Simpson, D.E. and Sibbald, R.R (1981) *Lake Nsezi, Richards Bay: Environmental Aspects of Multipurpose Water Use.* CSIR Special Report WAT60, 1 - 41.

Kelbe, B.E., Snyman, N-M. and Rawlins, B.K. (1993) *Environmental Impact Assessment Alcor Site 1, Richards Bay.* Hydrological Research Unit, Consultancy Report.

Krikken, A. and van Nieuwkerk, E.R. (1997) *Preliminary Investigation of Geohydrological Processes in the Richards Bay Area (South Africa).* Short Research Assignment at the University of Zululand for Free University of Amsterdam.

Meyer, R. (1997) *Geological information from Geohydrological Investigations on the Zululand Coastal Plain.* IN: Maputaland. Focus on the Quarternary Evoltion of the South-East African Coastal Plain. Edited by G.A. Botha. Council for Geoscience, Silverton.

Pitman, W.V. (1980) *Hydrology of the Coastal Lakes of Maputaland.* IN: Studies on the Ecology of Maputaland. Edited by M.N. Bruton and K.H. Cooper. Cape and Transvaal Printers.

Rawlins, B.K. (1991) *A Geohydrological Assessment of the Behaviour and Response of the Zululand coastal plain to both environmental influences and human activity.* M.Sc thesis, University of Zululand.

Rawlins, B.K. (1992a) *The Response of a Shallow Aquifer to Rainfall: The Effects of Surface and Subsurface Conditions.* IN: Interdisciplinary Approaches in Hydrology and Hydrogeology. American Institute of Hydrology. pp 22-30

Rawlins, B.K. (1992b) *The Response of a Shallow Aquifer to Rainfall: The Effects of Surface and Subsurface Conditions.* IN: Interdisciplinary Approaches in Hydrology and Hydrogeology. American Institute of Hydrology pp 31-45

Rawlins, B.K., Kelbe, B.E and Germishuyse, T. (1997) *Hydrology and Geohydrology of the Moebase Area, Moçambique.* Hydrological Research Unit, Consultancy Report

Schulze, B.R. (1947) *The Climates of South Africa According to the Classification of Köppen and Thornthwaite.* S. Afr. Geogr. J., 29, 32 - 42.

South African Government (1997) *White Paper on Water Policy, South Africa.* 30 April 1997.

Todd, D.K. , 1980 , *Groundwater Hydrology (second edition).* John Wiley and sons, Inc., New York

Townley, L.R., Turner, J.V., Barr, A.D., Trefry, M.G., Wright, K.D., Gailitis, V., Harris, C.J. and Johnston, C.D. (1993) *Wetlands of the Swan Coastal Plain.* Vol 3. Interaction between Lakes, Wetlands and Unconfined Aquifers. Water Authority of Western Australia.

van Wyk, W.L. (1963) *Groundwater Studies in Northern Natal, Zululand and Surrounding Areas.* Geological Survey of South Africa, Memoir S2.

Walmsey, R.D. and Grobler, J.H. (1986) *An Evolution of the Impact of Urban and Recreational Development on the Ecology and Usage of Lake Mzingazi.* FRD Ecosystems Programme Occasional Report Series No 28 254-259. CSIR Pretoria.