

**GEOHYDROLOGICAL STUDIES
OF THE
WESTERN SHORES
OF
LAKE ST LUCIA**

by

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DECLARATION

I, Vaward Wandile Nomquphu, declare that the dissertation ***Geohydrological Studies of the Western Shores of Lake St Lucia*** is my own original and unaided work, unless specifically indicated to the contrary in the text, and that it is not being submitted concurrently for any other degree at any other University.

Signed:



V.W. NOMQUPHU

Dedication

This manuscript is dedicated to my mother, Mrs Solina M. Nomquphu, for her faith in education and especially for all the sacrifices she has made for the sake of her children's education and their future.

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ABSTRACT

Lake St Lucia is a sensitive estuarine system of international importance which is threatened with over-development within its catchment area by afforestation, overgrazing, proposed dredge mining on the eastern shores and other exploitations. These disturbances and proposed developments have invoked considerable public concern for the sustainability of the Lake St Lucia system. This study looks at the contribution of the groundwater from the western shores area to the lake system in order to evaluate its importance to sustaining the ecology of the system.

Under severe drought conditions, the lake experiences considerable lowering of water levels which are accompanied by high rises in salinity levels because of the low freshwater recharge. While the western shores catchment of Lake St Lucia has a number of rivers that contribute freshwater to regulate the salinity of St Lucia, most of these rivers are non-perennial and have been exploited by developments within their catchments. In this study the aquifer system of the southern portion of the western shores area of Lake St Lucia is delineated with the specific intention of defining the coastal geohydrology of the western shores in order to determine its contribution to the water balance of Lake St Lucia.

The geological succession of the Zululand coastal plain is described using geophysical information and borehole data which have been compared with field observations and findings in adjacent areas. The general stratigraphic succession, constructed from a number of electrical resistivity soundings and a few boreholes drilled around the western shores area of Lake St Lucia, is described as the first step in defining a conceptual model of the present system for numerical simulation studies. The resistivity soundings have shown that the permeable succession is restricted to post-Cretaceous sediments.

The low permeable Cretaceous siltstones, the Lebombo volcanics and the Karoo sediments were all selected to coincide with the base of the numerical model. The

overlying, semi-permeable to permeable, upward-fining calcareous and clayey sands of Pleistocene age, known as the Port Durnford Formation, were generally designated as the second layer (LAYER 2) of the model. The electrical resistivity soundings reveal that, on the western shores, the Port Durnford Formation has a thickness of 0 to 30 metres. Overlying the Port Durnford Formation is a relatively thin cover of unconsolidated aeolian, alluvial and estuarine sands of Holocene age which were generally selected as the top layer (LAYER 1) of the model. The upper surface of these coversands coincide with the surface topography, and they range in thickness from 0 to 8 metres and play a major role in the hydraulics of the shallow coastal aquifer.

A three-dimensional finite difference model (INTERSAT), was developed from the conceptual geological model. This model was used to determine piezometric surfaces and subsurface flow into Lake St Lucia. Geohydrological and other hydrological parameters assigned to the model were estimated from existing literature and published reports because there were no observation data available. The model parameters for effective rainfall and evapotranspiration were derived from consideration of landuse features to account for surface-groundwater interactions. After the steady state condition had been achieved, the model was validated by comparing the simulated piezometric surfaces (heads) and simulated stream recharge against the observed water table elevations and estimated outflow from rivers, respectively.

The simulation results have shown that the groundwater contribution from the western shores to the lake is approximately $40 \times 10^6 \text{ m}^3/\text{year}$. This component of the water budget may be sufficient to have a buffering effect on the salinity of the lake along the edges of the shores if it is released in times of surface flow droughts.

To quantitatively evaluate the groundwater contribution from this area and other sections of the lake system, the presently existing network of electrical resistivity surveys needs to be supplemented with the boreholes or observation wells that should be scattered over the area. From these records a good groundwater database could be built. It is recommended that simulation studies should be extended to the northern shores in order to evaluate its contribution to the water budget of Lake St Lucia.

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CHAPTER 1

INTRODUCTION

Lake St Lucia is a large shallow body of water about 380 square kilometres in surface area with an average depth of less than 1½ metres (Hobday, 1976). It is situated on the environmentally sensitive Zululand coastal plain along the eastern seaboard of the Republic of South Africa, between latitude 27°50' and 28°25' south, and longitude 32°21' and 32°34' east (Figure 1.1). Lake St Lucia is the largest estuarine system in Africa (Begg, 1978) and is threatened by developments in its primary catchments which result in reduced fresh water inflow to the lake system.

Under severe drought conditions the lake experiences considerable fluctuations in salinity levels (Lindley and Scott, 1987; Hutchison and Pitman, 1973). This situation is a result of low freshwater recharge into the lake under high evaporation loads. According to Fielding *et al* (1990), the bottom of the lake is lower than the mean sea level and this aids the net influx of sea water into the lake. Thus, the lake's salinity levels reach extreme concentrations under drought conditions and this may have adverse effects on the lake's ecosystem. This was observed during the extremely dry year in 1948 when, during July, salinity measurements in the lake ranged from 35 000 to 52 000 mg/l (Hutchison and Pitman 1973). These salinity levels were significantly higher than the salt concentration of sea water which is roughly 35 000 mg/l. Observation of salinity from 1969 to 1972 showed that parts of the lake system were as saline as the Dead Sea (Begg, 1978). The lake flora and fauna can be adversely affected by these high salinity levels.

Bredenkamp *et al* (1993) have demonstrated that a linear relationship between the rainfall in the area and lake salinity levels exists. They suggest that this

relationship indicates that "the overall hydrological balance of the system can be related to the rainfall deficiency or rainfall surplus relative to the rainfall mean". They also show that there is a lag between the salinity fluctuations and the cumulative rainfall departure. This lag implies that "the carry over of the catchment memory effect results in a significant delay in the salinity response to the rainfall variations". Kelbe and Rawlins (1992) have suggested, however, that groundwater stored during extreme rainfall periods may subsequently be released at later stages and that such release in drought periods may have a strong influence in damping salinity fluctuations of the lake in some locations.

Begg (1978) identifies a number of factors which promote high salinities in the lake. The main factor is the "freshwater starvation" which can be attributed to changes in weather conditions (alternating drought conditions and flood events) as well as conflicting catchment utilization which include afforestation, irrigation, dam construction, and domestic and industrial water supplies.

The effects of massive commercial plantations of fast growing pine and *Eucalyptus* trees on the hydrological balance within the lake catchment were investigated as far back as 1964, when the government instituted a Commission of Enquiry to "investigate the alleged threat to plant and animal life in St Lucia" (Kriel, 1966). Lindley and Scott (1987), indicate that the primary concern of the government was the fluctuation of the lake salinity. Despite the Commission's far reaching recommendations about the conservation of the area around the lake system in order to ensure that the lake receives sufficient supplies of fresh water, commercial afforestation continued to expand gradually reducing inflow from adjacent areas of the lake (Lindley and Scott, 1987). This has had a significant impact on groundwater reserves and in the recharge to the lake (Tinley, 1971).

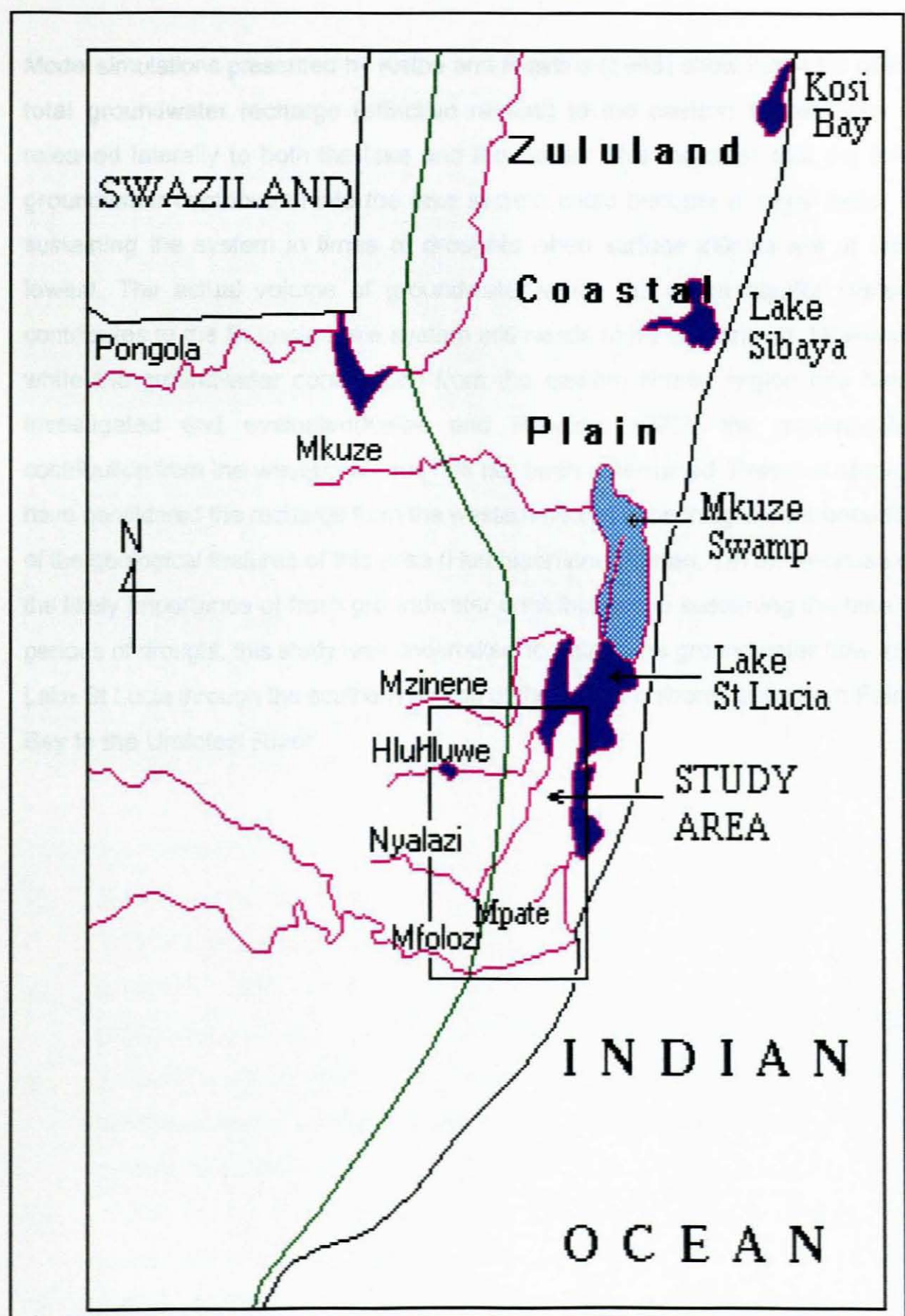


Figure 1.1 Regional map of the Zululand coastal plain

Model simulations presented by Kelbe and Rawlins (1993) show that 43% of the total groundwater recharge (effective rainfall) to the eastern shores area is released laterally to both the lake and the ocean. This indicates that the total groundwater contribution into the lake system could become a major factor in sustaining the system in times of droughts when surface inflows are at their lowest. The actual volume of groundwater which the entire aquifer system contributes to the St Lucia Lake system still needs to be determined. However, while the groundwater contribution from the eastern shores region has been investigated and evaluated (Kelbe and Rawlins, 1993), the groundwater contribution from the western shores has not been determined. Previous studies have considered the recharge from the western shores to be insignificant because of the geological features of this area (Hutchison and Pitman, 1973). Because of the likely importance of fresh groundwater contributions in sustaining the lake in periods of drought, this study was undertaken to determine groundwater flow into Lake St Lucia through the southern portion of the western shores area from False Bay to the Umfolozi River.

CHAPTER 2 STUDY OBJECTIVES

The objective of this study was to examine the geohydrology of the western shores of Lake St Lucia in order to determine groundwater flow from the western shores into the lake. The hydrogeological maps were derived from available information in order to form a conceptual model of the geology of the area. This conceptual model was then used to derive parameters for a finite difference model of groundwater flow in order to simulate the groundwater flow into the lake.

The numerical model chosen for this study was the INTERSAT groundwater model developed by Voorhees and Kirkner (1986) and revised in Voorhees (1991). INTERSAT is a physically based, process-orientated, three-dimensional, numerical model based on the deterministic simulation of the natural conditions. This groundwater model requires the collection and assimilation of field data in order to define representative parameter values for simulating the physical characteristics of the groundwater process.

The study was carried out by means of:

- @ detailed literature review pertaining to the geography, geology, hydrology and geohydrology of the study area;
- @ collection and collation of all geological, hydrological, geohydrological and climatological data that could be traced;
- @ formulation (development) of a conceptual geological model for specifying the numerical geohydrological model which is based on geological information;
- @ identifying input parameters for the INTERSAT Model from the conceptual model and data;
- @ model (INTERSAT) simulation, validation and application to estimate the groundwater flow to the lake recharge.

CHAPTER 3

GEOGRAPHIC DESCRIPTION OF THE STUDY AREA

3.1 Location

The area investigated for this study is situated on the south-western shores of Lake St Lucia. The area extends for 50 km from False Bay (latitude $28^{\circ}00'S$) to the Umfolozi River (latitude $28^{\circ}28'S$). The area lies between longitudes $32^{\circ}15'E$ and $32^{\circ}26'E$ and covers part of the flat-lying coastal plain which forms part of the greater Zululand coastal plain (Figure 3.1). The northern parts of the Lake system comprising the Mkuze estuary and the northern sections of False Bay

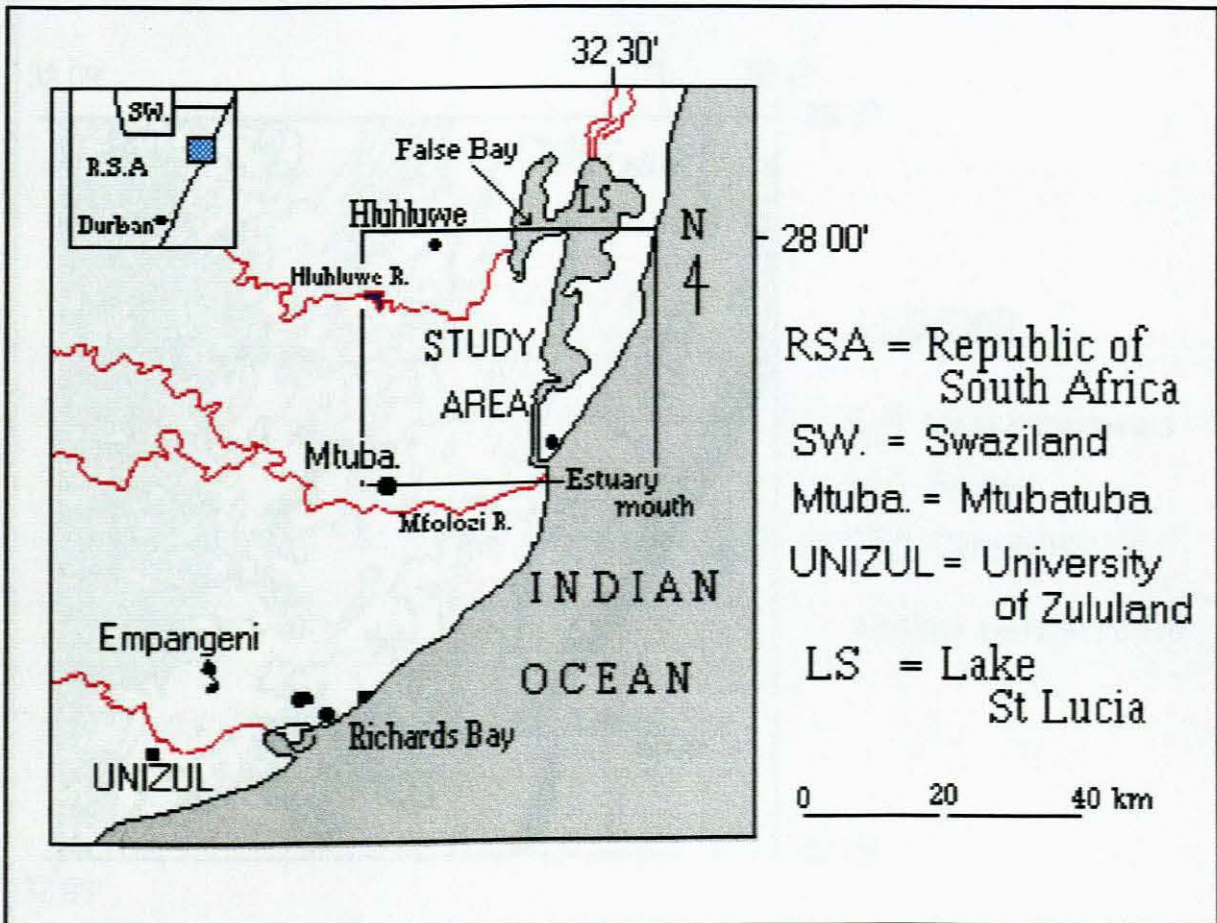


Figure 3.1 Locality map of the study area.

were not considered in this study. During the project, the eastern shores were

also excluded because they had been studied in great detail by Kelbe and Rawlins (1992).

3.2 Surface Topography

The topography of the Zululand coastal plain is a manifestation of the changes in the relative level of the sea and some tectonic movement (Hobday, 1979). A contour map of the study area, captured on GIS from topographical maps issued by the Government Printers, (1979) is given in Figure 3.2.

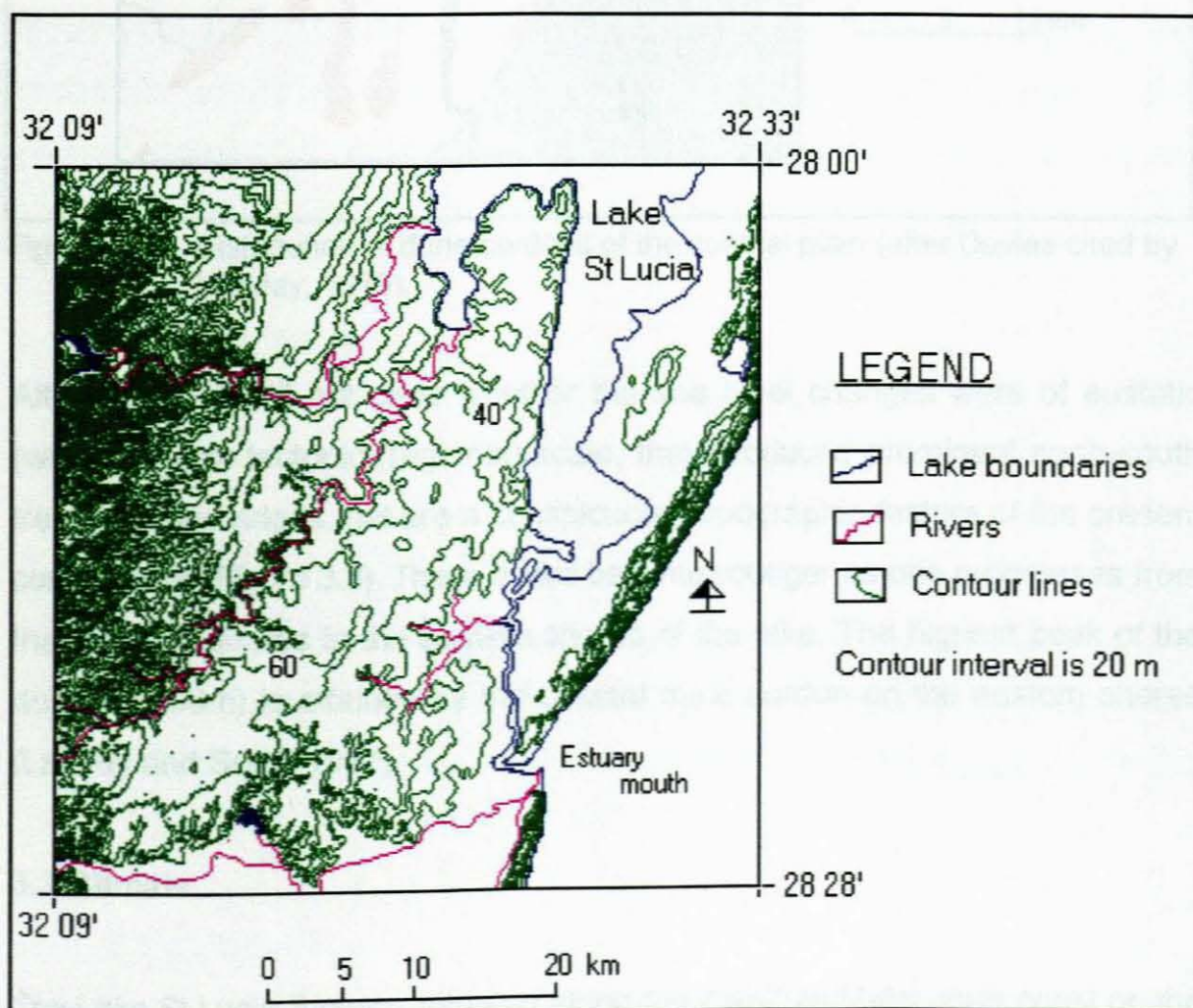


Figure 3.2 Digitized topographical map of St Lucia based on topographical sheet series of St Lucia produced by the Government Printers between 1979 and 1981.

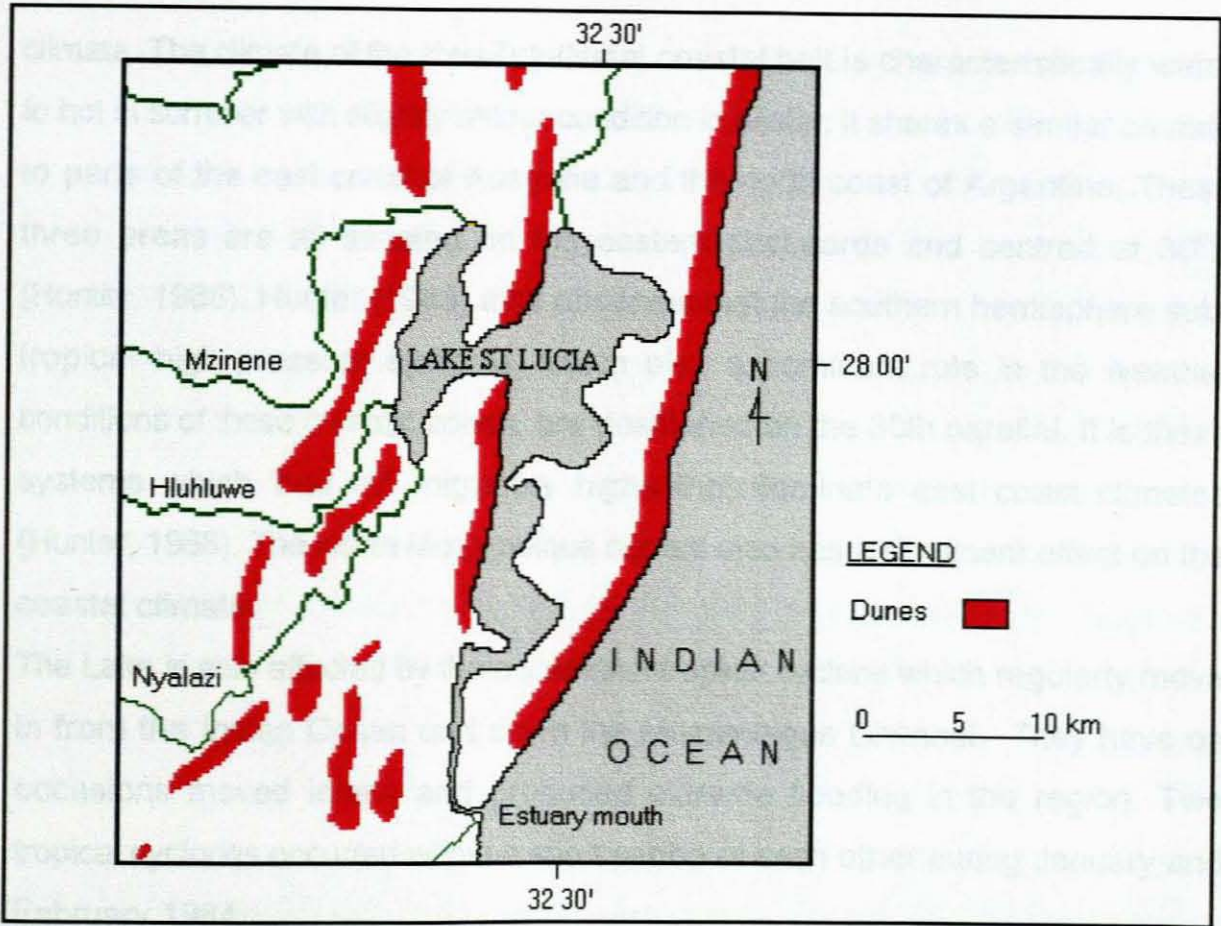


Figure 3.3 Distribution of dune cordons of the coastal plain (after Davies cited by Hobday, 1979).

3.3.1 Temperature

Although, it is still not clear whether the sea level changes were of eustatic (worldwide) or tectonic (regional) scale, they produced prominent north-south trending dune ridges that are a conspicuous topographic feature of the present coastal plain (Figure 3.3). These dunes become younger as one progresses from the western shores to the eastern shores of the lake. The highest peak of the dunes (>100m) is attained by the coastal dune cordon on the eastern shores (Lindley and Scott, 1987).

The mean annual temperature of the study area is 21.3°C (Dreyer, 1982)

3.3 Climate

3.3.1 Rainfall

The Lake St Lucia System, situated along the KwaZulu/Natal north coast on the eastern seaboard of South Africa, experiences a warm, humid and subtropical

climate. The climate of the KwaZulu/Natal coastal belt is characteristically warm to hot in summer with slightly milder condition in winter. It shares a similar climate to parts of the east coast of Australia and the north coast of Argentine. These three areas are all situated on the eastern seaboard and centred at 30°S (Hunter, 1988). Hunter (1988) also observes that the southern hemisphere subtropical high pressure systems, which play a dominant role in the weather conditions of these climatic zones, are positioned on the 30th parallel. It is these systems which 'bud off' migratory highs that dominate east coast climates (Hunter, 1988). The warm Mozambique current also has a dominant effect on the coastal climate.

The Lake is also affected by the occasional tropical cyclone which regularly move in from the Indian Ocean and down the Mozambique Channel. They have on occasions moved inland and produced extreme flooding in the region. Two tropical cyclones occurred within a short period of each other during January and February 1984.

3.3.1 Temperature

Summer seasons (October to March) are warm to hot with the monthly maximum temperatures ranging between 24°C and 28°C.

Winters (April to September) are mild with mean monthly maximum temperatures of between 16°C and 22°C. The average annual temperature as recorded at Charter's Creek weather station (see Figure 6.6) in the middle of the study area, is 21.5°C (Taylor, 1982).

3.3.2 Rainfall

Rainfall is considered to be the major type of precipitation received in the

area, although no dew or fog measurements have been made. Nevertheless, rainfall would be the primary source of recharge to groundwater (Kelbe and Rawlins, 1992). The main rainy season is in summer when maximum rainfalls are recorded. The minimum rainfall occurs during the winter months. Hutchison (1976) estimated that the mean annual precipitation ranges from more than 1300 mm at Cape St Lucia to less than 700 mm north-west of the lake. This, according to Kriel (1965), decreases to even lower values northwards along the Mkuze River. Generalized rainfall maps for the year and each month have been presented by Schulze (1982) and described in more detail in Chapter 6.

3.3.3 Evaporation

Evaporation is high in this climatic region in response to high temperatures and radiation loads. The western shores area of Lake St Lucia has several evaporation measuring stations from which Hutchison (1976) compiled iso-evaporation map. Unlike the rainfall, the actual evaporation increases from 1461 mm near the coast (Mbazwane) in a westerly direction to reach a peak of 1688 mm in the Hluhluwe river valley (Hluhluwe Dam).

Potential evapotranspiration maps for each month have also been presented by Schulze (1982).

3.4 Drainage

The Zululand coastal plain is chiefly a flat region with small rolling hills which are usually dune relics. The Lake St Lucia System on the Zululand coastal plain is maintained by five major rivers which drain small to large catchments areas. These "exotic" rivers (Tinley, 1971) include the Nyalazi, Hluhluwe, Mzinene,

Mkuze and Mpate (Figure 1.1). The Umfolozi River to the south of the lake was diverted in 1952 from the Lake Estuary to its present separate mouth, and thus does not have a major influence on the water levels and salinities of the Lake.

The Nyalazi and Hluhluwe rivers have their origin in the high region of the basaltic formation (Lebombo) to the west of the lake system and they enter the lake through the southern and south-western end of False Bay, respectively. The Mpate river drains a small catchment in the coastal plain and discharges directly into the Estuary Basin. The Mzinene River enters the northern reaches of False Bay and also has its origin in the high elevation of the western regions. The Mkuze River drains the largest catchment and enters the Lake through a large swamp north of the Lake. According to Tinley (1971) the size and strategic position of the Mkuze River, directly opposite the Estuary, is important as it is sufficient to flush out the lake periodically during extreme rainfall events that occur with tropical cyclones.

The upper catchments of most of these rivers are exploited for agricultural and domestic purposes. All these rivers, except the Mkuze River, are non-perennial (Kriel, 1965).

3.5 Vegetation and Land-use

The western shores area of Lake St Lucia is shrouded by a diverse vegetation cover which includes natural grasslands, scattered indigenous shrubs, thickets and trees, swamps, indigenous forests, and commercial plantations. This diverse vegetation cover forms an integral part of the lake ecosystem. The swamps and wetlands form a vital filter and sponge areas for the lake system. However, much of the natural vegetation of the catchment area of the lake has been replaced with commercial forest plantations which are known to have reduced inflow to the

Lake (Lindley and Scott, 1987). This is particularly prevalent on the western shores area of the Lake where extensive exotic plantations and indigenous forests occur.

3.6 Hydrology

According to Perkins (1993), direct inflow into the lake is derived from a catchment area of about 7515 km². Cornelius (1993) has estimated the natural mean annual surface inflow of freshwater to the lake from the various catchments using simulation studies because the measured flows in most rivers are not considered reliable enough. The total simulated mean annual run-off (MAR) under natural conditions was approximately 417 million cubic metres. This has been reduced to 362 million cubic metres under the present land-use conditions (Cornelius, 1993). This estimate is close to the 460 million cubic metres estimated for the average annual inflow derived by Nanni (1982). The individual components of the Nyalazi, Hluhluwe, Mzinene, Mpate and Mkuze Rivers were also estimated by Cornelius (1993) and are given in Table 3.1. The Mkuze River is estimated to discharge nearly two times the total discharge of all the other rivers combined.

The mean annual groundwater flow into the lake from the eastern shores has been estimated as $4 \times 10^6 \text{m}^3$ by Kelbe and Rawlins (1992). There are no major rivers draining the eastern shores region which indicates that all the effective rainfall must enter the lake through the groundwater. Consequently, sections of the western shores must also contribute a substantial proportion of discharge into the lake system which has been through the groundwater. The $4 \times 10^6 \text{m}^3/\text{year}$ estimated groundwater flow from the eastern shores is approximately 10% of the MAR for the Hluhluwe River and close to 25% of the Mpate River. This may be a major contribution during extreme drought conditions.

Table 3.1 Natural (Nat) and present (Pres) mean annual run-off (MAR) of five major rivers of Lake St Lucia system (after Cornelius, 1993). Also included is the Mean Annual Precipitation (MAP).

River	Catchment (km²)	MAP(mm)	MAR(Nat) (10⁶m³)	MAR (Pres) (10⁶m³)
Mpate	250	1100	26	18
Nyalazi	710	900	39	27
Hluhluwe	1030	900	56	44
Mzinene	710	690	30	29
Mkuze	3385	795	266	244

CHAPTER 4 GEOLOGY AND SOILS

4.1 Early Geological Formations (Pre-Cambrian to Cambrian)

The geology of the St Lucia catchment area ranges from Pre-Cambrian and Cambrian period (Ca. 3100 Ma) rocks to recent unconsolidated sediments. The general geological succession of this area is given in Table 4.1.

The basement of the St Lucia geology is formed by the Empangeni gneiss of the Kaapvaal Craton (Wolmarans & Du Preez, 1986). These potassic granites and amphibolites rocks are exposed further south of St Lucia, at locations to the west of Empangeni.

Resting unconformably on these Precambrian (to Cambrian) rocks is the Natal Group, a sandstone sequence of fluvial origin (Tankard *et al*, 1982; Wolmarans and Du Preez, 1986). This Group consists of a medium-grained, purplish quartzofeldspathic sandstone succession and minor conglomerates that outcrop on the central part of the St Lucia catchment near Hluhluwe Game Reserve (Wolmarans and Du Preez, 1986).

The Karoo Supergroup unconformably overlies the Natal Group. The basement Dwyka Formation of the Karoo Supergroup is a tillite-dominated succession which rests with distinct unconformity on Precambrian rocks (Tankard *et al*, 1982).

The Dwyka Formation is conformably overlain by a succession of the Eccca Group sediments. The Eccca succession ranges from the basal mudstone and shale of the Pietermaritzburg Formation, through the white-grey sandstones and grey

Table 4.1 Generalised stratigraphic succession (modified from von Veh and Andersen, 1990; and Worthington, 1978).

PERIOD	EPOCH	GROUP	FORMATION
Quaternary	Recent (Holocene)		Alluvial and estuarine sands with silt and clays. Grey and reddish brown aeolian sands
	Pleistocene		Berea red sands. Light-grey sandy limestone. Light-grey, yellowish-orange sands and clayey sand of the Port Durnford Formation. Lignite layer.
Tertiary	Pliocene-Miocene		Shelly limestone and calcarenites of the Uloa Formation.
	Palaeocene		Siltstones of the Richards Bay units.
Cretaceous	Senonian	Zululand	Siltstone of the St Lucia Formation. Glauconitic, marine siltstone or fine clayey sandstone of the Mzinene Formation. Conglomerate, grit and sandstone interbedded with shallow-water siltstone of the Makatini Formation.
Jurassic		Lebombo (Basalts)	Amygdaloidal trachybasalts, airfall deposits (Bumbeni Complex).
Permian to Cambrian		Ecca	Blue-black micaceous shale and mudstone of the Volkrust Formation. Medium-grained, white-grey sandstone and grey micaceous shale of the Vryheid Formation. Black mudstone and shale of the Pietermaritzburg Formation.
Pre-Cambrian		Empangeni	Gneissic granites, amphibolites

micaceous shales of the Vryheid Formation, to the black or bluish-shale and mudstone of the Volksrust Formation (Wolmarans and Du Preez, 1986), these rock types occur on the western portion of the study area (Figure 4.1).

The Ecca sediments are disconformably overlain by the volcanics of the Lebombo Group (Wolmarans and Du Preez, 1986). Frankel (1960) reports that exposures of the Lebombo basalts in the Umsinduzi River valley along the exposed portion of the Empangeni-Eteza Fault, are in direct contact with the basement gneissic granite. The Lebombo Group of the Karoo Supergroup consists of the basic basalts which are overlain by acidic rhyolites (Cleverly and Bristow, 1979) and to the east by younger Cretaceous sediments.

According to Tankard *et al* (1982) the basaltic and rhyolitic lavas of the Lebombo Group were violently extruded during the Jurassic period and persisted intermittently into Cretaceous time. Tankard *et al* (1982) suggest that basaltic

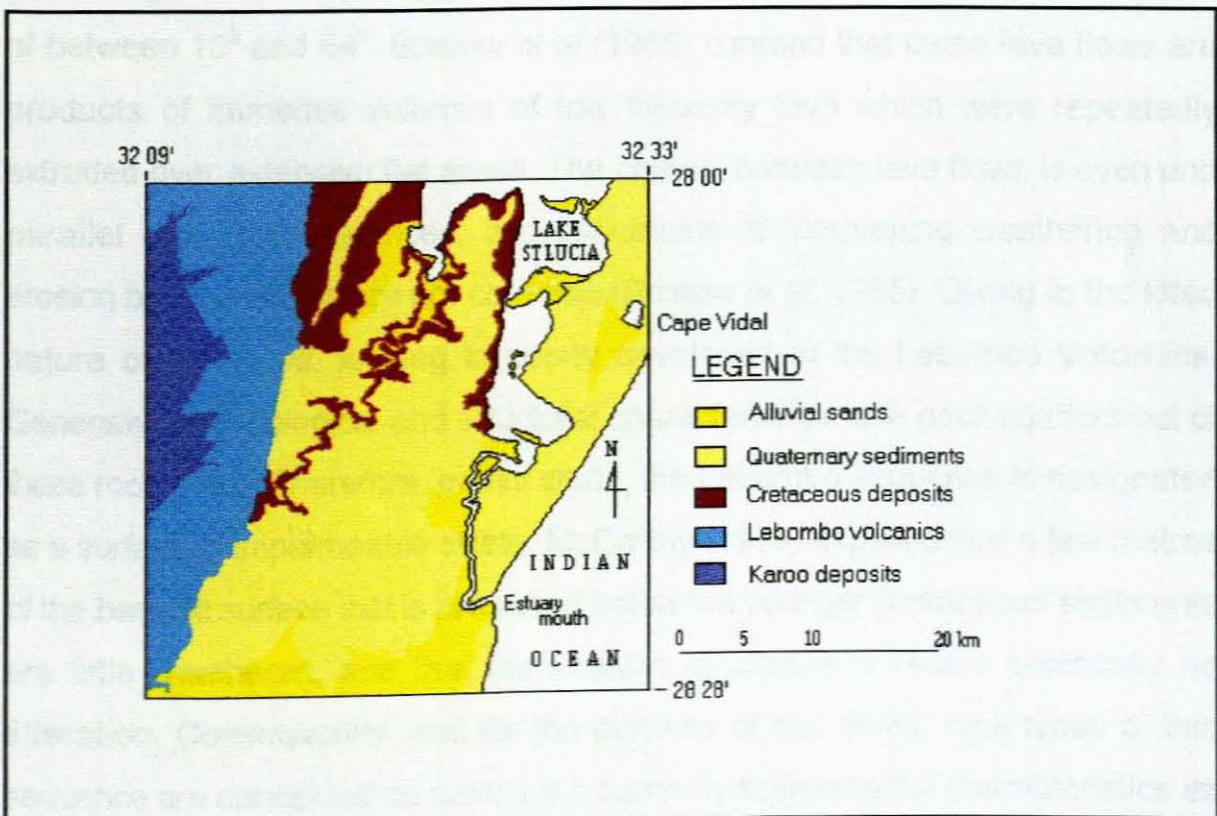


Figure 4.1 Surface geological map of St Lucia area.

outpourings were a manifestation of the Gondwana breakup, and this volcanism marked the termination of the Karoo sedimentation. This view is supported by McCarthy (1979) who summarises the evolution and demeanour of the Lebombo monoclinical structure as follows : "Great east-west tension, probably associated with the fragmentation of the Gondwanaland, permitted shallow emplacement of a large wedge of basic magma toward the inland margin of the monoclinical structure. Reduced tension and confinement of this basic magma allowed time for differentiation and also assimilation of Karoo sediments and Archean granite, leading eventually to the eruption of acid lavas." McCarthy also hints that the lower 5000 metres of basalt were supplied by fissures which form a north-south parallel dyke swarm along the axis of the Lebombo monoclinical structure.

Bristow *et al* (1985), who studied the geology of the Lebombo volcanics comprehensively, observe that basaltic lavas found in the lower portion of the southern Lebombo volcanic belt consist almost entirely of a sequence of alternating massive and amygdaloidal flows which are tilted to the east at angles of between 10° and 64° . Bristow *et al* (1985) contend that these lava flows are products of immense volumes of low viscosity lava which were repeatedly extruded over extensive flat areas. The contact between lava flows is even and parallel over long distances, and indications of intervening weathering and erosion between flows are not common (Bristow *et al*, 1985). Owing to the tilted nature of the flows, jointing is poorly developed in the Lebombo Volcanics. Generally, the lithological and structural characteristics make poor aquifers out of these rock types. Therefore, in this study, the Lebombo sequence is designated as a surface of impermeable strata. McCarthy (1979) explains that a few metres of the basaltic surface that is preserved below the younger Cretaceous sediments are little weathered, and that the basaltic groundmass shows practically no alteration. Consequently, and for the purpose of this study, rock types of this sequence are conceived as having the same hydrogeological characteristics as

the overlying impermeable Cretaceous siltstones described next, which Wolmarans and Du Preez (1986) refer to as the Zululand Group.

4.2 Early Marine Deposits

The entire Zululand Coastal Plain to the east of the Lebombo volcanics in Figure 4.1, is underlain by the nearly flat-lying Cretaceous to Tertiary/Palaeocene consolidated sedimentary rocks which abut landwards against the late Karoo volcanics of the Lebombo Group (Hobday, 1979) as shown in Figure 4.2. Cretaceous sediments are developed extensively beneath the coastal plain which stretches from Zululand through Mozambique (Tankard *et al*, 1982). The sedimentary succession of the Cretaceous age, the Zululand Group, includes three formations (Tankard *et al*, 1982):

- * the conglomerates, sandstones and siltstones of the Makatini Formation;

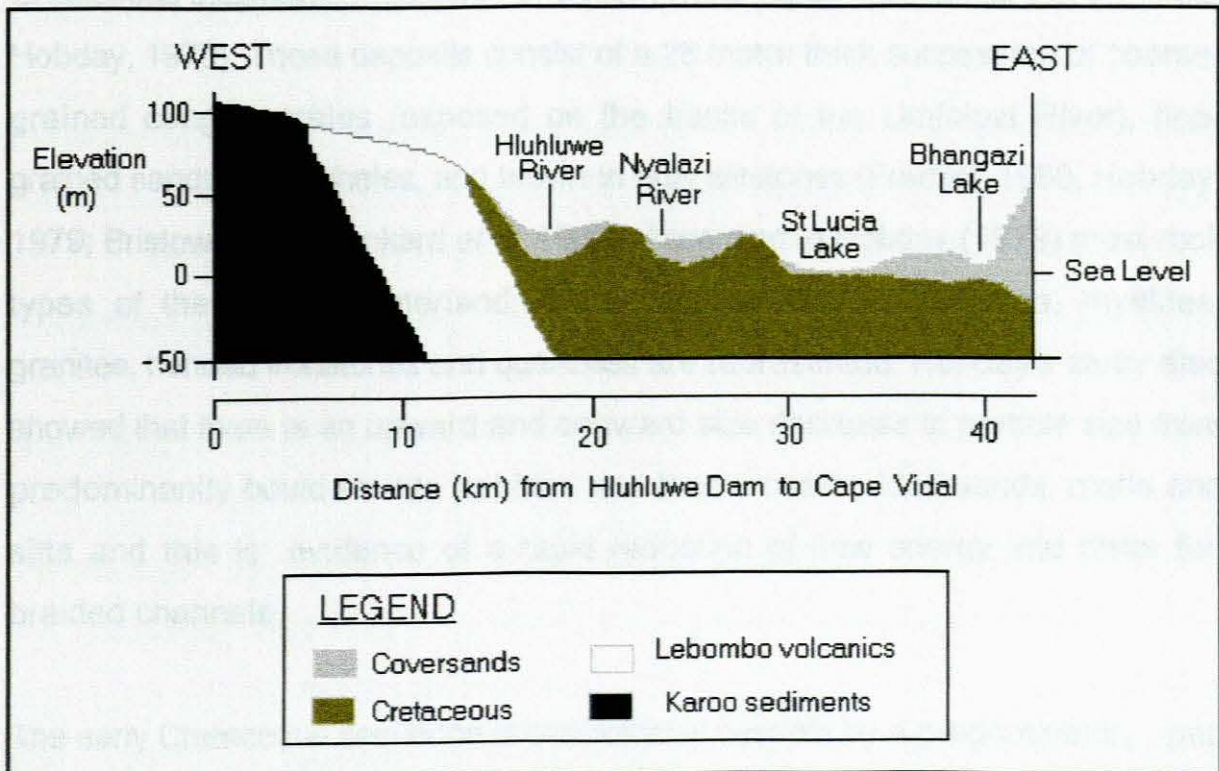


Figure 4.2 Stratigraphic section of the study area through the transect shown in Figure 4.1. The vertical scale is greatly exaggerated. The slopes are 1-3°.

- * the richly fossiliferous glauconitic siltstones and fine-grained sandstones of the Mzinene Formation, and
- * the St Lucia Formation.

These sediments of the Zululand Group form a wedge that thickens in a seaward direction from zero thickness in the west where it abuts the Lebombo group (Figure 4.2), to some 3000 metres near the coastline (Maud, 1980). The angle of dip of the surface of the Cretaceous sequence flattens from 3° in the western exposure to less than 1° in the east (King, 1970). Rocks of this sequence are intermittently exposed along the valleys of the Hluhluwe and Nyalazi Rivers and isolated outcrops are also found along the edges of the continental shelf (King, 1970) and Mfolozi Valley (Hobday, 1979).

During the breakup of Gondwanaland, rifting and uplift accompanied by north-south tensional faulting, created a seaward-stepping margin over which the early Cretaceous sediments (Makatini Formation) were deposited (Tankard *et al*, 1982; Hobday, 1979). These deposits consist of a 26 metre thick succession of coarse-grained conglomerates (exposed on the banks of the Umfolozi River), fine-grained sandstones, shales, and brown to grey siltstones (Frankel, 1960; Hobday, 1979; Bristow, 1985; Tankard *et al*, 1982). According to Hobday (1979) most rock types of the eroded hinterland, which include basalts, dolerites, rhyolites, granites, banded ironstones and quartzites are represented. Hobday's study also showed that there is an upward and seaward size decrease in particle size from predominantly boulders into pebbles and then cross-bedded sands, marls and silts and this is evidence of a rapid reduction of flow energy into distal fan braided channels.

The early Cretaceous sequence is conformably overlain by a predominantly open marine succession of yellow-brown-grey siltstones, shelly limestones, sandstones, mudstones and khaki-coloured shale bands of the Upper to Middle

Cretaceous (Bristow, 1985; Frankel, 1960). Hobday (1979) suggests that these sediments must have been the result of "both the progressive widening of the proto-ocean gulf and the worldwide transgressive character of the Senonian and Maestrichtian epochs."

According to Maud and Orr (1975) exploratory boreholes drilled in Richards Bay, show that the Cretaceous succession is generally composed entirely of the medium-hard, fine sandy siltstones with occasional thin clayey lenses and very hard sandy limestones. They found that both Cretaceous and Palaeocene sedimentary rocks have a gentle seaward dip of some 1° to 3° . On the eastern shores area of Lake St Lucia, these gently seaward-dipping rock types lie approximately 30 metres below present mean sea level (Lynn, 1989). The geophysical soundings supplied by Mr R. Meyer of the CSIR (1993) reveal that these sediments lie approximately 35 metres above mean sea level (AMSL) on the west-central part of the study area where the younger Cretaceous sequence comes into contact with the older Lebombo volcanics.

Because of their lithological characteristics, the compacted and fine-grained Cretaceous and Palaeocene siltstones have very low permeability. The same is true for the very fine to fine-grained Lowermost Pleistocene (Recent) deposits (Worthington, 1978).

4.3 Recent Deposits

Cretaceous sediments are unconformably overlain by nearly flat-lying discontinuous sediments of Tertiary age (Hobday, 1979; Maud and Orr, 1975). These are very shallow-water marine and terrestrial sediments that are relatively thin. Thickness of up to 30 metres have been reported by Maud (1980). However, Maud and Orr (1975) report, from boreholes drilled at Richards Bay, that the

maximum thickness of Tertiary (Miocene) sediments in this area does not exceed 6 metres. These sediments consist of a lower coarse coquina limestone overlying the highly fossiliferous Cretaceous limestone, and are, in turn, overlain by a greyish-white sandy-shelly limestone.

Rocks of the Tertiary age are exposed as outliers at Uloa, Sapolwana, Umkwelane Hill, Mfolozi River valley and at the Hell's Gates area on the shores of Lake St Lucia system. They are said to occur at a significantly higher elevation at Hell's Gates than at those found at Richards Bay area (Maud and Orr, 1975; Frankel, 1960; King, 1970).

The Tertiary sediments are, in turn, unconformably overlain by a complex succession of partially consolidated sandy deposits of the Port Durnford Formation (Pleistocene). The Port Durnford Formation has been comprehensively studied by Hobday and Orme (1974) who found that this sequence consists of a lower argillaceous member overlain by an upper arenaceous member. Maud (1968) describes the stratigraphic succession of this Formation (from bottom to top) as follows:

- Red and yellow mottled consolidated sand
- Yellow mottled consolidated sand passing downwards into strongly cross-bedded white consolidated sand (aeolian deposition)
- Lignite or peat with admixed sand
- Yellow brown ferruginised sandstone
- Blue grey sandy mudstone with fossil remains

According to Maud (1968) and Hobday and Orme (1974) the lower more argillaceous member was deposited under transgressive conditions. This is evidenced by the presence of a truly blue-grey sandy mudstone with fossil

remains. The lower more argillaceous member of the Port Durnford Formation is overlain by a marine regressive member which was deposited under littoral and subaerial conditions as evidenced by the lignite bed and the cross-bedded aeolian consolidated sand. Maud (1968) reports that the thickness of these old red sand beds is 20 to 25 metres. The lithology of these sediments is suggestive of a marine shallow-water, terrestrial and fresh-water lacustrine deposition (Maud, 1980 and Hobday, 1979). Good outcrops of this Port Durnford Formation are found along sea-cliffs (Maud and Orr, 1974) and isolated exposures also occur along the margins of Lake St Lucia.

Lithology of the St Lucia Estuary

The Port Durnford beds are overlain by a relatively thin cover of unconsolidated to partially compacted late-Pleistocene to Recent sands. They are comprised of successive units of boulder beds, old red sands, younger coversands, coastal dunes and calcarenites of aeolian, estuarine and alluvial origin (Hobday, 1979; Tinley, 1987). This lithology, according to Hobday (1979), reflects a complex history of erosion and sedimentation during the Quaternary period. This view is supported by Frankel (1968) who observes that Tertiary and Quaternary shallow-water as well as dune sediments along the Natal and Zululand coastal region must have originated as a result of minor eustatic or epeirogenic movements which caused transgressions and regressions over large areas of the coastal region.

Maputaland

The Zululand coastal plain is characterized by the north-south trending coastal dune ridges (see Figure 3.3 in Chapter 3). These dunes attain elevations of approximately 190 metres to the south of the St Lucia Estuary and flatten out northwards into very low hummocky structures of Maputaland (Hobday, 1976). The dune ridges consist of homogeneous sand which overlies boulder and pebble bearing deposits. Hobday (1976) attributes these sands to aeolian processes which accompanied marine regressions. He also ascribes the basal coarser (estuarine or beach) deposits to transgressive-regressive couplet.

The western shores' dune ridges are covered by a very fine-grained and well sorted sand. The entire coastal plain is blanketed with these coversands whose thickness ranges from 0.5 to 3 metres (Hobday, 1976). Hobday (1976) suggests that these were derived by leaching of the red sands. Generally, the coversands include aeolian foredune complexes, fluvial and alluvial sediments infilling buried channels, and unconsolidated Holocene sediments. They are comprised of fine to medium, well-rounded grains of sand that display high permeabilities and porosities. These geohydrological properties decrease with depth due to increase in compaction (Rawlins, 1991). The coversands play a very important role in the hydraulics of the St Lucia aquifer system.

4.4 Soils

Soils in the coastal region of Natal are noticeably related both to the parent material which was diversified by the eustatic or epeirogenic movements during the late-Jurassic time and to climatic conditions (Maud, 1968). Maud (1968) observes that these coastal soils are distinctively young and lack marked profile differentiation.

Of the 19 Natal soil groups identified by Fitzpatrick (cited by Schulze, 1982), the study area consists of three major ones (Figure 4.3). These include, from east to west,

- the coastal grey and red sands (Group 19),
- the red structured /apedal freely drained clays and duplex soils (Group 5),
- the black and red structured clays and duplex soils (Group 11),

According to Maud (1968), the coastal red sands are a product of the former aeolian material which originated from the weathering of aeolinities during the "period of tropical weathering". These coastal soils are very sandy and much

leached and hence are rapidly draining and infertile with low agricultural potential (Maud, 1980). Bruton (1980) reports that these coastal sandy soils have low moisture holding capacity and a depth of up to 3 metres. The sandy nature and high permeability of these soils promote high infiltration rates and little surface runoff (Rawlins, 1991). Maud (1980) observes that on dune areas the soils are also leached and rapidly draining, but on the interdune areas the water table is perched on the surface of the more clayey Port Durnford Beds. In the west of the study area, the foothills of the Lebombo Range are covered by shallow red structured and/or apedal, freely drained clays and duplex soils derived from basalts and rhyolites (Schulze, 1982).

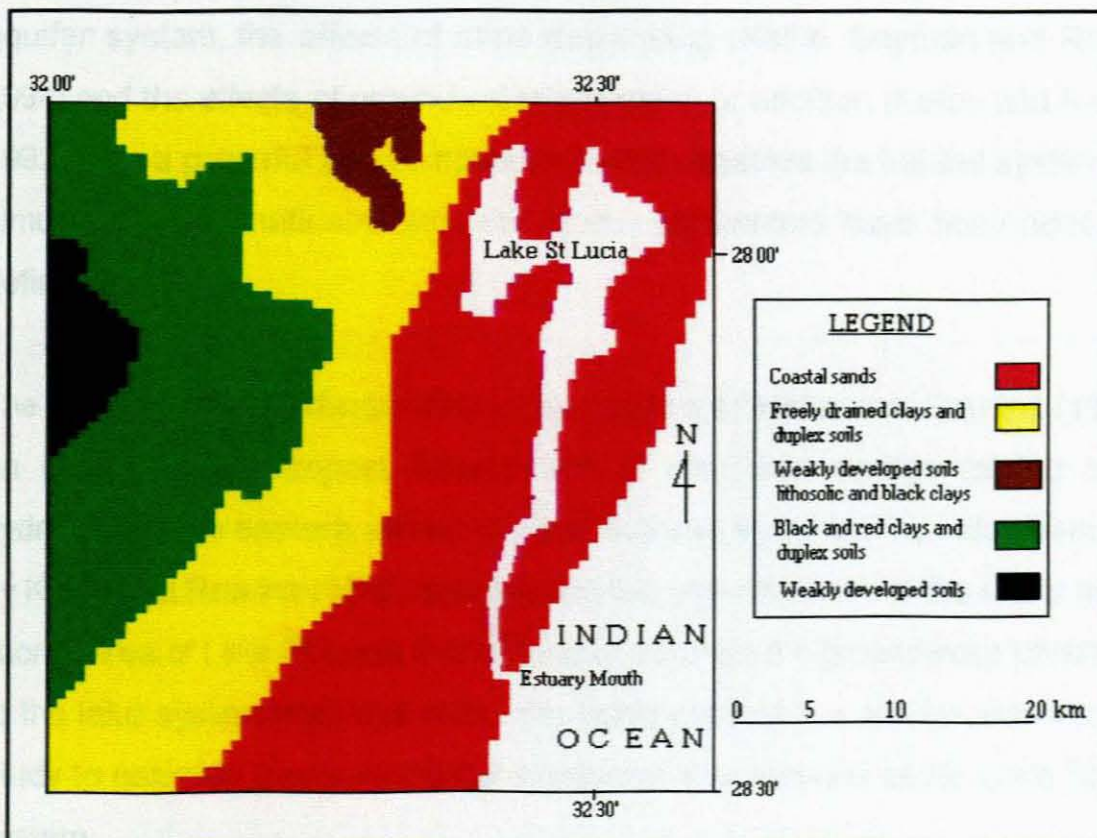


Figure 4.3 Generalised soils map of the St Lucia system (after Fitzpatrick cited by Schulze, 1982).

CHAPTER 5

DESCRIPTION OF THE MODEL AND ITS PARAMETER REQUIREMENTS

In order to estimate the groundwater flow contribution to the lake, numerical modelling was used to simulate the behaviour and response of the groundwater to the geological and climatic characteristics of this area. The model used in this study (INTERSAT) was selected by the Department of Hydrology at the University of Zululand after an assessment of the relative capabilities of groundwater models available at the time (Kelbe and Rawlins, 1991).

INTERSAT is specifically designed as an aid in solving geohydrological problems and incorporates several components for determining the water balance of an aquifer system, the effects of mine dewatering (Kelbe, Snyman and Rawlins, 1994) and the effects of groundwater extraction or addition (Kelbe and Rawlins, 1992). It is a powerful and complex tool which enables the natural system to be simulated mathematically once the model parameters have been adequately defined.

The INTERSAT groundwater model was applied by Kelbe and Rawlins (1992) in an Environmental Impact Assessment of proposed dredge mining on the hydrology of the eastern shores of Lake St Lucia system. It has also been used by Kelbe and Rawlins (1992) to determine the water balance of the entire eastern shores area of Lake St Lucia system and to estimate the groundwater contribution to the lake system from this area. It is being applied in a similar manner in this study to estimate the groundwater discharge into sections of the Lake St Lucia system.

5.1 General Description of the Model

The INTERSAT groundwater model is a quasi-3D finite difference model which was developed by Voorhees and Kirkner (1986) and revised by Voorhees (1991). 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. It can accommodate up to eight layers of differing geology. It uses finite difference linearization to solve the groundwater flow equations.

5.2 Mathematical Description of the Model

There is very little description of the concepts and mathematical coding in the User Manual provided with the INTERSAT model computer programme (Voorhees and Kirkner, 1986). Consequently, it was necessary to refer to standard texts (Kinzelbach, 1986) to understand and estimate the model parameters before the model could be applied. The INTERSAT User Manual (Voorhees and Kirkner, 1986) gives examples of specific applications and the expected results and these examples were used to derive an understanding of the model parameters during application. Since there is no detailed description of the model in the user manual, the basic concepts are summarized and the model parameters identified in the next sections from various sources (Voorhees and Kirkner, 1986; Kinzelbach, 1986; and Kelbe and Rawlins, 1992).

The INTERSAT groundwater model describes the subsurface hydraulics using a finite difference linearization approach to solve the groundwater flow equations based on the three-dimensional vector volume (Voorhees and Kirkner, 1986). The finite difference approach upon which the groundwater 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 the specific

flow rate (V) is proportional to the negative head gradient (∇h).

$$V = -K_f \nabla h \quad (1)$$

where

$V = (V_x, V_y, V_z)$ is the velocity vector

$\nabla = (\delta/\delta x, \delta/\delta y, \delta/\delta z)$

and K_f is the permeability. K_f is specified for each direction which allows one to take into account the anisotropic conditions of flow.

The differential equation for saturated flow is derived by taking a water balance around a control volume which extends in the vertical direction from the top to the bottom of the aquifer unit as illustrated in Figure 5.1. The net flow entering the control volume over a selected time interval of $[t, t+\Delta t]$ must balance out the change in the water stored. Flows that are considered in the model are the horizontal flows and the vertical recharges (or abstractions) made through the top and bottom surfaces of the control volume.

Thus, the water balance is given by:

$$\Delta t[(mV_x|_{x+\Delta x}\Delta y)-(mV_x|_x\Delta y)+(mV_y|_{y+\Delta y}\Delta x)-(mV_y|_y\Delta x)]+(q\Delta x\Delta y) = S\Delta x\Delta y(h[t+\Delta t]-h[t]) \quad (2)$$

where

m = the depth of the aquifer

q = the vertical recharge or discharge (abstraction) rate per unit area, and

S = the storage coefficient. This variable expresses the volume of water which is stored additionally by compressibility in a column of the aquifer with unit cross-sectional area and depth (height), m , if the hydraulic head, h , is increased by one unit.

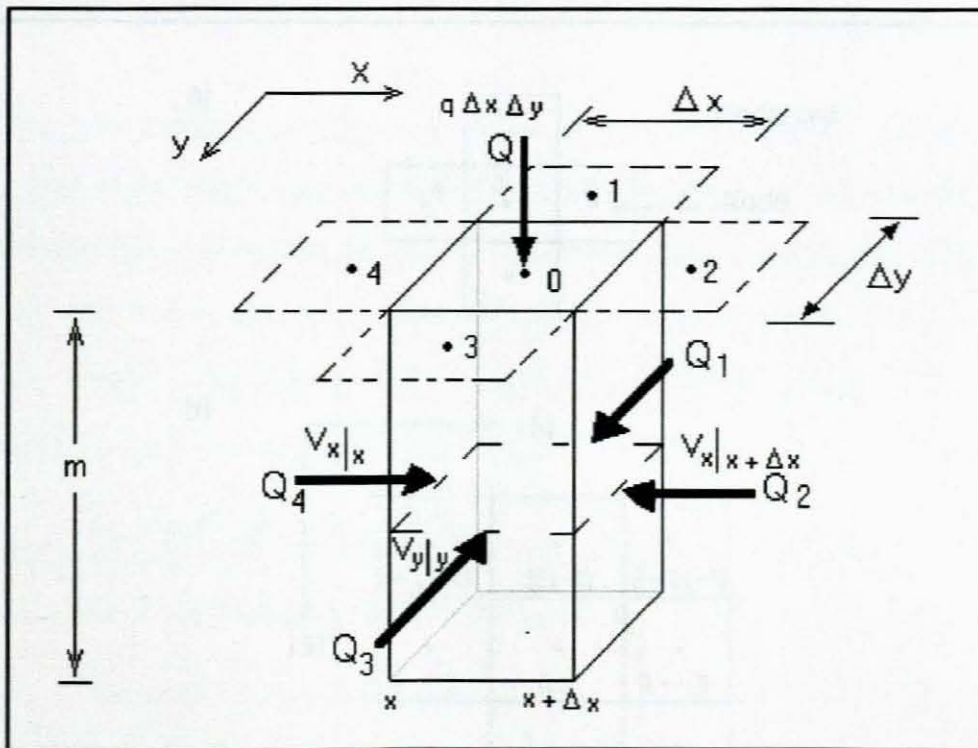


Figure 5.1 Water balance around one nodal cell (after Kinzelbach, 1986).

Dividing equation (2) by $\Delta t \Delta x \Delta y$ and taking the limits $\Delta x \rightarrow 0, \Delta y \rightarrow 0, \Delta t \rightarrow 0$, gives a partial differential equation:

$$\nabla(m V \nabla h) + q = S \delta h / \delta t \quad (3)$$

On substituting Darcy's Law for the velocity of water through a porous medium this becomes:

$$\nabla(m K \nabla h) + q = S \delta h / \delta t \quad (4)$$

In an unconfined aquifer situation, the transmissivity (mK) becomes a function of head as the saturated thickness varies with the water table. Thus, equation (4) above becomes:

$$\nabla[(h-b) m K \nabla h] + q = N_e \delta h / \delta t \quad (5)$$

where the effective porosity, N_e , has replaced the storage coefficient, S ; and $(h-b)$

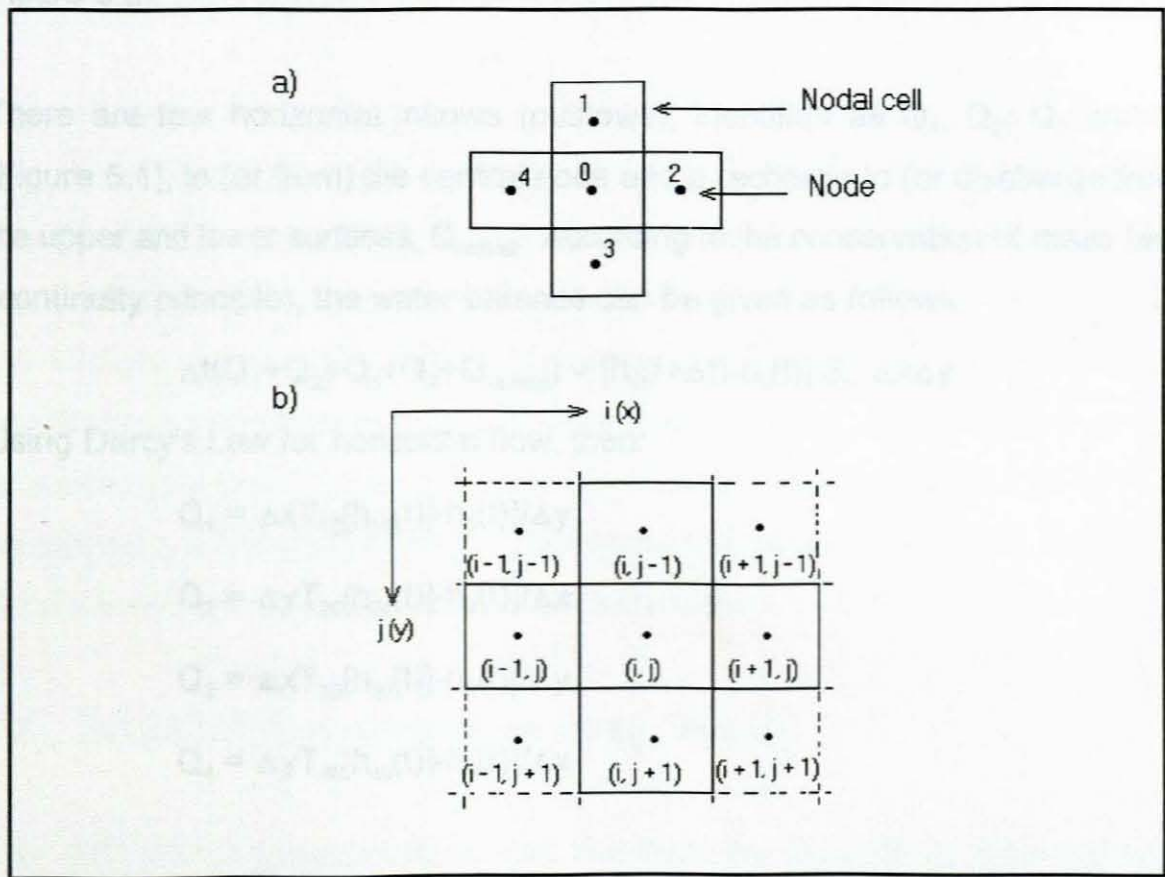


Figure 5.2 Local (a) and global (b) nomenclature of nodes (after Kinzelbach, 1986).

is the depth of the water table in the layer. The above flow equation can be solved analytically only under very simple idealistic conditions, and the solution generally requires discretization in space and time (Kinzelbach, 1986).

The differential numerical method of solution replaces the partial differential equation of flow by a set of finite difference equations in discretized space and time. The aquifer is first divided up into a rectangular grid where the nodal distances in the x and y directions (Δx , Δy) may vary. The centre of a cell is called a node, and the volume associated with a node extends in a vertical direction over the whole thickness of flow. The central node about which a water balance is taken, is denoted by a zero, 0; and the four surrounding nodes are labelled 1, 2, 3 and 4 in a clockwise direction starting with the upper node, as shown by

Figure 5.2.

There are four horizontal inflows (outflows), identified as Q_1 , Q_2 , Q_3 and Q_4 (Figure 5.1), to (or from) the central node and a recharge to (or discharge from) the upper and lower surfaces, Q_{vertical} . According to the conservation of mass laws (continuity principle), the water balance can be given as follows:

$$\Delta t(Q_1+Q_2+Q_3+Q_4+Q_{\text{vertical}}) = [h_0(t+\Delta t)-h_0(t)] S_0 \Delta x \Delta y$$

Using Darcy's Law for horizontal flow, then:

$$Q_1 = \Delta x T_{10}[h_{10}(t)-h_0(t)]/\Delta y$$

$$Q_2 = \Delta y T_{20}[h_{20}(t)-h_0(t)]/\Delta x$$

$$Q_3 = \Delta x T_{30}[h_{30}(t)-h_0(t)]/\Delta y$$

$$Q_4 = \Delta y T_{40}[h_{40}(t)-h_0(t)]/\Delta x$$

where it is assumed that average flows Q_1 , Q_2 , Q_3 and Q_4 over a given time interval can be approximated by piezometer head values at some time t contained in the interval $[t_0, t_0+\Delta t]$.

T_{10} , T_{20} , T_{30} and T_{40} are spatial average values of the transmissivities between nodes 0 and 1, 0 and 2, 0 and 3, and 0 and 4, respectively (Kinzelbach, 1986).

The above equations can then be solved for each node using an iterative method (Kinzelbach, 1986). Steady state conditions are characterised by $\delta h/\delta t=0$, and can only be solved by implicit solution methods because the explicit method of solution becomes unstable for extremely large Δt (Kinzelbach, 1986). The INTERSAT Model provides several iterative methods of solution but the one which was used in this study because it gave the fastest convergence and was the most stable was the Gauss-Seidel technique applied in the Alternating

Direction Implicit (ADI) scheme of Prickett and Longuist (1971).

The INTERSAT model requires the estimation of representative parameter values for the transmissivity (T) and storage coefficient (S) of each node. The specification of transmissivity is derived from estimates of aquifer thickness and the hydraulic permeabilities of each node. The model also requires estimates of the vertical components of recharge and discharge Q_{vertical} . These vertical components involve other hydrological processes and it is necessary to derive conceptual models of the relevant conditions to determine estimates of their contributions to the water balance. The conceptual models are discussed in more details in the next section on parameter estimation.

5.3 INTERSAT Model Parameter Requirements

The INTERSAT groundwater model requires the input of a wide range of parameters which include, amongst others, model grid dimensions, boundary conditions, recharge/discharge, storage and flow parameters.

5.3.1 Model grid and boundary selection

The selection of the model grid is a function of the boundary conditions of the system. That is, boundaries of the model have to be identified first and foremost.

Anderson and Woessner (1992) defined boundary conditions as mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain. Since the equations of flow are partial differential equations with respect to time and space, both the initial conditions in the whole modelled

domain and the boundary conditions must be given for the model solution.

Three possible types of boundary conditions may apply to any part of the modelled domain (Boonstra and de Ridder, 1981; and Kinzelbach, 1986):

- a) Dirichlets - these are boundary conditions of the first kind which prescribe the head value (ie constant head).

The Dirichlets or specified head boundaries are assumed to represent an inexhaustible supply of water. The groundwater system may pull water from or discharge water into the boundary without changing the head at the specified location. In block-centred finite difference grids, specified head boundaries are located directly at the node but flux boundaries are located at the outside edge of the block. Values for heads and fluxes at the boundaries must be determined from field measurements. Examples, include large water bodies such as lakes and oceans where the water body is sufficiently large for the fluxes to have negligible impact on the head. They also include water courses such as rivers and irrigation canals where there is a sufficient supply of water to sustain the fluxes without impacting on the heads.

- b) Neumann - these are boundary conditions of the second kind or zero flux (no-flow) boundaries.

The Neumann or zero flux boundaries can be defined as those places where flows are insignificant compared to flows in the main aquifer. A zero flux or no-flow (Neumann) boundary may represent impervious boundaries with zero flux such as unweathered massive

rock types, compacted clay layers, a groundwater divide, a streamline, or a fault that isolates the aquifer from other permeable strata. They also represent the groundwater divides between aquifers where the water table gradient becomes zero.

In a block-centred finite difference grid, no-flow boundaries are simulated by assigning zero transmissivities (hydraulic conductivities) in the “inactive” cells just outside the boundary. In this way the boundary is set at the edge of the first active block.

- c) Boundary conditions of the third kind (also referred to as semi-pervious or mixed boundary conditions) are flow-controlled boundaries.

These mixed boundaries have also been referred to as recharge boundaries, through which a certain volume of groundwater enters the aquifer per unit of time from adjacent strata whose hydraulic head and/or transmissivity are known (Boonstra and de Ridder, 1981). That is, these boundary conditions specify a linear contribution of head and flux at the boundary (*ie* a leakage boundary). They also define the surface (vertical) recharge and discharge conditions.

5.3.2 Initial conditions

Initial conditions refer to the head distribution everywhere in the system at the beginning of the transient simulation period and thus represent boundary conditions in time. These initial conditions are seldom known and consequently the initial boundary condition must be estimated for

known situations such as average climatic conditions or short term extreme events.

The INTERSAT groundwater model needs an initial estimate (starting value) of the hydraulic head. The model then recalculates the head at each node during each time step to represent the known situation. In this study, the user-specified initial head distribution is derived for a steady-state condition which represents the long term average climatic state. The transient simulation then start from assumed average climatic conditions. Thus, initial head distribution represents dynamic average steady-state conditions where head varies spatially, and flow into the system equals flow out of the system.

5.3.3 Hydraulic parameter

The rate at which water can pass through a saturated aquifer of unit depth under a unit hydraulic gradient is termed transmissivity. The model requires that the hydraulic conductivity and the thickness of the aquifer must be defined in order to compute the transmissivity at each node.

The model also requires estimates of the storage coefficient for both confined and unconfined conditions. Since the model domain is primarily the unconsolidated coastal aquifer, the unconfined (water table) storage coefficient is generally used in this study. It may be necessary to revise this if the regions to the west of the coastal plain have a strong influence on the groundwater recharge along the lake shoreline.

5.3.4 Net vertical recharge and discharge

Anderson and Woessner (1992) define recharge as the volume of

infiltrated water that crosses the water table and becomes part of the groundwater flow system. Discharge is the groundwater that moves upwards across the water table surface and discharges directly to the topographical surface or to the unsaturated zone. Thus, the net recharge is an algebraic sum of the external fluxes of precipitation (rainfall), evapotranspiration and surface run-off. Owing to the fact that many of these processes take place in the unsaturated zone of an aquifer, they are not simulated in the model. Anderson and Woessner (1992) cite a number of interrelated reasons for the difficulty in modelling the unsaturated zone which include, among others:

- * the difficulty in assessing the relationship between unsaturated hydraulic conductivity and pressure head as well as the soil moisture characteristic curve (which defines moisture content and tension); and that
- * such a relationship differs depending on whether the soil is draining or wetting (*ie* it shows hysteresis).

A model which attempts to combine the surface and sub-surface hydrology involving the saturated and unsaturated zones is the SHE model. This model was developed by several national agencies in Europe and is not generally available. Since the INTERSAT groundwater model is not capable of modelling the unsaturated zone, the recharge to the aquifer is estimated by examining the contributing factors in a separate conceptual model.

In unconfined aquifers, recharge through the upper surface boundary of the model domain can occur over the entire aquifer through rainfall which may be supplemented by recharge from surface water bodies. However, the

recharge may be limited by the presence of natural or artificial impermeable materials overlying parts of the recharge area. Generally, the amount of recharge, q_{in} , in a particular area is influenced by many factors which include the vegetation cover, topography, nature of soils, and by the duration, intensity, and frequency of precipitation on the surface of the unsaturated zone.

The primary processes of natural vertical discharge from the groundwater, q_{out} , from the unsaturated/or vadose zone include evaporation, evapotranspiration, and vertical leakage into rivers and drains. Thus, effective recharge ($q_{groundwater}$) to the aquifer from rainfall through the unsaturated zone is given the non-linear processes and interactions described above.

The above situation is illustrated in Figure 5.3. This illustration of the recharge model is adapted from the SACRAMENTO MODEL given by

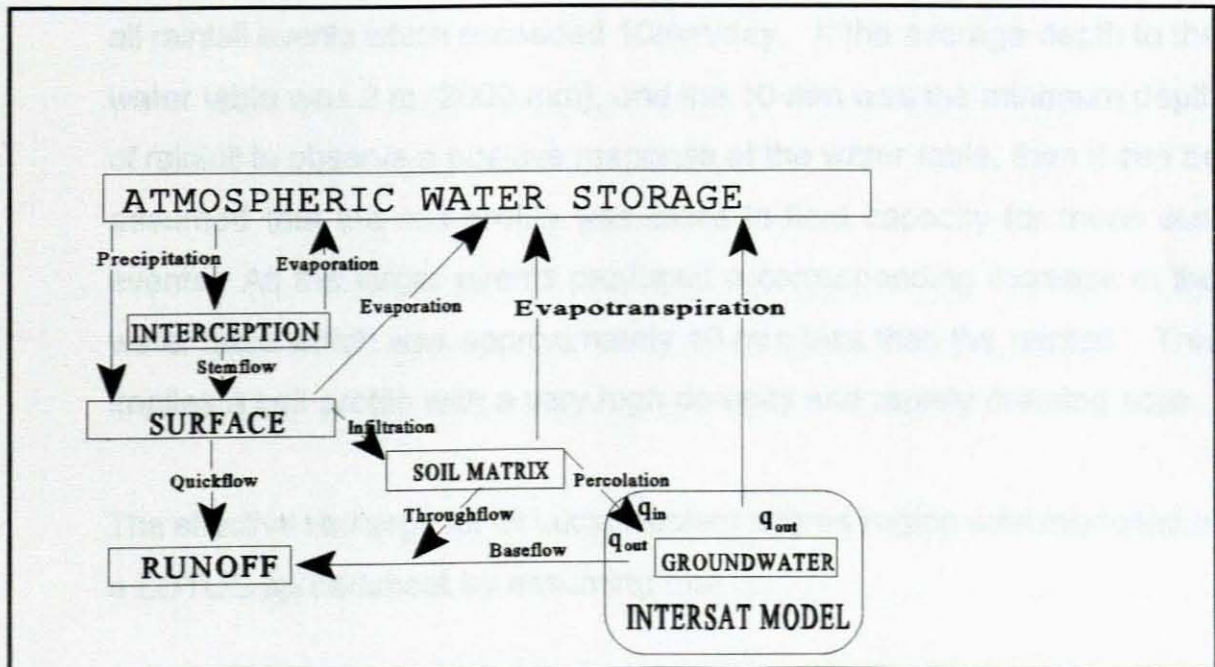


Figure 5.3 Illustration of the Surface Recharge Model (adapted from Khan and Mawdsley, 1982).

Khan and Mawdsley (1982). The boxes represent zones where water is temporarily stored, and the arrows represent hydrologic transport processes. This model was adapted in this study to estimate the amount of water that recharges the groundwater through the processes indicated as q_{in} and q_{out} .

Water from the surface may infiltrate the unsaturated zone and then percolate into the saturated zones, or evaporate back to the atmosphere. As the INTERSAT groundwater model does not simulate the unsaturated conditions, the situation in this zone should be modelled separately and assigned to the model parameters as part of the effective recharge.

This recharge was modelled from the observed response of the water table to individual rainfall events presented by Kelbe and Rawlins (1992). Their observed response for a shallow aquifer on the eastern shores region of St Lucia (Figure 5.4) indicated that the water table increased in elevation for all rainfall events which exceeded 10mm/day. If the average depth to the water table was 2 m (2000 mm), and the 10 mm was the minimum depth of rainfall to observe a positive response at the water table, then it can be assumed that the soil profile was close to field capacity for these size events. All the larger events produced a corresponding increase in the water table which was approximately 10 mm less than the rainfall. This implies a soil profile with a very high porosity and rapidly draining soils.

The effective recharge for St Lucia western shores region was modelled in a LOTUS spreadsheet by assuming that :

- (1) 10 mm accumulated daily rainfall was required to satisfy all the processes on the surface and in the unsaturated zone. This included

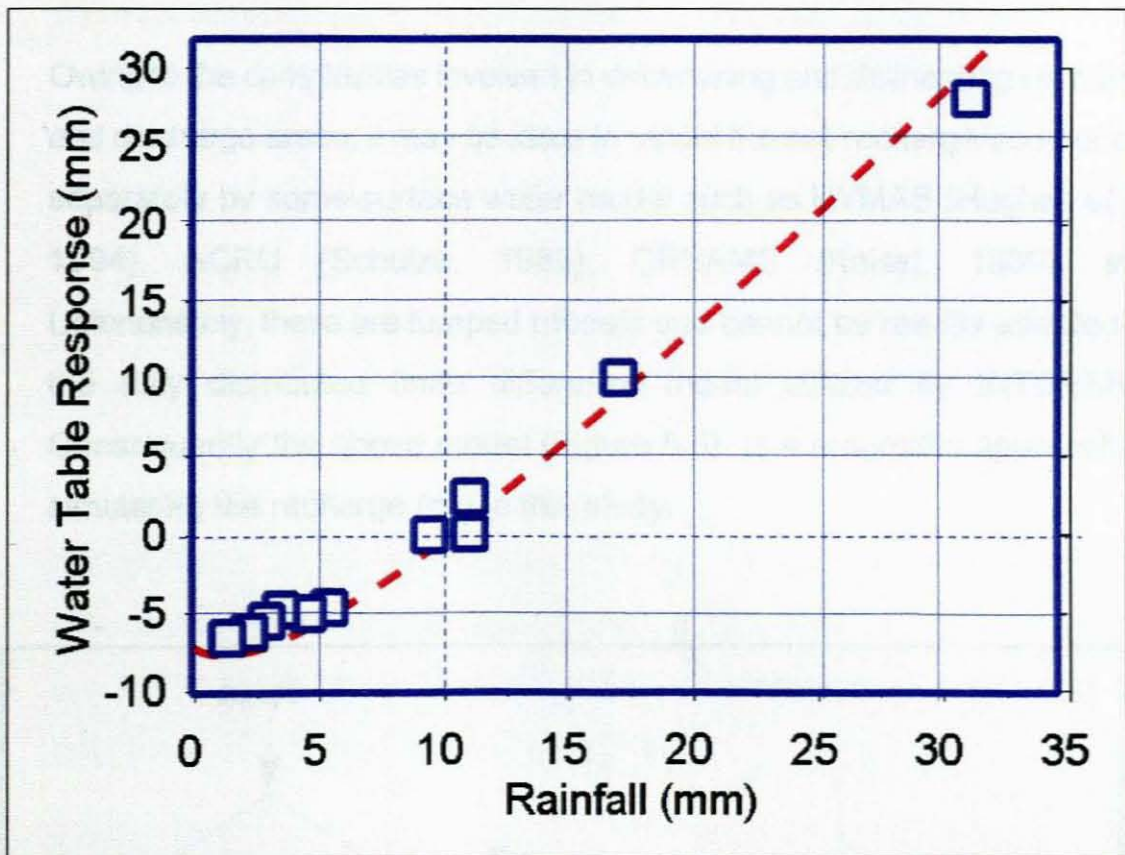


Figure 5.4 Groundwater response to incident rainfall on the eastern shores (after Kelbe and Rawlins, 1992).

vegetation interception, soil moisture storage and evaporation over a five day period before any recharge occurs. This model assumes a water loss of 2mm/day from interception and evaporation. The evapotranspiration from the groundwater through the vegetation which has roots extending into the capillary zone would be an additional loss simulated by the INTERSAT model.

- (2) Any rain falling within the 5 days since the initial 10mm event (ie within the 5 day depletion period) only required a proportion of the rainfall to replenish the soil moisture storage (up to a maximum of 10mm) and the rest of the rainfall was added directly to groundwater recharge, as illustrated in Figure 5.5.

Owing to the complexities involved in determining and delineating recharge and discharge areas, it may be ideal to model the net recharge component separately by some surface water model such as HYMAS (Hughes *et al*, 1994), ACRU (Schulze, 1988), CREAMS (Knisel, 1980), *etc.* Unfortunately, these are lumped models and cannot be readily adapted to the fully distributed finite difference model utilized by INTERSAT. Consequently the above model (Figure 5.5) is a pragmatic approach to simulating the recharge (q_{in}) in this study.

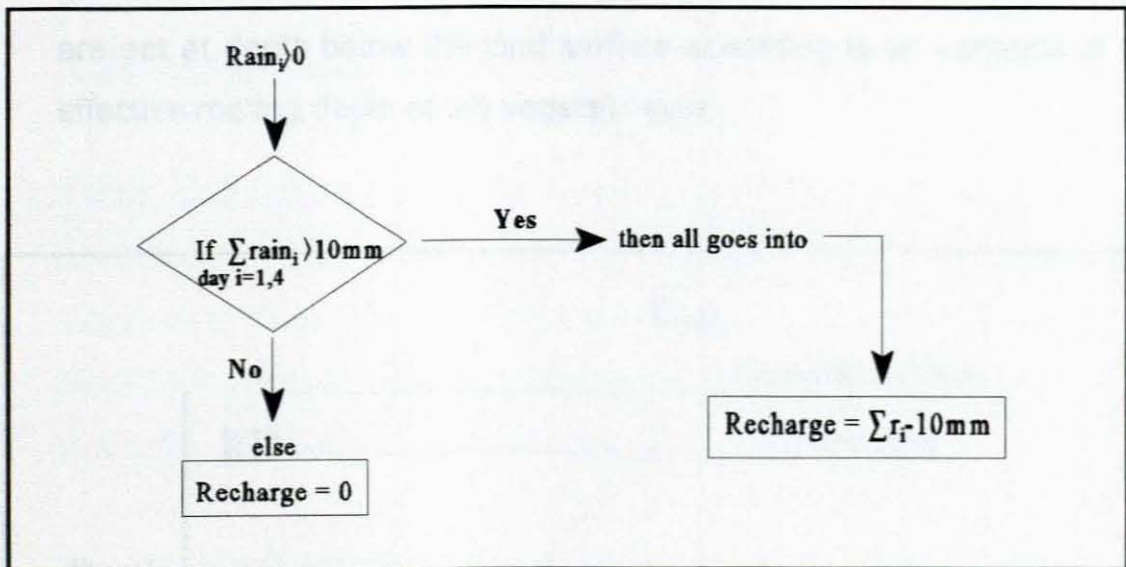


Figure 5.5 Illustration of the effective recharge model.

5.3.5 Evaporation from the groundwater

Evaporation from the groundwater is defined as the process by which water is lost through the soil surface. In the INTERSAT groundwater model the actual evaporation or evapotranspiration (E_a) from the groundwater is simulated as a vertical flux through the groundwater surface (Voorhees and Kirkner, 1986). This flux is conceived to proceed at a maximum rate, E_{max} ,

given as a conductance when the driving head (water table elevation in an unconfined aquifer) is at or above a specified lower limit of elevation, RD (Figure 5.6). This lower, RD, simulates a continuous or unlimited supply of water that enable vegetation to transpire at the maximum rate.

When the water table elevation (h) falls below this lower limit (RD), the evapotranspiration rate decreases linearly to zero when the water table reaches an assigned extinction level, RH. If the water table drops below the extinction level, hydraulic contact between the vegetation and the groundwater is assumed to be lost and evapotranspiration from the groundwater is assumed to cease. Both the lower limit and extinction depth are set at depth below the land surface according to an estimate of the effective rooting depth of the vegetal cover.

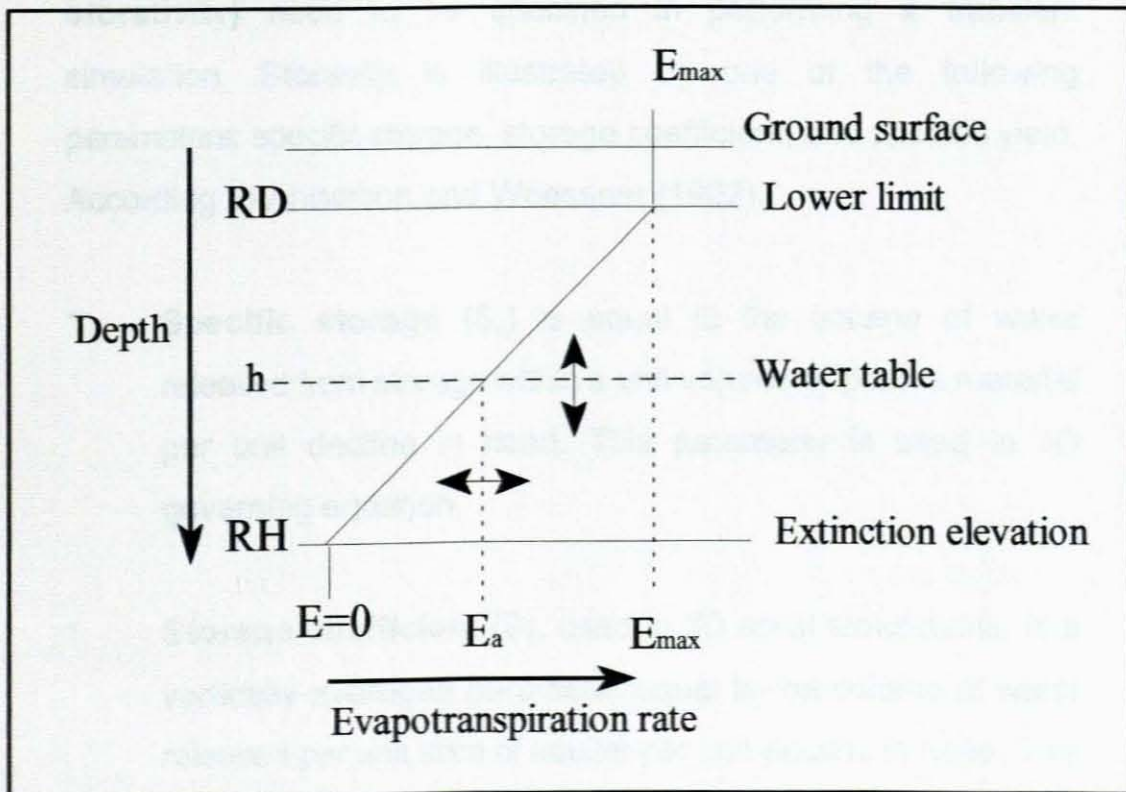


Figure 5.6 Diagrammatic representation of the evaporation model (after Kelbe and Rawlins, 1992).

The maximum evapotranspiration rate (E_{max}), which occurs when the water table elevation (h) is close to the surface is assigned to each cell from which evapotranspiration (E_T) may occur. The discharge through the evapotranspiration process described in Figure 5.6, Q_{ET} , is calculated by the model as follows:

$$Q_{ET} = Q_{ETM} \text{ for } h > RD$$

$$Q_{ET} = 0 \text{ for } h < RH$$

$$Q_{ET} = Q_{ETM} (h - RH)/d \text{ for } RH \leq h \leq RD$$

where $Q_{ETM} = E_{max} \Delta x \Delta y$,

h = elevation of the water table,

5.3.6 Storage parameters

Parameters that describe water to and from storage (referred to as **storativity**) need to be specified in performing a transient simulation. Storativity is illustrated by one of the following parameters: specific storage, storage coefficient, and specific yield. According to Anderson and Woessner (1992):

- * **Specific storage (S_s)** is equal to the volume of water released from storage within a unit volume of porous material per unit decline in head. This parameter is used in 3D governing equation.
- * **Storage coefficient (S)**, used in 2D areal simulations, is a vertically averaged parameter equal to the volume of water released per unit area of aquifer per unit decline in head. This parameter is calculated from estimates of specific storage. The relevant storage parameter for unconfined aquifer is

specific yield.

- * **Specific yield (S_y)** or Water table storage coefficient is a measure of volume of water per volume of porous material released by gravity drainage in response to decline of water table.

Specific yield and storage coefficient as well as transmissivity values can be measured during pumping tests. Porosity and permeability values can also be estimated from field measurements.

During a transient simulation, water is released from or taken into storage within the porous material. Heads change with time as a result of this transfer of water. When the transfer to and from storage stops, the system reaches steady state and heads become constant.

CHAPTER 6

CONCEPTUALIZATION AND PARAMETERIZATION OF THE NUMERICAL MODELS FOR THE STUDY AREA

Anderson and Woessner (1992) define a conceptual model as a pictorial representation of the groundwater flow system from which the dimensions of the numerical model and the design of the grid are decided. This pictorial representation is frequently presented as a block diagram or a cross section through the area. A conceptual model is based on the analysis of data concerning the physical characteristics and the lateral and vertical dimensions of geologic formations. Geological and geophysical logs are synthesized in order:

- ▶ to classify formations as aquifer or aquitard,
- ▶ to determine the thickness and boundaries of each layer,
- ▶ to define homogenous hydraulic characteristics of units, and
- ▶ to estimate the initial heads (Figure 6.1).

6.1 Conceptualized Model of the Hydrogeology

The surveyed area was geophysically surveyed by the Council for Scientific and Industrial Research (CSIR), using the Electrical Resistivity Method. These resistivity soundings as well as stratigraphic sequences for the western shores area of Lake St Lucia were provided by Meyer (1992). These soundings were used together with borehole data (also supplied by CSIR) to reconstruct the geophysical log from which the geologic units of

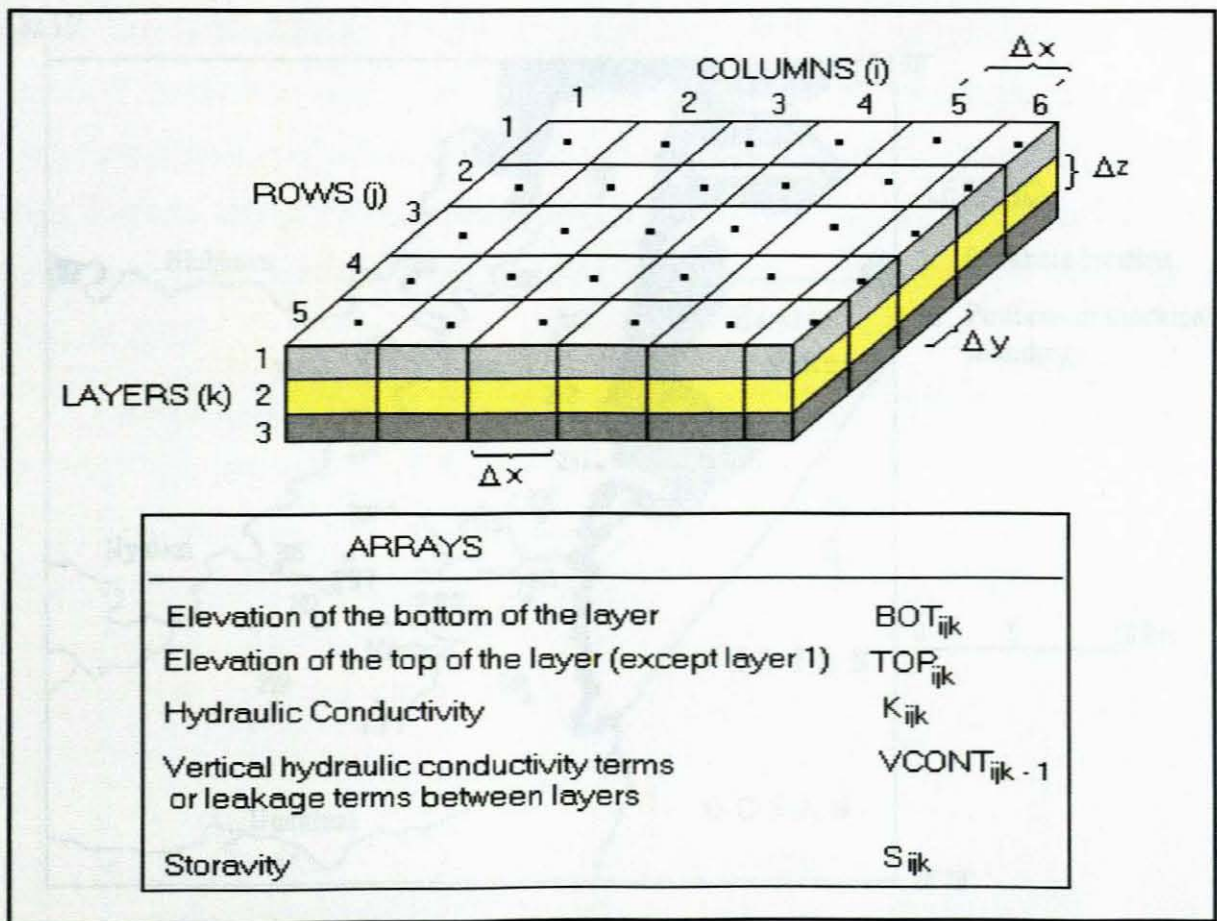


Figure 6.1 Schematic diagram of a three-dimensional conceptual model with hydrostratigraphic units represented by one or more layers (after Anderson and Woessner, 1992).

The Cretaceous bedrock is composed by multi-layered matrix deposits of the Fort similar hydrogeologic properties were derived. Figure 6.2 shows the study site and the location of all available soundings and borehole logs (Meyer, 1992) used in the study.

Resistivity interpretations (by Meyer, 1992) of the various geologic formations of the surveyed area were used to determine the upper surface of the Cretaceous system, which is composed mainly of siltstones. For the purpose of this model, this formation was assumed to form an impermeable bedrock and consequently the upper surface of the Cretaceous (with resistivity values $<25 \Omega.m$) was defined as the model boundary.

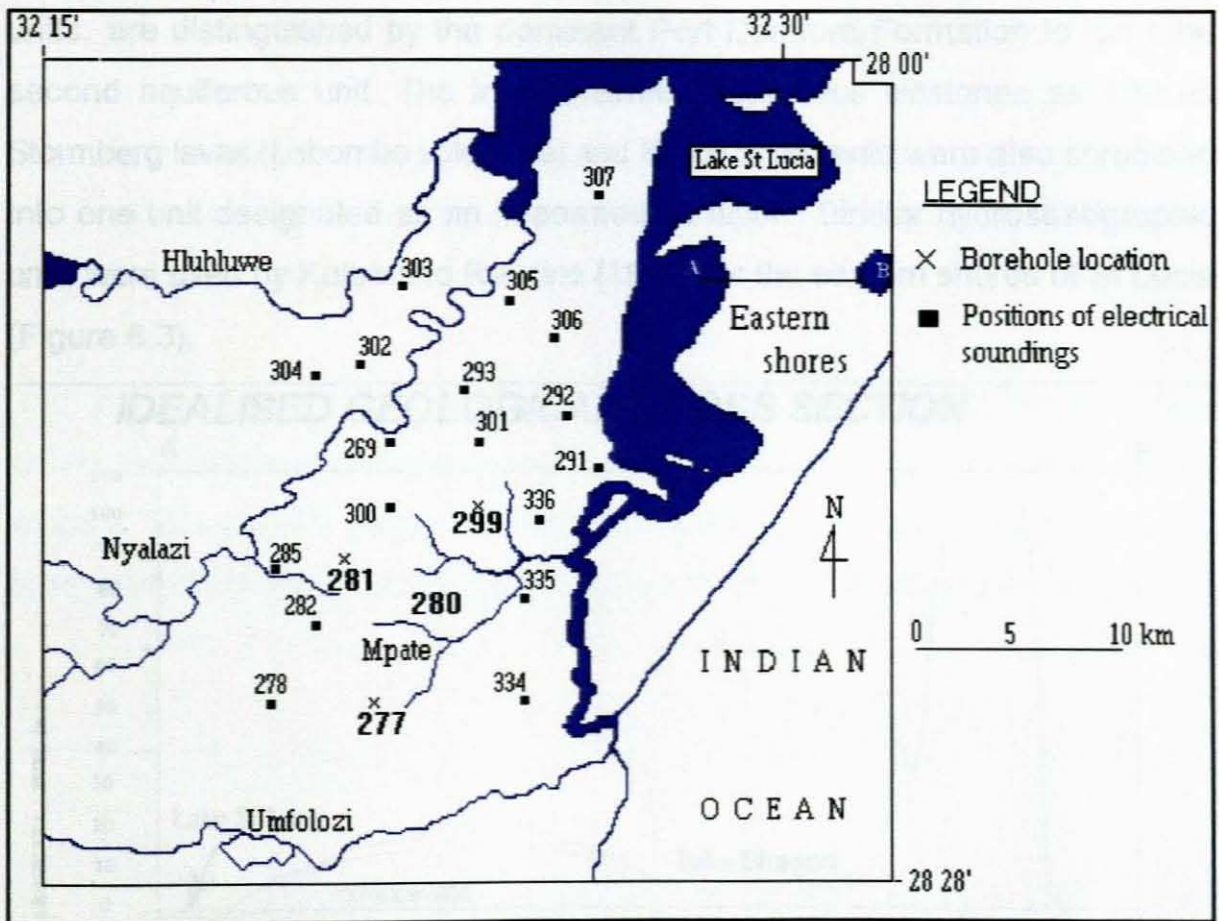


Figure 6.2 Positions of electrical soundings and borehole locations for the western shores area (after Meyer, 1992).

The Cretaceous bedrock is overlain by multi-layered marine deposits of the Port Dumford Formation whose resistivity soundings range between 25 and 400 $\Omega \cdot m$ (Meyer, 1992). This formation is in turn overlain by a highly resistive layer which has been designated as unconsolidated coversands. This layer is composed of alluvial, aeolian and estuarine sands with resistivities greater than 400 $\Omega \cdot m$.

For this study, adjacent geologic units of similar hydrogeologic properties were combined into one unit designated as either an aquifer or an aquifuge. The more recent (Holocene) cover sands were combined with units of highly permeable, unconsolidated Pleistocene sands of alluvial, estuarine and aeolian origin to form one aquiferous hydrostratigraphic unit/layer called the Coversands. The less permeable Pleistocene deposits, including the thin and rarely occurring Miocene

units, are distinguished by the dominant Port Durnford Formation to form the second aquiferous unit. The impermeable Cretaceous siltstones as well as Stormberg lavas (Lebombo volcanics) and Karoo sediments were also combined into one unit designated as an impermeable layer. Similar hydrostratigraphic units were used by Kelbe and Rawlins (1992) for the eastern shores of St Lucia (Figure 6.3).

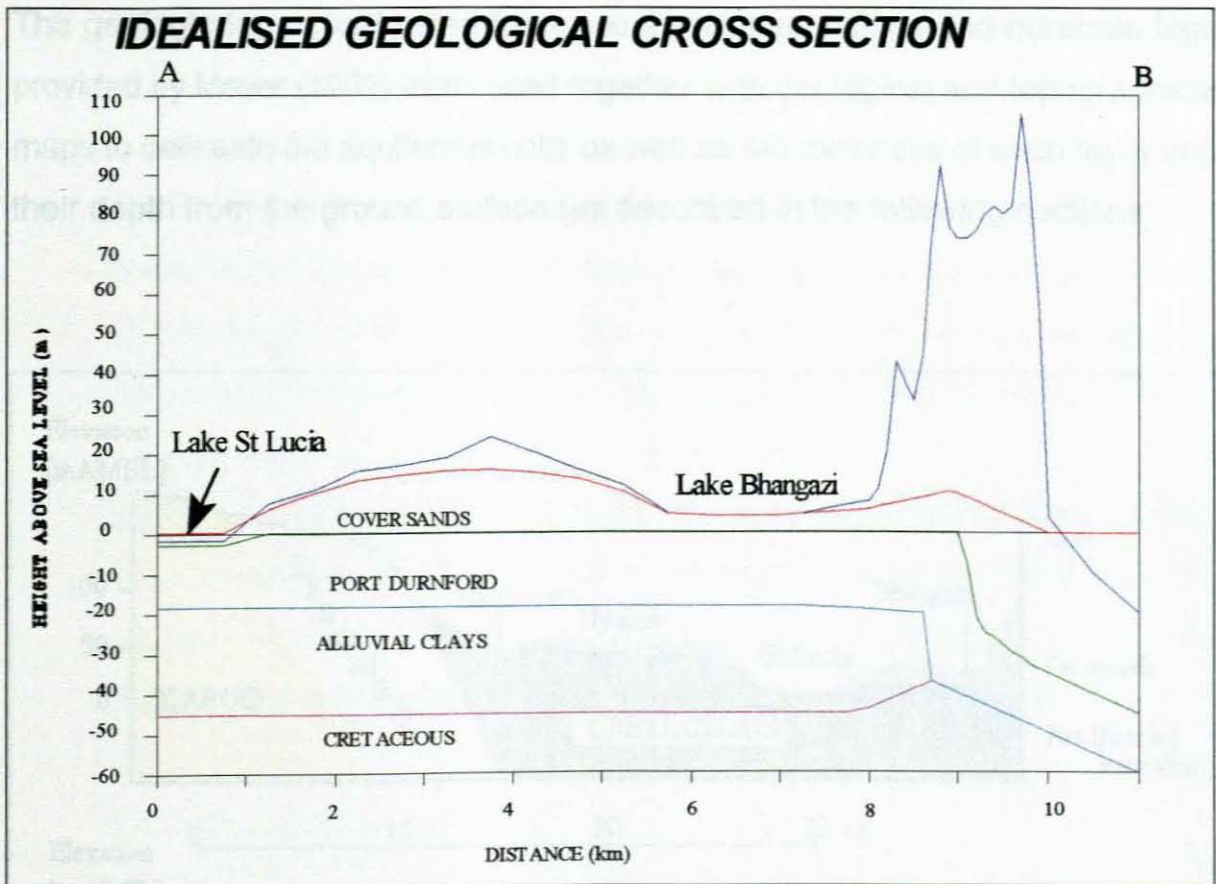


Figure 6.3 Idealised Geological Cross-Section of the Eastern Shores through section AB (after Kelbe and Rawlins, 1992).

Broadly speaking, the study area has three locally defined hydrostratigraphic units described below and shown in Figure 6.4:

- ▶ LAYER 1 - Coversands;

- ▶ LAYER 2 - the Port Durnford Formation, and
- ▶ the bottom layer of the model is represented by the impermeable sequence (Cretaceous siltstones, Lebombo volcanics and Karoo sediments).

The geologic logs constructed from geophysical soundings and borehole logs provided by Meyer (1992) were used together with geological and topographical maps to delineate the aquiferous units as well as the thickness of each layer and their depth from the ground surface (as described in the following sections):

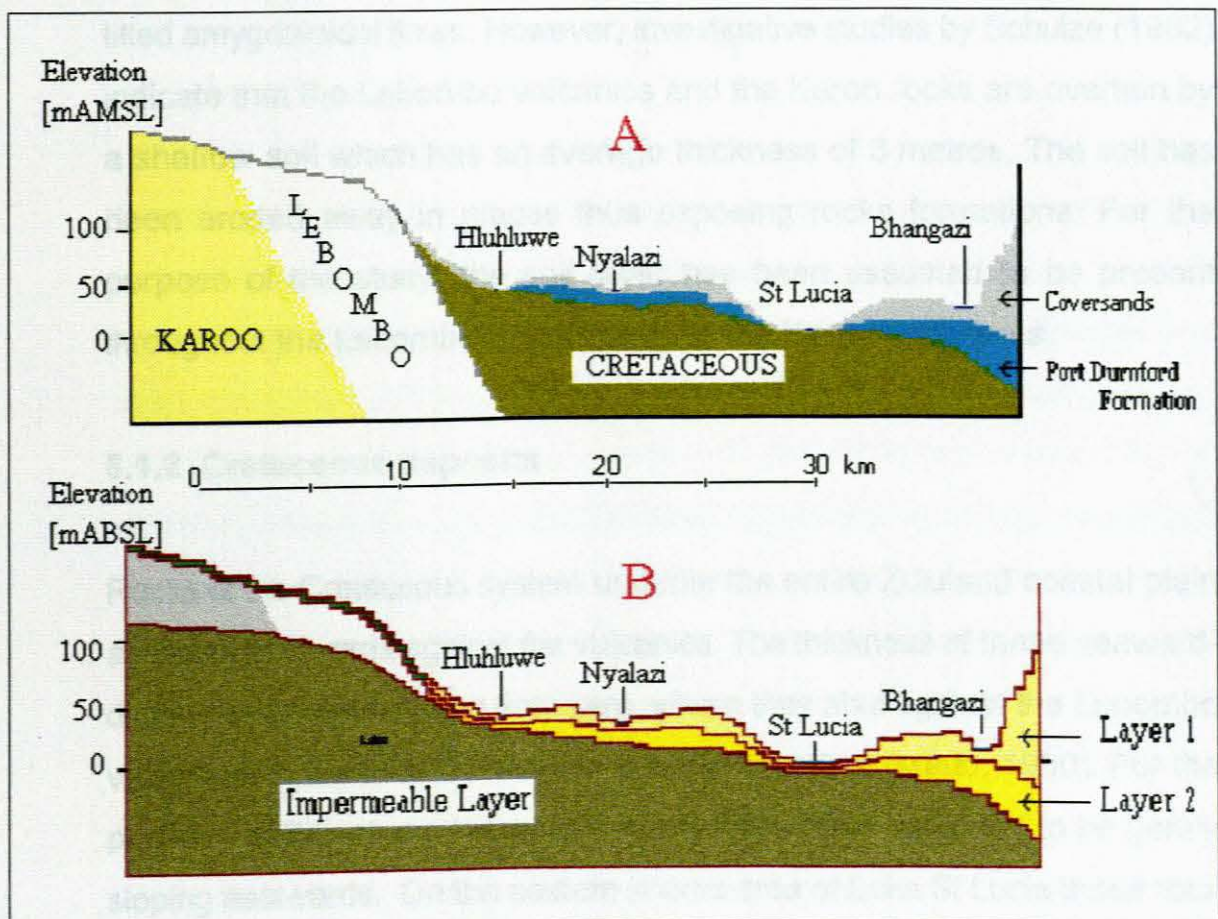


Figure 6.4 Transformation of a geological information into a conceptual model, (A) physical transect, and (B) conceptual transect.

6.1.1 Lebombo volcanics

Studies by Bristow et al (1985) show that some units of the basaltic lavas of the southern Lebombo volcanic belt are tilted to the east at angles of between 10° and 64° . A major section of the Lebombo volcanics in the study area is dipping eastward. Consequently, for the purposes of this study, Lebombo volcanics have been assumed to dip at a mid-range angle of 45° in an easterly direction.

According to Bristow et al (1985) and McCarthy (1979), jointing is poorly developed in the sequences of massive basaltic groundmass and there are no indications of intervening weathering and erosion between eastward-tilted amygdaloidal flows. However, investigative studies by Schulze (1982) indicate that the Lebombo volcanics and the Karoo rocks are overlain by a shallow soil which has an average thickness of 3 metres. The soil has been eroded away in places thus exposing rocks formations. For the purpose of the study, the soil layer has been assumed to be present throughout the Lebombo volcanics up to the Karoo sediments.

6.1.2 Cretaceous deposits

Rocks of the Cretaceous system underlie the entire Zululand coastal plain and abut landwards against the volcanics. The thickness of these seaward-dipping sediments ranges from zero, where they abut against the Lebombo volcanics, to some 3000 metres near the coastline (Maud, 1980). For the purpose of this study, these sediments have been assumed to be gently sloping eastwards. On the eastern shores area of Lake St Lucia these rock types lie approximately 30 metres below present MSL (Lynn, 1989). Electrical resistivity soundings (Meyer, 1992), however, reveal that these

sediments lie 35 m above MSL in some sections of the western shores area. The surface elevation of these deposits was derived by interpolation of geophysical logs (constructed from the resistivity soundings of all the survey points), and imposing a 3° eastward slope observed by Maud (1980). Assumed paeleo-channels were inferred from rivers and geological logs.

The contour map showing the elevation of the Cretaceous surface was constructed by hand and then digitized and captured into the IDRISI GIS system (Eastman, 1990) for importing into the INTERSAT Model. Mrs Snyman provided a computer programme for interfacing the IDRISI GIS and the INTERSAT groundwater model.

6.1.3 Port Durnford Formation

There are records of Miocene (Uloa) above the Cretaceous deposits, but these formations are believed to be discontinuous and isolated in the St Lucia area (Hobday, 1976). Thus, this geological formation (Miocene) has been assumed to be insignificant in terms of the model simulation for the lake system. Therefore, the Miocene unit was incorporated into the Port Durnford Formation during the interpretation of the resistivity soundings. The surface elevation of the Port Durnford Formation was estimated in the same manner as the elevation of the Cretaceous sediments. Geophysical logs (constructed from electrical resistivity soundings) from all survey points were examined. The stratigraphy was extrapolated by drawing a number of cross-sections in different directions over the surveyed area. Depth from the surface to the Port Durnford Formation was estimated at each survey point, and a contour map showing the elevation of the Port Durnford was derived by hand. This contour map was then digitized and

captured in the IDRISI GIS system. The electrical resistivity soundings have revealed that the thickness of this formation varies from 0 in the west to 30 metres AMSL in the eastern sections of the study area.

6.1.4 Coversands

The entire western shores area of Lake St Lucia is covered by a veneer of mainly unconsolidated aeolian and alluvial sands, designated as coversands. This succession, the thickness of which ranges from 0.5 to 3 metres on the western shores, is composed of fine to medium, well-rounded grains of sand that display high permeabilities and porosities. These geohydrological characteristics are expected to decrease with depth due to increase in compaction (Rawlins, 1991). The highly permeable coversands represent a primary aquifer and play a major role in the hydraulics of the shallow coastal aquifer. The western sectors of the study area which are predominately fractured Karoo and Lebombo rock aquifers have been conceptualized as thin cover of clayey duplex soils with permeabilities two orders of magnitude lower than the coastal sands.

The study area is also characterised by north-south trending dune ridges, which consist of very fine-grained, well sorted, and light-coloured, wind-deposited sand (Hobday, 1976). The hydraulic properties of these dunes are similar to those of the coversands (Davies et al, 1992) and consequently they are incorporated into the single layer of coversands. The surface elevation of the coversands coincides with the surface topography of the study area.

The surface topography was digitized from topographical maps and captured in the IDRISI GIS system and then exported into the groundwater

model in the same manner as the preceding geological formations. The top surface of the Port Durnford Formation forms the bottom surface of the coversands, and the top surface of the Cretaceous is the bottom surface of the Port Durnford Formation.

Of the three main hydrostratigraphic units defined above, it is the Port Durnford Formation and the coversands that are considered to form the primary model layers. The impermeable Cretaceous sediments have been selected to coincide with the impermeable base of the model, and their overlying soil mantle is assumed to be similar to the coversands.

6.2 The Numerical Model Description

The general description of the model was presented in section 5. This section describes the estimation of representative parameter values for the chosen study area.

6.2.1 Dimensions of grid

The INTERSAT Model is capable of simulating a 60 by 60 matrix with variable spacing. To accommodate the size of the model for the western shores area, a grid of 50 km in length and 40 km in width, which covers an area of approximately 2000 km², was chosen. This was rasterised into a grid of 60 by 60 columns and rows. Each node had a measured size of 670 m (east-west) by 833 m (north-south) and covered an area of approximately 0.56 km². This grid was subsequently reduced to the area shown in Figure 6.5 by eliminating 15 columns of the model covering the eastern shores section for reasons described later.

6.2.2 Boundary conditions

The study area is bounded to the east by Lake St Lucia and the Estuary. Taking Lake St Lucia and the estuary together, their mean surface elevation ranges from zero metres above mean sea level (m AMSL) in the south (estuary mouth) to 0.7 m AMSL in the north. According to Kelbe and Rawlins (1992), the water level of the Lake fluctuates in response to tidal motion, wind action, and as a result of the seasonal and extreme variability of rainfall. The gradient from mean sea level at the estuary mouth to a mean surface elevation of 0.7m at the northern extremity of the lake have been accounted for in the model as a constant head gradient, seasonal variation in tidal conditions have been ignored.

Unlike the eastern shores section of the lake, the western shores area of Lake St Lucia is characterized by several ephemeral streams and a few perennial rivers (Figure 3.1). These rivers were also set as constant heads where the river surface was set at the same elevation as the stream bed. Because of the nature of the crude rasterization in finite difference modelling (670 m by 833 m grid) in relation to the river dimensions (5 to 30 m width), the stream elevation had to be adjusted manually to create a steady gradient in the river course. These constant head streams also create a boundary between the western sections of the study area and the lake shore.

The study area is bounded to the south by the Umfolozi River whose nodes were also assigned constant head values. Where the river was south of the grid, the boundary nodes were considered to represent the river as a constant head. Consequently, all nodes south of the river were assumed to have no effect on the area of interest.

Table 6.1 Mean annual precipitation (MAP) and mean daily recharge rate (MDRR) for stations with long records.

STAT NO	STATION NAME	LAT deg	LONG deg	MAP mm	MDRR mm	LENG REC
339352	Kangela	28 22	32 12	895	1.76	64
339357	Riverview	28 26	32 11	847	1.63	60
339441	Dukuduku	28 21	32 15	870	1.74	52
339523	Nyalazi For Stat	28 13	32 18	1014	2.07	39
339538	Uloa	28 28	32 18	1108	2.33	62
339681	Estuary For Stat	28 20	32 23	1193	2.55	39
339720	Cape St Lucia	28 30	32 24	1410	2.94	30
339731	Charters Creek	28 11	32 25	1044	2.01	14
339734	Makakatana	28 14	32 25	1058	2.18	62
339756	Fanies Island	28 07	32 26	921	1.82	42
339856	St Lucia Estuary	28 16	32 29	1310	2.88	33
340010	Cape Vidal	28 10	32 31	1080	2.94	36
375688	False Bay Camp	27 58	32 23	707	1.61	42

STAT NO = station number
 LAT deg = latitude in degrees
 LONG deg = longitude in degrees
 MAP = mean annual precipitation in millimetres
 MDRR mm = mean daily recharge rates in millimetres/day
 LENG REC = length of record in years

The raw daily rainfall data was down loaded from the Computer Centre for Water Research (CCWR Risk System) via the UNINET into the local PC hard drive. From there the data for each rainfall station were imported into a spreadsheet in order to model effective rainfall (recharge) for input into the INTERSAT Model in accordance with the model in Figure 5.5.

Rainfall stations with continuous records, especially for the period from 1979 to 1992 (a period of both drought and heavy rainfall events), were selected for effective recharge estimation. The rest of the stations were discarded. The effective recharge was estimated using the method

explained in section 5.3.4.

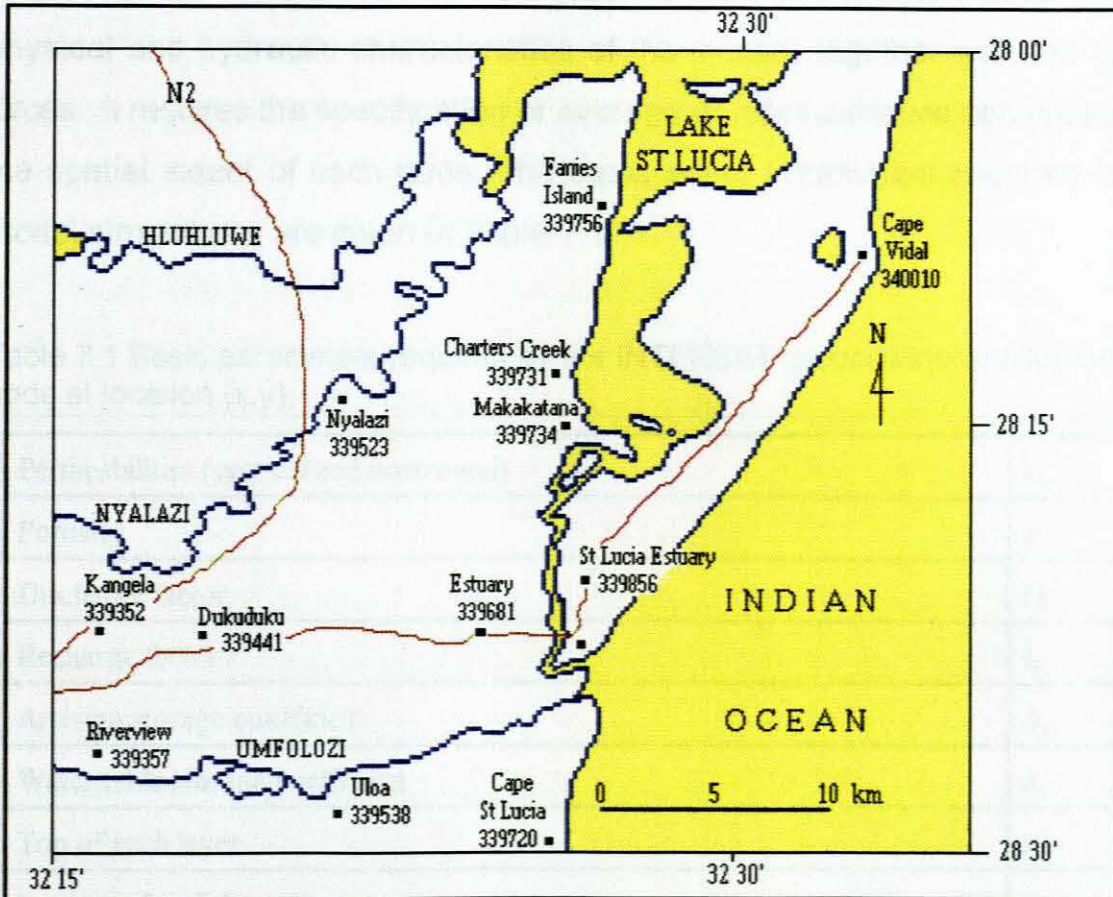


Figure 6.5 Location map of weather stations used in this study which have long rainfall records.

CHAPTER 7

DATA SELECTION FOR THE NUMERICAL MODEL

The INTERSAT groundwater model requires the input of data that reflects the physical and hydraulic characteristics of the system together with the driving forces. It requires the specification of average or representative conditions over the spatial extent of each node. The basic set of parameters required for the model simulations are given in Table 7.1.

Table 7.1 Basic parameters required by the INTERSAT groundwater model for each node at location (x,y).

Permeabilities (vertical and horizontal)	k_i
Porosity	P
Discharge factor	Q_i
Recharge factor	I_f
Artesian storage coefficient	S_a
Water table storage coefficient	S_w
Top of each layer	z_t
Bottom of each layer	z_b
Extinction elevation for evaporation	RH
Extinction depth for evaporation	RD
Evaporation factor	Q

The parameters specified in Table 7.1 are assigned to each of the regularly spaced nodes of the model grid. This chapter outlines the source and method of parameter specification for this spatial grid.

The maps of the geology, topography and land use for this region, as described in the previous chapters, were digitized and captured on the IDRISI Geographic Information System (GIS) (Eastman, 1990) for use in the specification of parameter values. IDRISI captures the Cartesian coordinates of contours (lines), points and polygons (areas) in a vector field which can be used in spatial analyses for parameter specification. The digitized vectors were converted into rasterised images of 300 by 300 pixel (picture element). These images were then processed before being reduced to the same matrix dimensions as the INTERSAT Model (60 by 60). The reduction in the number of rows and columns to 60 by 60, was accomplished by pixel thinning or pixel aggregation with the contraction factor in the x (columns) and y (rows) direction being independently defined.

With pixel **thinning**, every n^{th} pixel is retained and all others discarded. This method was used when the images were composed of discrete features, such as geological lithology and landuse. With pixel **aggregation**, the reduced image pixels are derived from an average of the n_x pixels specified in the x direction and the n_y pixels specified in the y direction. This method was used when the images were composed of continuous variables such as topographical elevation.

The surface elevations of the topographical features of the study area were captured from 1:50 000 topographical maps produced in 1979 and 1982 by the Department of Survey and Mapping, Pretoria. The land-use features were captured from aerial photographs flown in 1986 by the Air Survey Company of Africa, Durban. The surface geology was derived from geological map of St Lucia produced by the Geological Survey, Pretoria, and other point data derived from various sources.

The information for the top and bottom surface elevations of each layer, as well

as the hydraulic features of each layer, were required for model simulations, and these were derived from resistivity logs supplied by the CSIR (Meyer, 1992) as described previously. The logs and sounding were drawn to scale by hand from information described in the next section and then contours estimated and captured using the GIS.

7.1 Derivation of the Surface Elevations of the Model Layers

The upper and lower surface elevations of the different layers were derived from various sources with greatly varying spatial resolutions. This required different techniques for the derivation of the surfaces which depended on the source and nature of the information.

7.1.1 Layer 1 surface

The top surface of layer 1 was selected to coincide with the surface topography as digitized from 1:50 000 maps (Figure 7.1). The depth of the lake was estimated from Hutchison's (1975) report. However, problems were experienced with the rivers because the pixel aggregation method caused rising and falling pixels (contours) along river courses which had to be corrected manually. Because the rivers were modelled as a constant head boundary, this may not have been a serious problem to the flow pattern.

Depths of the underlying Port Durnford Formation and the impervious Cretaceous strata in the coastal plain regions of the study area were estimated from the geophysical sounding provided by Meyer (1992). These estimates of depth to the different strata were used to define the lower surface elevations of layer 1. This was assumed to coincide with the upper

surface elevations of layer 2 illustrated in Figure 7.2. The geophysical soundings were plotted on a map and then contoured by hand and in accordance with surface features and general trends described earlier.

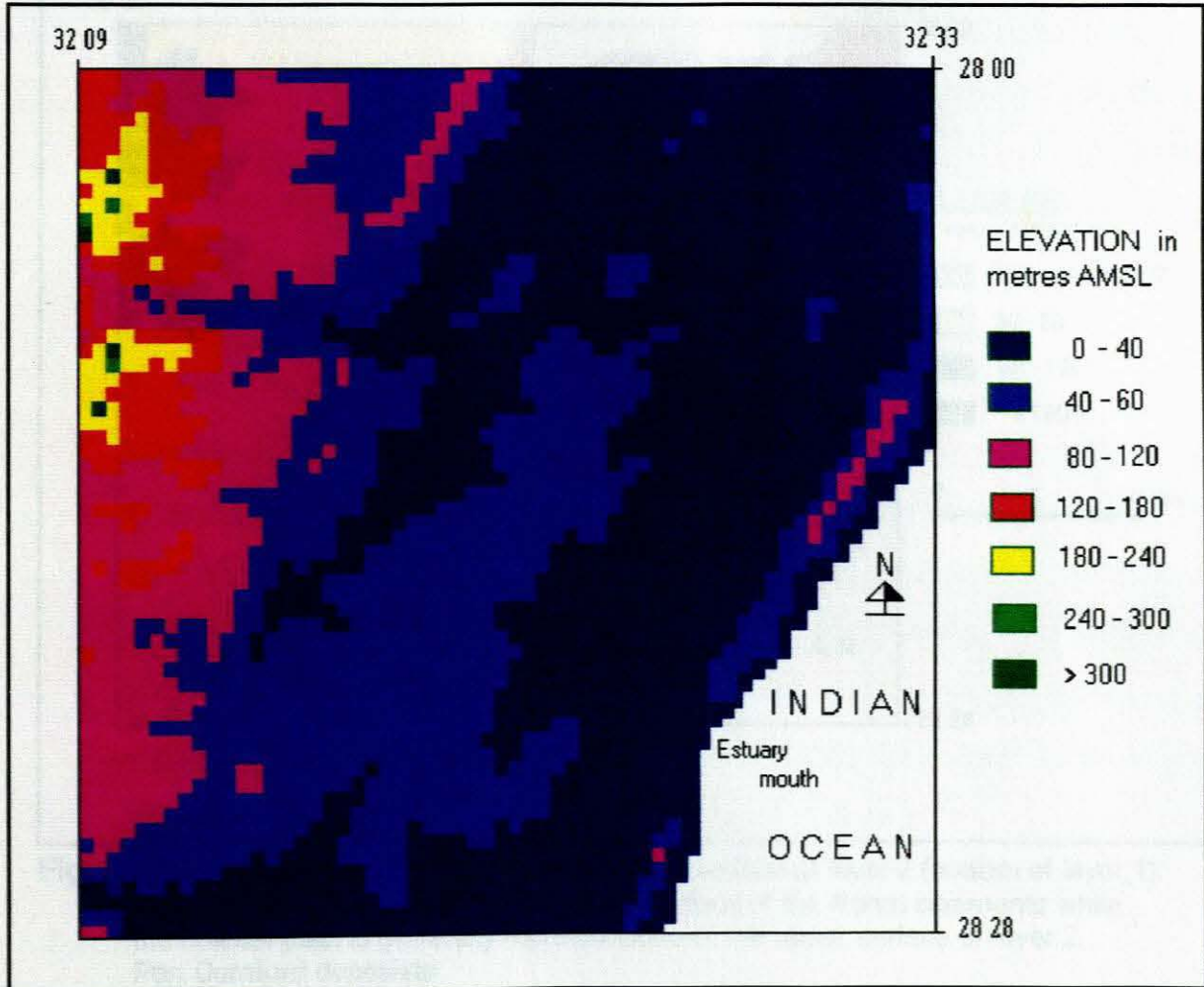


Figure 7.1 Surface Elevation Model of the surface topography (top of the Coversands) as used in the INTERSAT Model.

The contours were then digitized into IDRISI and rasterised in the same manner as the topographical surface. It was necessary in the GIS to overlay the upper and lower surfaces to ensure that they did not overlap. A minimum thickness of 1 meter was assumed for each layer. This was implemented in the model by subtracting the two surface images and then reassigning the minimum threshold value to all the pixels with a difference

of less than the required thickness. The resulting image of layer thickness was then subtracted from the upper surface image to obtain the lower surface elevations.

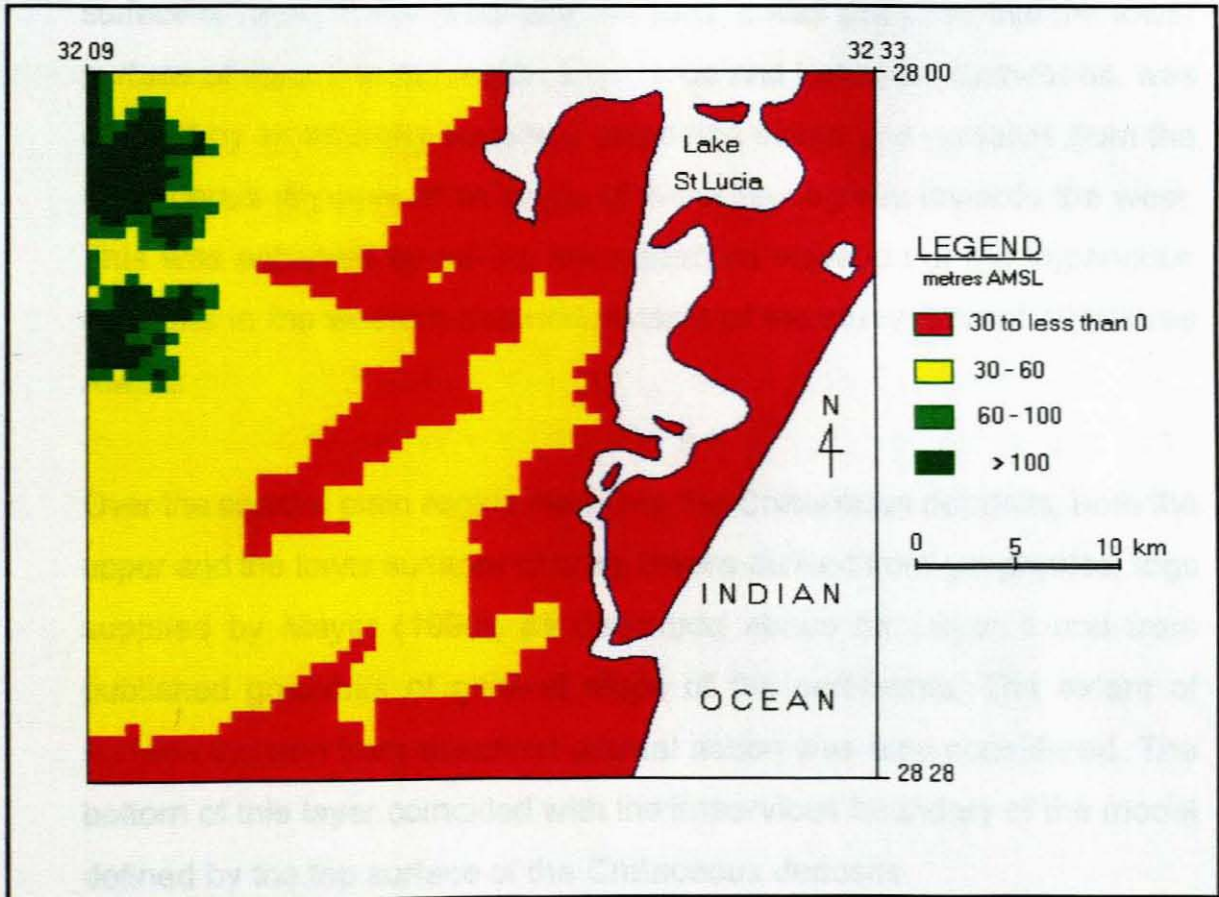


Figure 7.2 Digital Elevation Model of the upper surface of layer 2 (bottom of layer 1). The western interior is mainly the upper surface of the Karoo sediments while the coastal plain is generally representative of the upper surface of layer 2, Port Durnford deposits.

For the western, interior sections of the study area which are dominated by the Karoo and Lebombo formations, layer 1 was defined as a soil mantle which had an average thickness throughout. Since there was very little information for this region it was assumed that the lower surface of layer 1 was at least 2m below the topographical surface.

7.1.2 Layer 2 surfaces

The upper surface of layer 2 was assumed to coincide with the lower surface of Layer 1. For pragmatic reasons, it was assumed that the lower surface of layer 2 in the region with Karoo and Lebombo formations, was defined by an arbitrary boundary extending inland and upwards from the Cretaceous deposits at an angle of about 20 degrees towards the west. This was achieved by setting the maximum elevation of the impervious deposits in the western (interior) section of the study area at 40 metres AMSL.

Over the coastal plain region overlying the Cretaceous deposits, both the upper and the lower surfaces of layer 2 were derived from geophysical logs supplied by Meyer (1992), as described above for Layer 1 and from published gradients of general slope of the sediments. The extent of surface incision from assumed alluvial action was also considered. The bottom of this layer coincided with the impervious boundary of the model defined by the top surface of the Cretaceous deposits.

7.2 General geohydrological parameters

Generally, the geohydrological characteristics of the study area's geological formations are not well documented due to the lack of a comprehensive investigation on the geohydrological features of the western shores. However, the extensive drilling and sampling programme conducted on the eastern shores of Lake St Lucia by Davies *et al*, (1992) have provided representative values for permeability, porosity and storage coefficient. These geohydrological parameter values have been idealised to provide representative values for both model layers. The Cretaceous siltstone which underlies the Port Dumford-dominated

layer 2 is assumed to be impermeable in the model simulations, and it is considered unlikely to play a significant role in the geohydrological functioning of the shallow subsurface aquifer. The geohydrological parameters used in the final model simulations as shown in Table 7.2 were adjusted in accordance with landuse features such as wetlands.

7.2.1 Layer 1

Layer 1 is comprised of all sandy units which include coversands, alluvial and aeolian sands. The hydraulic properties of these sands which were derived from laboratory analysis and field tests by Davies *et al* (1992), were found to be relatively similar. Therefore, it was assumed that the hydrologic response of the units within the sequence will be similar. For model purposes, it was assumed that the coversands have the general permeabilities of 22m/day (0.025cm/s) as well as porosity of 45% (Table 7.2). The storage coefficient for these unconsolidated sands was assumed to be 35% with a specific retention of 10%.

7.2.2 Layer 2

The second layer of the model was selected to generally coincide with the Port Dumford formation. The hydraulic properties of this formation were derived from Davies *et al* (1992). Layer 2 is assumed to have a permeability of 7m/day (0.008cm/s) and a porosity of 42% as shown in Table 7.2. This layer, with a greater silt content, was assumed to have a much lower storage coefficient of 20% and a specific retention of 22%.

Table 7.2 General geohydrological parameters used in the final model simulations

PARAMETER	MODEL LAYERS	
	Layer 1	Layer 2
Permeability (m/day)	22	7
Porosity (%)	45	42
Storage coefficient (%)	35	20
Specific retention (%)	10	22

7.3 Recharge rate

The daily recharge rates (percolation rates) derived from the rainfall model described earlier were averaged over each month, and the annual mean daily recharge rates (MDRR) for each hydrological year were calculated from these monthly mean daily recharge rates. The variation in the monthly mean of the daily recharge rates within and between each station are shown in the Box and Whisker plot of Figure 7.4. The station mean generally varies between 1.5 and 2.5mm/day, or 547 and 912mm/year.

The long term mean daily recharge rates for each station were used to derive a contour map of the daily recharge rate for the study area (Figure 7.5) using a spatial mapping program SURFER. This spatial map was imported into the INTERSAT groundwater model as the effective recharge rate for average climatic conditions.

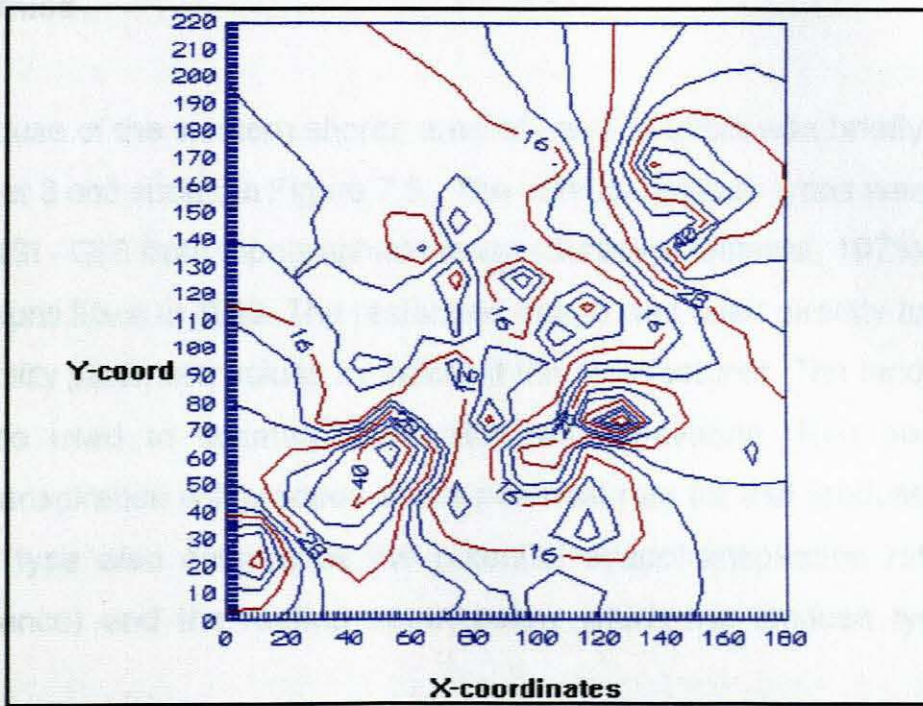


Figure 7.3 Contour map of long term estimate of effective recharge (MDRR) (10^{-1} mm).

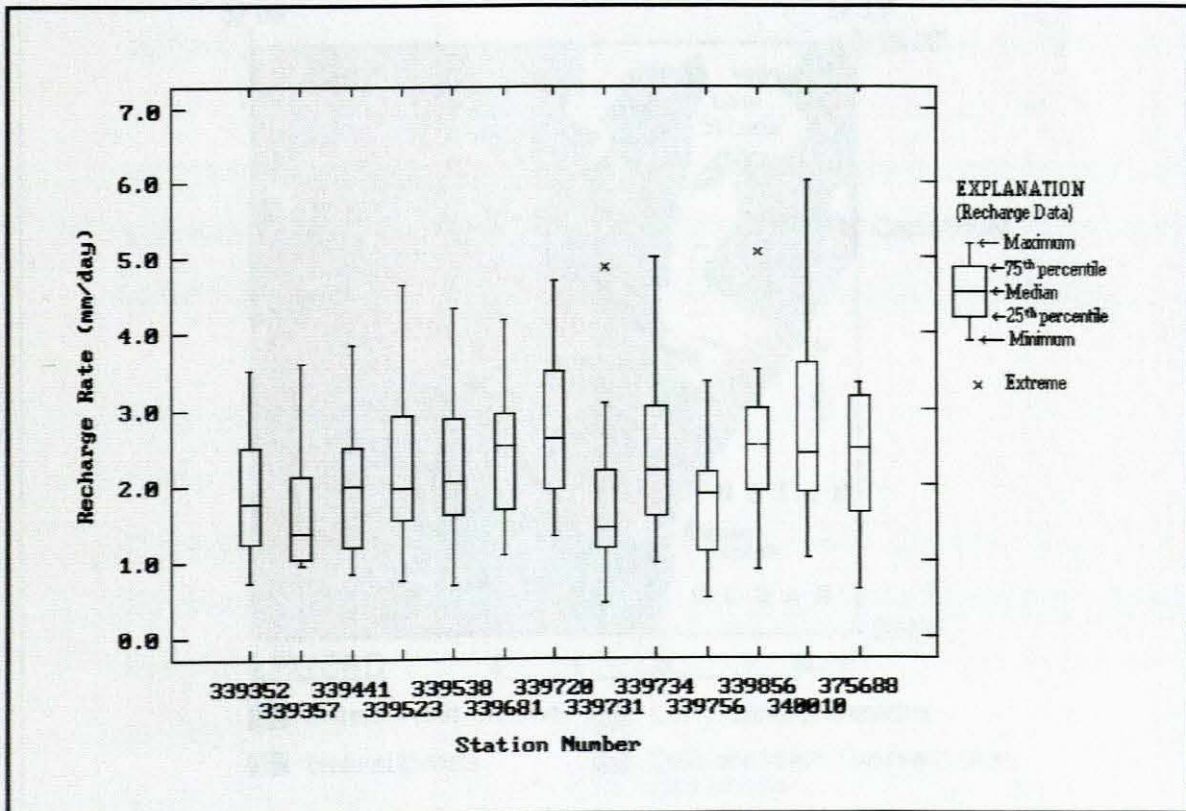


Figure 7.4 Multiple Box-and-Whisker Plot of the daily mean recharge rates.

7.4 Landuse

The landuse of the western shores area of Lake St Lucia was briefly described in Chapter 3 and shown in Figure 7.5. The various landuse types were captured into IDRISI - GIS from topographical maps (Surveyor General, 1975) and aerial photographs flown in 1993. The rasterised image was used directly to adjust the permeability parameter values for selected landuse features. The landuse image was also used to estimate the water table elevation (RH) above which evapotranspiration will proceed at the potential rate for that landuse type. The landuse type also determines the potential evapotranspiration rate (vertical conductance) and the rooting depth below which the landuse type has no

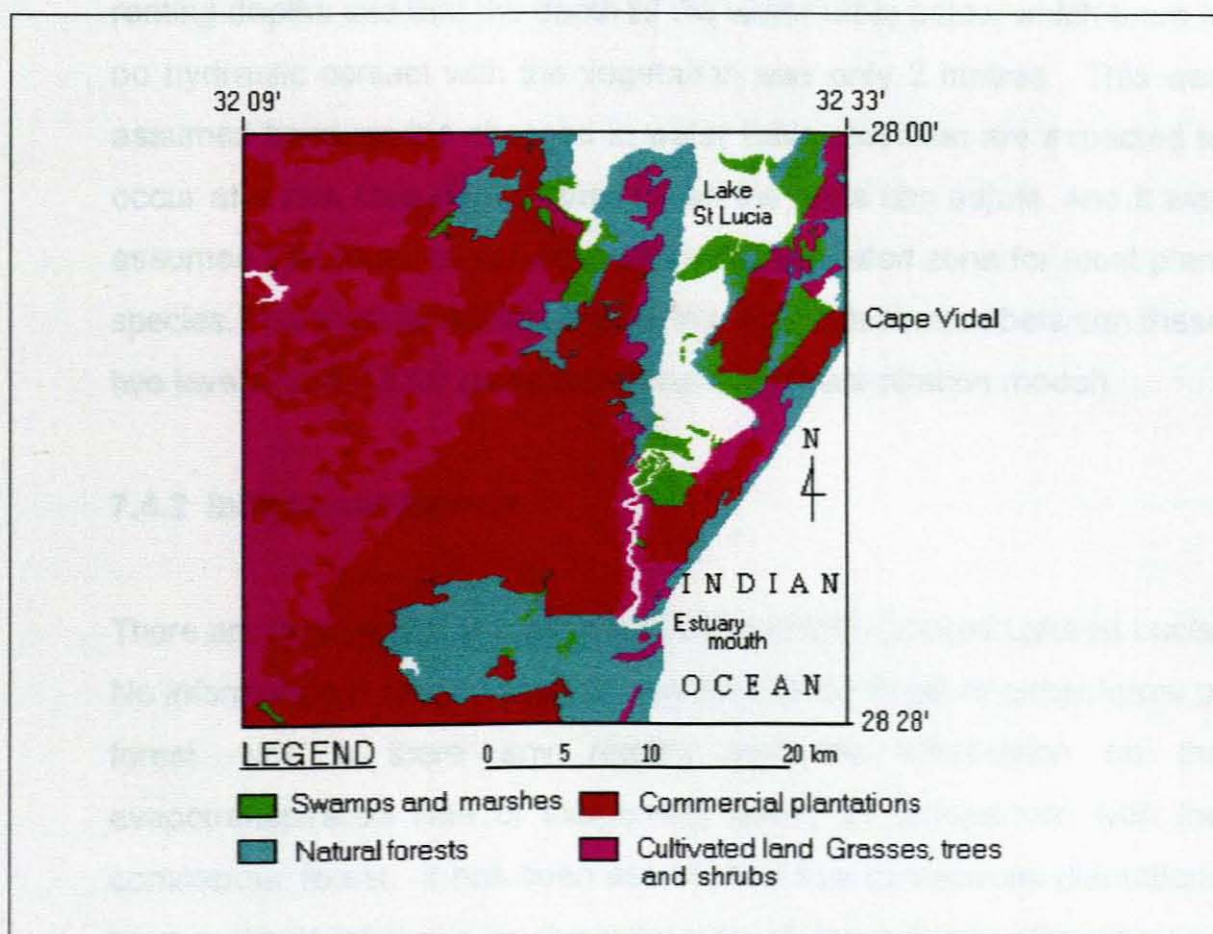


Figure 7.5 Spatial distribution of various landuse features of the Lake St Lucia system

hydraulic contact with the water table. The spatial distribution of the various landuse types is shown in Figure 7.5. There are four main types of landuse considered to have sufficiently well defined impact on evapotranspiration for this study.

7.4.1 Swamps and marshes

Swamps and marshes represent geomorphological features which have water surface that are generally exposed at the topographical surface. Consequently, they are expected to function at the potential evapotranspiration rate when the water table is within 1 metre of the topographical surface. It was assumed that these features have shallow rooting depths and that the depth of the water table below which there is no hydraulic contact with the vegetation was only 2 metres. This was assumed because the changes in water table elevation are expected to occur at a rate considerably faster than the roots can adjust. And it was assumed that roots do not exist within the saturated zone for most plant species. There will be a linear decline in evapotranspiration between these two levels (see 7.5 for more details on evapotranspiration model).

7.4.2 Indigenous forests

There are large areas of swamp and dune forests around Lake St Lucia. No information is readily available on the rooting depth of either forms of forest. Nor is there any readily available information on the evapotranspiration rate of indigenous forest for comparison with the commercial forest. It has been established that commercial plantations have a direct influence on the extraction of groundwater (Rawlins and Kelbe, 1991) but nothing on indigenous forests. Consequently, it has been

assumed that both commercial plantations and indigenous forests have a similar rooting depth. However, swamp forest do survive with water tables very close to the surface while commercial forests tend to invade swampy areas only when they have dried up. Consequently, the rooting depth for all forests will be considered similar but the areas with swamp forest will assume higher water table conditions under potential evapotranspiration.

7.4.3 Grasslands, shrubs and scattered trees

The landuse type designated as grassland, shrubs and scattered trees is considered to be representative of undisturbed natural or pristine conditions in all the areas. Large portions of these areas have been cultivated and forested (Figure 7.6).

7.4.4 Cultivated lands

The areas under cultivation have little direct input to the catchment area which is directly affecting the discharge into the lake. Consequently they were assigned similar parameter values as natural grasslands and shrubs.

7.4.5 Commercial forests

The western shores have extensive areas which are covered with commercial forests. The effects of afforestation on groundwater and the lake system have been studied by Lindley and Scott (1987).

7.5 Evapotranspiration

The rate of the withdrawal of water from the soil by a plant through

evapotranspiration depends primarily on the atmospheric demand and vegetation characteristics which include the rooting depth of the plant, the root distribution and their density. Roots in the unsaturated zone are fully dependent on residual soil moisture. However, roots which are in the capillary fringe zone just above the water table are assumed to experience no moisture deficit and will transpire at the maximum rate. Thus, roots that are in hydraulic contact with the water table can have a major influence on the water loss from the water table. Because of the relative ease with which roots can abstract water from the water table, the magnitude of evapotranspiration from different vegetation covers must be included in the model simulations. However, the initial 10 mm loss in rainfall which was not included in the recharge is assumed to represent the average water loss from surface and unsaturated processes, so the evapotranspiration loss from the water table is a fraction of the total potential loss which must be estimated.

To include evaporation from the groundwater in the model, all land-use features were assigned potential "groundwater" evapotranspiration rates which represent a fraction of the potential evapotranspiration rate (atmospheric demand).

The perennial, deep-rooted pine trees and natural forests transpire at a rate in excess of 1100 mm/year (Lindley and Scott, 1987), which amounts to approximately 3 mm/day. Kelbe and Rawlins (1992) used the modified Penman equation to calculate the mean potential evapotranspiration rate (E_p) for the eastern shores using data from an automatic weather station. They estimated that the 'potential' evapotranspiration rate for groundwater extraction from the saturated layer is 2 mm/day. Because no such observation were found for the western shores areas, it was assumed that the rates observed for the eastern shores are representative of the conditions in the western shores area as shown in Table 7.3.

Table 7.3 Potential evapotranspiration rates, E_p , (mm/day) for different land use features.

LAND-USE	E_p , mm/day
Lakes and dams	2
Swamps and marshes	2
Natural forests	3
Commercial forests	3
Grasslands	2
Cultivated lands	2

The depth of the water table at which the evaporation starts to decline (RD) and the extinction level (RH) below which the water table loses hydraulic contact with roots, producing no evaporation, vary from plant species to plant species. Although both features, RD and RH, are a function of the rooting depth of the vegetation (Kelbe and Rawlins, 1992), there are no well defined values for different vegetation types. Therefore, the assumption made in this study was that evaporation will occur at the 'potential' rate if the water table is within a metre of the surface. As the water table elevation falls during dry periods, evaporation is assumed to continually decrease until the water table elevation reaches an extinction level, RH. At this depth, evaporation is assumed to be nil.

The selection of the RH values for different types of vegetation is based on rooting depth (Table 7.4). In his "Rooting strategies by plantation trees" Scott (1993) has shown that both *Pinus elliottii* and *Eucalyptus grandis* species have deep root systems of up to 8 and 13.7 metres, respectively. In this study, the average extinction level (RH) of deep-rooted natural and commercial forests was assumed to be 10.7 m. The relatively shallow-rooted pastures (grasses and

agricultural crops) have been assumed to withdraw groundwater for evaporation from a maximum depth of 3.0 metres in this study area.

Table 7.4 The lower limit (RD) and extinction level (RH) below the surface used in the INTERSAT Model for different land use features.

LAND-USE	RD (m)	RH (m)
Lakes and dams	0.0	1.0
Swamps and marshes	0.0	1.7
Forests	3.0	10.7
Trees and Grasses	1.5	7.6
Cultivated lands	1.5	7.6

The rooting depth is also a function of the soil type and depth. Therefore, the rooting depth of different landuse types should be adjusted to account for different soil properties. Presumably, the soil depth as well as the rooting depth on the western shores is much lower than those observed for the eastern shores. Consequently, the RH and RD values were adjusted arbitrarily by an assumed correction factor for those areas where the top layer of the model was not between 5 and 15 metres thick. These correction factors are given in Table 7.5.

Table 7.5 Correction factor assumed to affect rooting depth in different soil depths

Layer Thickness (m)	Correction Factor
< 5	0.5
5 to 15	1.0

CHAPTER 8

MODEL CALIBRATION

8.1 Initial Stabilization

Initially, the model was set up for a 60 x 60 grid. To overcome problems with instability in the initial model runs, several changes were made to the parameters assigned to the model. Firstly, the model layers were adjusted to have a minimum thickness of 1.5 metres. This was particularly important at the edge of the lake and estuary to avoid the model layers from coinciding. Secondly, the bottom impervious surface was set to a maximum height of 40 metres AMSL derived from an assumed slope and known elevation.

The model was still found to be unstable and caused divergence in the iteration solutions with daily time steps. The number of rows and columns was reduced to 60 by 45 (Figure 8.1) by removing 15 columns from the right hand side of the model which represented most of the eastern shores area that had already been studied by Kelbe and Rawlins (1992). This stabilized the model simulation and steady state conditions were achieved using daily time steps. The model was initially run for 100 000 days to achieve steady state conditions for the whole model domain using mean recharge and evaporation conditions. However, the water balance for the model domain was evaluated but found to be unacceptable. There were imbalances between input and output. Further corrections to the model were done by adjusting the slopes and heads of all river courses to remove irregularities caused by the pixel thinning techniques. The model was re-run for a further 100 000 day simulation period and the water balance for the entire area approached negligible imbalance between input and output.

8.2 Water Balance Regions

A set of rectangular grids covering a selection of nodes enclosing all constant head nodes for each of the rivers and the lake shore lines were specified in order to calculate water balance for the various systems. For the rivers, this grid was specified to estimate all groundwater flow to the constant head nodes representing rivers (Figure 8.2). The INTERSAT model calculates the water balance of inflows and outflows integrated over those nodes specified within each

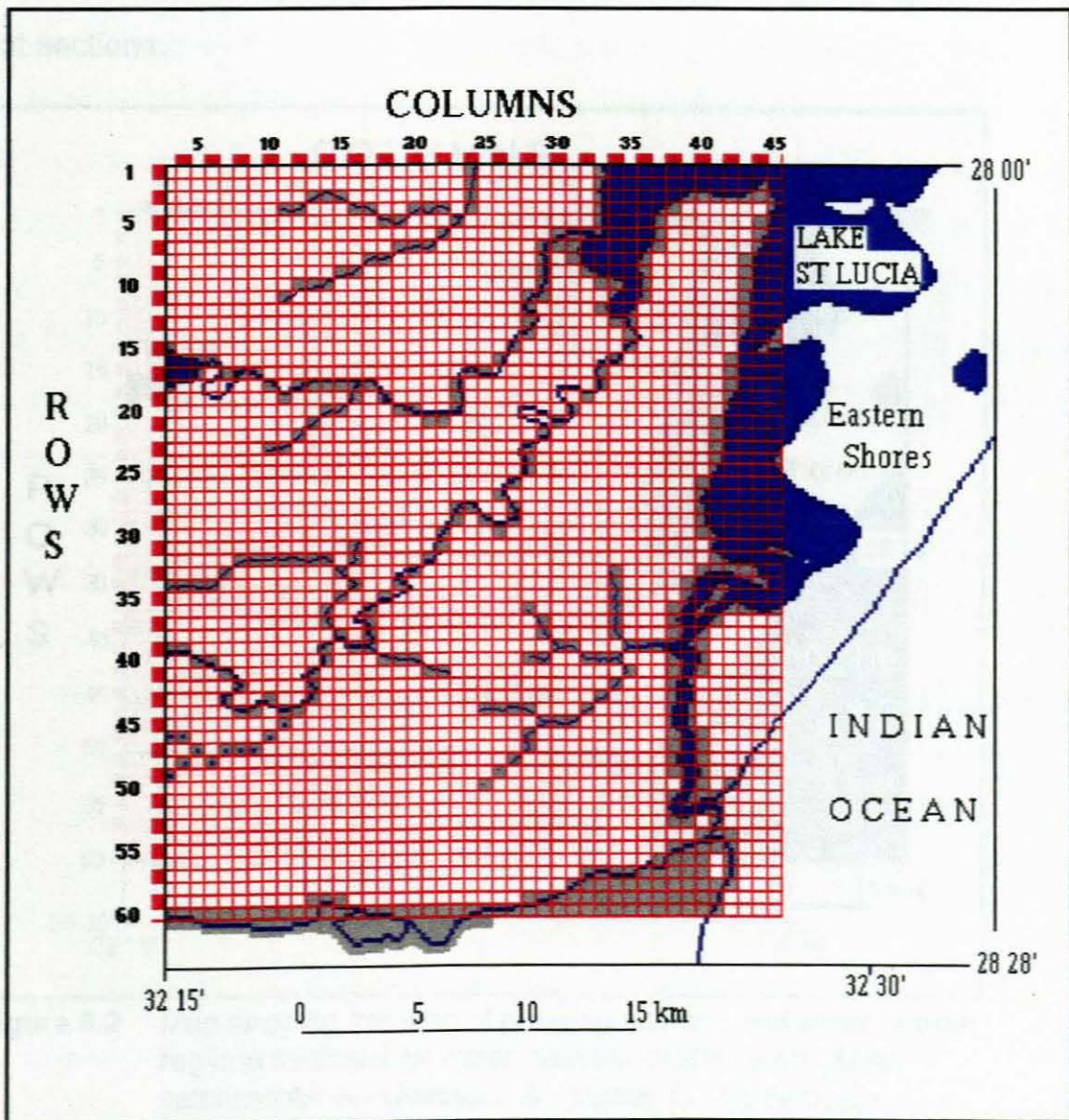


Figure 8.1 Map showing grid dimensions and boundary conditions as used in the INTERSAT Model. Shaded areas represent constant head nodes.

region. This provides an indication of the groundwater fluxes from (to) active nodes (*ie* those that are not constrained by constant head conditions) and to (from) inactive nodes (*ie* those specified as infinite storage with constant head) as well as vertical fluxes (*ie* surface recharge and discharge rates). Since only the constant head nodes in each region represent the river system to be evaluated, the water flux to constant head nodes is assumed to represent the groundwater flow to these systems. In a more conventional sense, this is equivalent to an estimation of the baseflow in river discharge. The results for the water balance of selected water budget regions (referred to as catchments) are described in the next sections.

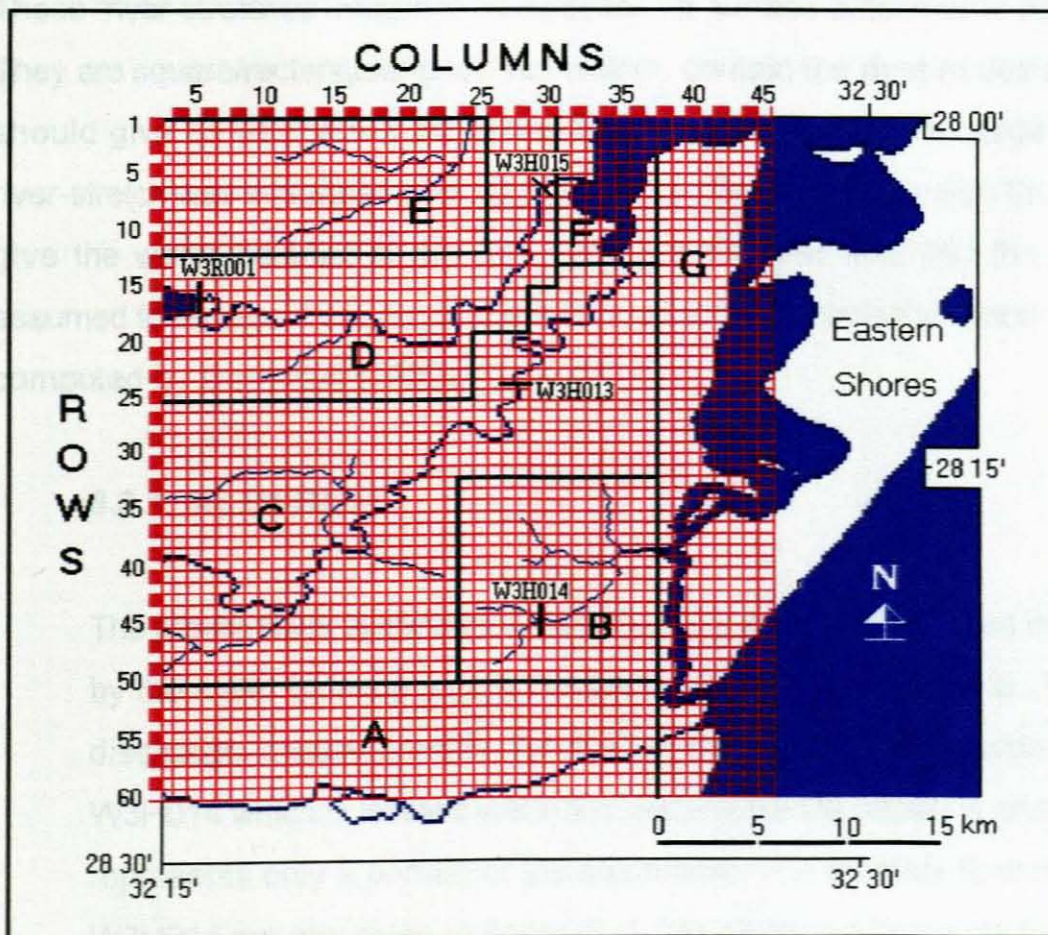


Figure 8.2 Map showing location of gauging stations and water budget regions selected for water balance examination. River catchments: A - Umfolozi, B - Mpate, C - Nyalazi, D - Hluhluwe (below the dam), E - Ncemane, F - False Bay, and G - Lake and Estuary.

8.3 Water Balance for River Catchments

Seven water balance regions shown in Figure 8.2 and labelled from A to G were selected for detailed water budget analysis in the calibration. Only two of these (the Mpate and Hluhluwe river catchments) could be used in the model calibration because they were entirely contained within the model domain (eg Mpate river) or the inflow to the river reach was measured (eg Hluhluwe river downstream of the dam). The general north-east, south-west trend of Nyalazi and Hluhluwe Rivers and their winding nature necessitated that each river be broken into several rectangular "river-stretches" in the water budget estimation (Figure 8.2). These "river-stretches" must not be mistaken for surface catchments boundaries. They are square/rectangular grids that entirely contain the river nodes and which should give an estimate of baseflow. The simulated water discharge into each river-stretch was integrated over all the constant head nodes within the region to give the water balance of the river. The groundwater flow into the river was assumed to represent the discharge and was compared with the runoff estimates computed by Cornelius (1993).

8.3.1. Mpate River

The Mpate River is contained entirely within the study area and is specified by the water balance region shown in Figure 8.2 as region B. The actual discharge measurements for the Mpate River are recorded at weir W3H014 which is located within the water balance region B and therefore represents only a portion of the catchment. The monthly flow records for W3H014 are presented in Appendix I. The historical flow data for this weir was provided by the Department of Water Affairs and Forestry. The actual mean annual outflow from W3H014 has been measured at $3.0 \times 10^6 \text{m}^3$ (Appendix I). Stassen and Mynhardt (1992) were critical of the flows

gauged at the Mpate River weir. They indicate that although this gauging station is well structured, it gauges only low flows. This causes "great difficulty in trying to compare simulated flows with gauged flows as peak flows were not gauged". In addition, the Mpate River weir is situated upstream of one of the three Mpate River tributaries. If it is assumed that the greatest portion of the river flow in these regions with highly permeable soils is derived mainly from baseflow, then the error in high flow measurements may be neglected in simulations of average conditions.

According to model simulations presented in Table 8.1, the Mpate River, which drains a small and densely forested catchment of approximately 250 km² west of the lake estuary, is recharged by groundwater (baseflow) at a daily rate of $11.9 \times 10^3 \text{ m}^3$ ($4.3 \times 10^6 \text{ m}^3/\text{year}$). This is similar to measured flow but accounts for roughly 25% of the total simulated discharge of $18 \times 10^6 \text{ m}^3/\text{year}$ calculated by Cornelius (1993).

Table 8.1 Water budget for region B (Mpate River catchment).

FLOW CONDITIONS		BOUNDARY		FLOWS (m ³ /day)
Total groundwater flow to inactive (river) nodes		External		11928
Total evapotranspiration loss from groundwater		Internal		75902
Total flow from rainfall recharge		Internal		73890
Unaccounted for balance		Internal		858
Face Flows (External)	North	South	East	West
Inflow to the catchment	+553	+229	-1090	-2229
Boundary losses	0	+400	-59	-2
River losses	+6	0	-51	-17

In estimating the runoff for the Mpate River catchment, daily rainfall events

which were greater than 50mm for all weather stations that occur in this catchment were summed to derive an estimate of surface runoff. This surface runoff is equivalent to $13.5 \times 10^6 \text{m}^3/\text{year}$, and if the simulated baseflow of $4.3 \times 10^6 \text{m}^3/\text{year}$ is added to the surface runoff then the estimated annual runoff becomes $17.8 \times 10^6 \text{m}^3/\text{year}$. This runoff estimate compares well with Cornelius' (1993) total simulated discharge of $18 \times 10^6 \text{m}^3/\text{year}$.

The $75.9 \times 10^3 \text{m}^3/\text{day}$ ($27.7 \times 10^6 \text{m}^3/\text{year}$) evapotranspiration loss from groundwater shown in Table 8.1 is slightly higher than the total rainfall recharge of $73.9 \times 10^3 \text{m}^3/\text{day}$ ($27 \times 10^6 \text{m}^3/\text{year}$). This high evapotranspiration loss may be related to the model concepts which would need further research in the development of this model.

It is also evident that the majority of the simulated outward groundwater flow, which is approximately $3.3 \times 10^3 \text{m}^3/\text{day}$, occurs through the eastern and western edge of the Mpate water balance region. This outward flow is greater than the inward flow ($0.78 \times 10^3 \text{m}^3/\text{day}$) which takes place at the northern and southern edge. Additionally, the outward flow at the western edge is greater than the outward flow at the eastern edge of the water balance region.

8.3.2. Hluhluwe River downstream of the dam

The Hluhluwe catchment downstream of the Hluhluwe Dam is contained within the study area and is within the area specified by the water balance region shown in Figure 8.2 as region D. The actual outflow in the Hluhluwe River is measured at two gauging stations. The discharge from the Hluhluwe Dam is measured at W3R001 and the outflow from the river

mouth into False Bay is measured at weir W3H015 (Figure 8.2). The monthly flow records for these two gauges are listed in Appendices II and III, respectively. These data were provided by the Department of Water Affairs and Forestry. The observed mean annual discharge at W3R001 (Hluhluwe Dam) is $40.6 \times 10^6 \text{m}^3$, while further downstream it is reduced to $12.3 \times 10^6 \text{m}^3$ at W3H015. The difference in discharge measurements between the upstream and the downstream weirs suggests that either the measurements are in error or there is large-scale ($>28.3 \times 10^6 \text{m}^3/\text{year}$) water abstraction downstream of weir W3R001 (Hluhluwe Dam). In their previous investigations Stassen and Mynhardt (1992) and Cornelius (1993) questioned the reliability of the historical flow records gauged from both weirs (W3R001 and W3H015). However, this flow data will be used reservedly for comparisons due to the lack of information on water extraction from the Hluhluwe River catchment. This lack of information restricts the assessment of the simulation for this river shown in Table 8.2.

Assuming that the annual flow measurements of $40.6 \times 10^6 \text{m}^3$ at W3R001 (Hluhluwe Dam) and $12.3 \times 10^6 \text{m}^3$ at W3h015 are correct, then this suggests that approximately $28.3 \times 10^6 \text{m}^3/\text{year}$ plus the simulated inflow (Table 8.2) of $29 \times 10^3 \text{m}^3/\text{day}$ ($10.7 \times 10^6 \text{m}^3/\text{year}$) is extracted between the dam and the river outlet (Table 8.2). Because the Hluhluwe catchment is covered by cultivated lands, shrubs and some commercial forests, therefore, this river loss may be caused by direct irrigation and evapotranspiration.

Additionally, there is a general surface outflow of $3 \times 10^3 \text{m}^3/\text{day}$ which is predominately toward the south, and this agrees with the expected outflow. Also, the recharge rate ($27.6 \times 10^6 \text{m}^3/\text{year}$) is expectedly higher than the evapotranspiration component ($20.3 \times 10^6 \text{m}^3/\text{year}$).

Table 8.2 Water budget for region D (Hluhluwe River catchment).

FLOW CONDITIONS		FLOWS (m ³ /day)			
Total groundwater flow to the inactive (river) nodes		29226			
Total evapotranspiration loss from the groundwater		55736			
Total flow from rainfall recharge		75651			
Unaccounted for balance		423			
Face Flows	North	South	East	West	
Inflow to the catchment	9469	-14586	-2652	4780	
Boundary losses	1549	-41	389	-114	
River losses	0	0	523	-394	

8.3.3 Nyalazi River

The Nyalazi River shown as region C in Figure 8.2 is included in the water balance analysis because it is centrally situated in the study area. Unfortunately, the gauging station, W3H013, from which flow recordings are taken has irregular records of only four years (Stassen and Mynhardt, 1992). Also, large sections of the upstream catchment of the Nyalazi River (region C) extend beyond the boundaries of the study area and nothing is known about the historical flow records in this portion of the catchment as the stream is ungauged. Therefore, the model results presented in Table 8.3 are first estimate but cannot be compared to other values.

Table 8.3 Water budget for region C (Nyalazi River catchment).

FLOW CONDITIONS	FLOWS (m ³ /day)
Total groundwater flow to the inactive (river) nodes	32402
Total evapotranspiration loss from the groundwater	57236
Total flow from rainfall recharge	77406
Unaccounted for balance	502

8.4 Model Comparison with borehole data

The study area has four boreholes which were monitored over a 2 year period. These boreholes are situated within the simulation area and therefore can be used for further assessment of the model. Data records for these boreholes are presented in Table 8.4. Model assessment was done by comparing the simulated values (heads) with the field-measured water table elevations.

Table 8.4 Water table observation.

DATE	WELL NUMBER			
	277	280	281	299
28/01/93	13.93	*	17.89	12.89
30/02/93	*	7.53	*	12.92
07/05/93	14.40	7.60	18.9	13.17
01/07/93	14.20	7.66	18.18	13.31
06/08/93	14.25	7.75	18.20	13.42
16/08/93	14.24	7.66	18.17	13.46
17/09/93	14.30	7.83	*	13.57
05/10/93	14.25	6.88	*	13.52
15/10/93	14.15	5.36	*	13.53
01/12/93	14.16	5.95	*	13.14
31/01/94	14.30	7.31	*	13.32
08/03/94	14.45	7.52	*	13.50
18/03/94	14.49	6.84	18.29	13.56
12/04/94	14.52	7.78	18.35	13.63
10/05/94	14.59	7.92	18.30	13.78
AVERAGE	14.30	7.26	18.29	13.38
SIMULATED	16.45	9.18	20.16	16.49

* No measurements were taken (borehole was tampered with).

After the model was run using initial conditions and the steady state situation attained, the system was assumed to be in an equilibrium state representing average hydrological conditions. The simulated heads were compared with the observed water table elevations by plotting field data against simulation predictions as shown in Figure 8.3. Although there is a 2.5 metre error no further calibration was deemed necessary.

WATER TABLE CONDITIONS

SIMULATED vs MEASURED

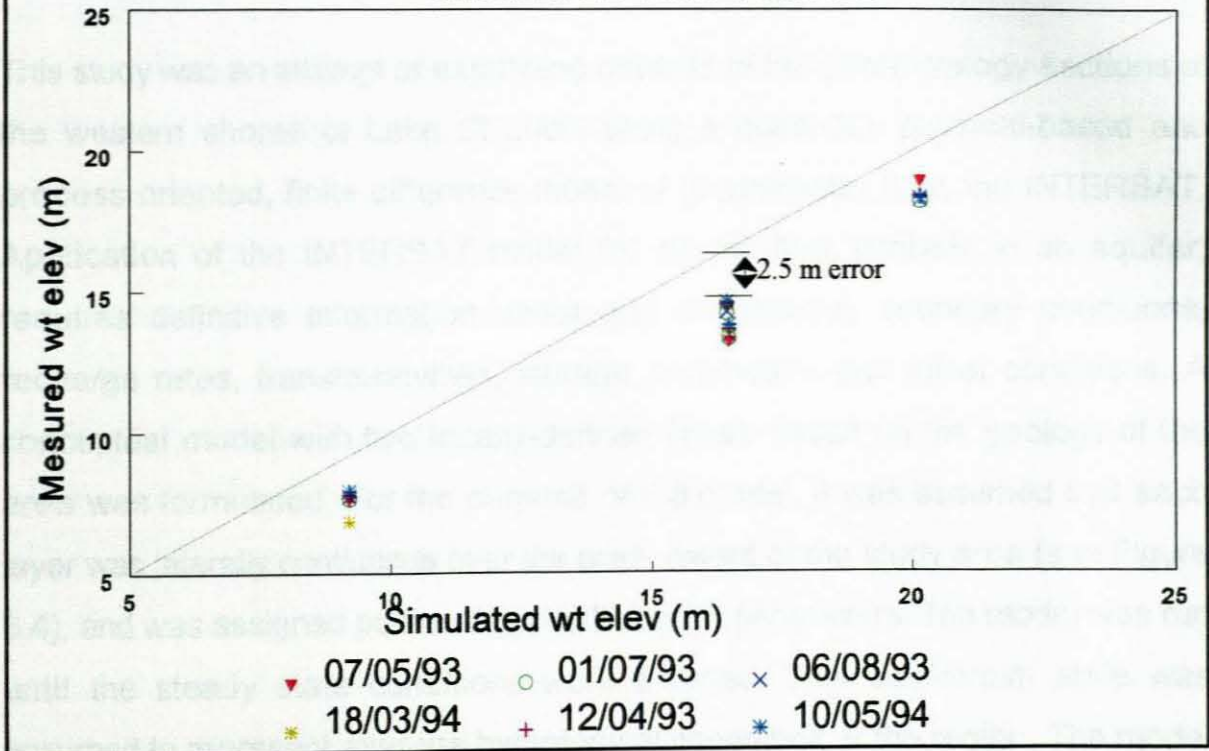


Figure 8.3 Averaged and simulated water table elevations from four western shores boreholes.

CHAPTER 9

SUMMARY AND CONCLUSIONS

This study was an attempt at examining aspects of the geohydrology sections of the western shores of Lake St Lucia using a quasi-3D, physical-based and process oriented, finite difference model of groundwater flow, the INTERSAT. Application of the INTERSAT model for steady flow analysis in an aquifer, requires definitive information about grid dimensions, boundary conditions, recharge rates, transmissivities, storage parameters and initial conditions. A conceptual model with two locally-defined layers based on the geology of the area was formulated. For the purpose of the model, it was assumed that each layer was laterally continuous over the areal extent of the study area (see Figure 6.4), and was assigned pertinent geohydrological parameters. The model was run until the steady state conditions were attained. This equilibrium state was assumed to represent average hydrological conditions of the region. The model simulations were assessed using the observed discharge and borehole data from available but limited information.

The western shores area is hydrologically distinct from the eastern shores region in that it has a number of flowing rivers which drain small catchments from the high-lying Lebombo volcanics and Karoo sediments. Eastwards towards the lake the geology is mainly aeolian and alluvial sands. The model results have shown that groundwater is released as a baseflow into rivers and this helps to sustain river flow in times of drought. This is demonstrated in the Mpate catchment in which a baseflow of $4.0 \times 10^6 \text{m}^3/\text{year}$ (Table 8.1) is a major recharge component as it constitutes 25% of Cornelius' (1993) simulated discharge of $18.0 \times 10^6 \text{m}^3/\text{year}$ for the Mpate River. Unfortunately, there is insufficient observational data to calibrate the model so further adjustments would be based on subjective assessments.

The model simulations for the Hluhluwe catchment show that the $10.7 \times 10^6 \text{m}^3/\text{year}$ simulated groundwater constitutes more than 86% of the total annual discharge of $12.3 \times 10^6 \text{m}^3/\text{year}$ measured at the Hluhluwe River mouth (at W3H015). The combined simulated baseflow for the Hluhluwe and Mpate catchment together form a total of approximately $23 \times 10^6 \text{m}^3/\text{year}$. If the baseflow of Nyalazi River, which has a bigger catchment, were to be incorporated by extrapolation, groundwater contribution into the lake from the western shores area could be in the order of $40 \times 10^6 \text{m}^3/\text{year}$. This suggests that groundwater contribution to the lake along the shorelines and through the rivers could be the major source of freshwater recharge. According to Kelbe and Rawlins (1992), this component may have a buffering effect on the salinity of the lake especially along the shore edges, if its delayed release coincides with drought conditions.

The application of the model in the present form has several deficiencies which, include amongst others:

- ▶ the complex geometry and heterogeneity of the geology is not adequately represented in this model.
- ▶ the interaction between nonlinearity of the model and the variance of its parameters in relation to the problems of scale was not looked into.
- ▶ the transient conditions were not examined because there was insufficient information to adequately calibrate the model.

These shortcomings could be overcome if sufficient and reliable field data were available in order to calibrate the model more accurately. The input of sufficient data could upgrade and improve the predictive capacity of the model. This, in turn, would increase the knowledge of the geohydrology of the western shores area of Lake St Lucia.

The number of the observations wells from which water table elevations and hydrogeological parameters for the model were measured are not sufficient for a detailed geohydrological investigation. However, the availability of fairly dense electrical resistivity soundings over the entire study area facilitated the deciphering of the geology and the delineation of aquiferous units. These geophysical soundings should, nevertheless, be supplemented with a good network of observation wells or boreholes to be dispersed over the entire western shores area if detailed geohydrological investigation is to be undertaken with a minimum level of empiricism necessary.

The historical flow data obtained from some of the rivers were unreliable due to either insufficient gauging stations in a catchment (as is the case with the Nyalazi River) or the gauging weirs were not strategically positioned (W3H013 - Nyalazi River, and W3H014 - Mpate River) or that the time over which recordings were taken was too short to yield dependable recordings.

Although the groundwater flow from the western shores into the lake could not be modelled very accurately, this study provides some insights into the geohydrological contributions to the functioning of the system and provides a useful basis for further research in the area.

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11. APPENDICES

APPEDIX I: Monthly runoff (10^6m^3) recorded at W3H014 for the Mpate River.

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL FLOW
1969/70	*	0.158	0.021	0.005	0.000	0.000	0.000	0.180	0.018	0.015	0.002	0.000	
1970/71	0.131	0.054	0.004	0.154	0.521	0.865+	0.456	1.709+	0.331	0.592	0.142	0.057	5.016+
1971/72	0.395	0.169	0.298	0.620	2.613+	0.847	0.827+	1.184	0.335	0.203	*	0.090	
1972/73	0.025	0.217	0.122	0.069	0.118	0.032	0.038	0.025	0.007	0.002	0.414	0.340	1.409
1973/74	0.268	0.969	0.206	0.322	0.297	0.354	0.072	0.485	0.268	0.118	0.035	0.014	3.408
1974/75	0.009	0.125	*	0.264	*	*	*	0.098	0.030	0.031	0.020	0.270	
1975/76	0.073	0.031	0.562	1.272+	2.126+	2.412+	2.071+	1.088	*	*	0.430	0.129	
1976/77	0.698	0.318	0.113	0.334	2.884+	1.662+	0.266	0.208	0.097	0.096	0.182	*	
1977/78	0.110	0.093	0.085	0.653	0.073	0.117	0.170	0.066	0.053	0.212	0.128	0.097	1.857
1978/79	0.563	0.192	0.083	0.008	0.004	0.035	0.059	0.205	0.071	0.070	0.053	0.049	1.392
1979/80	0.086	0.035	*	*	0.010	0.002	0.000	0.000	0.000	0.000	0.000	0.051	
1980/81	0.016	0.000	0.006	0.018	0.002	0.000	0.000	0.095	0.143	0.030	0.030	0.429	0.769
1981/82	0.073	0.077	0.054	*	0.000	0.037	0.155	0.019	0.072	0.022	0.007	0.000	
1982/83	0.000	0.014	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.003	0.087	0.023	0.128
1983/84	*	0.188	0.201	*	*	*	*	0.152	0.717	1.331+	0.670	0.441	
1984/85	0.274	0.315	0.131	0.582	1.919+	0.940+	0.205	0.077	0.672	1.397+	0.215	0.758	7.485+
1985/86	0.640+	0.755+	0.112	0.021	0.017	0.005	0.076	0.073	0.135	0.018	0.011	0.021	1.884+
1986/87	0.019	0.058	0.012	0.170	0.008	0.298	0.128	0.069	*	0.153	0.820+	2.144+	
1987/88	1.648	0.827	0.474	0.160	2.638+	2.783+	0.422	0.236	0.233	0.389	0.122	0.235	10.167+
1988/89	0.622	0.099	0.912+	0.252	1.588+	0.194	0.055	0.133	0.281	0.130	0.036	0.162	4.464+
1989/90	0.062	1.248+	0.613	0.168	0.644	0.362	0.223	0.096	0.035	0.024	0.275	0.178	3.928+
1990/91	0.460	0.164	0.269	0.203	0.433	1.032	0.275	1.388+	0.311	0.301	0.094	0.048	4.978+
1991/92	0.101	0.032	0.043	0.016	0.006	0.019	0.002	0.000	0.000	0.000	0.000	0.000	0.219
1992/93	0.000	0.000	0.009	0.000	0.029	0.023	0.001	0.000	0.000	0.000	0.000	0.000	0.062
1993/94	0.245	0.023	0.010	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.279
MEANS	0.26	0.25	0.17	0.21	0.64	0.51	0.25	0.30	0.15	0.21	0.15	0.22	2.965
%	8.75	8.08	5.82	7.07	21.55	17.17	8.42	10.10	5.05	7.07	5.05	7.41	100

MEAN ANNUAL RUNOFF = 2.97

- # : NO RECORD
- * : RECORD INCOMPLETE
- + : MORE THAN

APPENDIX II: Monthly runoff (10^6m^3) recorded at W3H022 for the outflow from Hluhluwe Dam.

YEAR/JAAR	OCT/OCT	NOV	DES/DEC	JAN	FEB	MRT/MAR	APR	MEI/MAY	JUN	JUL	AUG	SEP	ANNUAL FLOW
1967/68	1.144	0.495	0.867	0.853	0.179	0.771	1.467	1.221	0.990	0.642	1.460	0.539	10.628
1968/69	0.023	0.060	0.091	2.458	2.155	1.724	0.014	0.399	0.296	0.856	0.764	1.155	9.995
1969/70	0.637	0.569	1.128	1.890	1.499	1.587	1.785	0.401	0.978	0.437	1.133	1.243	13.287
1970/71	0.982	0.690	1.192	1.042	1.382	1.218	0.780	0.565	0.526	0.477	0.389	0.597	9.840
1971/72	0.448	0.658	0.242	1.126	33.164+	14.242	2.060	2.276	1.303	0.849	0.866	0.622	57.856+
1972/73	0.726	1.013	0.816	0.810	1.375	1.522	1.176	1.058	0.528	0.928	0.493	7.705+	18.150+
1973/74	9.649+	6.048	6.711	5.857	1.699	1.211	1.095	1.100	0.781	0.504	0.928	0.923	36.506+
1974/75	1.792	1.017	0.584	0.566	11.295+	16.420+	2.972	1.725	1.274	0.985	0.928	1.367	40.925+
1975/76	2.383	1.381	15.936+	50.190+	19.271	18.977+	18.603	6.105	1.839	1.995	1.756	1.169	139.61+
1976/77	2.109	2.344	1.864	1.750	84.203+	14.027	4.000	2.661	1.514	1.318	1.042	1.311	118.14+
1977/78	1.926	2.305	1.891	6.346	2.029	15.694+	1.966	1.729	1.614	1.174	1.437	2.237	40.348+
1978/79	1.338	2.629	3.151	2.145	1.755	2.082	1.798	1.140	1.442	1.642	1.436	1.409	21.967
1979/80	1.097	1.713	0.944	1.589	1.147	1.484	1.498	0.531	0.455	0.426	0.501	0.195	11.580
1980/81	0.246	0.198	0.499	0.526	0.276	1.030	0.845	4.279	1.305	0.646	0.818	3.850	14.518
1981/82	8.649+	2.198	1.187	0.912	1.040	2.011	1.655	1.292	1.132	1.114	1.179	1.199	23.568+
1982/83	2.382	1.486	1.354	1.377	1.157	1.289	0.703	0.689	0.204	0.000	0.070	0.142	10.853
1983/84	0.150	0.138	0.315	*	#	*	5.961	1.388	1.127	2.939	1.620	4.364	
1984/85	1.510	1.284	1.230	6.824	39.452+	5.035	1.522	1.434	1.038	0.958	0.806	0.850	61.943+
1985/86	4.475+	9.703	1.702	1.277	2.310	1.681	1.470	1.962	1.452	1.308	1.332	1.236	29.908+
1986/87	1.321	1.277	1.176	1.322	1.360	1.765	1.095	1.136	1.095	1.146	0.943	17.432+	31.068+
1987/88	13.309	8.447	10.492	2.128	12.721+	34.419+	2.853	1.451	1.175	1.612	1.220	1.332	91.159+
1988/89	3.373	1.357	2.428	3.698	22.399+	3.956	1.580	1.342	1.124	1.308	1.407	1.177	45.149+
1989/90	1.274	17.246+	43.538+	13.691+	5.933	7.780	3.027	1.577	1.251	1.268	1.269	1.232	99.09+
1990/91	1.298	1.254	1.302	6.755	13.932	15.685+	1.265	25.430+	4.328	2.942	1.768	2.220	78.179+
1991/92	1.299	1.791	1.309	1.298	1.585	1.696	1.626	1.643	1.091	1.008	0.949	0.960	16.255
1992/93	0.995	0.981	1.175	1.085	0.923	0.999	0.952	0.879	0.654	0.576	0.457	0.693	10.369
1993/94	30.701+	1.473	7.243	9.880+	0.815	0.950	0.887	0.863	0.911	0.903	0.848	0.883	56.357+
MEANS	3.53	2.58	4.09	4.94	9.87	6.31	2.28	2.46	1.28	1.00	0.97	1.99	40.64
%	8.68	6.36	10.06	12.15	24.28	15.53	5.62	6.06	3.16	2.46	2.39	4.89	100

MEAN ANNUAL RUNOFF = 40.54

- # : NO RECORD
- * : RECORD INCOMPLETE
- + : MORE THAN

APPENDIX III: Monthly runoff (10⁶m³) for the Hluhluwe River recorded at W3H015 near False Bay.

YEAR/JAAR	OKT/OCT	NOV	DES/DEC	JAN	FEB	MRT/MAR	APR	MEI/MAY	JUN	JUL	AUG	SEP	ANNUAL FLOW
1969/70	*	0.049	0.016	0.000	0.042	0.089	0.036	0.247	0.051	0.016	0.020	0.020	
1970/71	*	*	0.022	0.013	0.046	0.106	0.149	0.313	0.041	0.073	0.053	0.001	
1971/72	0.080	0.073	0.296	0.136	1.410+	3.942+	2.546+	2.300+	1.469	0.883	0.721	0.330	14.186+
1972/73	0.003	0.200	0.586	*	*	0.124	0.175	0.176	0.098	0.003	0.284	0.235+	
1973/74	3.541+	3.255+	3.427+	3.352+	1.298+	0.598	0.144	0.714	0.669	0.154	0.085	0.006	17.243+
1974/75	0.316	0.269	0.385	0.402	1.991+	3.942+	3.083+	1.748	0.839	0.418	0.194	0.628	14.215+
1975/76	1.748+	0.379	2.591+	3.942+	3.687+	*	*	3.939+	3.226+	2.577+	2.005+	0.884	
1976/77	1.558	1.581	0.565	0.449	3.461+	3.942+	3.686+	2.367+	1.073	0.742	0.951	1.252+	21.627+
1977/78	2.314	*	0.505	1.852+	*	3.107+	1.154	0.289	0.139	0.978	0.447	1.052	
1978/79	1.596	1.247+	2.305+	0.371	0.113	0.003	0.021	0.117	0.091	0.064	0.151	0.081	6.160+
1979/80	0.096	0.044	0.114	0.015	0.045	0.011	0.017	0.037	0.029	0.022	0.022	0.083	0.535
1980/81	0.007	0.000	0.009	0.370	0.427	0.039	0.016	1.867+	2.075+	0.625	0.306	2.275+	8.016+
1981/82	2.639+	1.647+	1.561+	0.055	0.000	0.059	0.509	0.095	0.212	0.027	0.000	0.000	6.804+
1982/83	0.155	0.710	0.070	0.133	0.057	0.030	0.019	0.017	0.045	0.067	0.123	0.040	1.466
1983/84	0.049	0.100	0.249	*	#	#	#	#	*	2.199+	1.971+	2.490+	
1984/85	1.379	1.052	0.588	2.487+	2.997+	3.805+	1.915+	*	*	1.420	0.833	0.621	
1985/86	0.671+	3.733+	2.649+	0.917	1.156+	1.177+	0.555	0.884	1.212	0.535	0.445	*	
1986/87	0.254	0.679	0.464	1.166	0.340	2.046	1.107	0.498	0.571	0.925	0.966	1.307+	10.323+
1987/88	3.969+	3.841+	3.968+	3.109+	3.063+	3.969+	3.679+	1.992	1.525	2.092	1.252	1.446	33.905+
1988/89	2.375+	1.311	2.169+	1.907+	3.194+	3.581+	1.413	0.855	1.085	0.922	0.601	0.640	20.053+
1989/90	0.832	2.625+	1.260+	1.190+	0.162	0.133	1.024	2.216	0.970	1.196	1.112	0.994	13.714+
1990/91	1.440	1.099	1.185	1.227+	3.585+	3.866+	2.550+	1.989+	0.255	0.141	0.026	0.000	17.363+
1991/92	0.647	1.646	*	*	0.405	0.789	0.448	0.478	0.467	0.599	0.545	0.226	
1992/93	0.051	0.264	0.961	0.442	0.612	0.811	0.874	0.136	0.051	0.333	0.060	0.001	4.596
1993/94	0.779+	0.036	1.714+	2.892+	0.186	0.000	0.000	0.000	0.000	0.258	0.299	0.176	6.340+
MEANS	1.06	1.03	1.11	1.06	1.13	1.45	1.00	0.93	0.65	0.69	0.54	0.59	12.28
%	8.63	8.43	9.01	8.61	9.21	11.78	8.18	7.58	5.27	5.62	4.39	4.82	100

MEAN ANNUAL RUNOFF = 12.28

- # : NO RECORD
- * : RECORD INCOMPLETE
- + : MORE THAN