A GEOHYDROLOGICAL ASSESSMENT OF THE BEHAVIOUR AND RESPONSE OF THE ZULULAND COASTAL PLAIN TO BOTH ENVIRONMENTAL INFLUENCES AND HUMAN ACTIVITY.

BY

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SUMMARY

The Zululand coastal plain on the eastern seaboard of South Africa contains large quantities of readily available fresh water. Lake St Lucia, located within the plain, is a wetland habitat internationally recognised for its environmental importance. Yet over the past few decades extensive forest developments have taken place within the lake catchment. The considerably higher transpiration rate of the fast growing trees planted there over those of grassland environments they replaced is well established. The effects on the hydrological balance of the lake and its environs of the greater water loss resulting from this land use modification has however been the subject of much speculation.

This study analyses the hydrological regime of the eastern shores plain over the 17 years from 1973 to 1990. During this period both wet and dry climatic conditions were experienced, and in 1981 a plantation covering 1100 ha was established. In order to clarify the magnitude and variability of hydrological parameters under natural and under altered conditions, comparisons were made between wet and dry periods, and between grasslands and forested areas. The extent to which plantations have modified the hydrological balance could thus be determined and placed in regional perspective.

The study began with reviews of the physiography of the eastern shores catchment area and of the existing data base

(chapter 2). Following a substantial upgrading of the hydrometric network (chapter 3), specific data collection took place. The components of the hydrological cycle were then assessed in order to identify differences in hydrological response both to climatic variability and to land use. The results of these assessments are presented as individual sections on meteorology (chapter 4), surface hydrology (chapter 5), and geohydrology (chapter 6).

It is the conclusion of the study that in this sub-tropical environment, with shallow depths to groundwater, commercial forests are responsible for an additional consumptive use of water of between 150 and 175 mm/year. In the regional perspective of the water balance of Lake St Lucia, the total forested area of 25 000 ha will thus be seen to lower average inflow to the lake by between 10% and 12%. During extreme dry periods this figure increases to approximately 30%.

Although they are greatest during dry climatic cycles, the effects of such a reduction in water yield are at all times significant. In the first place, the water balance of the lake is seriously affected. In the second, with a reduction in its fresh water input, the salinity balance of the lake cannot but be influenced. In the third, changes in this salinity balance will have a direct impact on the flora and fauna of the lake and its environs. It is to be hoped that following the proposed future removal of the plantations from the eastern shores, the situation will improve. However, the remaining 20 000 ha under commercial forestry on the western shores will continue to have a significant effect upon the hydrology of Lake St Lucia.

OPSOMMING

Die Zoeloelandse kusvlakte aan die ooskus van Suid-Afrika bevat groot hoeveelhede geredelik beskikbare varswater. Die St Lucia-meer op hierdie vlakte is 'n vleigebiedhabitat wat internasionaal erken word as 'n belangrike natuurbewarings-gebied. Die afgelope paar dekades is daar egter groot plantasies tot stand gebring binne die meer se opvangsgebied. Daar is onteenseglik bewys dat die transpirasie van die vinnig groeierde bome veel hoër is as dié van die grasvelde wat deur die plantasies vervang is. Daar is egter baie bespiegel oor die uitwerking wat die groter waterverlies, as gevolg van die veranderde grondgebruik, op die hidrologiese balans van die meer en sy omgewing het.

In hierdie studie word die hidrologiese regime van die kusvlakte aan die oostelike oewer van die meer oor die 17 jaar vanaf 1973 tot 1990 geanaliseer. Gedurende hierdie periode is droe sowel as nat weersomstandighede ondervind. In 1981 is 'n plantasie van 1100 ha aangeplant. Ten einde die grootheid en veranderlikheid van die hidrologiese parameters onder natuurlike en gewysigde omstandighede vas te stel, is vergelykings gedoen tussen droë en nat periodes en tussen grasvelde en aangeplante bosgebiede. Sodoende kon daar vasgestel word in watter mate die plantasies die hidrologiese balansgewysig het en kon dit in perspektief geplaas word met betrekking tot die bepaalde gebied.

Die studie het begin met 'n oorsig oor sowel die fisiografie

van die opvangsgebiede aan die oostelike oewer as oor die bestaande databasis (hoofstuk 2). 'n Aansienlike opgradering van die hidrometriese netwerk (hoofstuk 3) is gevolg deur die versameling van spesifieke data. Die komponente van die hidrologiese siklus is daarna bepaal ten einde die verskille te identifiseer in die hidrologiese reaksie op sowel klimaats- as grondgebruiksveranderinge. Die resultate hiervan word aangebied as afsonderlike afdelings oor meteorologie (hoofstuk 4), oppervlakhidrologie (hoofstuk 5) en geohidrologie (hoofstuk 6).

Die gevolgtrekking waartoe in hierdie studie gekom word, is dat in hierdie subtropiese omgewing met sy vlak oppervlakwater, kommersiële plantasies verantwoordelik is vir die gebruik van 'n addisionele 150 mm tot 175 mm water per jaar. In perspektief geplaas met betrekking tot die waterbalans van die St Lucia-meer, kom dit daarop neer dat die totale plantasiegebied van 25 000 ha die watertoevloei tot die meer verminder met tussen 10% en 12%, en gedurende uiters droë tydperke toeneem tot ongeveer 30%.

Hoewel die uitwerking van verminderde watertoevloei die grootste is gedurende die droë klimaatsiklus, het dit te alle tye 'n groot impak. In die eerste plek word die waterbalans van die meer ernstig beïnvloed. Tweedens is dit onvermydelik dat 'n afname in die toevloei van varswater die soutgehalte van die meer sal beïnvloed. Derdens het 'n verandering in die soutsoutgehalte van die meer 'n direkte impak op die flora en fauna van die meer en sy omgewing. Daar word gehoop dat die voorgestelde verwydering van die plantasies aan die oostelike oewer van die meer die situasie sal verbeter. Die oorblywende 20 000 ha kommersiële plantasies aan die westelike oewer sal egter steeds 'n aansienlike uitwerking op die hidrologie van die St Lucia-meer hê.

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CHAPTER 1

INTRODUCTION

The Zululand coastal plain is an environmentally sensitive region located on the eastern seaboard of South Africa. It extends from Mtunzini in the south to Kosi Bay on the Mozambique border, a distance of some 250 km (Figure 1.1). This area of approximately 9000 km^2 is comprised geologically of unconsolidated alluvial, esturine and aeolian sands and clays which under natural conditions contain a large, reliable and potentially high yielding aquifer (Worthington, 1978). The presence of this aquifer has led to the recognition of good development prospects for both industry and agriculture (Worthington, 1978).

In the south, the development of Richards Bay in the early 1970s involved the creation of a deep water harbour, the establishment of an industrial centre, and the expansion of residential areas. The high water demands envisaged from such development were expected to be supplied locally from both ground and surface water resources (Bachmat, 1975). Hydrological studies were commissioned to determine the quantity and quality of these local water resources (Bachmat, 1975, Du Preez, 1975, and Worthington, 1978). The specific emphasis of these studies was on water management and water supply for Richards Bay, thus they allowed the hydrological regime around Richards Bay to be more fully understood. Since the area is situated on the coastal plain, however, the

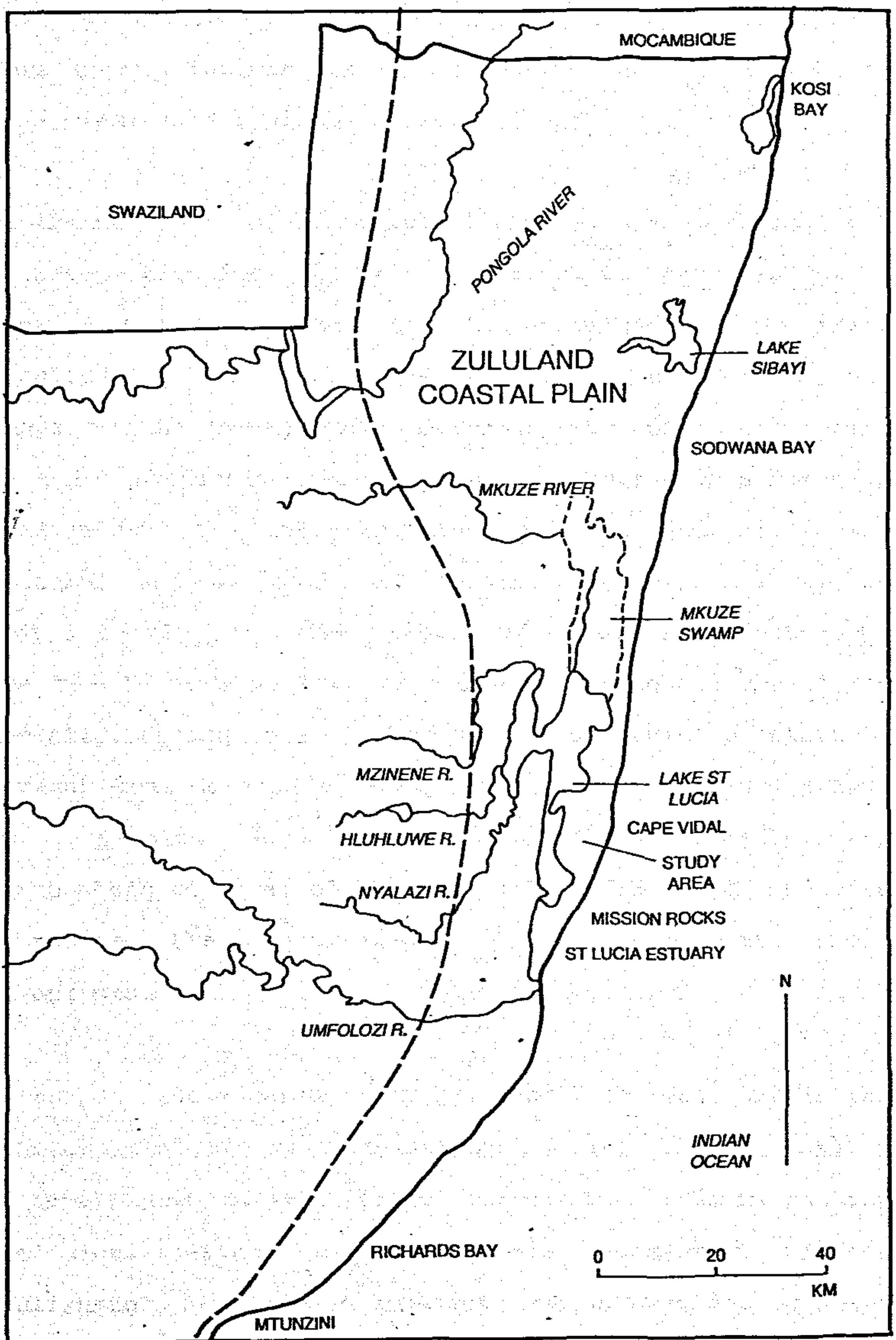


Figure 1.1 Regional map of the Zululand coastal plain

geological and geohydrological information they produced also offers useful indications of the conditions to be expected over a wider extent of the plain.

Over the remainder of the Zululand coastal plain, agriculture and conservation form the main land uses. Consequently little attention has been given to the hydrology of the area. Agriculturally the region is relatively undeveloped, due perhaps to the predominance of thin and sandy soils which have a low productive capacity, and to the region's relative isolation from the major markets. As groundwater is readily available, and as soil and location factors are not so crucial, fairly extensive timber and sugar cane plantations since the 1950s have been established throughout the plain. Especially during the 1960s and 1970s these plantations underwent considerable expansion and now cover large areas. This expansion took place rather haphazardly and unfortunately no parallel hydrological studies were conducted to assess the environmental consequences of these developments.

In the St Lucia area, various modifications within the catchment area gave rise to concern as early as 1954 (Day et al, 1954). One of the major causes for concern was the hydrological effect on the lake ecosystem of the establishment of large plantations of exotic fast growing trees around the lake. A government Commission of Enquiry appointed to "investigate the alleged threat to plant and animal life in St Lucia lake" stated that "...large plantations of exotic trees in the St Lucia catchment may affect the runoff [into the lake] deleteriously" (Kriel, 1966). This commission recommended that "further development of the St Lucia catchment area should be planned to be carried out in such a way that sufficient water supplies to the Lake are ensured..." and that "hydrological investigations should be continued and expanded so that calculation of water requirements [of the lake system] can be improved...". Following the publication of the report of this Commission of Enquiry, much investigative research was conducted. However this generally took the form of reviews of previous work and led to recommendations for future research.

Following reviews of available information in 1968, Nanni concluded that the "forest plantations in the vicinity of the lake could have no more than a slight effect on the salinity of the lake's water". This conclusion was at odds with the findings of Tinley, who in 1969, had argued that since groundwater seepage was solely responsible for maintaining Lake Sibaya (Figure 1.1), it must play an important role in the water balance of Lake St Lucia. Consequently, any forestry induced reduction of inflow from the peripheral areas of the lake would have an influence on its salinity balance. Tinley went on to recommend that sand plains peripheral to the lake should be urgently restored to their original state.

In 1970, in response to the recommendations of the Commission of Enquiry (Kriel, 1966), the Natal Provincial Administration initiated the collection of hydrological and meteorological data as well as a programme of hydrological research around Lake St Lucia. This programme resulted in reports by Hutchison and Pitman (1973), and by Hutchison (1974a, 1974b, 1975, and 1976a) which indicated that the water losses resulting from plantations situated on the eastern shores of the lake amounted to an average 3 x 10^6 m^3/year. In his presentation to the St Lucia Scientific Advisory Council Hutchison was specific in ascribing the sole significant cause of the present extreme salinity conditions in the lake, to developments such as irrigation, afforestation and dam construction (Hutchison, 1976b in Heydoorn, 1976).

Despite this proliferation of hydrological research which highlighted the likely detrimental consequences of afforestation, plantations continued to expand in size and number on both the eastern and the western shores of the lake during the 1970s and 1980s.

In the 1980s several bodies, including the kwaZulu Department of Agriculture and Forestry (Berridge, 1986), the Division of Geohydrology of the Department of Water Affairs (Muller, 1986), the South African Forestry Research Institute (Lindley and Scott, 1987), and the Natal Parks, Game and Fish Preservation Board (Porter, 1987), expressed interest in the further examination of the hydrological consequences of afforestation. Problems they identified as being associated with the development of large scale timber plantations in the

Zululand coastal plain are summarised below:

1. The inflow of water to Lake St Lucia, which has already been severely affected by inland water resources developments, notably the Hluhluwe Dam, is now mostly restricted to direct precipitation and to seepage flows from the areas bordering the lake (Tinley, 1971). It is possible that even these seepage flows are being progressively reduced by the consumptive use of groundwater by exotic timber plantations (Porter, 1987).

It is further possible that the increasing fluctuations in the salinity of the lake - which have many environmental implications - are due to the same phenomenon. Taking up the argument begun in the 1960s between Nanni and Tinley, the South African Forestry Research Institute found otherwise, however in their assessment of the impact of pine plantations on the groundwater resources of the eastern shores (Lindley and Scott, 1987). They concluded, in spite of acknowledging "estimated reductions in fresh water [yield] (up to 20%) to the surface water [due to afforestation]", that reductions in fresh water inputs attributed to afforestation "...have a negligible influence on general lake salinity...".

2. The timber plantations around Lake Sibaya suffer from a water shortage during dry periods, leading to a decline in growth and in some cases the death of trees (Berridge, 1986).

3. The alteration of the geohydrology in the region has had

or may have the following effects in certain areas: unviability for further agricultural development; increased cost of water extraction for human use; and potential harm to the water quality of the region (Berridge, 1986 and Muller, 1986).

This study of the geohydrology of a part of the St Lucia aquifer has been conducted with the aim of clarifying the extent and magnitude of these problems. Its objective was to monitor the hydrological regime of a section of the Zululand coastal plain in order to evaluate the effects both of natural environmental fluctuations and of human induced land use modifications upon the water balance of the area. Attaining this objective should allow estimates to be made of the hydrological response of the system to future changes in land use.

The study area selected is situated within the Eastern Shores State Forest adjacent to Lake St Lucia between Cape Vidal and Mission Rocks (Figure 1.1). Here, as a consequence of the controlled and limited plantation development, it was possible to identify distinct areas with different land uses. Since there was an established groundwater monitoring network with a data-base covering 17 years the region could be assessed under a wide range of climatic conditions. And given the area selected and the time period available it was possible to investigate the hydrological responses to the plantation progressively from its planting to its maturation. The remainder of the commercial forest cycle (clear-felling and re-establishing) could not be covered since harvesting is only programmed for 1992 (Owen, 1989), and re-establishment after this clear-felling, is not, at present, envisaged (Lubke, 1990). However, the effects of plantation removal can be inferred on the basis of the behaviour of the surrounding un-forested areas, remaining to be confirmed by future investigations.

A comprehensive literature search was undertaken by the Council for Scientific and Industrial Research. It showed that the effects of both environment and human activity on shallow geohydrological conditions have been studied extensively and that much attention has been devoted to vegetation-hydrology inter-relationships. The 400 entries produced by the search cover many aspects of the project and pertain to many parts of the world. The direct extrapolation of this published information to the Eastern Shores State Forest was not feasible since the climatic, geological and geohydrological differences between this area and other sites were too great. Yet these studies did provide useful indicators of the magnitude and variability of the results to be expected.

In recent years much work has been done on the quantification of evaporation from different types and densities of vegetation. Bosch and Hewlett, in their review of 94 catchment experiments (1982), estimated that a change in vegetation cover from grasslands to mature conifers or eucalypts causes a reduction in total water yield of approximately 400 mm/year. Greenwood et al (1985) indicated that annual evaporation loss from various *Eucalyptus* species was between 1300 and 1900 mm higher than from grazed pastures. Experimental work conducted by Bosch (1979 and 1982) reported by Lindley and Scott (1987), indicated that the pine trees in the Cathedral Peak and Jonkershoek catchments start to use more water than grasslands after approximately four to five years. The increase continues for 20 to 25 years, after which it stabilises.

Carbon et al (1982) suggested that *Pinus pinaster*, in a Western Australian environment similar to the Zululand coastal plain, could reduce groundwater recharge by tapping soil moisture to a greater degree than stands of hardwood trees. However, the extent to which pine trees de-water a region was questioned by Riekirk et al (1978). In a coastal plain environment in Florida, where water was readily available, their study showed evaporation losses accountable to *Pinus elliottii* were only the equivalent of 58% of the annual rainfall total.

On the Zululand coastal plain, the sandy terrain enables pine trees to develop deep tap-roots which extend below the water table and which are greatly branched in the unsaturated zone (Haigh, 1966). Consequently the trees are able not only to utilise the water from the saturated layer, but also to extract available moisture from the unsaturated zone. The efficiency with which they can utilise the unsaturated zone is confirmed by the example of pine trees planted on the high coastal dunes between St Lucia and Cape Vidal. These trees are unlikely to have formed tap-roots deep enough to reach the water table which is up to 100 m below the dune crests (Lynn, 1990), but still appear to be healthy.

This study began with reviews of the physiography of the eastern shores catchment area, and of the existing data-base (chapter 2). Following a substantial upgrading of the hydrometric network (outlined in chapter 3) specific data collection took place. The components of the hydrological cycle were then assessed in order to define differences in hydrological response both to climatic variability and to land. The results from these assessments are presented as individual sections on meteorology (chapter 4), surface hydrology (chapter 5) and geohydrology (chapter 6).

CHAPTER 2

CATCHMENT AND DATA DESCRIPTIONS

Geographically, the eastern shores plain is located on the isthmus between Lake St Lucia and the Indian Ocean (Figure 2.1). This isthmus is, in its entirety, un-alienated State land: there is no private land ownership. The study area lies within the Eastern Shores State Forest and the St Lucia National Park. The former is currently under the joint jurisdiction of the Natal Parks Board (NPB) and the Department of Forestry, whereas the latter is under the sole control of the NPB. Apart from the specific areas devoted to commercial forests, the entire region is maintained as a conservation area, the fauna and flora being managed and controlled by the NPB. The study area comprises a low lying plain bounded to the west by Lake St Lucia and to the east by the Mfabeni swamp (Figure 2.1). A commercial plantation forms a continuous unit in the centre of the plain and is surrounded by managed grasslands and swampy areas. As the St Lucia National Park extends 800 m from the lake shoreline, no forest development has occurred along the edges of the plain.

For many years, and at the initiation of various bodies, a range of hydrological and meteorological parameters have been recorded within and surrounding the area. Since the requirements and the purposes of the data have differed, there is little uniformity in the data base. As a consequence the data have had to be collated into a standard form to

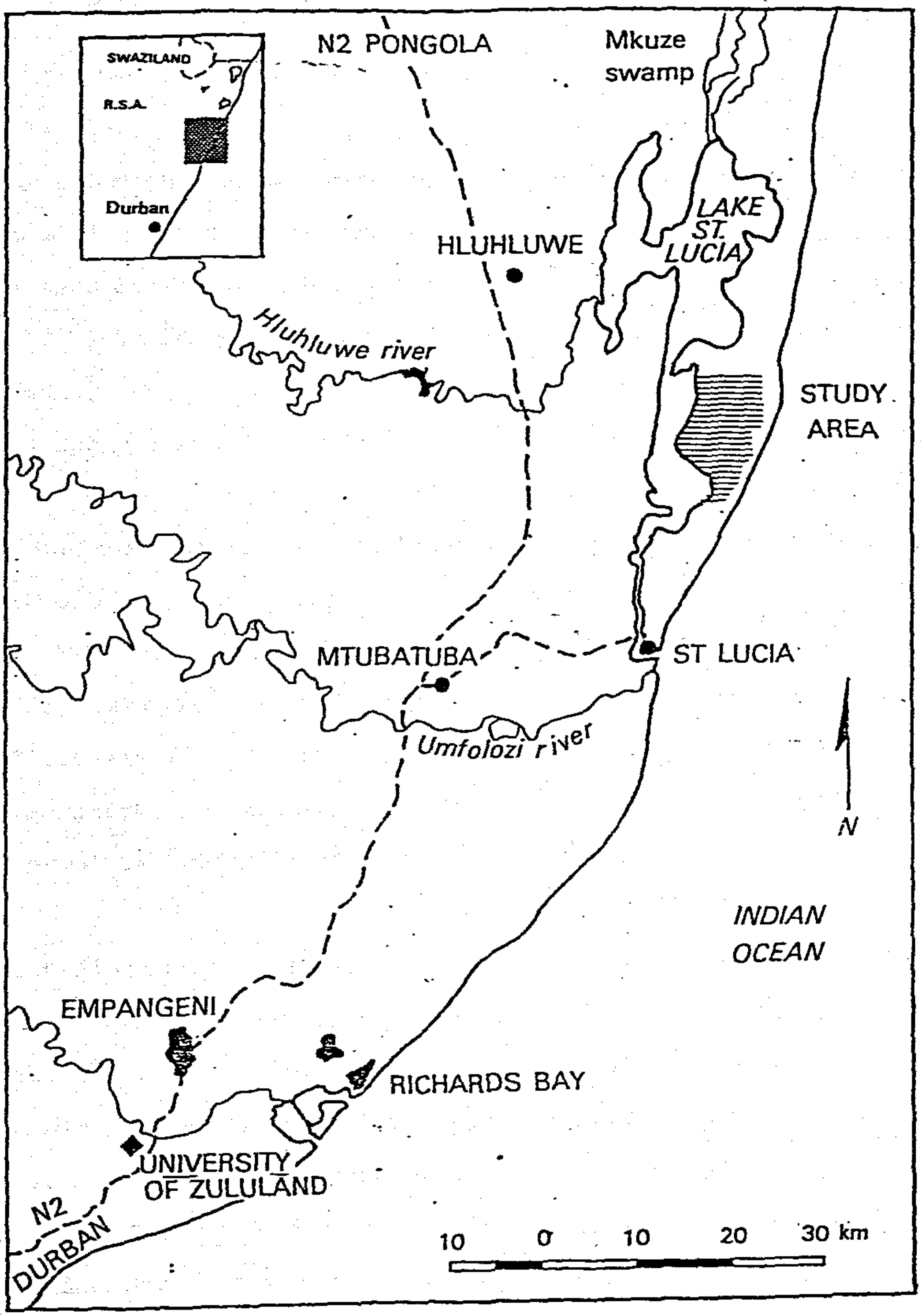


Figure 2.1 Location map of the study area

facilitate this particular study.

2.1 METEOROLOGY

Meteorological data have been collected at several sites around the study area for varying periods by both official (Weather Bureau) and private observers (Taylor, 1982) (Figure 2.2). Variables monitored include rainfall, temperature, humidity, air pressure, evaporation, barometric pressure, wind speed and wind direction.

The Weather Bureau of the Department of Environment Affairs controls 11 observation stations within the area east of 32 15' and between latitudes 28 00' and 28 30'. At 9 of these stations daily recordings of rainfall only are taken. Additional readings are taken at Riverview (0339357) of temperature and wind, and at Cape St Lucia (0339720) of temperature, barometric pressure and wind.

Rainfall recording stations are reasonably well distributed around the study area (Figure 2.2), however, there are no stations within the eastern shores plain. Some records, notably those for Cape St Lucia (0339720), extend over at least 60 years; and others (Fanies Island - 0339756 and St Lucia Estuary - 0339856) have, in addition to 37 years of recorded data, synthetic, generated records for a further 29 years.

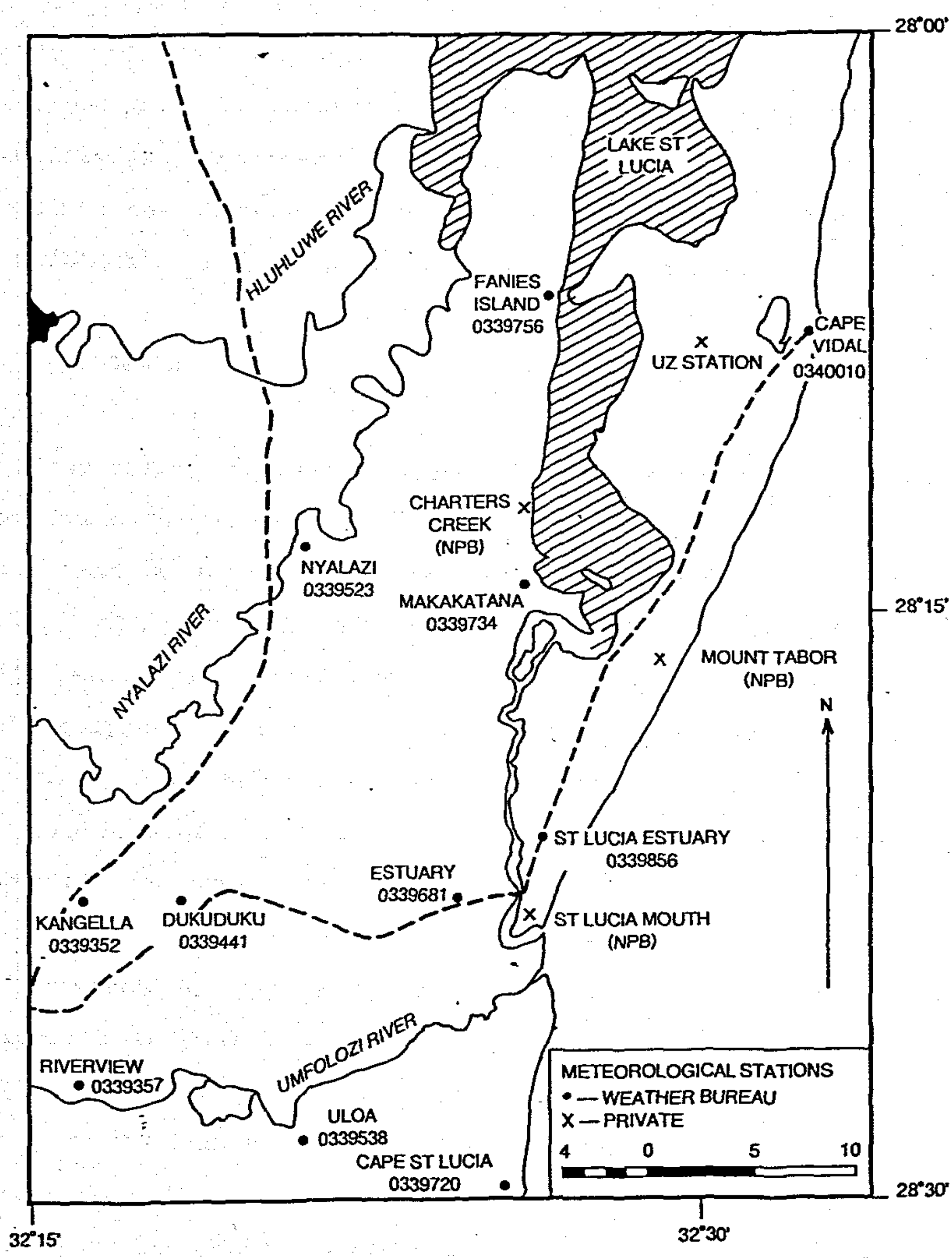


Figure 2.2 Meteorological stations within and surrounding the study area

Around the study area there are a number of additional meteorological observation stations run by the Natal Parks Board and by other research bodies (Figure 2.2). Variables recorded include rainfall, temperature, wind, evaporation, humidity and barometric pressure. Generally only spot readings have been taken, but on the western shores there is an automatic weather station in operation (Taylor, 1987).

2.2 TOPOGRAPHY

The topography of the eastern shores is characterised by a low lying undulating plain bounded on the west by Lake St Lucia and on the east by the high coastal dune belt (Figure 2.3). This plain is dissected by the swampy Mfabeni depression which drains to the south west. A central dune belt composed of red sands is situated in the northern half of the study area to the west of the Mfabeni depression. The descriptions of two transects that follows will clarify this topographical configuration.

In transect A, the northern sector of the research area (Figure 2.4), the flat areas to the west of the central dune belt are about 1.5 km wide with a topographic elevation of up to 20 m above mean sea level (a.m.s.l.). The central dune belt rises steeply to 70 m a.m.s.l then falls off rapidly to the Mfabeni depression. This depression is a level swampy area up to 3 km wide and only 5 to 10m a.m.s.l. On the eastern side of the depression the land rises first gradually and then steeply to over 100 m on the coastal dune belt.

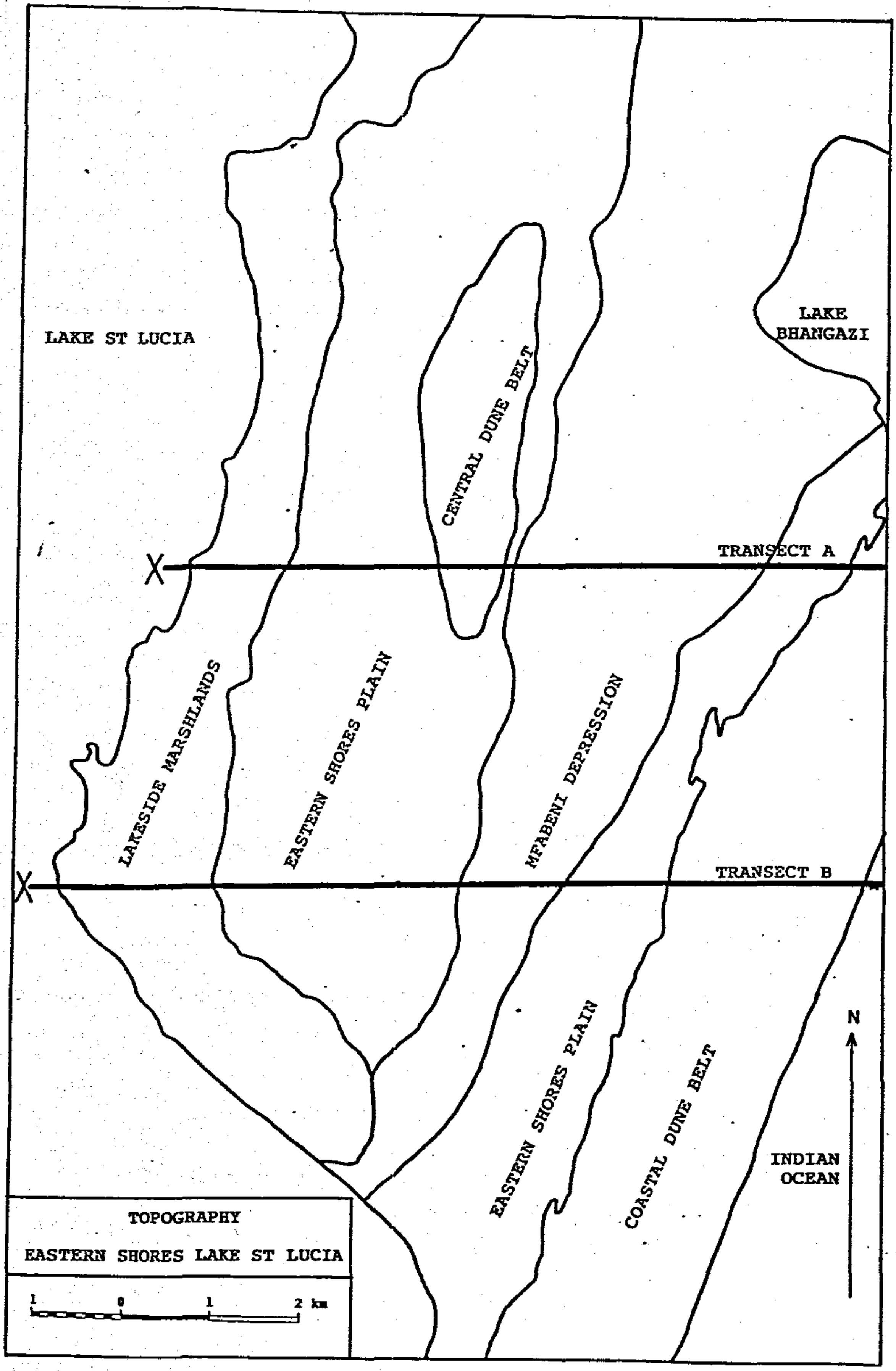


Figure 2.3 Topographical features of the study area

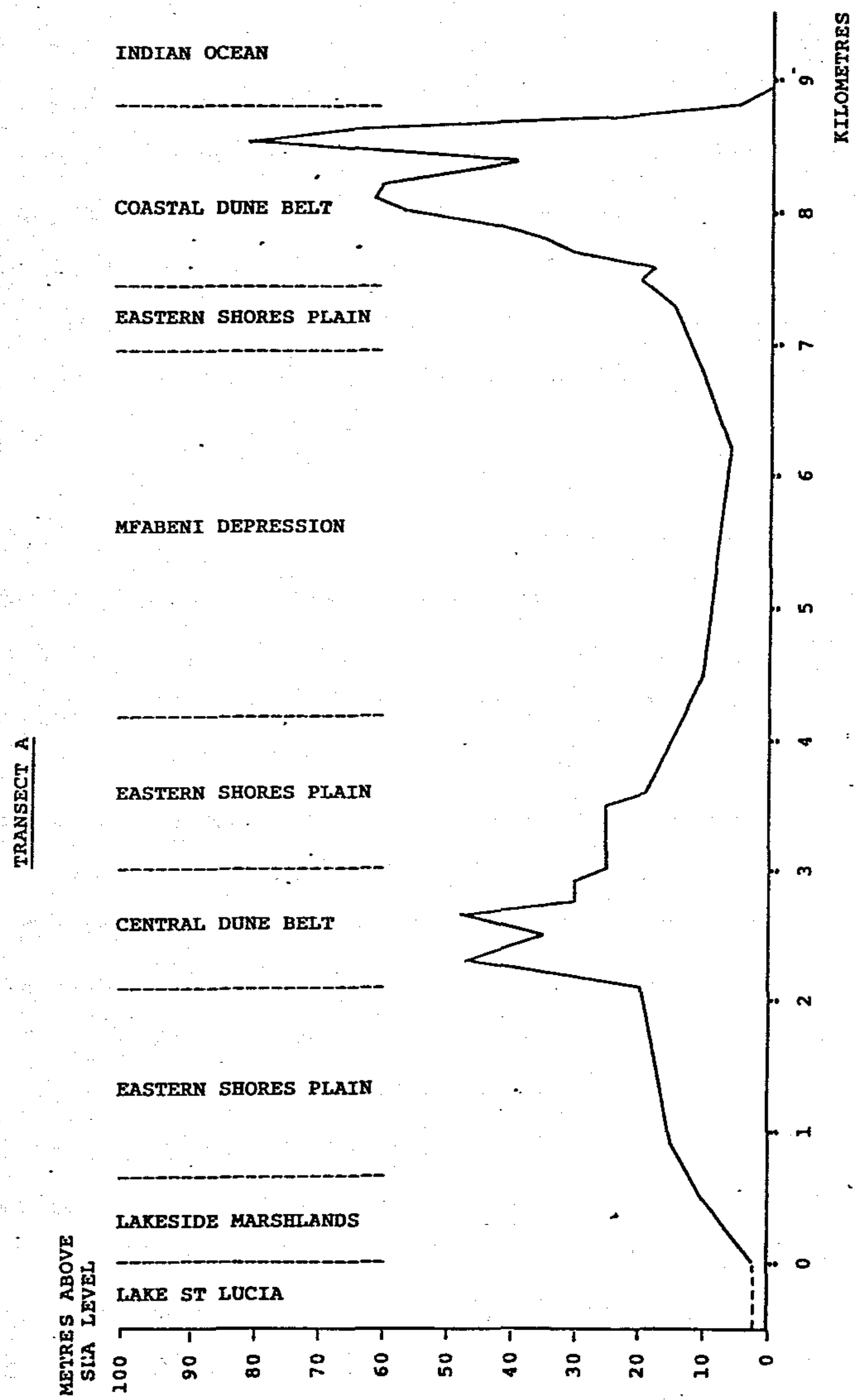


Figure 2.4 Transect A - Through the northern part of the study area

Transect B, to the south of transect A (Figure 2.5), traverses the widest point in the research area. It consists of a much wider section (4 km) of low lying undulating plain without a central dune zone. The plain falls gradually to the Mfabeni depression, which is, at this point only 1 km wide with an elevation of about 7 m. To the east of the depression is a shallow rise to the base of the coastal dune belt, whose elevation rises steeply to over 100 m in this the widest part of the coastal dunes.

The Eastern shores plain can be compared to an island, surrounded on all sides by low lying saturated regions. The lake, to the west and south, has a mean elevation of 0.40 m a.m.s.l, which fluctuates both in response to tidal motion and to climatic variations within the lake catchment area. The Mfabeni swamp, to the east of the plain, consists of a large area of low lying grasslands that are usually water-logged. To the north-east, Lake Bhangazi forms a permanent open water body which drains to the south into the Mfabeni swamp. To the north, low lying grasslands drop gradually to the lake shore over several kilometres. From orthophoto maps, the swamp area can be seen to vary from 16.5 to 19.0 km². Its perimeter remains fairly constant at around 33 km. The swamp attains a maximum elevation of 8 m (a.m.s.l.) at Lake Bhangazi. Its level falls gradually (slope 0.05%) to the level of Lake St Lucia at 0.4 m. The catchment area draining to the swamp is approximately 32 km², 62% of which is situated on its western side.

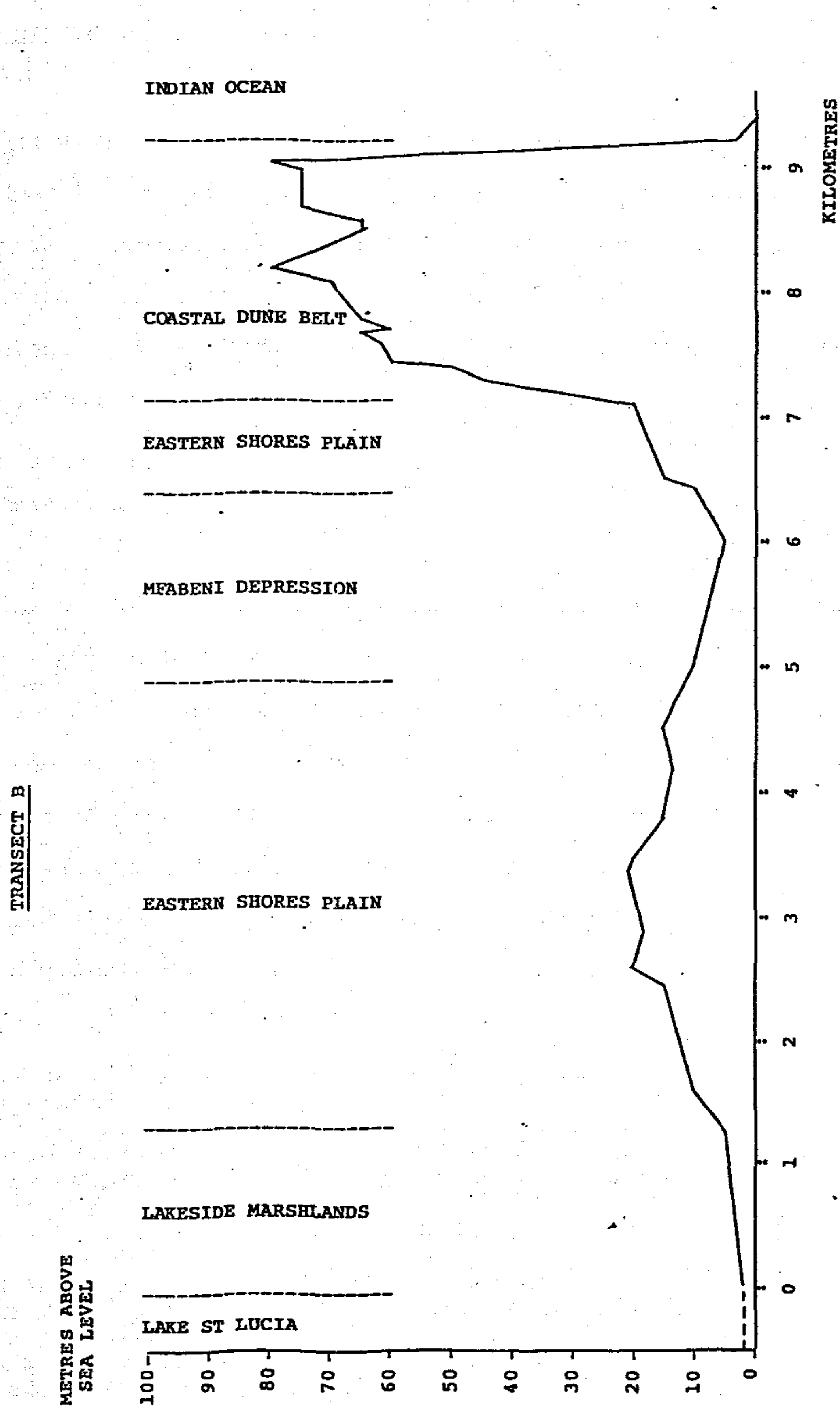


Figure 2.5 Transect B - Through the southern part of the study area

2.3 VEGETATION AND LAND USE

The vegetation covering the study area can be divided into four broad types: natural though managed indigenous grasslands containing scattered shrubs and trees; hygrophilous grasslands; swamp forests; and exotic timber plantations. The distribution of these vegetation types is shown in Figure 2.6.

2.3.1 Grasslands

Large areas in the south and east of the study area are covered by indigenous grasslands. Although managed by burning, these are assumed to represent the original vegetation cover of all the non water-logged areas. The vegetation consists of grasses interspersed with isolated thickets of small trees and bushes. Lubke et al (1989) have identified the common or constant and dominant species found in these grasslands as including:

GRASSES

Aristida junciformis
Themeda triandra
Imperata cylindrica
Cympobogan validus
Digitaria eriantha

SHRUBS

Eugenia capensis
Helichrysum kraussi
Diospyros villosa
Anthospermum herbaceum
Maytenus heterophylla

HERBS

Thesium sp.
Cassytha filiformis
Acalypha petiolaris
Cyperus marginatus
Cissampelos hirta
Gerbera piloselloides
Vernonia oligocephala
Senecio cf. erubescens

CREEPERS AND LIANES

Smilax kraussiana
Thunbergia atriplicifolia

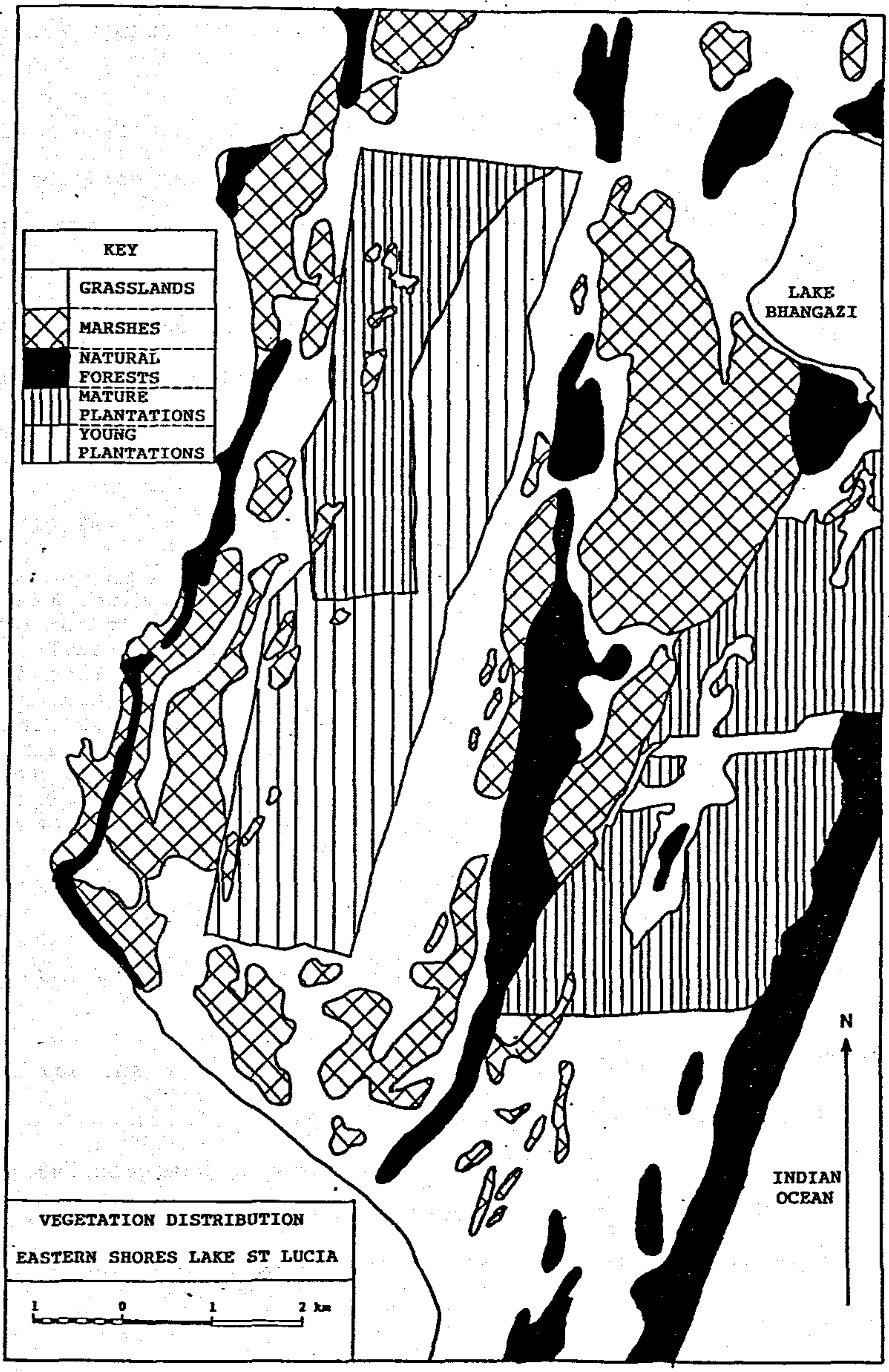


Figure 2.6 Vegetation map of the study area

2.3.2 Hygrophilous Grasslands

In the lower lying pans, marshes, and lakeside areas, the vegetation consists of water plants such as reeds and sedges. In the perennially wet areas these plants are widespread whereas in the ephemeral pans they are interspersed with the grasses found on the higher regions. According to Lubke et al (1989) the characteristic species of these hygrophilous grasslands are:

GRASSES	SEDGES (Cyperaceae)
Ischaemum fasciculatum	*Eleocharis limosa*
Hermathria altissima	*Cyperus tenax*
Andropogon huillensis	*C. leptocladus*
A. festiciformis	*C. obtusiflorus*
Themedia Triandra	*C. sexangularis*
Panicum dregeanum	*Pycreus sp.*
Acroceras macrum	*Fimbristylis complanata*
Sporobolus subtilis	*Bullostylus contexta*
Eragrostis capensis	*Rhynohospora brownii*
Digitaria longiflora	*R. corymbosa*
Monocymbium ceresiiforme	*R. holoschoenoides*
Stenotaphrum secundatum	*R. madagascariensis*
	Kyllinga spp
	Restio spp (Restionaceae)

2.3.3 Swamp Forests

Along the Nkazana stream channel, in parts of the Mfabeni swamp, and along the edges of Lake St Lucia, wooded areas exist composed of mangroves and other trees. Species found in the area include *Bruguiera gymnorrhiza, Rhizophora mucronata, Avicennia marina and Barringtonia racemosa* (Hutchings, 1991).

2.3.4 Commercial Plantation

The commercial Sibomveni plantation, covers an area of 1628 hectares. A species of pine (*pinus elliottii*) from the coastal plains of south-eastern U S A has been planted. Also found within the plantation are *Sapium integerrimum*, *Microsorium scolopendrium* and *Smilax kraussiana* (Lubke et al, 1989). The harvested wood is used primarily in the pulp and paper industries. Planting occurred in two separate stages. In the northern sector development began in the early 1960's when some 500 hectares were planted. These trees are now fully mature and felling is due to commence in 1992. In 1981 an additional 1100 hectares were planted to the south and east of the 1961 plantation. These younger trees are now over 8 m high.

2.4 GEOLOGY AND SOILS

The geology of this region has been studied by various researchers over the past thirty years. Due to the different purposes of these studies, different emphasis has been placed on particular geological features. The level of detail of the studies and the comprehensiveness of the field work conducted also varies. During 1989 and 1990, extensive drilling was conducted to the east of the study area as part of an Environmental Impact Assessment (Lynn, 1990). The geological information thus gained has proved invaluable in clarifying the nature of the geology underlying the study area. The stratigraphic sequence present in the eastern shores is outlined in table 2.1.

Table 2.1 Generalized stratigraphic succession (after Lynn, 1989)

FORMATION	AGE
. Alluvium . Grey and reddish brown aeolian sand	Recent 0 - 10 000 years BP
. Berea red type sand . Light grey sandy limestone . Port Durnford formation light grey, yellowish orange sands and clayey sands	Pleistocene 10 000 - 2m years BP
. light grey weathered orange sandy limestone with basal conglomerate	Pliocene-Miocene 2m - 20m years BP
. Siltstone	Cretaceous 60m - 135m years BP

This stratigraphic sequence has been compiled with reference to what should be present in a complete sequence. In some areas, sections of the stratigraphic column are absent or modified. Figure 2.7 is a representative cross-section through the study area showing the configuration of the geological formations.

2.4.1 Cretaceous Deposits

The base of the stratigraphic sequence outlined is the Cretaceous layer, This layer is very thick and lies unconformably on pre-cretaceous granites or lavas. This interface is more than 1000 m below the present day sea level (Hobday, 1979) and consequently the pre-cretaceous strata will have no influence on the shallow geohydrological regime of the eastern shores. In the study area, the layer which underlies the entire Zululand coastal plain, its' upper surface at or just below mean sea level (Hobday, 1979). Recent drilling (Lynn, 1990) has confirmed its depth at about 30 m below MSL.

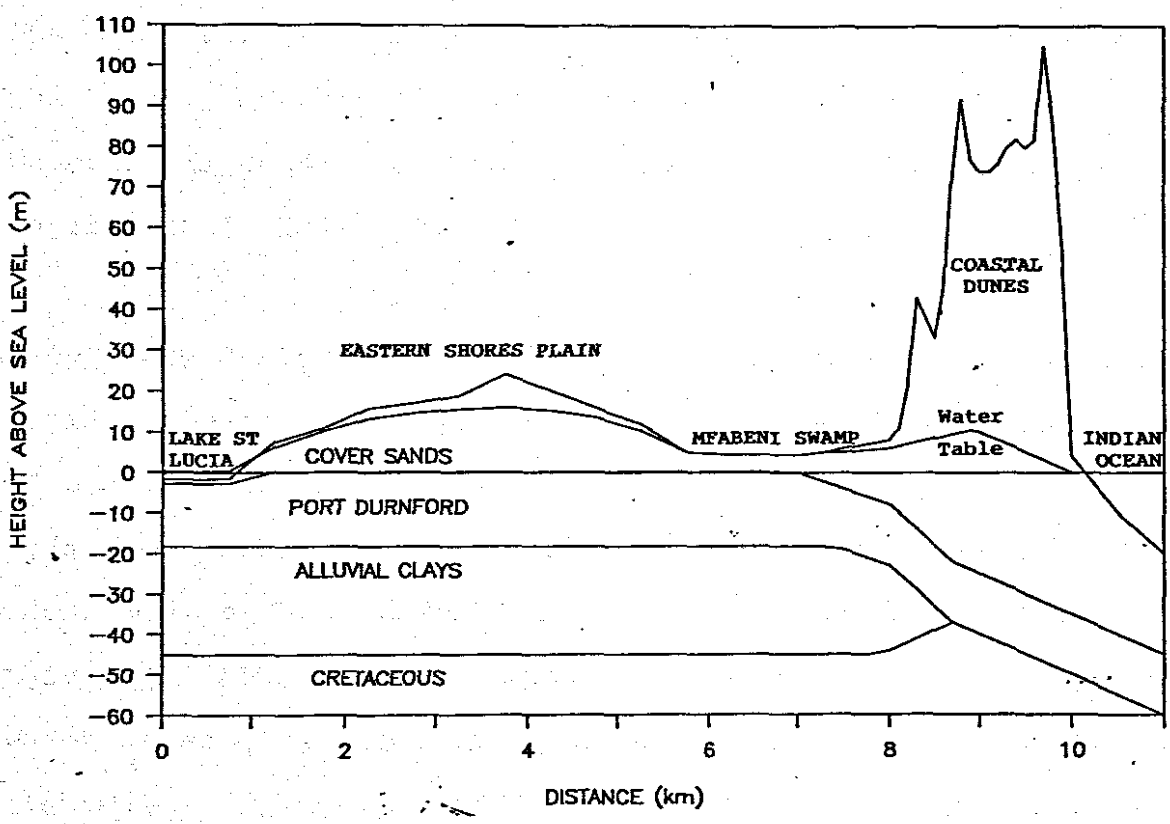


Figure 2.7 Idealized geological cross section

Rocks associated with this layer are mainly sandstones, mudstones and shales which all dip gently in a seaward direction (van Wyk, 1963 and Du Preez, 1975). As this layer lies completely below sea level, it is not likely to play any major role in the shallow subsurface hydrology.

2.4.2 The Port Durnford Deposits

These deposits overlie the cretaceous layer and are composed of sands and clayey sands forming distinct layers of differing colours (Lynn, 1989). They appear to vary in thickness between 10 and 30 m in this region with their top layers being at mean sea level. Recent drilling (Lynn, 1990) has confirmed their presence, their continuity and their thickness. Towards the lake the upper layers of the Port Durnford deposits have been reworked to form a thick (30 m) layer of alluvial clay.

Laboratory analyses of samples from this formation as well as field evaluation indicate that these deposits have porosities of approximately 42% and permeabilities ranging from 0.0001 cm/sec to 0.001 cm/sec. (0.09 to 0.9 m/day) (Lynn, 1990). These values fall within the expected range for deposits of this type (Todd, 1980). Specific yields (the percentage of water capable of draining under the force of gravity) should lie within the range of 10 to 23% (Todd, 1980) thus leaving 19% to 32% as specific retention.

2.4.3 Cover Sands

The cover sands lie over the Port Durnford deposits and form the surface topography. They consist of fine to medium, well rounded grains of sand that display high permeabilities and porosities, though these decrease with depth due to compaction. At the crest of the coastal dunes these sands have a maximum thickness of about 100 m; this decreases to just 3 m on the plains. As the present beach is too narrow to supply the large quantities of sand required to form such high dunes, it can be inferred that the sand was derived during a period of lower sea level (Hobday, 1979). The presence of dense natural vegetation serves to confirm that the dune formation process is now in a period of stasis.

The cover sands contain distinct layers of unconsolidated sands, silts, clays and organic material. These layers and lenses have widely differing hydraulic properties and can be expected to influence the groundwater flow rates and directions greatly. The high porosities and permeabilities of the sand layers, allow unrestricted water movement, whereas the reduced permeabilities of the silts and clays will tend to restrict flow and thus give rise to shallow perched aquifers above the main water body. Representative values for the geohydrological parameters of these sands have been determined (Lynn, 1990). The porosity has been measured at 45%, the specific yield at 35%, and the permeability at 0.028 cm/s (24 m/day). This indicates that the sands are generally more porous and permeable than the Port Durnford deposits and consequently form the most hydrologically active strata.

2.4.4 Soils

Due to their high sand content, the soils found in the area are not particularly well developed, thus they are not readily distinguishable from the cover sands. Humus content is generally low, except in the immediate surface layer in areas of dense vegetation. In many places profiles obtained using a soil auger indicate that the surface layer is composed almost totally of sand with a very low organic content. Elsewhere a layer up to 0.5 m in depth exists consisting of sand and organic material. As a consequence of the sandy nature of these surface layers, high infiltration rates and minimal surface runoff are characteristic.

2.5 SURFACE HYDROLOGY

The presence of surface water in the study area is limited. The Mfabeni depression and its outlet to the south, the Nkazana stream, form the largest surface water unit, though there are in addition numerous unconnected shallow pans and marshy areas. Lake St Lucia, which forms the western boundary of the study area, is also of relevance however as its fluctuations are likely to have some influence on groundwater flow rates and quantities.

2.5.1 The Mfabeni Depression

The Mfabeni depression, situated between the study area and the coastal dunes, is a large shallow swampy area connecting Lake Bhangazi with Lake St Lucia. Sources of water for this depression include direct precipitation, groundwater seepage from the surrounding higher areas, and, for some of the time, outflow from Lake Bhangazi. Groundwater inflow is dependent on the water table elevation surrounding the plain and on the hydraulic characteristics of the aquifer. The swamp, under existing conditions, experiences considerable fluctuations in its surface area and water depth in response to seasonal and annual variations in rainfall. Generally there is a higher inflow and consequently a larger surface area and greater water depth during the wet season when the water table is high. Inflow to the swamp from Lake Bhangazi is variable and mainly regulated by the relative levels of the swamp and the lake.

The primary outflow to Lake St Lucia from the Mfabeni depression is through the Nkazana stream (Figure 2.9). On the recommendation of Nanni (1977), a crude Parshall flume was constructed on this stream in 1979 and measurements were taken periodically until 1984, when the flume became inoperative. Given the condition of the flume the re-establishment of monitoring at this site was not possible. Consequently it was of high priority that a replacement be designed and constructed so that this important parameter could be incorporated into the water balance calculations.

2.5.2 Unconnected Pans and Wetlands

Many unconnected pans and wetlands occur in depressions in the undulating topography where the groundwater table makes contact with the surfaces. A series of wetlands occur where the coastal dune cordon meets the low lying plain, increasing in size and number towards the lake. Since they are fairly small, these wetlands have not been individually monitored, however from aerial photography, field evaluation, and discussions with local observers it seems that the pans fluctuate in size and water depth in direct response to natural climatic variation (Porter, 1987). Only the larger and/or very low lying wetlands seem to be perennial features, the remainder being generally ephemeral or intermittent.

Afforestation has significantly reduced the number and size of wetlands originally situated within plantations. From an evaluation of aerial photographs it is apparent that during the early years of plantation development the pans within the plantations remained clear of trees due to the water-logged conditions (Figure 2.8). However, with the high evapo-transpiration rates associated with the maturing forest, the pans dried sufficiently for trees to become established. The pans now form pockets of younger trees within the plantations and the 'wetlands' are now only active for short periods following heavy rain (Figure 2.8). Even after the rainfall associated with tropical cyclone Domoina in 1984 they did not remain under water for any extended period (Porter, 1987).

2.5.3 Lake St Lucia

The water levels of Lake St Lucia have, since 1958, been monitored at several locations by the Department of Water Affairs. These levels change continually in response to tidal motion, prevailing winds and other hydrological and geohydrological fluctuations. The lake surface area thus varies considerably and has been estimated to vary between 230 and 410 km^2 (Kriel, 1966). The total catchment area of the lake originally covered 19 600 km^2, though this was reduced to 8 900 km^2 when the new mouth was created for the Umfolozi river in 1952. This reduction did not appear to directly affect the water balance of the lake to any great extent, however there were indirect effects consequent from the alteration of estuarine dynamics affecting the free exchange of water to and from the ocean. The major inflow components of the lake comprise surface flow from the Mkuze, Msinduze, Hluhluwe and Nyalazi rivers and subsurface flow from the sand deposits underlying the eastern (Kelbe and Rawlins, 1990b) and western shores.

Mean annual inflow to the lake under unaltered conditions but excluding flow from the Umfolozi river has been estimated at between 222 x 10^6 and 364 x 10^6 m^3 (Hutchison and Pitman, 1973). Surface inflow to the lake has been considerably reduced by human influences such as afforestation, agriculture and dam construction in the catchments of the feeder rivers. Subsurface inflow has also been significantly reduced by extensive afforestation both on the western and the eastern shores. According to Hutchison and Pitman (1973) the total reduction in inflow is expected to be between 19% and 36%. The consequences of the reduced inflow have been discussed at length by Kriel, 1966; Tinley, 1971; Nanni, 1982; and Lindley and Scott, 1987 with the conclusion being that the salinity balance of the lake is now less stable than

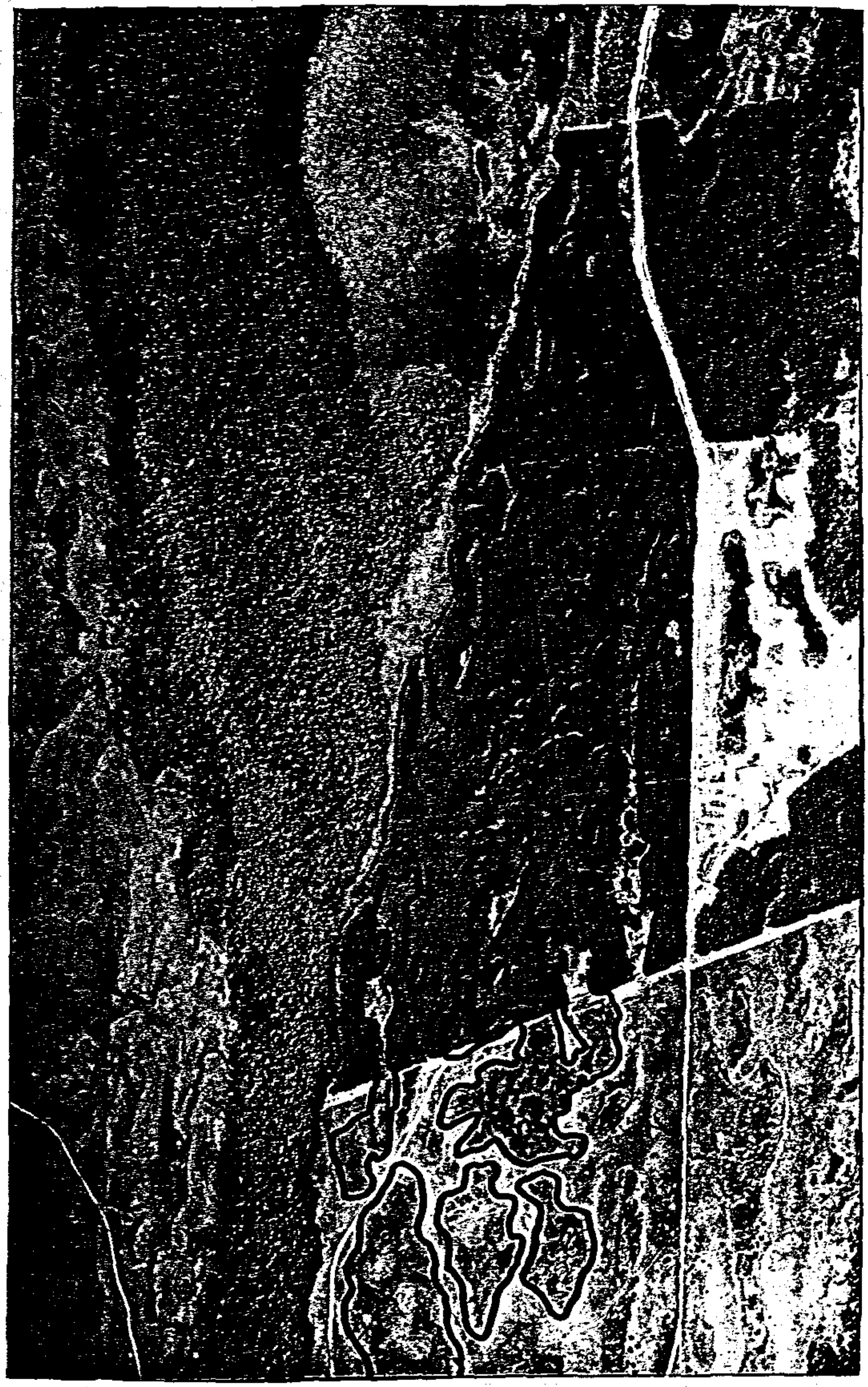


Figure 2.8 Aerial photograph showing a section of the KwaSheleni planation in 1989. Outline shows the extent of wetlands in 1979 (from orthophoto maps)

in the past. Higher salinities now being experienced during drier periods. In 1971, Tinley ascertained that groundwater seepage to the lake was the only remaining fresh water source capable of maintaining the lake salinity at acceptable levels. Afforestation since 1971 on both the eastern and western shores has undoubtedly reduced this inflow further.

In spite of a relatively small catchment area, the eastern shores of the lake appear to play a significant role in the water balance of the lake. At present the Eastern Shores State Forest contains a forested area covering approximately 5000 ha. The consequences of an increased water loss from these plantations include the reduction of flow both to the lake and to the sea, a reduction in groundwater storage, and a lowering of water tables.

2.6 SUBSURFACE HYDROLOGY

Situated within the study area, and aligned in four east-west transects, is a network of nineteen shallow boreholes (Figure 2.9). Drilled in 1973 by the Natal Provincial Administration, their locations were based to some extent, on the recommendations of van Zijl (1971). Only two of these boreholes (A2 and D1) were constructed using large diameter casings (150 mm) and thus presumably fitted with well screens. The remaining seventeen boreholes were constructed using 18 mm galvanized piping and are unlikely to have had well screens installed.

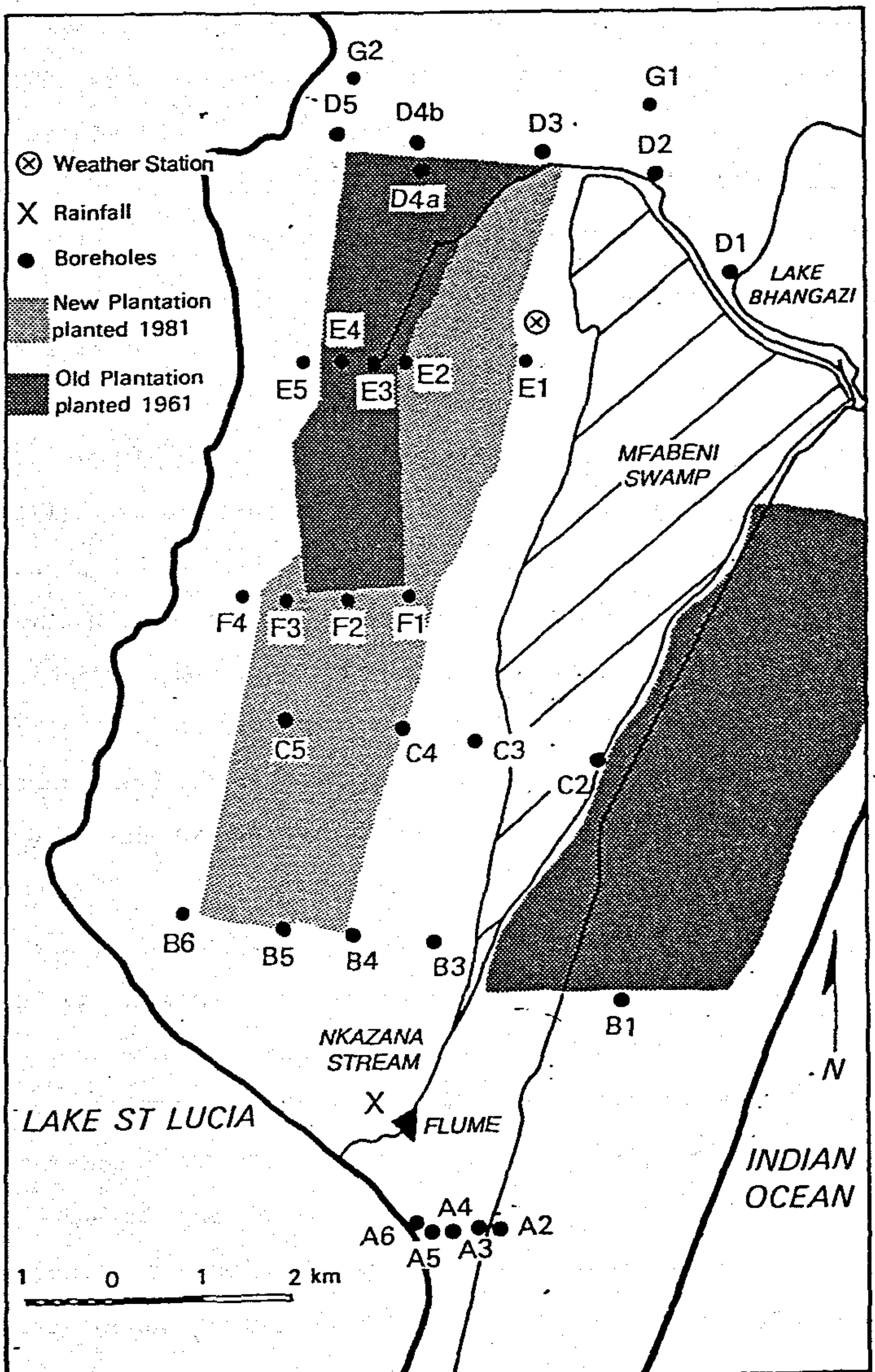


Figure 2.9 Geohydrological monitoring network

The four lines of boreholes A - D are situated mainly to the west of the St Lucia - Cape Vidal road on the Eastern Shores plain. The most southerly line (A) consists of five boreholes approximately 100 m apart. The boreholes comprising this line all are within 800 m of the lake shore in the St Lucia Park. Consequently, the vegetation along this line is composed of natural grasslands with scattered small trees and bushes (Figure 2.6).

Line B, about 3 km to the north of line A, consisted originally of six boreholes sited approximately 1 km apart. Borehole B2, however, appears to have been abandoned soon after completion. The western end of this line is situated on the southern boundary of the young sector of the Sibomveni plantation; the central part of the line goes through natural grasslands; and the eastern end is situated on the southern boundary of the KwaSheleni plantation of mature trees.

The C line, comprising 4 boreholes is situated about 2 km north of the B line and the holes are again about 1 km apart. The western end of the line (boreholes C4 and C5) is within the young (1981) sector of the Sibomveni plantation. To the east, boreholes C2 and C3 are situated in natural grasslands either side of the marshes and swamp forests of the Mfabeni depression. Borehole C2 is within 2 m of the open swamp water and consequently water levels measured here serve to provide a record of swamp level fluctuations.

The D line, 6 km to the north of the C line, runs adjacent to the northern boundary of the mature (1961) Sibomveni plantation. Again, the six boreholes comprising this line are approximately 1 km apart. The exceptions are boreholes D4a and D4b which are within 50 m of each other. D4a being just inside the mature plantation and D4b being just outside. Borehole D1 is situated on the shoreline of Bhangazi Lake and serves as an indicator of the lake level fluctuations. North of the D line is an extensive region of natural grasslands.

The borehole lines E, F and G depicted on Figure 2.9 represent new lines of boreholes created specifically for this study and are discussed later.

CHAPTER 3

METHODOLOGY OF THE STUDY

In order to determine the effect of modifications to the vegetation cover on the hydrological regime of the area a representative and reliable data-base was essential. Although data monitoring had been conducted in the area for many years, it was aimed at meeting different needs and requirements and hence varies considerably in format. It was therefore necessary to collate existing data with reference to the requirements of this study. Inadequacies in the data-base were identified and attempts were made to overcome them by upgrading the data collection network.

3.1 METEOROLOGICAL NETWORK

Since the existing stations either were too far removed from the study area or did not cover a complete range of meteorological variables, it was considered essential to establish a comprehensive meteorological station. After examination of possible sites for a fully automatic weather station, the eastern border of the Sibomveni plantation was selected (Figure 2.9). This site was considered ideal as it is open to the north-easterly and the south-westerly prevailing winds, and it is at the same elevation as the top of the adjacent tree canopy.

After the erection of a fenced 10 m square enclosure, a

Campbell CR 10 data logger with extended memory (64 k bytes) was installed to monitor rainfall, temperature, solar radiation, relative humidity and wind speed (Kelbe and Rawlins, 1990a). The data logger was interfaced to a cassette tape recorder for external data storage. This allowed data collection to continue even while the system was left unattended in the field for long periods. The data logger was installed in a fibre glass box under a radiation shield to protect it from the harsh environment. The data logger enclosure, together with all the sensors, was mounted on an aluminium tripod. The logger was powered by a 12V lead acid battery which was maintained by a 5W solar panel.

Numerous problems were encountered during the establishment of this meteorological station. Several sensors appeared to be faulty, and corrosion of the termination panel led to recorder failure. In addition, interference from wild animals meant that all the wiring had to be enclosed within conduit tubing. These preliminary problems delayed the collection of meteorological data until late 1988. Continuous and complete records were forthcoming during 1989 and these have been collated, processed and published (Kelbe and Rawlins, 1990a). During 1990, further problems were experienced with the recording system, which have yet to be resolved. Valuable meteorological interpretations are possible, however from data recorded during the one complete year (1989) of station operation.

3.2 HYDROLOGICAL NETWORK

The Nkazana stream is situated at the southern end of the Mfabeni depression and links it to Lake St Lucia. It forms the only surface outflow component of the system. On the recommendation of Nanni (1977), a crude Parshall flume was constructed on this stream and measurements were taken periodically from 1979 to 1984. In 1984 the flume became inoperative as a result of the high discharges caused by tropical cyclones Domoina and Imboa. Since this outflow component forms an integral part of the water balance of the study area, methods to re-establish flow monitoring had to be investigated.

After examination of the existing inoperative flume, repair was considered unfeasible as the stream bed now by-passes the flume. In Addition it was evident that the flume was under-designed, and even moderate flows would overtop the structure.

The possibility of constructing a concrete weir on the upstream side of the existing road crossing was investigated but rejected on the grounds of cost, interference from and to traffic, and detrimental environmental effects resulting from the creation of an upstream pool.

The solution was thus to build a completely new flume and to install it at a point close to the existing flume. After a full evaluation of various types of flumes with regard to measurement accuracy, ease of construction, ease of installation, and cost, the flume selected was a short throated Parshall flume made of fibre-glass resin (Ackers et al, 1978).

The Parshall flume, developed in the 1920's in the United States has been used extensively at water treatment plants and on irrigation schemes (Ackers et al, 1978). It consists of a short parallel throat preceded by a uniformly expanding section (Figure 3.1). The floor is horizontal in the converging section, slopes downwards in the throat, and is inclined upwards in the expansion. The control section, at which the depth is critical, occurs near to the downstream end of the convergence, upstream from the throat.

Under high flow conditions, flow through flumes of this type is likely to become drowned and ceases to conform to the design rating curve. Consequently, two head measurements have to be made: the upstream gauging point, in the converging approach section, is used for low flow conditions. The downstream gauging point, at the downstream end of the parallel throat section, serves to record whether flow conditions are drowned, and is used in the rating formula for these conditions.

Twenty-two standard designs of the flume exist (Ackers et al, 1978) covering discharges from 10 to 93 000 l/s. The throat widths for these designs range from 25 mm to 15 m. For this particular stream size and discharge a throat width of 610 mm

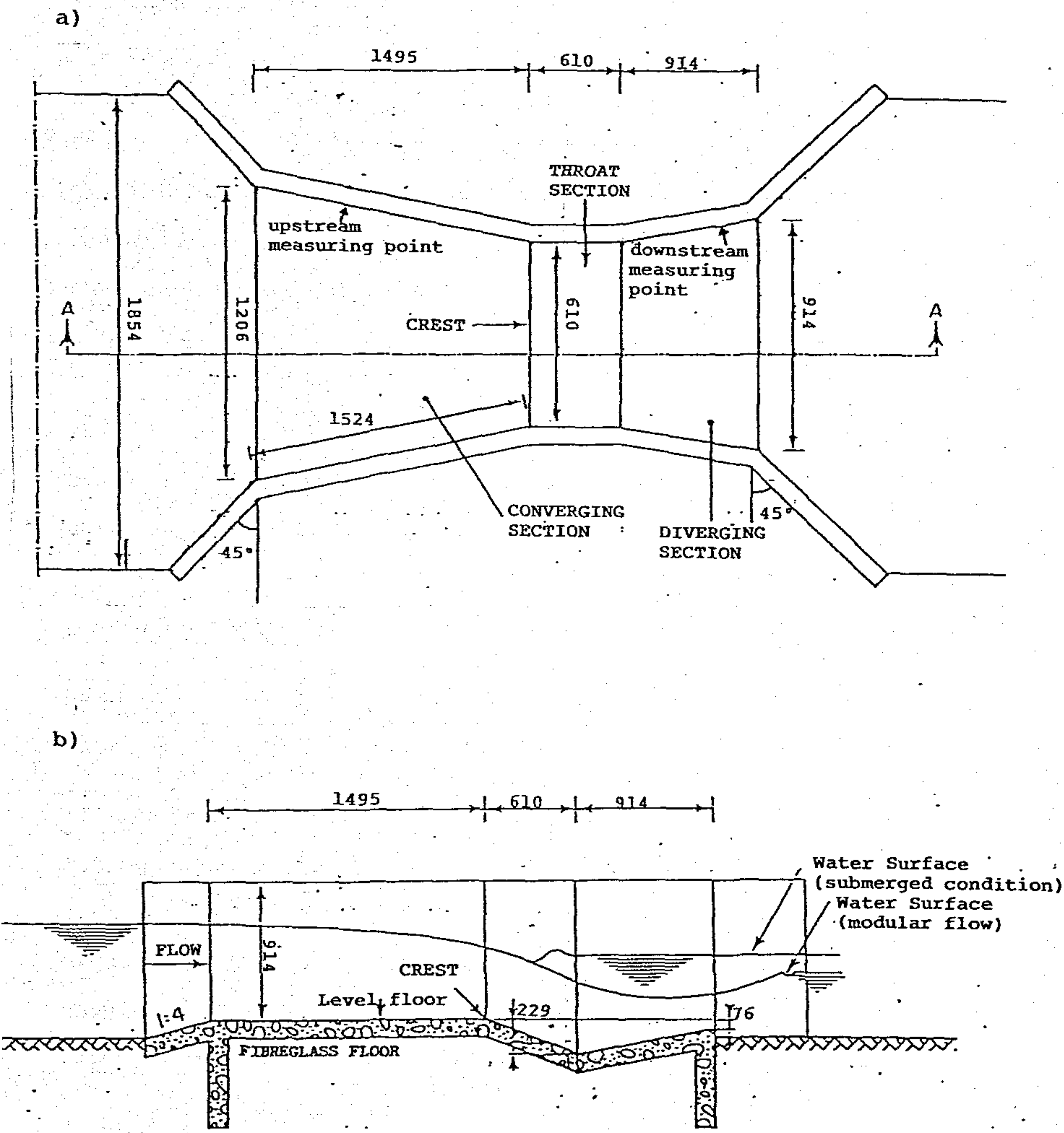


Figure 3.1 Geometry of the Parshall Flume a) Plan view and b) side view (All dimensions in mm)

was selected, with a discharge range from 12.1 to 937 l/s. Although not sufficient to measure extreme flood conditions experienced occasionally, it was considered adequate to measure most events. It was impractical to make a larger flume since it was constructed off site using fibre-glass panels. Also transport and installation of a larger flume would have been too problematic. The maximum dimensions of the constructed flume (made of fibre-glass 5 mm thick) are 4 m long, 2 m wide and 1 m deep.

The standard stage-discharge relationship of this type of flume is dependent on the dimensions of the flume and for this throat width, the rating equation used is:

$Q = 1.428\ h^{1.550}$ ....(3.1)

Where h = the water stage at the upstream end of the converging section.

It was not feasible to confirm the applicability of this rating equation to the constructed flume throughout the range of discharges because the flume was inaccessible during the high flow events. However, several current meter flow gaugings were conducted under low flow conditions and the flume dimensions and installation conformed to the design.

A suitable site on the Nkazana stream was selected and the flume was installed in May 1989. The flume was bedded into the stream and the side walls strengthened and sealed with concrete blocks and sand (Figure 3.2). The flow through the a)

b)

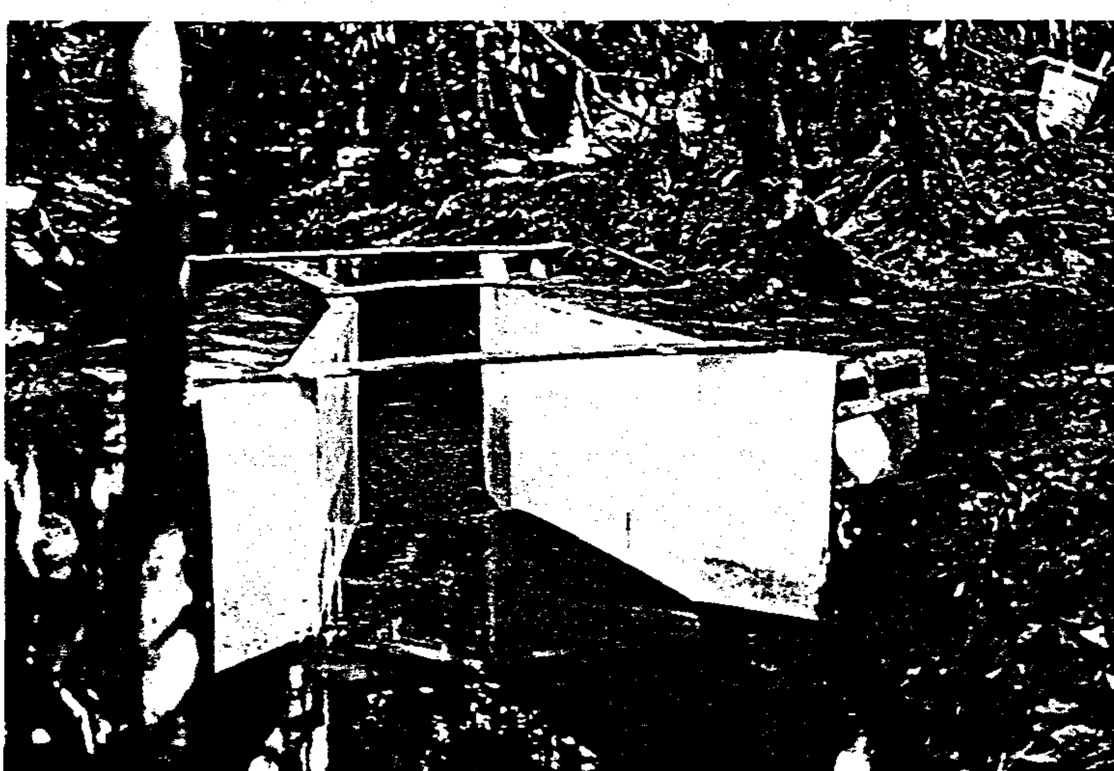


Figure 3.2 Photographs of a) the old and b) the new flumes on the Nkazana stream

flume was measured and compared to the flow upstream of the flume to confirm that minimum leakage occurred under and around the structure. To measure the water stage, 25 mm irrigation pipes were attached to the sides of the flume to contain piezometers located flush with holes drilled through the sidewall. The pipes led to a junction box situated well above the maximum expected flood level. This contained a CR 10 data logger. From this junction box a cable housed in 25 mm piping was laid underground to a meteorological site 50 m to the west of the flume in a grassland area. Two GEOKON piezometers were interfaced to the data logger to measure the water stage at two locations in the flume. The data logger was powered by a 12V lead acid battery maintained by a 5W solar panel. The data logger was programmed to provide records of hourly and daily mean values of water stage and temperature.

Both the flume and its instrumentation gave problems. Due to heavy rains and consequent high discharges in November 1989, the flume foundations were seriously undermined and a portion of the flow bypassed the flume on its eastern bank. It was therefore necessary to modify the flume by raising it by 30cm and substantially reinforcing the foundations and side walls. In addition the side channel was closed by means of sand bags. These modifications prevented much of the leakage, though due to the spongy nature of the stream bed it was impossible to seal the flume completely.

An additional problem experienced at the flume was the failure of the piezometers to give prolonged and accurate service. Data collection has, as a result, been intermittent. Although these instruments proved successful in recording water levels at borehole E1, they appear to be unreliable here. This may be due to the high levels of humidity found under the swamp forest canopy. Some useful data, has nevertheless been forthcoming. This has proved useful for the determination of the hydrological characteristics of the Nkazana stream (Chapter 5).

3.3 GEOHYDROLOGICAL NETWORK

The borehole network established in 1973 consists of nineteen shallow small diameter boreholes (Figure 2.9). Little was known about how these boreholes were drilled, developed and completed. In addition it was likely that fine sediments had progressively accumulated around the casings over their period of operation. Thus the ability the network to reflect groundwater fluctuations accurately was questionable. Fortunately, slug tests were conducted on all the boreholes in 1974 and again in 1985.

These slug tests involve injecting water into the boreholes, and then recording the rate of water level fall. The rate of fall is dependant on both the aquifer characteristics (hydraulic conductivity, transmissivity porosity and permeability) and the condition of the borehole (a clogged borehole will retard the free movement of the water, and thus the raised water level takes a considerable time to attain prior levels).

No records exist of the slug tests conducted in 1974, however they were detected in the data set as a rapid rise in water level on 9 January 1974 (Appendix B). All of the boreholes with the exception of boreholes A5 and A6 regained their previous levels by the following reading (11 January 1974). Thus 17 of the boreholes were confirmed as functioning adequately 9 months after their installation.

Slug tests were repeated in 1985 by the South African Forestry Research Institute (Lindley and Scott, 1987). Results from these tests (Table 3.1) indicate that five boreholes were completely isolated from the aquifer and provide completely spurious data. A further four boreholes showed inadequate hydraulic contact with the aquifer. The remaining eight small diameter boreholes and the two larger diameter boreholes appeared to be providing reliable data. Assessment of the complete borehole hydrographs (appendix C) partially confirms these findings with the exception of borehole A5 and also indicates when the boreholes became inoperative (Table 3.1). Apart from boreholes A5 and A6, it appears that the records at all the boreholes are representative until the 1983/84 rainfall season. It is likely that the extreme rainfall events occurring during that season (Cyclones Domoina and Imboa) were responsible for the deterioration of five boreholes.

Table 3.1 1985 Slug test results (After: Lindley and Scott, 1987) and assessment of dates records are valid until

BOREHOLE	% RECOVERY AFTER 4.5 HRS	% RECOVERY AFTER 24 HRS	CONDITION	VALID UNTIL
A2	14	70	GOOD	
A3	30	63	GOOD	
A4	77	100	GOOD	
A5	73	100	POOR	1974?
A6	8	30	FAIR	1973
B1	10	36	FAIR	
B3	0	0	POOR	1984
B4	76	100	GOOD	
B5	0	0	POOR	1983
C2	100	100	GOOD	
C3	93	100	GOOD	
C4	4	19	FAIR	
C5	100	100	GOOD	
D1	100	100	GOOD	
D2	0	0	POOR	1984
D3	0	0	POOR	1984
D4a	11	46	FAIR	
D4b	92	100	GOOD	
D5	0	0	POOR	1984

It was obvious from this assessment that the borehole network had to be substantially remediated, or that a parallel network had to be created. Hand augering at locations adjacent to the existing boreholes was achieved with little difficulty, and the water table attained quickly. However, due to rapid collapse of the saturated sands into the holes, augering un-cased holes below the water table proved problematic. It was decided therefore that a network of cased large diameter boreholes fitted with screens should be installed to duplicate and expand upon the existing network.

Because the new boreholes had to be effective for the duration of the study, and because they had to be capable of monitoring water levels even during drier periods, it was necessary for them to extend at least 2 metres below the water table. To achieve this permanent holes wider in diameter than the existing boreholes were drilled and fitted with casings and screens. The casings selected were 6 m lengths of PVC pipe, 160 mm in diameter. One metre long screens were created at the base of the pipes by sawing 30 mm long cuts, spaced 20 mm apart, around them.

Methods suitable for sinking boreholes in sandy areas with high water tables were investigated, and two of these tested. The first utilised a system of jetting and suction to allow the boreholes to be sunk quickly and easily below the shallow water table. The second, a manual method, involved hand augering to the water table, then manually forcing the casing into the ground whilst augering the sandy slurry from within the casing. Unfortunately, operational problems were experienced with the former method. The high rate of water extraction from the borehole needed to produce a jet of sufficient force caused pump priming problems which rendered the method unusable. The second method was a qualified success. Although augering was rapid in the unsaturated zone, it proved to be slow and difficult below the water table. Also, sticky clay horizons were encountered in several holes which prevented further augering. The maximum depth attained below the water table was approximately 2 m, with the maximum total borehole depth below the surface was 8 m: in a region where the water table was 7 m below the ground surface.

The suitability of the existing borehole network was assessed in terms of the study objectives. Many of the existing locations were deemed suitable for monitoring the regions' groundwater fluctuations but it was felt that further locations should be investigated, especially within the mature section of the Sibomveni plantation.

In total 28 new boreholes were sunk to form a new, expanded, network which duplicated all the existing boreholes and included in addition the E, F and G lines and borehole B6 depicted on Figure 2.9. These served to fill in gaps perceived in the network and so monitor more fully the groundwater fluctuations of the region. The boreholes were all cleaned, flushed and developed by augering out accumulated sediment from the bottom of the casings and then removing the fine silt from around the screen inlets by means of surging. After a two week period, the boreholes were internally re-augered to remove any further sediment accumulation. Following this process, periodic checks of the borehole depths, indicated that no significant sediment accumulation had occurred.

To obtain a continuous water level hydrograph, a borehole (E1) was installed at the meteorological station to the east of the plantation. This borehole was sited some 500 metres to the south of the weather station and at the same distance east (20 metres) from the plantation. Since the site for this borehole was selected on the plain surrounding the meteorological station, the same hand augering method could be employed at low cost. Sinking the hole immediately adjacent to the meteorological station would have necessitated the use of a mechanical drilling rig. This borehole was fitted with a GEOKON vibrating wire piezometer connected to the datalogger at the meteorological station by means of a 5 core cable inserted in 25 mm PVC irrigation pipe and buried 0.5 metres underground. This last measure was considered necessary as cables connected to the weather station had previously been destroyed wild animals. The datalogger was programmed to provide a continuous measure of the water depth and the water temperature in the borehole (Kelbe and Rawlins, 1990a).

The efficiency of the new boreholes was assessed to ensure that they would reflect groundwater variations accurately. Slug tests were conducted at each of the new boreholes and recovery rates measured. Figure 3.3 shows the recovery rates at four typical boreholes and confirm that, despite localised differences between the boreholes, all showed good hydraulic contact with the aquifer attaining at least a 95% recovery within one hour.

The borehole network was monitored on a fortnightly basis, initially by the Natal Provincial Administration and since 1988 by the Natal Parks Board. With the exception of periods when accessibility was difficult or when transport was unobtainable, the data has been collected consistently.

a)A6

b)D4b

c)E3

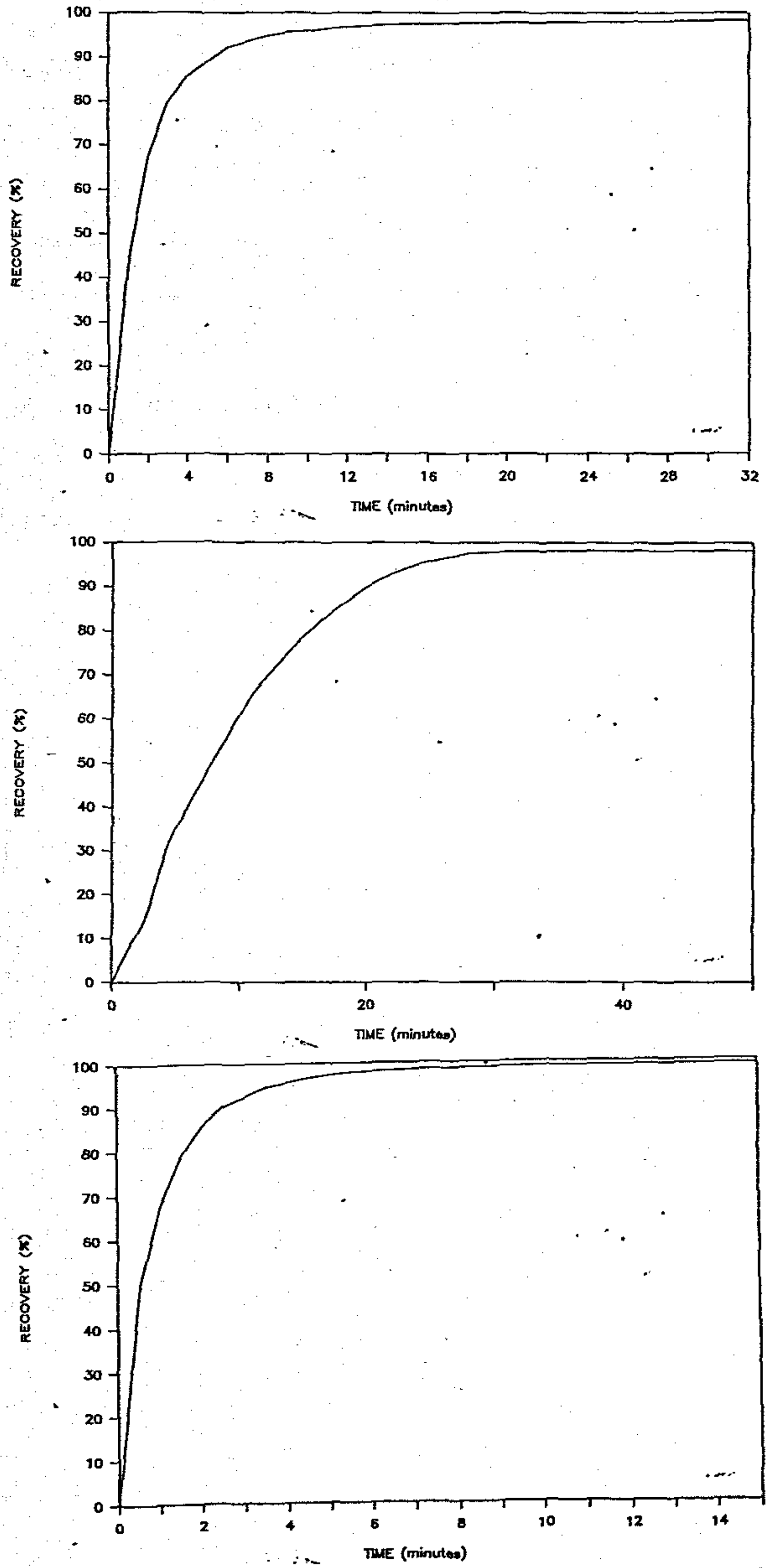


Figure 3.3 Recovery rates following slug tests at selected boreholes

Measurements were obtained by lowering a gauge from the borehole top which emits a signal when contact is made with the water. The depth to water measured from the top of the casing was recorded and subsequently adjusted to indicate the water level above mean sea level. The newly drilled boreholes were added to the measurement routine which continued to monitor all of the old boreholes.

CHAPTER 4

METEOROLOGICAL ANALYSIS

As outlined in Chapter 2.2, meteorological observations have been taken at several locations around the study area. The length of meteorological records at these locations varies up to a maximum of 67 years (Cape St Lucia - 0339720). Since all of the established stations are located outside the study area a full weather station had to be established within it to allow a more locally specific understanding of its climatic regime. Although the station in the study area has only been operative for one complete year, the recordings obtained (Kelbe and Rawlins, 1990a) have proved invaluable for substantiating interpolations from around the study area.

4.1 RAINFALL

The fully automatic weather station (the UZ station) was established in 1988 (Figure 2.2). As the length of record thus far obtained is too short for temporal analysis, recourse has had to be made to data from established rainfall stations situated close to the study area. Rainfall records for nine measuring stations located around Lake St Lucia (Figure 2.2) have been collated and assessed. Their mean monthly and annual data are tabulated in Table 4.1.

The mean values calculated have been from various record lengths of not less than 12 years. Of significance is that mean annual totals from stations to the west of the lake are uniformly less than 1200 mm whereas those from stations to the east of the lake are on average greater than 1200 mm. From these figures it may be inferred that rainfall decreases progressively with distance from the sea.

Table 4.1 Mean monthly rainfall at selected recording stations

STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	YEARS
CAPE VIDAL 0340010	190.6	176.0	133.0	94.7	161.2	66.0	63.2	71.7	84.4	95.3	124.0	125.0	1385.0	17
MOUNT TABOR NPB	160.6	165.5	157.1	95.6	122.4	67.8	71.6	77.6	100.7	99.5	126.6	118.0	1363.0	19
ST LUCIA EST. 0339856	157.1	151.0	165.9	121.8	92.9	69.0	64.1	66.3	78.1	104.7	115.7	123.5	1310.5	38
ESTUARY MOUTH NPB	184.5	151.2	115.1	100.3	90.3	73.3	83.3	68.2	86.2	109.9	127.4	104.4	1294.3	15
CAPE ST LUCIA 0339720	193.0	127.7	148.4	135.6	106.7	84.1	98.7	80.3	121.7	95.4	114.5	101.5	1405.5	65
FANIES ISLAND 0339756	124.0	116.8	122.6	79.1	47.5	38.2	35.3	36.1	59.7	71.0	91.3	96.6	915.0	38
CHARTERS CREEK NPB	148.9	182.7	118.4	80.1	61.3	48.6	45.6	54.0	93.2	81.2	103.8	98.2	1116.0	17
NYALAZI 0339523	146.5	161.8	108.4	70.2	91.6	29.1	51.8	48.3	71.4	72.6	102.4	121.2	1075.4	12
MAKAKATANA 0339734	170.7	154.2	119.3	76.4	78.5	48.8	63.5	49.7	77.6	109.4	116.5	103.5	1167.9	18

The study area does not contain a rainfall monitoring station with a sufficient length of record to allow an accurate determination of its rainfall characteristics. Given its location with respect to the existing stations, however, an estimate of its rainfall can be made. Although situated on the eastern shores of the lake, the study area is further from the sea than any of the coastal stations, which are all located within the coastal dune cordon. Consequently its rainfall is likely to be less than 1200 mm. And being approximately the same distance from the Indian Ocean as the Makakatana station (Figure 2.2), can be expected to receive a rainfall similar to or slightly greater than Makakatana (1168 mm).

Long term rainfall characteristics cannot, however, be inferred from Makakatana station records since these are available only for 18 years. Two stations, at Fanies Island (0339756) and St Lucia Estuary (0339856) have been selected as a basis for analysis because they have 38 years of actual data and a further 27 years of generated data (Appendix A), and since the climatological characteristics of the study area are likely to be somewhere between these two extremes. Rainfall statistics for these two stations are displayed in Table 4.2.

Table 4.2 Rainfall Statistics for the St Lucia Region

Station	Fanies Island (WB0339756)					St Lucia Estuary (WB0339856)				
Period	Mean	Median	St Dev	CV	Skew	Mean	Median	St Dev	CV	Skew
January	124.0	92.3	110.2	87.6	1.6	157.1	125.5	159.3	96.1	2.8
February	116.8	94.3	85.1	76.6	1.8	151.0	126.6	94.6	64.2	1.1
March	122.6	96.8	95.1	77.4	1.8	165.9	116.7	127.6	76.1	1.4
April	79.1	62.6	57.7	71.7	1.7	121.8	94.8	107.7	87.6	2.5
May	47.5	37.9	40.4	83.1	1.4	92.9	69.8	63.6	66.8	1.8
June	38.2	30.0	35.1	97.0	1.7	69.0	62.3	51.4	76.9	1.2
July	35.3	14.8	53.3	148.1	2.8	64.1	51.4	49.0	75.1	1.9
August	36.1	26.6	38.2	110.8	2.3	66.3	48.2	64.6	97.1	2.2
September	59.7	41.8	54.5	95.8	1.4	78.1	61.8	46.8	63.2	0.7
October	71.0	55.5	41.7	60.2	1.0	104.7	74.7	62.4	60.9	1.2
November	91.3	74.1	60.0	67.0	1.2	115.7	98.6	77.0	66.7	1.1
December	96.6	80.1	67.1	70.1	1.6	123.5	95.3	90.2	74.8	1.0
Annual	915.0	891.3	252.8	28.0	0.3	1310.5	1258.8	361.5	27.7	0.7

4.1.1 Annual Rainfall

Annual rainfall totals for the two stations range between 450 and 1500 mm at Fanies Island (0339756), and between 750 and 2150 mm at St Lucia Estuary (0339856). The mean annual rainfall values give a good indication of the areal variability with rainfall decreasing with distance from the sea. It is further evident from the annual values for median, standard deviation and skew given in Table 4.2 that variations between years are also considerable.

Annual rainfall series for both stations are given in Figure 4.1. Annual rainfall totals are consistently higher at St Lucia Estuary than at Fanies Island. Linear regression analysis performed between these two rainfall series (Figure 4.2) showed a reasonably good relationship between annual recorded rainfall at each station (r^2=0.72). A synthetic record applicable to the UZ station was then created (Appendix A) using equation 4.1, which assumes a linear decrease in rainfall with distance from the ocean. Approximate distances from the coastline are respectively: St Lucia Estuary (0339856) 2 km; Fanies Island (0339756) 13 km; and the UZ station 5 km. This synthetic rainfall series obviously displays similar statistical parameters to the two source rainfall series. The generated long term mean annual and median annual rainfall totals being 1199 mm and 1170 mm respectively.

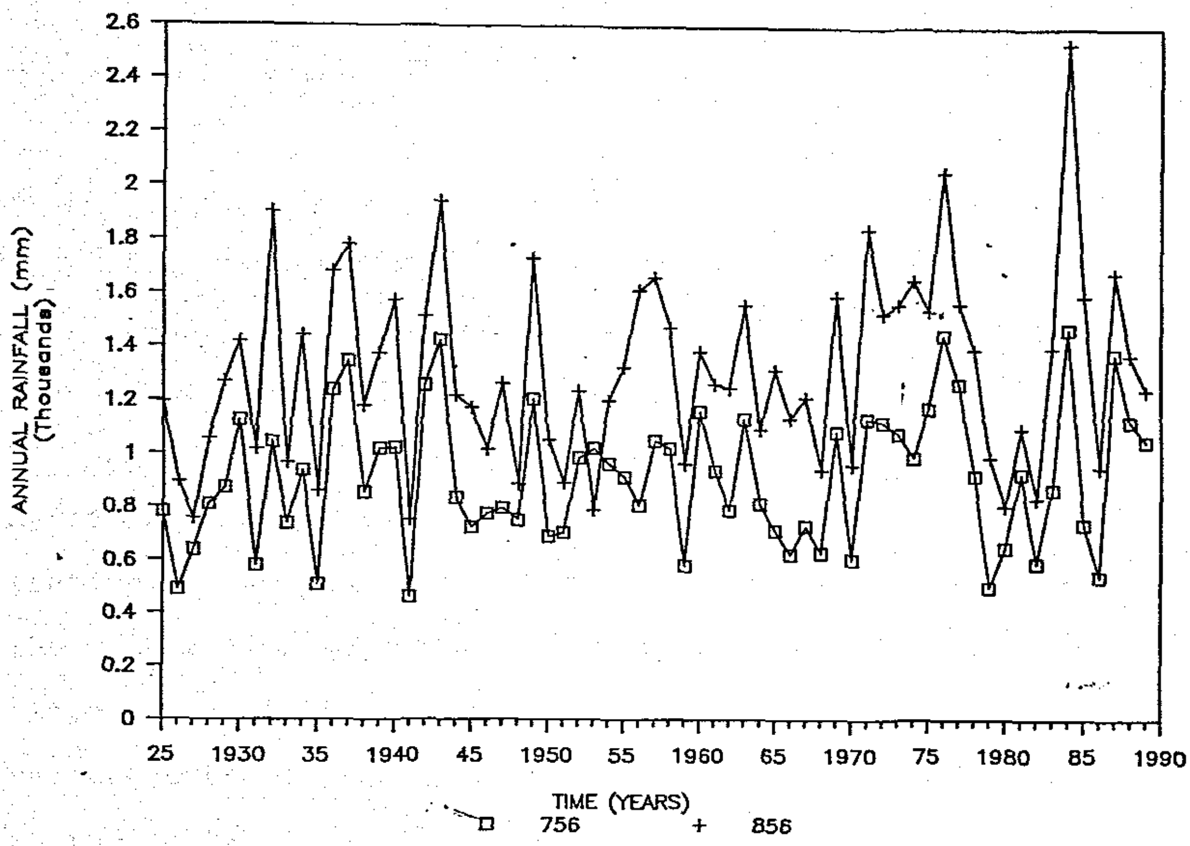


Figure 4.1 Annual rainfall series at Fanies Island (0339756) and St Lucia Estuary (0339856)

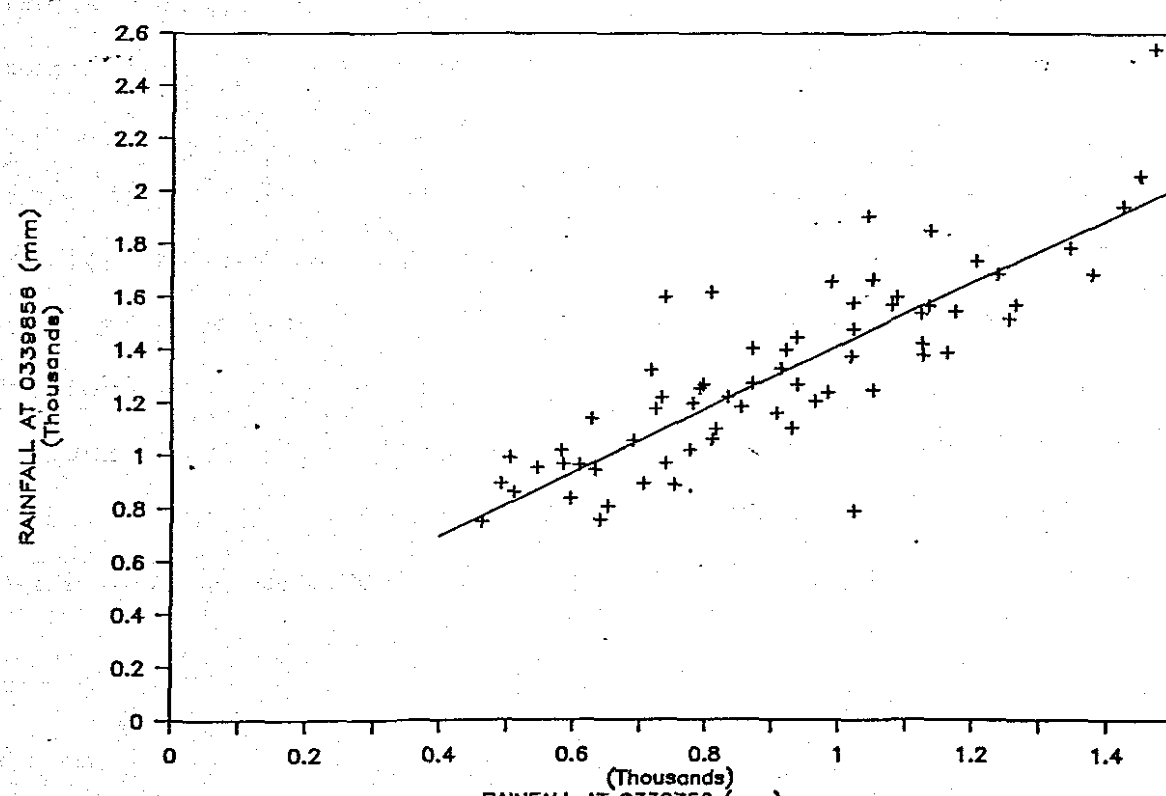


Figure 4.2 Correlation between annual rainfall at Fanies Island (0339756) and St Lucia Estuary (0339856)

$$P_{UZ} = P_{856} - (P_{856} - P_{756})/3.6 \quad \text{.......................(4.1)}$$

Where:

P_{UZ} represents the annual rainfall at the UZ station,

P_{856} represents the annual rainfall at St Lucia Estuary

and P_{756} represents the annual rainfall at Fanies Island.

Median annual rainfall is, at both St Lucia and Fanies Island stations, somewhat lower than mean rainfall. Both this and the rather high standard deviations reflect the occurrence of extreme rainfall events in the area. Tropical cyclones causing extremely heavy rainfall influence the Zululand coast sporadically. Eight of the 40 years since 1950 have been thus affected (Kovacs et al, 1985). In addition, the region occasionally receives extreme rainfall from cut-off low pressure conditions (Van Bladeren and Burger, 1989).

Frequency analyses were conducted on the annual rainfall series of the two stations (Kelbe and Rawlins, 1990b) and on the synthesised record of the UZ station. These rainfall series were fitted to the Log Pearson Type 3 distribution (Figure 4.3). From this analysis, rainfall depths associated with selected recurrence intervals for each of these series were derived and are presented in Table 4.3.

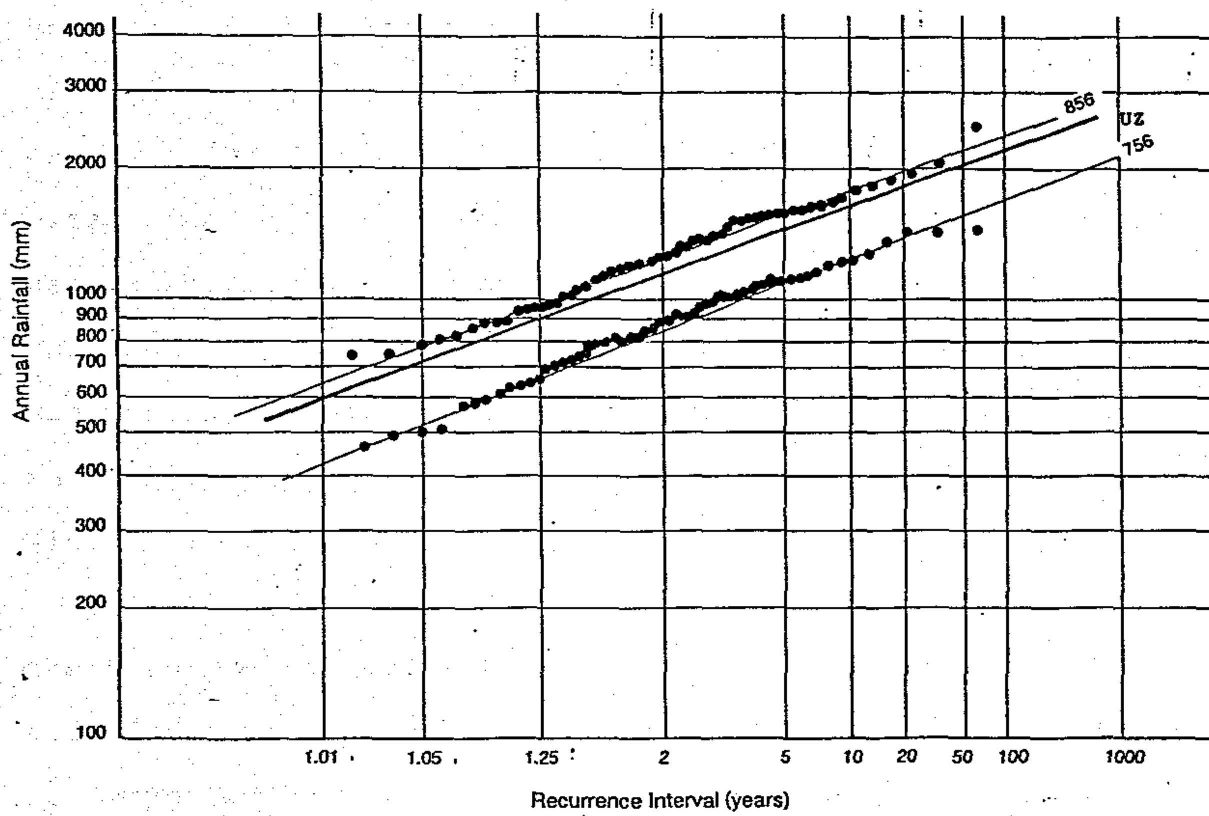


Figure 4.3 Probability analysis of annual rainfall totals at Fanies Island (0339756), St Lucia Estuary (0339856) and UZ (synthetic record)

Table 4.3 Annual rainfall depths associated with various recurrence intervals at Fanies Island (0339756), St Lucia Estuary (0339856) and the UZ station

RECURRENCE INTERVAL (YRS)	756 (mm)	856 (mm)	UZ (mm)
2	840	1240	1150
10	1230	1790	1620
20	1380	1990	1800
50	1540	2200	2030
100	1680	2380	2200

4.1.2 Monthly Rainfall

Monthly rainfall varies throughout the season in a well defined annual cycle. The wettest months are usually January or March, with slightly lower rainfall in February. The driest months are June, July and August. The 'wet' season generally begins in October and lasts until April or May and the dominant rainfall producing mechanisms are tropical and subtropical. Unlike much of South Africa, significant rainfalls do occur during the dry season, usually associated with frontal movement.

The mean monthly rainfall values for the two stations (Table 4.2) indicate that consistently more rainfall is received by St Lucia Estuary than by Fanies Island. A synthetic monthly rainfall series for the UZ station was created, again on the basis of relative distances from the sea (equation 4.2).

$$P_{UZ} = P_{856} - (P_{856} - P_{756})/3.6 \quad \text{.......................(4.2)}$$

Where:

P_{UZ} represents the monthly rainfall at the UZ station,

P_{856} represents the monthly rainfall at St Lucia Estuary

and P_{756} represents the monthly rainfall at Fanies Island.

The mean monthly rainfall distributions for the Fanies Island, St Lucia Estuary and the UZ meteorological station are given in Table 4.4. This shows that the generated mean monthly rainfall totals at the UZ station lie within the bounds of rainfall at the two source stations, and that the seasonal distribution rainfall is similar at all three stations.

Table 4.4 Monthly distribution of rainfall at Fanies Island (0339756), St Lucia Estuary (0339856) and the UZ station

MONTH	756		856		UZ	
	mm	%	mm	%	mm	%
January	124.0	13.5	157.1	12.0	148.1	12.2
February	116.8	12.7	151.0	11.5	141.7	11.7
March	122.6	13.4	165.9	12.6	154.1	12.7
April	79.1	8.6	121.8	9.3	109.9	9.1
May	47.5	5.2	92.9	7.1	80.5	6.6
June	38.2	4.2	69.0	5.3	60.6	5.0
July	35.3	3.8	64.1	4.9	55.7	4.6
August	36.1	3.9	66.3	5.1	58.5	4.8
September	59.7	6.5	78.1	6.0	72.2	6.0
October	71.0	7.7	104.7	8.0	93.6	7.7
November	91.3	10.0	115.7	8.8	119.8	9.9
December	96.6	10.5	123.5	9.4	117.2	9.7

Probability analysis was performed on the annual series of maximum monthly rainfall for the two source stations (Kelbe and Rawlins, 1990b), as well as for the synthetic series at the UZ station (Figure 4.4). From this analysis were derived, rainfall depths associated with selected recurrence intervals for each of these series (Table 4.5).

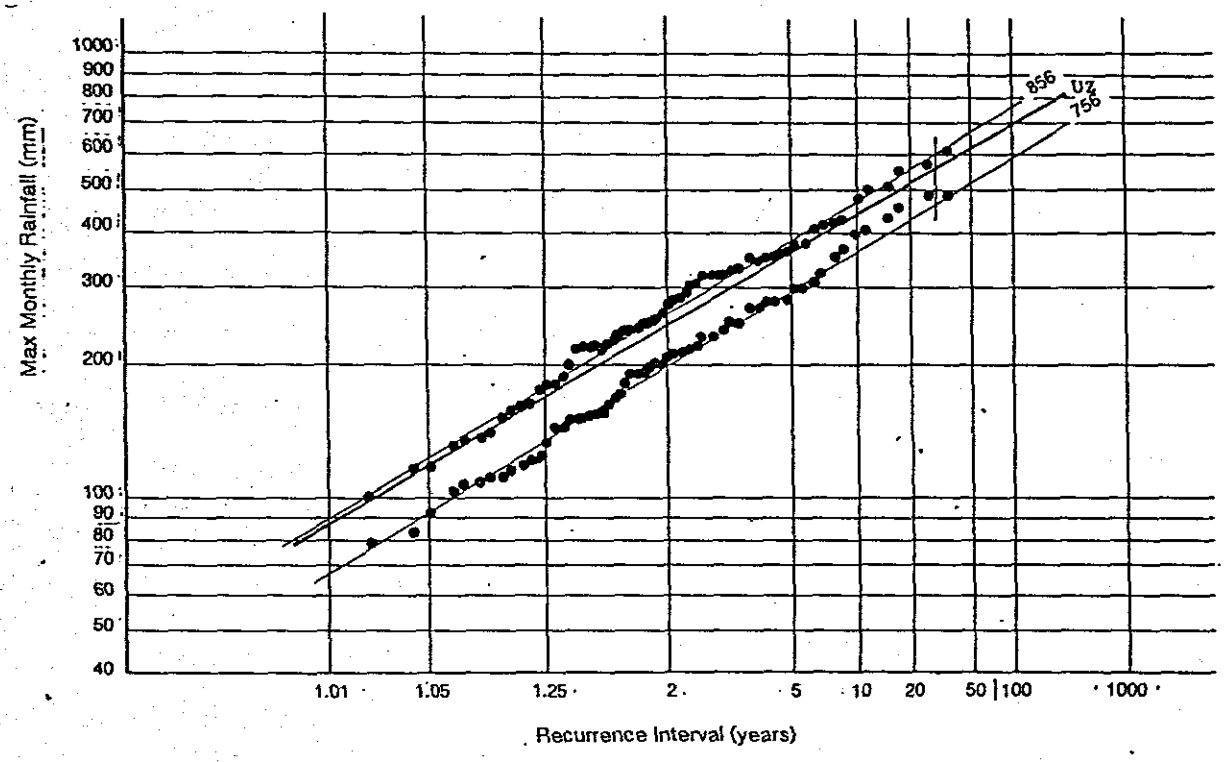


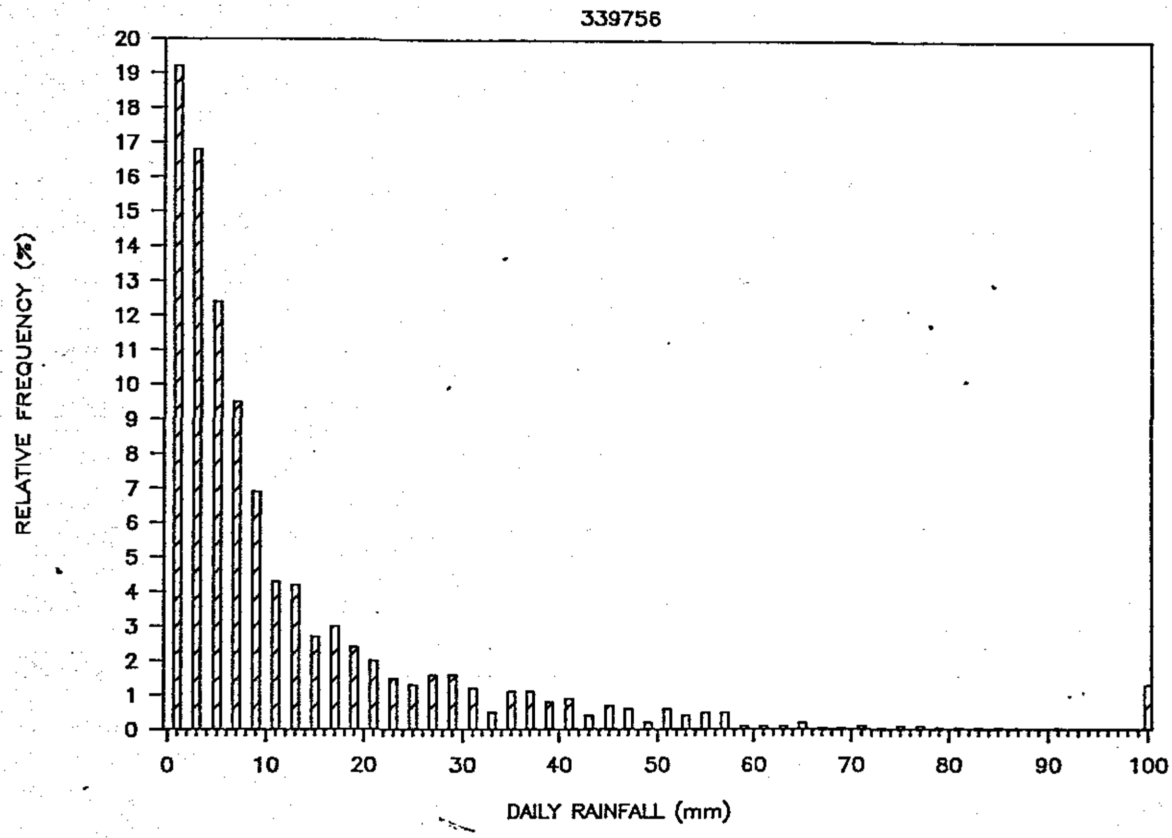
Figure 4.4 Probability analysis of MAXIMUM monthly rainfall at Fanies Island (0339756) and St Lucia Estuary (0339856) and UZ (synthetic record)

Table 4.5 Annual monthly maximum rainfall depths associated with various recurrence intervals at Fanies Island (0339756), St Lucia Estuary (0339856) and the UZ station

RECURRENCE INTERVAL (YRS)	756 (mm)	856 (mm)	UZ (mm)
2	200	270	250
10	360	470	440
20	430	550	510
50	520	670	610
100	600	770	690

4.1.3 Daily Rainfall

Daily rainfall totals occurring over the study area range from infrequent extremely high events associated with tropical cyclones to more moderate events associated with convective and frontal activity. Analysis of the daily records at both stations (Kelbe and Rawlins, 1990b), (Figure 4.5) indicates that fewer than 2% of the days when rain occurred produced rainfall in excess of 100 mm. Conversely over 50% of rain-days produced rainfall depths of less than 10 mm: contributing some 24% of the total rainfall. For the purposes of this study the definition of groundwater recharge resulting from rainfall is important because, as shown in section 6.2, recharge from any rain-day producing less than 10 mm of rainfall does not significantly affect the groundwater body. Consequently about 24% of total annual rainfall does not contribute to groundwater recharge. It is surmised to be absorbed by interception loss and soil moisture recharge, or is re-evaporated soon after the rainfall event.



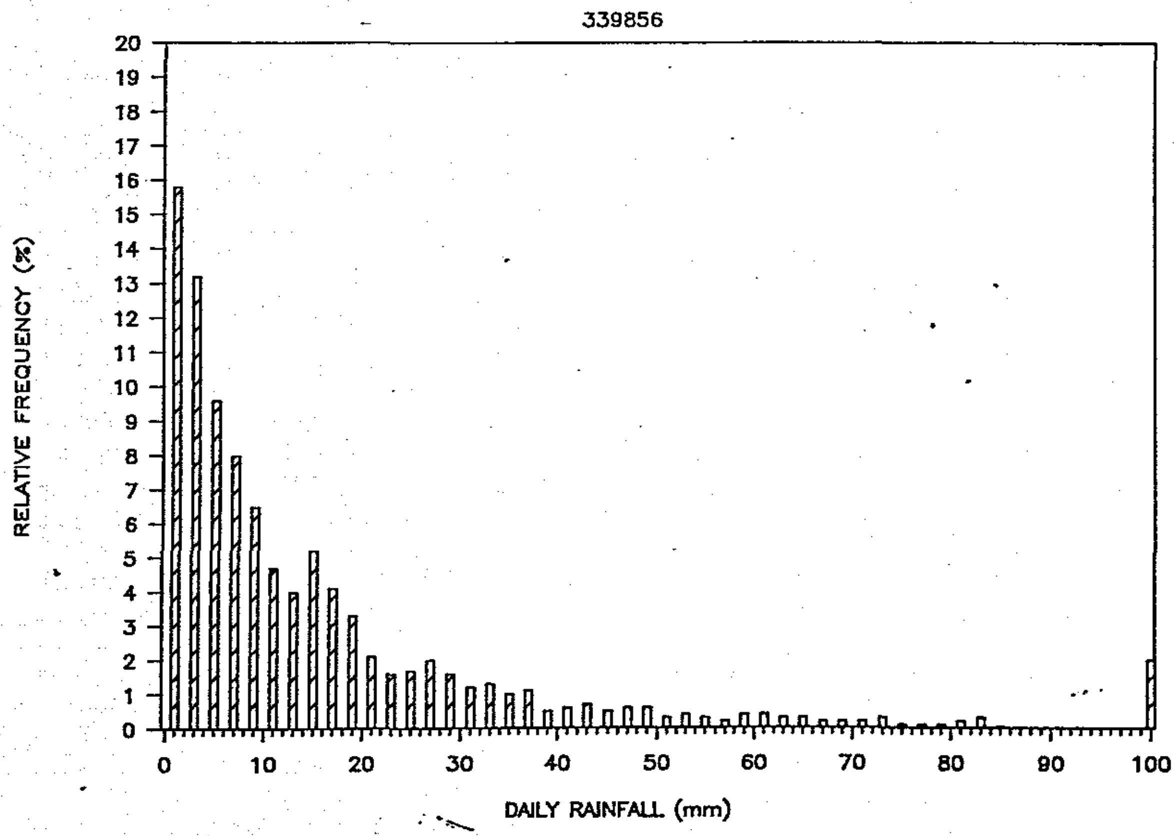


Figure 4.5 Relative frequency distribution for daily rainfall at Fanies Island (0339756) and St Lucia Estuary (0339856)

4.1.4 Recorded Rainfall at the UZ Station.

Rainfall has been measured at the Eastern Shores (UZ) meteorological station since October 1988. A synopsis of the record of hourly data for 1989 (Kelbe and Rawlins, 1990a) follows.

Monthly rainfall during 1989 at the UZ station is outlined in Table 4.6 and compared with the recorded values for 1989 at Fanies Island and St Lucia Estuary, as well as with the synthesised record for the UZ station derived from these values.

Table 4.6 Monthly Rainfall for 1989

MONTH	UZ (meas) (mm)	UZ (syn) (mm)	DIFFERENCE (mm)	0339756 (mm)	0339856 (mm)
January	41.4	59.5	+ 18.1	34.5	62.0
February	434.8	308.7	-126.1	316.5	307.9
March	62.6	28.8	- 8.6	52.5	26.5
April	49.0	49.4	+ 0.4	36.5	54.3
May	82.2	80.4	- 1.8	40.5	84.4
June	102.2	87.8	- 14.4	41.4	92.4
July	56.8	60.0	+ 3.2	10.0	65.0
August	20.8	10.3	- 10.5	4.0	10.9
September	92.2	96.3	+ 4.1	54.3	100.5
October	123.4	94.9	- 28.5	69.4	97.5
November	299.6	241.9	- 57.7	312.0	234.9
December	86.0	110.0	+ 24.0	70.0	115.1
Annual	1451.0	1229.0	-222.0	1041.6	1251.4

It appears, from Table 4.6, that the synthetic record under-estimates annual rainfall. Although in several months there is an over-estimation of monthly rainfall, the under-estimation of rainfall for months receiving rainfall in excess of 100 mm is particularly significant. Though recorded annual rainfall at the UZ station exceeded that at station 0339856, the high rainfall months of February, October and November account for a measured rainfall excess of 212 mm. The remaining months conform well to the hypothesis of a decrease in rainfall with distance from the sea. Since it is the high rainfall months that appear to be responsible for the difference in annual totals, it is postulated that the inability of manually-read raingauges to record rainfall in excess of the raingauge capacity is a possible cause of this discrepancy.

Rainfall occurred on 163 individual days at the UZ weather station. However, on 49 of these days (30% of the total), the rainfall recorded was the minimum detectable 0.2 mm. It is likely that most of this rainfall can be attributed to precipitated dew collecting in the raingauge since this rainfall occurred either in the late evening or the early morning on 47 of these days. A further 78 days (48%) produced rainfall between 0.2 and 10.0 mm. Rainfall from these lesser events totalled 233.0 mm or only 16% of the annual total. The bulk of the annual rainfall (1227.8 mm) resulted from only 36 days. Apart from a period in February when 277 mm were recorded over five days, these events were spread fairly evenly throughout the year. Daily rainfall in excess of 100 mm was recorded on only 2 days (4/2/89 = 140.4 mm and 28/11/89 = 110.8 mm).

4.2 EVAPORATION AND EVAPOTRANSPIRATION

Evaporation close to the study area has not been recorded directly by means of evaporation pans for any great length of time. Interpolations by Hutchison and Pitman, (1973) from recorded data at 11 stations in northern Natal estimated mean annual Symons tank evaporation in the study area at approximately 1320 mm. Charters Creek, the nearest station to the study area (Figure 2.2) had a 15 year record, which gave a mean annual evaporation rate of 1348 mm.

Evaporation in the study area was further assessed by calculating daily potential evapotranspiration at the UZ weather station site. The Penman equation (Penman, 1948) was applied to recorded measurements of meteorological variables (Kelbe and Rawlins, 1990a). The aerodynamic resistance for a short grass (0.05 m) was calculated using a roughness coefficient equivalent to 13% of vegetation height. The potential evapotranspiration thus derived for 1989 amounted to 1752.5 mm (Table 4.7 and Figure 4.6). This derived annual potential evapotranspiration is 33% higher than the estimated mean Symons tank evaporation for the area.

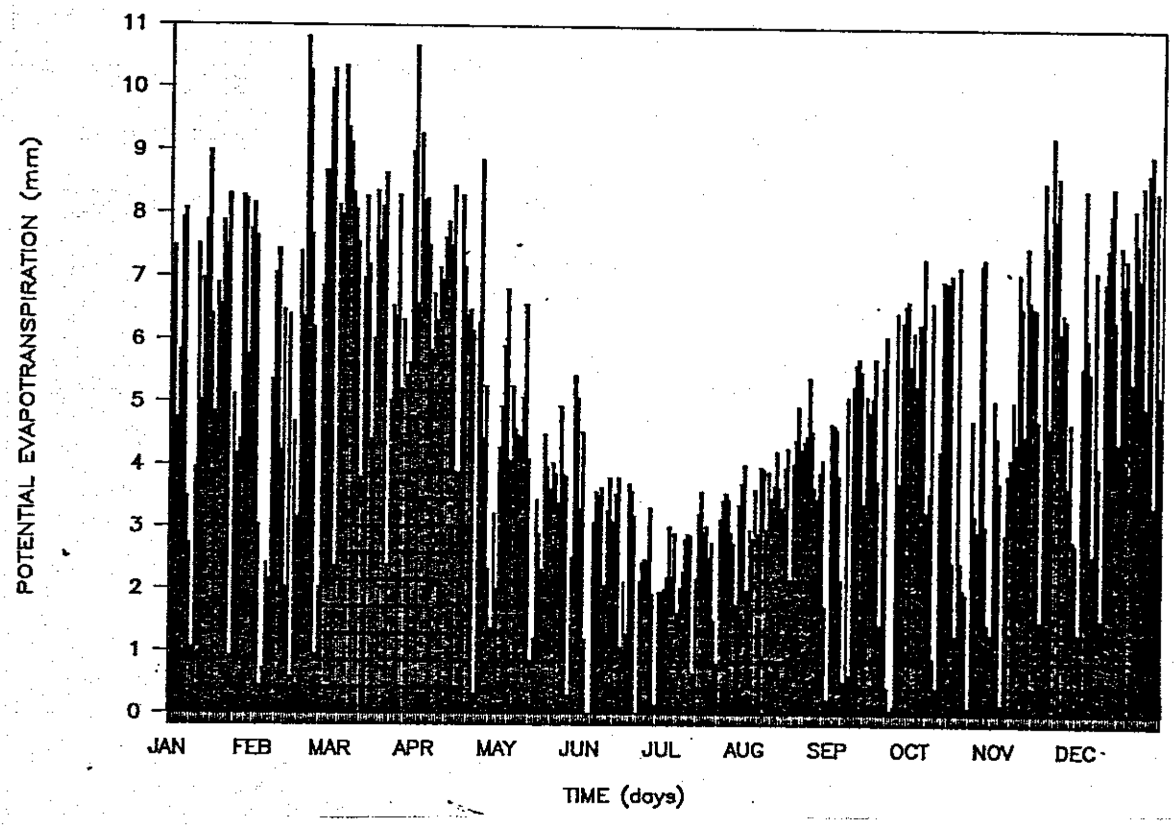


Figure 4.6 Estimates of daily potential evapotranspiration during 1989 at the UZ station.

Table 4.7 Monthly potential evapotranspiration calculated at the UZ Meteorological station

MONTH	POTENTIAL EVAPOTRANSPIRATION (mm/month)	(mm/day)
January	190.0	6.13
February	156.0	5.57
March	223.2	7.20
April	180.9	6.03
May	124.3	4.01
June	75.9	2.53
July	82.8	2.67
August	112.2	3.62
September	125.7	4.19
October	132.7	4.28
November	160.2	5.34
December	189.1	6.10
Annual	1752.5	4.80

4.3 TEMPERATURE AND RADIATION

Maximum and minimum air temperatures have been recorded by the Weather Bureau at Charters Creek (Figure 2.2). Mean monthly maximum and minimum temperatures for this station are outlined in Table 4.8 (from Hutchison and Pitman, 1973).

Table 4.8 Mean monthly air temperatures: Charters Creek

MONTH	MAXIMUM °C	MINIMUM °C
January	30.0	19.3
February	30.3	19.2
March	29.6	18.9
April	27.8	16.7
May	25.3	13.2
June	23.6	10.6
July	23.5	10.3
August	24.2	12.0
September	25.8	14.6
October	26.5	16.4
November	27.9	17.7
December	29.2	18.6
Annual	27.0	15.6

Hourly temperature and solar radiation, as well as daily maximum and minimum temperature were recorded at the UZ station during 1989. These are displayed as mean monthly values in Table 4.9.

The mean monthly maximum temperatures calculated for the UZ station are consistently lower than those at Charters Creek, whereas mean monthly minimum temperatures are consistently higher. This results in a smaller range between the maximum and the minimum temperature at the UZ station than at

Charters Creek. This discrepancy could be due to local differences between the sites, especially as the UZ station is situated on a topographic rise, whereas the Charters Creek station is only just above mean sea level.

Table 4.9 Monthly temperature and radiation data for 1989 at the UZ weather station

MONTH	MEAN °C	MAXIMUM °C	MINIMUM °C	RADIATION (MJ/m^2)
January	23.49	27.63	19.56	23.72
February	23.58	27.72	20.40	18.75
March	24.01	28.51	20.05	19.78
April	21.13	26.48	16.70	15.88
May	19.74	25.06	15.81	12.56
June	16.86	22.33	12.15	10.35
July	16.92	22.79	12.24	12.45
August	19.76	25.82	15.22	14.69
September	19.16	24.30	14.86	16.77
October	19.99	24.50	16.06	16.71
November	22.09	26.43	18.77	19.33
December	23.71	28.01	19.96	22.68

4.4 WIND SPEED AND DIRECTION

Wind speed and direction have been recorded at the St Lucia Estuary Mouth station and at the Listers Point station in False Bay. The prevailing winds experienced at these stations are south-westerly (35.5%) and north-easterly (33.4%) at Listers Point, and west-south-westerly (33.0%) and north-north-easterly (35.6%) at the Estuary Mouth (Hutchison and Pitman, 1973). Table 4.10 outlines monthly average wind speeds at both stations and shows that annual wind speeds average 5 m/s, with the windiest months being from September to February.

Table 4.10 Monthly average wind speeds at the Estuary Mouth and Listers Point

MONTH	Estuary Mouth (m/s)	Listers Point (m/s)
January	5.16	5.52
February	5.56	5.31
March	4.66	4.73
April	4.19	4.44
May	4.54	4.77
June	4.43	3.74
July	4.42	4.04
August	4.98	4.95
September	5.64	5.60
October	5.18	5.90
November	5.89	5.72
December	5.69	6.20
Annual	5.08	5.14

At the UZ station wind speed was recorded during 1989, (Table 4.11), but due to instrument failure, wind direction was not. Mean monthly wind speeds are consistently lower than those recorded at the Estuary Mouth and Listers Point stations, however a similar seasonal pattern is evident. These lower values are possibly, as for the temperature data, caused by the differences in exposure and altitude between this station and the Weather Bureau stations. In addition the maximum daily gust speeds which were monitored have been averaged to provide an indication of monthly gust speed variation.

Table 4.11 Mean monthly wind speeds and mean maximum daily gust speeds at the UZ meteorological station

MONTH	Mean daily (m/s)	Mean daily maximum (m/s)
January	3.65	10.37
February	3.61	9.93
March	3.32	9.34
April	3.33	9.71
May	3.08	8.38
June	2.70	7.99
July	3.48	9.98
August	4.18	10.34
September	4.58	12.25
October	4.52	12.18
November	4.40	11.78
December	4.31	11.23
Annual	3.76	10.29

CHAPTER 5

HYDROLOGICAL ANALYSIS

The surface water components of the eastern shores area comprise the Mfabeni system, Lake Bhangazi and the Nkazana stream, as well as numerous unconnected ephemeral and intermittent pans and wetlands. These components have been assessed to produce indications of their status under average climatic conditions as well as their behaviour and response to wet and to dry climatic extremes.

5.1 THE MFABENI SYSTEM

Swamp levels have been recorded by means of a shallow borehole situated on the eastern edge of the swamp (borehole C2 in Figure 2.9). Measurements for the period 1973-1990 (Figure 5.1) show the fluctuations in water level due to natural climatic variation. The swamp level at borehole C2 during average climatic conditions is approximately 7.1 m above mean sea level (a.m.s.l.). During the extreme dry and wet conditions experienced during the past 17 years, this level has ranged from a minimum of 6.2m to a maximum of 8.0m.

Further to the north, Lake Bhangazi forms a permanently open water body. This lake is connected to the swamp through two outlets artificially maintained by concrete culverts. Fluctuations in Lake Bhangazi similar to the swamp have been recorded at borehole D1 situated on the lake shore (Figure 5.2).

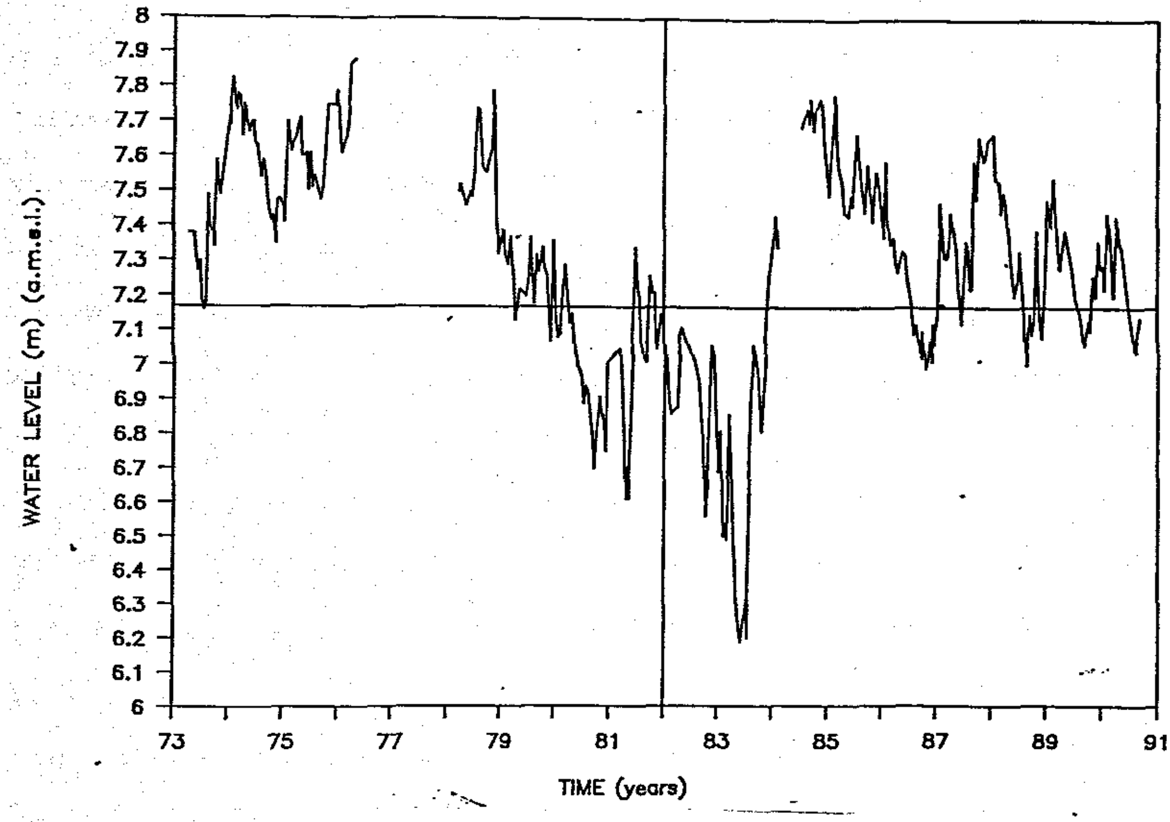


Figure 5.1 Water level hydrograph at borehole C2 for the period 1973 to 1990

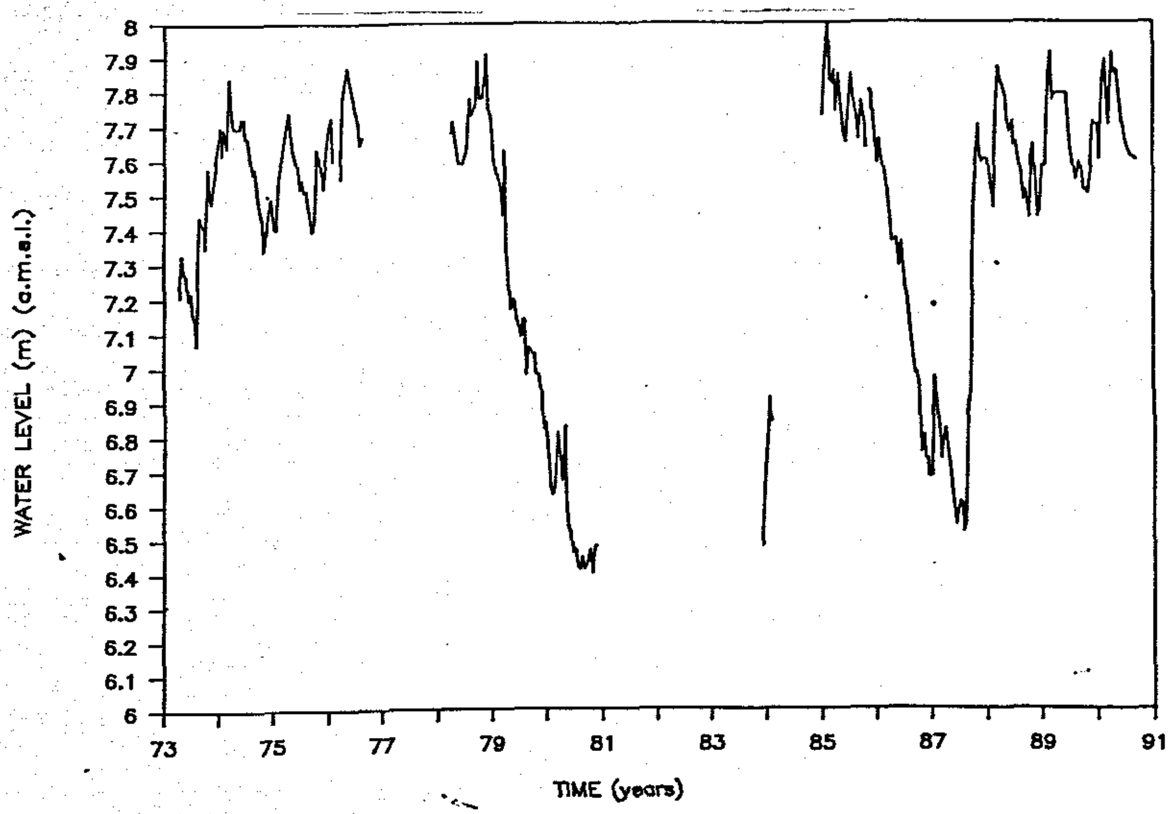


Figure 5.2 Water level hydrograph at borehole D1 for the period 1973 to 1990

The major outflow from the swamp system occurs through the Nkazana stream. Using a crude Parshall flume constructed near the mouth of this stream, sporadic measurements of discharge were taken from 1979 to 1984, when the flume became inoperative. Total flow was estimated to average 1 000 000 m^3/year (2740 m^3/day) (Lindley and Scott, 1987). Estimates of low and high annual flows were 125 000 m^3 in 1980 and 3 500 000 m^3 in 1984. Discharge rates ranged from below 0.0015 m^3/s to well above the 0.110 m^3/s design capacity of the flume. In order to evaluate this discharge more effectively, a short throated Parshall flume was installed in the Nkazana stream in 1989. Discharge measurements for the period 28/6/89 to 14/10/89 are displayed in Figure 5.3, and swamp water level recordings at borehole C2 for the same period in Figure 5.4. Unfortunately, instrument failure precluded a longer period of observation at the flume. From Figures 5.3 and 5.4 it appears that the period of measurement from 28/6/89 to 15/8/89 at the Nkazana stream corresponds to a period of average swamp level and consequently should indicate average discharge conditions. Discharge for this period ranged between 400 and 7000 m^3/day, with an average discharge of 1200 m^3/day.

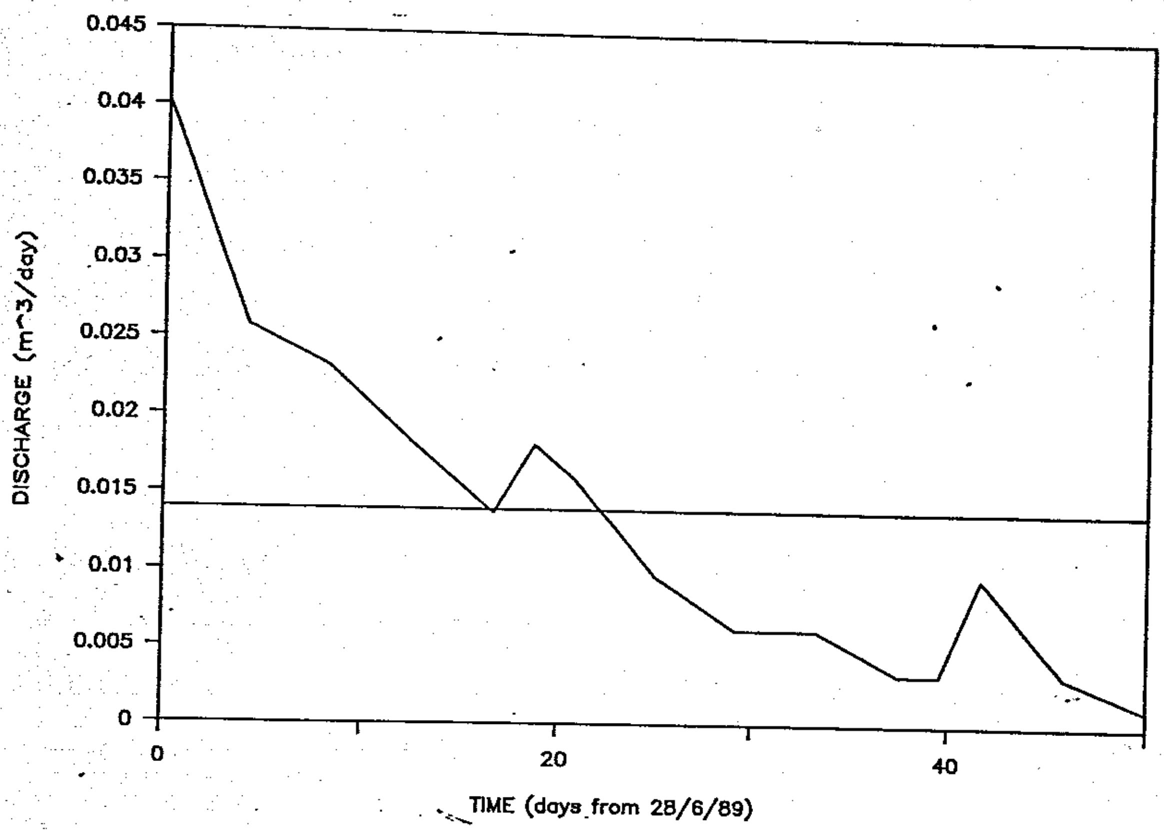


Figure 5.3 Discharge at the Nkazana stream from 28/6/89 to 14/10/89

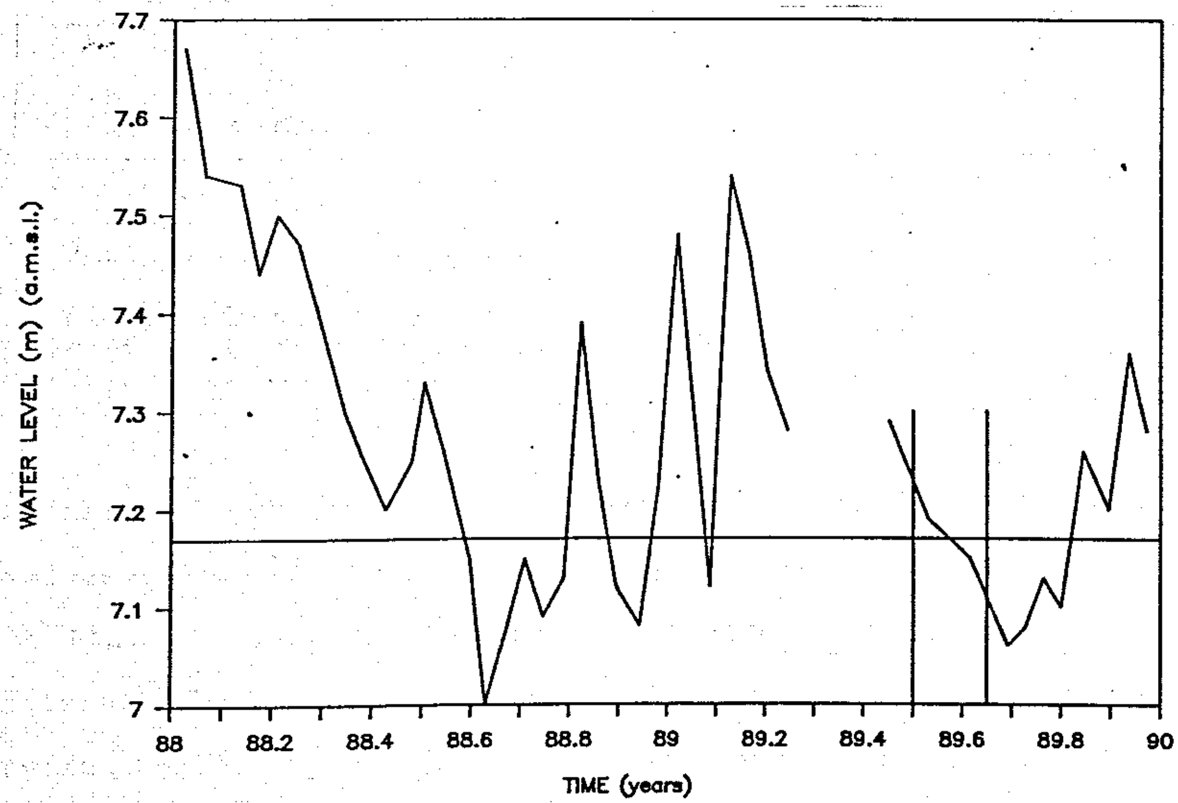


Figure 5.4 Water level hydrograph at borehole C2 during 1988 and 1989 (the period between 28/6/89 and 14/10/89 is depicted by vertical lines)

5.1.1 Water Balance under Average Conditions

In order to quantify the effect of possible perturbations to the hydrological regime, it was necessary to derive a water balance for the swamp under existing conditions. This water balance derived for mean conditions is outlined in Table 5.1.

Table 5.1 Water balance of the Mfabeni swamp

COMPONENT	MAGNITUDE (m3/day)
INPUTS (measured)	
Rainfall WB0339756 (915 mm/year)	44 375
Rainfall WB0339856 (1310 mm/year)	63 900
Rainfall UZ (synthetic) (1200 mm/year)	58 575
OUTPUTS (estimated)	
Evapotranspiration (1750 mm/year)	85 200
Discharge (Nkazana stream)	1 200
TOTAL OUTPUTS	86 400
BALANCE (Input from seepage)	
Limits (from WB stations)	-42 025 to -22 500
Estimated (from UZ synthetic rainfall)	-27 825

Rainfall input to the swamp has been presented as three values based on average annual rainfall at Fanies Island, at St Lucia Estuary, and at the UZ station (synthesised). The rainfall depth was multiplied by swamp area to produce an average daily input volume. Since the average annual rainfall over the swamp is expected to be similar to the synthetic UZ station average at around 1200 mm (Chapter 4) the calculated deficit is -27 825 m^3/day. This deficit is accounted for by the unmeasured seepage inflow from the swamp catchment area. If the catchment area (32 km^2) is partitioned between the western plain (20 km^2) and the eastern dune area (12 km^2), 62% of the total swamp inflow is likely to be derived from the study area. From the water balance calculations the expected inflow from the eastern shores plain is likely to be between 13950 and 26050 m^3/day. This inflow, if it is evenly distributed along the swamp perimeter (14 km), equates to an average daily seepage outflow loss from each kilometre of the edge of the plain of between 1000 and 1850 m^3/day. If the synthesised rainfall for the UZ station is taken as representative of the entire study area then the inflow equates to 1230 m^3/day/km.

The section of the eastern shores plain under consideration has a perimeter of about 28.6 km, and an area of approximately 40 km^2. If it is assumed that the outflow to the swamp is of a similar magnitude as the outflow to the lake, the total average daily outflow equates to 35 200 m^3/day. When distributed evenly over the catchment area this daily outflow is equivalent to a rainfall depth of 0.88 mm. Thus, during an average year, the seepage outflow from the plain is derived from 320 mm of rainfall (27% of the average rainfall total).

5.1.2 Response to Wet and Dry Extremes

The response of the swamp to periods of above and below average rainfall was assessed with reference to the water level hydrograph obtained from borehole C2. During the cyclonic rainfall events Domoina and Imboa the total discharge rate into the swamp increased as a consequence of both the raised water table and direct precipitation onto the swamp of approximately 0.9 metres. This caused a substantial rise in the water surface elevation of the swamp and there was a corresponding increase in its surface area. This effect was extremely rapid, rendering extensive areas inaccessible for several months. Discharge rates remained high for a considerable period as water taken into storage during the cyclones was slowly released to the swamp. Hydrographs from all the boreholes indicate that water levels were above average for a period of about three years; hence it is likely that the discharge from the eastern shores plain into the swamp remained above average for the same period before returning to 'normal' (Kelbe and Rawlins, 1990b). Measurements of swamp level at borehole C2 (Figure 5.1) before and after this event are available and serve to confirm this conclusion. Unfortunately no measurements of the peak stage are available for the six month period following the cyclones as the area was inaccessible and the borehole itself was under water. To produce an estimate of the peak stage at this borehole the recession curve of the swamp hydrograph was extrapolated back to the time of the cyclones (Figure 5.5).

In response to these raised water levels in the swamp, discharge through the Nkazana stream responded similarly and high flows resulted. The stream is assumed to have been flowing at bank-full capacity at the road crossing 1 km from the lake (Figure 2.9) following the cyclones (Porter, 1987).

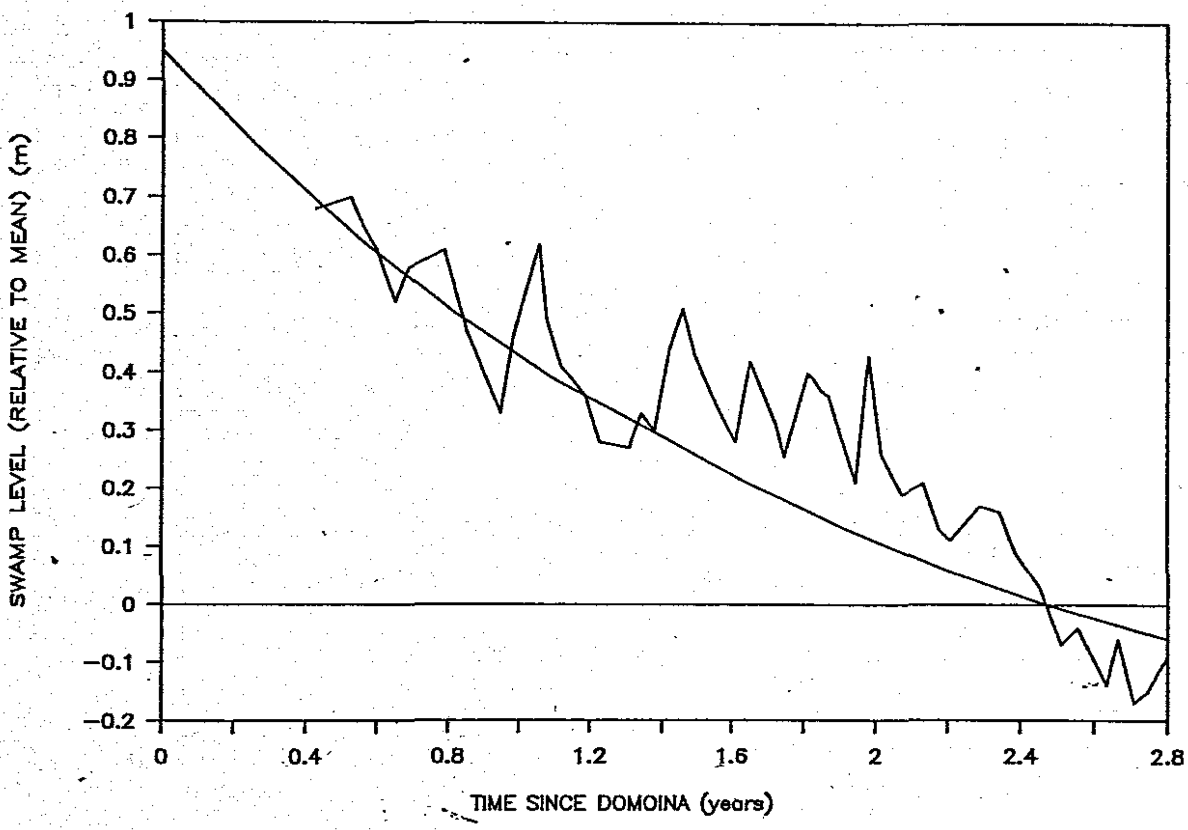


Figure 5.5 Recession rate at borehole C2 following cyclones Domoina and Imboa

The cross-section of the stream at this location was surveyed (Figure 5.6) to obtain the wetted perimeter (61 m) and the cross-sectional area (31 m^2). The slope of the free water surface was estimated from surveys and maps to be 0.001. The hydraulic resistance was estimated by assuming a Manning coefficient of 0.133 for a water course that has well established trees throughout the entire cross-section. The discharge at bank-full condition was derived from equation 5.1 (van Langenhove, 1983) to be approximately 4.8 m^3/s.

$$Q = \sqrt{S/R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

Where S = the slope of the free water surface

and $R = n^2 \dfrac{P^{4/3}}{A^{10/3}}$ where n = the Manning coefficient ($sm^{-1/3}$)
P = the wetted perimeter (m)
and A = the cross section area (m^2)

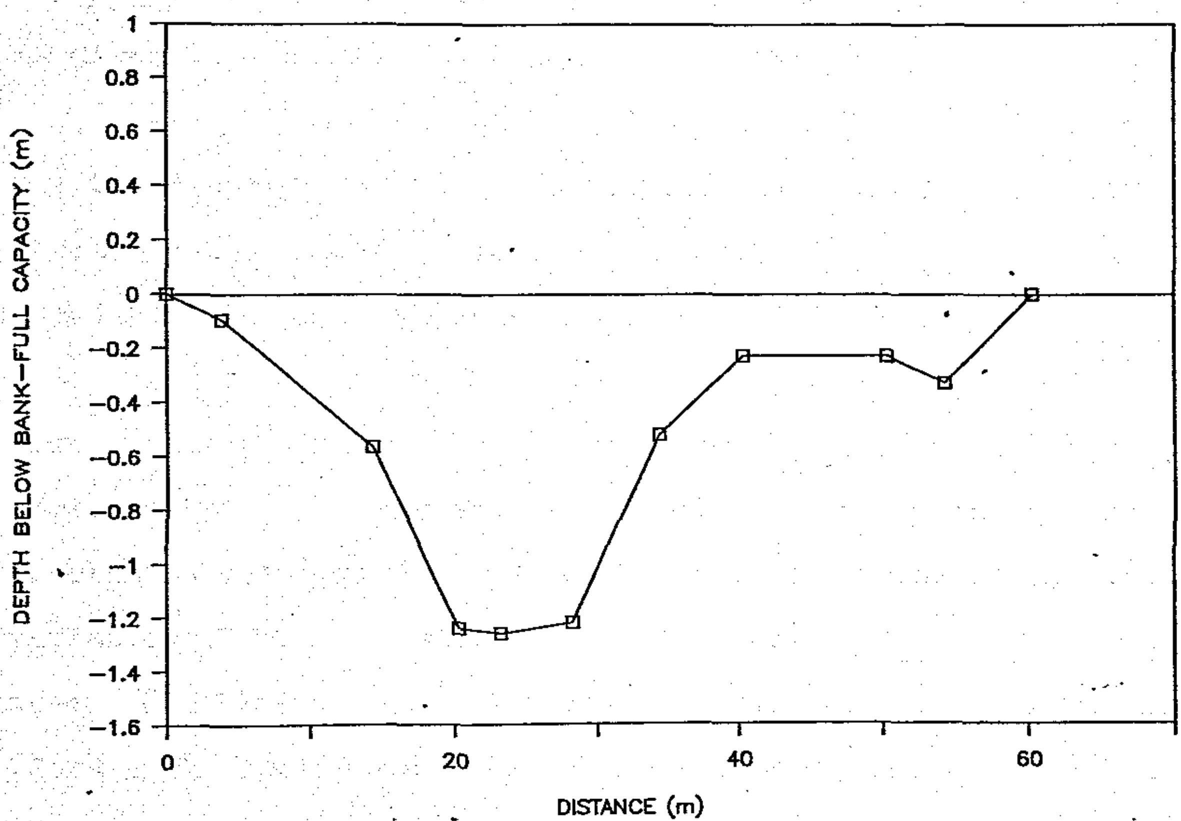


Figure 5.6 Cross-section through the Nkazana stream at the road crossing

This derived bank-full discharge was assumed to correspond to the raised swamp surface elevation of 0.95 m above 'normal'. As described above, under average conditions the discharge of the Nkazana stream is approximately 0.014 m^3/s (1200 m^3/day), which corresponds to an average swamp elevation (7.1 m a.m.s.l.) (Figure 5.1) and to the average swamp water surface area (derived from orthophoto maps) of 17.75 km^2.

Since the discharge at the Nkazana stream is directly related to the hydraulic head within the swamp it is assumed that the discharge receded to average conditions in the same manner as the swamp levels. A rating curve between swamp level and stream discharge was derived based on this relationship. This is given in Equation 5.2 below.

$Q = 5.038\ h + 0.014$ ....(5.2)

Where Q = the Nkazana discharge (m^3/s)

and h = the increase in swamp level (m)

From interpretation of orthophoto maps and aerial photographs, it appears that the swamp surface area fluctuates between 16.5 and 19.0 km^2 in response to climatic variations. During average climatic conditions, the swamp area (including Lake Bhangazi) was estimated to be 17.75 km^2. During the peak inflows associated with cyclone Domoina the area expanded to a maximum of 19.0 km^2. Since the topography immediately adjacent to the swamp is characterised by uniformly shallow slopes, the increase in surface area was assumed to be linearly related to the increase in water stage. A rating curve between surface area and discharge (Equation 5.3) at the Nkazana stream was derived in a similar manner to the curve for stage-vs-discharge (equation 5.2) described above.

$Q = 3.829\ a + 0.014$ ....(5.3)

Where Q = the Nkazana discharge (m^3/s)

and a = the increase in swamp area (km^2)

At the Nkazana stream, the recession of flow from 4.8 m^3/s to 0.014 m^3/s during the 3 year period following cyclone Domoina yields an additional discharge volume of 151.2 x 10^6 m^3. If it is assumed that the additional direct rainfall input from the cyclones to the swamp (17.1 x 10^6 m^3) all contributed to this excess flow and that all other rainfall during the 3 year period maintained average flow or was evaporated, then 134.1 x 10^6 m^3 was derived from groundwater seepage into the swamp. The contribution from the catchment to the west of the swamp (62% of the total catchment), thus equates to 83.1 x 10^6 m^3 or 5.9 x 10^6 m^3/km of swamp edge. Discharge from the study area during this period is therefore calculated to be 169.8 x 10^6 m^3 (5.9 x 10^6 x perimeter). This is equivalent to an annual rainfall depth of 1400 mm over the plain area of 40 km^2. It appears therefore, that the majority of the water input resulting from extreme rainfall events increases groundwater storage and then contributes, over an extended period, to increased groundwater seepage.

During periods of below average rainfall there is a consequent reduction in swamp water level, swamp area and stream discharge. The period from January 1982 to July 1983 typifies such a period. Rainfall during this period was 600 mm less than average at Fanies Island (0339756) and 970 mm less than average at St Lucia Estuary (0339856). The synthetic record for the UZ station indicates a deficit below mean rainfall of 875 mm. Water levels at boreholes C2 and D1 consistently fell during this period to their lowest recorded levels between 1973 and 1990 (figures 5.1 and 5.2). Allied to the decreasing water levels would have been a corresponding decrease in swamp surface area. From orthophoto maps and historical aerial photographs, it is clear that the swamp is topographically contained within a shallow basin. Though difficult to measure retrospectively, perennial swamp area is unlikely even during this dry period to have decreased below 16.5 km^2.

Although reliable recordings of discharge through the Nkazana stream for this period are unavailable, it is likely that they were very low or even ceased altogether. As a consequence of low recharge and hence lowered water levels, groundwater seepage into the swamp from its catchment area would have also decreased.

CHAPTER 6

GEOHYDROLOGICAL ANALYSIS

Geohydrological analysis has been conducted on both the historic data collected from the small diameter boreholes (1973-1990) and the new data received from the large diameter boreholes installed in 1987/88. These analyses compared the water table fluctuations experienced at various locations within the study area with the aim of detecting different geohydrological behaviour under conditions of different climate and different vegetation cover, and in response to vegetation change) during the period of record.

6.1 OVERVIEW OF RECORD

A number of trends are apparent in the data collected from these boreholes over the period 1973 to 1990. To illustrate these, the complete water level hydrographs at all of the boreholes within the study area are given in Appendix B, and the complete monthly rainfall series for St Lucia Estuary (0339856) in Figure 6.1.

At least during the first ten years of operation, most of the boreholes had good hydraulic contact with their aquifers. Thus water levels fluctuate fairly conformably in response to rainfall variations. Also apparent is a rapid aquifer response to recharge events associated with rainfall, with months of high rainfall corresponding to a rise in water level at each borehole. In drier periods the water levels at the different boreholes drop at varying rates and by varying magnitudes.

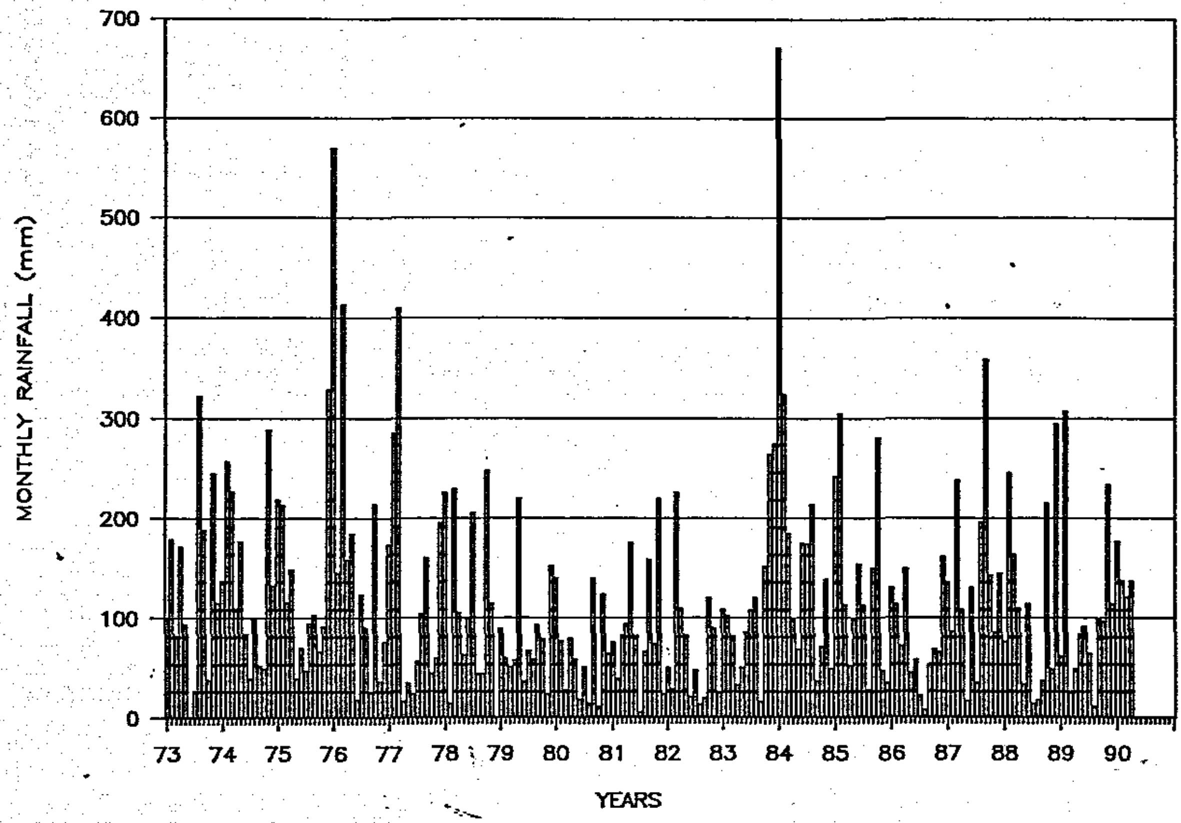


Figure 6.1 Rainfall record (0339856) for the period 1973 to 1990

From 1973 to 1976, rainfall was consistently above average and water levels remained high. Very high rainfall in December 1975, January 1976 and March 1976 (Figure 6.2) led to all functioning boreholes attaining maximum water levels. Unfortunately, there was a period from August 1976 to March 1978 when monitoring ceased and thus no data is available. It appears that during this period water levels remained above average following the high rainfalls of 1976, though they had all dropped by about 1 m by 1978.

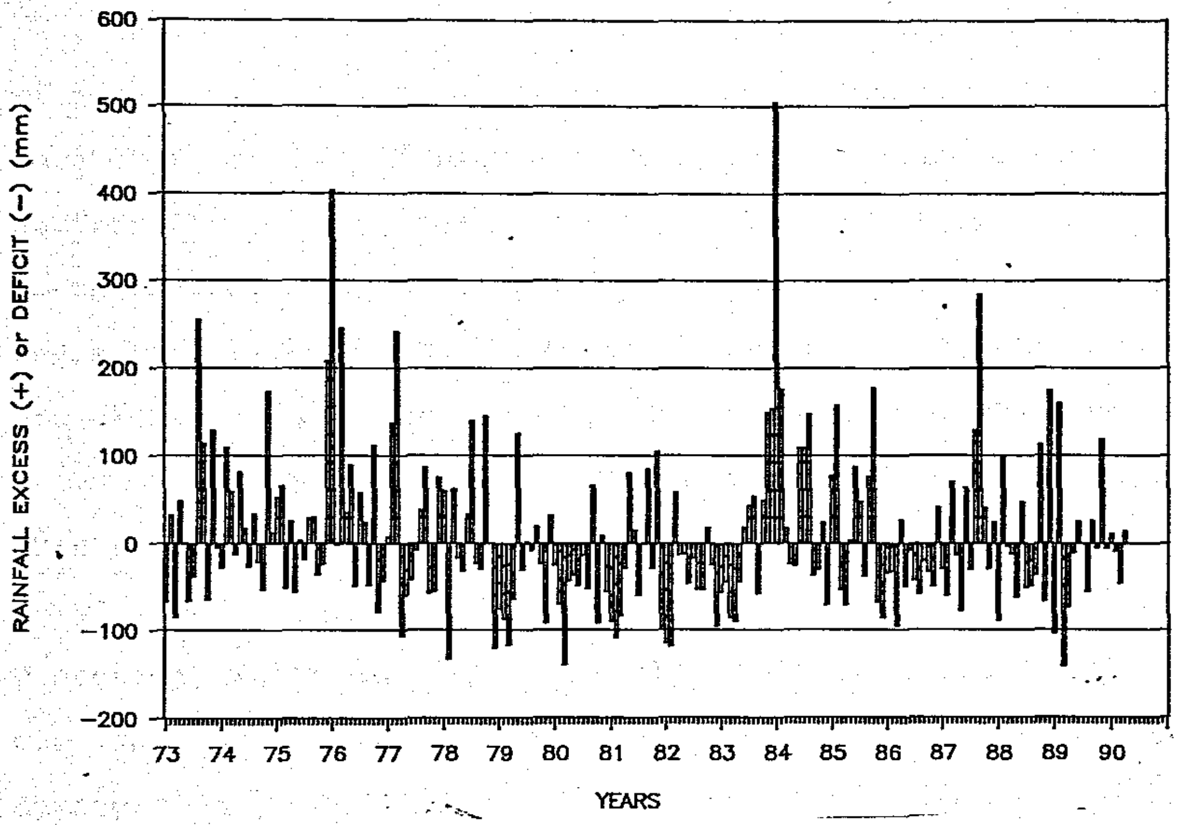


Figure 6.2 Deviation of actual monthly rainfall from mean monthly rainfall during the period 1973 to 1990

During the period 1978 to 1981 period, most boreholes show a consistent decline in water levels with very few minor fluctuations. This corresponds with a period of intermittent and below average rainfall (Figure 6.2), and hence recharge was low. With discharge exceeding recharge, storage declined. The increased depth of the zone of aeration also resulted in more complete absorption of minor rainfall events in the unsaturated layer which were thus unable to contribute directly to groundwater recharge.

In early 1981, many of the boreholes show a small rise in water levels, corresponding to a period of above average rainfall in the 1980/81 wet season (Figure 6.2). The magnitude of this response differs at different boreholes with six boreholes showing no increase. Since two of these boreholes in 1974 displayed poor hydraulic contact with the aquifer (A5 and A6), the lack of response is likely to be due to their deteriorated condition. The remaining four boreholes where no response was detected comprise the D line which are close to the mature section of the plantation. This could be as a consequence of a thicker unsaturated zone absorbing this rainfall.

Decreasing water levels across the whole area from 1981 to mid-1983 correspond to the below average rainfall inputs during this period (Figure 6.2), and to groundwater storage reduced in a similar manner to the period 1978 to 1981.

From the middle of 1983, consistently above average rainfall led to a widespread increase in storage which re-attained maximum levels in early 1984 in response to the two tropical cyclones, Domoina and Imboa. Rainfall associated with these cyclones caused an excess of more than 600 mm over mean in January and February. Water level response to these events was widespread. The degree of rise ranged from 1 m to over 3 m and levels attained were similar to those reached during 1976. The rate of rise varied, some holes having an immediate response and others being considerably delayed. This delay, since it was probably due to poor hydraulic contact, again served to distinguish between reliable and unreliable boreholes.

Following these major rainfall events, high water table levels were maintained by major storms occurring during 1984 and 1985. Since the water table was close to the surface, the response of groundwater to rainfall was good. However the constant levels shown since 1984 at some boreholes is indicative of their failure during this period.

The period of below average rainfall from 1986 to September 1987 is characterised by declining water levels at all the functioning boreholes. The rates of recession experienced in this period compare well with those during the 1978/81 dry period at those boreholes where no major change in vegetation cover occurred. Given the somewhat shorter time period of this dry cycle, water levels do not drop to levels achieved in 1981. At boreholes where a change in vegetation occurred (C4 and C5), however the recession rates appear to have increased and levels achieved in 1987 are similar to those in 1981. This aspect is covered in detail in the following section.

Heavy rainfall in September 1987, though of lesser magnitude than that of early 1984, recharged the aquifers considerably. As in 1984, the magnitude of the water level rise was widespread though it did vary between boreholes.

Between 1987 and 1990, several months with above average rainfall (Figure 6.2) served to maintain water levels at slightly above average. The hydrographs for this period display a seasonal pattern of summer rise followed by winter recession. Data available for this period from the newly installed boreholes, confirms that several of the older boreholes (A5, A6, B3, B5, D2, D3, and D5) were, by then, inadequate, while others (A3, B4, C2, C3, D4a, and D4b) gave valid records.

6.2 GROUNDWATER RESPONSE TO INDIVIDUAL RAINFALL EVENTS

Continuous water level data for borehole E1 situated at the weather station is available for the dry season recession period from 21 June to 9 October 1989 (Figure 6.3). These data are compared to the rainfall for the same period recorded at the weather station (Figure 6.4). With rainfall totalling 170 mm, the water table declined by 0.28 m from 2.171 m to 2.449 m below ground level.

Three rainfall events significant enough to raise the water table were experienced. The first occurred on 1 July (day 11) when 17 mm of rain increased water levels by 10 mm; the second on 20/21 July (days 30/31) when 31 mm of rain increased water levels by 46 mm; and the third, from 22 to 26 September (days 94-98) when 66 mm of rain raised levels by 137 mm. In each instance the retarded response of 3 days between maximum rainfall and maximum water table elevation gives the percolation time for water to move through the unsaturated zone (Kelbe and Rawlins, 1990b).

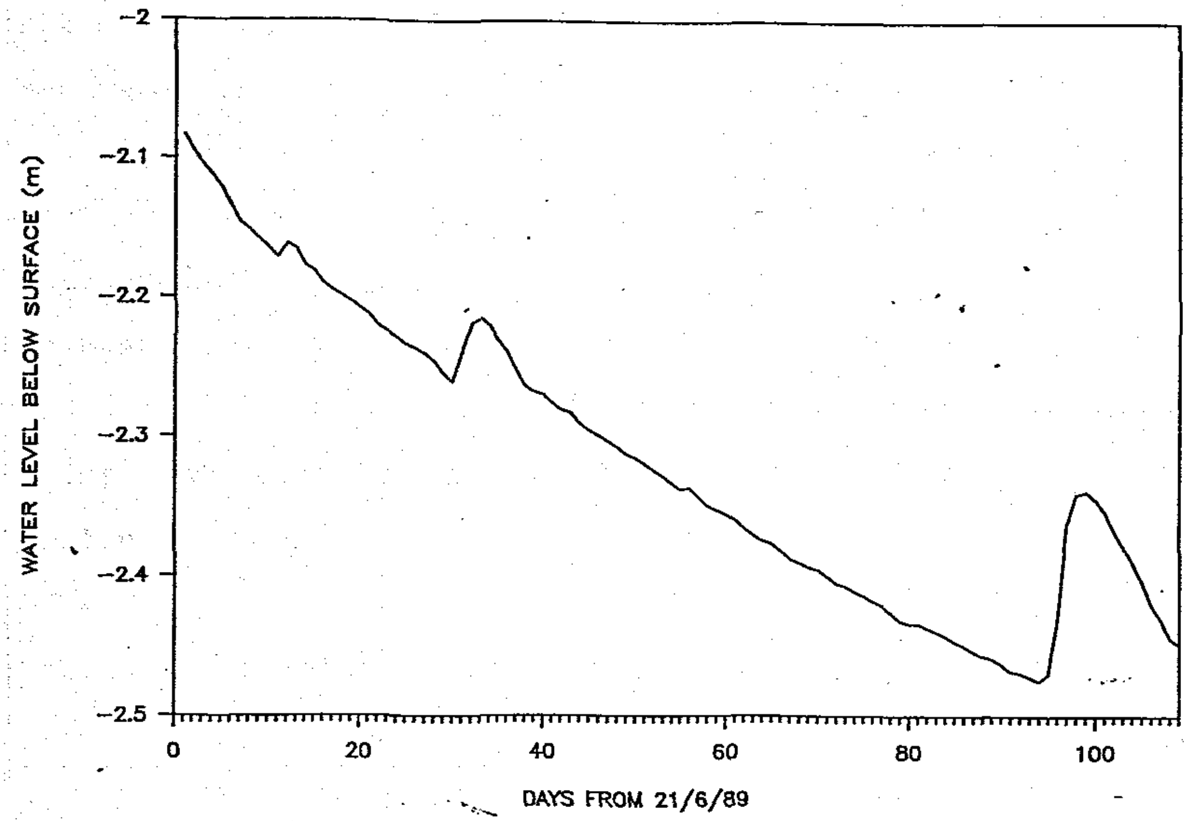


Figure 6.3 Water table hydrograph continuously monitored at borehole E1 (21/6/89 - 9/10/89)

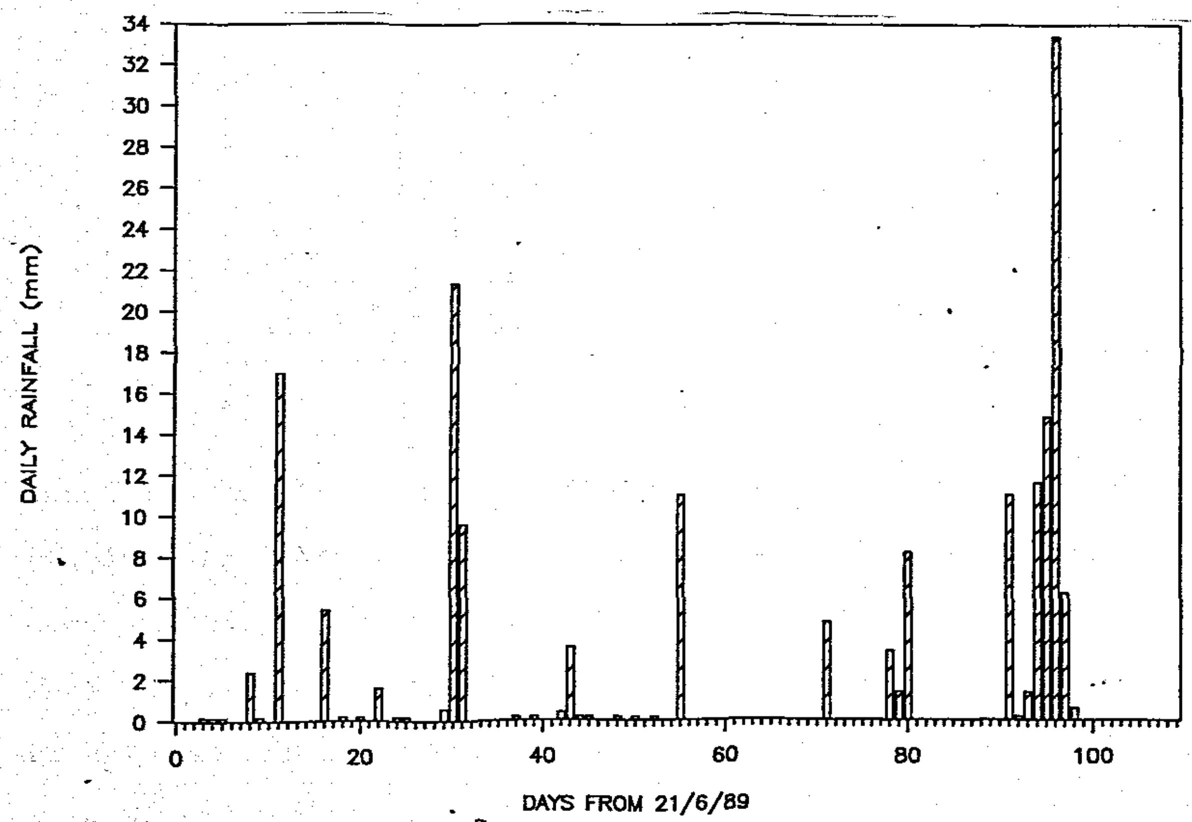


Figure 6.4 Rainfall at the UZ station (21/6/89 - 9/10/89)

Although the effect of scattered small rainfall events on the saturated zone is small, some of these events (Table 6.1), nevertheless gave rise to a slight, detectable decrease in the groundwater recession rate. In these instances most of the rainfall input would have been absorbed by the unsaturated zone. The minimal effect on the saturated zone was ascribed rather to decreased evapotranspiration on cooler rainy days than to an input of recharged water (Kelbe and Rawlins, 1990b)

Table 6.1 Rainfall events and corresponding water table response at borehole E1

EVENT DATE	RAINFALL (mm)	WATER TABLE RESPONSE (mm)
28/6/89	2.4	- 6.0
1/7/89	17.0	+ 10.0
6/7/89	5.4	- 4.5
12/7/89	1.6	- 6.0
20 to 21/7/89	31.0	+ 46.0
2/8/89	3.6	- 5.0
14/8/89	11.0	- 2.0
30/8/89	4.8	- 5.0
6/9/89	3.4	- 5.0
7 to 8/9/89	9.6	0
19/9/89	11.0	0
22 to 25/9/89	66.0	+137.0

Rainfall events and corresponding water table responses (Table 2.1) (adjusted for the lag period) are plotted against each other in Figure 6.5. From this Figure it is apparent that the water table, at a depth of 2-3 m below the surface in a grassland environment, will respond to a rainfall event exceeding approximately 10 mm. Obviously antecedent conditions, which play a role not accounted for in this analysis, will vary considerably over the course of a year, however, if it is assumed that the period of record was representative of average conditions, an estimate of annual effective rainfall could be made. The distribution of daily rainfall for rainfall stations at Fanies Island (0339756) and St Lucia Estuary (0339856) indicates that over 50% of rain-days do not produce precipitation depths greater than 10 mm (Chapter 4.1.3). Since these rain-days account for approximately 25% of the annual rainfall total, the mean annual effective groundwater recharge at the UZ weather station is reduced from the 1200 mm of total rainfall to 900 mm, with the 300 mm difference being accounted for by interception losses and unsaturated zone recharge.

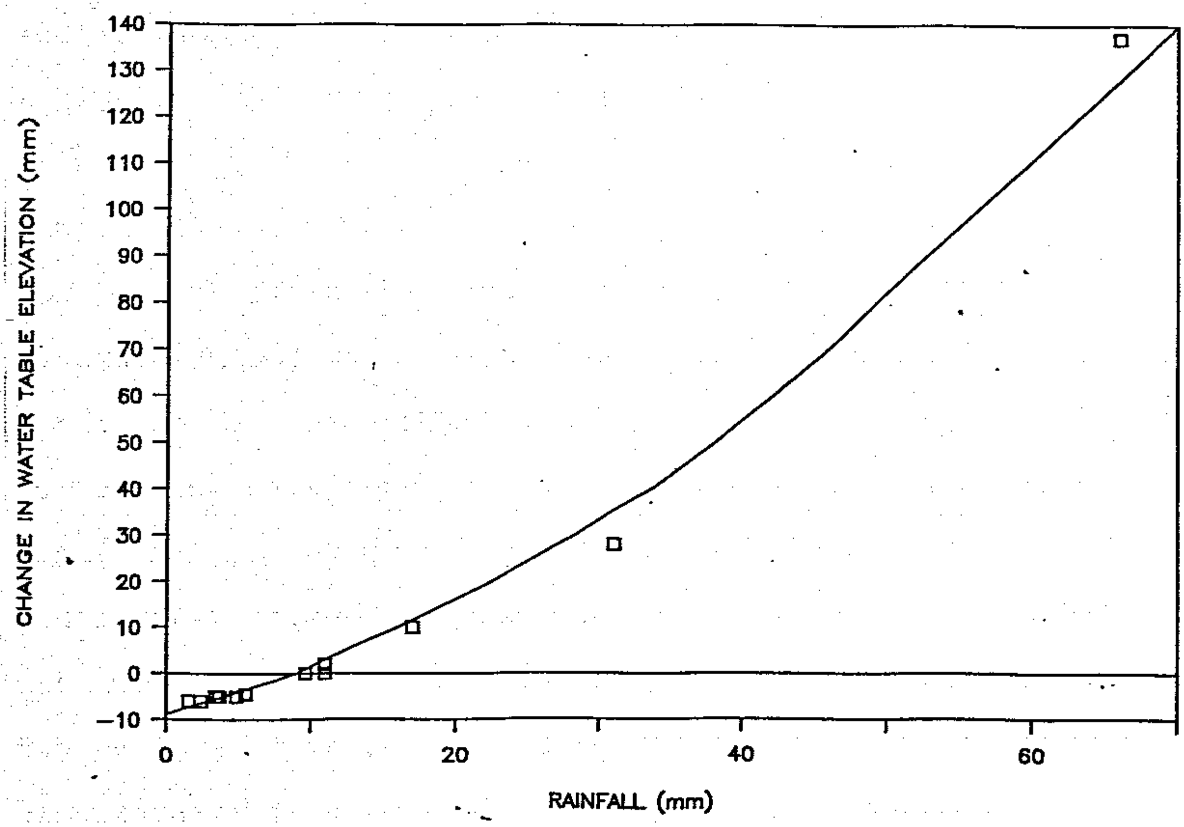


Figure 6.5 Rainfall and water table response at the UZ station

6.3 COMPARISON BETWEEN PERIODS

A major perturbation during the period of historical record was the establishment of a plantation in 1981. Two periods (1979 and 1986) with similar characteristics were used as a basis of comparison of water table conditions before and after 1981. The relative rates of water table decline were then analysed at selected boreholes for both periods in order to assess the effects of plantation development on ground-water.

The mechanisms responsible for the rate of decline of a water table in this situation include the geological and geohydrological characteristics surrounding the borehole, the initial head as represented by the elevation of the water table, and the recharge and discharge rates.

Since the comparison was between recession rates at the same borehole at different times, the geological structure and the geohydrological conditions (porosity, permeability, storage coefficient, hydraulic conductivity and transmissivity) surrounding each borehole can be assumed to have remained the same. An implication of this assumption is that the hydraulic continuity between the selected boreholes and the aquifer did not change significantly during the seven years between the two periods. Thus only those boreholes which appeared to show good results in slug tests in 1985 were considered.

The periods were selected so as to minimise the effects of different initial heads of water before each recession period. With starting points at all the boreholes analysed being within 10 cm of each other, the subsurface inflow and outflow components of the water balance at each borehole should have remained similar.

To allow a direct comparison between the two periods, the recharge to the study area had to be similar. An assessment of rainfall records for the two periods (Table 6.2 and Figure 6.6) showed both to be below average and similarly distributed through the year.

Table 6.2 Rainfall records for 1979 and 1986

	339856 1979		339856 1986	
MONTH	TOTAL (mm)	ACCUM (mm)	TOTAL (mm)	ACCUM (mm)
January	88.7	88.7	124.8	124.8
February	66.9	155.6	87.8	212.6
March	107.2	262.8	54.3	266.9
April	65.2	328.0	145.7	412.6
May	120.7	448.7	42.7	455.3
June	0.0	448.7	66.4	521.7
July	18.9	467.6	7.2	528.9
August	32.5	500.1	10.7	539.6
September	77.5	577.6	63.0	602.6
October	98.6	676.2	73.5	676.1
November	26.1	702.3	60.3	736.4
December	109.3	811.6	128.1	864.5
Annual	811.6		864.5	

Discharge from the study area is in the form of groundwater outflow (covered above) and evapotranspiration. Evapotranspiration rates vary according to the depth of the water table below the surface and according to the type of vegetation growing on the surface. Given the similarity of heads at the start of the two periods, at boreholes where the vegetation remained the same evapotranspiration should also have remained the same, and consequently water table recession rates should be similar for the two periods. If vegetation changed between the first and second period at a particular boreholes, and gave rise to a change in evapotranspiration rates, then this change should be reflected in water table recession rates.

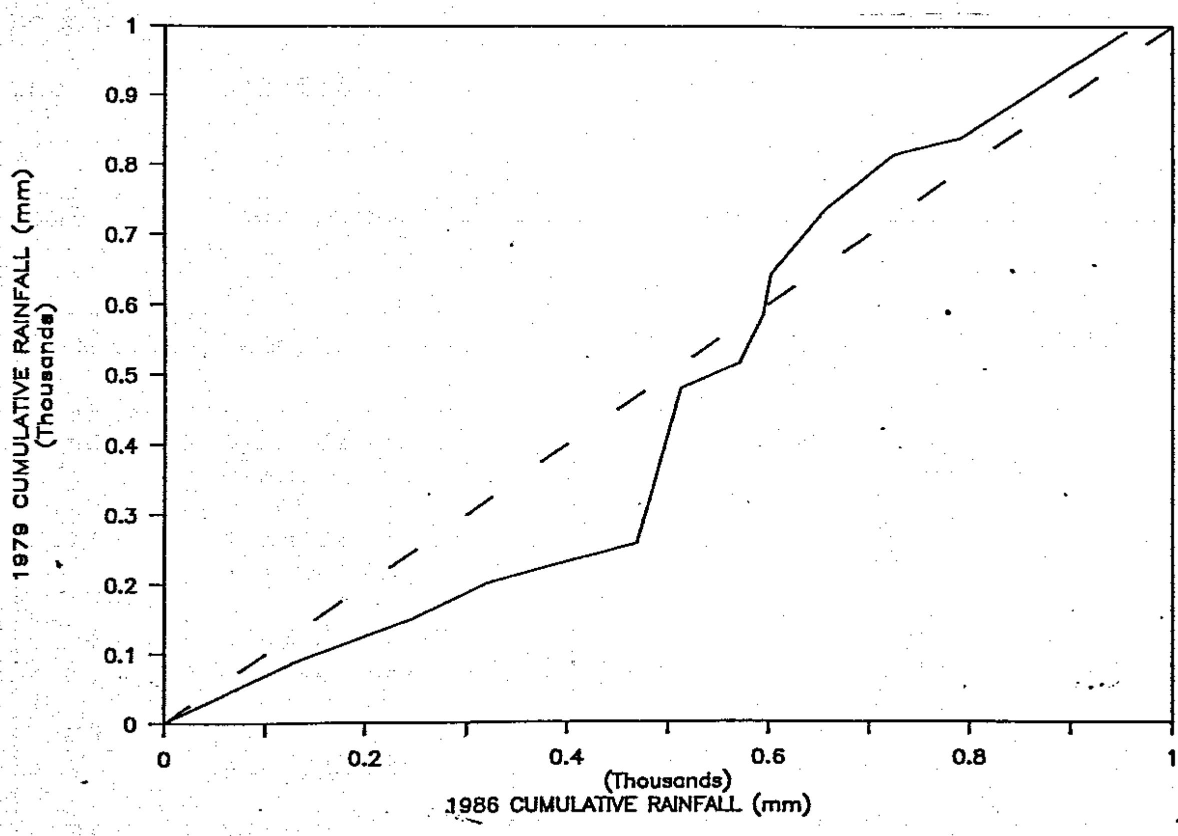


Figure 6.6 Cumulative rainfall in 1979 and 1986

The rates of recession of the eight boreholes that appeared to have a relatively unimpared hydraulic contact with the aquifer were compared. The location of these boreholes in relation to the 1981 plantation was as follows: two were within the 1981 plantation; one was 100 m from it; one was

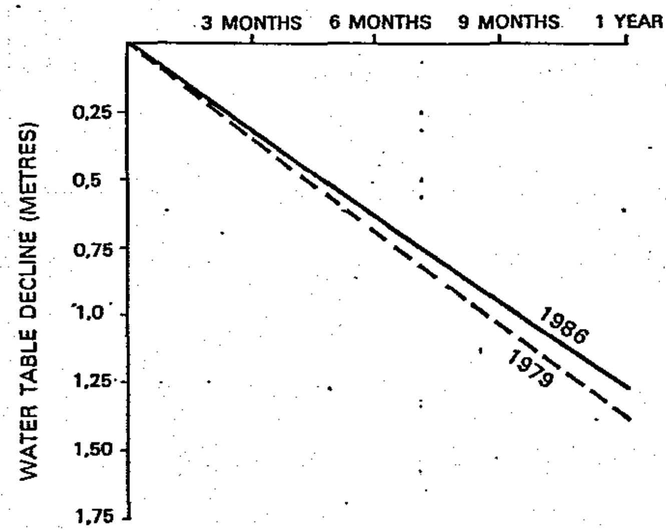
1 km away; and three were located at least 3 km away from the plantation. A further borehole, B1 was adjacent to the established 1960 plantation.

Regression analysis was performed on the water level recessions to allow direct comparison between the two periods, and the best fit straight lines for water level recessions were thus obtained (Table 6.3). From this Table a significant difference in the recession rates at some of the boreholes is evident, most notably those within or close to the 1981 plantation.

Table 6.3 Regression analysis of borehole recession rates 1979 and 1986

BOREHOLE	LOCATION	YEAR	TOTAL DECLINE	r^2	CHANGE
A2	3 km from 1981 Plantation	1979 1986	1.38 1.27	0.98 0.99	- 8%
A3	3 km from 1981 Plantation	1979 1986	1.20 1.25	0.96 0.98	+ 4%
A4	3 km from 1981 Plantation	1979 1986	1.25 1.21	0.96 0.97	- 3%
C3	1 km from 1981 Plantation	1979 1986	0.65 0.70	0.97 0.89	+ 7%
B1	Adjacent to 1961 Mature Plantation	1979 1986	0.81 0.92	0.97 0.96	+13%
B4	20 m from 1981 Plantation	1979 1986	0.81 1.30	0.84 0.95	+60%
C4	Inside 1981 Plantation	1979 1986	1.21 1.66	0.97 0.97	+37%
C5	Inside 1981 Plantation	1979 1986	0.90 1.20	0.99 0.99	+33%

a)



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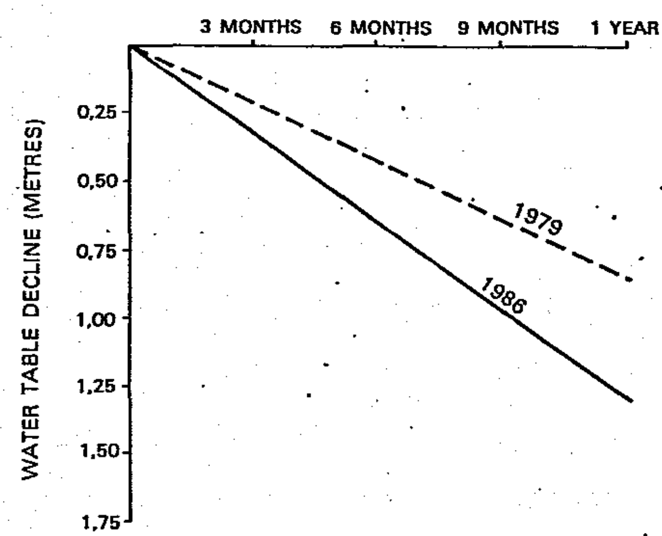

c)

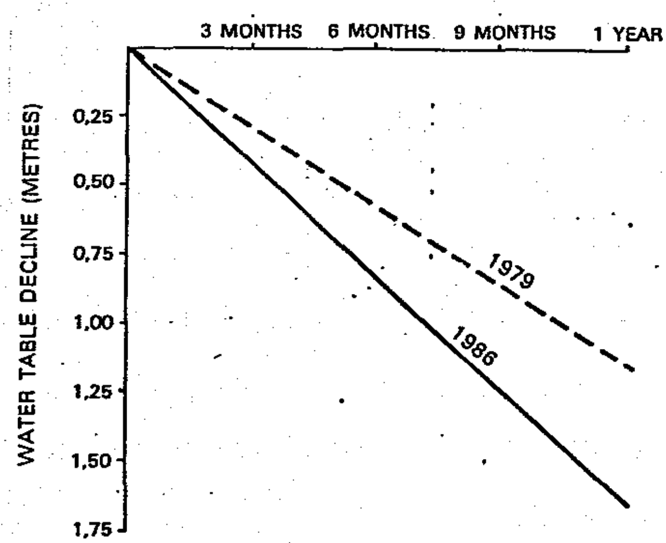

Figure 6.7 Comparative water table recessions during 1979 and 1986 (a) Borehole A2 (b) Borehole C4 (c) Borehole B4

Boreholes A2, A3 and A4, situated at least 3 km from the 1981 plantation experienced no change in vegetation cover and show little change in recession rates (Figure 6.7a) This continuity confirms that the climatic and geohydrological characteristics of the two periods selected were similar.

Boreholes C4 and C5, within the plantation, show a 30% to 40% increase in recession rates following the establishment of the 1981 plantation (Figure 6.7b). As this increase cannot be accounted for by variations in rainfall or seepage flow it is clearly due to a significant increase in evapotranspiration associated with the consumptive use by the young (5 year old) trees.

Borehole B4, situated 100 metres away from the plantation, also shows a considerable increase in recession rate (60%) (Figure 6.7c). Although the increase is greater than within the plantation it nevertheless serves to confirm the trend apparent within the plantation.

Borehole C3, situated 1 km away from the plantation, shows a small increase in recession rate, which may be due to increased consumptive use by the plantation. However, this borehole is situated in close proximity to the Mfabeni swamp and therefore its recession rate is more likely to be controlled by the level of the swamp than by any other factor.

Borehole B1, located adjacent to the mature plantation, also displays a slight increase in recession rates. This may be due to the fact that the plantation was adjacent to the borehole during both periods and that the evapotranspiration rates from 18 year old trees is similar to that from 25 year old trees. The slight increase detected, is possibly due to an increase in interception loss by the more mature trees.

It can be estimated from these results that in regions such as this with readily available water, the establishment of fast growing tree species can significantly increase the consumptive use from the saturated zone by up to 40% (Table 6.3). The extent of this effect appears to be fairly limited, extending to at most 1 km away from the plantation.

Since hydraulic heads were initially similar, groundwater seepage flow from the plantation areas was assumed to have been similar during the two periods. However, the faster recession under the plantation would have led to some additional decrease in seepage outflow greater than that under grassland areas. This effect, incorporated into the above recessions as a decrease in the outflow component, would add to the evapotranspirational loss attributable to the forest.

In soils of this type with porosities of 45% and specific yields of 35% (Lynn, 1990), the additional annual water loss resultant from forest establishment, reflected in the additional water level drop of between 0.3 m and 0.49 m, amounts to between 100 and 170 mm/year (1000 to 1700 m^3/ha/year). This regional loss would be further increased by the reduced recharge effectiveness of rainfall consequent on an increased interception loss.

The effects of afforestation on consumptive use appear to be most marked during the early years of the growth cycle of the trees as evidenced by the results from borehole B1. These effects probably lessen with age after the groundwater readily available prior to planting is exhausted. Once this initial resource is utilised then it is only the infrequent major recharge events that are able to redress the water deficits. In this region major replenishment of the aquifers occurs intermittently following extreme rainfall events such as those in 1976 and 1984. These events were of a sufficient magnitude to recharge the aquifer fully at all locations and to bring the water table close to the surface. Lesser heavy rainfall events, such as that occurring in 1987, were of sufficient magnitude to redress the deficits partially, but not to recharge the aquifer over its full extent.

6.4 COMPARISON BETWEEN BOREHOLES

In order to assess further the effects of vegetation cover on groundwater behaviour, water table hydrographs from the newly installed boreholes were assessed. Boreholes from all vegetation covers were selected to provide representative water table fluctuations over an 18 month period. This period, from 14 March 1988 to 9 September 1989, covered two dry winter seasons and the intervening 1988/89 wet season. The starting point, 14 March 1988, represented the maximum recorded water level following the 1987/88 wet season. For purposes of comparison, all the hydrographs were adjusted to begin with this level as a common datum. Though this procedure would cloud any effects of differing hydraulic head on recession rates, the effects of head were assumed to be negligible in comparison with the effects of rainfall and evapotranspiration.

Covering the undisturbed situation in the area over this period, the hydrograph for borehole C2, sited on the eastern edge of the Mfabeni swamp, and the monthly rainfall record at the UZ weather station are presented in Figures 6.8 and 6.9. A significant water table response to rainfall is evident from these Figures, with small events retarding the seasonal recession rate and larger rainfall events recharging the aquifer and raising the water table.

Figure 6.8 shows that during the drier winter period following the 1987/88 wet season, water tables dropped consistently. However several rainfall events able to raise the water levels temporarily occurred during this season (days 80 to 120). The greater and more frequent rainfall in the spring of 1988 resulted in a more marked groundwater response. During this period the water table did not remain elevated for prolonged periods, however, and water levels dropped rapidly following these rainfall events (days 180 to 280). This rapid drop is possibly due to high consumptive use during spring. During the summer, with high rainfall in December and February, water tables rose to the levels achieved during the previous summer. Following the peak in March (day

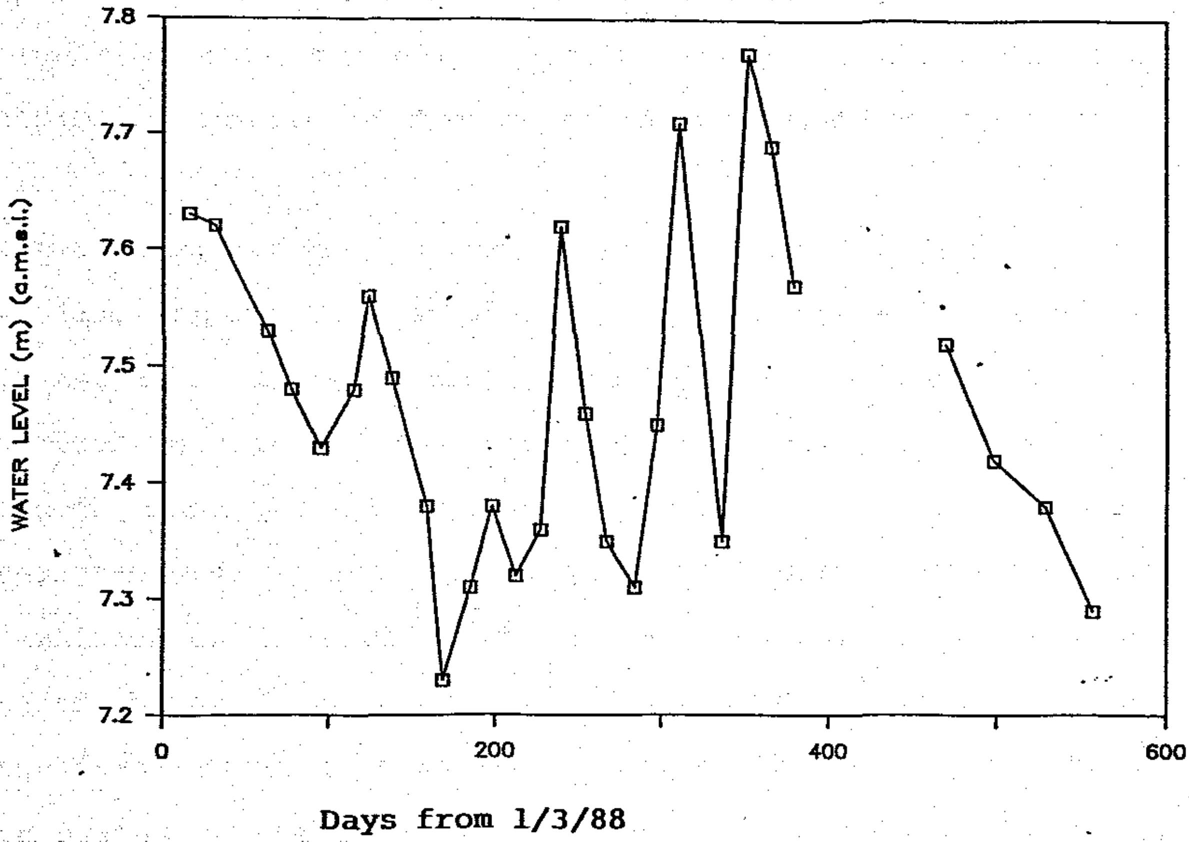

Figure 6.8 Water table hydrograph at borehole C2 (1988-1989)

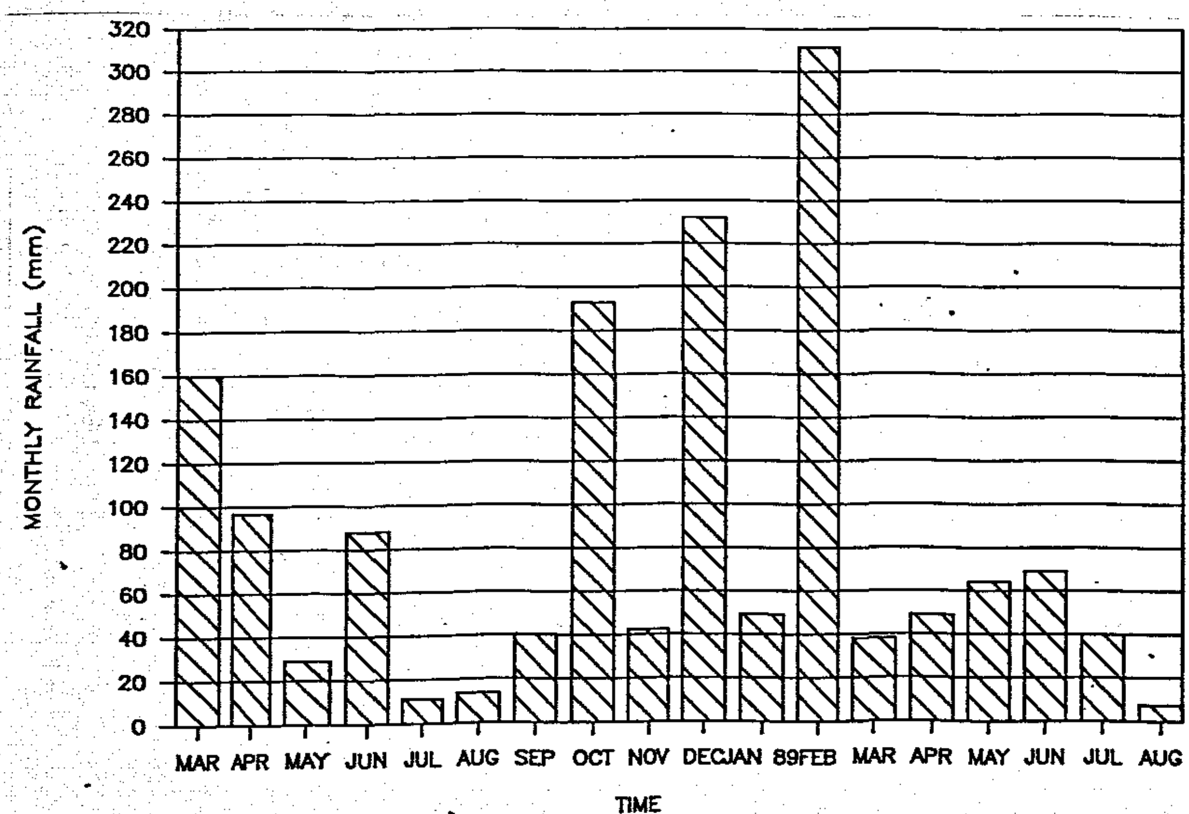

Figure 6.9 Synthesised monthly rainfall at the UZ station (1988-1989)

360) the levels receded, at first quickly and then more slowly as consumptive use declined during winter. This recession is similar to that experienced in the 1988 dry season.

Direct comparison of borehole sites located under different surface covers show similar hydrograph shapes. Figure 6.10 illustrates the hydrographs recorded for the swamp (C2), the natural grasslands (B3) and the young pine plantation (F3). Though recharge and recession periods are reflected in all environments, there are significant differences in the magnitude of these fluctuations. The recession rates recorded under the grasslands and under the plantation are similar for the first 80 days as water is used by the vegetation and as it drains to the lower lying areas. This drainage serves to maintain swamp levels which thus show a slower recession rate than the grasslands and the plantation.

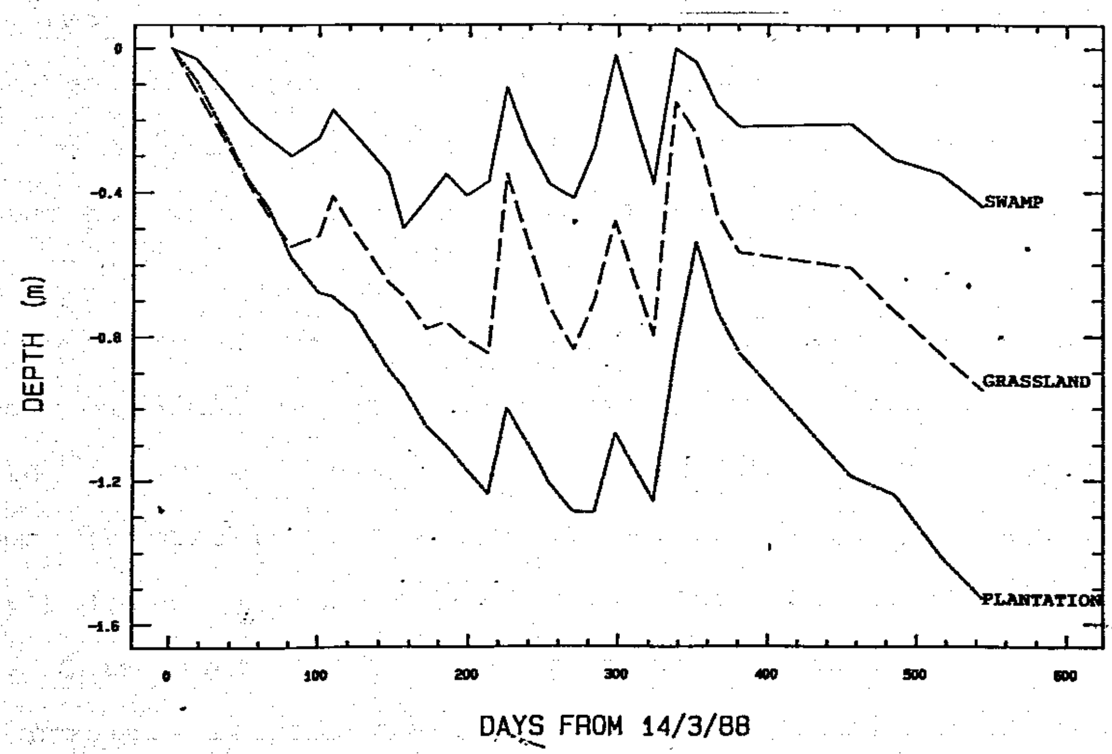

Figure 6.10 Water table hydrographs for different vegetated environments (1988-1989)

The grassland and swamp areas show similar responses to dry season rainfall, these responses are reflected by raised water levels. Within the plantation, however, dry season rainfall has a diminished effect. No increase in water level results but there is a retardation of the recession rate. This response is possibly due to a combination of the increased interception loss in forested areas, and the higher dry season consumptive use of the trees. The net effect is that in non-forested areas, water table elevations are maintained by rainfall whereas in forested areas the recession continues unabated with the consequential depletion of groundwater storage.

With the onset of greater rainfall in the spring of 1988, the relatively drier forested areas are not recharged to the same extent as are the grasslands. The response to rainfall in the forested areas is diminished, with more water required to recharge the deeper and drier unsaturated zone. In addition the early season growth demands of the fast growing trees appear to use the available moisture more rapidly.

The recovery of water levels in March in response to high summer rainfall is experienced under all environments. Yet while the swamp levels reach those of the previous season, under the grasslands the recovery is to 70% of the previous year's level, and under the forests the recovery is only to 57%. This gives added weight to the observations outlined in the previous section that it is only the occasional extreme rainfall events that completely recharge the aquifer over its entire extent. The rate at which the aquifer is recharged in response to this input also differs, with the forested areas recharging at a slower rate than the other environments. The rise to peak in the forested areas is achieved some 15 days after that in the non-forested areas.

Hydrograph recessions for the 1989 dry season show the same characteristics as those for 1988. These similar recession rates indicate that there has been no significant change in the factors that control water table fluctuations between these two consecutive years.

The hydrographs can be divided into three seasonal periods: a winter recession, the rate of which is controlled by the type of environment; a spring equilibrium period in which recharge equals discharge giving relatively static water levels; and a summer recharge period in which all environments experience a rise in water levels. Since the forested areas have been depleted more than the non-forested areas in the dry season, and since their soil storage deficit is greater, greater volumes of recharge to the deeper unsaturated zone are possible. In the non-forested areas, however, since the capacity for recharge is lower, and since the water table is closer to the ground surface, more water is lost to surface runoff and to open water evaporation. The absolute recharge to forested areas is therefore greater than that to non-forested areas. In years of average rainfall, however, the net losses (recharge *minus* evapotrans-piration) from the forests are greater than those from the grasslands. This leads to a progressive reduction in the groundwater storage in forested areas; a deficit only redressed by the large inputs from extreme events such as those that occurred in 1976 and 1984.

Quantifying the recorded hydrographs (Figure 6.10) in terms of water table response gives a figure for the additional loss under the forests equivalent to an additional dry season water level fall of approximately 0.40 m. The additional fall during the wet season is 0.10 m. This total additional fall of 0.50 m, when account is made of the specific yield of the aquifer (35%) is equivalent to a greater annual forest evapotranspiration loss of 175 mm. This figure confirms those determined in section 6.3 (100 to 170 mm).

The hydrograph variations between the mature (27 year old) and young (8 year old) plantations presented in Figure 6.11. do not reveal a significant difference between the two forests. Both plantations experience identical water table fluctuations, suggesting similar behaviour, though it is possible that the combined effects of greater interception loss and lower consumptive use by mature trees are equivalent to the combination of lower interception loss and greater consumptive use by young trees. To assess whether this is the case, hydrographs from the middle of the plantations and from just outside the plantations were evaluated. For the young plantation the hydrographs are almost identical (Figure 6.12a), indicating that the influence of afforestation on groundwater extends at least 40m beyond the forest perimeter.

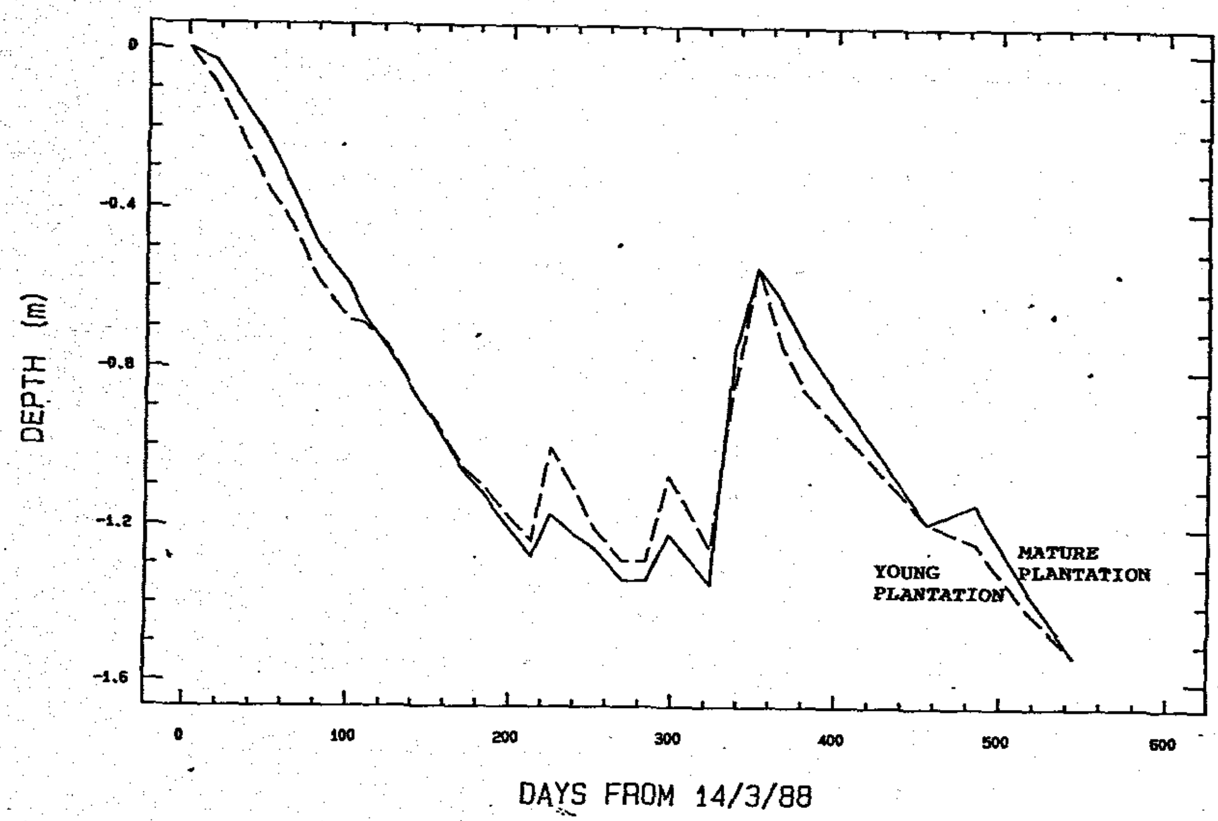

Figure 6.11 Water table hydrographs in mature and young plantations (1988-1989)

The hydrographs inside and outside the mature plantation (Figure 6.12b) display different responses however. The hydrograph within the mature plantation is similar to that for the young plantation but 30 metres outside the mature plantation the recession rate is slower and the response to rainfall is greater. This pattern possibly reflects the effect of a lower interception loss in grassland areas. This would mean that the effect of interception loss increases with plantation age as leaf surface area increases, whereas the effects of consumptive use decrease with age as the tree growth rates decline. The gross water use comprising both interception loss and evapotranspiration within the plantation, however remains the same as the plantation matures.

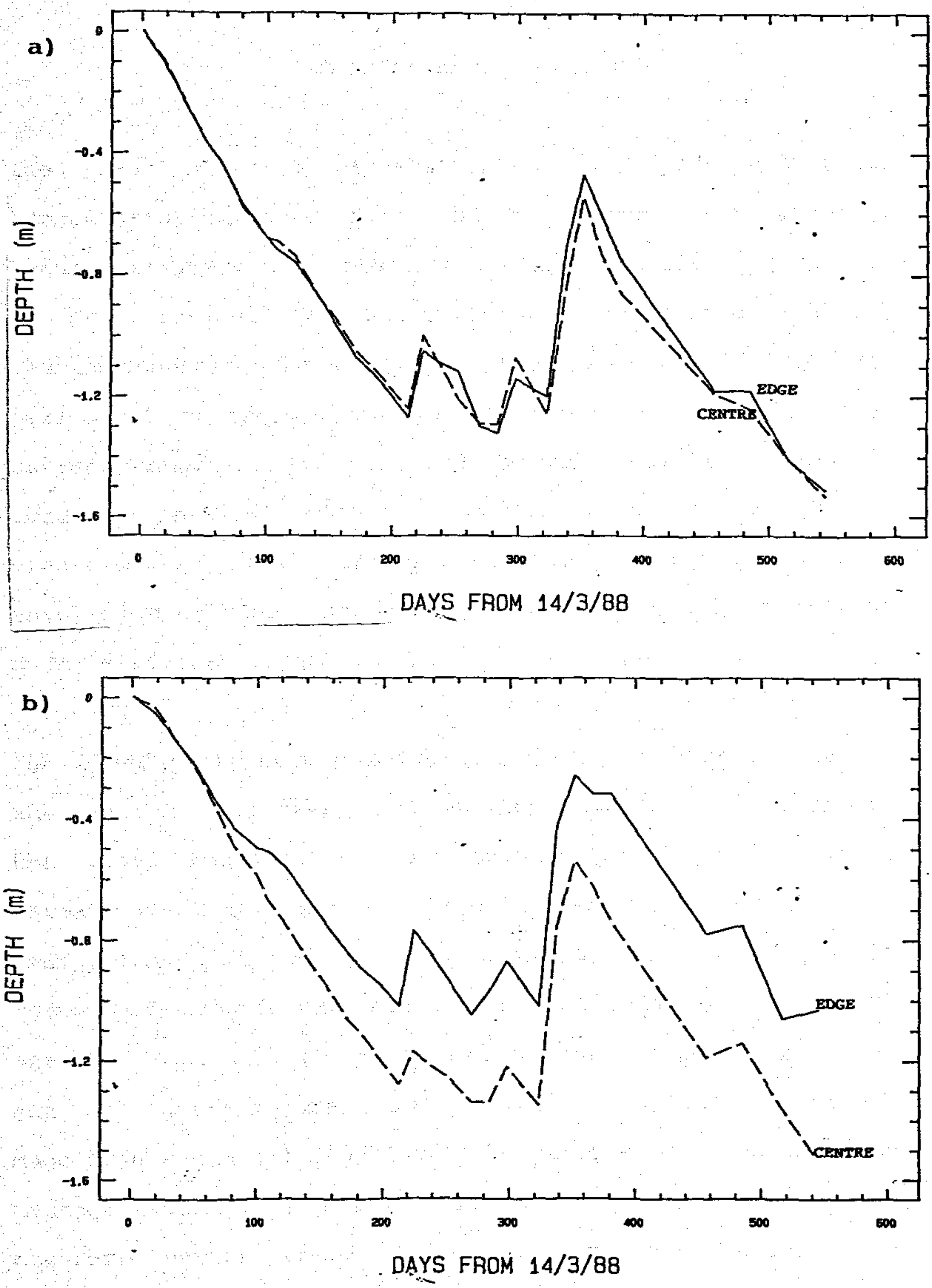

Figure 6.12 Water table hydrographs within and on the edge of (a) the young plantation and (b) the mature plantation

CHAPTER 7

DISCUSSION AND CONCLUSIONS

The principal aims of this study were to evaluate the hydrological response of the shallow groundwater body both to natural environmental fluctuations and to human induced land use modifications. This evaluation was facilitated greatly by the representativeness of the study area over the 17 year period of record, since in addition to the wet and dry extreme conditions it included, a major change in land use. occurred in 1981 with the establishment of a 1100 ha plantation of *Pinus Elliottii*. The methodology of the study involved comparing groundwater behaviour both over time and under different vegetation cover.

The close relationship between shallow subsurface water and the surface processes in this environment was evident from the rapid response of the groundwater body to climatic variation. From the distinctly seasonal water level hydrographs recorded at all locations, it appears that the volume of groundwater storage is directly related to the seasonal distribution of rainfall. Super-imposed upon this seasonal pattern are water level variations of greater magnitude which correspond well to periods of above and below average rainfall. The magnitude of the groundwater response, however, varies under different vegetation types. Thus comparisons could be made between vegetation type and groundwater response in order to determine the effects of land use change on the hydrological regime.

Rainfall volume and variability appear to be the dominant controlling influence on the geohydrological regime. as is evidenced by the similarity of measured water table hydrographs under all environments. Though intermittent extreme rainfall events are capable of redressing any imbalance caused by other factors, between these events the effects of differential consumptive use by different vegetation covers become more significant.

From an analysis of groundwater hydrographs under different types of vegetation, the effects of land use on the local hydrology could be quantified. Increased water loss under forested conditions, as reflected by faster recession rates than under grassland areas, was calculated to be equivalent to a depth of between 150 and 175 mm/year. This increase can be attributed to the higher rates of transpiration and rainfall interception associated with the trees. It appears that the areal extent of this effect is limited to the immediate vicinity of the forest. Assuming this value to be representative of all the forested areas in the eastern shores (5000 ha), the total increase in water loss that can be attributed to the trees during average climatic conditions amounts to between 7.50 and 8.75 x 10^6 m^3/year.

The mean annual inflow under unaltered conditions to Lake St Lucia was estimated by Hutchison and Pitman (1973) as 364 x 10^6 m^3. The reduction in water availability from the eastern shores thus amounts to between 2% and 2.6% of the total. The Zululand plain contains a further 20 000 ha under commercial plantations which are likely to have a response similar to that of the eastern shores. The estimated total inflow reduction from all forested areas is therefore likely to be between 37 and 43 x 10^6 m^3 (10% to 12% of the unaltered condition).

Reductions to the average inflow to the lake as a result of catchment modifications excluding forestry were estimated by Hutchison and Pitman (1973) to amount to 53 x 10^6 m^3 (14.6%). It therefore appears that the combined effects of all catchment modifications total about 80 x 10^6 m^3 or 22% of the average inflow.

Since the shallow groundwater is readily available for the consumption of trees, they are probably transpiring in average climatic periods at their maximum rate. During extreme wet periods water loss is unlikely to be significantly different thus the reduction of inflow to the lake will form a lower percentage of the total. During dry periods however, the trees are likely to continue using water at only slightly reduced rates and consequently the low inflow of 100 x 10^6 m^3 estimated for an extreme dry period by Hutchison and Pitman (1973) is likely to be reduced by some 30%.

Although they are greatest during dry climatic cycles, the effects of such a reduction are at all times significant. In the first place, the water balance of the lake is seriously affected. In the second, with a reduction in its fresh water input, the salinity balance of the lake cannot but be influenced. In the third, changes in this salinity balance will have a direct impact on the flora and fauna of the lake and its environs. It is to be hoped that the situation will improve following the proposed future removal of the plantations from the eastern shores (Lubke, 1990). However, the remaining 20 000 ha under commercial forestry on the western shores will continue to have a significant effect upon the hydrology of Lake St Lucia.

Further hydrological monitoring and analysis in this area is envisaged to clarify these findings. Specific attention will be paid to assessing the hydrological response once clear-felling commences in 1992; to defining effective rainfall; to partitioning rainfall between interception loss, unsaturated zone recharge, and groundwater recharge; and, by means of mathematical simulations, to modelling the complete water balance of the eastern shores plain under existing and proposed future land uses.

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APPENDIX A

MONTHLY RAINFALL RECORDS (1924 - 1990) FOR FANIES ISLAND (0339756), ST LUCIA ESTUARY (0339856) AND THE UZ STATION (SYNTHESISED)

The records contained for Fanies Island and St Lucia Estuary were obtained from the Computer Centre for Water Research of the University of Natal. Records prior to 1951 were artificially generated though it is not known by whom or by what means. The synthetic record for the UZ station was derived from the other two stations by means of the technique described in Chapter 4.

339756	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1924	83.6	142.2	152.7	40.4	35.7	22.4	18.8	27.6	151.4	35.3	103.5	95.9	909.5
1925	102.1	269.6	0.0	75.7	42.7	8.8	29.2	6.1	60.6	90.8	55.7	40.1	781.4
1926	28.2	33.5	109.0	33.9	21.5	11.6	21.0	2.3	42.7	51.4	69.5	64.7	489.3
1927	71.6	64.5	119.4	28.8	47.3	18.8	17.1	1.5	37.9	90.0	63.5	80.1	640.5
1928	104.6	63.7	72.6	46.0	80.8	32.1	20.2	46.7	88.9	47.9	62.5	145.0	811.0
1929	68.7	59.3	229.1	57.4	31.1	53.5	39.6	49.7	133.0	51.5	58.7	41.5	873.1
1930	399.3	73.6	284.3	69.5	18.5	28.2	33.2	44.0	5.1	23.8	107.2	40.6	1127.3
1931	34.1	47.7	82.5	48.3	17.6	21.9	62.1	2.6	9.9	33.3	114.0	107.5	581.5
1932	36.9	206.0	96.9	255.2	117.1	36.2	0.0	17.3	16.8	39.5	114.0	109.8	1045.7
1933	141.8	151.0	69.9	37.8	15.4	45.6	0.8	33.1	20.7	50.5	82.9	90.1	739.6
1934	160.0	84.7	101.4	104.1	77.0	46.3	61.5	49.1	6.2	32.6	86.2	129.4	938.5
1935	56.4	39.6	83.7	42.7	44.1	70.4	3.9	68.4	5.9	36.8	26.4	30.8	509.1
1936	166.5	119.0	161.9	83.6	92.2	76.4	44.4	27.2	64.5	87.1	280.8	36.8	1240.4
1937	283.6	194.9	135.1	121.1	20.9	72.3	43.4	52.1	40.9	34.3	75.7	272.1	1346.4
1938	71.6	79.8	94.0	38.0	24.3	35.3	155.8	73.1	10.9	65.8	15.9	190.9	855.4
1939	57.9	270.4	140.2	24.2	88.3	35.0	12.1	26.6	105.0	22.1	235.4	3.1	1020.3
1940	102.7	22.6	296.6	40.2	116.9	61.1	1.9	2.6	9.9	51.3	202.2	116.2	1024.2
1941	71.6	13.8	94.0	43.5	0.9	10.0	6.7	13.5	38.2	32.1	45.2	91.9	461.4
1942	323.8	65.7	154.9	82.6	154.2	0.0	0.0	34.2	70.4	49.3	166.6	155.9	1257.6
1943	27.0	190.2	458.3	194.3	33.0	31.0	116.4	59.6	13.8	64.8	117.3	120.3	1426.0
1944	47.2	146.8	91.5	39.6	3.5	144.9	31.2	15.7	111.4	62.5	54.2	87.5	836.0
1945	99.5	133.2	205.0	50.7	72.4	16.9	0.0	15.2	6.5	71.9	1.2	51.8	724.3
1946	250.7	79.6	182.2	48.9	14.1	5.6	0.0	8.6	32.2	38.6	38.9	76.5	775.9
1947	56.6	108.9	124.3	63.6	38.1	60.0	31.7	4.7	68.1	46.5	90.9	104.2	797.6
1948	40.2	138.7	234.4	58.5	9.1	0.0	0.0	2.9	69.2	59.5	102.0	37.8	752.3
1949	255.1	134.5	51.7	301.1	34.4	34.1	2.2	7.6	95.5	45.9	94.0	152.5	1208.6
1950	133.3	112.1	57.6	84.1	59.0	9.9	3.6	14.9	0.0	49.0	12.3	154.8	690.6
1951	55.2	37.8	59.7	154.2	22.7	17.5	10.9	117.4	43.4	106.1	4.6	75.5	705.0
1952	127.0	83.3	119.1	60.7	72.3	33.8	123.4	7.1	2.8	33.3	139.9	184.1	986.8
1953	25.3	66.2	105.3	103.4	54.6	8.6	96.5	17.4	237.5	124.0	135.9	48.6	1023.3
1954	15.2	90.6	36.5	200.7	102.8	33.6	14.0	55.9	96.5	166.7	66.8	88.1	967.4
1955	235.5	83.6	268.6	46.9	39.5	13.6	0.0	0.0	22.5	63.9	116.0	26.0	916.1
1956	0.0	138.7	140.2	46.6	36.2	37.7	0.0	41.0	61.5	87.0	25.0	195.8	809.7
1957	138.5	84.4	96.6	192.8	5.5	30.0	55.0	30.5	163.5	171.5	38.1	46.5	1052.9
1958	355.0	143.8	8.5	89.8	6.0	56.5	20.1	11.0	86.5	81.5	46.5	119.0	1024.2
1959	103.0	18.3	40.8	17.2	62.0	0.0	13.5	67.0	44.0	96.5	79.0	43.0	584.3
1960	7.6	108.0	167.0	132.0	40.5	4.4	10.5	29.5	67.0	41.2	187.2	370.1	1165.0
1961	144.7	51.8	84.9	131.0	37.8	154.0	13.5	26.7	61.0	108.0	84.0	43.0	940.4
1962	75.5	9.0	120.5	95.5	2.7	0.0	4.5	91.5	4.0	69.5	232.5	86.7	791.9
1963	64.5	126.5	96.5	36.5	12.4	117.0	310.0	7.0	0.0	145.5	44.0	178.0	1137.9
1964	199.5	60.0	35.5	193.0	37.9	8.5	12.5	14.0	10.0	162.5	42.0	41.0	816.4
1965	36.5	44.0	81.2	46.5	41.0	29.2	15.0	168.5	54.5	112.5	57.0	32.0	717.9
1966	210.5	100.5	12.0	45.0	15.5	17.5	5.0	48.0	25.0	28.5	58.0	62.9	628.4
1967	85.0	133.0	65.0	103.0	27.5	12.0	48.5	4.5	74.7	83.7	68.5	28.5	733.9
1968	34.2	111.5	67.0	41.0	31.5	40.0	14.5	59.3	39.0	66.8	88.0	40.0	632.8
1969	25.0	58.5	491.6	103.0	52.3	14.5	36.0	3.5	36.9	165.2	25.0	77.5	1089.0
1970	37.7	61.5	43.0	19.8	82.0	36.0	4.5	20.0	45.5	120.5	92.0	46.0	608.5

339756	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1971	127.5	139.5	180.2	49.9	125.5	11.0	67.0	0.7	66.1	96.5	56.1	219.6	1139.6
1972	149.3	409.0	141.6	28.0	145.5	17.5	32.3	0.5	13.0	19.6	90.0	80.0	1126.3
1973	64.0	115.0	42.5	90.0	33.5	6.0	11.1	202.0	218.5	31.5	151.5	116.0	1081.6
1974	134.0	107.5	102.0	62.6	100.5	46.5	18.0	12.5	10.5	32.5	217.5	147.5	991.6
1975	136.0	279.4	108.0	69.2	13.5	32.5	8.5	15.5	190.0	51.5	67.5	206.0	1177.6
1976	500.8	98.0	260.5	139.5	46.5	1.0	95.0	30.8	7.0	144.0	72.5	55.0	1450.6
1977	172.0	437.5	229.5	25.5	7.5	7.0	4.0	52.0	109.5	36.5	56.0	130.5	1267.5
1978	172.0	30.0	63.5	83.5	11.0	48.2	134.0	34.5	36.0	157.5	109.5	43.0	922.7
1979	43.0	5.0	31.5	70.0	79.5	17.5	9.0	37.0	59.5	32.0	40.0	79.0	503.0
1980	46.5	151.5	20.5	79.0	43.5	2.5	16.0	11.5	125.5	12.5	62.9	80.0	651.9
1981	145.0	105.5	74.5	15.0	190.5	65.0	5.5	38.5	130.5	38.0	108.0	16.0	932.0
1982	46.0	46.0	87.5	107.5	60.0	34.0	8.5	2.9	6.2	85.3	72.0	39.0	594.9
1983	80.0	44.2	43.2	42.0	35.0	28.0	107.1	85.0	12.5	63.5	211.0	120.0	871.5
1984	488.0	149.5	179.0	107.0	43.0	114.5	152.9	77.0	19.7	30.5	84.3	28.0	1473.4
1985	245.1	252.2	16.3	53.8	33.5	138.0	- - - - - - -	MISSING	DATA	- - - - - - -			
1986	35.5	72.3	61.2	66.7	2.0	43.2	0.0	11.6	34.2	62.7	44.1	111.2	544.7
1987	216.2	15.5	200.1	38.5	7.0	161.0	42.5	195.0	253.4	88.4	39.3	123.0	1379.9
1988	103.5	288.9	155.5	81.0	24.5	56.6	8.0	8.7	44.6	165.6	35.5	156.2	1128.6
1989	34.5	316.5	52.5	36.5	40.5	41.1	10.0	4.0	54.3	69.4	312.0	70.0	1041.6
1990	118.0	104.5	139.5										
MEAN	124.0	116.8	122.6	79.1	47.5	38.2	35.3	36.1	59.7	71.0	91.3	96.6	915.0
MEDIAN	92.3	94.3	96.8	62.6	37.9	30.0	14.8	26.6	41.8	55.5	74.1	80.1	891.3

339856	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1924	109.4	178.3	88.2	53.8	88.9	46.7	49.5	55.6	160.2	73.1	134.3	120.2	1158.2
1925	133.0	349.0	0.0	109.7	180.1	26.1	58.6	0.4	116.8	100.2	72.9	49.7	1196.5
1926	38.6	65.8	251.2	43.4	61.7	30.3	51.4	13.9	73.9	91.7	90.6	80.8	893.3
1927	94.1	96.7	4.5	35.3	80.5	42.4	72.1	28.5	57.4	61.4	82.9	100.2	756.0
1928	136.1	117.8	114.3	62.6	108.5	62.1	41.4	30.1	47.3	70.1	81.7	187.4	1059.4
1929	90.4	68.8	353.9	80.7	77.4	95.1	53.8	108.7	142.1	75.1	76.7	48.2	1270.9
1930	512.4	95.2	149.1	99.9	73.6	95.0	62.8	81.1	28.1	36.4	139.0	46.9	1419.5
1931	46.1	123.1	180.2	66.3	54.7	78.5	89.1	13.9	32.3	49.6	147.8	137.1	1018.7
1932	49.8	325.9	222.6	623.3	169.9	66.1	24.9	37.8	38.2	58.3	147.8	140.0	1904.6
1933	183.6	170.5	44.4	50.4	55.7	30.7	33.3	63.3	41.5	73.6	107.9	113.6	968.5
1934	207.0	220.5	90.0	159.1	77.6	155.6	88.6	89.4	29.1	48.6	112.1	166.5	1444.1
1935	74.6	53.1	115.7	58.5	131.9	119.3	36.1	120.8	28.8	54.5	35.3	33.8	862.4
1936	215.2	178.3	124.4	125.5	178.4	128.4	73.0	53.9	79.0	124.9	361.9	41.9	1684.8
1937	364.7	168.5	169.5	186.9	39.1	122.2	72.1	94.2	58.8	51.0	98.6	358.4	1784.0
1938	94.1	143.6	61.0	50.7	64.1	66.0	174.5	128.3	33.1	95.0	21.9	249.2	1181.5
1939	76.5	232.2	260.7	28.0	164.6	65.6	43.5	52.9	113.7	34.0	303.6	0.0	1375.3
1940	133.8	40.8	429.7	54.4	247.6	105.2	34.2	13.9	32.3	74.7	261.0	148.7	1576.3
1941	94.1	64.3	89.6	59.7	66.0	27.6	38.6	31.6	56.5	47.9	59.5	116.0	751.4
1942	416.0	66.5	231.5	123.8	105.3	9.4	24.9	65.2	84.1	72.0	215.3	202.1	1616.1
1943	37.1	163.4	614.8	307.0	81.3	59.6	138.6	106.4	35.6	93.6	152.0	154.2	1943.6
1944	62.9	199.9	129.7	53.3	54.1	232.3	61.0	35.2	119.2	90.4	71.0	110.0	1219.0
1945	129.6	224.8	379.5	71.5	72.6	38.2	25.7	34.4	29.4	103.6	3.0	62.0	1174.3
1946	322.8	70.3	173.0	68.6	58.3	21.0	24.9	23.6	51.4	57.1	51.3	95.3	1017.6
1947	74.9	204.9	245.9	92.8	63.6	103.6	61.4	17.4	82.1	68.1	118.1	132.6	1265.4
1948	53.9	129.8	161.5	84.3	56.8	12.3	29.1	14.3	83.1	86.2	132.3	43.2	886.8
1949	328.4	142.7	100.2	482.2	66.6	64.2	34.6	22.0	105.6	67.2	122.1	197.5	1733.3
1950	172.9	123.3	152.9	126.4	71.1	27.5	35.8	33.9	22.1	71.5	17.2	200.6	1055.2
1951	73.1	39.1	97.0	123.2	59.2	39.4	44.1	152.3	54.9	114.4	7.2	88.4	892.3
1952	125.2	54.8	40.6	81.8	69.4	74.8	148.7	17.5	27.4	59.6	251.0	288.4	1239.2
1953	34.9	62.1	109.8	39.8	67.0	19.7	66.5	37.9	109.3	73.9	111.6	57.7	790.2
1954	22.1	225.6	91.0	126.9	140.6	63.5	29.2	57.7	78.7	236.1	87.2	46.8	1205.4
1955	280.3	95.8	325.7	81.1	68.3	28.9	24.9	36.7	61.0	105.9	151.2	68.2	1328.0
1956	9.4	239.8	273.0	64.8	97.6	69.8	26.4	124.7	88.6	173.5	72.9	375.0	1615.5
1957	158.9	271.2	154.5	329.7	66.1	9.4	90.2	100.3	189.3	267.7	26.1	0.0	1663.4
1958	421.8	184.2	25.1	129.3	59.4	81.5	46.3	40.1	95.7	151.0	39.9	200.4	1474.7
1959	150.1	57.1	72.7	35.2	109.0	9.4	49.4	86.3	61.8	158.3	103.5	74.8	967.6
1960	26.8	92.6	190.7	338.3	53.6	17.8	31.5	19.5	72.5	53.8	176.2	314.9	1388.2
1961	242.3	72.6	68.7	149.2	28.1	194.1	90.4	75.5	75.0	119.0	66.7	84.7	1266.3
1962	86.5	38.7	260.9	163.1	39.2	4.0	53.5	140.1	18.2	117.2	196.8	134.0	1252.2
1963	76.6	217.4	182.7	100.0	45.5	207.1	264.0	16.4	0.5	182.3	59.2	211.7	1563.4
1964	127.0	92.3	78.9	278.3	22.5	23.3	59.5	20.8	21.9	216.0	82.5	74.5	1097.5
1965	97.1	112.5	98.6	106.3	69.8	119.5	19.6	319.5	110.3	150.0	79.5	39.8	1322.5
1966	349.5	168.5	43.0	84.4	14.5	47.5	24.2	95.4	82.5	54.8	107.2	68.5	1140.0
1967	86.0	194.4	114.0	255.6	94.2	47.0	100.0	14.0	68.5	155.3	52.7	36.5	1218.2
1968	108.3	137.4	102.3	52.1	68.0	84.0	29.0	89.2	52.0	58.5	126.8	37.2	944.8
1969	63.0	75.7	553.6	241.3	86.8	42.0	75.0	7.5	152.2	162.5	60.0	76.3	1595.9
1970	22.5	43.1	64.7	26.5	214.6	62.3	14.5	22.1	79.3	219.5	142.7	52.5	964.3

339856	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1971	187.0	195.3	240.5	61.8	357.0	72.0	129.8	3.8	119.4	127.2	138.7	216.0	1848.5
1972	200.5	503.5	116.7	131.5	222.2	34.5	74.0	24.0	7.5	45.0	96.7	74.0	1530.1
1973	98.5	179.5	82.3	172.0	94.5	0.5	26.8	322.4	188.5	38.0	245.0	115.7	1563.7
1974	137.5	257.0	227.5	110.3	177.0	84.5	38.8	100.5	52.5	49.5	289.0	133.0	1657.1
1975	219.1	213.7	116.1	148.8	38.8	70.5	47.0	95.1	103.9	66.4	92.1	329.2	1540.7
1976	570.0	145.5	414.0	158.4	184.9	18.0	124.4	91.0	26.0	214.7	36.0	76.8	2059.7
1977	174.0	285.5	410.0	16.0	35.0	24.0	57.0	104.5	161.0	45.0	60.0	196.0	1568.0
1978	226.0	14.0	230.0	105.7	63.5	100.4	206.0	43.5	44.2	248.2	115.2	0.0	1396.7
1979	89.8	60.2	51.0	58.2	221.0	36.5	67.5	58.5	93.4	79.3	23.5	153.0	991.9
1980	140.7	76.9	27.8	79.9	58.4	18.2	51.5	14.1	140.3	11.1	124.4	64.3	807.6
1981	75.9	39.0	83.5	94.8	176.1	82.4	5.5	67.0	159.3	74.5	220.8	23.7	1102.5
1982	50.5	28.6	226.5	110.0	82.8	20.7	48.0	13.3	20.0	121.2	90.5	25.3	837.4
1983	109.2	102.9	82.0	33.0	50.9	86.0	108.7	121.0	16.0	152.7	265.2	275.0	1402.6
1984	610.0	324.6	185.3	99.4	69.4	175.9	174.7	214.5	37.0	72.5	139.6	49.5	2152.4
1985	242.9	305.6	114.2	52.2	99.1	154.5	113.5	28.1	150.8	281.2	47.6	34.5	1624.2
1986	131.5	114.4	72.4	150.1	45.2	58.5	22.5	7.9	53.7	69.3	66.1	162.1	953.7
1987	135.9	87.0	238.9	109.0	17.1	131.4	35.0	196.6	359.2	143.5	86.0	145.4	1685.0
1988	77.0	246.1	164.2	110.2	33.4	114.7	14.0	18.1	37.4	216.0	48.6	295.7	1375.4
1989	62.0	307.9	26.5	54.3	84.4	92.4	65.0	10.9	100.5	97.5	234.9	115.1	1251.4
1990	177.4	138.1	122.0	137.7									
MEAN	157.1	151.0	165.9	121.8	92.9	69.0	64.1	66.3	78.1	104.7	115.7	123.5	1310.5
MEDIAN	125.2	126.6	116.7	94.8	69.8	62.1	51.4	48.2	61.8	74.7	98.6	95.3	1258.8

UZ	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1924	102.4	168.5	105.8	50.1	74.4	40.1	41.1	48.0	157.8	62.8	125.9	113.6	1090.4
1925	124.6	327.3	0.0	100.4	142.6	21.4	50.6	2.0	101.5	97.6	68.2	47.1	1083.3
1926	35.8	57.0	212.4	40.8	50.7	25.2	43.1	10.7	65.4	80.7	84.8	76.4	783.1
1927	88.0	87.9	35.8	33.5	71.4	36.0	57.1	21.1	52.1	69.2	77.6	94.7	724.5
1928	127.5	103.0	102.9	58.1	100.9	53.9	35.6	34.6	58.6	64.0	76.5	175.8	991.7
1929	84.5	66.2	319.9	74.3	64.8	83.8	49.9	92.6	139.6	68.7	71.8	46.4	1162.4
1930	481.6	89.3	186.0	91.6	58.6	76.8	54.7	71.0	21.8	33.0	130.3	45.2	1339.8
1931	42.8	102.5	153.6	61.4	44.6	63.1	81.7	10.8	26.2	45.2	138.6	129.0	899.5
1932	46.3	293.2	188.3	522.9	155.5	57.9	18.1	32.2	32.4	53.2	138.6	131.8	1670.4
1933	172.2	165.2	51.4	47.0	44.7	34.8	24.4	55.1	35.8	67.3	101.1	107.2	906.1
1934	194.2	183.5	93.1	144.1	77.4	125.8	81.2	78.4	22.9	44.2	105.0	156.4	1306.2
1935	69.6	49.4	107.0	54.2	108.0	106.0	27.3	106.5	22.6	49.7	32.9	33.0	766.0
1936	201.9	162.1	134.6	114.1	154.9	114.2	65.2	46.6	75.0	114.6	339.8	40.5	1563.6
1937	342.6	175.7	160.1	169.0	34.1	108.6	64.3	82.7	53.9	46.4	92.4	334.9	1664.7
1938	88.0	126.2	70.0	47.2	53.2	57.6	169.4	113.2	27.0	87.0	20.3	233.3	1092.6
1939	71.4	242.6	227.8	27.0	143.8	57.3	34.9	45.7	111.3	30.8	285.0	0.8	1278.5
1940	125.3	35.8	393.4	50.5	212.0	93.2	25.4	10.8	26.2	68.3	245.0	139.8	1425.7
1941	88.0	50.5	90.8	55.3	48.2	22.8	29.9	26.7	51.5	43.6	55.6	109.4	672.3
1942	390.9	66.3	210.6	112.6	118.6	6.8	18.1	56.7	80.4	65.8	202.0	189.5	1518.3
1943	34.3	170.7	572.1	276.3	68.1	51.8	132.5	93.6	29.7	85.7	142.5	145.0	1802.4
1944	58.6	185.4	119.3	49.6	40.3	208.5	52.9	29.9	117.1	82.8	66.4	103.9	1114.5
1945	121.4	199.8	331.9	65.8	72.5	32.4	18.7	29.2	23.2	95.0	2.5	59.2	1051.6
1946	303.1	72.8	175.5	63.2	46.2	16.8	18.1	19.5	46.2	52.1	47.9	90.2	951.7
1947	69.9	178.7	212.7	84.8	56.6	91.7	53.3	13.9	78.3	62.2	110.7	124.9	1137.8
1948	50.2	132.2	181.4	77.3	43.8	8.9	21.2	11.2	79.3	78.9	124.0	41.7	850.1
1949	308.4	140.5	87.0	432.8	57.8	56.0	25.8	18.1	102.8	61.4	114.4	185.2	1590.2
1950	162.1	120.2	126.9	114.9	67.8	22.7	27.0	28.7	16.1	65.4	15.9	188.1	955.8
1951	68.2	38.7	86.8	131.7	49.2	33.4	35.0	142.8	51.8	112.1	6.5	84.9	841.2
1952	125.7	62.6	62.0	76.0	70.2	63.6	141.8	14.7	20.7	52.4	220.7	260.0	1170.4
1953	32.3	63.2	108.6	57.1	63.6	16.7	74.7	32.3	144.3	87.6	118.2	55.2	853.8
1954	20.2	188.8	76.1	147.0	130.3	55.3	25.1	57.2	83.6	217.2	81.6	58.1	1140.5
1955	268.1	92.5	310.1	71.8	60.4	24.7	18.1	26.7	50.5	94.4	141.6	56.7	1215.7
1956	6.8	212.2	236.8	59.8	80.9	61.0	19.2	101.9	81.2	149.9	59.8	326.1	1395.7
1957	153.3	220.3	138.7	292.4	49.6	15.0	80.6	81.3	182.3	241.5	29.4	12.7	1496.9
1958	403.6	173.2	20.6	118.5	44.8	74.7	39.2	32.2	93.2	132.0	41.7	178.2	1351.8
1959	137.3	46.5	64.0	30.3	96.2	6.8	39.6	81.0	56.9	141.4	96.8	66.1	863.1
1960	21.6	96.8	184.2	282.0	50.0	14.1	25.8	22.2	71.0	50.4	179.2	330.0	1327.3
1961	215.7	66.9	73.1	144.2	30.7	183.2	69.4	62.2	71.2	116.0	71.4	73.3	1177.4
1962	83.5	30.6	222.6	144.7	29.2	2.9	40.1	126.8	14.3	104.2	206.5	121.1	1126.7
1963	73.3	192.6	159.2	82.7	36.5	182.5	276.5	13.8	0.4	172.3	55.1	202.5	1447.4
1964	146.8	83.5	67.1	255.0	26.7	19.3	46.7	18.9	18.7	201.4	71.5	65.4	1020.8
1965	80.6	93.8	93.9	90.0	61.9	94.9	18.3	278.3	95.1	139.8	73.4	37.7	1157.6
1966	311.6	150.0	34.5	73.7	14.8	39.3	19.0	82.5	66.8	47.6	93.8	67.0	1000.5
1967	85.7	177.7	100.6	214.0	76.0	37.5	86.0	11.4	70.2	135.8	57.0	34.3	1086.1
1968	88.1	130.3	92.7	49.1	58.0	72.0	25.0	81.0	48.5	60.8	116.2	38.0	859.7
1969	52.6	71.0	536.7	203.6	77.4	34.5	64.4	6.4	120.8	163.2	50.5	76.6	1457.7
1970	26.6	48.1	58.8	24.7	178.4	55.1	11.8	21.5	70.1	192.5	128.9	50.7	867.3

UZ	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1971	170.8	180.1	224.1	58.6	293.9	55.4	112.7	3.0	104.9	118.8	116.2	217.0	1655.2
1972	186.5	477.7	123.5	103.3	201.3	29.9	62.6	17.6	9.0	38.1	94.9	75.6	1420.0
1973	89.1	161.9	71.4	149.6	77.9	2.0	22.5	289.6	196.7	36.2	219.5	115.8	1432.2
1974	136.5	216.2	193.3	97.3	156.1	74.1	33.1	76.5	41.0	44.9	269.5	137.0	1475.6
1975	196.4	231.6	113.9	127.1	31.9	60.1	36.5	73.4	127.4	62.3	85.4	295.6	1441.7
1976	551.1	132.5	372.1	153.2	147.2	13.4	116.4	74.6	20.8	195.4	46.0	70.9	1893.6
1977	173.5	327.0	360.8	18.6	27.5	19.4	42.5	90.2	147.0	42.7	58.9	178.1	1486.0
1978	211.3	18.4	184.6	99.6	49.2	86.2	186.4	41.0	42.0	223.5	113.6	11.7	1267.4
1979	77.0	45.1	45.7	61.4	182.4	31.3	51.5	52.6	84.2	66.4	28.0	132.8	858.6
1980	115.0	97.2	25.8	79.7	54.3	13.9	41.8	13.4	136.3	11.5	107.6	68.6	765.1
1981	94.7	57.1	81.0	73.0	180.0	77.7	5.5	59.2	151.4	64.5	190.0	21.6	1056.0
1982	49.3	33.3	188.6	109.3	76.6	24.3	37.2	10.5	16.2	111.4	85.5	29.0	771.3
1983	101.2	86.9	71.4	35.5	46.6	70.2	108.3	111.2	15.0	128.4	250.4	232.7	1257.8
1984	576.7	276.8	183.6	101.5	62.2	159.2	168.8	177.0	32.3	61.0	124.5	43.6	1967.2
1985	243.5	291.0	87.5	52.6	81.2	150.0	- - - - - - - MISSING DATA - - - - - - -						
1986	105.3	102.9	69.3	127.4	33.4	54.3	16.4	8.9	48.4	67.5	60.1	148.2	842.2
1987	157.8	67.5	228.3	89.8	14.3	139.5	37.0	196.2	330.3	128.5	73.3	139.3	1601.8
1988	84.2	257.8	161.8	102.2	31.0	98.9	12.4	15.5	39.4	202.3	45.0	257.7	1308.1
1989	54.5	310.2	33.6	49.4	72.4	78.5	50.0	9.0	87.9	89.8	255.9	102.8	1194.2
1990	161.2	128.9	126.8										
MEAN	148.1	141.7	154.1	109.9	80.5	60.6	55.7	58.5	72.2	93.6	119.8	117.2	1199.1
MEDIAN	115.0	130.3	126.8	84.8	63.6	55.3	41.1	45.7	65.4	78.9	94.9	103.9	1170.4

APPENDIX B

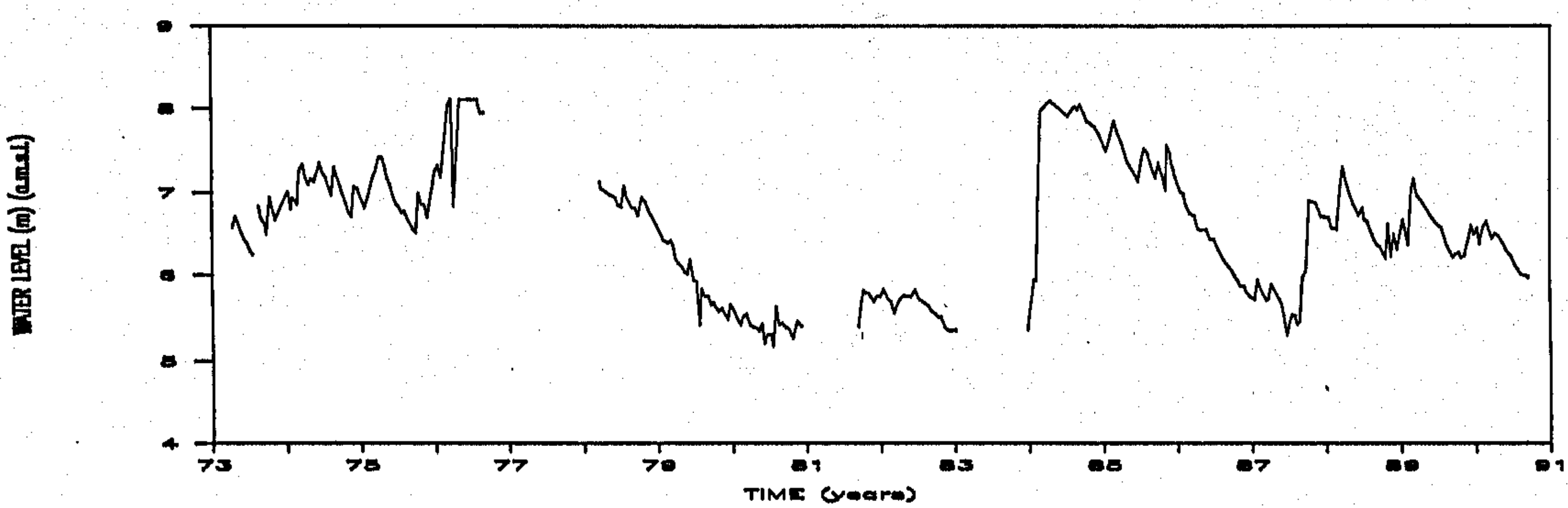
COMPLETE WATER LEVEL HYDROGRAPHS FOR BOREHOLES IN THE STUDY AREA (1973 - 1990)

These hydrographs were constructed from data contained in the original (hand written) monthly returns from the observer(s) responsible for collecting the data. All water levels are in metres and refer to the elevation of the water surface above estuary mean sea level. Levels for 'old' (1973) boreholes were derived from surveying conducted following their installation, and levels for 'new' (1987/88) boreholes were derived from surveying in 1990. The absence of records from some 'new' boreholes indicates that these have not yet been surveyed.

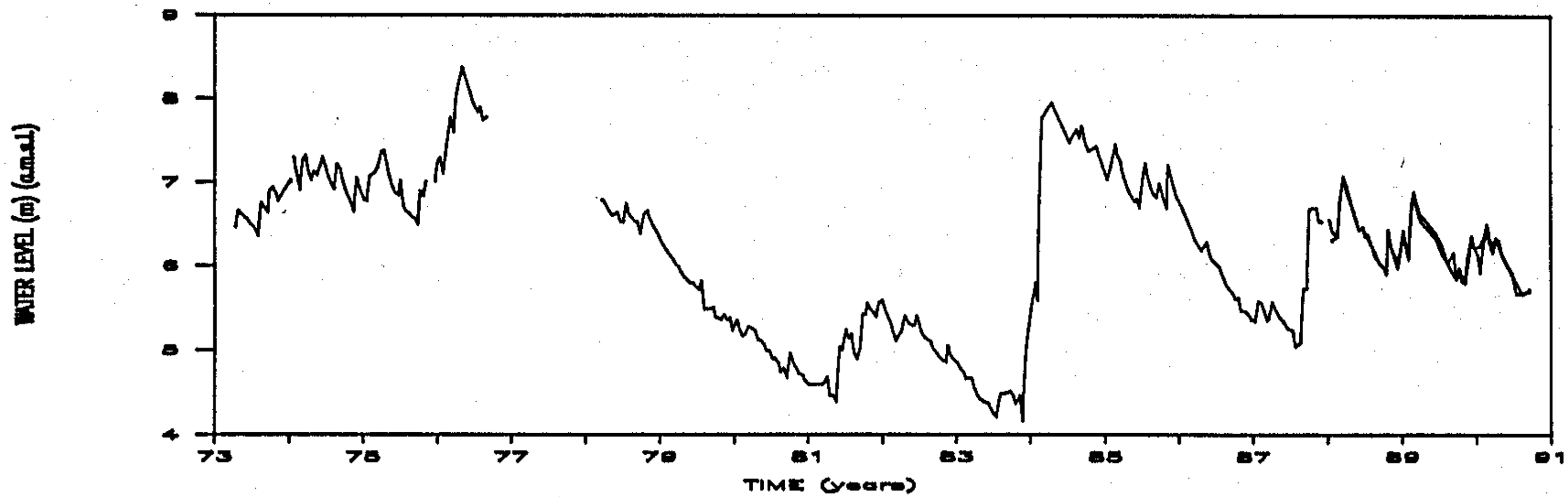
Where detected, errors in data collection (as reflected by an 'unreasonable' rise or fall in water level over a short time period) have been removed from the record. Slug tests in January 1984, October 1985 and September 1987 remain in the hydrographs as rapid, usually short duration, peaks. Significant gaps in the hydrographs correspond to periods when data collection was suspended, this suspension was either during periods when data collection ceased, or when the water level dropped below the maximum borehole depth.

For the period since 1987, two hydrographs are displayed, one refers to the 'old' borehole and the other to the adjacent 'new' borehole. Where it is not evident which is which and where the boreholes show different hydrographs, the new borehole hydrograph is indicated by the letter 'N'.

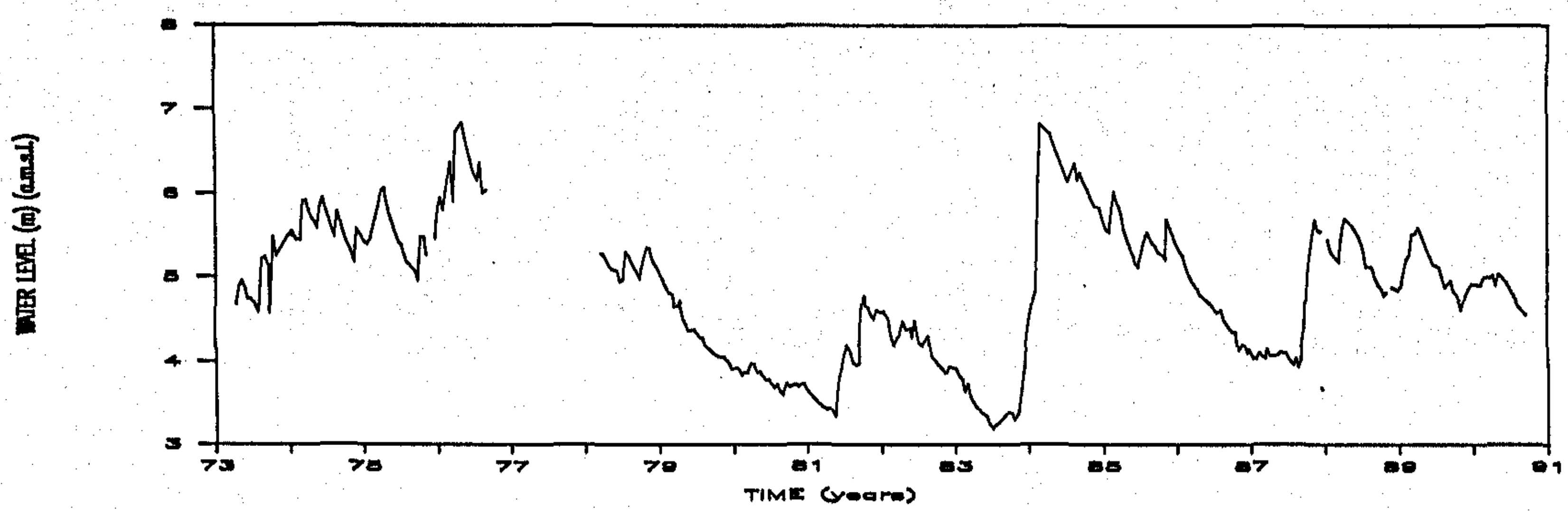
BOREHOLE A2



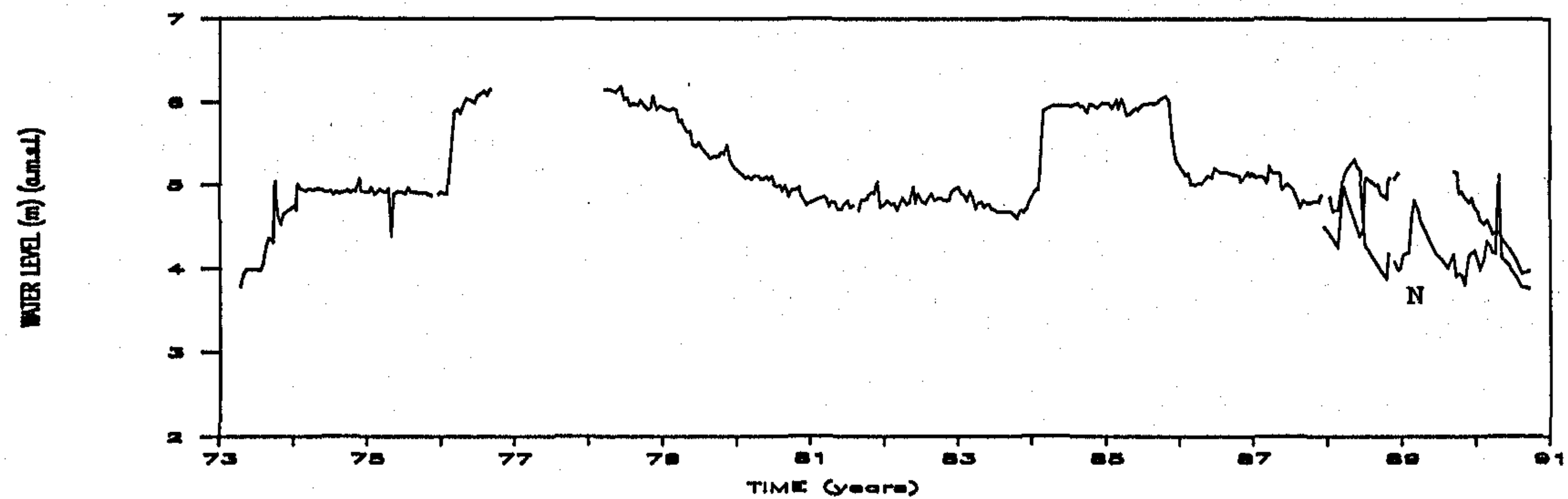
BOREHOLE A3

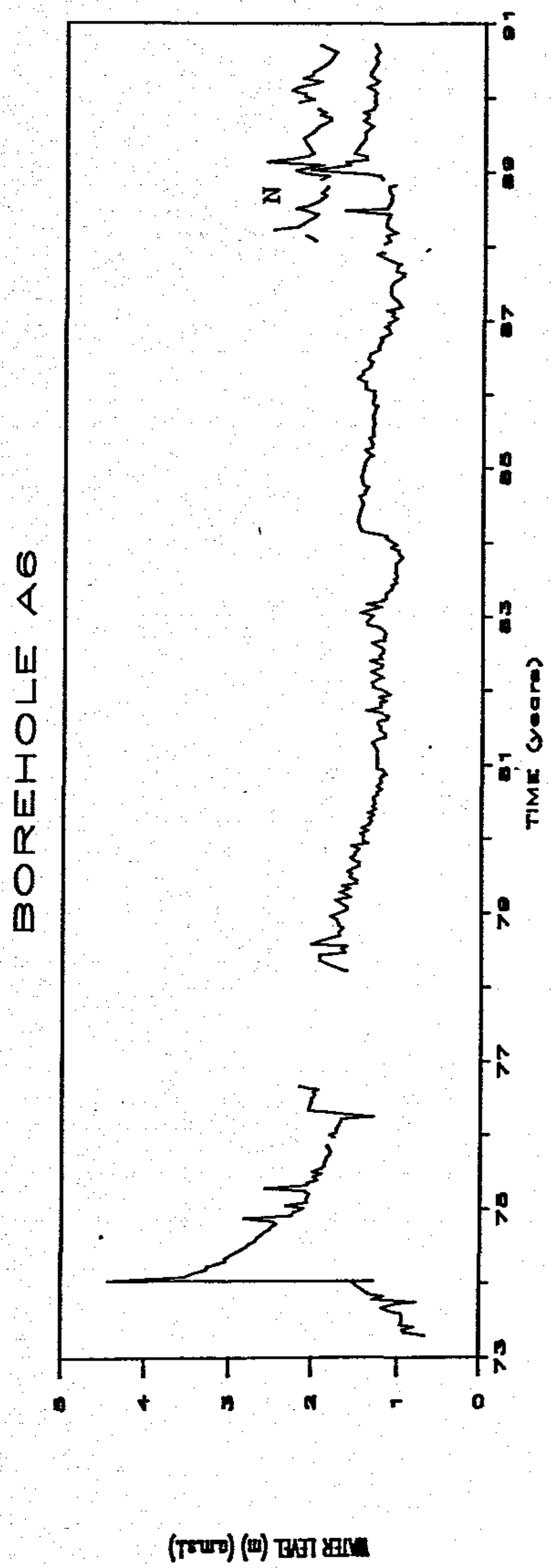


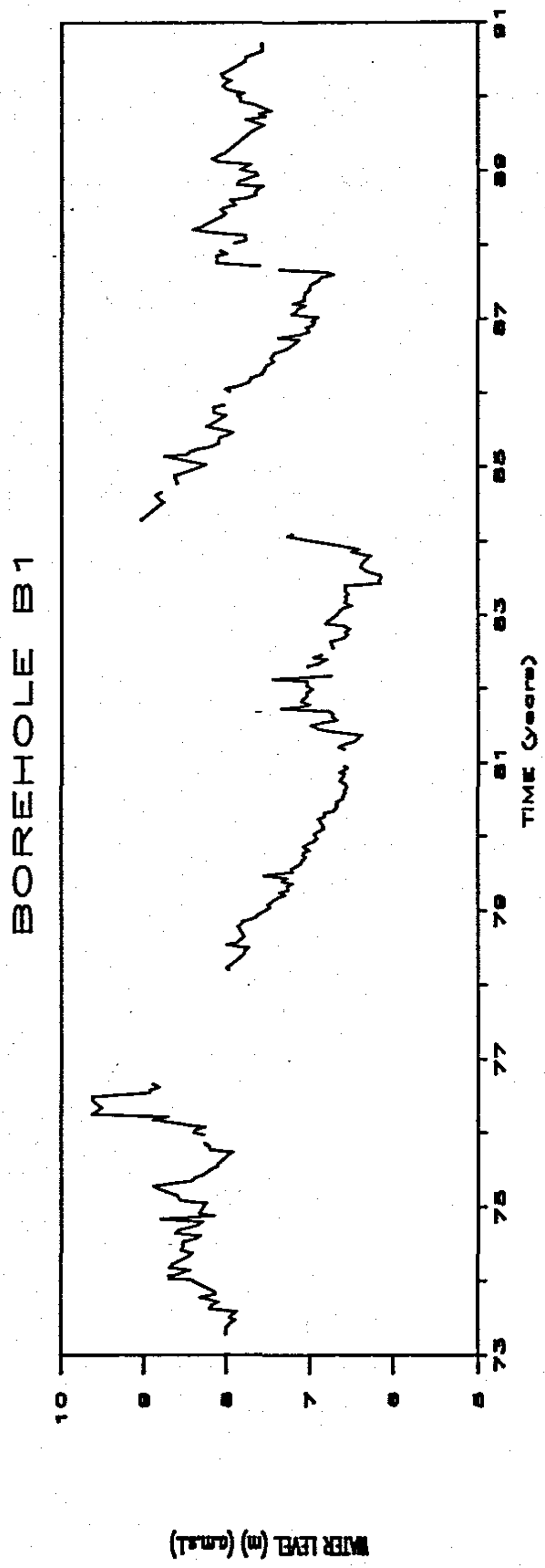
BOREHOLE A4



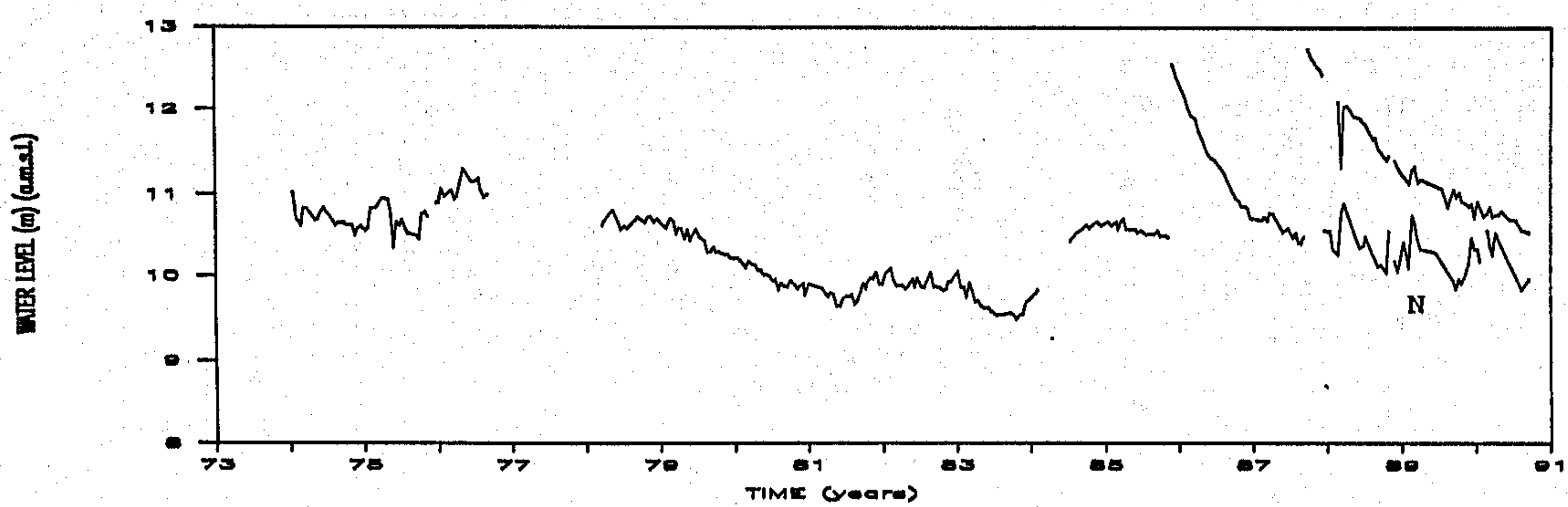
BOREHOLE A5



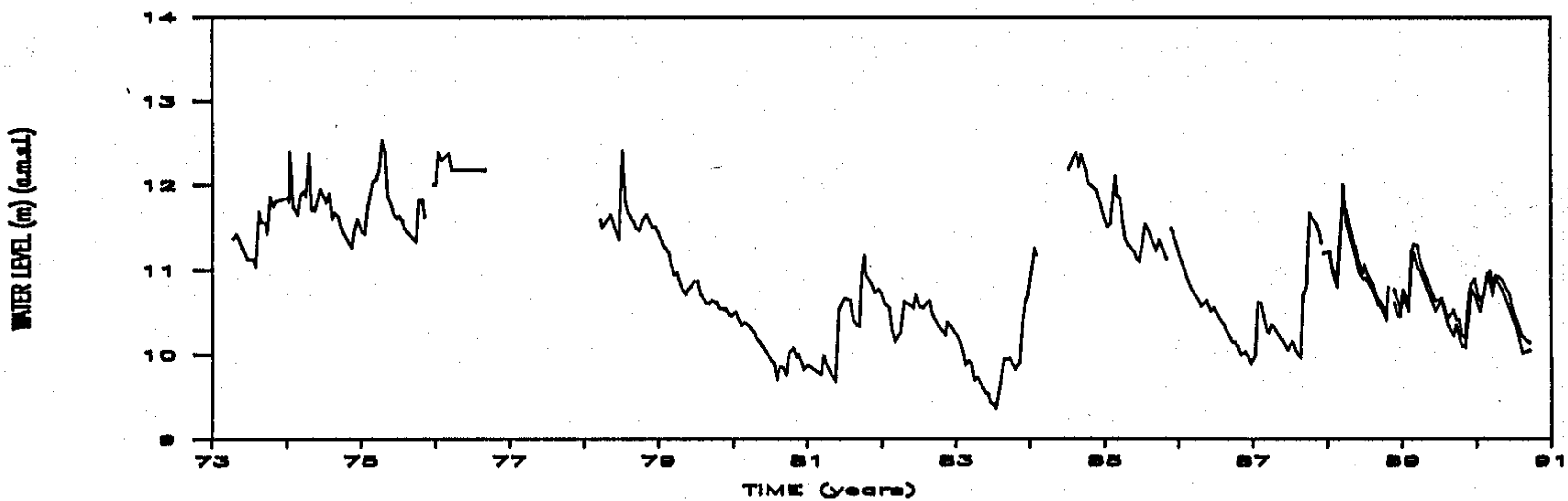

BOREHOLE A6
TIME (years)
WATER LEVEL (m) (a.m.s.l.)
N
73
75
77
79
81
83
85
87
89
91
0
1
2
3
4
5

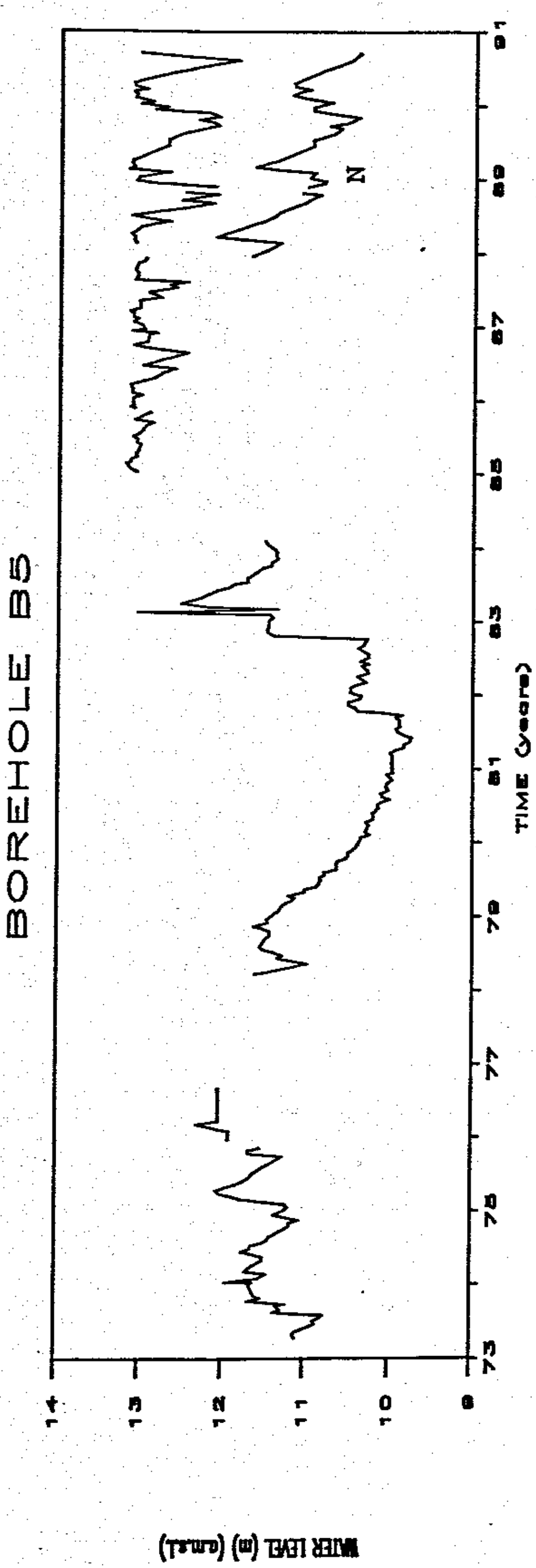

BOREHOLE B1
TIME (years)
WATER LEVEL (m) (a.m.s.l.)
73
75
77
79
81
83
85
87
89
91
5
6
7
8
9
10

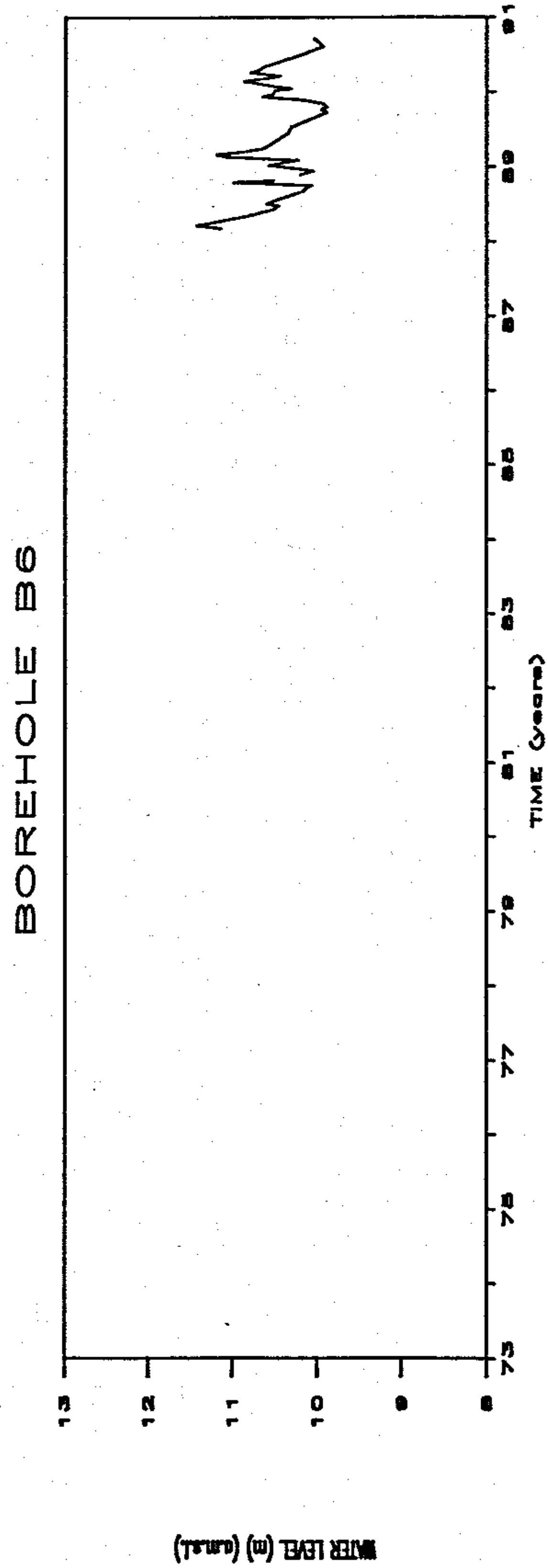
BOREHOLE B3

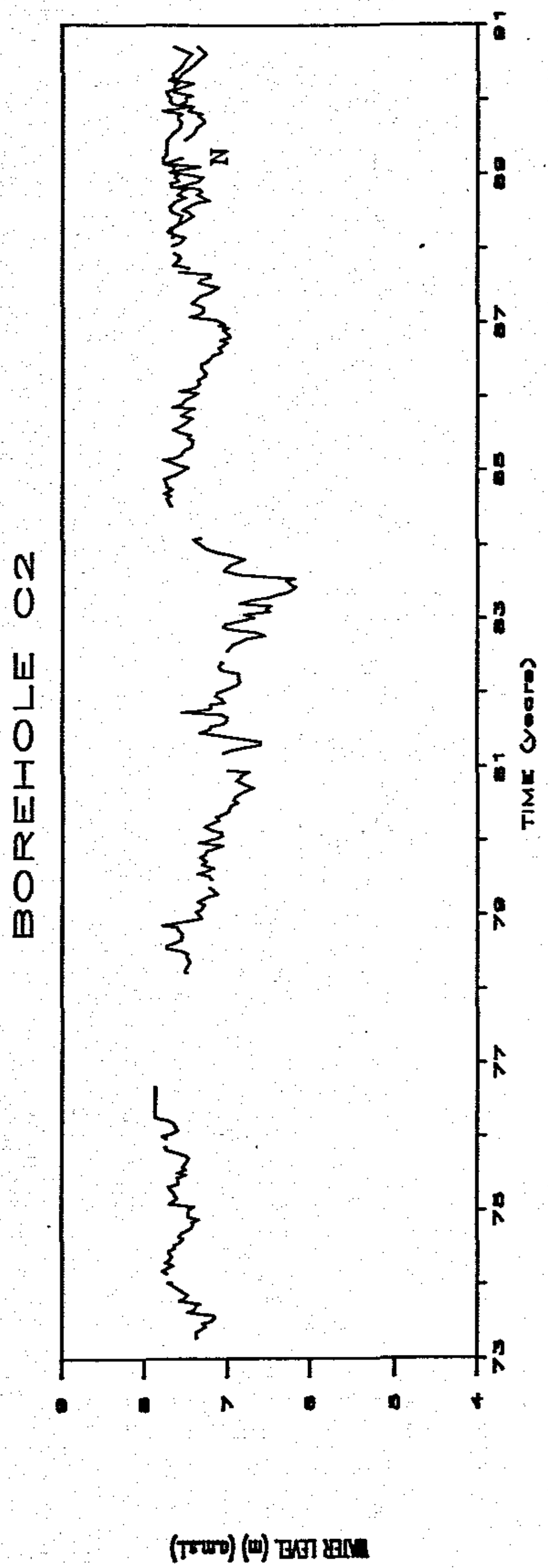


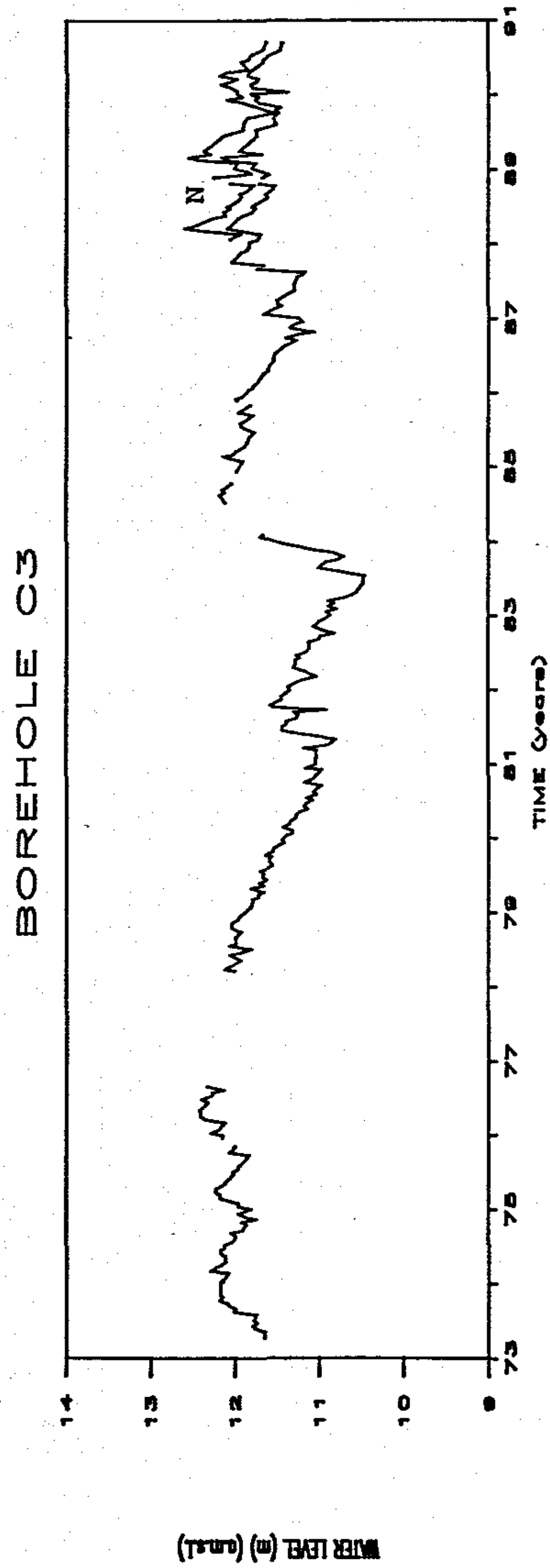
BOREHOLE B4



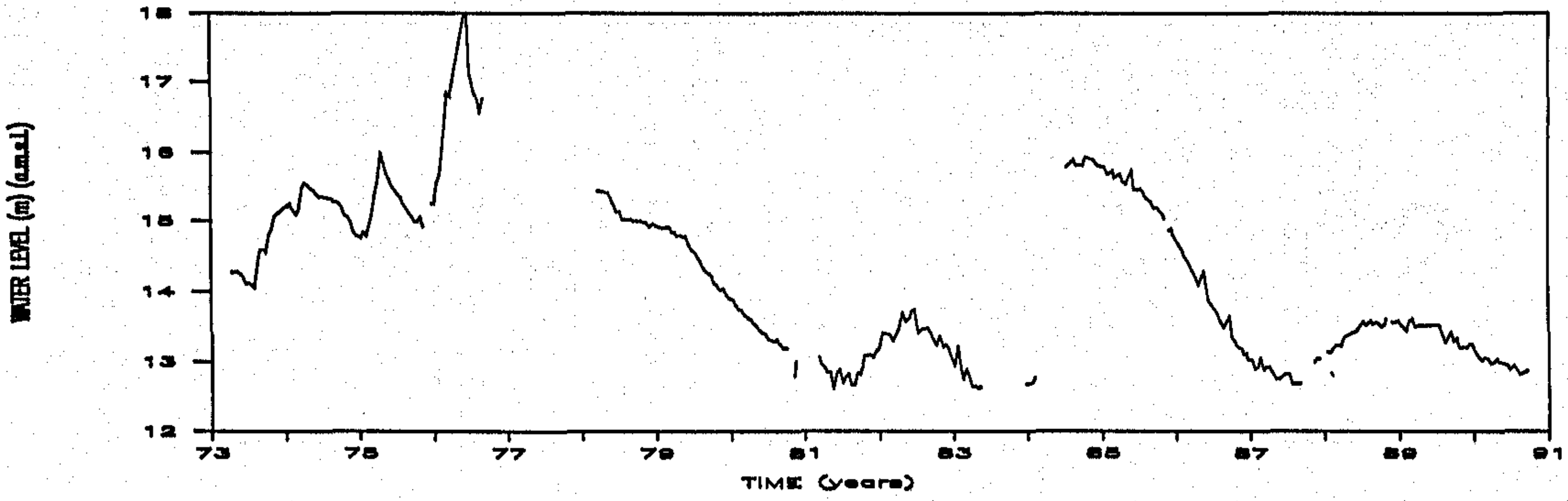

BOREHOLE B5
TIME (years)
WATER LEVEL (m) (a.m.s.l)
N


BOREHOLE B6
TIME (years)
WATER LEVEL (m) (a.m.s.l)

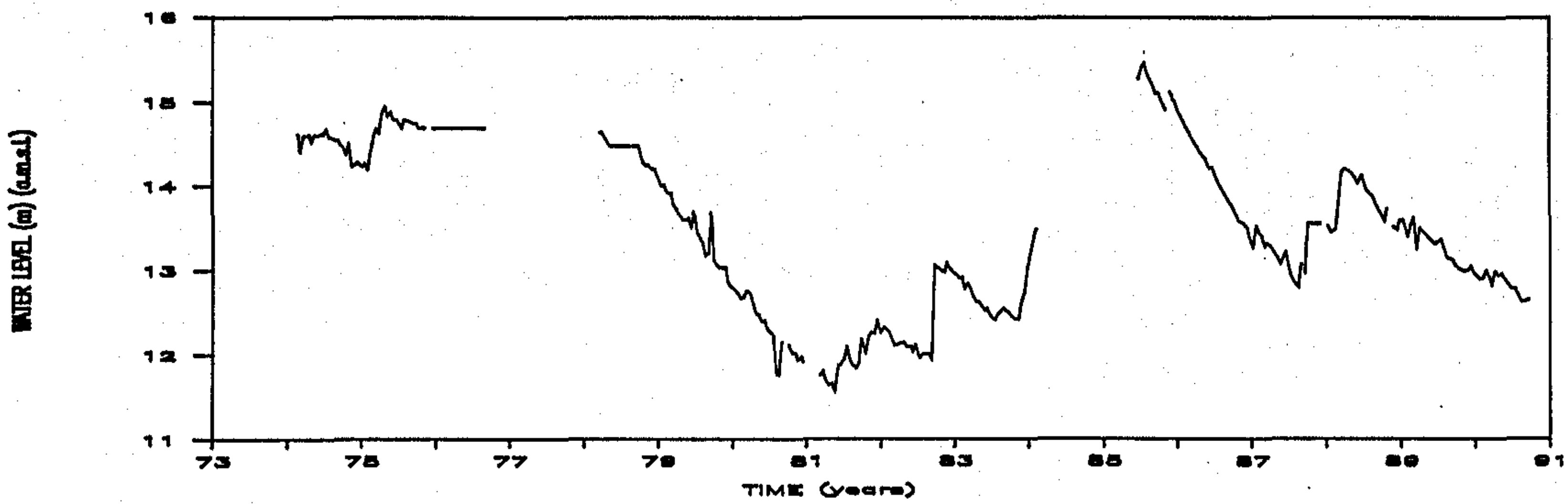

BOREHOLE C2
N
TIME (years)
73
75
77
79
81
83
85
87
89
91
WATER LEVEL (m) (a.m.s.l)
9
8
7
6
5
4

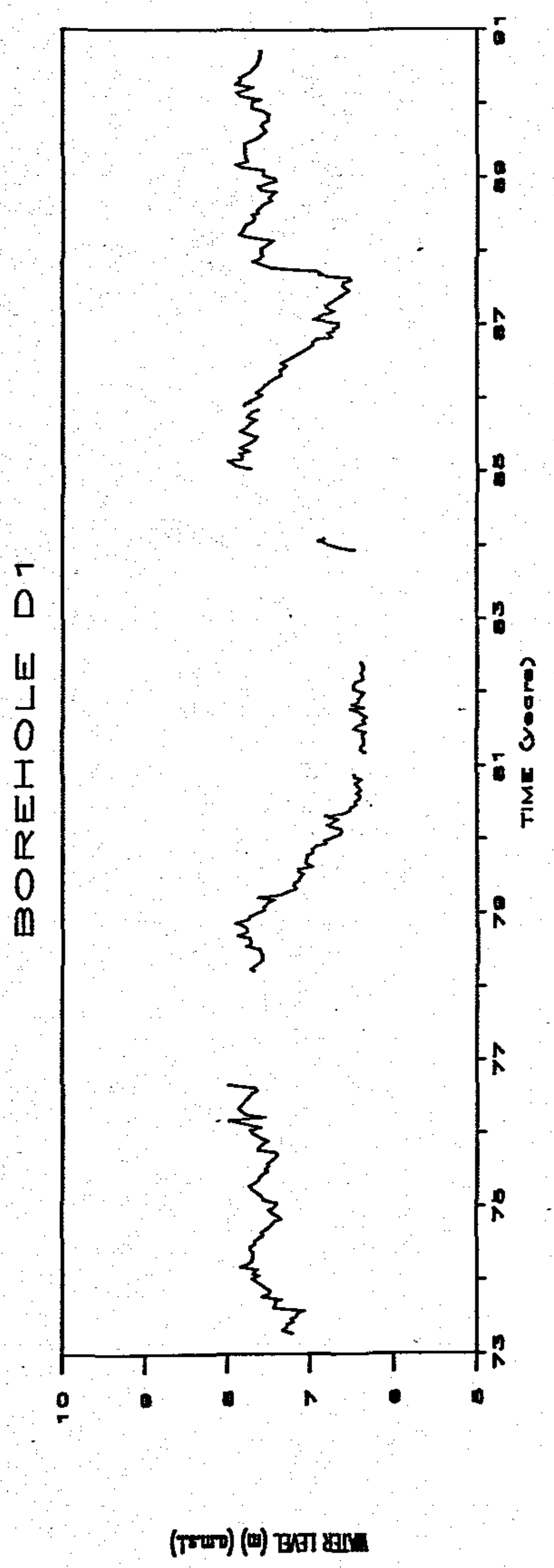

BOREHOLE C3
N
TIME (years)
73
75
77
79
81
83
85
87
89
91
WATER LEVEL (m) (a.m.s.l)
14
13
12
11
10
9

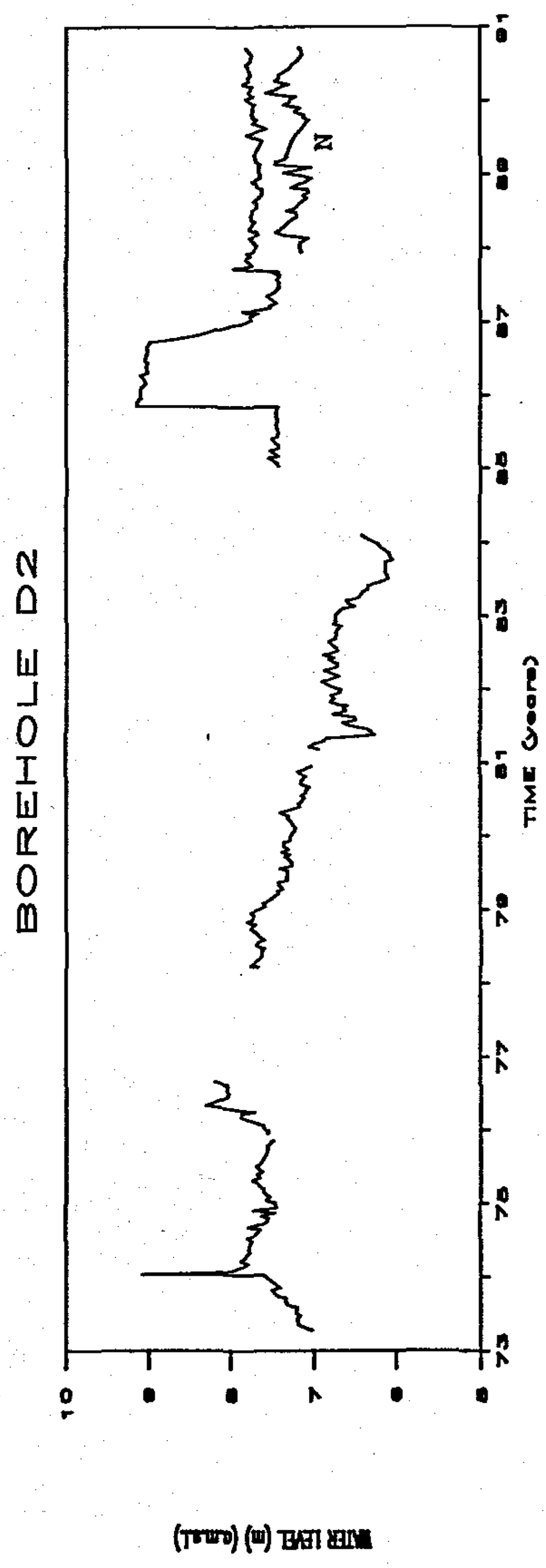
BOREHOLE C4

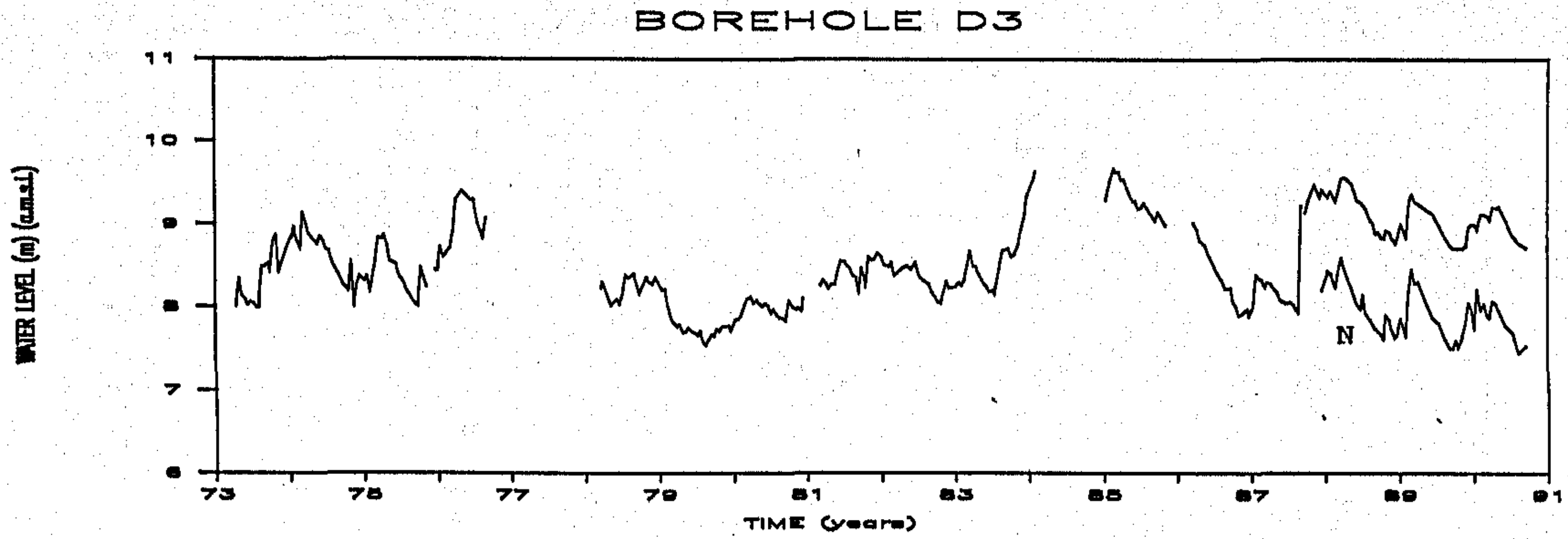


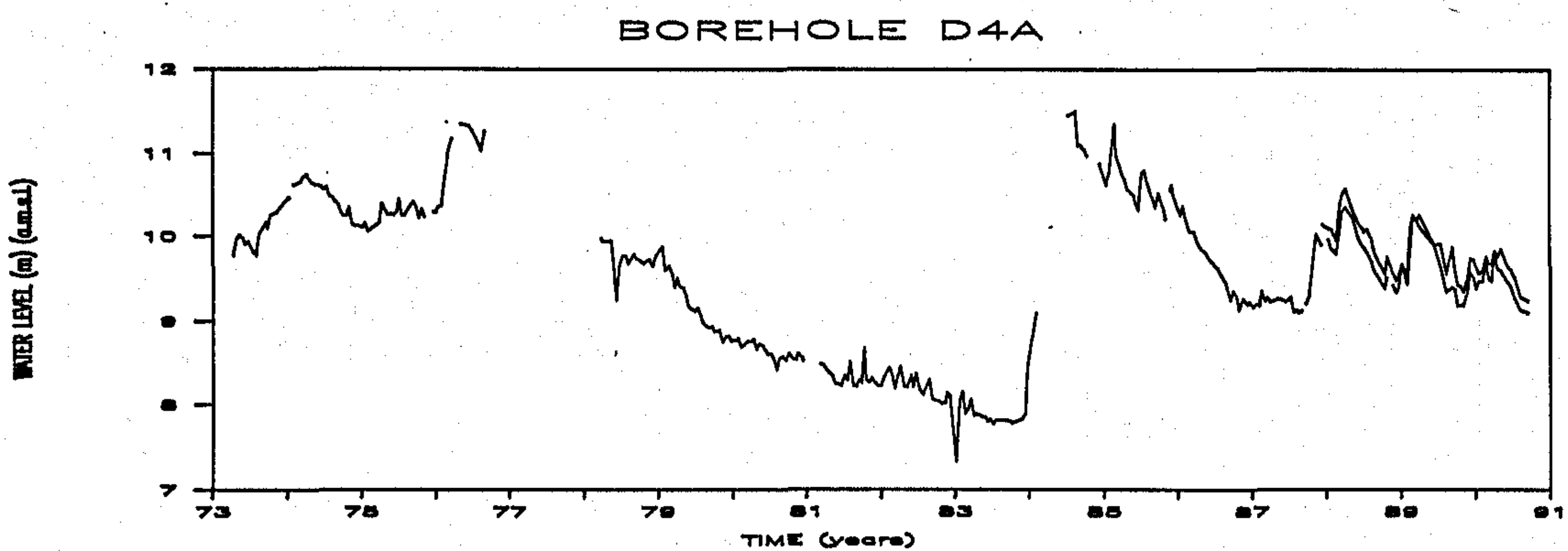
BOREHOLE C5



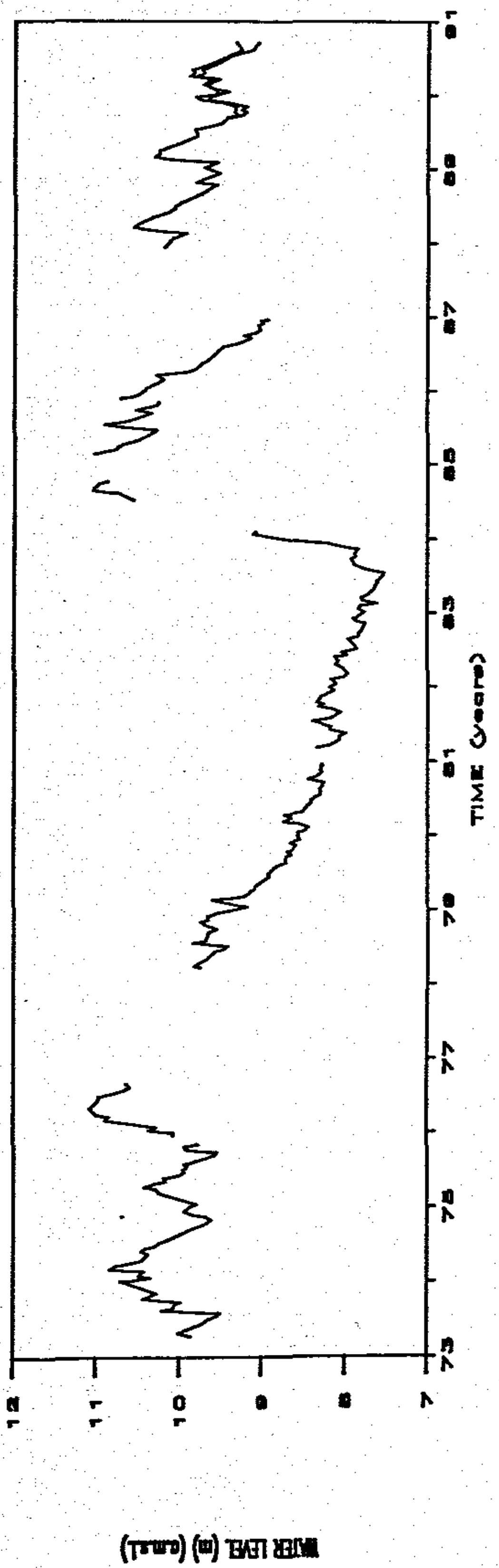

BOREHOLE D1
TIME (years)
WATER LEVEL (m) (a.m.s.l)


BOREHOLE D2
TIME (years)
WATER LEVEL (m) (a.m.s.l)

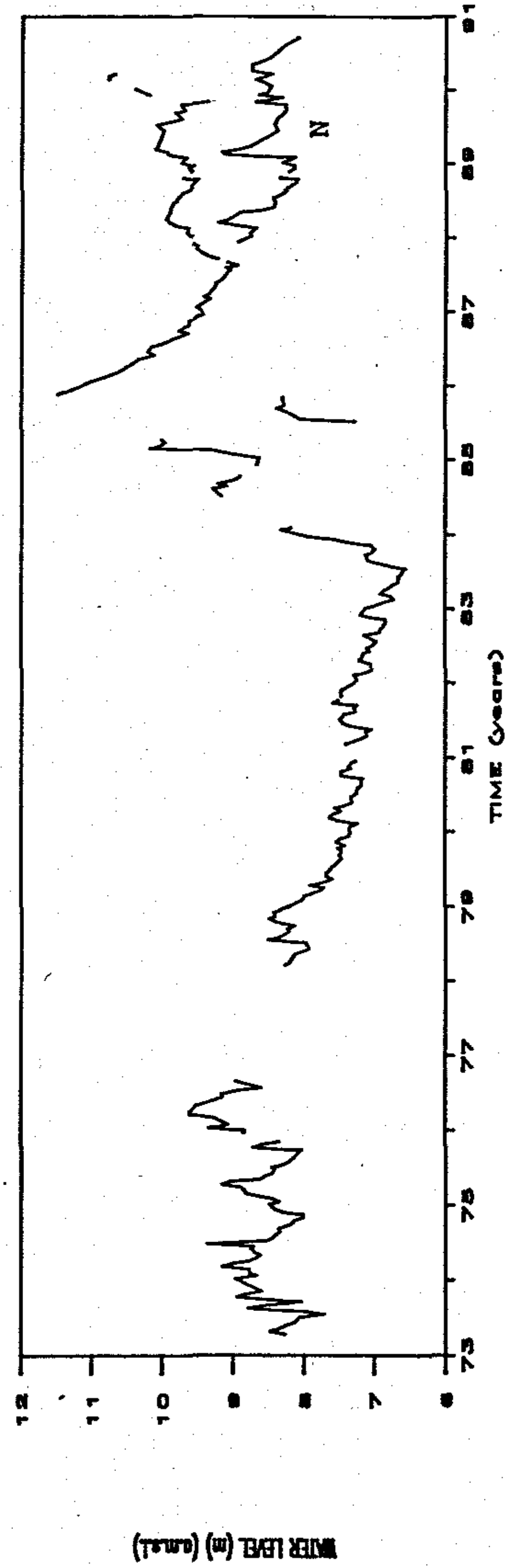

BOREHOLE D3
WATER LEVEL (m) (a.m.s.l.)
11
10
9
8
7
6
73
75
77
79
81
83
85
87
89
91
TIME (years)
N

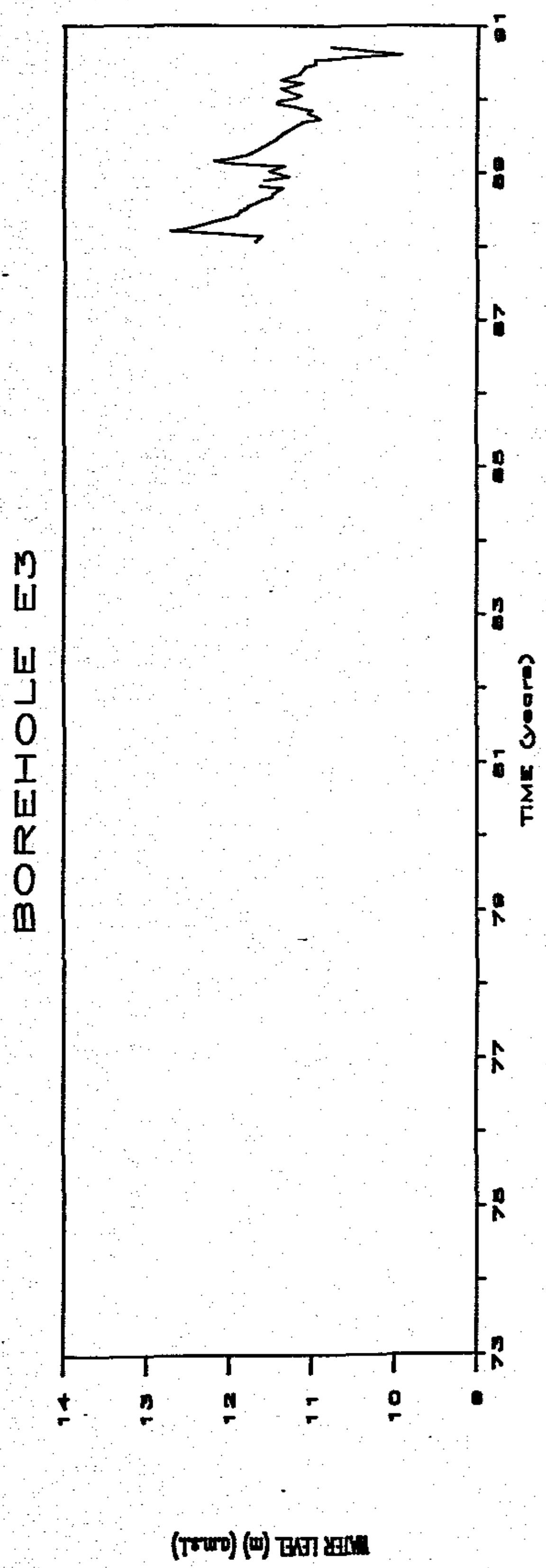

BOREHOLE D4A
WATER LEVEL (m) (a.m.s.l.)
12
11
10
9
8
7
73
75
77
79
81
83
85
87
89
91
TIME (years)

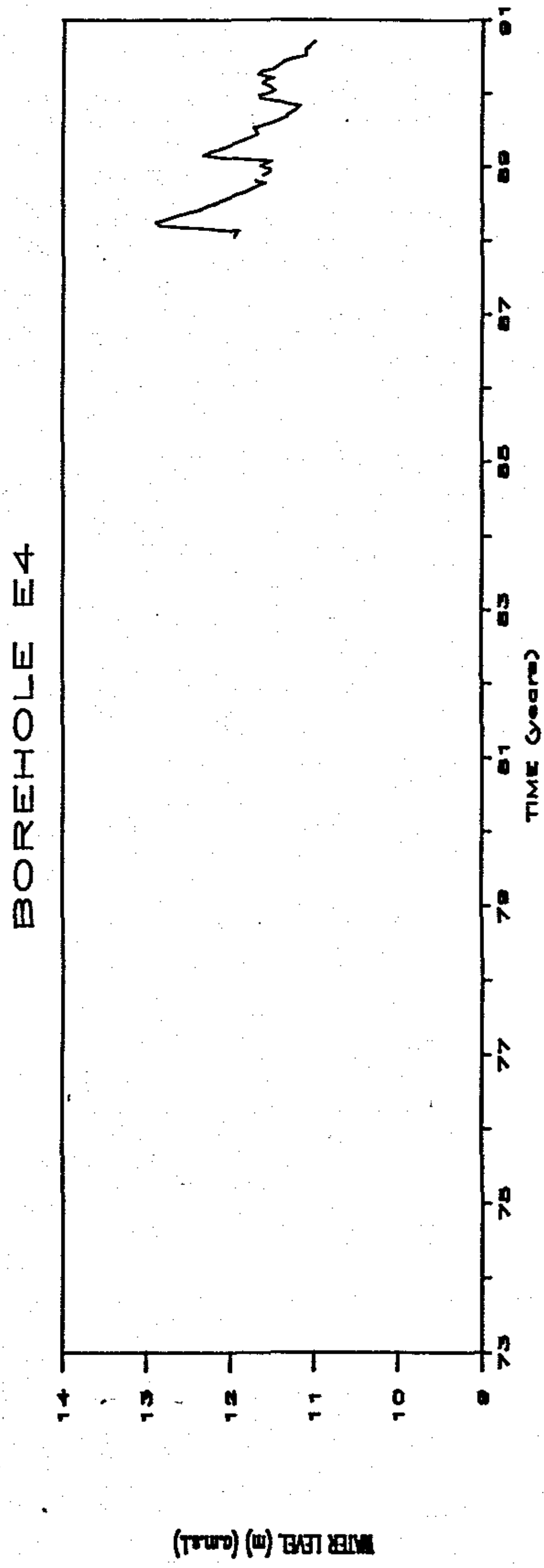
BOREHOLE D4B

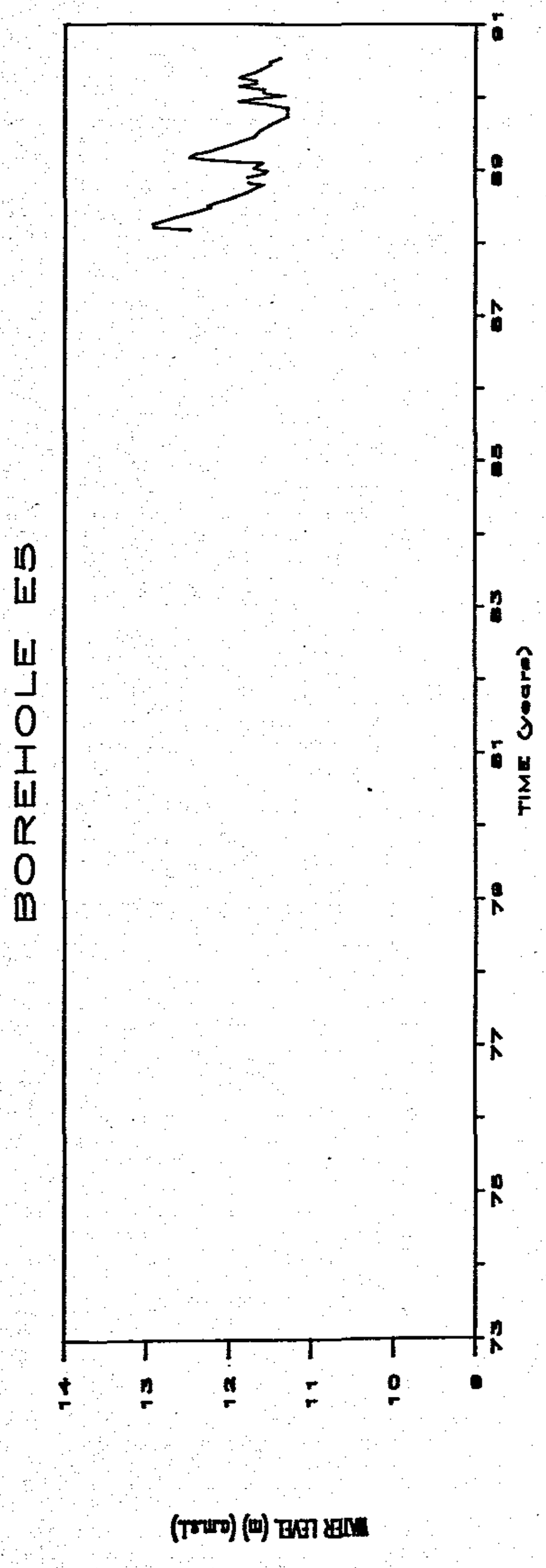


BOREHOLE D5




BOREHOLE E3
TIME (years)
WATER LEVEL (m) (a.m.s.l)
73
75
77
79
81
83
85
87
89
91
9
10
11
12
13
14


BOREHOLE E4
TIME (years)
WATER LEVEL (m) (a.m.s.l)
73
75
77
79
81
83
85
87
89
91
9
10
11
12
13
14


BOREHOLE E5
14
13
12
11
10
9
WATER LEVEL (m) (amsl)
73
75
77
79
81
83
85
87
89
91
TIME (years)