# Catchment Water Balance

J. J. Lambourne, T. J. Coleman
and D. Stephenson

WRC Report No.183/9/93

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by

J.J. LAMBOURNE, T.J. COLEMAN, AND D. STEPHENSON

Water Systems Research Group
University of the Witwatersrand
Johannesburg, 2000, South Africa

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WATER RESEARCH COMMISSION

# EFFECTS OF URBANIZATION ON CATCHMENT WATER BALANCE

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ABSTRACT

The catchments in Sandton, Transvaal were monitored using equipment to measure various hydrological and meteorological parameters. These parameters comprised rainfall depth, runoff stage, borehole levels, water consumption, wind speed, atmosphere pressure, humidity, wind directions, temperature and sewage flow. Whilst the catchments are adjacent, one is urbanised and the other is a form or undeveloped catchment.

The results of data collection from the two catchments covering the period 1986-1991 are presented in the form of monthly average or accumulations. The interaction of the individual parameters is discussed in detail with a view to assessing the mechanisms within each catchment.

Periods of missing data, most notably the runoff data are patched using a simulation model. A simple Total Evaporation calculation was issued but found to be inadequate. A coarse-level water balance is presented and inaccuracies in the data examined. It was found that suburban development increased surface runoff by a factor of 5 or more over an otherwise similar undeveloped catchment. The frequency of flood runoff from the developed catchment was increased as a result of rapid concentration of flow. The Total Evaporation loss constituted 67% of precipitation for both catchments, garden watering appearing to compensate for the increased runoff from the urban catchment.

Areas that need special research to enable a more finely tuned water balance to be produced are outlined.

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## CHAPTER 1 : INTRODUCTION

One of the objectives of the project on the effect of urbanisation on the catchment water balance, was to compare the catchment water balance between an urbanised and a rural catchment. To this end, two catchments were used in the study, one which is a virgin rural catchment (sited at Waterval farm) and the other one is urbanised (sited at Sunninghill Park). Both these catchments are described in detail in a report by Lambourne and Coleman entitled 'Descriptions of two adjacent research catchments". A discussion of the effects of urbanisation on runoff in catchments is given in a report by Stephenson entitled 'An Analysis of the effects of Urbanisation on Runoff'. Both these reports form part of this series (Nos. 2 & 1 respectively).

Ideally, a paired catchment experimental approach should be used, where the two catchments are gauged prior to urbanisation occurring on one of them. However, from a practical point of view, this was not possible in this instance, as the time scale would have possibly involved decades (always assuming that one of the catchments was likely to be zoned for residential development). To overcome this problem, two catchments were chosen, of which one was already urbanised to a great degree. These sites are situated on the granitic dome that is situated between Pretoria and Johannesburg. The catchments are similar in size, measuring approximately 75ha, and are adjacent to each other and have similar topography and geological conditions.

Catchment water balances are perhaps the goal of the hydrologist's task in water management. Dooge, (1987) defined this task as the seeking of better solutions to the water balance problem. In simple terms the water balance for an urban catchment may be expressed (assuming a unit surface area that extends from the roof level to a depth in the ground through which there is not a net exchange of water) as a depth or column of water.

This can be expressed (for urban catchments) as an equation of the form :

$$P+D-R-E-O=\frac{\Delta S}{\Delta T}$$

where P is the precipitation, D is the piped water supply, R is the total runoff, E is the total evaporation, O is the sewer outflow from the domestic and industrial properties and delta S/delta T is the water storage change in the soil column. The runoff can further be subdivided into storm runoff and baseflow.

Urban catchment water balances differ from those of rural or undeveloped catchments in that in addition to the rainfall-runoff system, there is usually a water supply retriculation system and organised water disposal (e.g.

gutters, sewers and servitudes). This additional system is composed of two sub-systems. The first being a 'closed' system which consists of water piped in and out of buildings (for drinking and water borne sanitary, industrial and cooling purposes). The second being an 'open' system which consists of piped water used for irrigation and/or swimming pools. Leakage of piped water supply would be categorised in this latter system. The interactions of the different components of the water balance are presented in Figure 1.1.

Information on urban catchment water balance investigations are rather sparse in the literature. A recent study by Grimmond *et al* (1986) developed a daily water balance model which was can be used to calculate the daily, monthly and yearly water balance components. They described the application of the model using a suburban district of Vancouver, Canada, comprising an area of 21ha.

Table 1 shows the list of studies and the annual water balance percentages related to each component of the Water Balance. This table will be compared with results from this study.

Table 1 - List of Annual Water Balance Studies in Urban Areas

| Author | Place | Area ($km^2$) | P % | I % | W % | E % | r % | w % |
|---|---|---|---|---|---|---|---|---|
| Lindh (1978) | Sweden | 4024 | 75 | 25 | - | 38 | 62 | 0 |
| Campbell (1982) | Mexico City | ? | 86 | 14 | - | 71 | 29 | 0 |
| Aston (1977) | Hong Kong | 1046 | 58 | 40 | 2 | 34 | 66 | 0 |
| Bell (1972) | Sydney | 1035 | 77 | 22 | 1 | 49 | 51 | 0 |
| L'vovich & Chernogayeva (1977) | Moscow | 879 | 100 | - | - | 57 | 43 | 0 |
| Grimmond & Oke (1986) | Vancouver | 0,21 | 68 | 32 | - | 32 | 68 | 0 |

R: Rainfall I: Water Supply
W: Groundwater Storage

E: Total Evaporation r: Runoff
w: Groundwater Storage Increment

After Grimmond and Oke (1986)

Obviously a direct comparison of the results from these studies (Table 1) is not straight forward. The reasons for this are varied and include geographic differences between the locations (e.g. climate, physiography, botany, soils, and differing patterns of urban development, social customs and type of industrial development) and techniques used to estimate or measure the components of the water balance. The piped water supply percentage also differs from 14 to 20 percent, which can be related to the division of water between industrial and domestic users and, in older reticulation networks, leakage from pipes.

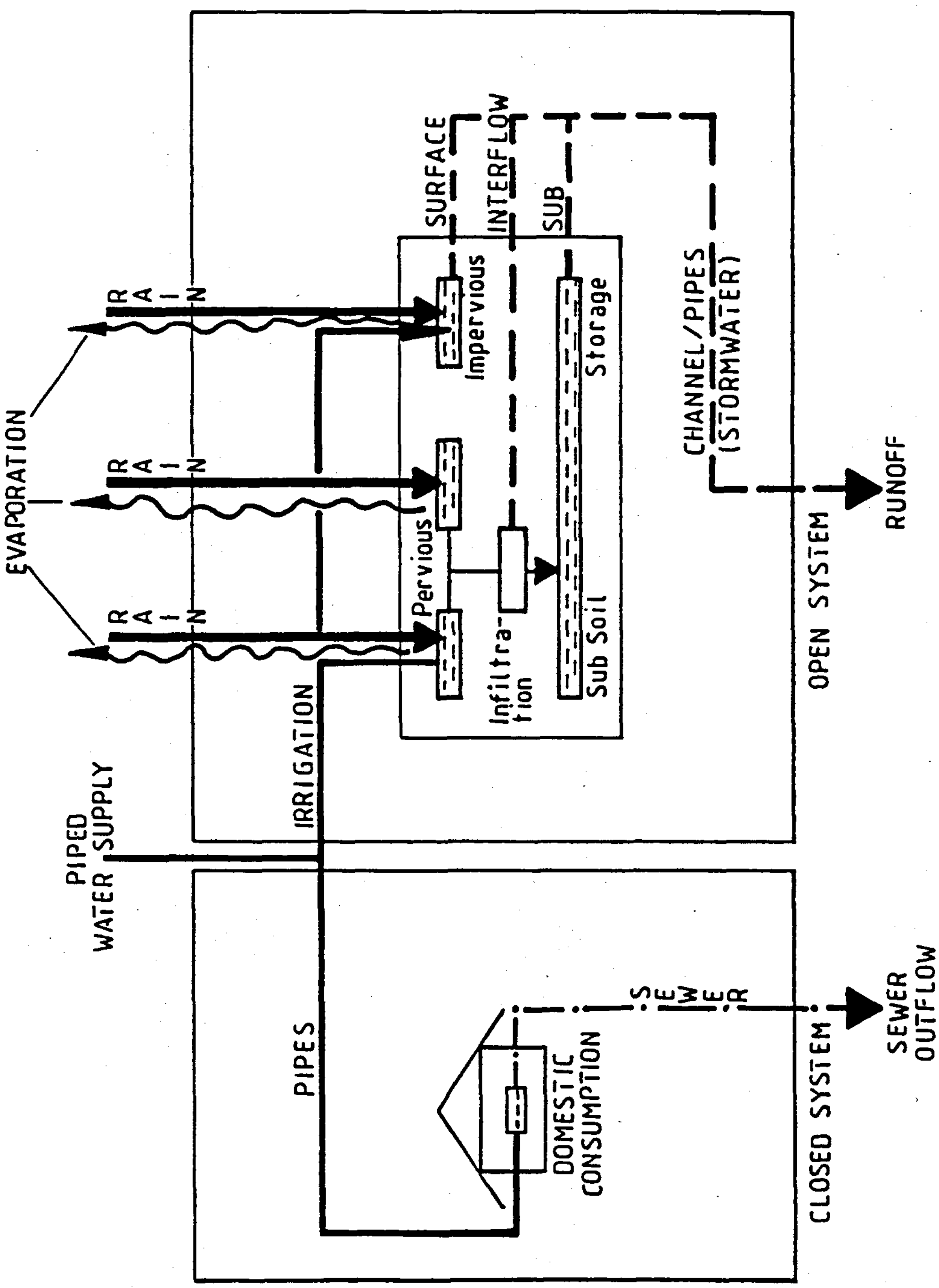



Figure 1.1 - Urban Catchment Water Balance Components

Whilst the groundwater storage component was neglible (owing to the slow response time of natural groundwater), the total evaporation component approached nearly 60% for a mid to high latitude site.

In most applications of water balance calculations in an urban environment, most of the components are estimated or modelled, except perhaps in the case of precipitation which can in all cases be easily measured.

In the following chapters of this report, the measurements and estimation methods that are applied for each component of the water balance are discussed, together with results of time series variation and comparisons over the period 1987 to 1991.

## CHAPTER 2 : PARAMETERS USED IN WATER BALANCE

### 2.1 Sites and Instrumentation

The urban catchment comprises part of Sunninghill Park, Sandton with a surface area of approximately 75ha. The catchment slopes from east to west with a fall of 50m over a distance of about one kilometre. This catchment has a well defined watercourse flowing through a park area in the centre of the catchment.

The extension has been zoned for residential development with provision for 136 erven. Of the 136 erven, eleven were earmarked for commercial and townhouse complex development. The size of erven for residential usage are of the order of $1500m^2$. The estimated impervious area on each of the developed housing is 25%, but this is mostly unconnected drainage, so the effective impervious area is significantly less.

There is an office block, shopping centre and a garage with associated parking facilities. These commercial areas have greater areas of paving then the housing developments with an estimated 75 to 90% impervious area. The road network is tarred and a piped stormwater and water supply network exists. Most of the residential areas are walled so the surface runoff is concentrated along driveways or at low points. At the head of the catchment is situated in the office complex of ESCOM (Electricity Supply Commission).

Runoff during dry periods occurs as a result of seepage from soil and groundwater systems at an impermeable barrier at the bottom end of the catchment. Sewerage is transported through a separate system of pipes and forms a closed system.

A catchment adjacent to the Sunninghill Park site which is part of Waterval Farm was used for the comparison. This catchment is a virgin catchment (i.e. without piped water supply, sewerage and stormwater networks) comprising some 75 hectares in area. Cattle grazing on the land has resulted in 'cattle tracks', the compression of the soil surface layers and alteration of the natural vegetation cover. The overland flow component tends to follow the 'cattle tracks' and does not therefore produce sheet flow. A sparse amount of trees cover the southern side of the catchment, these being mainly of the Blue Gum variety. The catchment slopes from west to east with a fall of 50m over approximately 800m. There is no defined watercourse present in the catchment. There is a further 32ha demarcated as a catchment but is not considered in this particular study.

The catchments from a geological point of view are situated on a granitic dome. There is a very thin top soil which overlays several metres of

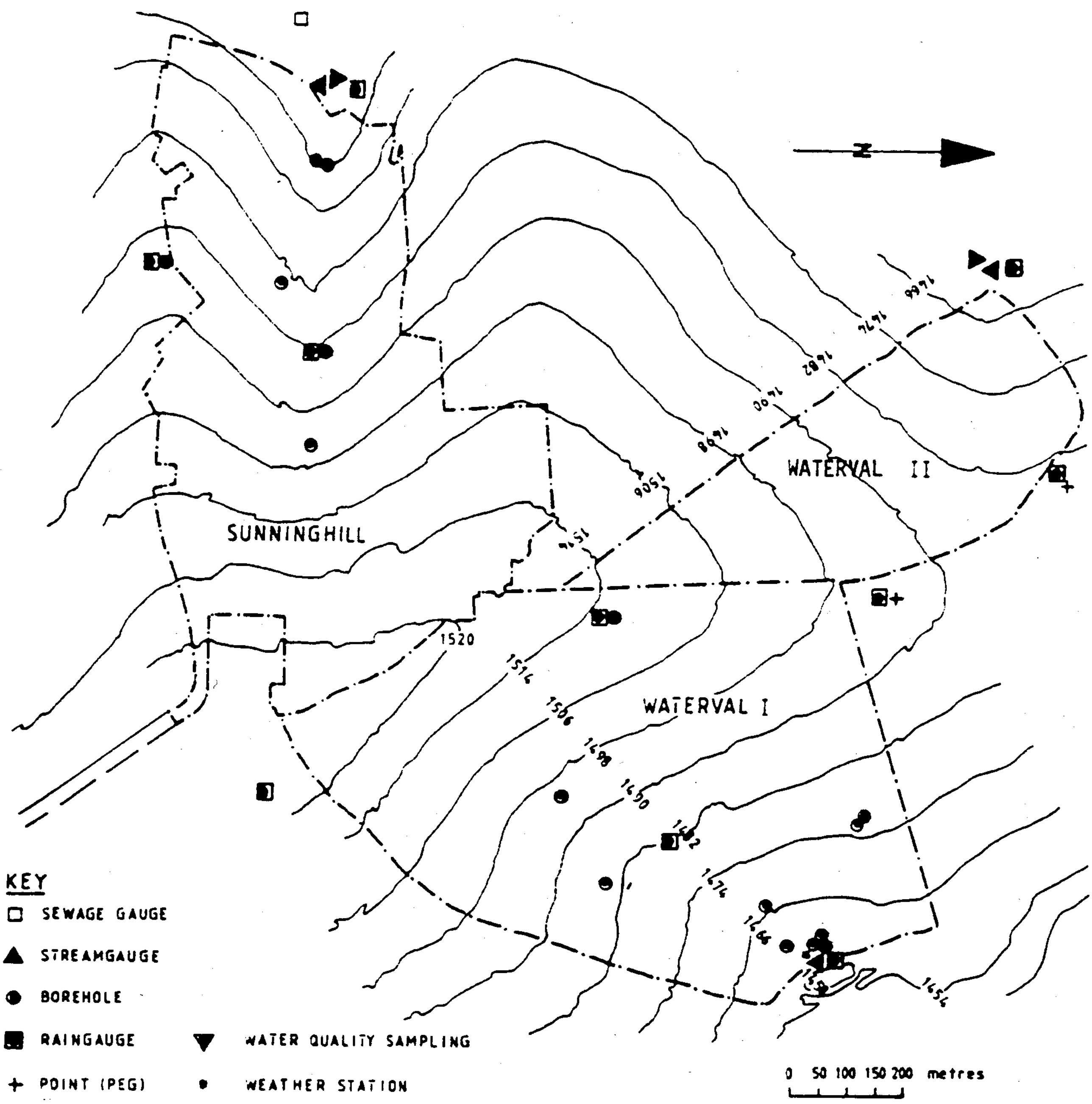



Figure 2.1 - Plan of the catchments and sites of Instrumentation

decomposed granite. Groundwater is thus located in the decomposed granitic layers and fissures within the parent rock.

Instrumentation of the catchments comprises a network of continous recording gauges and discrete measurements of other parameters. A plan of the catchments and the sites of the instrumentation are presented in Figure 2.1. Rainfall is measured using .2mm (depth) tipping bucket instruments at eight sites within the two catchments (an effective cover of 5 raingauges per $km^2$).

Runoff (combined surface and baseflow) are recorded at the outlet of both catchments. In Sunninghill Park, a V-notch Crump weir together with a stilling well and a pressure transducer were used. Since there is a constant flow in the catchment, it is possible to measure both the surface and baseflow components of runoff. In the Waterval farm catchment, a V-notch plate weir together with specially designed cut-off channels result in surface runoff being measured only.

Boreholes have been drilled in both catchments in an attempt to assess the geology of the area and the 'water levels' which occur in penetrated fissures. Naturally in a fissure rock material, traditional methods of borehole assessment of groundwater level do not necessary apply. The borehole levels are measured on a weekly basis and not continuously. A separate discussion on the Groundwater Hydrology aspects of the catchment is present in Report 3 of this series.

A weather station has been sited at the lower end of the Waterval catchment in order to assess certain meteorological parameters. These parameters are wind speed, wind direction, temperature (maximum and minimum), relative humidity, atmospheric pressure and total radiation (including both direct and diffusive).

In the Urbanised catchment there is piped water supply to each stand which is measured by municipality dial meters. These meters are read by the municipality once every three months, which hinders short time step accuracy. Sewerage from the same catchment is transported through a single half-round pipe at the outlet. Measurement of this parameter is using a ultrasonic device suspended in a manhole. The depth of fluid in the half pipe is measured and a rating table prepared which gives an estimate of flow volumes.

## 2.2 Descriptions of Parameters

Each parameter that is either measured or estimated from measurements is described in detail with reference to the data collected. Trends in the data are discussed and conclusions drawn. The quality of the data is also discussed, in the context of the effect of the variable on the total water balance.

### 2.2.1. Rainfall

#### 2.2.1.1 Introduction

Eight 0,2mm tipping bucket units were sited within the boundaries of the two catchments. The tip of the bucket actuates a pulse in the current to the data logger. The shift from the low to high state results in the pulse being detected by the data logger circuitry. These pulses are accumulated over a fixed five minute period and recorded by the data logger. Thus the resolution of the data is five minutes. Where there are periods of zero rainfall, no information is recorded by the data logging equipment.

Tipping bucket gauges with 0,2mm perform well in areas of high intensity, short duration rainfall events. Where long duration, low intensity events occur, these instruments can underpredict the total duration and the starting time of the storm event.

Each of the tipping bucket units were calibrated and the calibration applied to the resultant data. The calibration figures seem to have little effect on the total daily precipitation amounts, as both positive and negative errors occur with the tipping bucket raingauges.

#### 2.2.1.2 Analysis of Data

The rainfall data covers a period from September 1986 to February 1991. There were equipment malfunctions of some of the gauges during the period of the record as a result of data logger breakdown or EPROM media failure. In the latter case EPROM 'chips' have a life of 100 erasures under the influence of ultra-violet light.

So as to produce an areal distribution of rainfall for each of the two catchments it was decided to utilitise some form of averaging procedure. This would also overcome problems that would occur with the missing rainfall periods. Since the variation of rainfall across the catchment was minimal, the use of the thiessen polygon form of weighting was applied. The weightings had to be calculated for every different type of raingauge configuration (with one or many raingauges missing). A computer program was written using a Monte Carlo method to simulate the areas which are within the zone of influence of each of the raingauges. Appendix 1 gives the diagrams of the gauges used in each simulation and the weightings given to each gauge.

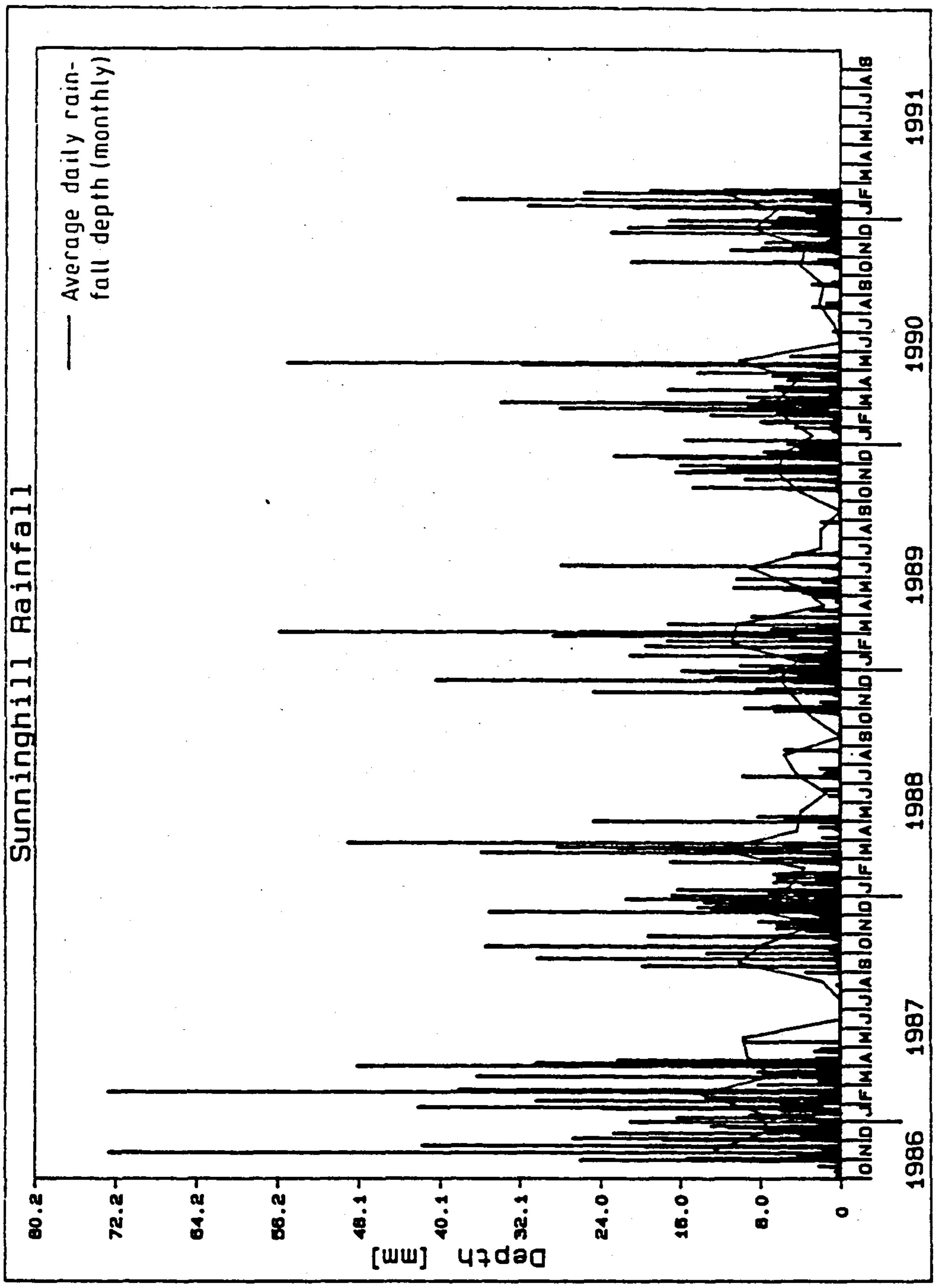



Figure 2.2 - Daily rainfall for Sunninghill Catchment

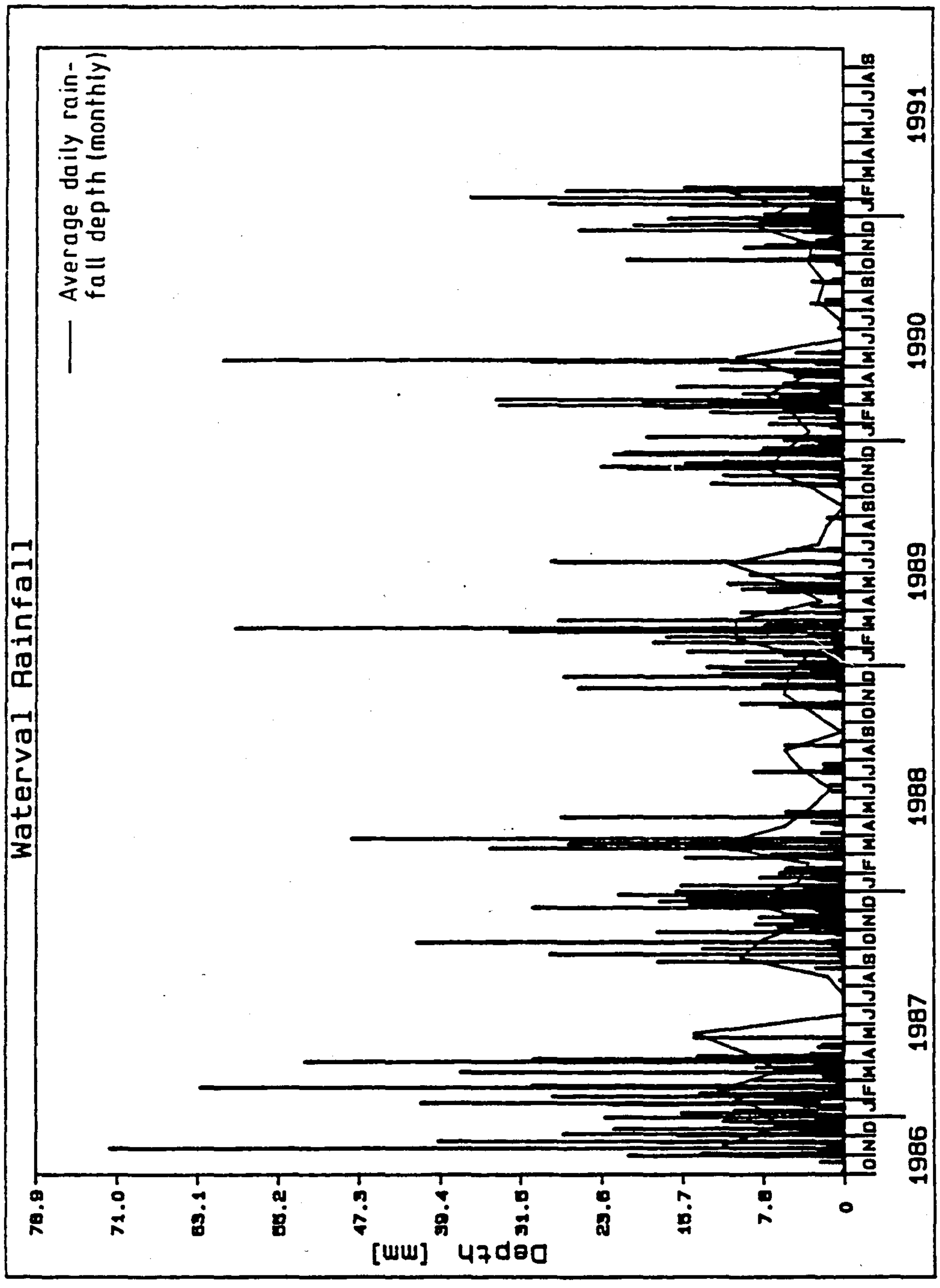



Figure 2.3 - Daily rainfall for Waterval Catchment

The rainfall was plotted for both the catchments on a daily basis for the purpose of the water balance. Two graphics depicting the rainfall events for the Sunninghill and Waterval catchments are presented in figures 2.2 and 2.3 respectively. It can be seen that the overall difference of the precipitation amounts in both catchments is minimal. Infact, close inspection of the data reveals that for storm events over 5mm, the variation across the catchments of the rainfall amounts is +/- 5 to 10%. This figure is well within the variation that would be expected due to measurement by small area collectors. Falls of rain of less than 5mm results in a far wider extreme of values between gauges; this being indicative of isolated "spotty" events. These will have relatively little effect in the overall water balance.

The annual precipitation amounts for both catchments are similar, although there is a definite trend to the ddata over the period 1986 to 1991. The first year of data (1986/1987) shows an accumulation above the normal average annual precipitation. The year 1986/87 rainfall was after a drought that occurred during the early part of the 1980s. The observed trend shows a decrease of precipitation each year from 1987. Tables 2.1 and 2.2 illustrate numerically the variation of both Annual Rainfall and monthly rainfall for both Sunninghill and Waterval catchments.

It is interesting to note that the number of rainfall days stays fairly constant throughout the period of the period considered in this report. This indicates that in below average rainfall years, there is more of a variation between catchment owing to more spotty rainfall.

Table 2.1 - Statistics of Rainfall (Sunninghill)

Annual Variation

| Year | MAP (mm) | No. Storm Events | Average Depth (mm) |
|---|---|---|---|
| 86/87 | 1090 | 118 | 9,2 |
| 87/88 | 691 | 107 | 6,4 |
| 88/89 | 647 | 108 | 6,0 |
| 89/90 | 608 | 110 | 5,5 |
| 90/91 | 447+ | 61+ | 7,3 |

+ indicates year is not complete at time of writing

Seasonal Variation % Annual Rainfall

| Year | O | N | D | J | F | M | A | M | J | J | A | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 86/87 | 3 | 16 | 15 | 15 | 21 | 8 | 15 | 1 | - | - | - | 6 |
| 87/88 | 15 | 6 | 23 | 10 | 6 | 29 | 4 | 2 | 1 | 3 | 1 | - |
| 88/89 | 3 | 9 | 18 | 11 | 24 | 18 | 2 | 6 | 8 | 1 | - | - |
| 89/90 | 4 | 17 | 15 | 5 | 15 | 19 | 6 | 17 | - | - | 1 | 1 |
| Ave. | 6 | 12 | 17 | 10 | 16 | 19 | 7 | 7 | 2 | 1 | 1 | 2 |

Table 2.2 - Statistics of Rainfall (Waterval)

Annual Variation

| Year | MAP (mm) | No. Storm Events | Average Depth (mm) |
|---|---|---|---|
| 86/87 | 1040 | 116 | 9,0 |
| 87/88 | 700 | 106 | 6,6 |
| 88/90 | 635 | 100 | 6,4 |
| 89/90 | 653 | 114 | 5,7 |
| 90/91 | 423+ | 61+ | 6,9 |

+ indicates year is not complete at time of writing

Seasonal Variation - % Annual Rainfall

| Year | O | N | D | J | F | M | A | M | J | J | A | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 86/87 | 3 | 16 | 15 | 15 | 19 | 8 | 15 | 1 | - | - | - | 8 |
| 87/88 | 16 | 7 | 24 | 9 | 5 | 29 | 2 | 2 | - | 2 | 1 | - |
| 88/89 | 3 | 7 | 15 | 8 | 25 | 20 | 2 | 9 | 9 | 1 | 1 | - |
| 89/90 | 3 | 19 | 15 | 6 | 13 | 21 | 5 | 16 | - | - | 1 | 1 |
| Ave. % | 6 | 12 | 17 | 9 | 16 | 20 | 7 | 7 | 2 | 1 | 1 | 1 |

The seasonal variation of rainfall is computed as the total rainfall for each month as a fraction of Annual Precipitation. The two catchments exhibit similar average seasonal variation. More noticeable is the duration of the rainy season. The years with lower than average falls show variation in the duration of the rainy season. Significant falls can be observed in April and May, whereas in above average years the season is confined to November to April. The start of the rainy season is also changeable and this feature will have a possible effect on the domestic water supply to the urbanised catchment, which is discussed in section 2.2.3 of this report.

### 2.2.2. Runoff

#### 2.2.2.1 Introduction

At the outlet of each of the two catchments (Sunninghill and Waterval I), a pressure transducer instrument together with a data logger device is situated. The pressure of water head above the instrument is measured and converted to stage, as pressure is a linear function of head. A stage-discharge curve has been calculated as there is not a wide variance of flows in which to calibrate the weirs. The waterval weir has the distinction of being dry except when large runoff events occur. The resolution of each of the two instruments is to within 5mm (accuracy of the Analogue to Digital convertor) and also has a temperature dependence. Three-quarters of the way through the study the Sunninghill Park MCS logger was replaced by a DDS-logger so that a water sampler could be connected.

The runoff instruments have caused the most problems with collection of data ranging from battery, logger, amplifier and EPROM chip failures. There has been a higher incidence of setting error in calibration than with any of the other instruments. Therefore the record of runoff from the two catchments is very sparse and too incomplete to use directly in the water balance calculations.

The runoff data instrumentation was improved during the Winter season of 1990 and methods of data collection enhanced. The Summer rainfall season (1990-91) has demonstrated that the quality of the data, using the improved system of data collection, will be sufficient for use directly in water balance studies in the catchment in the future seasons. Only one week of data was lost as a result of a circuit malfunction in the DDS logger.

#### 2.2.2.2 Runoff Simulation

a) WITSKM Model -

The first approach to the simulation of runoff from both catchments was using the WITSKM model which was developed under the contract. The WITSKM model as a semi-lumped model capable of single event simulations (see Runoff Management Modelling - Report No. 8 by Coleman and

Stephenson). The single event model was calibrated on the Sunninghill Park Catchment for a series of storms. The WITSKM model was further enhanced to produce a version capable of a continuous simulation. In order to model the dry cycles that are inherent in continuous simulation models, an evaporation component was added. This evaporation component uses average monthly potential evaporation figures.

The continuous simulation version of WITSKM was tested on the Pinetown Catchment in Durban as part of a research project to develop a water quality model. The calibration for the Pinetown data was successful using the model. The continuous model was applied to Sunninghill Catchment to calibrate on a week at the beginning of December 1990, for which a series of runoff data was available with three storm events, the first on day 2, the second on day 3 and the third a few days later. Manipulation of the infiltration rates (i.e. saturated hydraulic conductivity parameters) and resizing of different modules were approaches that afforded reasonable calibration. The first storm was not correctly reproduced which could be attributed to 'warm-up' of the model. The second and third storms were acceptable. The verification run which was attempted using the period of December 1990 and January 1991. The result of the verification was that the model failed to reproduce the observed runoff with any degree of accuracy.

The calibration parameters that can be altered made no appreciable difference to the overall verification. The Evaporation/drying routine appears to not model the characteristics of the catchment correctly.

b) <u>Pitman Daily Model</u>

The second modelling approach to calculation of runoff from both catchments was using the Pitman Daily Runoff Model (Pitman, 1976).
This model is a conceptual continuous event model which was adapted from the Pitman monthly model (Pitman, 1973). The model is essentially a curve fitting or black-box system of water budgeting routines. This is through virtue of the fact that most of the parameters have emprical non-physically based values.

The calibration of the daily model on Sunninghill Park for the month of December was undertaken firstly using parameters suggested by Pitman (1976). The calibration showed that the model suffered the familiar problem as WITSKM, in the daily runoff values. When a five year period of flows were generated using the model, the monthly accumulations for the month that observed data was available, were acceptable. Owing to the faster processing time of the Pitman model, the model was used to generate monthly and daily flows for the catchments. The Pitman model calculates an interflow component which in the case of Waterval, is not measured at the weir site.

c) Conductivity of Simulation

It was apparent that the simulations undertaken were not able to generate the individual storm events, (obviously the Pitman model is only capable of daily average flows, being driven by daily rainfall data). The evaporation routine and discretisation appeared to be the problem with WITSKM and the strict lumping in the Pitman model prevents accurate results.

The patched runoff data (expressed in volumetric terms) are presented in figures 2.4 and 2.5 for the Sunninghill and Waterval I catchments respectively. The way the plots are presented are such that volumes of flow are adequate to explain the variation and response of both catchments. The runoff in these diagrams includes both the surface runoff, interflow and baseflow components. The Sunninghill catchment runoff inhibits observed baseflow on a continuous basis.

#### 2.2.2.3 Analysis of Data

Inspection of the runoff data (figures 2.4, 2.5) shows that the Sunninghill catchment produces a greater runoff component than that of the Waterval catchment, which is not surprising. It is apparent that the construction of townhouse stands within the Sunninghill catchment has had a fairly profound effect on the runoff from the catchment. This is especially noticeable for the small rainfall events where the response from the catchment is greater since a townhouse complex was built near to the outlet of the catchment. An average of 15% of rainfall is produced as runoff from the Sunninghill catchment, where only 7% is produced in the Waterval catchment. It must be borne in mind that the runoff shown in figures 2.4 and 2.5 will contain baseflow.

From the soil survey and land type analysed (Description of Catchments Report, No 2 in this series) it is apparent that the soils have a high interflow potential and are clayey. The modelling techniques used in the patching of the runoff data do not adequately account for the soil unit mechanism. Further research into the soil water fluxes and enhanced modelling will be required to adequately simulate the runoff from the catchment.

From simulations of the Waterval catchment (Holden, - report in this series), approximately only one third of the waterval catchment contributes to the runoff producing mechanism. Since this bottom third is composed of high clay content soils, it is apparent that the clay has to be saturated before any runoff can occur. The dry winters result in cracking occuring in these soils.

The effect of the increased urbanised tracts in the Sunninghill catchment is difficult to observe in the diagrams owing to the decrease in rainfall observed over the period of the project.

It can be seen from the diagram that the Waterval catchment runoff plot (figure 2.5) shows a baseflow component. Whilst the weir at Waterval is dry during non-rainfall events, it is possible that interflow/groundwater flow is occuring underneath the weir and cut-off wall. During the winter season below the dam and road, the vegetation is green and lush, thus indicating that water is being supplied. Therefore the baseflow component of ~1 l/s is assumed to be an outflow from the catchment.

To directly compare the surface runoffs (neglecting the baseflow component) of the two catchments, the baseflow component (which appears to be a constant value) was removed from the total runoff values. The information was plotted in the form of a Double mass curve of Sunninghill surface runoff versus Waterval Surface Runoff (figure 2.6). The graph shows that the flows from Sunninghill are at least 5 times greater than Surface runoff measured in Waterval. Whilst the greater volumes of rainfall and hence runoff occurred during the 1986/7 season, it is apparent that the increased urbanisation in Sunninghill (townhouse development) in later years has marked increases in surface runoff.

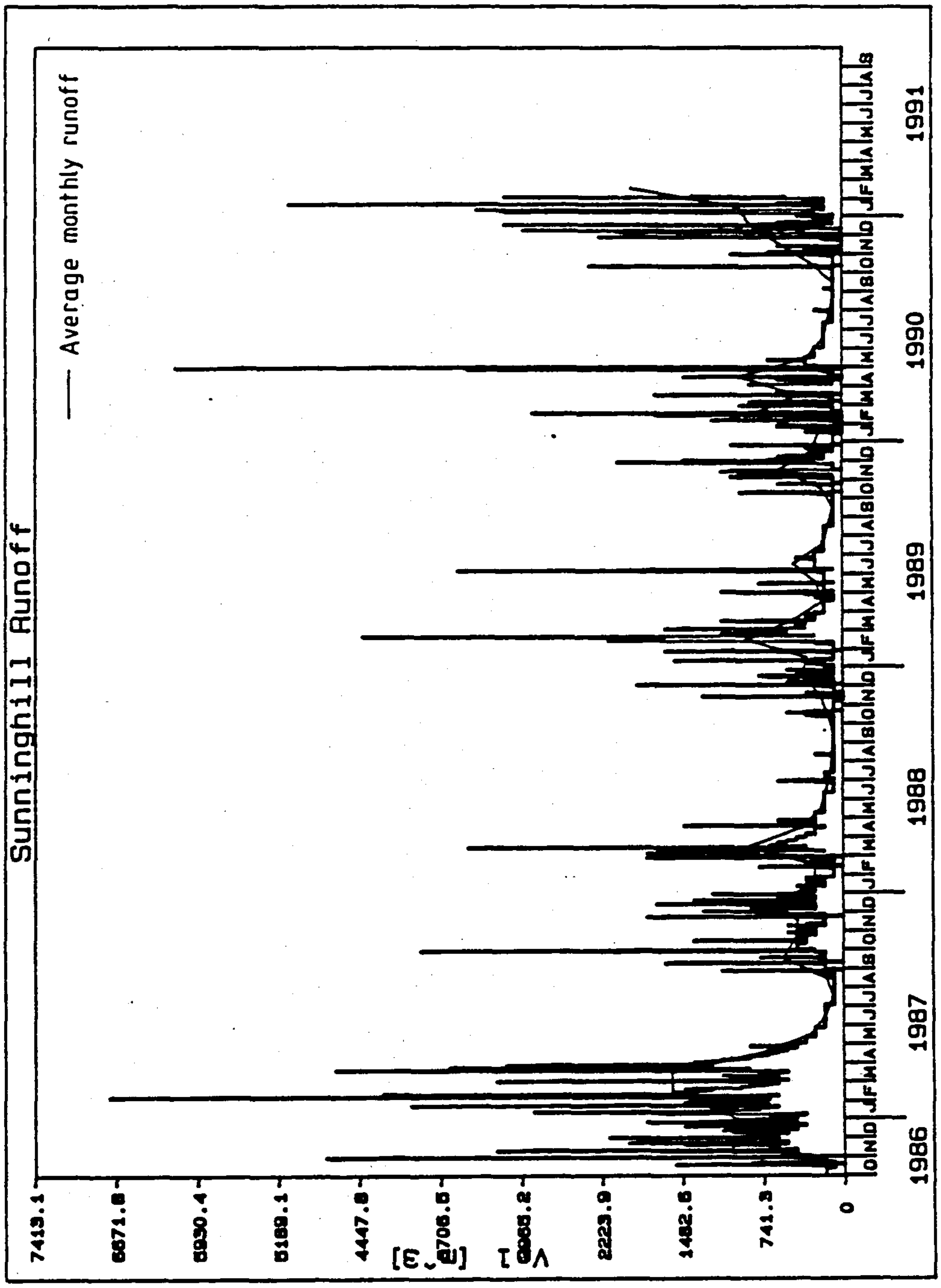
### 2.2.3 Domestic Water Consumption

#### 2.2.3.1 Introduction

Nearly all the occupied stands within the Sunninghill Catchment have been supplied with domestic water supply from the local municipality. Standard meters are used to determine the kl consumption of each user. These meters are read once every quarter by the Muncipality who calculate the actual consumption. This data is extracted from the meter books by the research group and accumulated to give a total consumption for the catchment. The water supply to the ESCOM site has been excluded from the water supply figures as firstly, as being a bulk user, the figures would influence the variation, and secondly, the use of domestic water for irrigation by ESCOM would be outside the catchment area.

Water supply figures are available for the present study from November 1986 to the present day. The catchment accumulated kl amounts have been converted to $m^3$/day. During the period of the record most the townhouse developments were built which provides a dramatic effect on the total water supply figures.

—— Average daily runoff




* includes baseflow component

Figure 2.4 - Sunninghill catchment runoff data (inc. Patches)

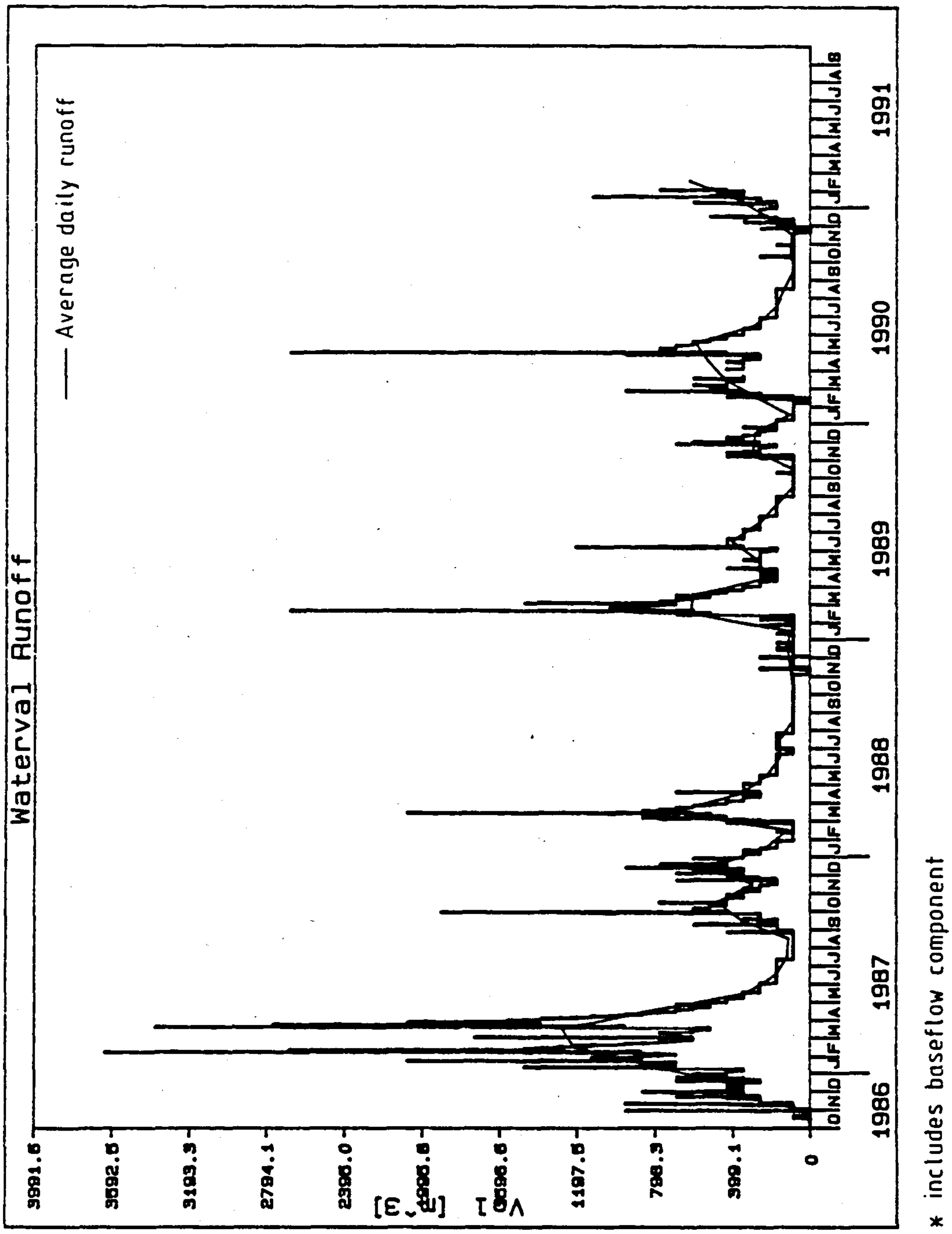



Figure 2.5 - Waterval catchment runoff data (inc. Patches)

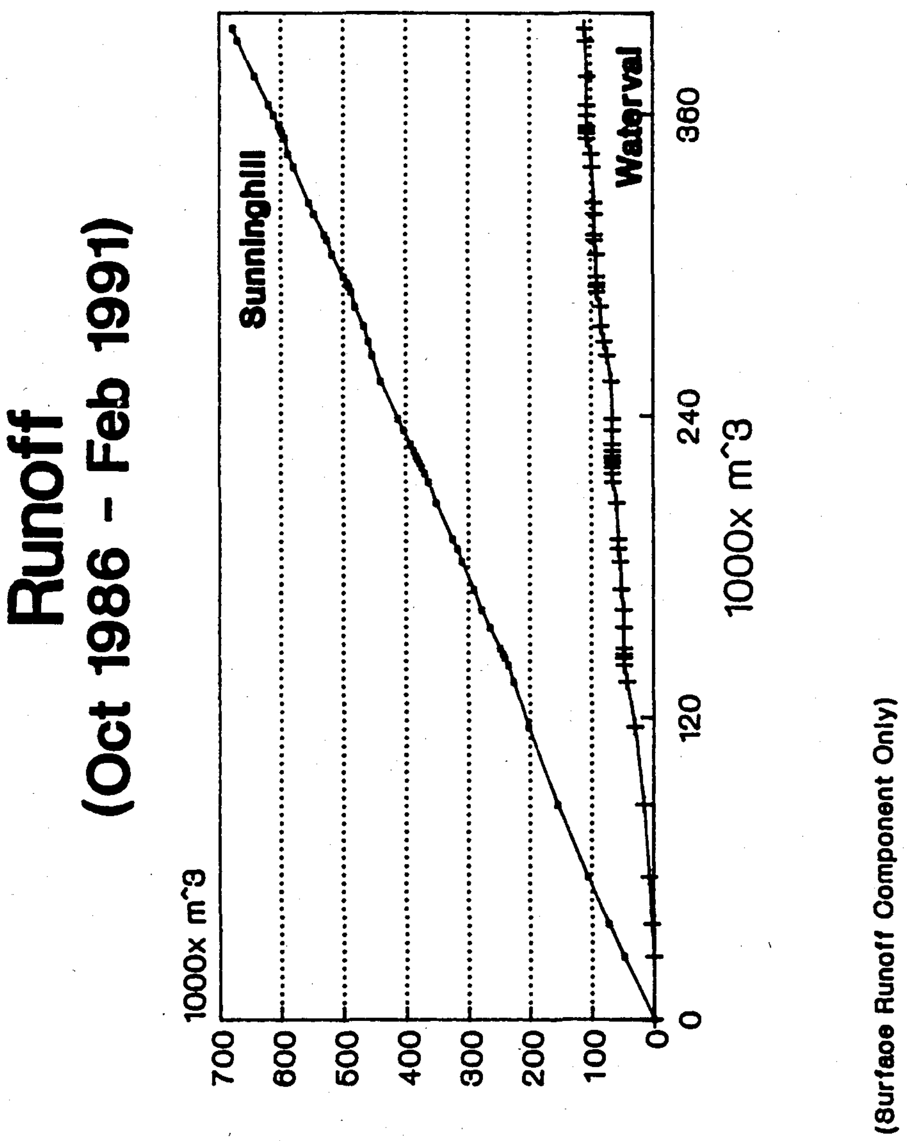



Fig 2.6 - Comparison of surface Runoff from Sunninghill and Waterval I catchments

2.2.3.2 Analysis of Data

The three monthly figures have been averaged over each month and calendar month figures produced which are presented in figure 2.7. There are three main components to the graph, namely,

(a) Overall Trend
(b) Rapid Increase in Consumption
(c) Cyclic Variations in Supply Requirements

a) The overall trend in the data is one of increase in the domestic usage of water in the catchment. From a $138m^3$/day consumption in 1986 to a $414m^3$/day consumption in November 1990 represents a nearly three fold increase in water usage by the catchment. It must be remembered that the latter figure has not been corrected for the cyclic variation or the rapid increases in water supply that have occurred.

b) The rapid increases in the consumption of domestic water occur as a result of expansion through increased development in the catchment. The inhabited stand count increased from 110 to 124 during the period October 1987 to 1988 during which the consumption rose from an average of $138m^3$/day to $190m^3$/day. The development of townshouses during the period October 1989 to August 1990 also resulted in a dramatic increase in the consumption figures. The characteristic of townhouse development is that whilst the units are built in a block, letting or selling of all the units occurs over a long time span. The development of stands within the catchment is graphically displayed in figures 2.8 - 2.12. The rapid increase in water consumption is through townhouse developments occurring in the period 1989-1990.

c) Cyclic variations in the water usage by the consumers of the catchment can be seasonally related. The cyclic increase in domestic water consumption occurs, in the main, during the later period of the winter months, before the summer rain season occurs. From April until September, the consumption of water increases, mainly to meet the demand of irrigation of gardens. However, this period of excess demand has increased in time as a result of the trend of the rainy season starting later, combined with a drier winter season.

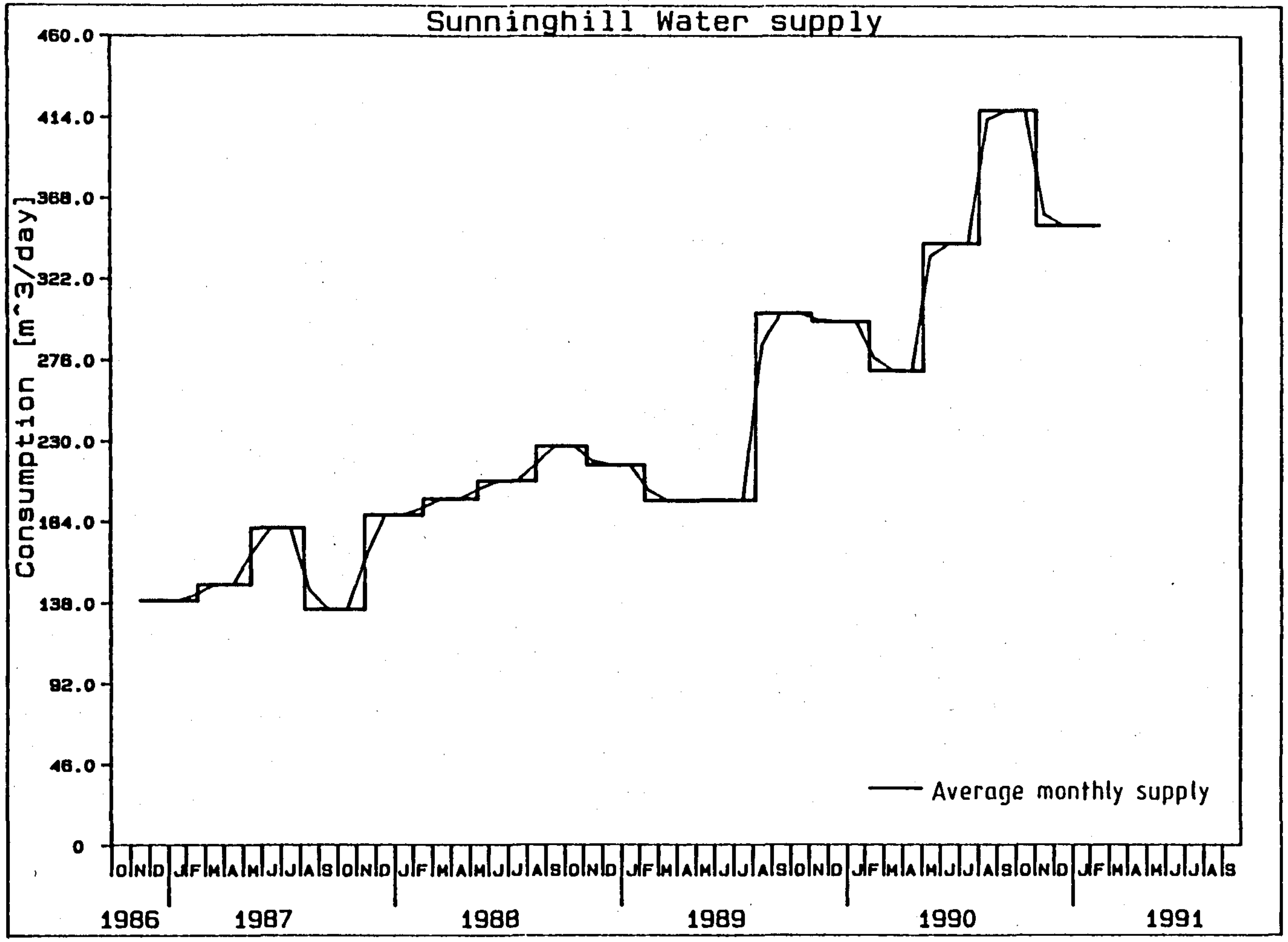



Figure 2.7 - Sunninghill - Domestic water consumption

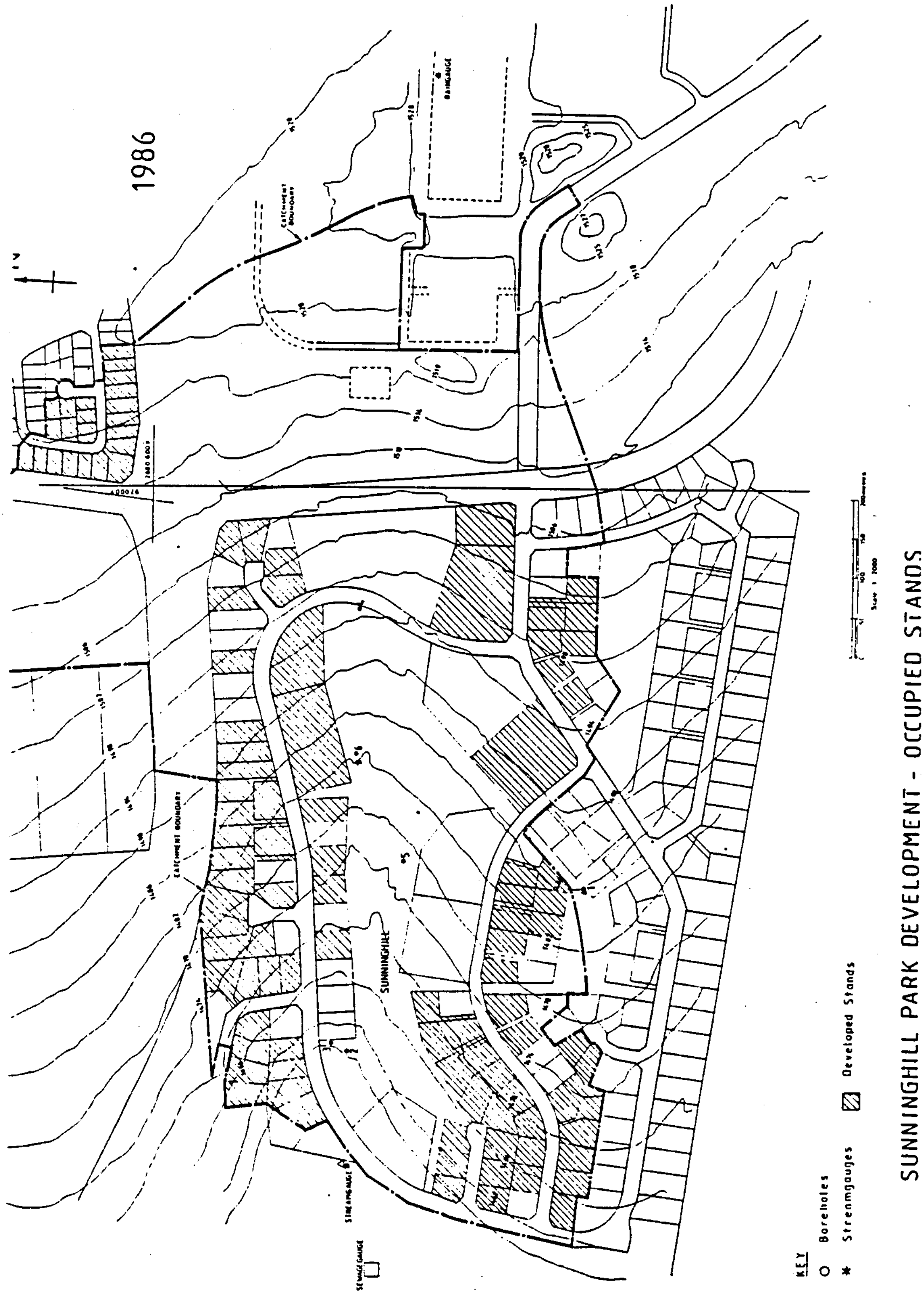
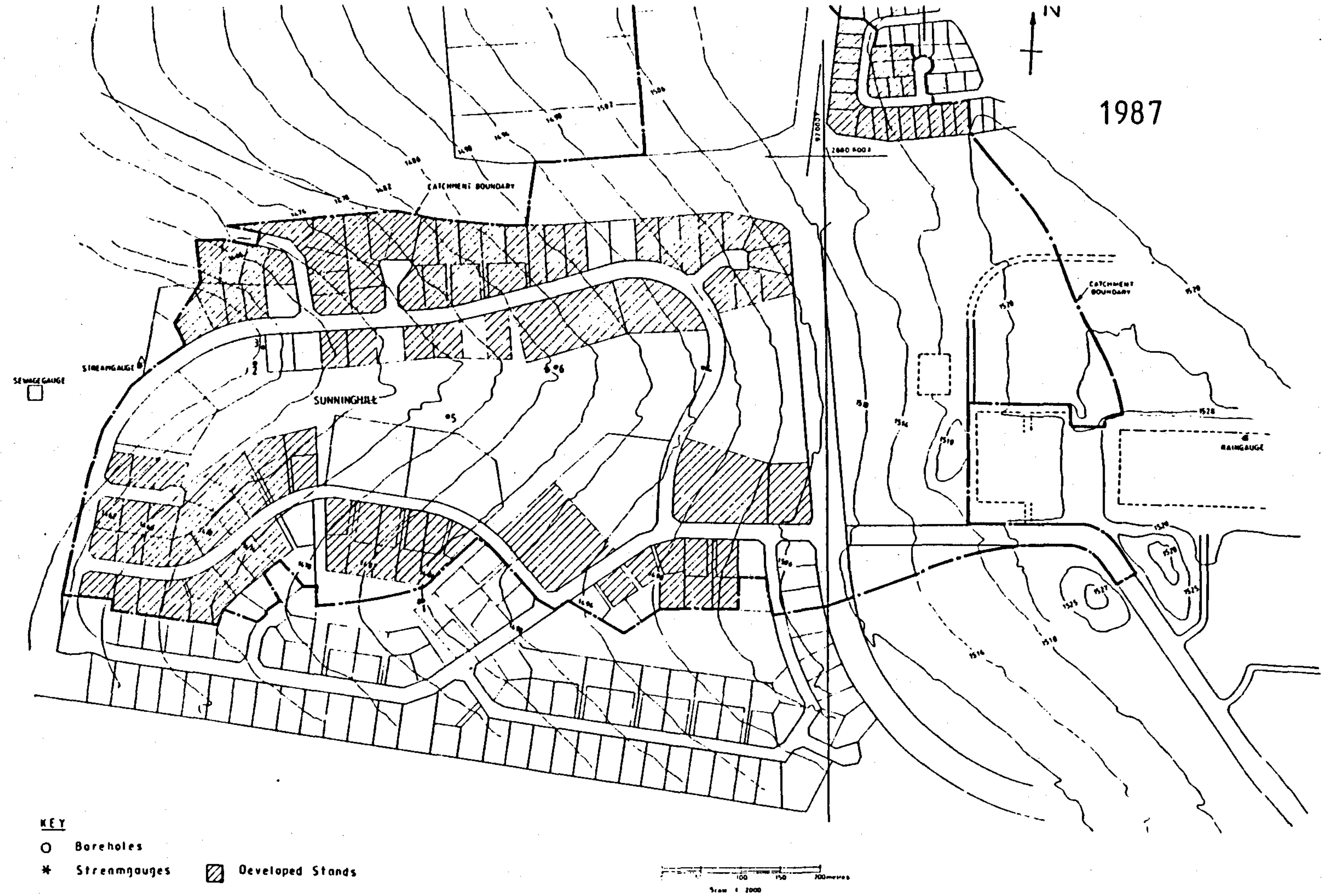



Figure 2.8 - Sunninghill - Development of Stands - 1986

Figure 2.9 - Sunninghill - Development of Stands - 1987




SUNNINGHILL PARK DEVELOPMENT - OCCUPIED STANDS

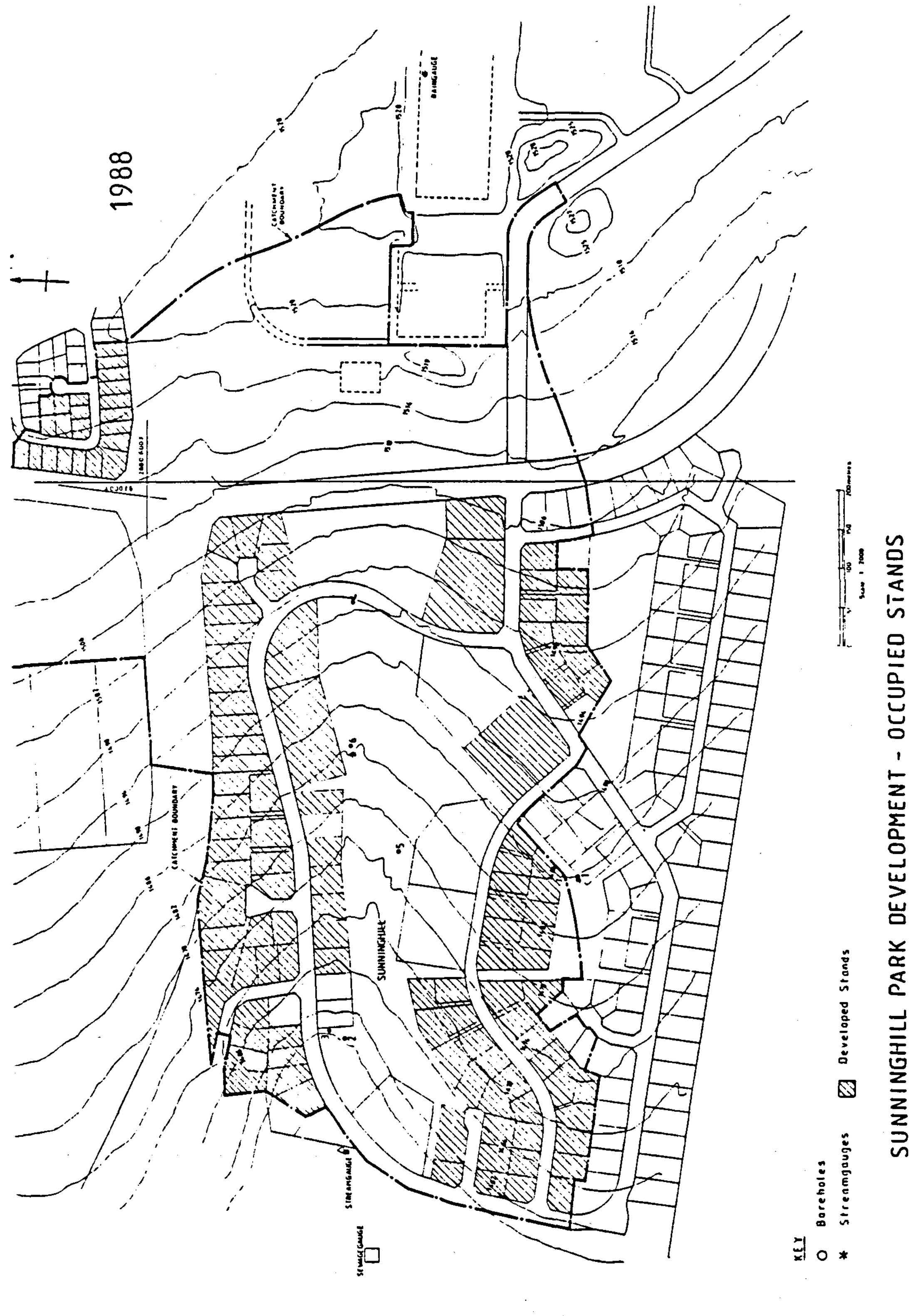



Figure 2.10 - Sunninghill - Development of Stands - 1988

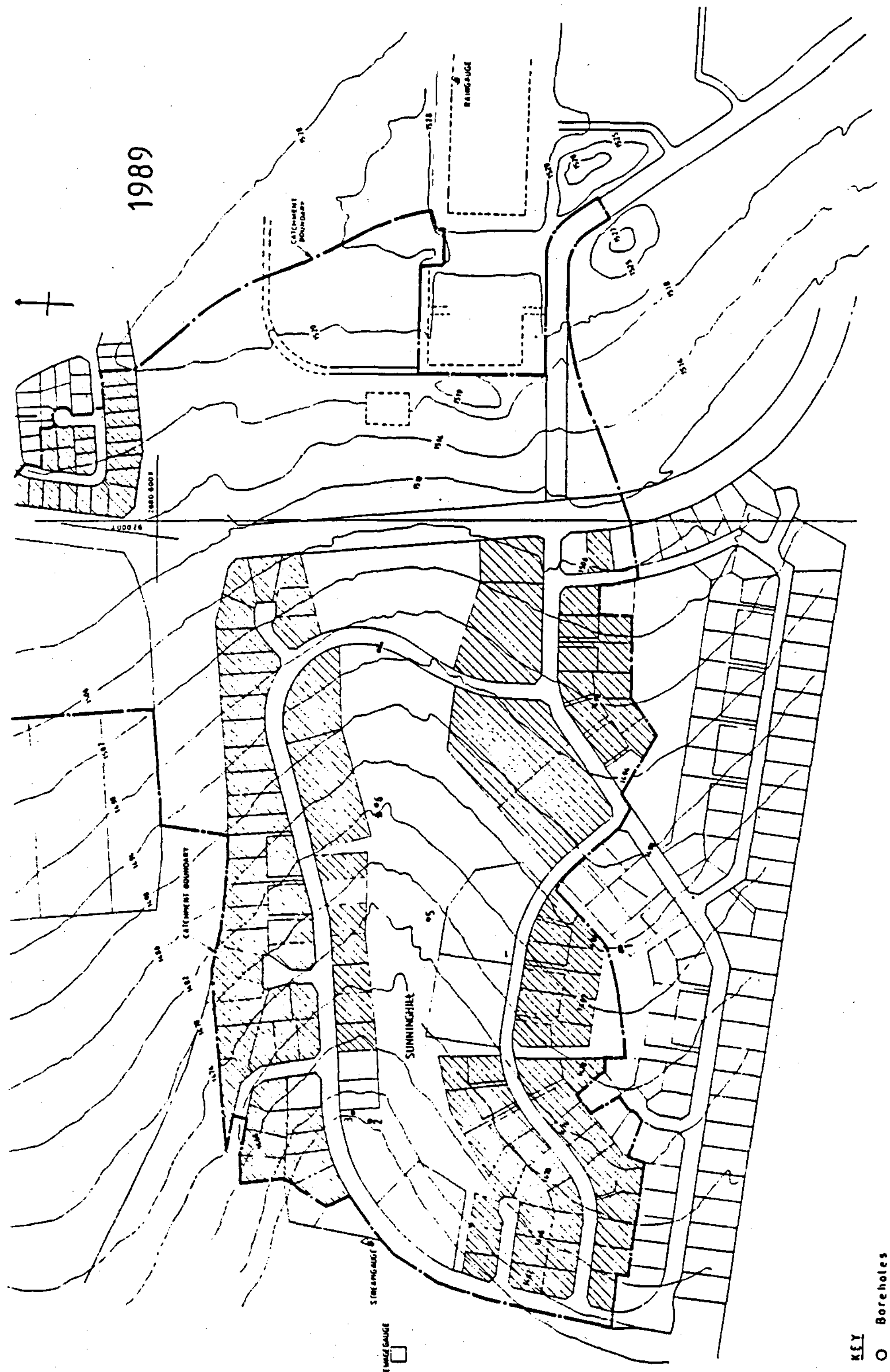



Figure 2.11 - Sunninghill - Development of Stands - 1989

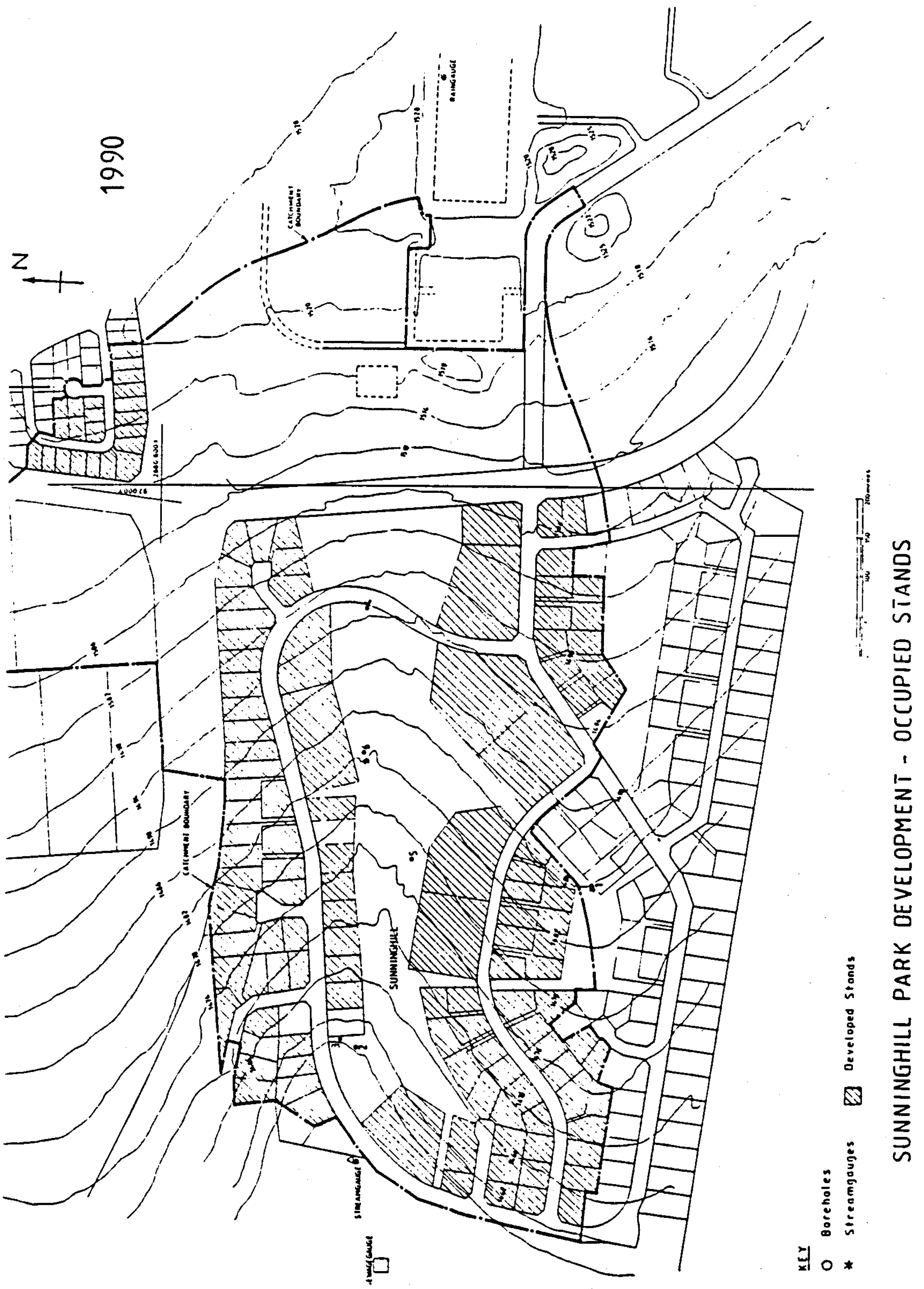



Figure 2.12 - Sunninghill - Development of Stands - 1990

### 2.2.4 Sewerage

#### 2.2.4.1 Introduction

There is one sewer pipe outflow from the Sunninghill catchment, adjacent to the streamflow gauge. The fluid in the pipe flows through a manhole at this point, which contains a half round pipe. An industrial ultrasonic device is suspended in the manhole which measures the depth of fluid in the half round pipe. A less expensive device was used initially, but corroded very quickly in the inhospitable atmosphere present in the manhole. The industrial device however consumes a large amount of power and several batteries were 'burnt out' before four large solar panels were used to treble charge the batteries. Even so, a sequence of days with cloud over results in the batteries being heavily depleted.

The site has been running since the end of 1988 successfully with a major interruption during 1990 when one of the solar panels was removed by thieves. The system samples the fluid level and averages the level over a period of 5 minute intervals. A stage-discharge curve was calculated taking into account the physical characteristics and long-section of the sewer pipe. The instrument had to be repaired in early 1991 owing to damage by the inhospitable environment.

Unfortunately the sewer pipe 'runs', in water hydraulic terms, in the the super-critical phase which means that the accuracy of measurement is not as good as a system 'running' at sub-critical level (the level at a weir is designed to produce in most cases). A coupled problem of accuracy is that in the stage-discharge calculation, we assume a homogenous fluid which in the case of sewerage is not true.

#### 2.2.4.2 Analysis of Data

Since the data is so variable and has only been in operation since 1988 with about 40% sampling rate, a time series graph is not possible to reproduce. There is a slight increase in volume over the two years, which would be as a result of the increased occupancy of the townhouse units. It would be expected that there should be a difference in sewer flows between the school holidays (i.e. December) and other months, but this is apparently not noticeable. The measurement resolution and high degree of sampling error could be smoothing out any variation in flow rate. The deflectivity of the sewage is variable and, this coupled with the water flow being supercritical result in large sampling errors.

Since sewage outflow data is only available for the period 1988 to 1990, and information would be needed for a greater length of record, a procedure to link the water supply to the sewer outflow had to be derived. The outlet was compared with the inflow and ratios obtained relating the sewer flow to water consumption. The ratios were then used to determine sewer flows for the rest of the period of record for water balance purposes.

### 2.2.5. Maximum Evaporation

#### 2.2.5.1 Introduction

The concepts of evaporation are both extensive and varied in their nature. Coupled with this is a confusion and abundance af terminology. De Jager (1989) attempts to improve the terminology by developing a new system based on the suggestions put forth by Monteith (1985).

The original concept of Potential Evapotranspiration, as defined by Penman (1948), was the evaporation from a short grass surface well supplied with water. Thus evapotranspiration from all cropped surfaces could be equated to the short grass reference. The architecture of the vegetation dramatically influences both the vapour transfer from the surface and the temperature at the surface. Thus the Potential Evapotranspiration (as defined by Penman 1948) is not applicable to the vast range of different vegetation covers.

De Jager (1989) defines the **Total Evaporation** from a natural surface to be the combined effects of the evaporation from the sub-stomatal cavities of leaves and the evaporation from the surface of the soil. This term is synonymous with Evapotranspiration.

The term Potential Evapotranspiration (as defined by Penman, 1948) is replaced by the term **Maximum Evaporation**. Therefore, when the soil water is capable of meeting the atmospheric demand the Maximum Evaporation is equated to the Total Evaporation.

To overcome the confusion in relating evaporation from a short grass surface well supplied with water, to the new terminology, this evaporation is termed the **Reference Evaporation**.

These terms that are defined above are used exclusively throughout this report.

The measurement of Maximum Evaporation by the use of evaporation pans is frought with problems, especially when transposing the data from one catchment to another. Bosman, 1985, found that the siting of the pan coupled with the type of local environment (i.e. the type and size of the vegetation surrounding the pan) influences the Maximum Evaporation value that is measured.

De Jager *et al* 1987 reported that the application of the Penman-Monteith equation (Thom, 1975) adapted for use with data from an automatic weather station provided accurate estimates of Maximum Evaporation. It was decided to use this approach to estimate the Maximum Evaporation for both the catchments.

A simplification that was introduced was that the Maximum Evaporation was the same for both catchments. In practice, the two catchments will differ since the radiation effects in the urbanised area will by influenced by variable albedo and diffusive radiation variation. It is also apparent that the relative humidity and wind speeds (as a result of eddies generated by building) will also be different.

The Maximum Evaporation was calculated using the data from the weather station that is situated in the bottom end of the Waterval catchment. The weather station parameters that were used were the air temperature, relative humidity, global solar radiation, and wind speed. These were sampled every 30 minutes and the Maximum Evaporation was calculated from these measurements and the values summated on a daily basis. This information was used with the Penman-Monteith equation to derive the Maximum Evaporation as shown in figure 2.13.

The Total Evaporation for the two catchments could only be effectively produced through simulation. The use of lysimeters is both costly and are restricted to plot size especially where several different types of vegetation/soil order combinations are present in the catchments. The simulation of the Total Evaporation is described and the results presented in Chapter 3 of this report.

2.2.5.2 Analysis of Data

The maximum evaporation curves follow a strict seasonal variation as would be expected, with a maximum occurring at the December/January period of the calendar. The average maximum evaporation is about 9mm/day. Overall there is little variation of the amplitude of the seasonal curves, which range from ± 5mm/day to 17mm/day.

The data collected form the weather station and processed using the Penman-Monteith equation can be tabulated to give average monthly Maximum Evaporation figures (Table 2.3).

Table 2.3 - Monthly Average Maximum Evaporation (mm/month)

| Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 279 | 316 | 345 | 341 | 242 | 254 | 192 | 168 | 139 | 143 | 214 | 279 |

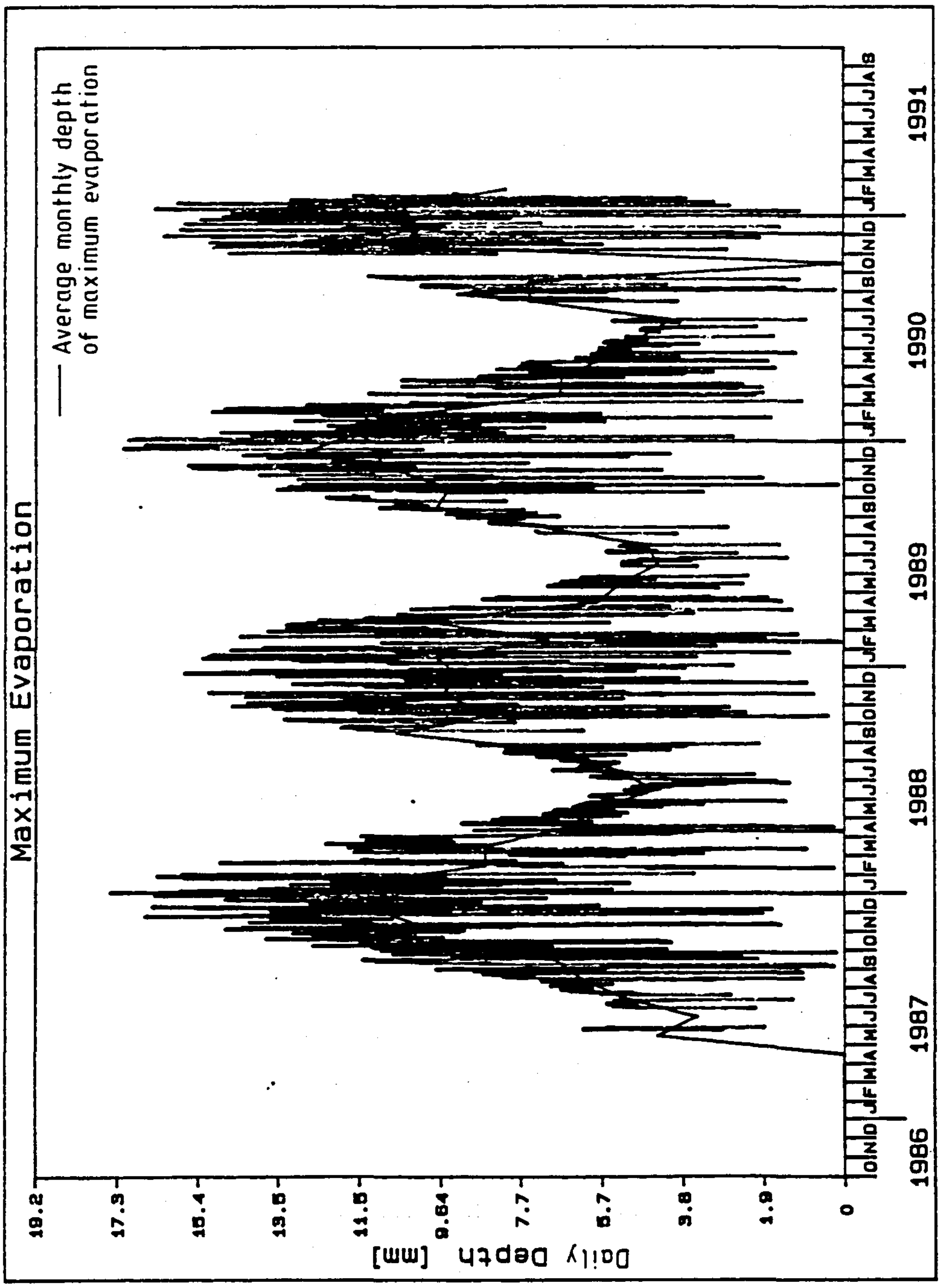



Figure 2.13 - Maximum Evaporation - Estimated

The values (Table 2.3) are higher than those produced by the H.R.U. (1981) in the Water Resources of South Africa. It must be borne in mind that the maps of Maximum Evaporation (referred to as Potential Evaporation) are firstly generalised contours from discrete data points, and secondly are measurements by the Symons Tank. The Symons Tank always produces values that are less than the American Class A-Pan, although both estimates suffer from problems as mentioned by Bosman (1985).

### 2.2.6. Borehole Levels

#### 2.2.6.1 Introduction

The geological structure of the catchments, is granitic, and contains various post-granitic phase intrusions. It is therefore not as easy as a granular sedimentary type rock to quantify the movement of groundwater. The classic method of using boreholes and assessing the movement between them does not directly apply in this case.

However, several boreholes were drilled into both catchments as part of the study to assess the groundwater component of the water balance. A report by Paling ('Subsurface Hydrology in the catchments No. 3') describes in more detail the mechanisms of groundwater movement in the catchments.

The boreholes, on average, were sampled manually on a weekly basis and the depth between the water level and the top of the casings were measured. These values were plotted out to show the variation of the water levels during the period of the study. As the vertical scales on each of the holes are different, the levels are plotted out on different graphs.

#### 2.2.6.2 Analysis of Data

Each of the borehole plots exhibits different characteristics which will be discussed for each catchment.

##### 2.2.6.2.1 Sunninghill Boreholes

The Sunninghill Boreholes are shown in the map in figure 2.14. The numbering systems is equivalent to those used in the figures of borehole water levels (figures 2.15 - 2.19). The graph of the time series for borehole 5 is omitted since the hole emits water at ground level on a continuous basis. The emission is absorbed by the soil surface. The borehole is artesian in operation. Boreholes 1-4 were constructed in the beginning of the Summer Season of 1986, the others (holes 5 and 6) were added in May 1989.

The overall pattern is a sharp rise during the first five months followed by a seasonal variation in water level. The initial rise could be the result of two mechanisms. One mechanism could the the stabilizing of the borehole after construction. The method of construction was using air pressure to remove the chips from the hole, which may have affected the water level in the hole. The second mechanism could be the result of an above average rainy season which was experienced after four years of below average rainfall. The more logical reason could be the former mechanism.

Being a granitic based geological environment the correlation between boreholes would be an inaccurate excercise, however qualitative results can be obtained from such a comparison. Borehole 1 is on the divide between Sunninghill Park and the catchment on its Southern perimimeter. It would be expected that its water levels would be deep (relative to the ground surface) and that in times of drought, water level changes would be more marked. Figure 2.15 indicates this trend, the average water level decreasing between 1987 and 1990.

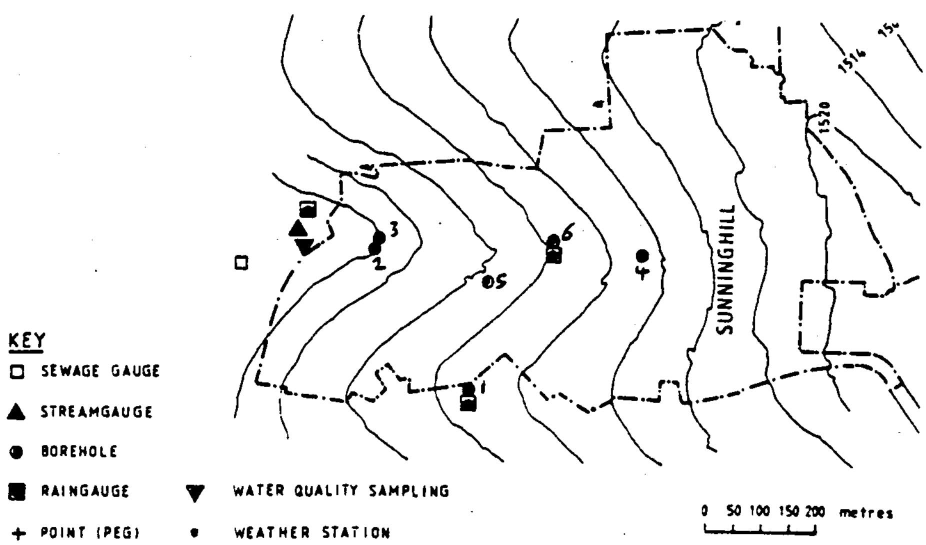



Figure 2.14 - Sunninghill - Borehole Sites Map

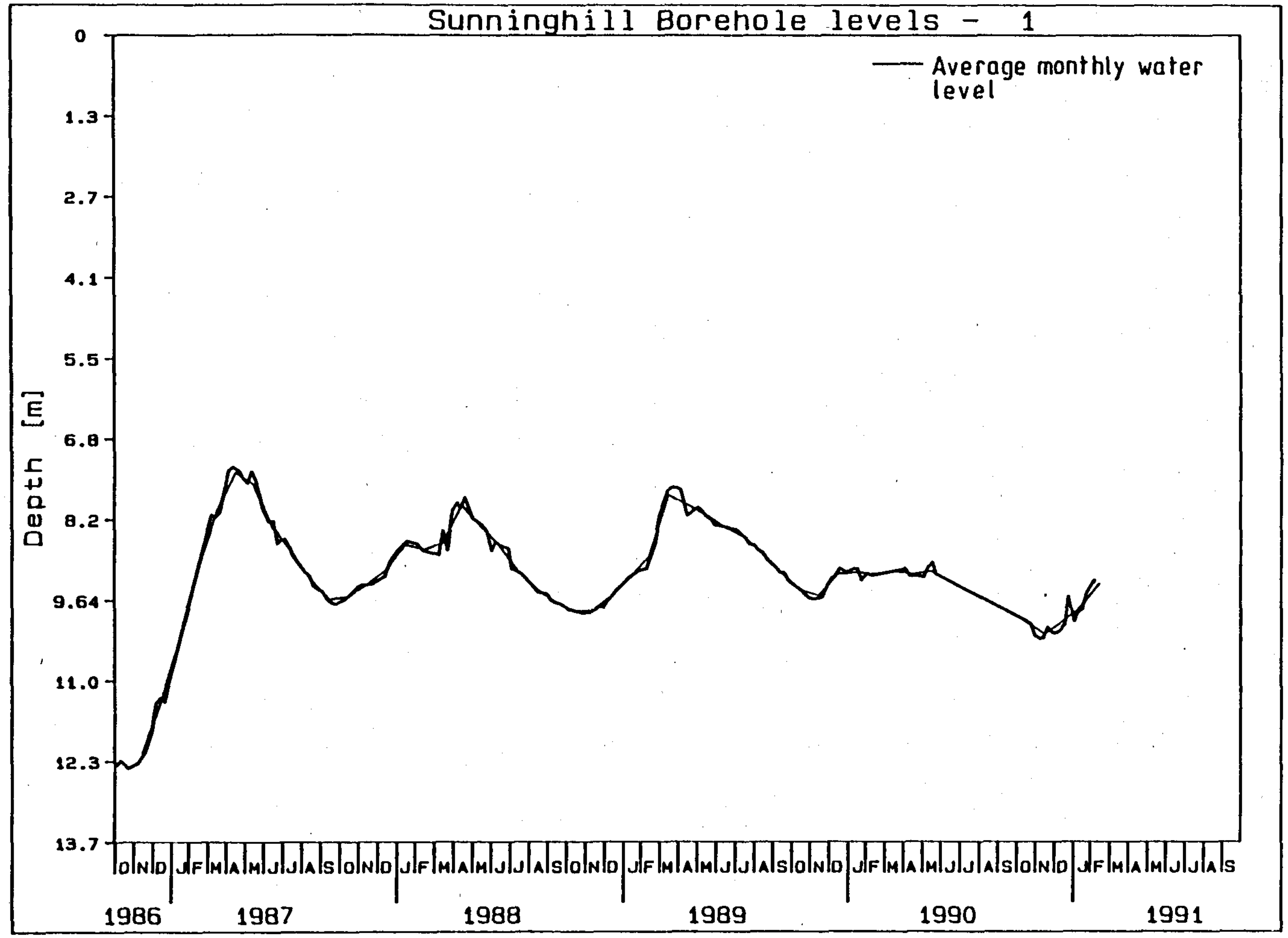



Figure 2.15 - Sunninghill - Borehole 1

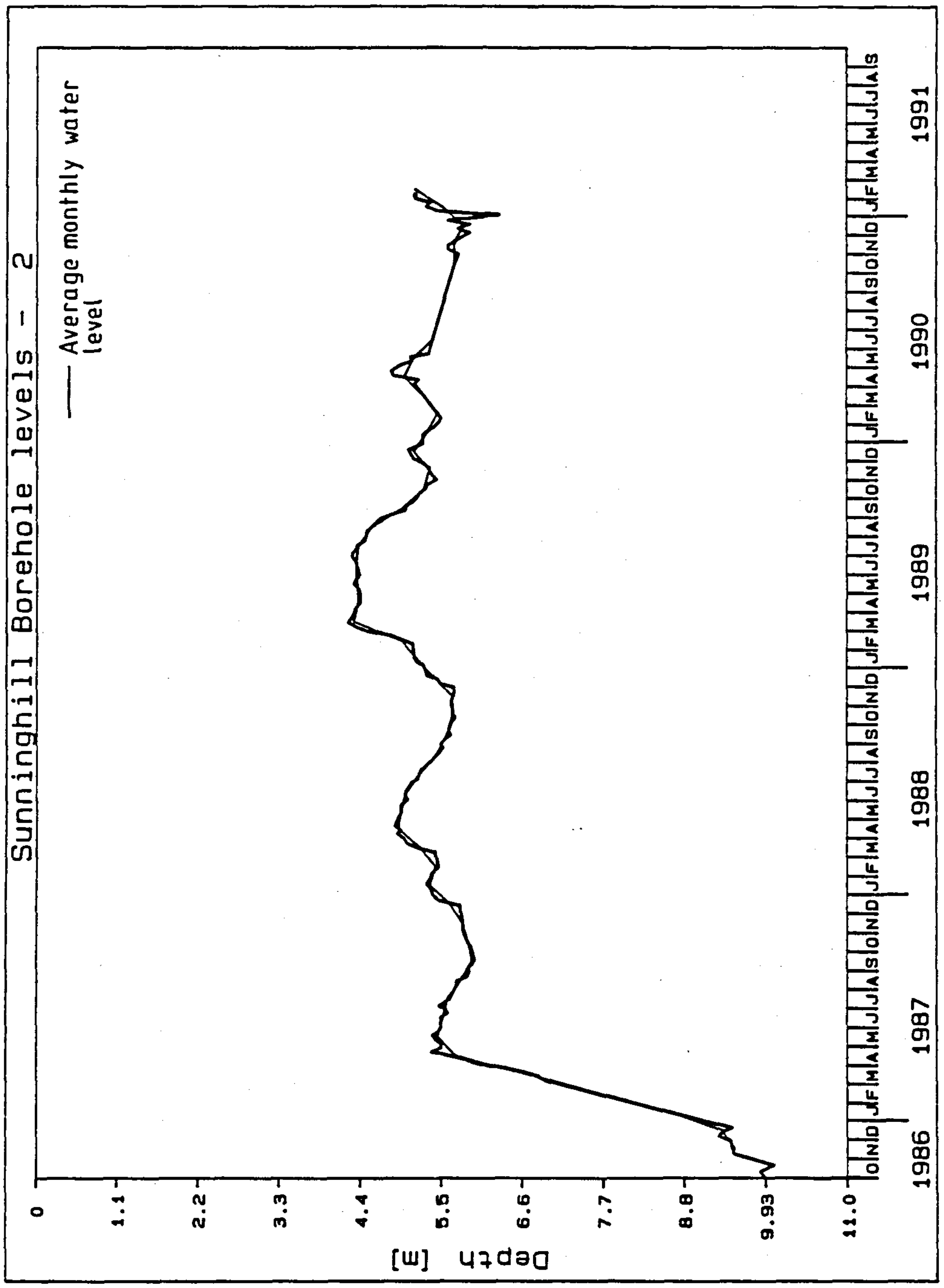



Figure 2.16 - Sunninghill - Borehole 2

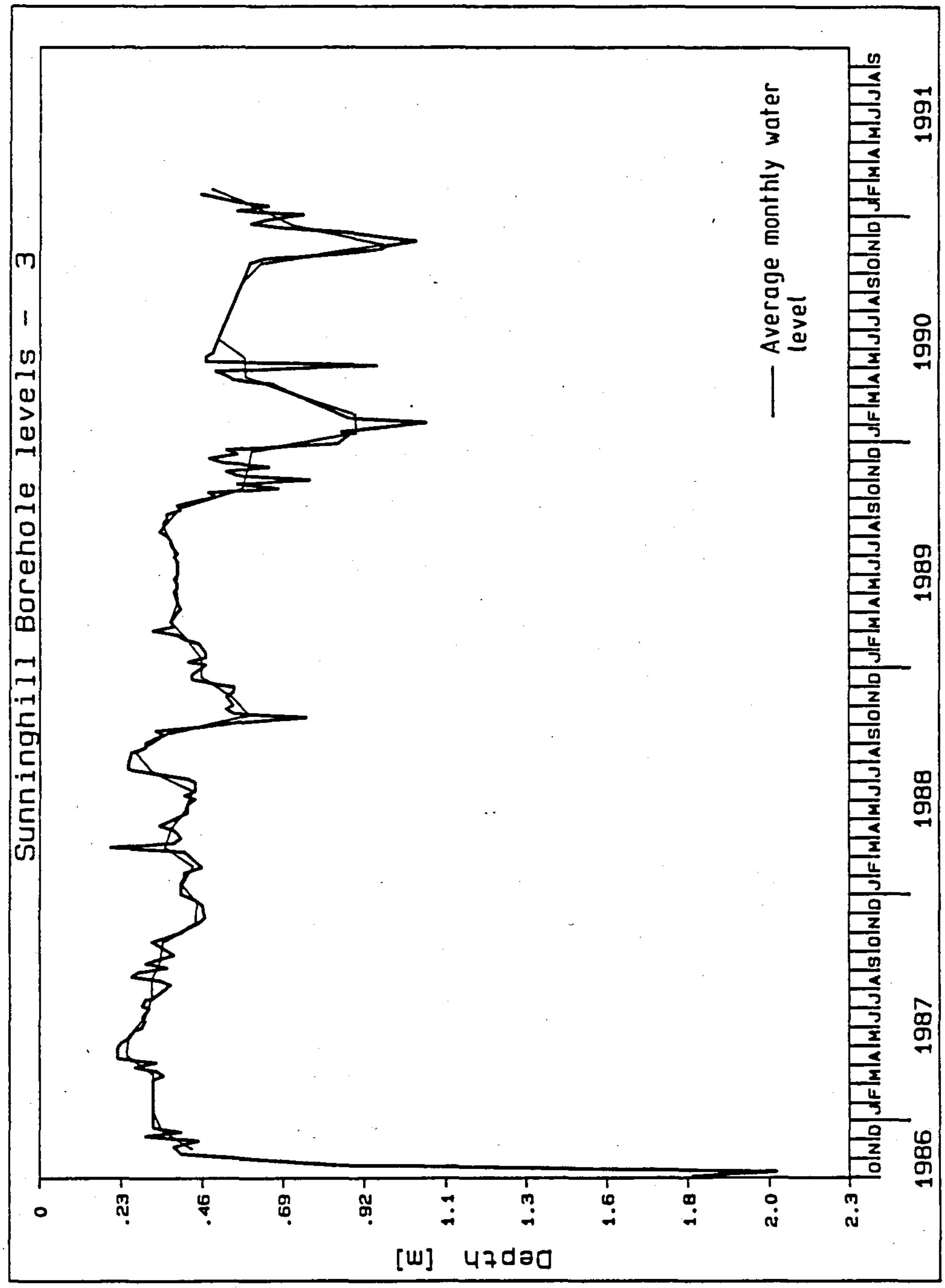



Figure 2.17 - Sunninghill - Borehole 3

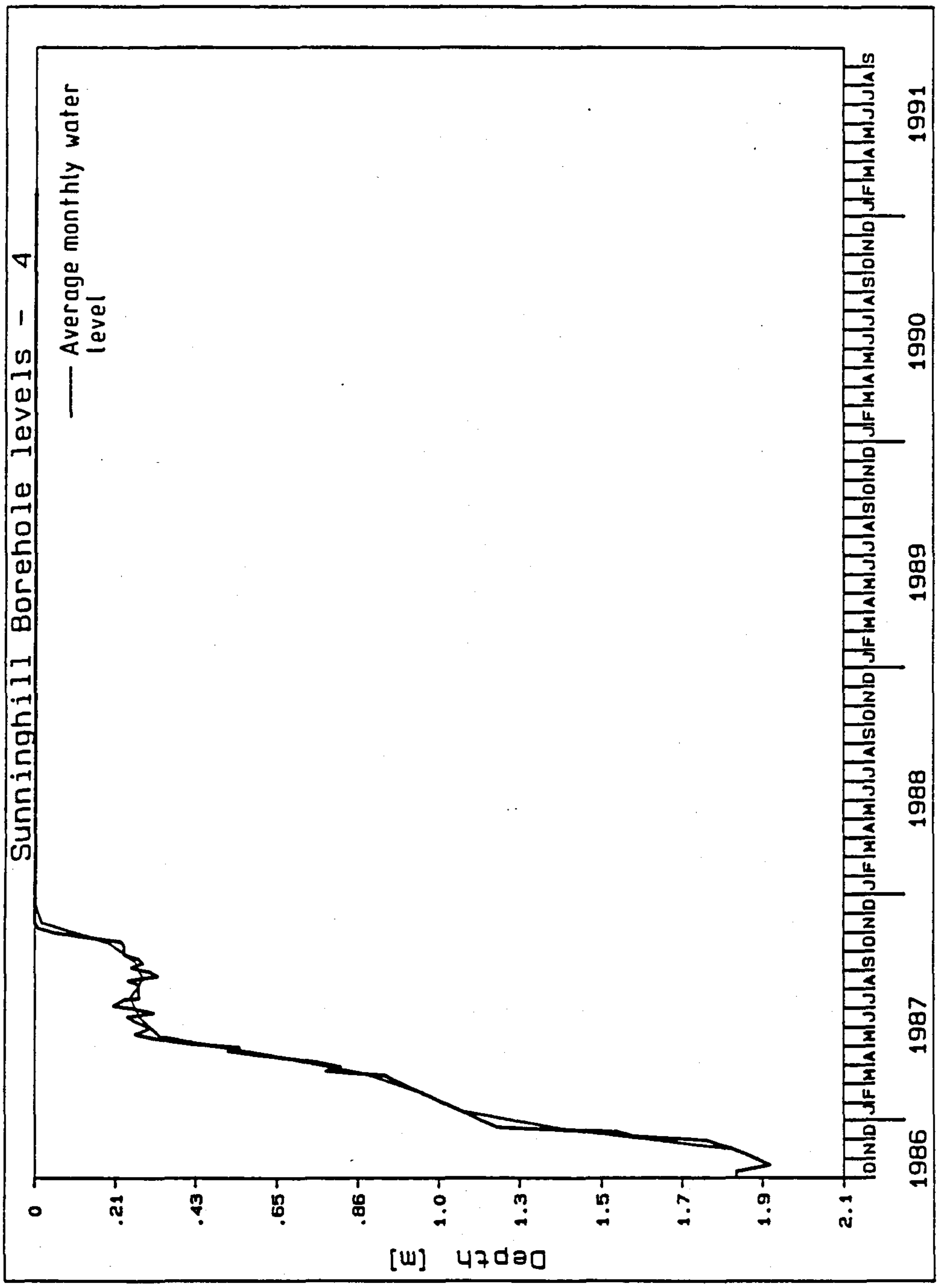



Figure 2.18 - Sunninghill - Borehole 4

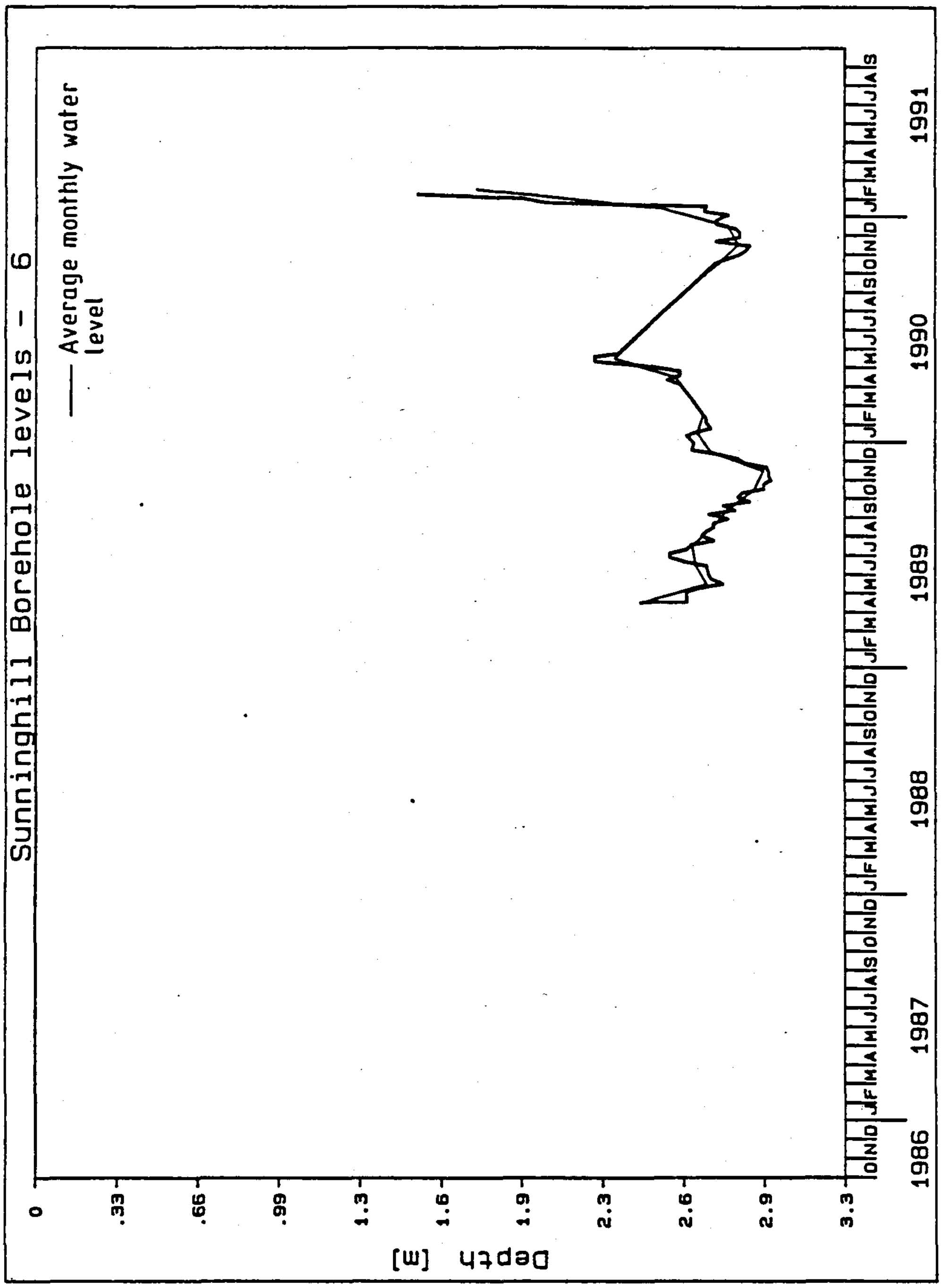



Figure 2.19 - Sunninghill - Borehole 6

Boreholes 2 and 3 are within a few metres of each other and exhibit different characteristics which showing the problems with groundwater variations in granite environments. Both sites are in the 'channel and floodplain' of the catchment, near to the outlet. Borehole 3 is near to an impermeable boundary which explains the high water level. There is a marshy area and fluctuations of water level are very erratic (soil water?). Borehole 2, however, shows a typical seasonal variation. The onset of below average rainfall is observed later in the time series than in borehole 1.

Both Boreholes 4 and 5 operate under artesian conditions, both being in the flood plain of the stream channel.

Borehole 6 (figure 2.19) is on the Northern flank of the flood plain and shows a fairly consistant trend seasonal variation. Being in the flood plain area the response in year 1990/1991 is significant as a result of the phenomena of variable source area hydrology concepts (Bednier, 1981).

#### 2.2.6.2.2 Waterval Boreholes

The Waterval Boreholes are shown in the map in figure 2.20. The borehole water level time series are presented in Figures 2.21 - 2.30. The boreholes are to be found in the top, middle and bottom area of the catchment. The major of the water levels that have been observed since 1986 exhibit a similar trend to these in Sunninghill Park.

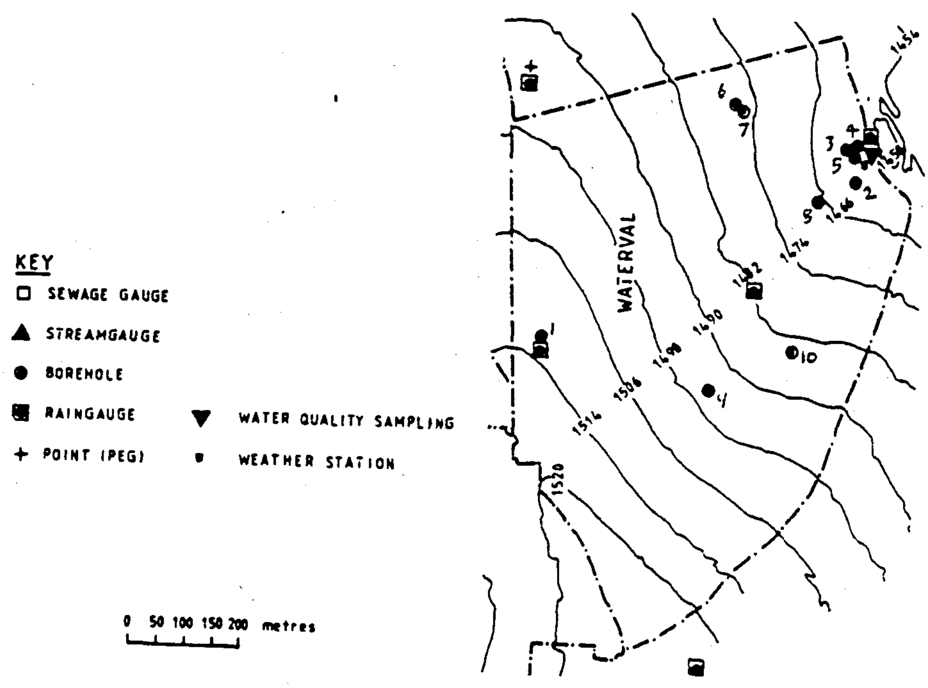



Figure 2.20 - Waterval - Map of Borehole sites

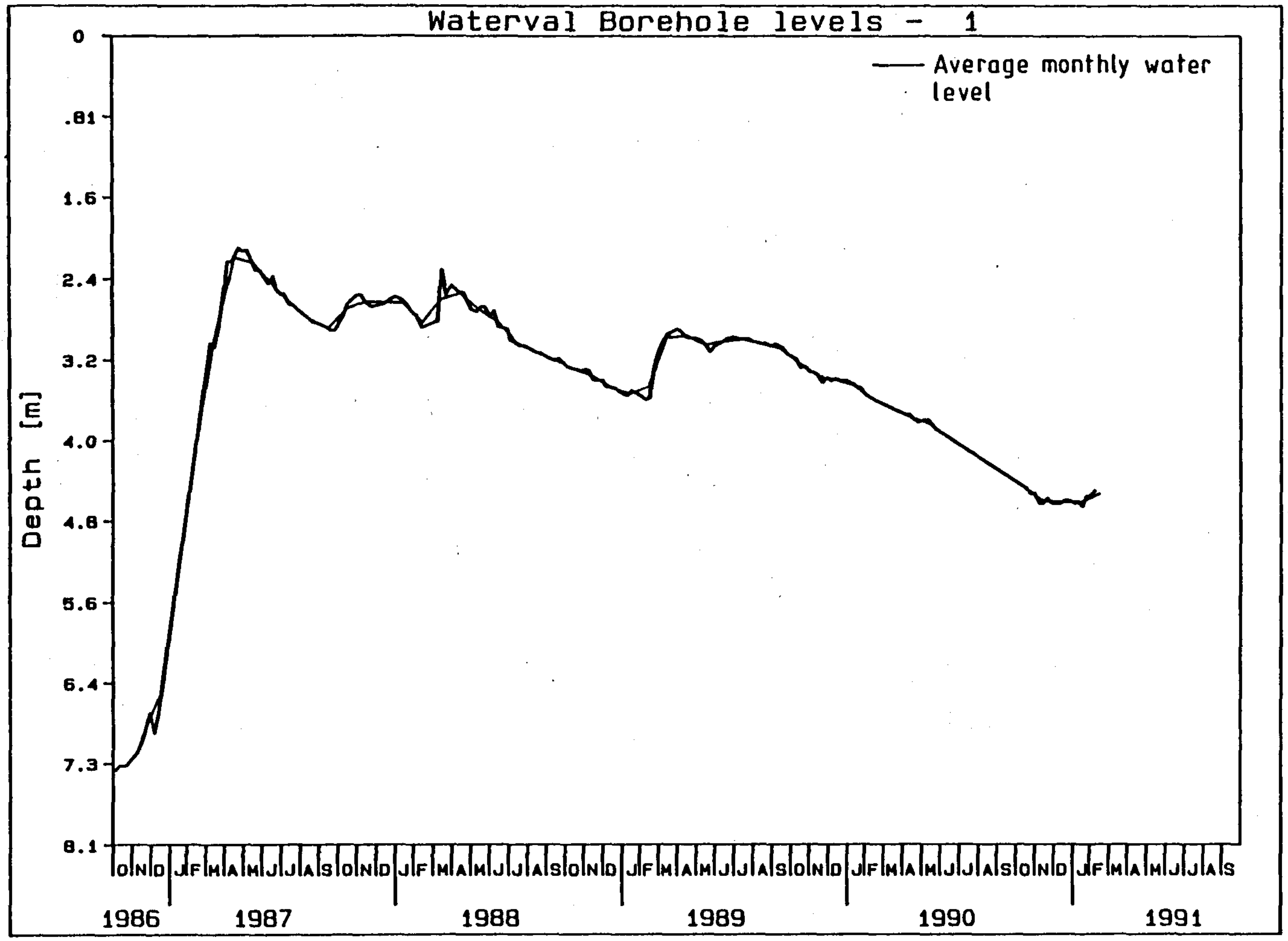



Figure 2.21 - Waterval - Borehole 1

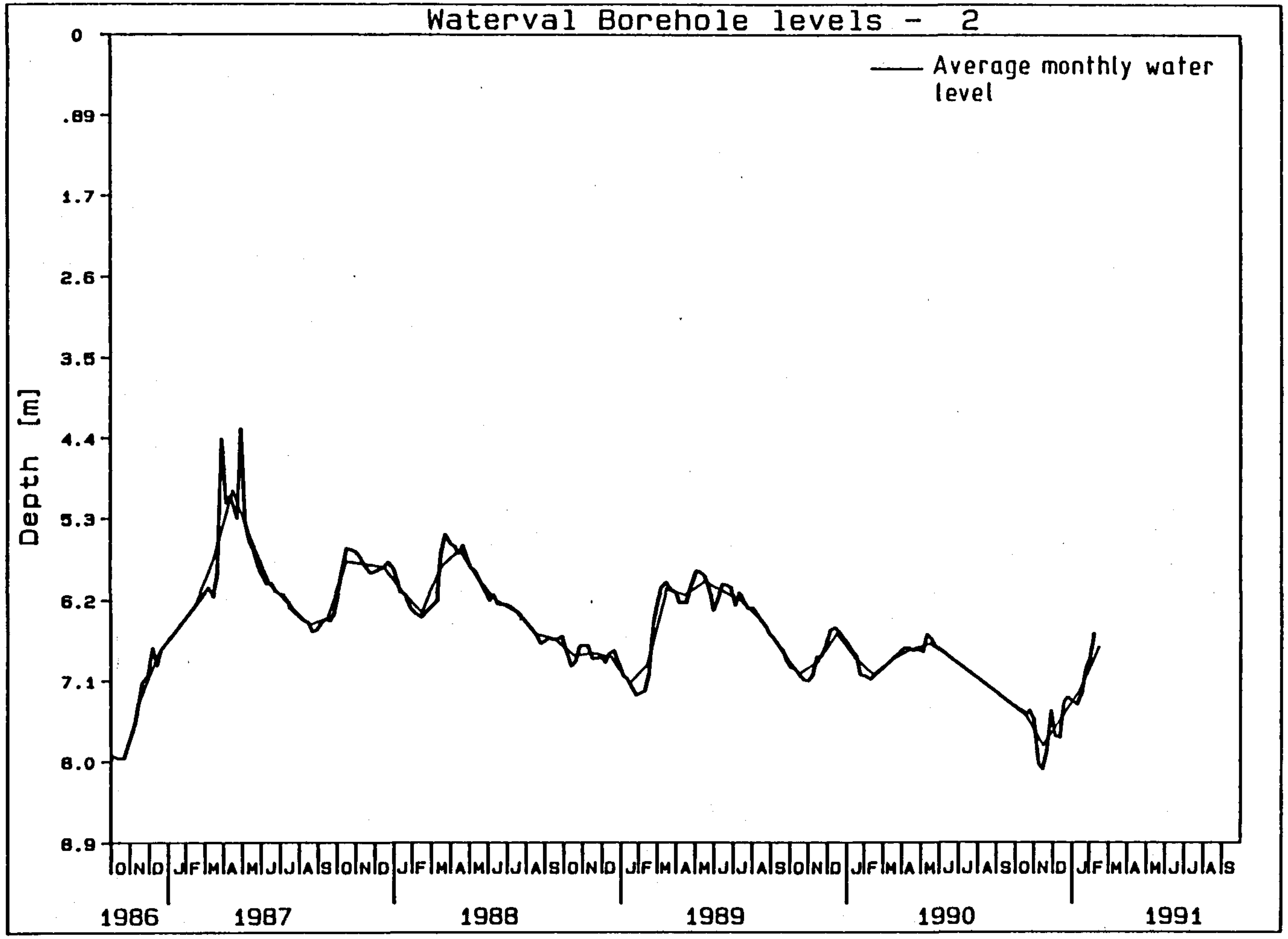



Figure 2.22 - Waterval - Borehole 2

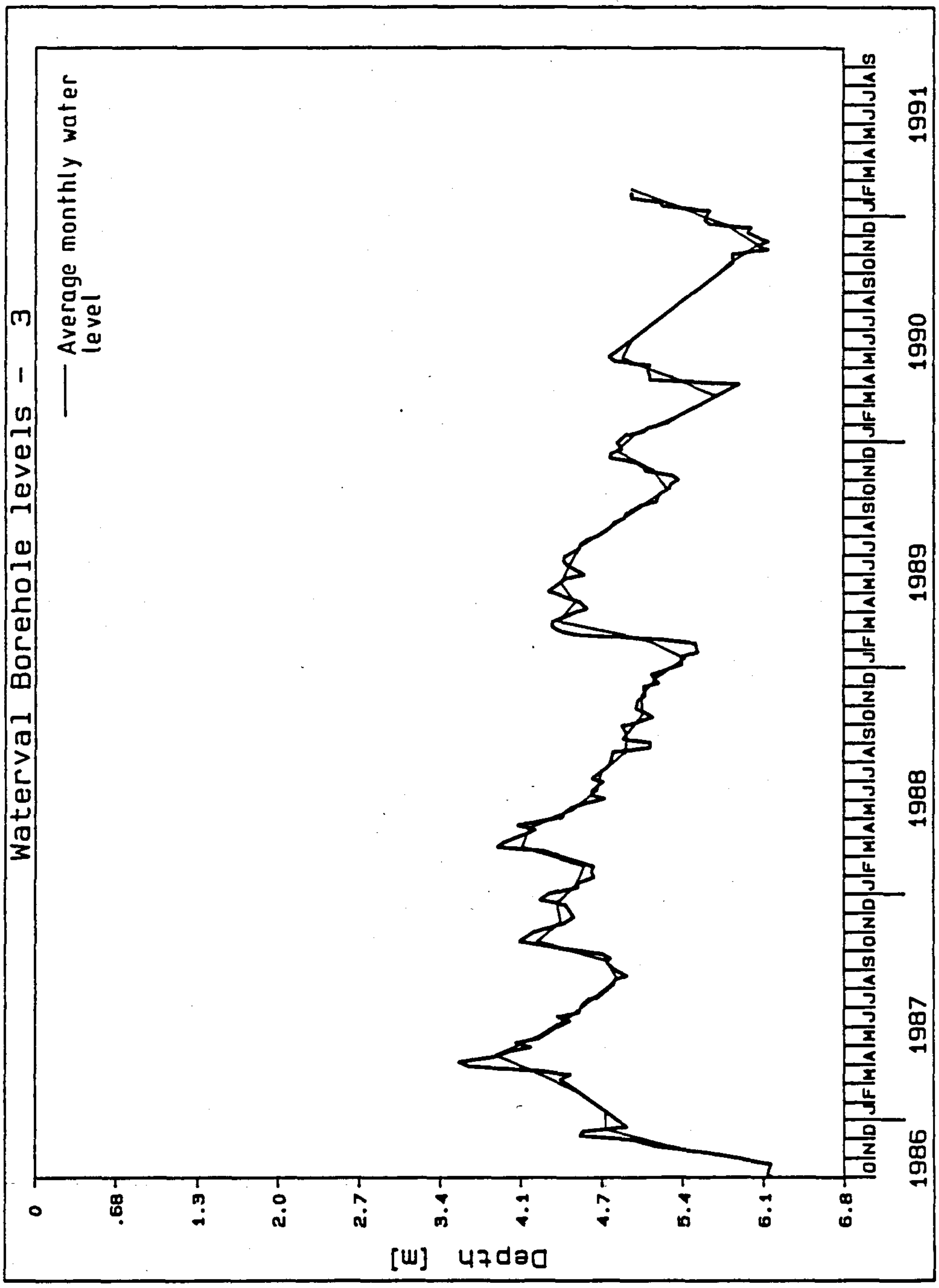



Figure 2.23 - Waterval - Borehole 3

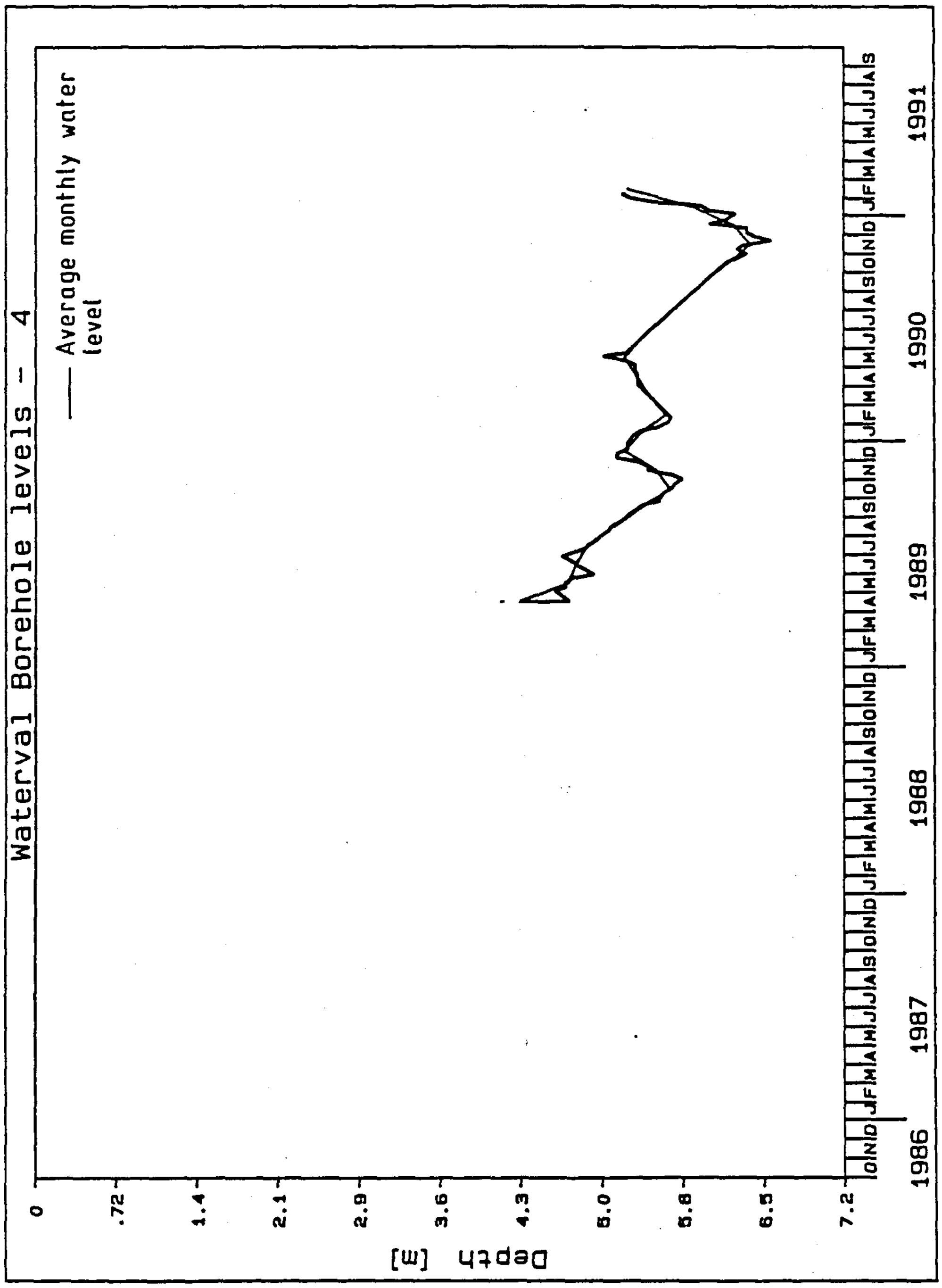



Figure 2.24 - Waterval - Borehole 4

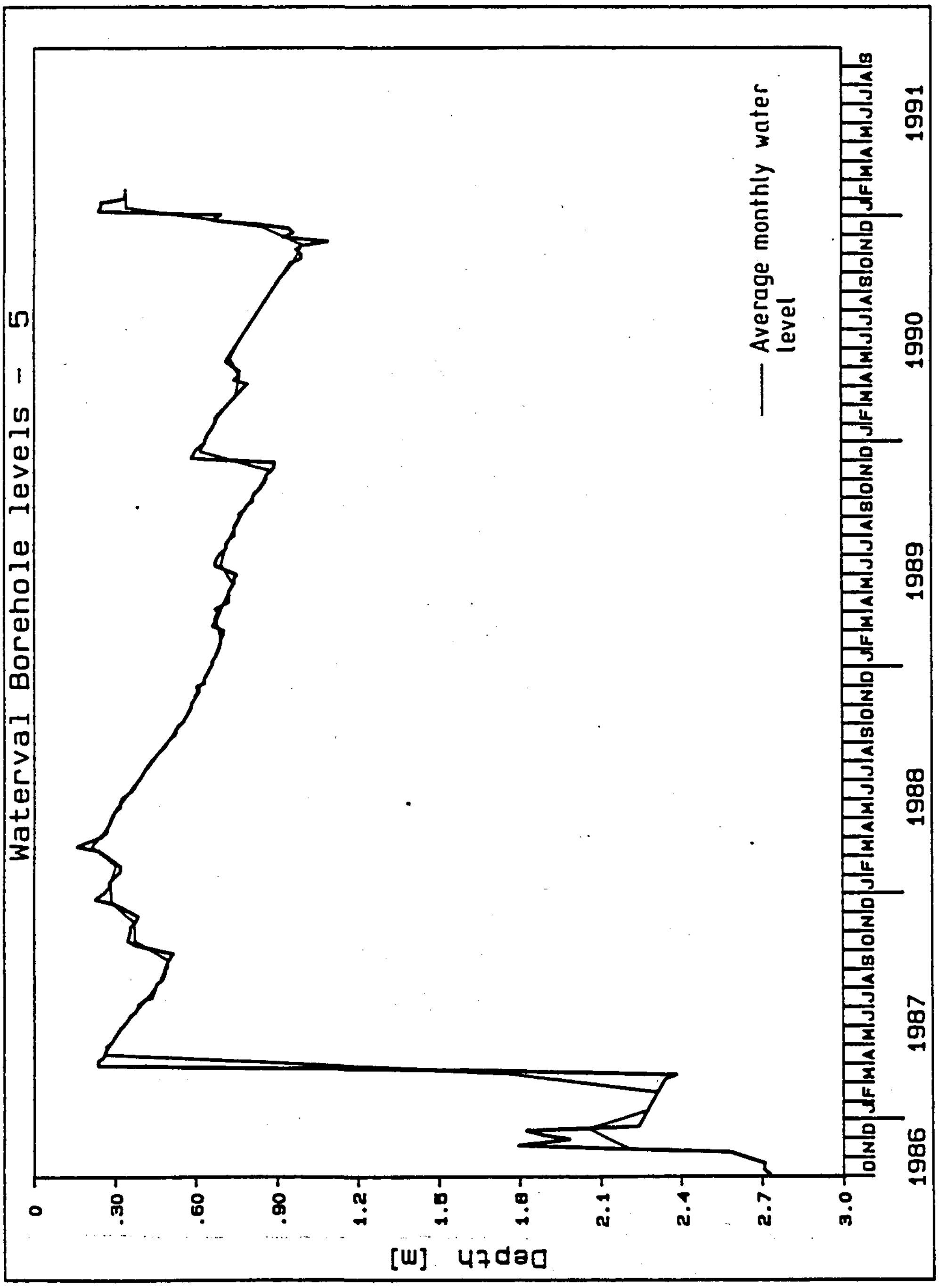



Figure 2.25 - Waterval - Borehole 5

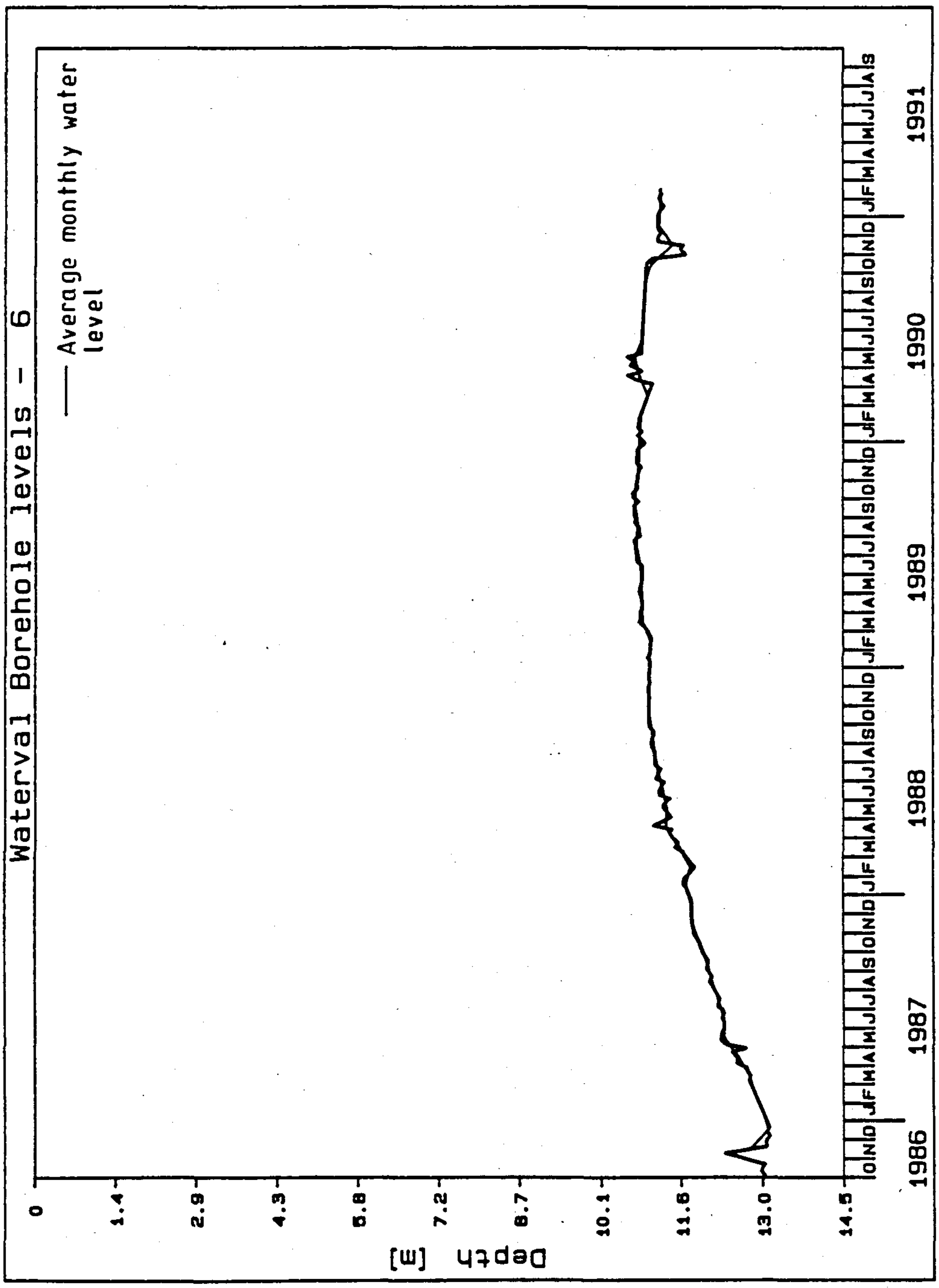



Figure 2.26 - Waterval - Borehole 6

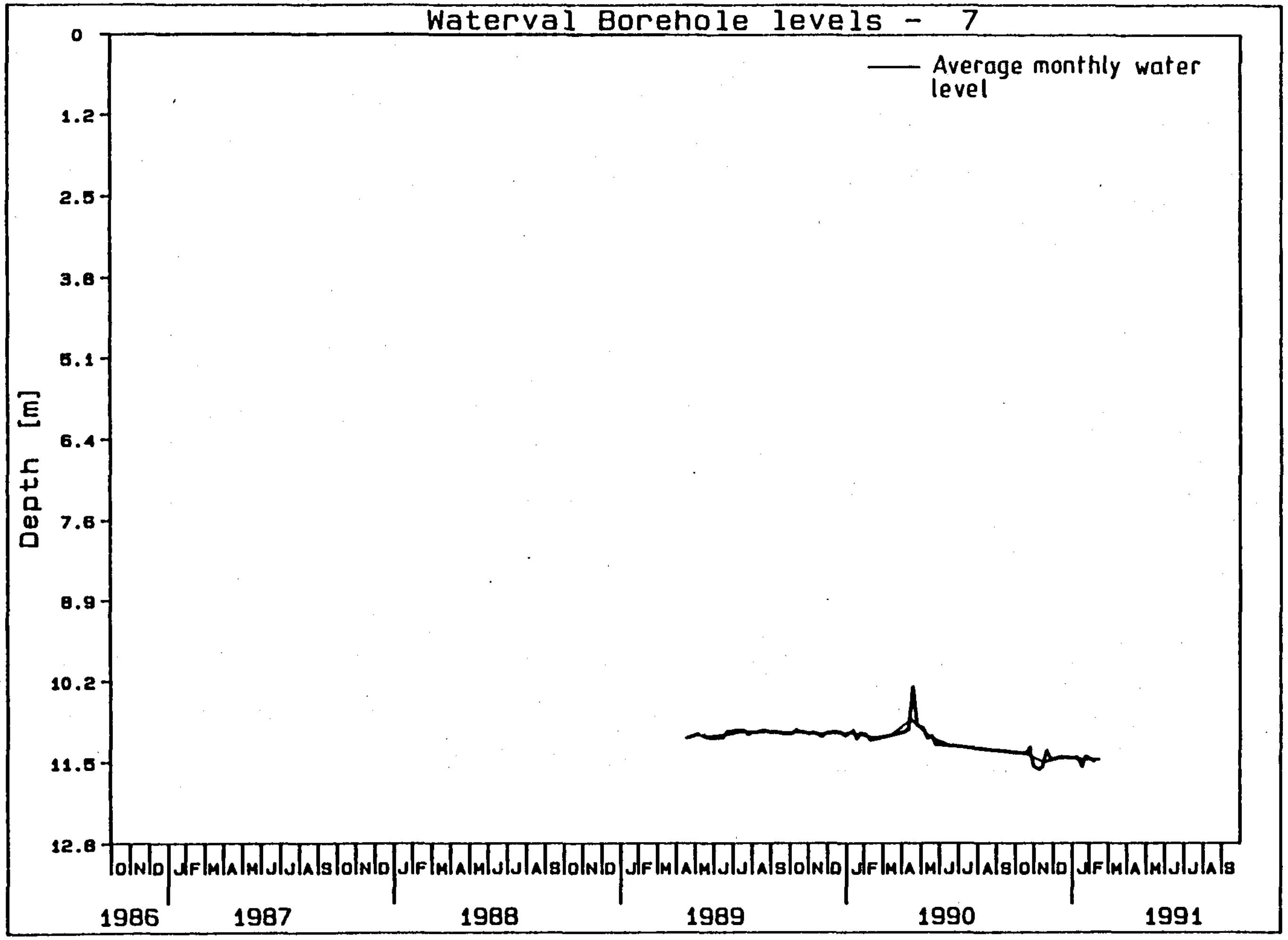



Figure 2.27 - Waterval - Borehole 7

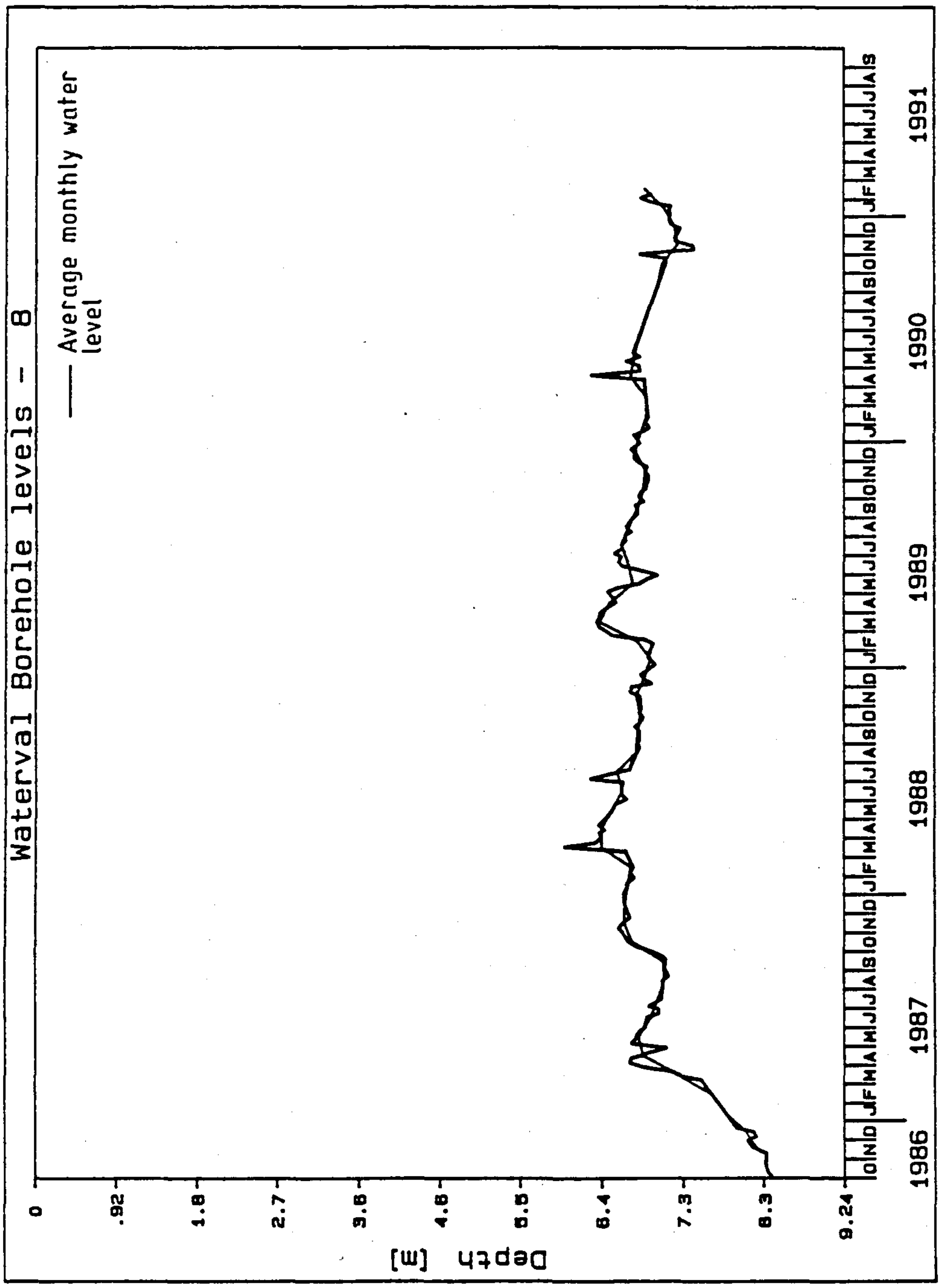



Figure 2.28 - Waterval - Borehole 8

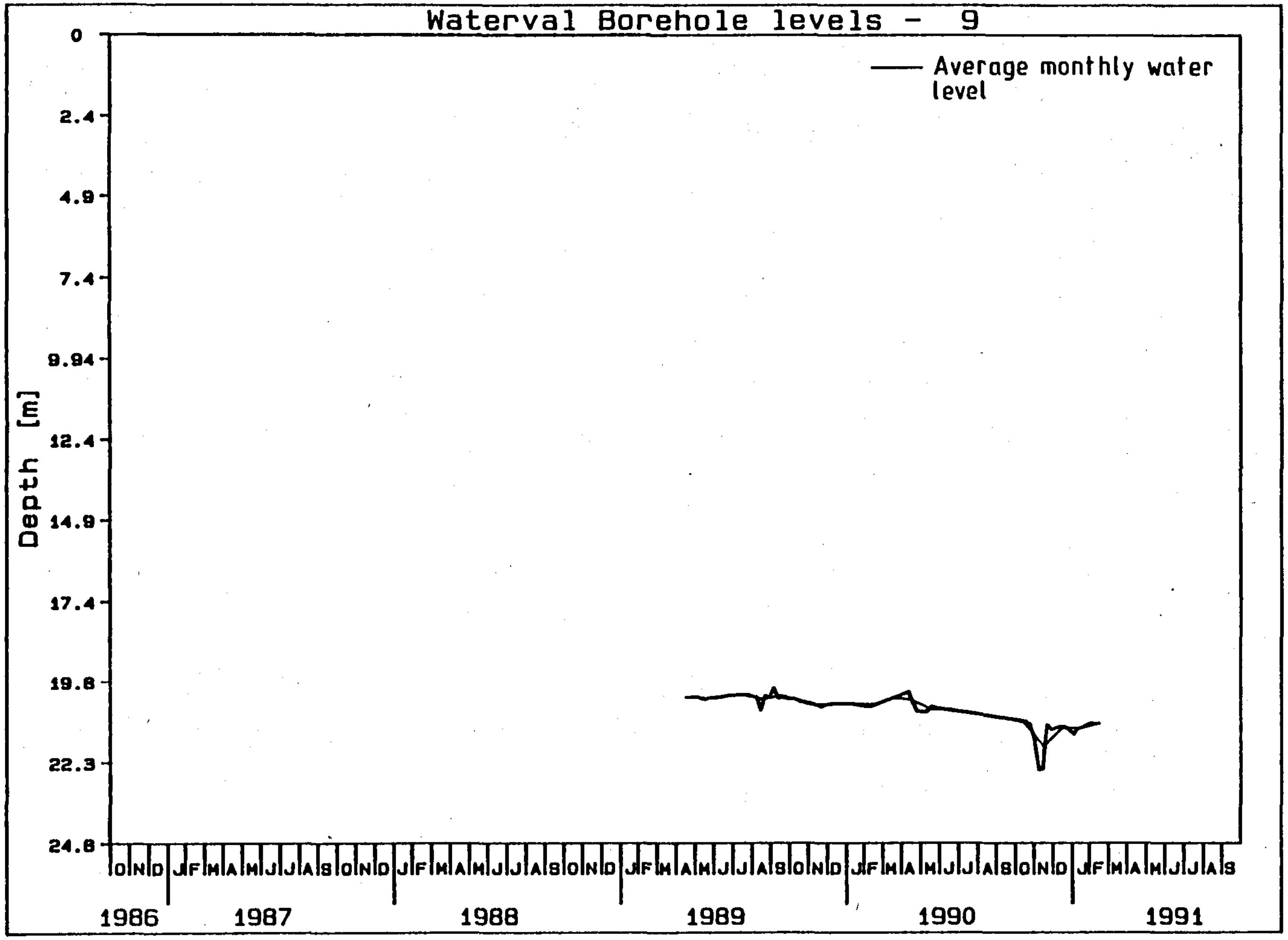



Figure 2.29 - Waterval - Borehole 9

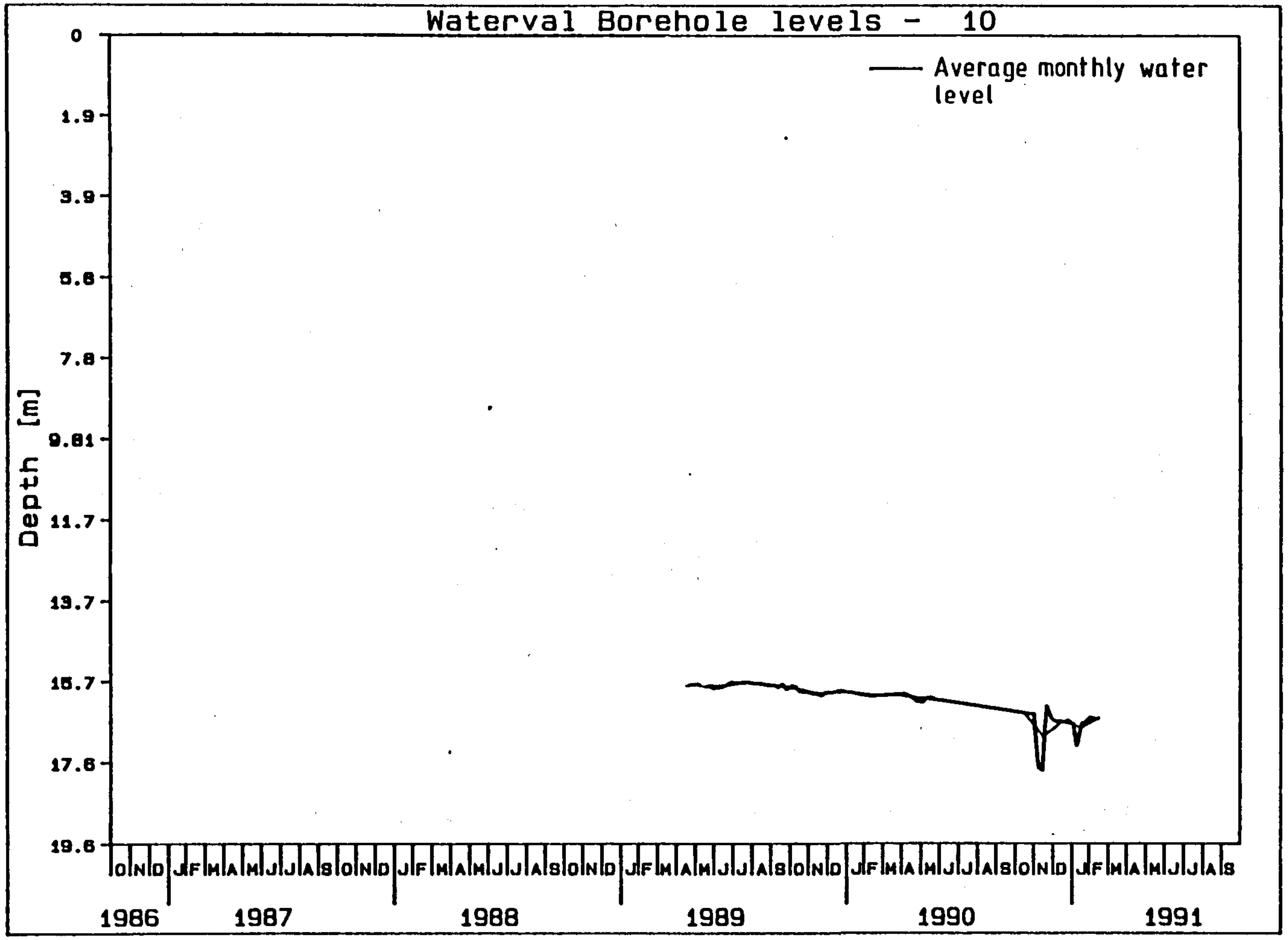



Figure 2.30 - Waterval - Borehole 10

Borehole 1 is the only hole that was sunk at the top of the catchment. The water level shows a dramatic change during the first few months of operation, and then a gradual decline throughout the rest of the observed record.

The boreholes 2,3,4 and 5 are all situated at the bottom end of the catchment within the area dominated by a high percentage clay topsoil. Similar trends are observed with the trend matching the overall rainfall depths. Borehole 5 is different from the others in that the water level is near the surface and therefore changes reflect more the change in water in soil than in the rock.

The middle of the catchment boreholes can be classified into two categories, one being 6,7 and 8 and the other 9 and 10. The geological reports (see catchment descriptions report) show that different soil/rock combinations occur in these two areas. This is also reflected in the vegetation. The change in water level in these boreholes is one of smooth variations. The boreholes 9 and 10 have water levels at a greater depth than the others and hence recharge and discharge from these is a slow process.

### 2.3 Summary

This Chapter contained a description and discussion of the parameters that were measured in the Waterval and Sunninghill catchments during the period September 1986 until February 1991. Each parameter; namely rainfall, runoff, water supply, sewage, maximum evaporation and borehole water levels were discussed. Graphical plots of the time series data in a suitable unit were also presented. The limitations and inconsistencies in the data stream were discussed, especially in relation to the runoff measurements.

The runoff data which was measured in both catchments was patched, using simulation methods, as the original data set was discontinuous. Two methods of simulating the missing runoff data were attempted, these being the application of the WITSKM model (the single event version is described in Report 8 in the series by Coleman and Stephenson) and the Daily Pitman Model (Pitman, 1976).

Both models were unsatisfactory at simulation of the daily flows from the catchments. The WITSKM model underpredicted the small events and over-predicted the large events. The calibration dataset to Sunninghill Park, which was used to successfully model the runoffs examined in the single event model report, was modified to account for the difference in urbanisation (i.e. increased urbanisation). However, during a long simulation of two months (December 1990 and January 1991) the discrepancies in flows were unacceptable. The Pitman model also was inaccurate in daily comparisons. The monthly totals from both models were of acceptable accuracy so it was decided to use the

Pitman model to generate monthly flows from daily simulation. The WITSKM model would have required modifications to the formulations of the routing equations, or, if left to calculate at five minute time steps would have taken $\pm$ $3^1/_2$ months of continuous calculation.

The runoff date is therefore an estimate of the actual runoff. In the case of both catchments, the runoff is a small fraction of the total water balance, so the errors in estimation are small when compared with estimates of Total Evaporation. Methods of overcoming the deficiencies in runoff simulation are presented in the Suggestions for future work section of this report.

## CHAPTER 3 WATER BALANCE OF CATCHMENTS

### 3.1 Introduction

The comparison of water balance between the two catchments was undertaken in this report using data presented in the previous chapter. Some of the data was simulated and others were the actual measured values in the catchment. Perhaps the biggest error will result from the estimation of the Total Evaporation. The Maximum Evaporation was estimated using the method described in the previous chapter. However, in terms of the water balance, information is required on the Total Evaporation.

This Chapter will discuss the calculation of the total evaporation and then present the full water balance based on the information, both collected and simulated.

### 3.2 Calculations of Total Evaporation

#### 3.2.1 Introduction

The procedure that was adopted for the estimation of the Total Evaporation would be expected to influence the final water balance. There are two approaches that can be used to estimate the Total Evaporation both of which use simulation techniques, as it was not possible to measure Total Evaporation over such a wide area. The use of lysimeters was contemplated, but was excluded as several plots would have to be measured which would entail large scale constructions and also add to the existing data logger problems. Being point source devices, the variability could only be achieved by the use of several instruments.

The two simulation techniques that could be used are a), people available water capacity (PAWC) calculations (De Jager et al 1989, Laker et al 1989), and b), the use of crop factors e.g. (Dent et al 1989). Both have their merits and disadvantages as will be discussed below. The PAWC model used rooting distribution and accounts in detail for the moisture fluxes from a biosphere point of view. Most of the parameters used in the modelling approach have been geared towards commercial crops and not natural terrain vegetation types. The other, more simple method uses crop factors that are applied to the Maximum Evaporation to estimate the Total Evaporation, dependent on the moisture content of the soil. A varying level of sophistication can be built into the model to account for the different growing seasons.

#### 3.2.2 Estimation of Total Evaporation

It was decided that, in keeping with the global water balance comparison of the two catchments, (bearing in mind that water supply in the Sunninghill catchment was measured only every 3 months and averaged) the latter model using crop factors would be used. Factors that were used in this rather simplistic approach were soil factors, vegetation factors and rainfall inputs. Also a surplus of water supply (excess over and above Sewage Outflow) was added in the Sunninghill Catchment as input to the soil/vegetation model.

The Maximum Evaporation (as computed in Section 2.2.5) was used to indicate the potential amount of moisture in the soil that could be evaporated. The vegetation factor was used to give a value of the interception of rainfall, and it was assumed that this will be evaporated directly. The infiltrated water will form part of the soil moisture store. Percolation of the water into the deeper soil/groundwater zone will be a function of the soil factor used in the model. Table 3.1a and 3.1b show the values used in the simplified total evaporation model for soils and vegetation respectively.

TABLE 3.1a - Soil Factors

| Soils Class | Percolation Rate cm/h |
|---|---|
| Sand | 12 |
| Sand, Loamy Sand | 5 |
| Loamy Sand | 3 |
| Sandy Clay | 0.15 |

TABLE 3.1b - Vegetation Factors

| Vegetation | Interception Amount mm |
|---|---|
| Houses, Roads | 0.1 |
| Veld with Rock | 0.5 |
| Lawn | 1 |
| Grass and Trees | 2 |
| Veld and Trees | 3 |
| Dense Trees | 4 |

The values of the two above Tables (3.1a and b) were then weighted according to the areas of occurrence in the catchment. It can be seen that no account was taken of the growing seasons.

The total evaporation was then calculated for both sites and is presented in figures 3.1 and 3.2 for Sunninghill and Waterval respectively. The graphical output is from July 1987 to February 1991 only, the reason being that the Weather Station was not commissioned until after the first years rainy season. The trend of the traces follow very clearly the rainfall, which is to be expected.

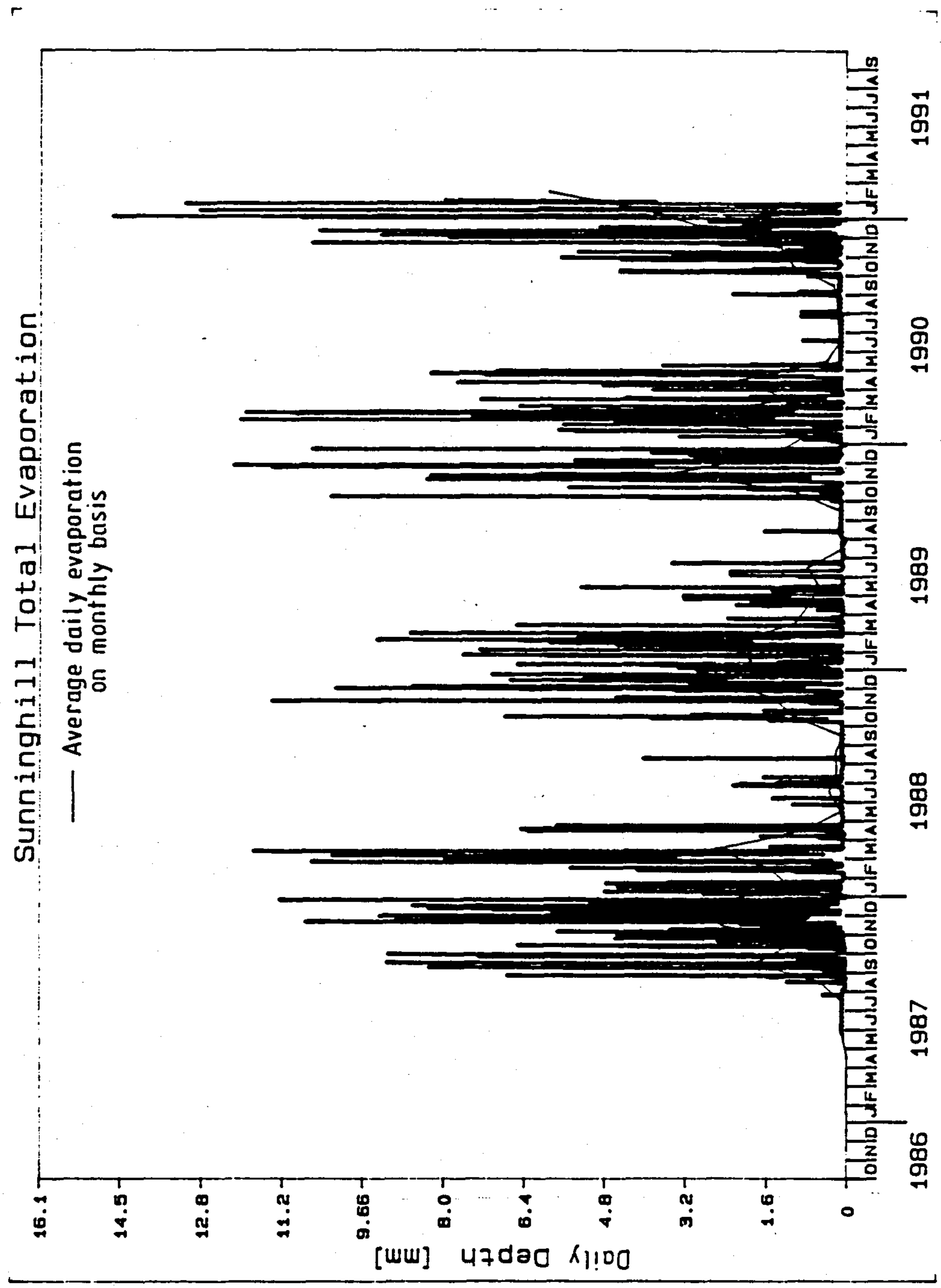



**Figure 3.1 - Sunninghill - Total Evaporation (Estimated)**

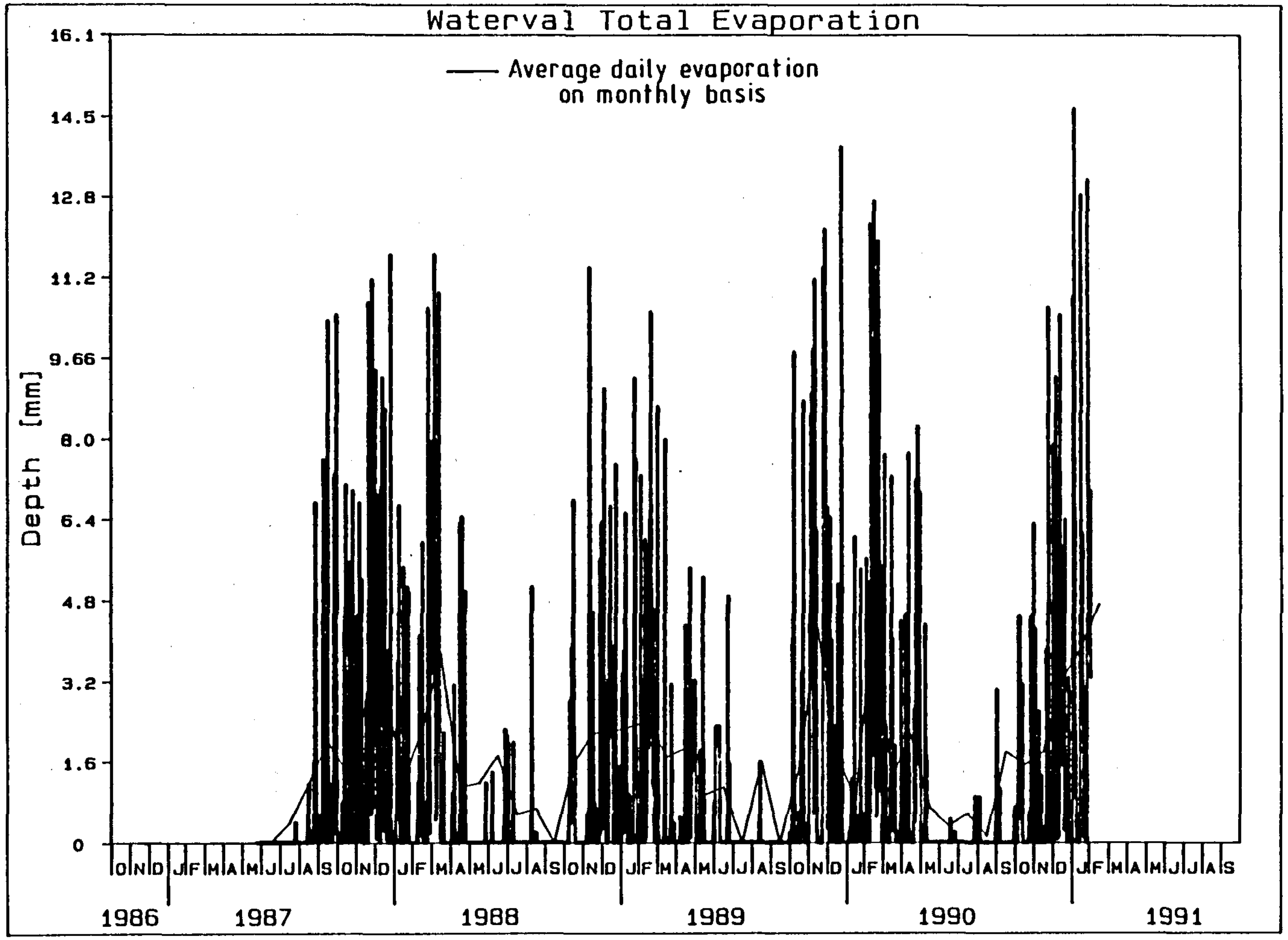



Figure 3.2 - Waterval - Total Evaporation (Estimated)

### 3.3 Water Balance

With the data collected in the two catchments, coupled with the estimated total evaporation, it is possible to assess the overall water balance. The values that were collected on a continuous or daily basis were summed to give monthly results. The water supply, being only every three months, was averaged over the period that the reading applied. The Weather Station parameters, which were used in the estimation of maximum evaporation, were available from 1987 (gauge was commissioned in Mid 1987) and hence all comparisons should only be compared from that date. The water balance before 1987 therefore only includes rainfall, water supply and runoff. The total evaporation has been omitted. The sewage flow was found to be a fraction of the total water supply (average of $2/_3$rds) and this assumption was made in use of the sewer flow, to patch from 1988 back to 1986.

Using the water balance equation stated in Section 1.1, the sub-surface store was calculated on a monthly basis. The parameters for each catchment were then plotted in absolute terms, where the monthly time series of flows (in 1 000$m^3$) in each component were presented (see figures 3.3 and 3.4). The Sunninghill Park Catchment (figure 3.3) has the extra urbanised parameters, namely water supply and sewer flow. The first rainy season in both graphs should be treated with caution since no Total Evaporation component is included. The decrease in rainfall in both catchments over the observation period can be seen in both graphs. The effect of urbanisation can be detected by the steady increase in water supply (in the Sunninghill Catchment). The Runoff from both the catchments only contains the surface or direct runoff, and the outflow from Sunninghill (2l/s) forms part of the subsurface store time series. The rainfall rate appears to decrease after 1986, whereas total evaporation continued to exhibit regular seasonal cycles.

Total surface runoff from Sunninghill (the interflow component has been removed from the data) is five times that from Waterval (fig 3.5). No difference in total evaporation resulted from the figures (fig 3.6) indicating that the possible increased garden water (although this was not directly measured) balanced the reduced vegetated area. The two diagrams (figures 3.5 and 3.6) were plotted using a double mass curve approach which shows the differences more clearly.

It must be borne in mind that the runoff was not observed in its entirety and that the record had to be patched by correlation with rainfall. Thus, the use of statistical procedures to detect differences that were not observed from the plots would not be justified.

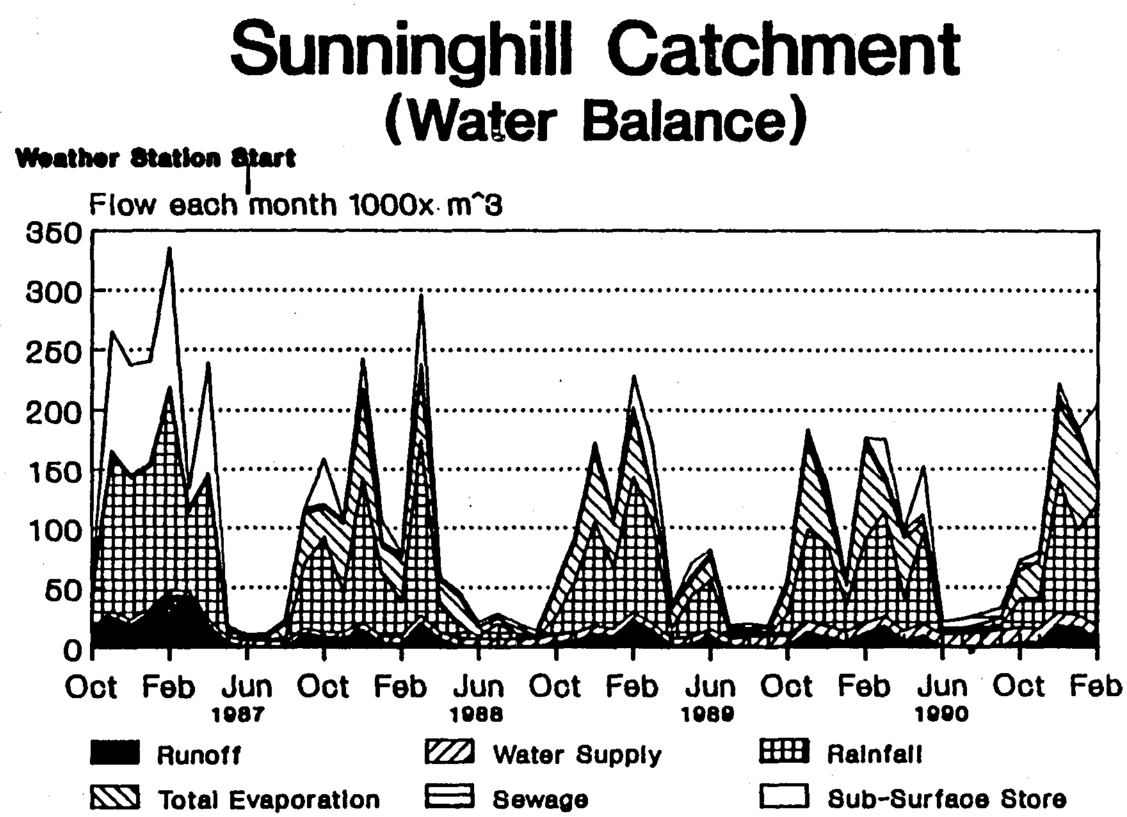



Figure 3.3 - Sunninghill - Absolute Mass Balance

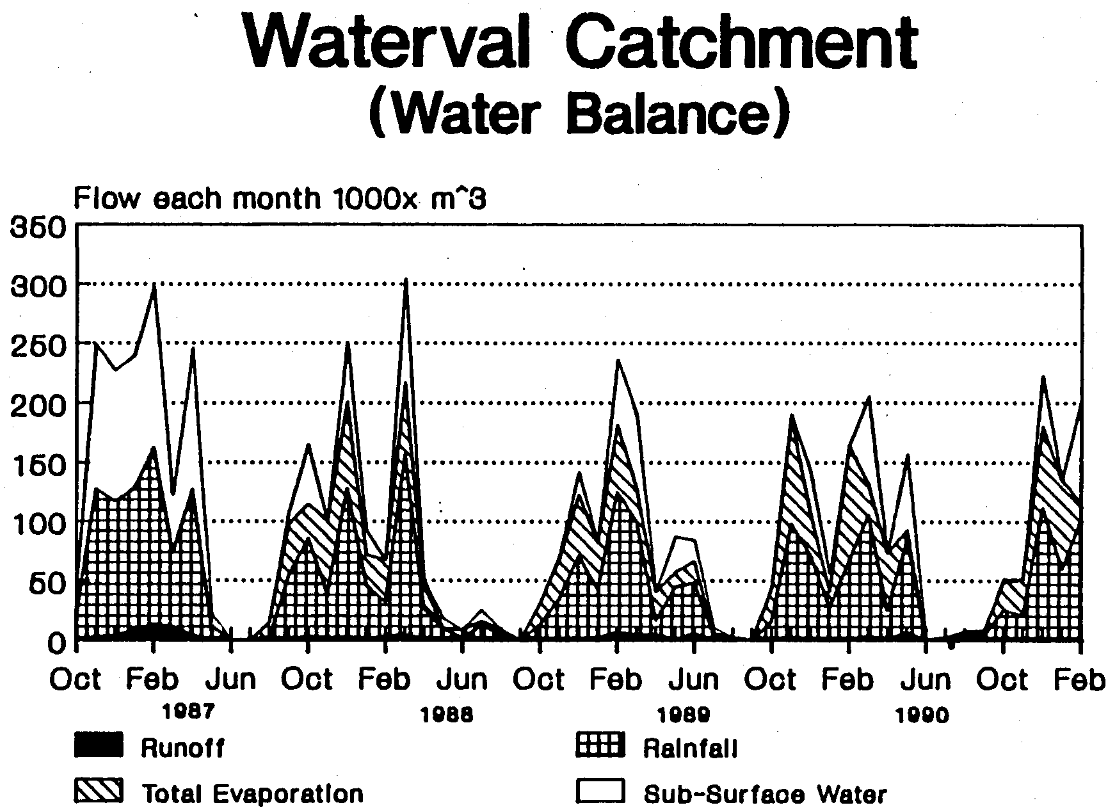



Figure 3.4 - Waterval - Absolute Mass Balance

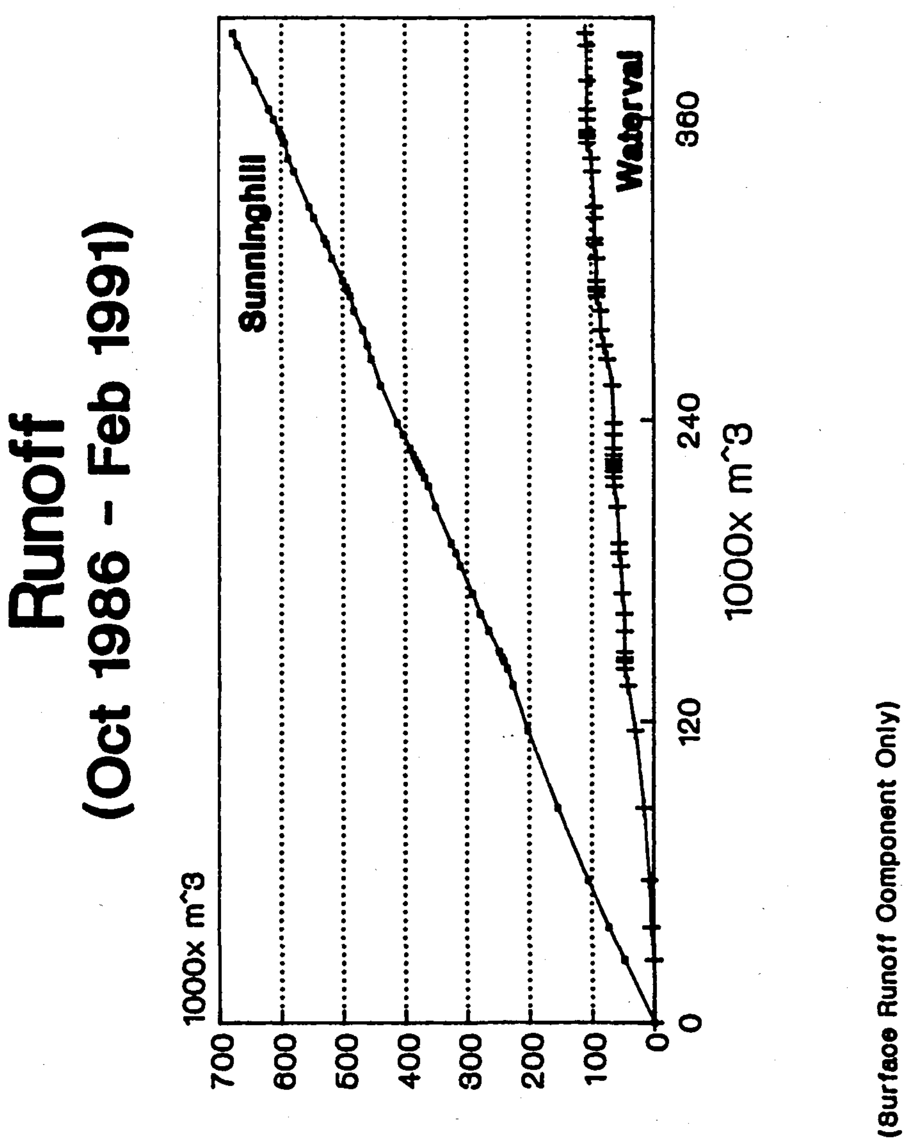



Figure 3.5 - Double Mass Curve Relationship of Sunninghill and Waterval Surface Runoff

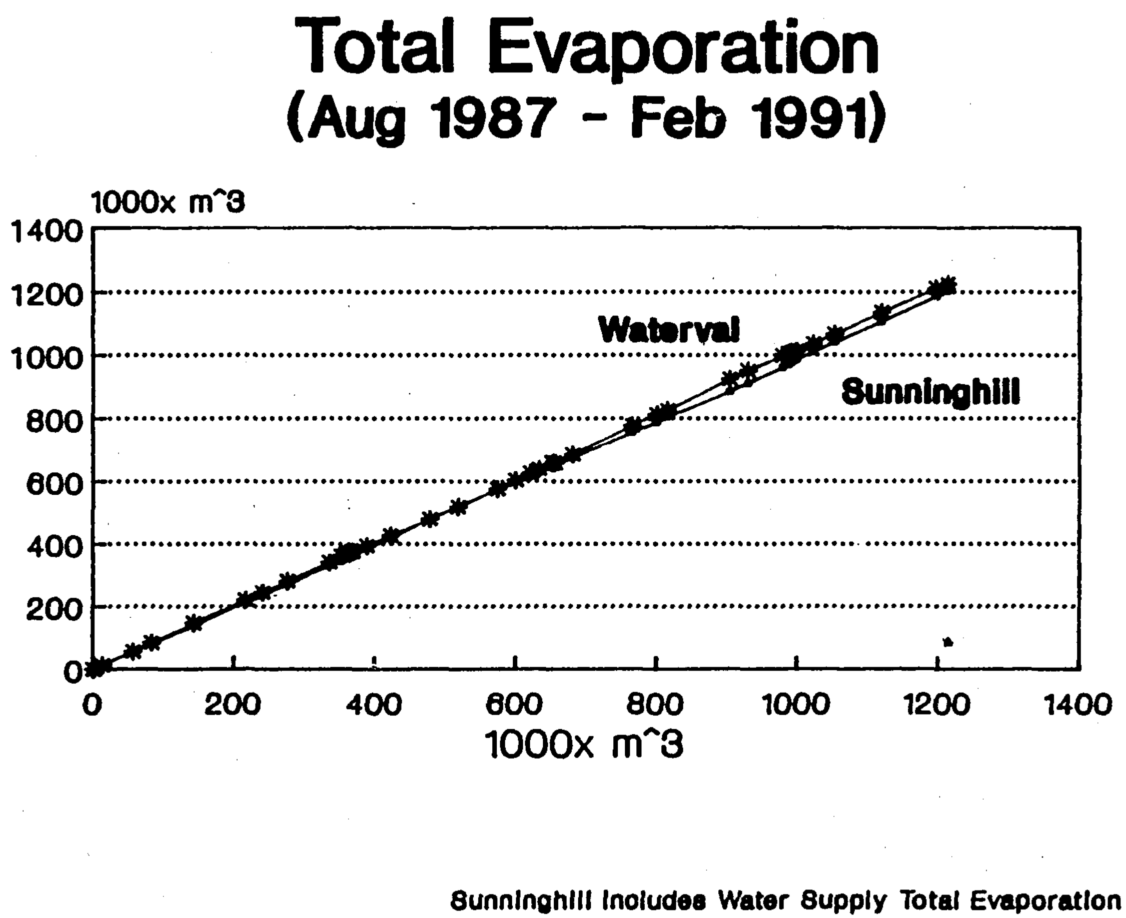



Figure 3.6 - Double Mass Curve Relationship of Sunninghill and Waterval Total Evaporation

## 3.4 Summary

This chapter described the method of calculation of the total evaporation component of the water balance. The assumptions and simplifications that were used in its estimation were stated. Water Balance diagrams in various different forms were presented to highlight the aspects of the water balances in the two catchments. The water balance diagrams were compared on the basis of the effect of urbanisation on the overall global monthly water balance of the catchments.

# CHAPTER 4 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

## 4.1 Conclusions

This report describes the data that was collected, the simulated and patched data sets, and the use of the information to provide a global water balance for the two catchments in this study. The aim of the study was the comparison of two adjacent catchments, one urbanised and the other rural. It was apparent that a learning curve in the use of electronic data gathering equipment had to be overcome before attempting studies of this nature. This conclusion was reflected in the quality of the data that was collected in the early stages of the project. In fact, it was only data collection in the last year of the study, that yielded data of sufficient quality for modelling purposes.

The study showed that varying levels of water balance study can be undertaken, dependent on the complexity and amount of raw data collected. Obviously with such a short time series it is not possible to use an annual water balance (which is common with other studies - see Grimmond and Oke 1986). At the other extreme the minimum time step of the collected data would determine the time interval used in the water balance. The water supply was only sampled on a three month basis, so theoretically a seasonal time interval should have been used. It was decided, however to average the water supply which would enable a monthly water balance to be undertaken. In keeping with such a coarse time step (certain parameters were measured on a finer time step), each catchment was lumped as one 'homogenous' unit.

The results of the study were by no means conclusive and various suggestions for further work have resulted. Suburban Development increased surface runoff by a factor of 5 over an otherwise similar undeveloped catchment. This is largely due to impermeable cover. The frequency of flood runoff for the developed catchment also increased due to rapid concentration of flow. The major loss, due to Total Evaporation was 67% of precipitation for both catchments, and water tables in both catchments varied similarly. Garden watering appeared to compensate for increased runoff from the suburban catchment.

A total numerical balance for the catchments is shown in figure 4.1.

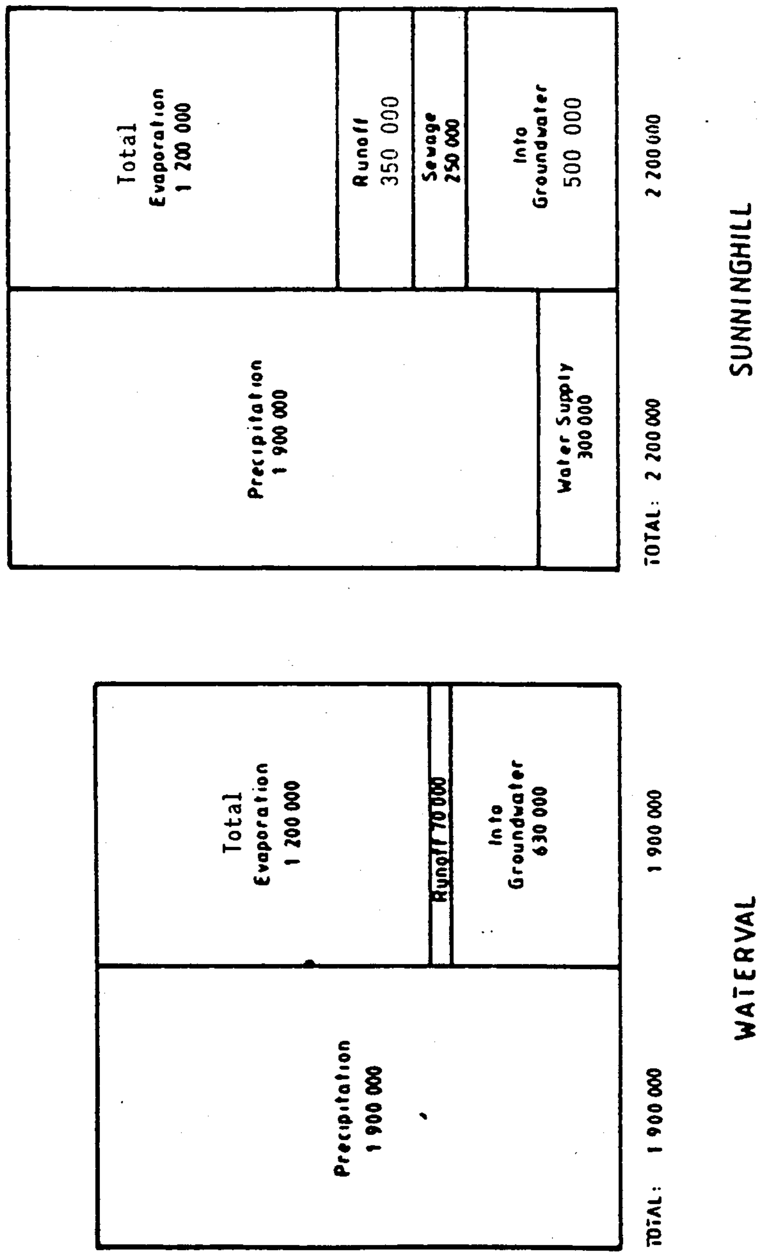



Figure 4.1 Total water balance of both catchments. Cumulative flow in $m^3$ over 3.5 years, August 1987 to February 1991

## 4.2 Recommendations for further work

The recommendations for further research are listed as follows.

The data set needs to be expanded using good quality data such that the errors introduced by the patching and simulation techniques are minimized. A wide range of meteorological conditions (from a rainfall point of view, i.e. a longer record of data) would allow the investigation of extremes in the catchments.

The estimation of total evaporation would be enhanced by employing both a distributed and seasonal growth modelling approach. Calibration of such a model using soil moisture access tubes (possibly neutron measurements) would be required. The verification of a soil/vegetation interface model would increase the understanding with a view to making the scale change from single event to continous modelling.

With the finer resolution in terms of space and time, a more sophisicated way of measurement of sewer flows would have to be developed. It was shown in this study that the man-made influence could only be considered as average values in the overall water balance. The water supply data also needs to be measured on a more frequent basis if the interaction between rainfall and water supply are to be understood such that the irrigation of gardens can be better managed. It was shown in this study that that increased water supply occurs when the soils in gardens are stressed.

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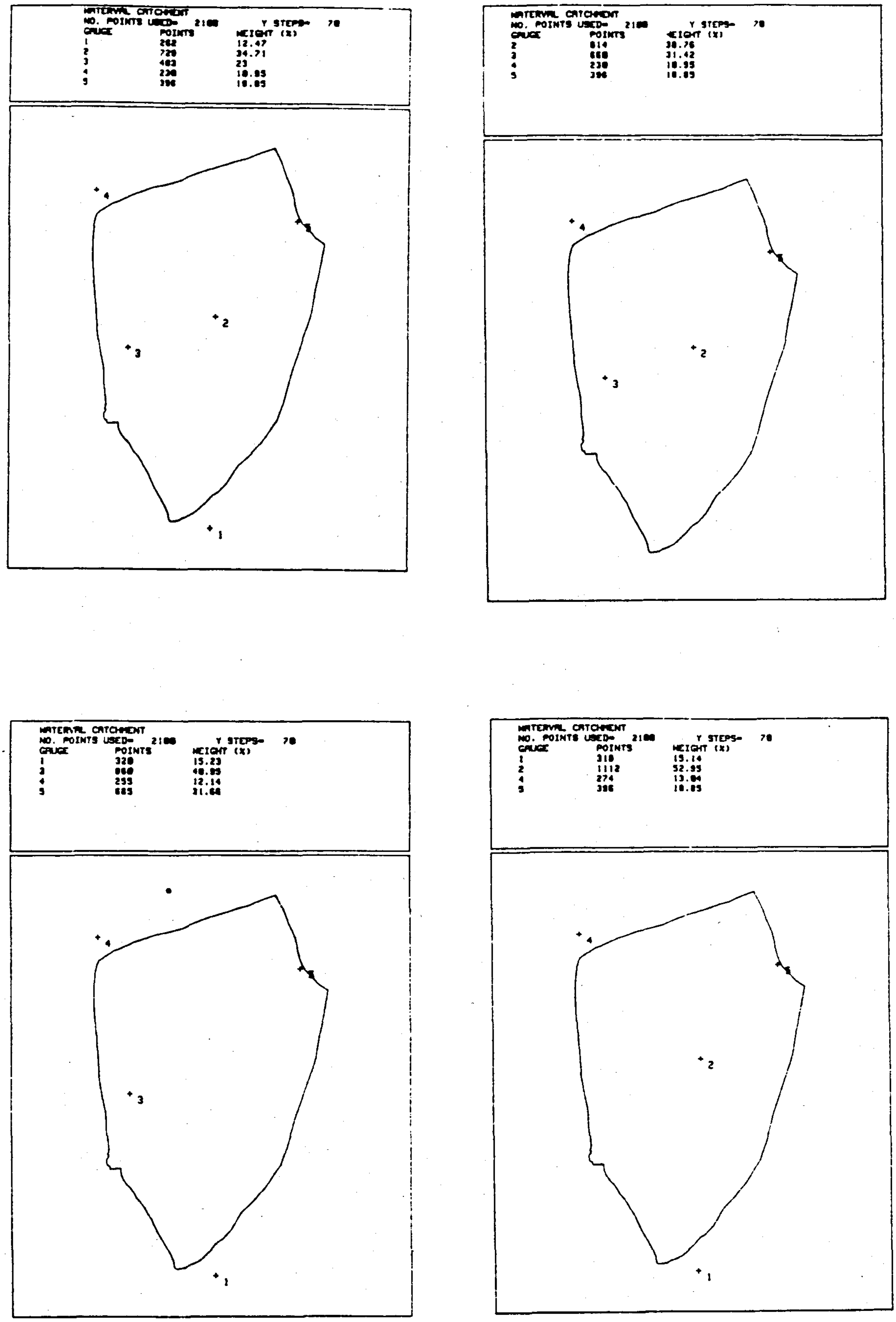
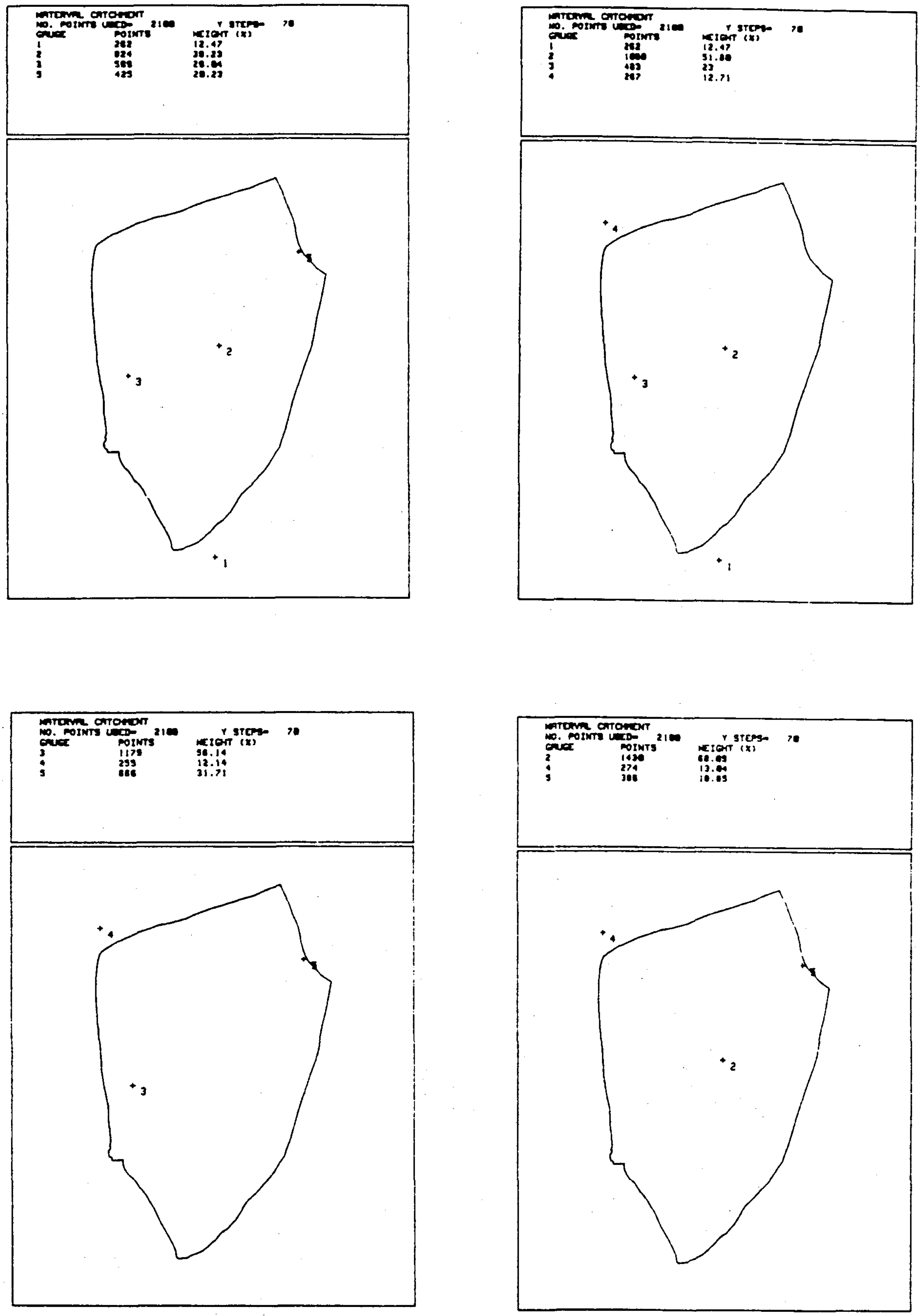



(a) Waterval Raingauge Weightings - 1

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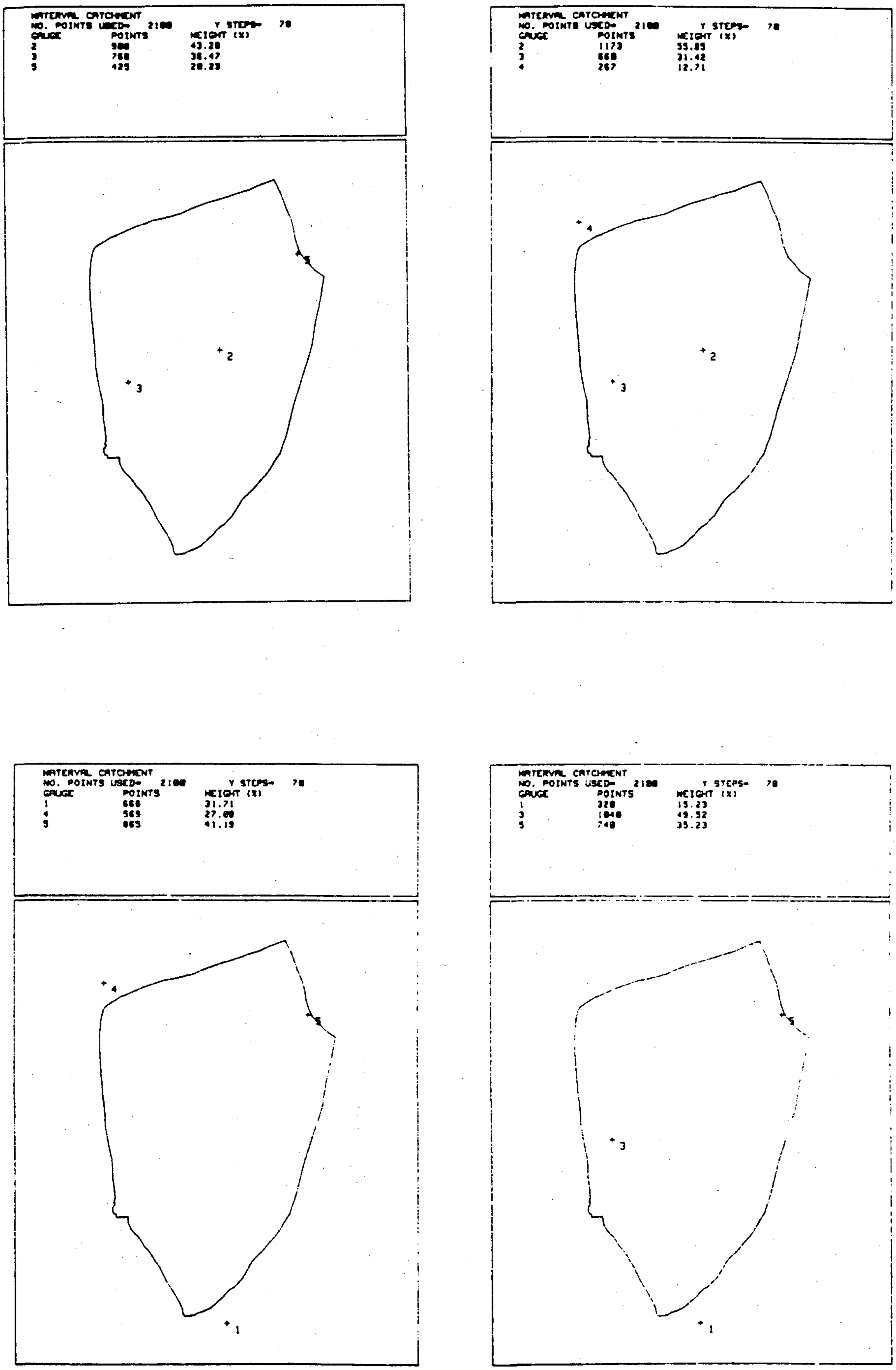


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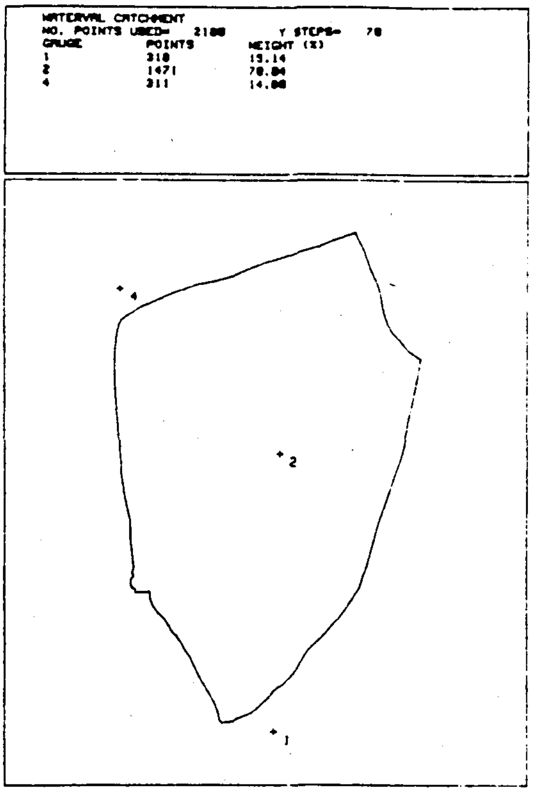


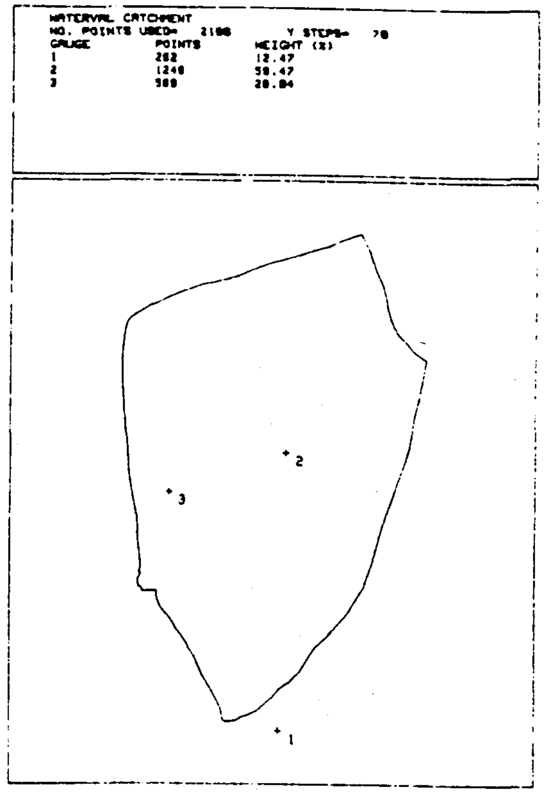


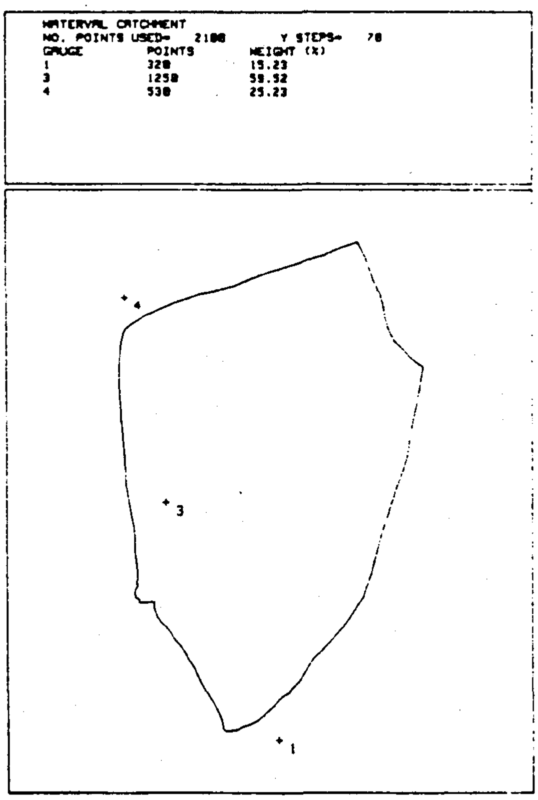


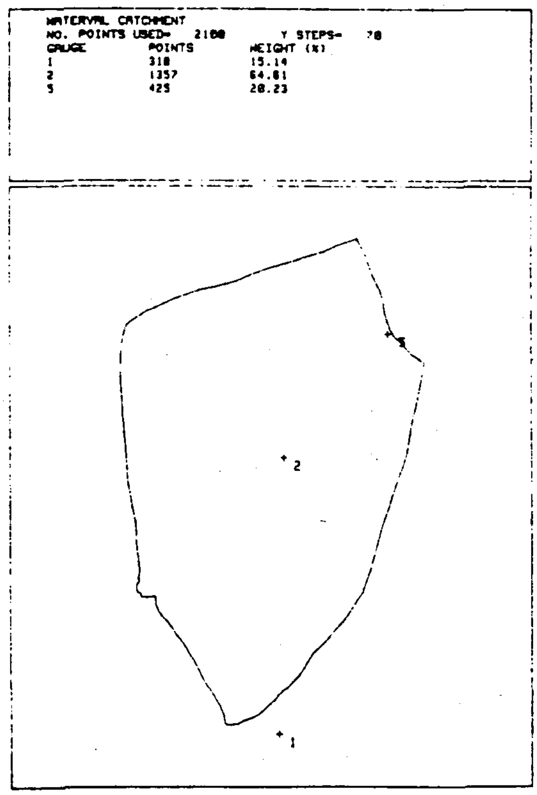


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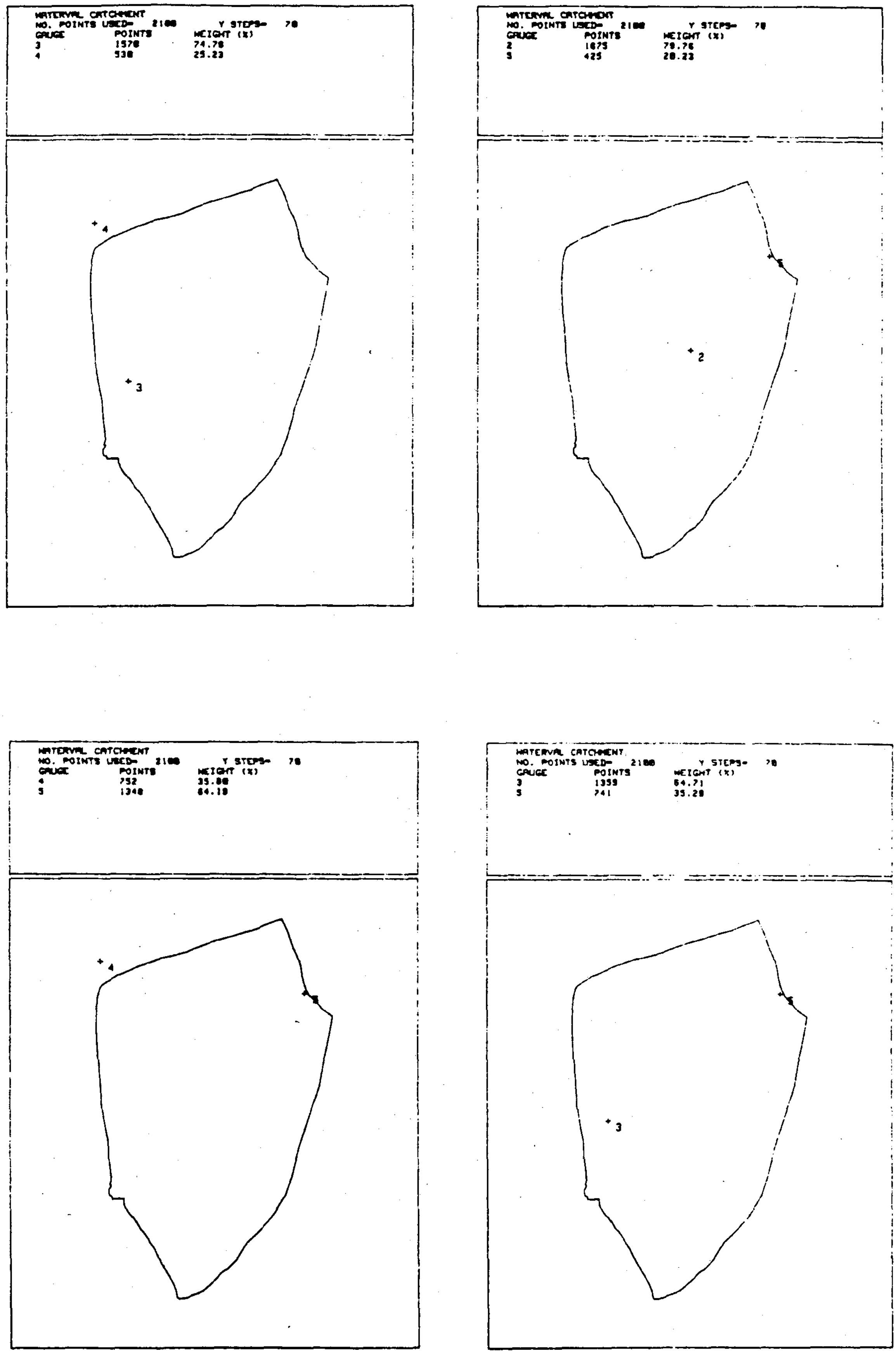
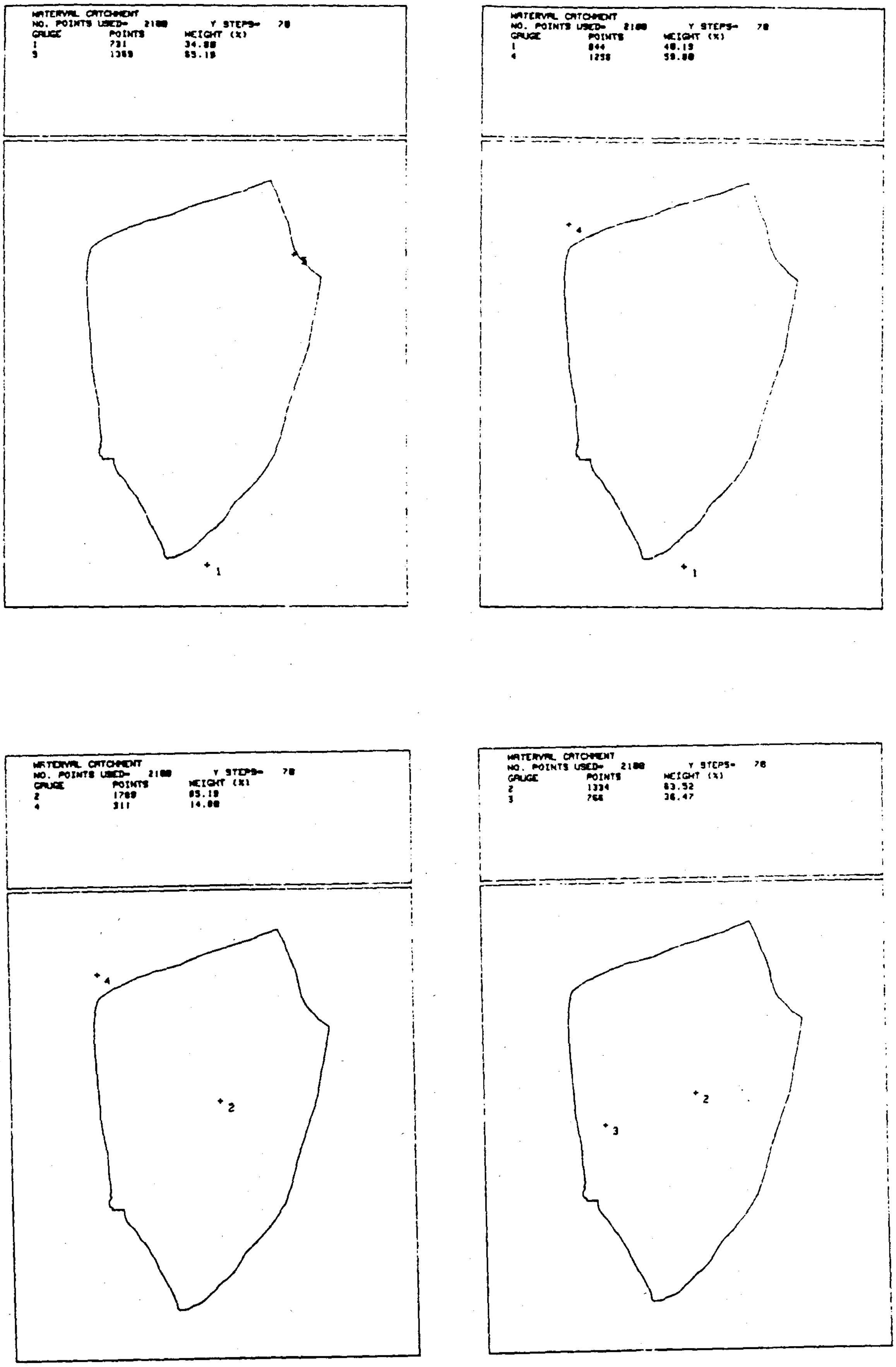
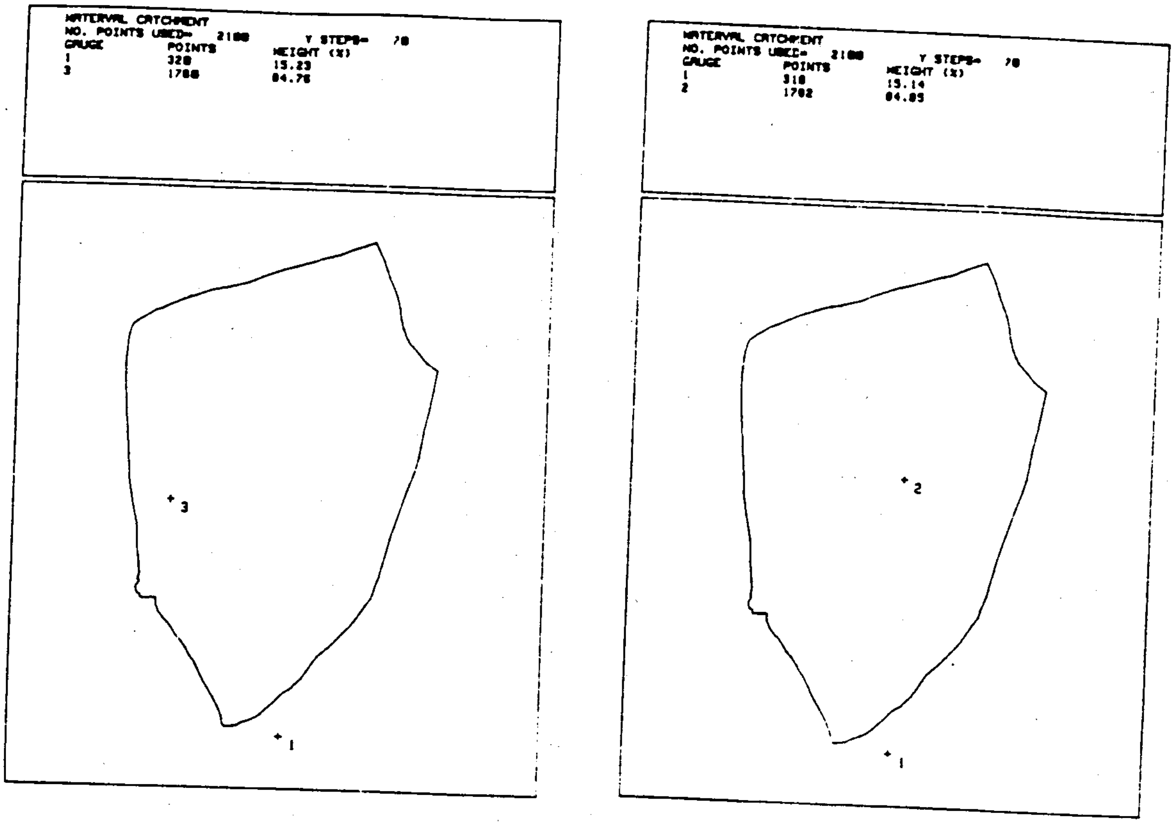



(a) Waterval Raingauge Weightings - 5




(a) Waterval Raingauge Weightings - 6

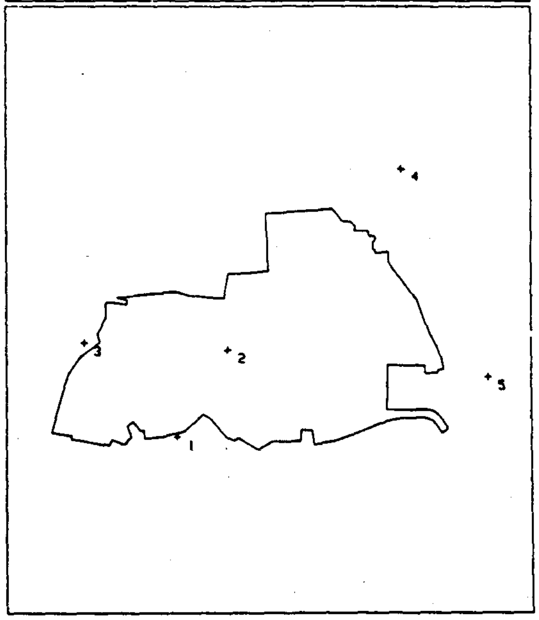



(a) Waterval Raingauge Weightings - 7

SUNNINGHILL CATCHMENT

NO. POINTS USED= 2604 Y STEPS= 50

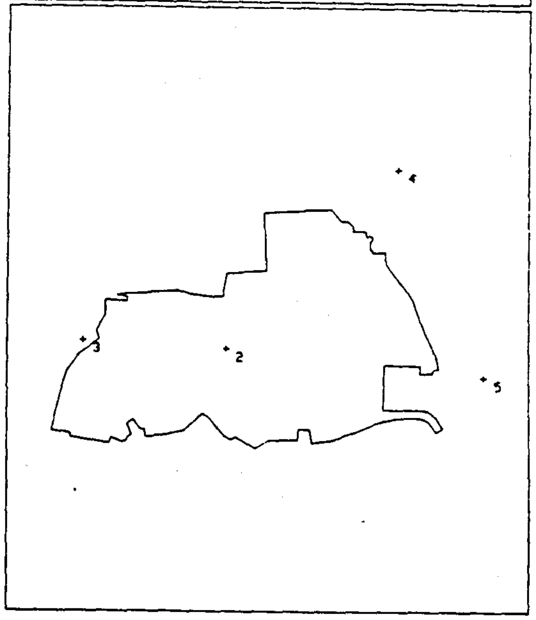
| GAUGE | POINTS | WEIGHT (%) |
|---|---|---|
| 1 | 321 | 12.32 |
| 2 | 1262 | 48.46 |
| 3 | 374 | 14.36 |
| 4 | 264 | 10.13 |
| 5 | 383 | 14.70 |




SUNNINGHILL CATCHMENT

NO. POINTS USED= 2604 Y STEPS= 50

| GAUGE | POINTS | WEIGHT (%) |
|---|---|---|
| 2 | 1468 | 56.37 |
| 3 | 489 | 18.77 |
| 4 | 264 | 10.13 |
| 5 | 383 | 14.70 |




SUNNINGHILL CATCHMENT

NO. POINTS USED= 2604 Y STEPS= 50

| GAUGE | POINTS | WEIGHT (%) |
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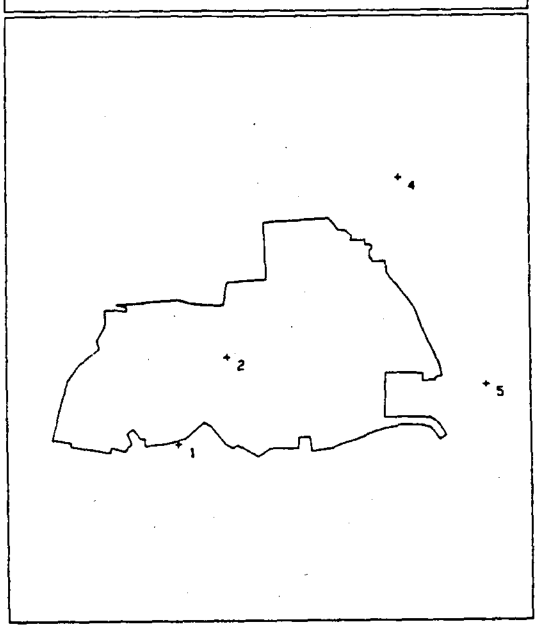
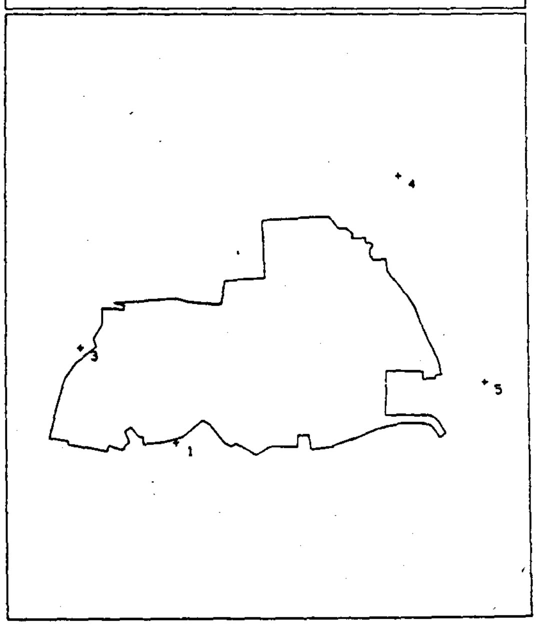
| 1 | 568 | 21.81 |
| 2 | 1389 | 53.34 |
| 4 | 264 | 10.13 |
| 5 | 383 | 14.70 |




SUNNINGHILL CATCHMENT

NO. POINTS USED= 2604 Y STEPS= 50

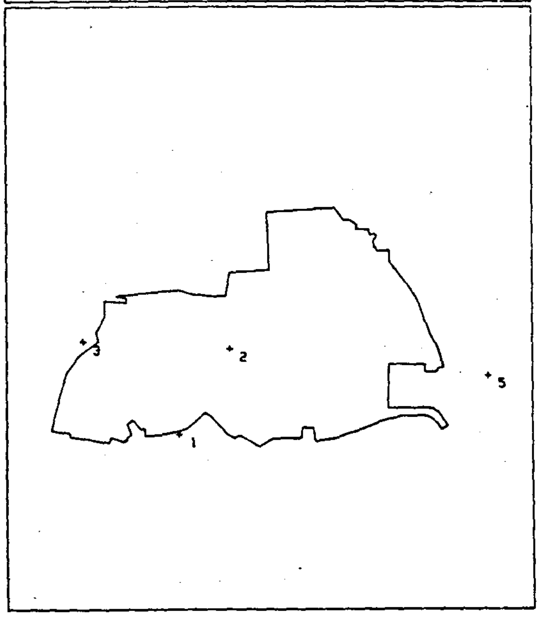
| GAUGE | POINTS | WEIGHT (%) |
|---|---|---|
| 1 | 1099 | 42.20 |
| 3 | 481 | 18.47 |
| 4 | 487 | 18.70 |
| 5 | 537 | 20.62 |




(b) Sunninghill Raingauge Weightings - 1

SUNNINGHILL CATCHMENT
NO. POINTS USED= 2604 Y STEPS= 50

| GAUGE | POINTS | WEIGHT (%) |
|---|---|---|
| 1 | 321 | 12.32 |
| 2 | 1463 | 56.18 |
| 3 | 374 | 14.36 |
| 5 | 446 | 17.12 |

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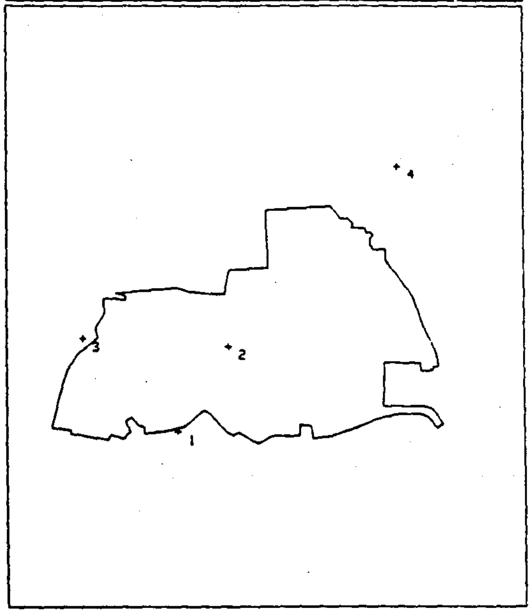
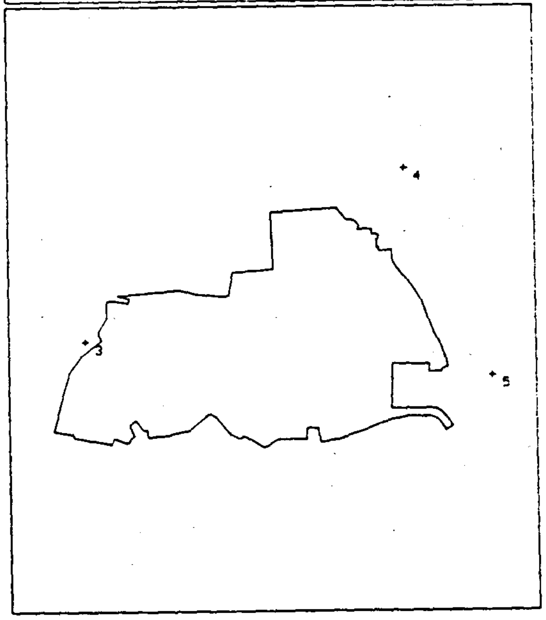
NO. POINTS USED= 2604 Y STEPS= 50

| GAUGE | POINTS | WEIGHT (%) |
|---|---|---|
| 1 | 321 | 12.32 |
| 2 | 1523 | 58.48 |
| 3 | 374 | 14.36 |
| 4 | 386 | 14.82 |



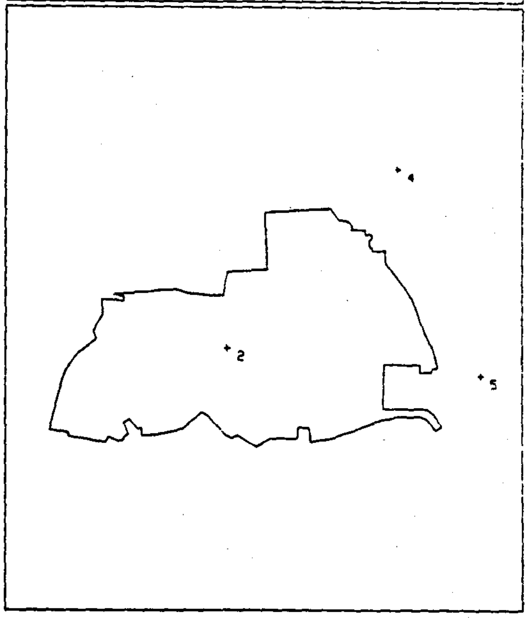

SUNNINGHILL CATCHMENT
NO. POINTS USED= 2604 Y STEPS= 50

| GAUGE | POINTS | WEIGHT (%) |
|---|---|---|
| 3 | 1312 | 50.38 |
| 4 | 546 | 20.96 |
| 5 | 746 | 28.64 |




SUNNINGHILL CATCHMENT
NO. POINTS USED= 2604 Y STEPS= 50

| GAUGE | POINTS | WEIGHT (%) |
|---|---|---|
| 2 | 1957 | 75.15 |
| 4 | 264 | 10.13 |
| 5 | 383 | 14.70 |




(b) Sunninghill Raingauge Weightings - 2

SUNNINGHILL CATCHMENT

NO. POINTS USED= 2604 Y STEPS= 50

| GAUGE | POINTS | WEIGHT (%) |
|---|---|---|
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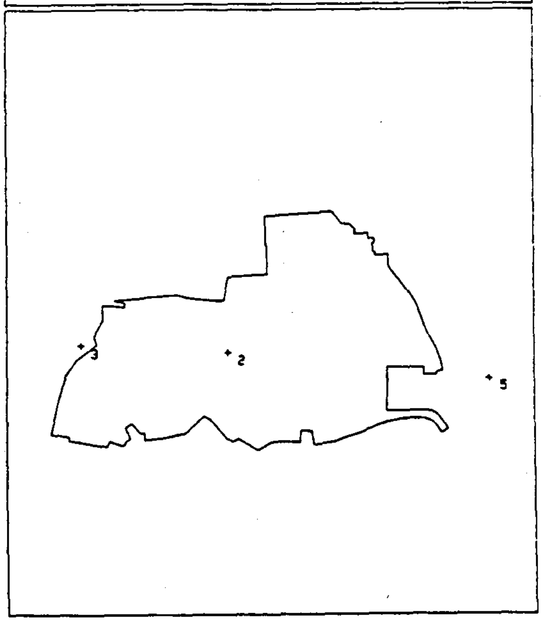
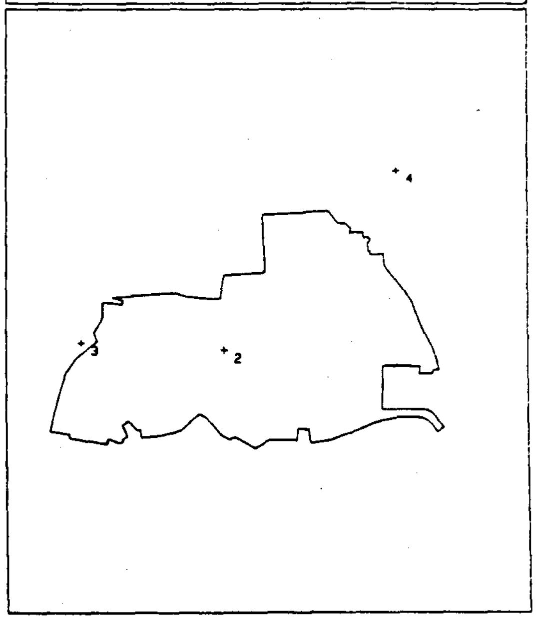
| 3 | 489 | 18.77 |
| 5 | 446 | 17.12 |




SUNNINGHILL CATCHMENT

NO. POINTS USED= 2604 Y STEPS= 50

| GAUGE | POINTS | WEIGHT (%) |
|---|---|---|
| 2 | 1729 | 66.39 |
| 3 | 489 | 18.77 |
| 4 | 386 | 14.82 |

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NO. POINTS USED= 2604 Y STEPS= 50

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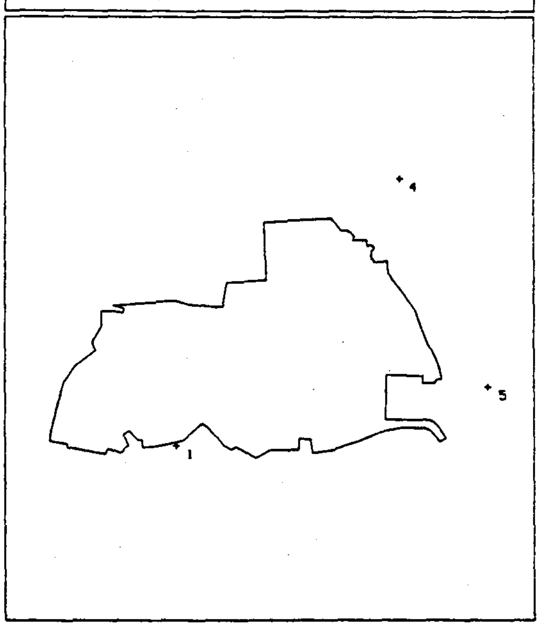
| 5 | 537 | 20.62 |




SUNNINGHILL CATCHMENT

NO. POINTS USED= 2604 Y STEPS= 50

| GAUGE | POINTS | WEIGHT (%) |
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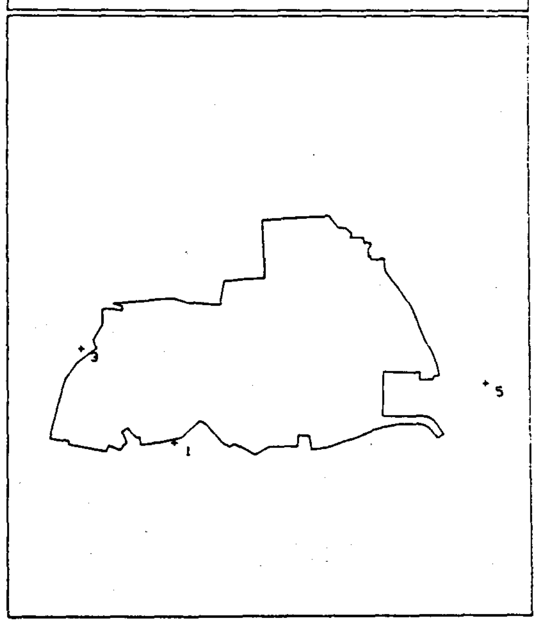
| 3 | 510 | 19.58 |
| 5 | 867 | 33.29 |

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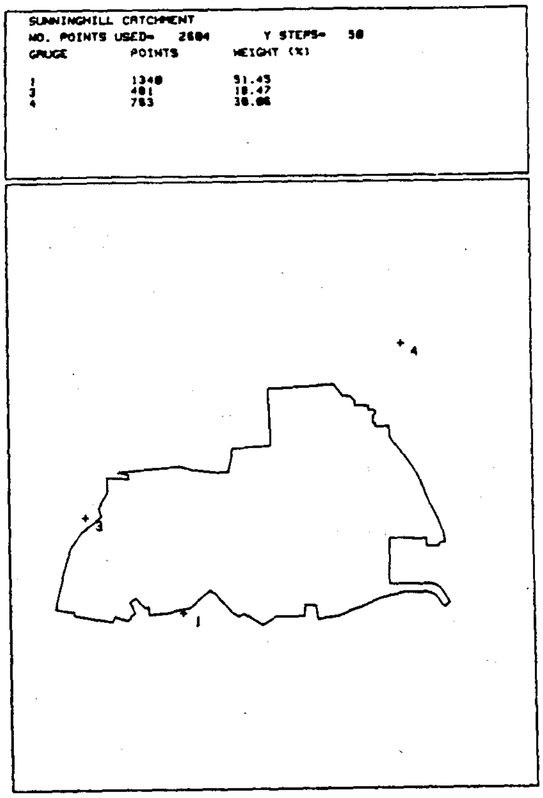
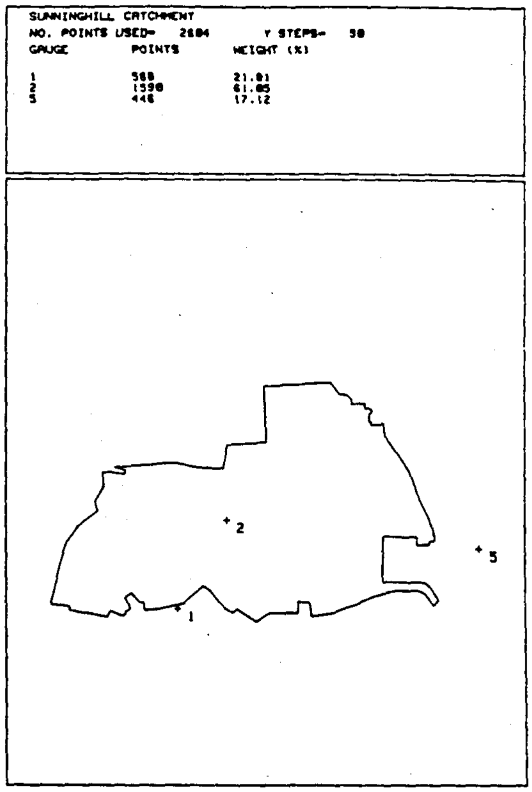
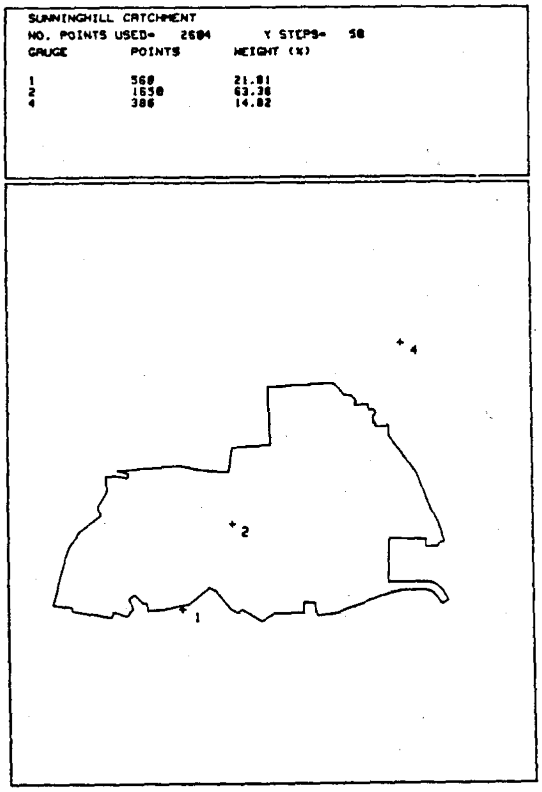
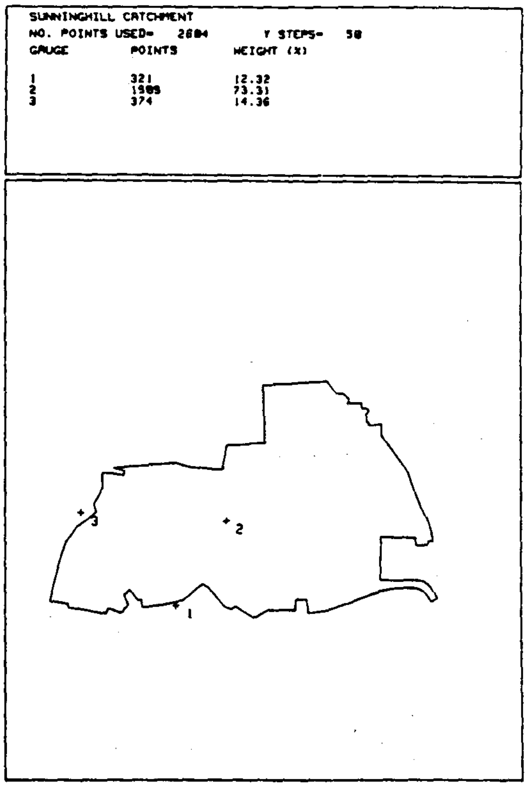
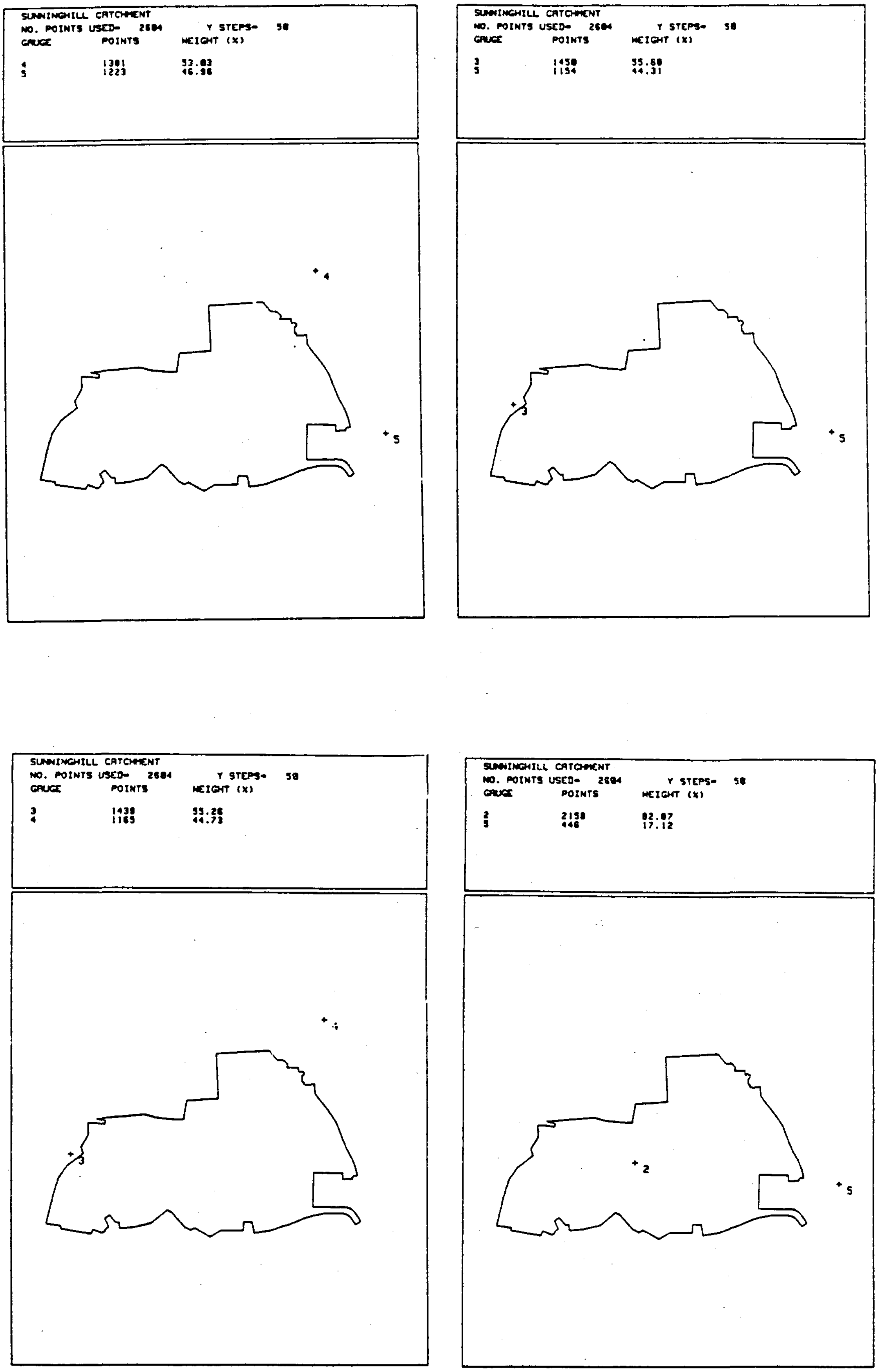


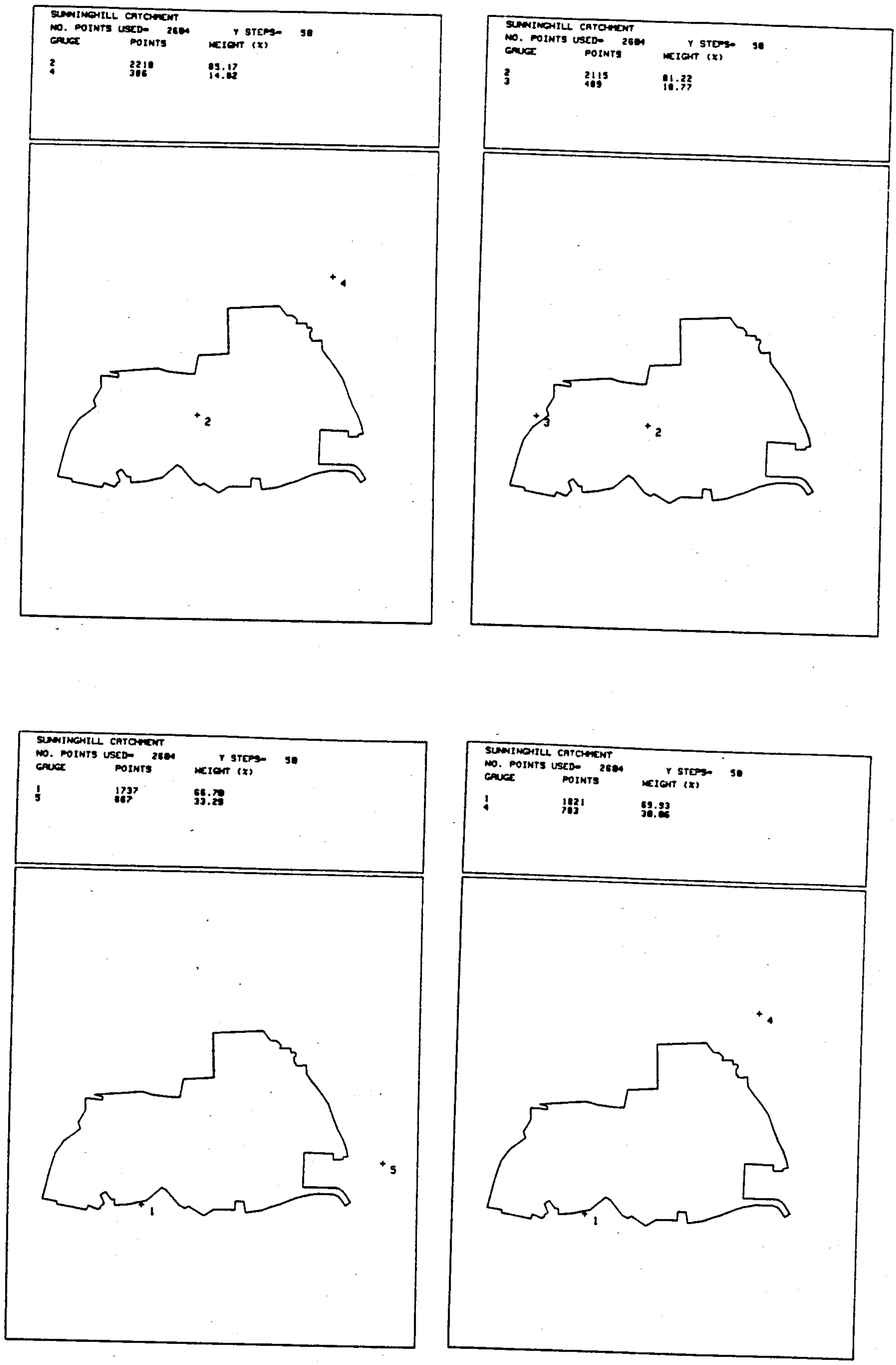



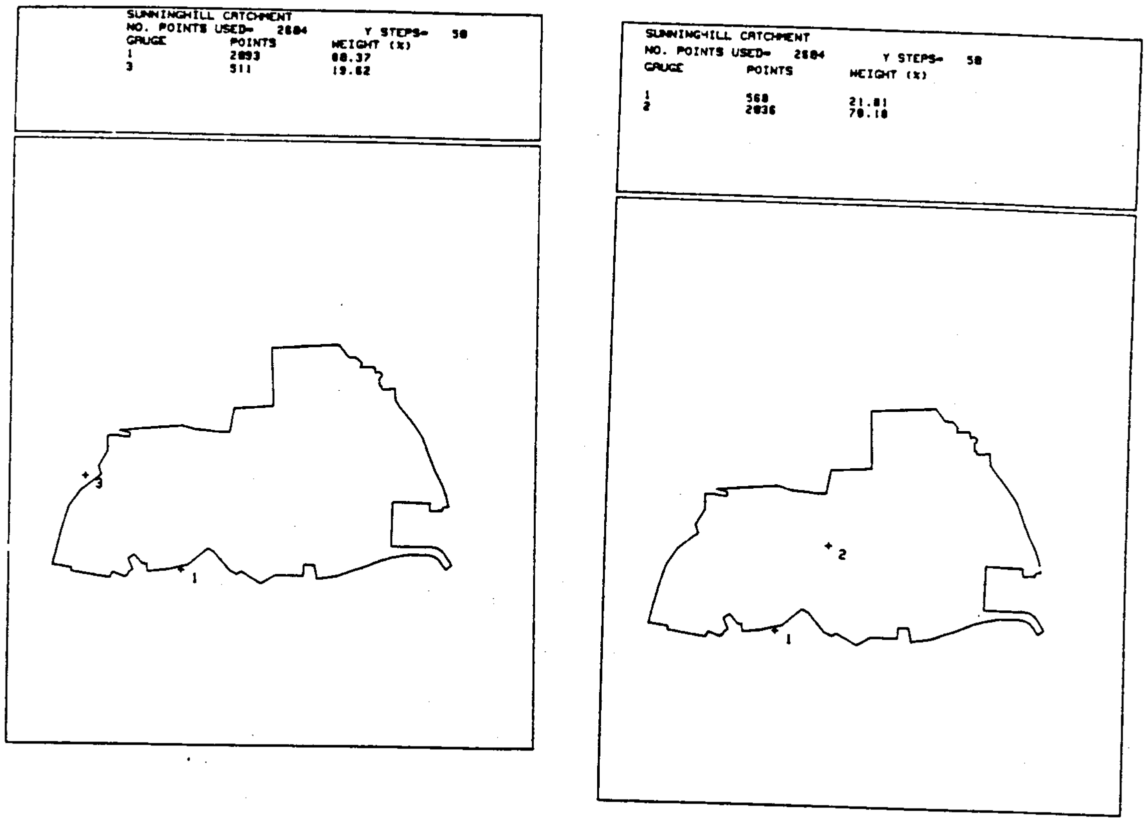

(b) Sunninghill Raingauge Weightings - 4




(b) Sunninghill Raingauge Weightings - 5




(b) Sunninghill Raingauge Weightings - 6




(b) Sunninghill Raingauge Weightings - 7