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The Bethlehem run-off augmentation research project: Past, present and future

S Mason-Williams

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HYDROLOGICAL RESEARCH INSTITUTE

Technical Report No TR 118

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Edited by

S. Mason-Williams

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1. INTRODUCTION

1.1 Aim of the report

The Directorate of Water Affairs is part of the Department of Environment Affairs. Its main function is the planning and provision of water to domestic, industrial and agricultural users in the Republic of South Africa.

The Hydrological Research Institute has the function of carrying out Department orientated research, concentrating on present and future problems related to water quantity and quality.

The Bethlehem Run-off Augmentation Research is one of the first multi-disciplinary projects undertaken at the Hydrological Research Institute. It is planned to stretch over a period of ten years and although most of the work will be carried out by our own staff, outside organisations have to be consulted and certain tasks are contracted out. Communication between the different bodies involved becomes very important.

This report is aimed at stimulating this communication. Hopefully, it will arouse the interest of national and overseas organisations and will provide enough of the basic facts about the project to set such interest on a sound basis.

1.2 Historical background

1.2.1 The national situation

Within the next forty years South Africa as a whole will have reached the point of maximum economic exploitation of the conventional surface and underground water resources (see Fig. 1.1). This situation has already been reached over large regions of the interior where water has to be imported at a high cost from, amongst others, the rivers east of the escarpment e.g. the Tugela-Vaal and Usutu-Vaal Schemes.

One of the unconventional resources with potential for development is rainfall enhancement and possibly associated run-off augmentation.

1.2.2 History of BRAR/BEWMEX projects

During 1969, the Bethlehem Weather Modification Experiment (BEWMEX) was conceived by the Interdepartmental Co-ordinating Committee for Hydrological Science as a joint venture between the (then) Department of Water Affairs and the Department of Transport (Weather Bureau). The original objectives were to answer the following questions:

(1) Is it possible to increase rainfall from supercooled cumulus clouds and, if so, is it possible to choose consistently the correct clouds for seeding?

(2) Does seeding alter the intensity, duration and area of the rainfall?

(3) Are there any large-scale effects of seeding and, if so, what is the net result of these effects on rainfall?

(4) Is there any danger of creating storms by seeding which are so vigorous as to produce damaging hail?

(5) Is it possible to reduce, or even eliminate, the incidence of damaging hail by cloud seeding?

(6) Does the seeding of hail storms have any effect on the rainfall from the storms and, if it does, what is this effect in terms of rainfall area, amount, intensity and duration?

(7) Are there any large-scale effects resulting from the seeding of hail storms which have an influence on the hail- and/or rainfall from any other clouds?

(8) Assuming positive results to be obtainable by cloud seeding, does the local climate provide sufficient seeding opportunities for noticeable benefits to be accrued?

(9) What will be the effect of augmentation from the agricultural and hydrological point of view?

(10) Do the consequences of these effects offset any advantage to be gained by weather modifications?

The first comprehensive report was presented in 1974 (Harrison, 1974) and the first progress and planning report produced at the Hydrological Research Institute appeared during August 1978. In 1979, the Interdepartmental Co-ordinating Committee for Hydrological Research recommended the formation of the Bethlehem Run-off Augmentation Research (BRAR) project to direct work on the hydrological aspects of weather modifications (points 9 and 10 above) while the BEWMEX project continued with the meteorological research required for cloud seeding.

1.2.3 Aims of the BRAR project

The hydrological research program will attempt to answer the following questions:

(a) By how much does a change in precipitation due to cloud seeding affect the run-off?

(b) How much of the altered run-off (assuming an increase) can be put to beneficial use?

The experimental approach finally adopted is given in section 2.2. Briefly, the modified rainfall signals received from the BEWMEX research are converted to run-off via calibrated rainfall/run-off models of acceptable accuracy. This approach also holds promise for investigating the effects of catchment land use changes on run-off. Therefore, due to the anticipated long duration of the BEWMEX project, the objectives of the BRAR project have been expanded to include this aspect of hydrological research. The BRAR project is now seen as a pilot study on the methodology and potential of catchment modelling in a typical and important dryland farming region in South Africa. These research catchments also form part of the catchment of the most important water supply dam in the country, namely Vaal Dam.

The research program will evaluate the following basic problems:

1. data network requirements and limitations for certain types of analyses and prediction.
2. the accuracy of data network input with regard to rainfall and evaporation at different time intervals with different types of mathematical simulation models.
3. land use parameters that can be successfully used in distributed models to assess the effects of changing land use on catchment water yields.
4. an analysis of catchment characteristics that in a given pedo-hydrological and climatological environment may be expected to dominate the behaviour of a catchment and the response to certain management practices or other man-induced changes.
5. the extrapolation of findings from small experimental catchments to much larger catchments with a more limited data base.

1.3 Location of the research area

1.3.1 The Vaal Dam catchment

Most of the domestic and industrial water supply to the Pretoria-Witwatersrand-Vereeniging (PWV) complex is extracted from the Vaal Dam by the Rand Water Board. Projected water requirements from the Vaal River are given in Table 1.1.

TABLE 1.1: Estimated water requirements from the Vaal River above the Vaal Dam ($10^6 m^3$ per annum) (Alexander, 1981)

	1980	2000	2020
Eastern Transvaal	75	525	807
Ex Vaal Dam and Barrage	863	2 397	4 218

Vaal Dam was constructed during the mid-thirties to serve the Reef complex and the Vaalharts irrigation scheme, some 400 km downstream. To meet the increasing water demands, water is imported from other catchments e.g. the Tugela-Vaal and Usutu-Vaal schemes. Water is also exported to the Olifants River. (See Fig. 1.2)

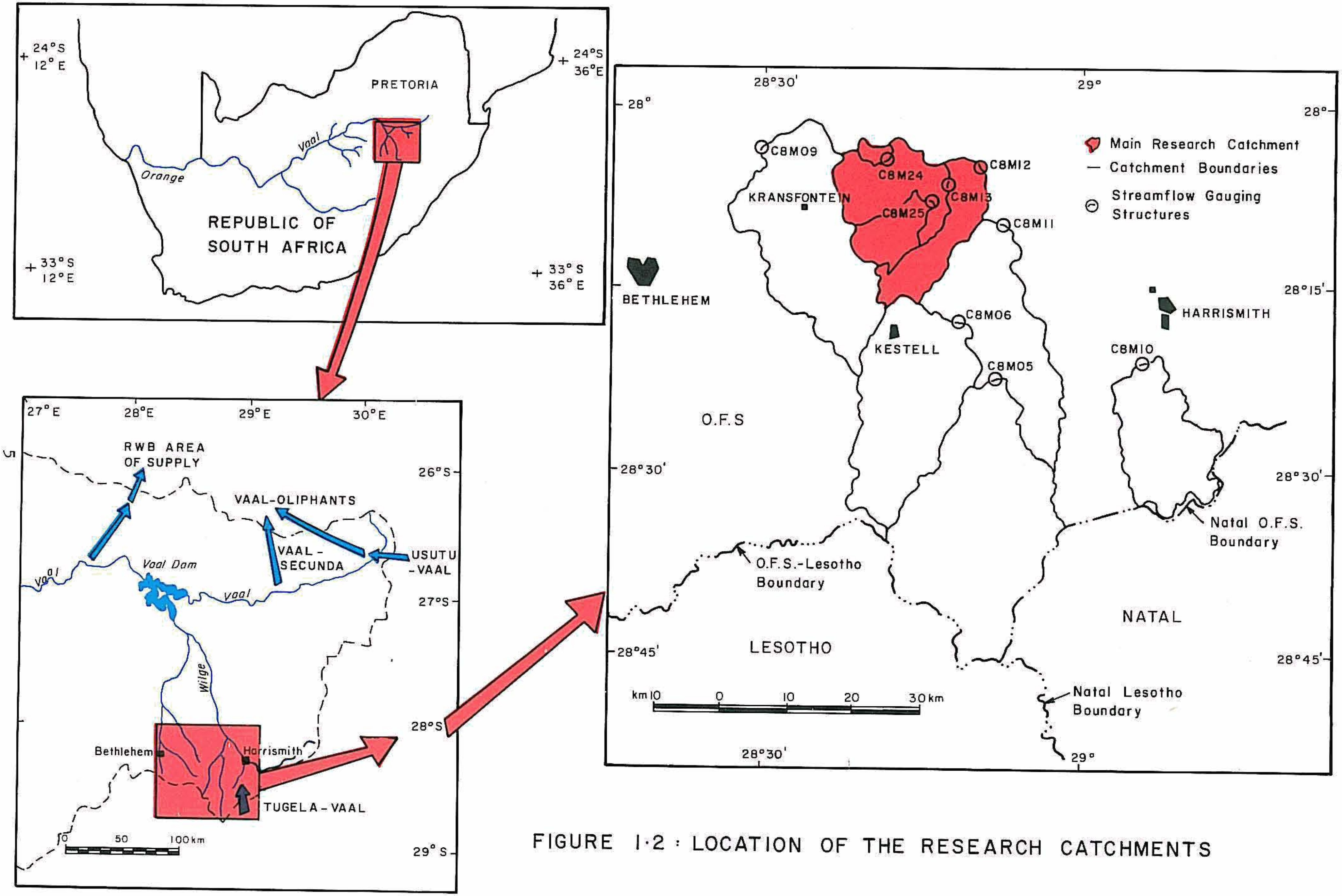

FIGURE 1·2 : LOCATION OF THE RESEARCH CATCHMENTS

This economic heartland of South Africa therefore may be considered to be the first region to become entitled to unconventional water resource development.

The catchment of Vaal Dam is 38 855 km^2 with a mean annual run-off (MAR) of 2 309 x $10^6 m^3$. (Middleton, Pitman and Midgley, 1981). The mean annual precipitation varies from 960 mm in the south eastern corner to 700 mm in the central regions of the catchment. The mean run-off is therefore in the order of 7,7% of the rainfall (Braune and Wessels, 1981).

1.3.2 The BRAR catchments

The research catchments are east of the town of Bethlehem in the upper reaches of the Wilge River which is a tributary of the Vaal River and thus runs into Vaal Dam. (See Fig. 1.2).

Details of the six research catchments are given in Table 1.2.

TABLE 1.2: Characteristics of the research catchments

Catchment gauge no.	Area (km^2)	Aspect	Altitude (m) Min.	Altitude (m) Max.
C8M09	465	NW	1 634	2 033
C8M10	250	N	1 631	2 095
C8M12	372	NE	1 600	1 801
C8M13	251	E	1 631	1 834
C8M24	9	NE	1 631	1 746
C8M25	83	SE	1 661	1 756

The last four catchments are nested the one into the other and form the area of intensive studies. The other two catchments are studied in less detail and will not be discussed much further in this report.

2. METHODOLOGY

2.1 Meteorological options

There are three main routes along which research could be conducted (Alexander, 1982):

(a) cloud physics studies, concentrating on those processes which lead to the production of rain and which could be manipulated to increase rainfall. The major difficulty to be overcome here is that of obtaining representative measurements in a dynamic storm system.

(b) treatment and control studies where the results of treatment are statistically compared with the non-treated (control) situation. This approach suffers from the problem of detecting the signal (effect) from the noise (large natural variability).

(c) development of conceptual numerical models. This is a relatively new and untested field of research which, however, shows much promise for future work.

The BEWMEX project has adopted the cloud processes approach and has collected several years of data associated with non-operational cloud seeding.

2.1.1 Brief outline of cloud seeding

Days featuring convective clouds occur approximately 70% of the time during the summer and offer the best opportunity for precipitation enhancement. They are initiated either by intense daytime surface heating, orographic influences or large scale weather systems moving through the region. The results range from widely scattered light showers to intensive heavy downpours containing hail.

Early studies have indicated that the "cold rain" process is dominant in these clouds. That is, the precipitation process is initiated by ice crystals below 0°C, usually -10°C. Here the ice crystals grow at the expense of water drops due to the reduced saturation vapour pressure of ice compared with water.

In trying to augment precipitation artificially one assumes that these ice crystals are naturally deficient and through seeding one hopes to introduce ice crystals to the cloud in higher quantities and at an earlier stage than would otherwise occur. There are two types of seeding that can be done for this purpose. The first, termed microphysical seeding, attempts to make the clouds precipitate more efficiently by introducing ice crystals of the order of 1 per litre above the freezing level. The second, dynamical seeding, tries to increase the moisture flux into the cloud by invigorating its updraft through the release of latent heat of the water drops on the increased number of ice nuclei. In this case 100 per litre is the order of magnitude of ice crystal concentrations sought.

On the Bethlehem Weather Modiciation Experiment both silver iodide and dry ice, dispersed from aircraft at approximately the -10°C level, are used as seeding agents. The seeding is done in a randomised fashion with only the aircrew in the seeding aircraft aware of the decision at the time. Prior to the seeding run, three aircraft flying at -15°C level, -10°C level and near cloud base penetrate the target cloud, the cloud itself being chosen by the scientist on board the aircraft flying at the -10°C level. The planes are instrumented to measure vertical motions as well as the size spectrum and types of particles encountered. Once the seeding run is complete the three aircraft again resume penetrations taking measurements with these instruments. Thus, together with the radar information a fairly complete picture of the cloud studies, some natural, some seeded can be obtained to study the precipitation process and how seeding affects it.

The research is designed to search for seedable situations, that is situations where seeding may have a beneficial effect on the precipitation process, either in intensity, area or duration. Questions that must be addressed in order to judge the economic viability of the procedure include in which stage and at what part of a given cloud system and in what quantities should seeding be carried out, and ultimately, how often do these situations occur and under what conditions.

2.2 Hydrological options

In the planning stages of the BRAR project, two methods were considered. The first method involves the statistical analysis of rainfall/run-off data, using, for example, target and control catchments. The second method involves the use of mathematical catchment models. The historical records at the Bethlehem catchments are still very short; moreover, the Weather Bureau does not employ cloud seeding techniques over target and control areas. Therefore, the first approach was discarded. and the second one, that of catchment modelling, was adopted.

Mathematical models are frequently separated in two main groups: deterministic (fixed input-output) and stochastic (random component in the input-output relationship). At this stage of the project it has been decided to concentrate on the use of deterministic simulation models where most parameter values vary within a range with some physical basis. Because of the spatial implications expected from cloud seeding, where the area of the storm may be affected by seeding, distributed models are preferred for simulation in the smaller catchments. The research catchments are nested, the one into the other, in order to investigate the problem of parameter transfer from one catchment to the other.

When it comes to extrapolation of research findings in the small areas to the catchment of the Vaal Dam as a whole one may have to use aggregated models, where the large catchment is considered to be a combination of smaller, lumped catchments linked together with a communal stream network.

The model's performance with regard to observed and simulated run-off will be tested on the basis of the coefficient of model efficiency (Aitken, 1973) using daily data of run-off volume.

2.3 Rainfall data requirements

Mathematical procedures for the estimation of areal rainfall from recorded point rainfall are being tested by the National Research Institute for Mathematical Sciences of the Council for Scientific and Industrial Research (CSIR).

It is anticipated that radar reflectivity data will improve but not replace recorded rainfall data as the prime input into the models, but radar data alone will have to be used to estimate the frequency, depth, duration and area of storm precipitation over the ultimate operational area (Alexander, 1982).

A continuous time series of rainfall events is being documented in the experimental area, together with the meteorological conditions associated with each event. Once seeding is commenced, the seeded events will be tagged. At the end of the experimental period, there will be a time series of mixed seeded and unseeded rainfall events. Given the anticipated effects of cloud seeding on the frequency, movement, growth, decay, depth, duration and area of storm rainfall, the observed mixed sequence can be converted into two parallel rainfall sequences by adjusting both the seeded and the unseeded events to allow for the estimated effects of seeding. The two series can then be routed through the rainfall run-off models and the effect of seeding on river flow determined (Alexander, 1982).

2.4 Data collection

Technical detail about instruments used is given in the appendix.

2.4.1 Rainfall

The BEWMEX project has erected about 300 raingauges in an area with a radius of 96 km around Bethlehem. Part of this network covers the C8M09 and C8M10 catchments.

In C8M12 and the enclosed catchments C8M13, C8M24 and C8M25 the rainfall is measured by a network erected and maintained by the BRAR project. This network became operational at the beginning of the 1980/81 season; the relatively dense network at C8M24 was started at the beginning of 1982/83 season. (See Fig. 2.1). Technical detail concerning the gauges and the recorders is given in the appendix.

2.4.2 River flow

Within the main research area, only weirs C8M12 and C8M13 existed at the start of the project. Additional weirs were constructed to give two nested catchments C8M24 and C8M25 (see Plate 1). The weir sites are seldom ideal as conditions suitable for river flow measurements are at a premium in this area and compromises had to be made. Stage height is recorded on weekly recording sheets and calibration of the weirs is supported by annual surveys of the cross sections below and above the weir. Markers for the automatic recording of maximum water levels at two cross-sections, above and below the weir, have been installed to aid calibration. More details are given in the appendix.

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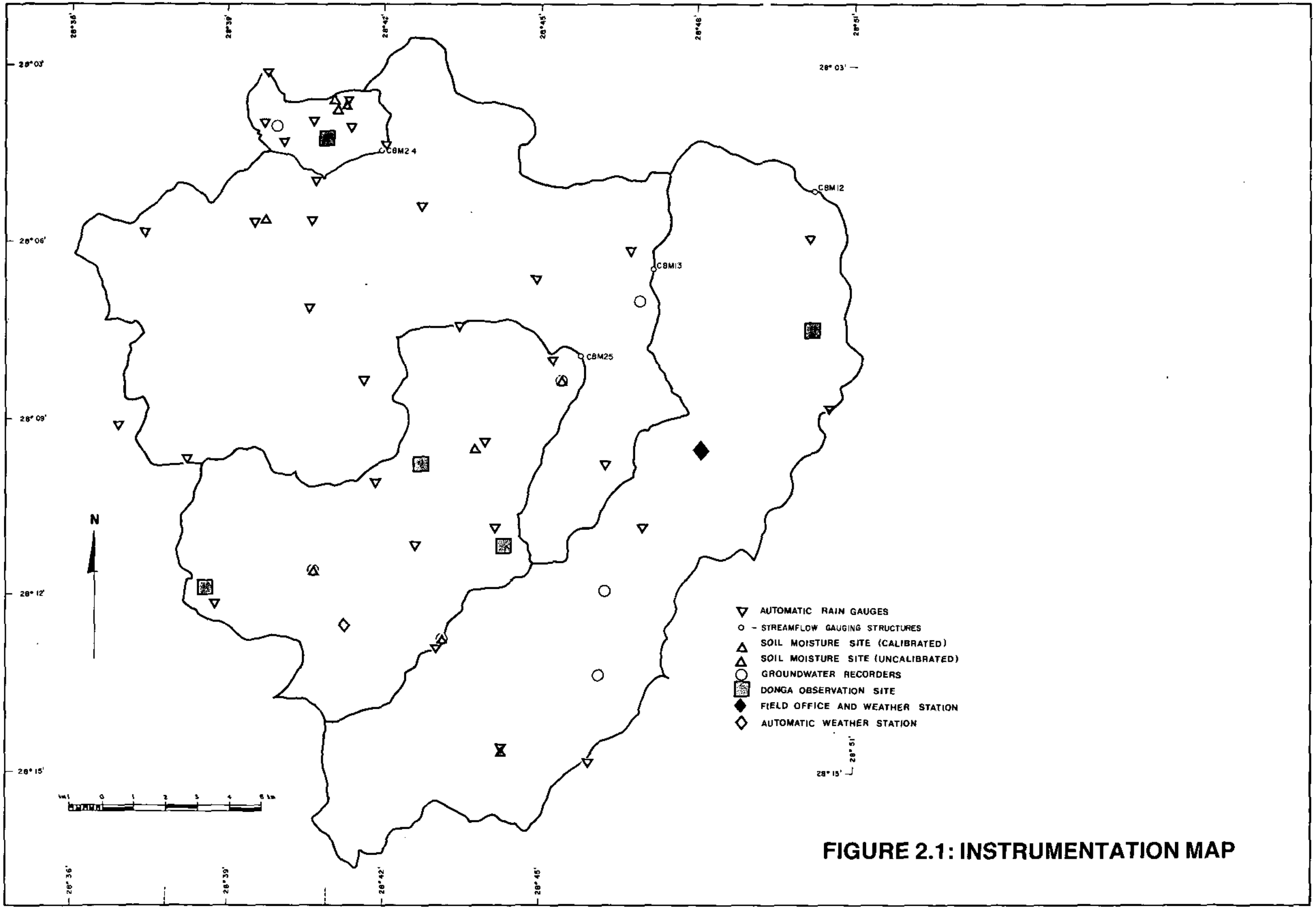


FIGURE 2.1: INSTRUMENTATION MAP

PLATE 1: Crump weir at C8M25

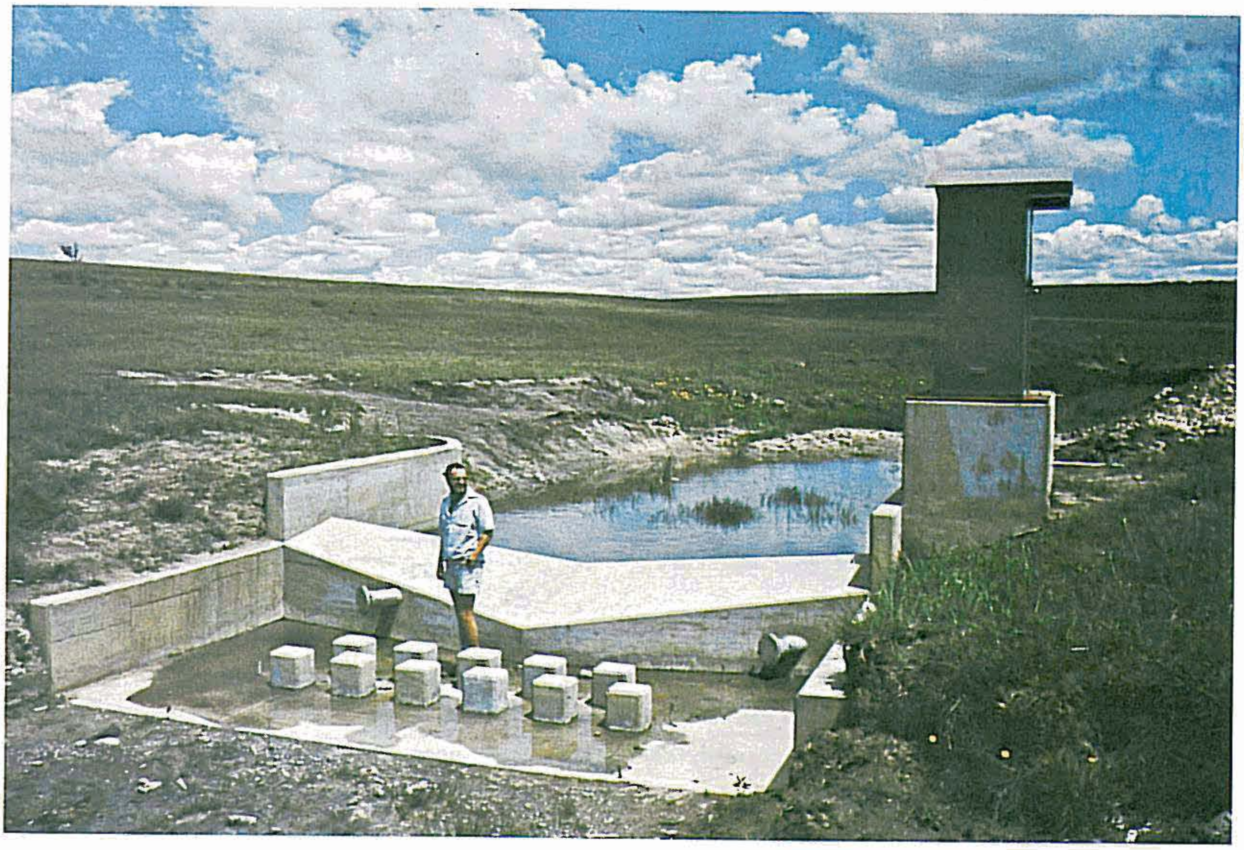
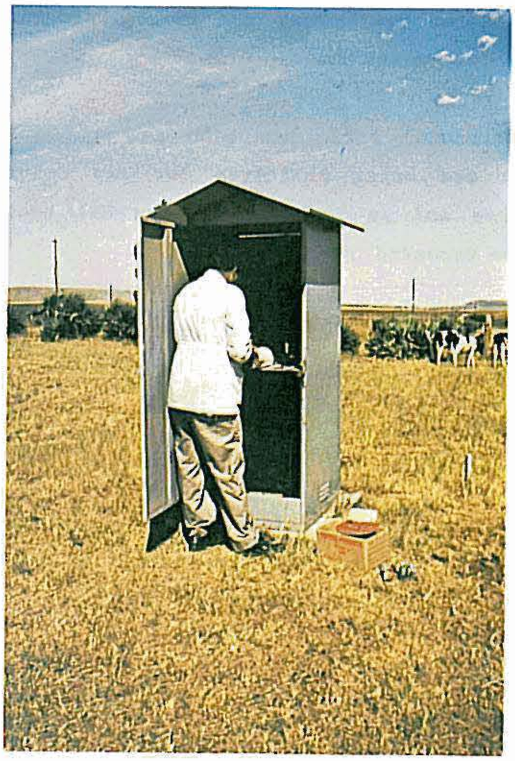


PLATE 2: Changing the chart of a groundwater recorder



2.4.3 Climatic data

For the purposes of the BEWMEX project several automatic weather stations have been erected in the BEWMEX operational area (within the 96 km radius), the station at Afrikaskop falling within our research catchments. A daily routine weather station, measuring sunshine hours, minimum and maximum temperatures, daily wind run and daily class A pan evaporation, has been erected on the farm Uitvlugt near the field office. (Fig. 2.1). Two automatic weather stations will be erected within the C8M12 catchment early in the 1983/84 season.

With regard to estimating potential evaporation rates of different vegetation covers and land use in the catchments, climatic data are preferred above pan evaporation data. The Penman-Monteith equation, adjusted for local conditions, has been shown to be useful for this purpose (Maaren, 1977, 1978).

2.4.4 Groundwater levels and soil moisture

Seven sites within C8M12 have been instrumented for continuous monitoring of groundwater levels on a monthly basis using Ott recorders mounted on top of the seven boreholes being studied (see Fig. 2.1 and Plate 2). Soil moisture data at several sites which represent different soils and land uses, are being collected using a neutron probe. For more detail regarding data collection and instrumentation, see the appendix.

2.4.5 Erosion

Assessment of cloud seeding effects upon the soil status is being carried out mainly by mathematical modelling. To define potential sites for testing the various erosion models, a detailed erosion hazard survey for the catchments was completed.

Information on the characteristics of the catchments' soils has been gathered for input into the erosion models. Five dongas are being monitored for any donga progression. Stereo photographs have been taken and an intensive survey has been carried out at each site and this process will be repeated every two years.

Dispersivity of the soils, indicating the level of erodibility, has been studied by taking soil samples from various areas throughout the catchment and from the dongas.

2.4.6 Land use

After initially having produced land use maps from extensive field surveys, it has been decided that, accepting some loss in accuracy, regular land use surveys will be carried out with the aid of LANDSAT: MSS images. Preliminary work shows promise.

2.5 Data management

Data files for the project are maintained on the disk packs of the Burroughs main frame computer. Separate data files are:

(a) Break point rainfall (DIGIT/RAIN series)
(b) Daily rainfall (DAILY/RAIN series)
(c) Break point river flow (DIGIT/RUN-OFF series)
(d) Daily flow (DAILY/RUN-OFF series)
(e) Rainfall maps on a square grid basis (AREAL/RAIN series)
(f) Climatic data (SIRI-format, to be developed)
(g) Land use, slope, soils etc. (LANDS series)
(h) Soil moisture data (SOILM series)

The format of the rainfall and river flow files is mainly the one generally adopted by the hydrological community in South Africa: the HRU-format.

The BRAR data management system consists of a hierarchy of computer programs designed to manipulate, reduce and retrieve information in a variety of forms. Special programs are written for the purpose of quality control.

A backup system of data files on normal 9 track 1 600 bpi tapes is maintained for emergency cases.

Because the project is orientated towards a seasonal simulation of hydrological behaviour, data files usually consist of two copies: one master file with all the data collected since the beginning of the project, and several seasonal files for easy handling.

As the data base for the project grows and actual use will increase, it is foreseen that modifications in the system may be required from time to time.

3. CATCHMENT CHARACTERISTICS

3.1 Physiography

Catchment C8M12 is characterised by gently undulating scenery (see Plate 3) with the main contrast in relief given by a few scattered inselbergs. Elevations in the catchment vary from 1 830 m in the southwest to 1 570 m at the C8M12 weir (see Fig 3.1). Slopes rarely exceed 12% and are less than 3% over most of the catchment (see Table 3.1).

TABLE 3.1: Slope categories in the BRAR catchments (after Howman, 1981)

Catchment number		C8M12	C8M13	C8M24	C8M25
Catchment area (km^2)		372,2	242,1	8,9	82,1
	0,0 - 3,0	65,5	62,0	22,5	56,3
Slope	3,1 - 6,1	26,3	29,0	35,9	29,6
categories	6,1 - 9,0	6,6	7,4	31,7	8,7
(%)	9,1 - 12,0	1,3	1,6	9,2	3,9
	12,1 - 15,0	0,3	0,0	0,7	1,5

To compare the morphological characteristics of the nested catchments, certain quantitative indices have been calculated and the results are summarized in Table 3.2.

River drainage operates along a network which alternates between deeply incised channels (see Plate 4) and marshy, vlei-like bottomlands. Intermittent flow occurs throughout most of the stream network. A feature of the catchment is the large number of pans or surface depressions (see Fig 3.2), whose area varies from less than a hectare to over forty hectares (see Table 3.3). The majority of the pans are shallow, with depths of less than 1,5 m and the deepest being 5,5 m. The catchment area of the thirty two pans (see Table 3.4) can be expected to capture a fair proportion of run-off which would otherwise have entered the drainage system. It is also of interest to note that the maximum pan storage for C8M12 is estimated to be 6 million m^3 (Table 3.4) while the Mean Annual Run-off for that catchment is roughly 5 million m^3.

PLATE 3: Typical catchment scenery

PLATE 4: Channel erosion

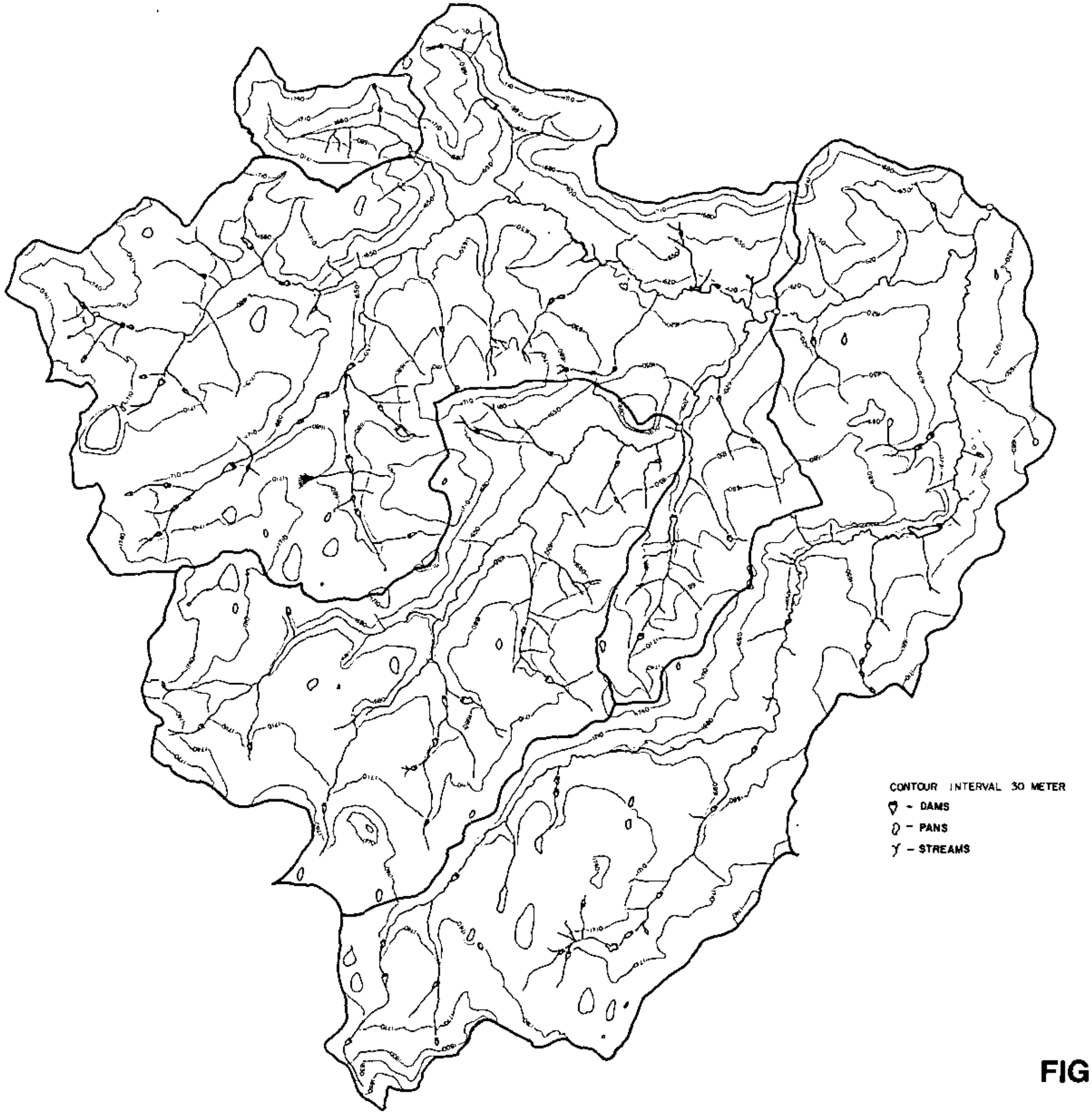


FIGURE 3.1: CATCHMENT RELIEF MAP

TABLE 3.2: Geomorphological indices of the BRAR catchments (Howman, 1980)

CATCHMENT NO.	C8M24	C8M25	C8M13	C8M12
AREA (km^2)	8,9	82,1	242,1	372,2
INDEX				
STREAM ORDER	Based on Horton's method of stream ordering, this index characterises the degree of development of a drainage network. A well drained basin is of a 5th order while a poorly drained basin is of a 2nd order.			
	3	4	5	5
BIFURCATION RATIO Rb	*This ratio is a measure of the degree of branching of streams in a river system. Having an important control* over the peakedness of the run-off hydrograph - a low Rb results in fewer but larger contributions to the run-off in the main channel. An Rb of 2 indicates a flat or rolling topography. An Rb of 4 indicates highly dissected mountainous region.			
	2,65 *Fairly flat and* rolling. Small degree of stream branching	3,44 *More hills and a* higher degree of stream branching	3,59 *Hills and high degree* of stream branching	3,88 *Hills and high degree* of stream branching
LENGTH RATIO Rl	Based on Horton's *method of stream ordering after renumeration - this index is indicative of the drainage* development of a catchment. The lower the length ratio, the lower the drainage density.			
	1,15	1,92	1,95	2,03
P - RATIO	The ratio is indicative of the ultimate degree of development of a drainage system and is a measure of channel storage. A high P ratio signifies a greater length of larger streams and therefore a greater channel storage per unit of drainage area.			
	0,43 Lowest channel capacity	0,56 Greatest channel capacity	0,54	0,52
LEMNISCATE RATIO	The ratio is a measure of how closely the actual drainage basin shape approaches that of its ideal lemniscate counterpart, e.g. tear or pear shaped form. A tear or pear shape is the norm in the absence of strong geological control. A ratio of 1,0 indicates little geological control, therefore the ideal; while a ratio of 0,0 indicates strong geological control.			
	0,83	0,73	0,69	0,71
HYPSOMETRIC CURVES	*The hypsometric curve is a pilot of the continuous function relating the elevation of the catchment basin to* their relative areas. The curve gives an indication of the stability of the catchment.			
	Equilibrium - slightly unstable	Equilibrium phase	Equilibrium phase	Equilibrium - tending towards monadnock
HYPSOMETRIC INTEGRAL	The hypsometric integral is a measure of the relative area below the hypsometric curve (expressed as a percentage in this instance). The integral provides an indication of stability. The lower the percentage the higher the stability of the catchment.			
	52% least stable	41%	41%	33% most stable

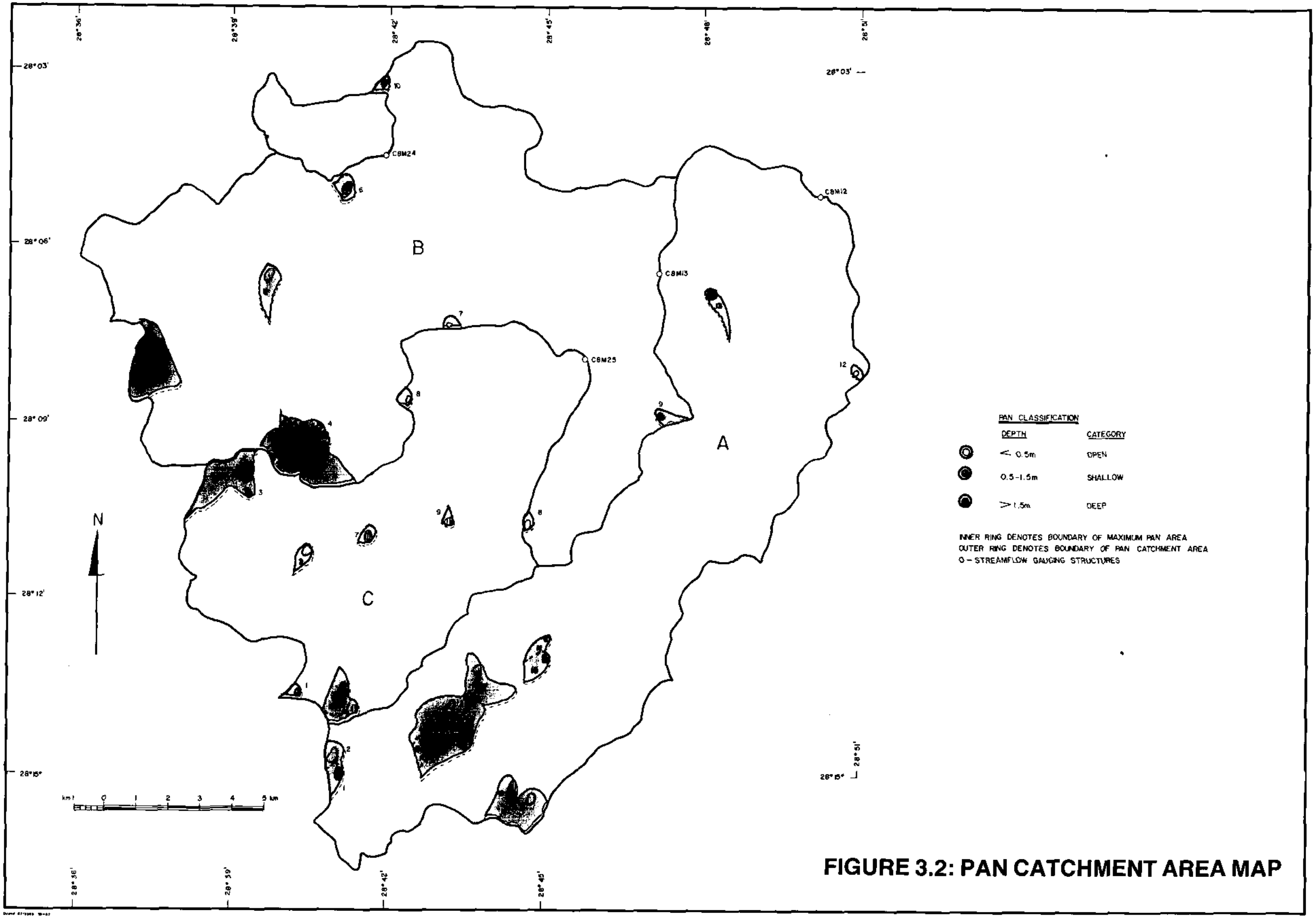


FIGURE 3.2: PAN CATCHMENT AREA MAP

TABLE 3.3: Individual pan data

Pan number*	Maximum depth (m)	Maximum area (ha)	Maximum storage (m^3)	Catchment area pan (ha)
A 1	2,5	10,5	262 500	43,45
A 2	open**	11,4	28 500	38,7
A 3	1,5	39,7	595 500	212,05
A 4	open	2,9	7 300	16,1
A 5	open	8,4	21 000	29,4
A 6	open	12,3	30 800	136,0
A 7	open	6,4	16 000	108,35
A 8	1,0	18,5	185 000	73,6
A 9	open	9,0	22 500	154,0
A10	0,5	3,2	16 000	46,25
A11	1,0	3,0	30 000	23,9
A12	open	1,2	3 000	11,2
A13	2,0	4,7	94 000	50,6
B 1	2,0	63,5	1 270 000	396,7
B 2a	0,7	2,7	18 900	156,3
B 2b	5,5	43,7	2 403 500	
B 3	1,5	12,2	183 000	191,4
B 4	open	2,1	5 300	29,1
B 5	open	9,4	23 500	142,4
B 6	3,5	14,3	500 500	38,9
B 7	open	0,95	2 400	2,85
B 8	open	3,6	9 000	15,9
B 9	1,0	1,3	13 000	19,2
B10	2,5	6,4	160 000	21,2
C 1	0,5	2,6	13 000	18,77
C 2	open	5,2	13 000	58,2
C 3	1,6	2,2	35 200	18,2
C 4	0,7	18,9	132 300	328,6
C 5	0,5	3,3	17 000	26,83
C 6	0,5	20,5	102 500	89,4
C 7	0,5	4,5	22 500	22,5
C 8	open	1,35	3 400	11,55
C 9	1,3	3,7	48 100	36,4

* Numbering system refers to Fig 3.2

** An open pan is one not enclosed by contours but where a surface depression is indicated. A depth of 0,25 m was arbitrarily chosen.

TABLE 3.4: Pan storage and catchment area

Catchment number	C8M12	C8M13	C8M25
Maximum pan area (km^2)	3,53	2,22	0,62
% Catchment area	0,95	0,92	0,76
Pan catchment area (km^2)	25,68	17,14	6,11
% Catchment area	6,84	7,08	7,44
Maximum pan storage (m^3)	6 288 200	4 976 100	387 000

3.2 Geology

The solid geology of the system is made up of the Beaufort and the Stormberg series of the Karoo system and is summarised in Fig 3.3.

The mudstones of the middle Beaufort series cover 38,8% of the catchment area (see Table 3.5) and occupy most of the lowlying eastern portions of the catchment. Although these mudstones are impermeable, the influence of dolerite dykes and sills together with the presence of a few thin interbedded sandstone bands might enable some water to reach the coarse grained buff sandstones of the lower section of the Middle Beaufort (Schultz, 1979).

The top of the middle Beaufort is marked by a thick sandstone band which covers 22,5% of the catchment area and which tends to cap the higher lying regions.

Overlying the sandstone marker horizon are the brightly coloured mudstones of the upper Beaufort series. These occupy a broad band veering north/south across the western part of the catchment. As with the mudstones of the eastern half of the catchment, these mudstones are also interbedded by sandstone bands and cut by numerous dolorite dykes and sills (Schultz, 1979).

The highest portions of the extreme western catchment boundary are made up of the coarse grained grits and sandstones of the Molento beds (Stormberg Series) which lie conformably on top of the Beaufort series.

TABLE 3.5: Surface areas of solid geology (Schultz, 1981)

Legend	Rock type	Area	% Total area
Stormberg Series	Sandstones	8,8 km^2	2,4
Upper Beaufort Series	Mudstones	114,2 km^2	30,7
Middle Beaufort Series	Sandstones	83,7 km^2	22,5
Middle Beaufort Series	Mudstones	144,5 km^2*	38,8
Dolerite Sills		21,0 km^2	5,6

*Schultz, Personal communication 1983

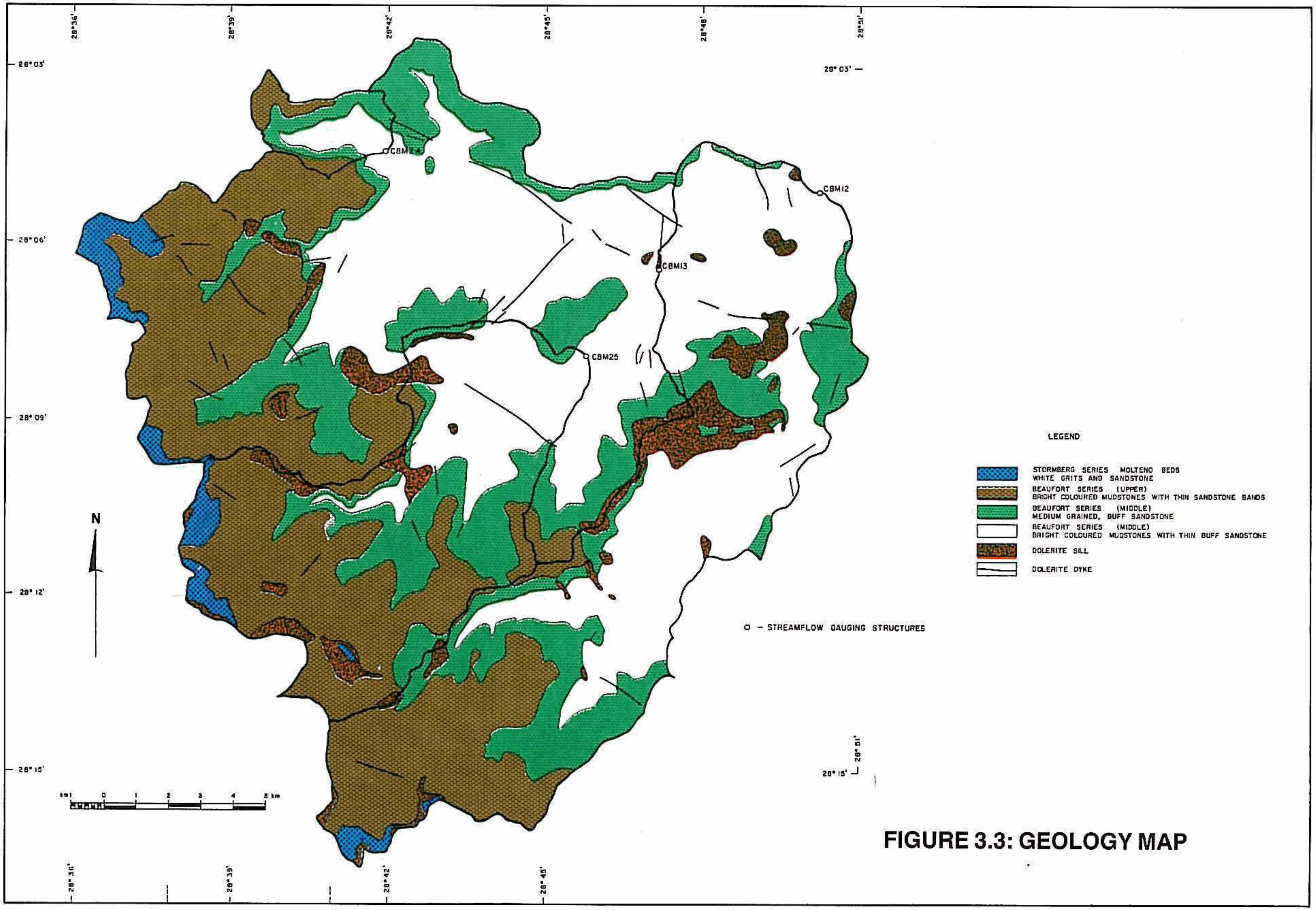


FIGURE 3.3: GEOLOGY MAP

3.3 Soils

3.3.1 Distribution pattern of soils

The soils of the area have been classified according to the first edition of the South African Binomial System (Maaren, 1979). This classification recognises two main levels of grouping: The soil FORM within which soil SERIES are defined. For easy reference soil forms and series are given geographical names, e.g. Avalon form, Heidelberg series. The soil form is based on a specified vertical arrangement of two or more diagnostic horizons. Soil series are separated with regard to texture, nature of the sandfraction and the degree of leaching and weathering. Looking at the soil pattern in the C8M12 catchment one finds that the uplands are dominantly occupied by light sandy soils of the Bleeksand series (see Plate 5), which is a brown or yellowish brown fine sandy topsoil overlying a yellowish brown fine sandy loam which via a zone of mottling, indicating occasional wetness, gradually merges into a zone of weathered bedrock. Along the major streams the soils are usually heavy, structured clays with strongly sodic subsoils (Valsrivier series). In the concave lower lying areas between the uplands and the major streams, the soils often belong to the class of duplex soils: light textured sandy topsoils abruptly overlying prismatic or structured clay soils, again usually sodic. (Estcourt and Kroonstad form soils).

For more detail see the soil map in Fig 3.4

3.3.2 Physical properties of the soils

3.3.2.1 Particle size distributions

Examples of representatives of the Bleeksand series are given in Table 3.6.

TABLE 3.6: Particle size distributions of upland soils (Bleeksand series) expressed in percentages

Depth (mm) Horizon	200 - 500 B21	100 - 300 B21	0 - 400 B21p	0 - 400 B21p
Gravel	3,5	1,0	1,5	1,0
Coarse sand	4,5	1,0	0,5	0,5
Medium sand	19,0	14,0	16,0	72,0
Fine sand	63,0	64,5	69,5	72,0
Silt	2,0	7,0	6,5	5,0
Clay	8,0	12,5	6,0	5,0

An example of the Valsrivier series of the low lying areas is given in Table 3.7

3.3.2.3 Water holding capacities and soil depth

The upper limit of the water holding capacity was determined in the field by taking subsurface samples between 20 and 24 hours after a good rain. For the upland Bleeksand series it is approximately 13,7% (W/W) which with a mean bulk density of 1,45 t m^{-3} means 20 vol % or 20 mm of water per 100 mm of depth. Estimated wilting point is in the order of 7-8 vol %.

Soil depth is variable but on average the uplands have about 600 mm depth available for normal root development. This means that about 72 mm of water is available for plant growth if fully recharged.

3.3.3 Soil moisture regimes

Details of site location and sampling methods are given in Figure 2.1 and in the Appendix. Soil moisture regimes have been drawn using the 1980/81 season's data, ie. gravimetric sampling, using dots where there is missing data. (See Fig. 3.5a-f)

From these graphs, comparison can be made between the soil moisture response to

(a) different land uses or
(b) different soil types or even
(c) different depths.

(a) Comparing different land use types

(i) Veld has a quicker response at the surface than either maize or wheat. The lower levels, too, seem to fluctuate rapidly.

(ii) The soil moisture related to maize increases early in the season (November) whereas wheat's response is noteably later (February). This is related to the growing seasons. When the plant is growing, it takes up the moisture in the soil or the water runs off. When fully grown, the cover is increased and thus less precipitation forms run-off and the water has time to infiltrate into the soil therefore the soil moisture is increased.

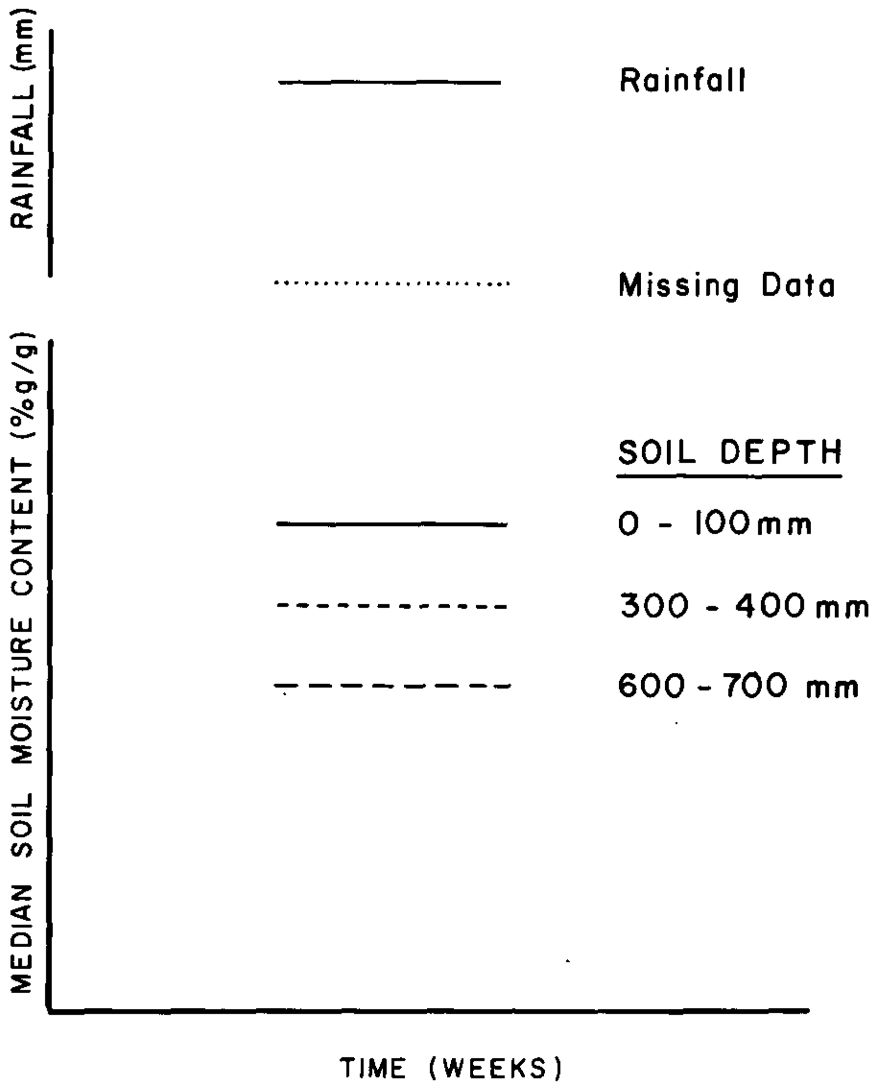
(iii) Maize gives rise to, on average, a higher soil moisture content over the season than either wheat or veld.

(b) Where the land use is constant, ie. veld, but the soil type is different, it is more difficult to make comparisons as the sites are located far from each other and thus may have differing rainfall amounts, causing differing responses in the soil moisture. (Figures 3.5 a, c, d)

All four soil types studied have an Orthic A horizon.

FIGURE 3.5

REFERENCE

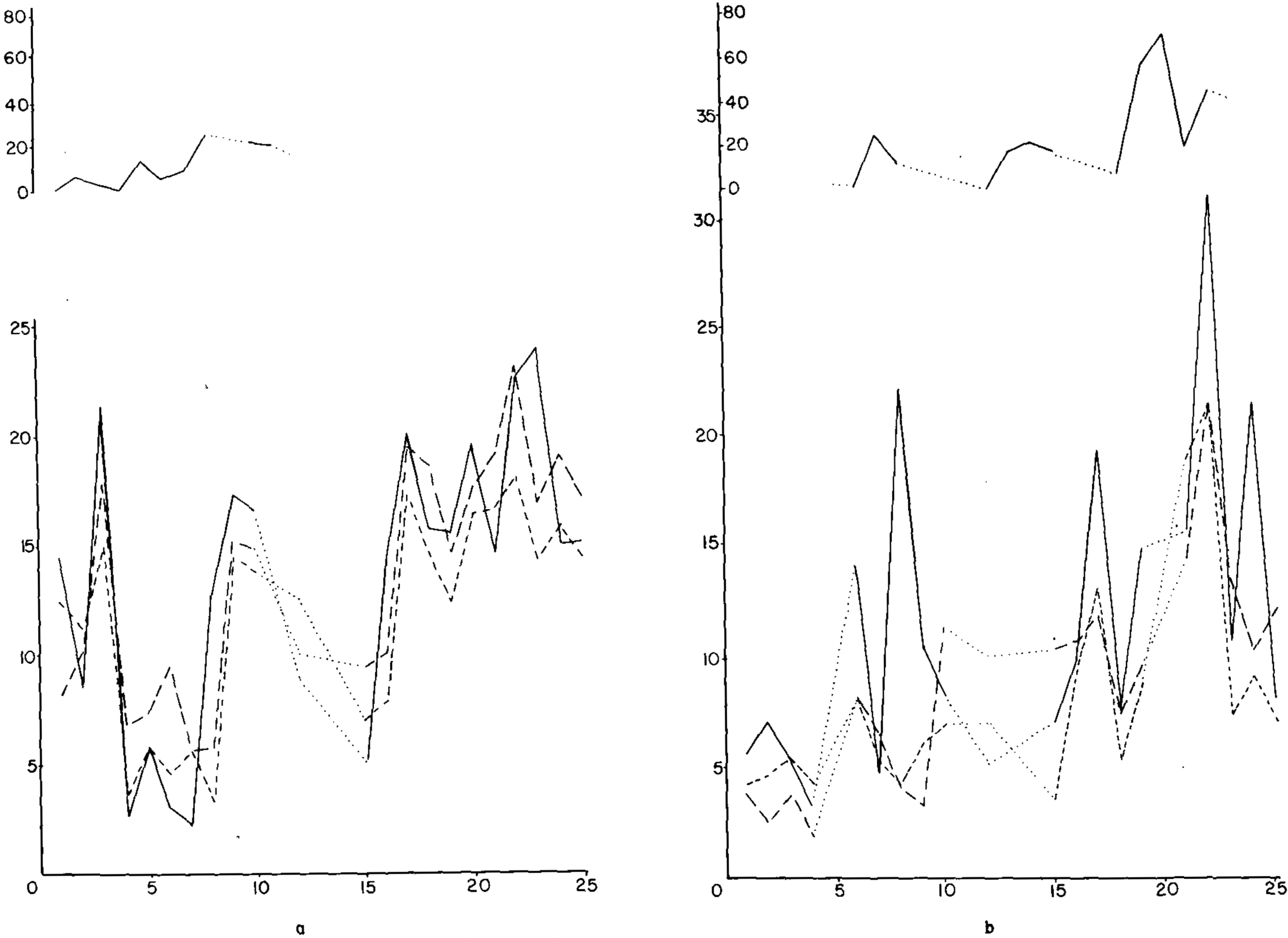


	SOIL TYPE	LANDUSE	RAINGAUGE SITE
a	Soetmelk	Veld	Geloof
b	Bleeksand	Veld	Joey's Home
c	Valsrivier	Veld	Tweespruit
d	Kroonstad	Veld	Sterkwater
e	Bleeksand	Maize	Joey's Home
f	Bleeksand	Wheat	Joey's Home

WEEK No.	DATE
1	7·10·80
5	4·11·80
10	9·12·80
15	13·1·81
20	17·2·81
25	24·3·81

KEY FOR FIGURE 3·5 a-f (SEE OVERLEAF)

FIGURE 3.5 (cont.)



a

b

Fig. 3·5 : Soil moisture regimes.

FIGURE 3.5 (cont.)

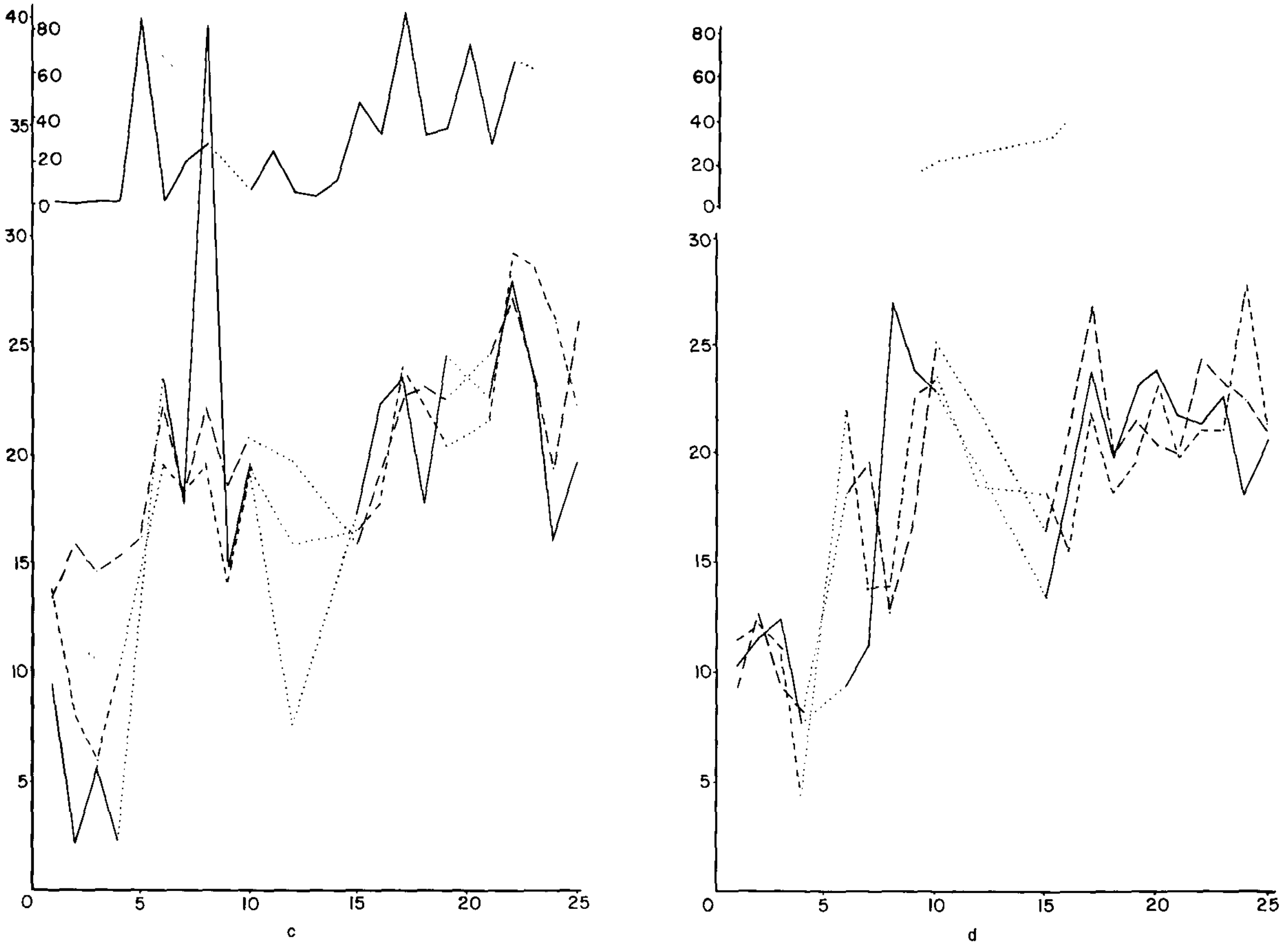


Fig. 3·5 : Soil moisture regimes

FIGURE 3.5 (cont.)

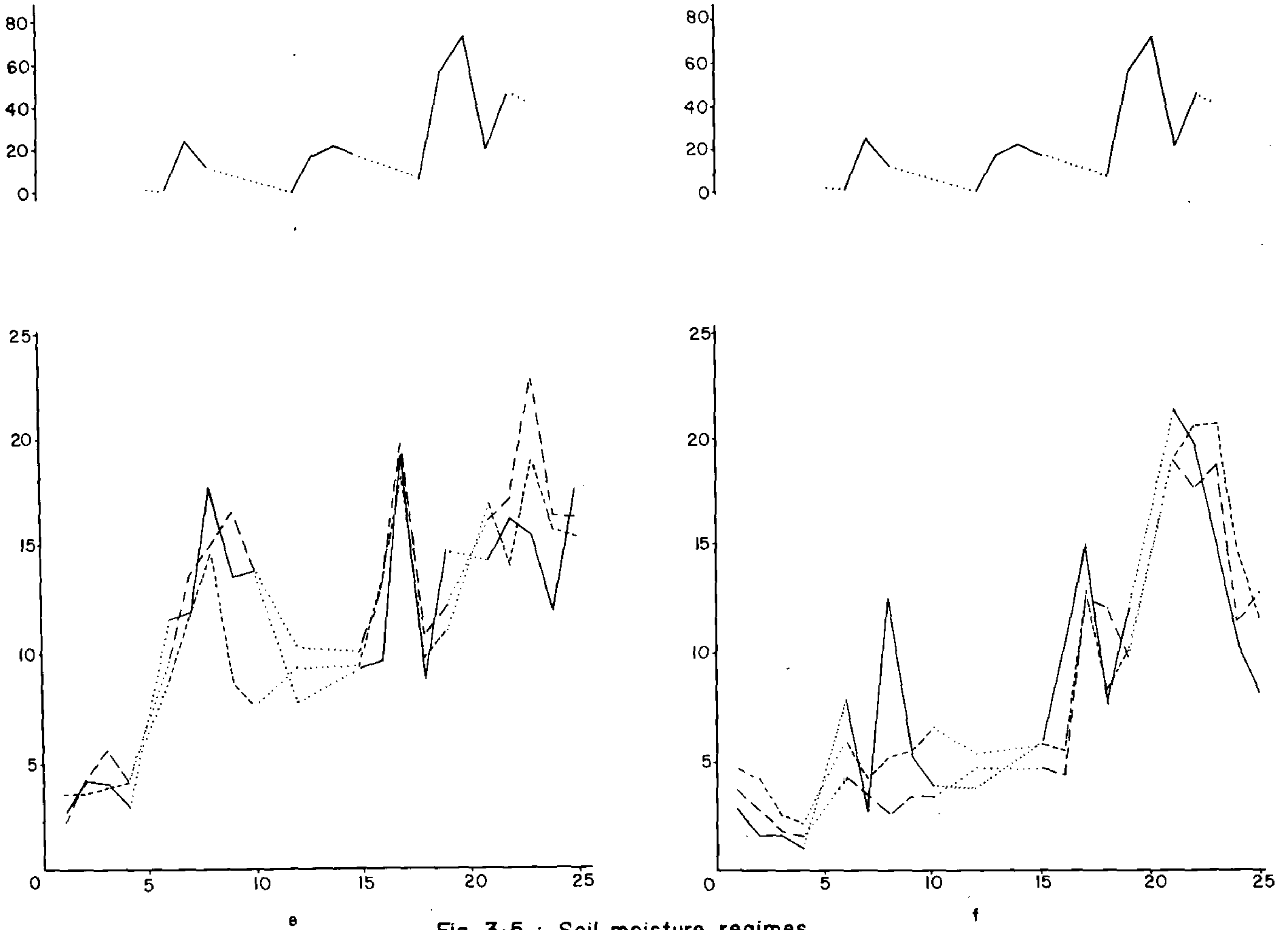


Fig. 3·5 : Soil moisture regimes.

The two upland sites (Joeys Home, Geloof) have soils of the Avalon form. The Bleeksand soil series at Joeys Home is less clayey (6-15%), in the yellow/brown apedal B horizon with fine sands, than the Soetmelk series at Geloof which has undifferentiated sands in this horizon and a clay content of 15-35%. (MacVicar et al., 1977). This feature is reflected in the soil moisture regimes where the Soetmelk series retains moisture because it has a higher clay percentage.

Valsrivier, being a bottomland soil at Tweespruit has a wide fluctuation of surface soil moisture as it is close to the river. It has a pedocutanic B horizon with 15-35% clay and calcareous characteristics, underlying the Orthic A horizon. Unconsolidated material exists at greater depths consisting of recently deposited sediments or decomposed rock without saprolite characteristics (MacVicar et al., 1977). This horizon retains water well as does the clayey B horizon, as shown in Figure 3.5.

The duplex soil is Kroonstad, located at Sterkwater. It has an E horizon underlying the orthic A, of 6-15% clay mixed with fine grained sands. This E horizon is hard when dry with mottling and streaking due to periodic saturation. This horizon overlies the Gleycutanic B horizon where material is intensely reduced as a result of prolonged saturation (MacVicar et al, 1977). Observation of the soil moisture regime notes shows up a marked delay time between surface saturation and the underlying B horizon in November. Once saturated the response is quicker (January/February).

(c) Generally the surface layer has a quick response, increasing rapidly after rain but decreasing when there is no precipitation. The subsurface layers have a more delayed reaction as moisture needs time to seep through. This also causes a diminished peak in the amount of moisture reaching these deeper soils. When there is little rain, these soils can retain the moisture for longer periods because evaporation affects the surface first.

3.3.4 Erosion

The effect of altered rainfall characteristics upon soil erosion has to be forecast as this area is prime agricultural land and soil loss is already a serious problem (Thwaites, 1983)

The erosion hazard survey of the catchments indicated areas of high and low erosion risk as well as actively eroding terrain. The region is shown to be prone to surface (wash) erosion, with conservation measures either ineffective or inadequate. Many small to medium size dongas are in evidence as well as severe channel erosion (see Plates 4 and 6).

To model the possible effects of cloud seeding on soil erosion, the Universal Soil Loss Equation, USLE, (Wischmeier and Smith, 1978) was adapted to South African conditions. Some results from the USLE are given in Table 3.8. The USLE, however, was proven to be inadequate for the demands of the BRAR project. So work is now progressing on an integrated hydrological model with erosion subroutine. This model, CREAMS (Chemical, Run-off, Erosion from Agricultural Management Systems) produces sediment yield data (Knisel, 1980). Strategically placed sediment sampling points will be used to provide calibration data for the CREAMS model and will also yield information for comparing soil loss and sediment yield.

Donga progression is also being studied and Table 3.9 shows the characteristics of five dongas and the amount of erosion each represents.

PLATE 6: Donga

TABLE 3.8: The effect of an assumed change in rainfall erosivity by rain-cloud seeding using the USLE

For a given environment: AVALON BLEEKSAND soil, maize at 1 m spacing, contour ploughed with a 200 m slope of 5% gradient.

Average annual soil loss (USLE) for that environment = 18,6 t/ha/yr with a rainfall erosivity (EI_{30}) for the Bethlehem area of 220 Joules/cm^2.mm/hr

Assume the EI_{30} index to be modified by seeding to 200, 260, or 285 J/cm^2.mm/hr: Soil losses (t/ha/yr) incurred by varying land use:

Land use	Contour ploughing				Contour strips				No conserv.			
Maize (1 m)	18,6	16,9	22,0	24,1	3,7	3,4	4,4	4,8	37	34	44	48
Maize (1,2 m)	23,3	21,2	27,5	30,2	4,6	4,2	5,5	6,0	47	43	55	61
Tramlyn maize	30,3	27,5	35,8	39,2	6,0	5,4	7,2	7,8	66	60	78	85
Wheat	23,3	21,2	27,5	30,2	4,6	4,2	5,5	6,0	47	43	55	61
Oats	21,0	19,0	24,8	27,2	4,2	3,8	5,0	5,4	41	37	49	53
Veld	2,3	2,1	2,7	3,0								
Burned veld	14,0	12,7	16,5	18,1								
Erosivity	220	200	260	285	220	200	260	285	220	200	260	285

The effect of the same assumed modifications of EI_{30} upon the BRAR test sites:

Site	Slope	Soil	Crop	System	220	200	260	285
1	450 m, 8%	Avalon	Wheat	Contour ploughed	43	39	51	56
2	150 m, 6%	Clovelly	Maize (1 m)	Contour stripped	5,4	4,9	6,4	7,0
3	100 m, 5%	Avalon	Maize (1 m)	No conservation	33	30	39	43
4	160 m, 5%	Kroonstad	Veld		22	20	26	29
5	220 m, 6%	Longlands	Veld		14	13	17	19
					Soil loss t/ha/yr			

TABLE 3.9: Dongas: features of erosion

Donga site	Length (m)	Eroded soil Volume (m^3)	Eroded soil Mass* (t)	Remarks
Springdale	235	2 050	3 100	Shallow, narrow, rock bottom
Suurfontein	288	3 500	5 250	Deep, narrow, v. active
Voorspoed	103	6 450	9 650	V. deep, broad, 2 main heads
Rietkuil	164	590	900	Shallow, newly formed
Mooimeisiesrus	97	1 200	1 800	Shallow, broad, rock bottom

* Assuming a bulk density of 1 500 kg/m^3

TABLE 3.10: *Extract of the analysis of some of the BRAR soils*

No.	Land use	Sediment analysis			Chemical analysis						Dispersivity		
		%> 75 μm	% Clay	% Silt	Mg	K	Ca	Na	*ESP*	*CEC*	pH	*% DISPN*	*New classification*
1	Wheat	49	5,6	2,0	7,7	4,9	27,2	7,2	12,5	57,7	6,4	20,0	Dispersive
2	Wheat	39	20,4	7,7	8,4	17,1	39,4	3,0	2,2	138,3	4,9	13,0	Non-dispersive
3	Maize	46	18,4	4,3	3,7	4,9	14,8	3,3	5,7	57,5	4,8	11,9	Marginal
4	Veld	44	20,7	6,7	18,9	8,0	57,2	8,9	6,2	143,6	5,3	24,5	Dispersive
5	Veld	53	5,9	2,6	4,5	8,2	19,9	2,6	3,1	84,4	5,2	25,0	Non-dispersive
6	Maize	62	5,3	1,3	1,8	3,9	11,7	2,9	7,9	36,6	4,8	14,3	Dispersive
7	Wheat	51	13,0	4,4	4,4	6,6	19,6	2,5	3,0	82,3	4,6	8,4	Non-dispersive
8	Wheat	56	12,3	4,0	6,0	11,5	31,2	3,2	4,4	71,9	5,6	13,5	Marginal
9	Maize	61	7,2	1,4	1,1	4,5	11,5	2,8	6,3	45,7	4,6	18,2	Marginal
10	Maize	52	10,1	2,9	2,3	5,4	16,2	3,1	5,4	57,4	4,6	13,0	Marginal
							mg/1			me/100g soil			

TABLE 3.11: Extract of the analysis of the monitored dongas

No.	Donga site	Hor.	Sediment analysis			Chemical analysis			Dispersivity		
			%> 75 µm	% Clay	% Silt	Na	ESP	CEC	pH	% DISPN.	New class.
1	Suurfontein	A	38	17,4	6,3	2,0	2,4	82,3	5,1	11,1	Non-dispersive
2		B	19	39,7	7,7	43,3	19,1	226,1	6,2	44,3	Highly dispersive
3	Rietkuil	A	33	16,1	9,0	3,7	3,2	115,5	5,5	13,5	Marginal
4		B	21	44,2	6,8	26,9	14,4	186,2	6,0	32,0	Dispersive
5	Voorspoed	A	42	11,9	5,5	2,3	3,0	75,6	4,2	9,6	Non-dispersive
6		B	44	28,6	4,4	4,7	4,5	104,8	4,9	20,6	Marginal
7	Springdale	A	31	18,3	6,9	1,3	1,3	98,7	4,9	9,4	Non-dispersive
8		B	22	58,5	3,1	3,7	2,7	135,1	4,8	22,1	Non-dispersive
9	Mooimeisiesrus	A	36	11,2	5,4	2,0	4,7	42,9	6,2	10,9	Marginal
10		B	38	19,5	5,9	2,3	4,5	51,3	6,8	28,0	Marginal
						mg/1	me/100 g soil				

FIGURE 3.7

FIG. 3·7 : Distribution of planting dates for maize and wheat in two areas (Maaren, 1980)

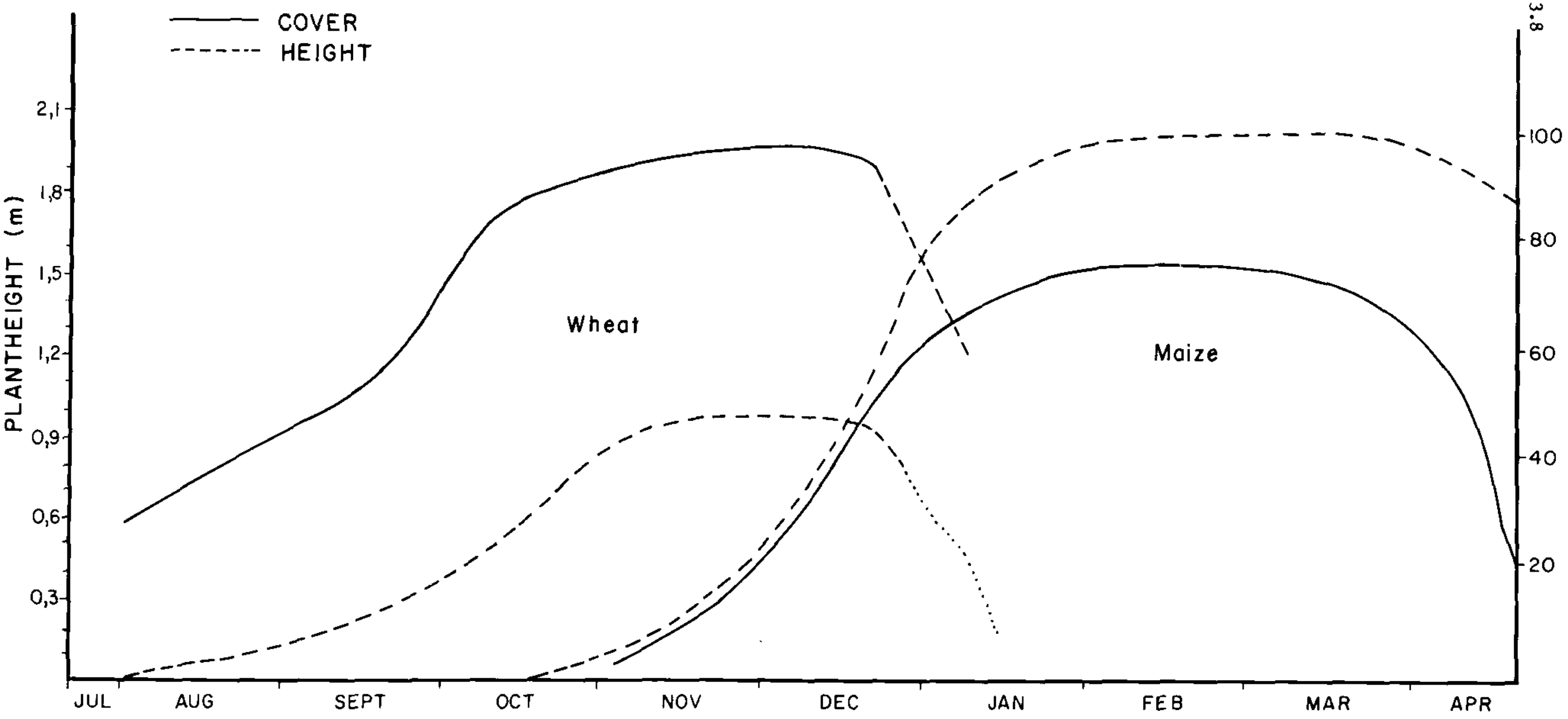


FIG. 3·8 : Plantheight and fractional cover in Bloukop area during 1979/80 season (Maaren, 1980)

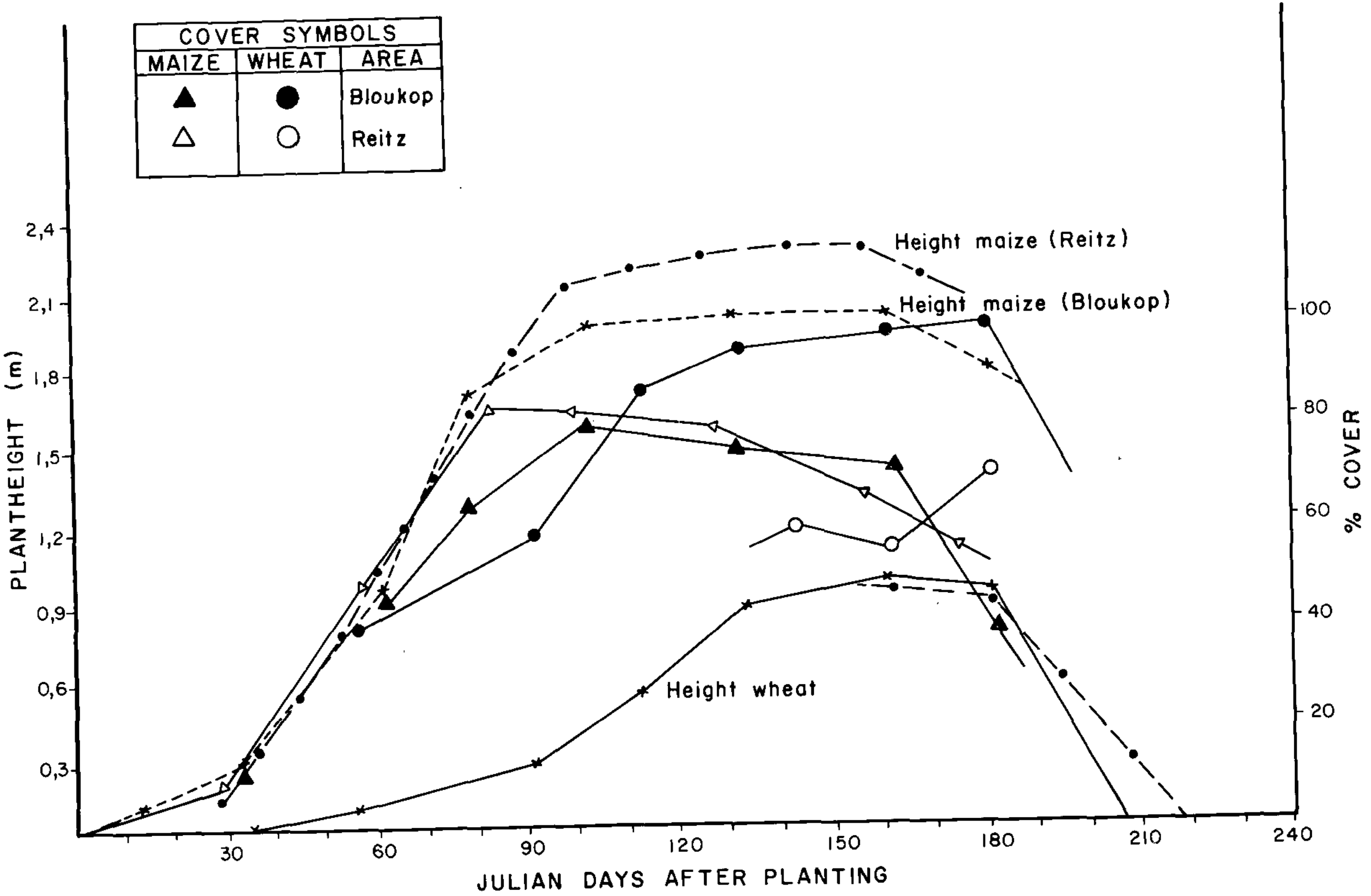


FIG. 3·9 : Important cover characteristics in two areas during 1979/80 (Maaren, 1980)

Another important feature of the dams, hydrologically speaking, is their catchment area (see Fig. 3.10). The data collected from orthophotos and given in Table 3.13 should provide some idea of the extent of the influence of these dams.

TABLE 3.13: Dam catchment areas

Catchment no.	Area of dam catchments (km^2)	% of total catchment area
C8M24	8,9	95,0
C8M25	48,5	59,2
C8M13	196,0	80,9
C8M12	296,6	79,7

The majority of the dams are very shallow, with depths of less than 3 m and thus are prone to high evaporation losses. They are mainly used for direct stock watering, although small scale irrigation occurs in a few cases.

There are two main types of dam within the catchment: those constructed across river channels (Plate 9), and smaller embankments usually semi-circular in shape constructed on hillsides (Plate 10). Both types are of very simple design using locally excavated material. The earth used is a highly dispersive sodic subsoil which is very erodible (see section 3.3.4) thus dam and spillway failure is relatively common (Plate 11).

Spillways are uncontrolled, grassed exits located at the end of the dam wall.

3.4.2 Roads

Roads in the area are fairly abundant. Tar roads crossing the area are the road from Bethlehem to Warden in the north and the road from Kransfontein via Afrika's Kop to Kestell which has been built during the 1979/80 season. The rest of the roads are good gravel roads. The influence of these roads on catchment behaviour is expected to be minimal. (Stickells, 1980a, 1980b).

3.4.3 Farm Dams

There are over 200 farm dams in catchment C8M12 whose maximum capacities range from less than 100 m^3 to over 100 000 m^3 (Kennedy, 1981). A study based on air photos (Kennedy, 1981) estimated that the total maximum dam storage capacity of C8M12 was approximately 640 000 m^3 in 1976. The mean annual run-off from C8M12 is approximately 5 million m^3 (see section 5.1), thus the total dam storage capacity would then be about 13% of the mean annual run-off. However, this percentage would be much higher during years of low flow. For example, in 1978, the annual run-off total was approximately 1 million m^3, thus in that year, the storage capacity would have been about 60% of the run-off. Also, the number and size of the dams has been increasing over the past twenty years and so the significance of this ratio can also be expected to rise.

PLATE 7: Contour walls

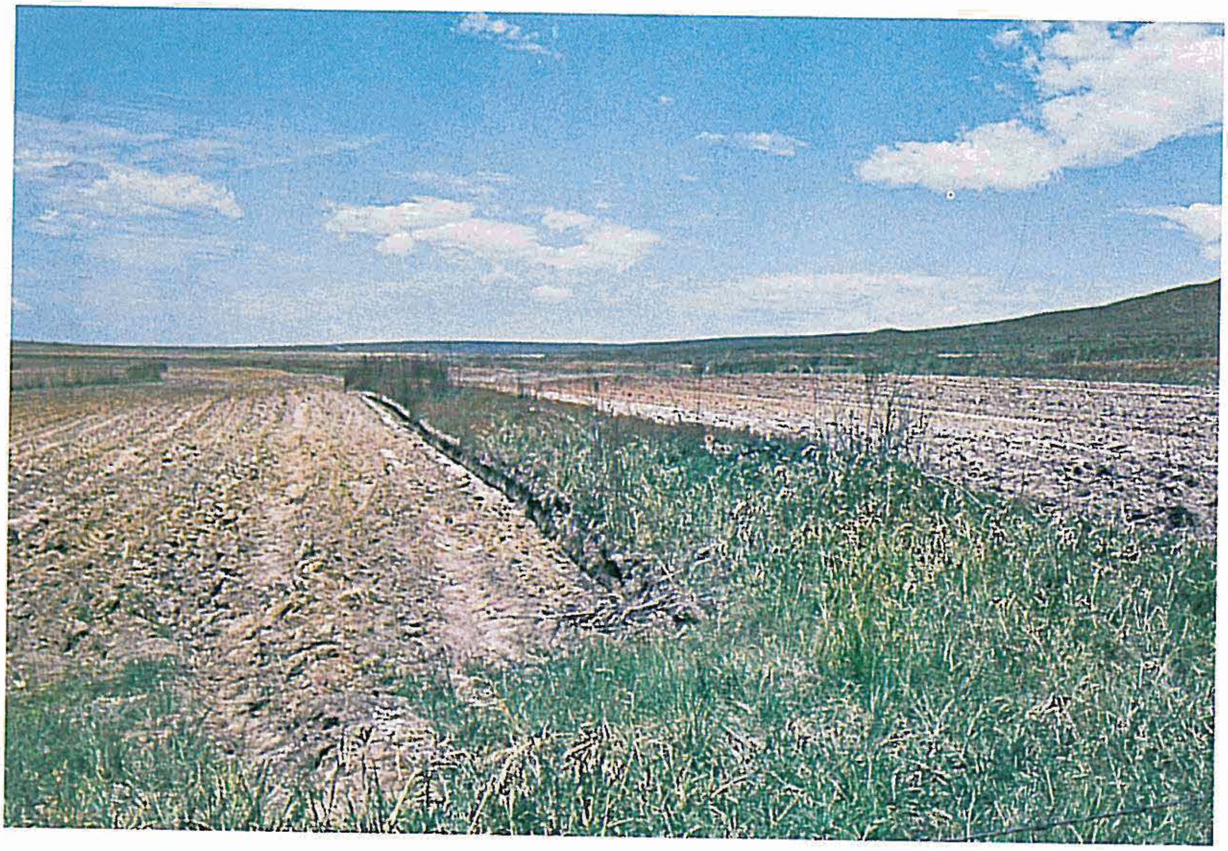


PLATE 8: Contour ploughing

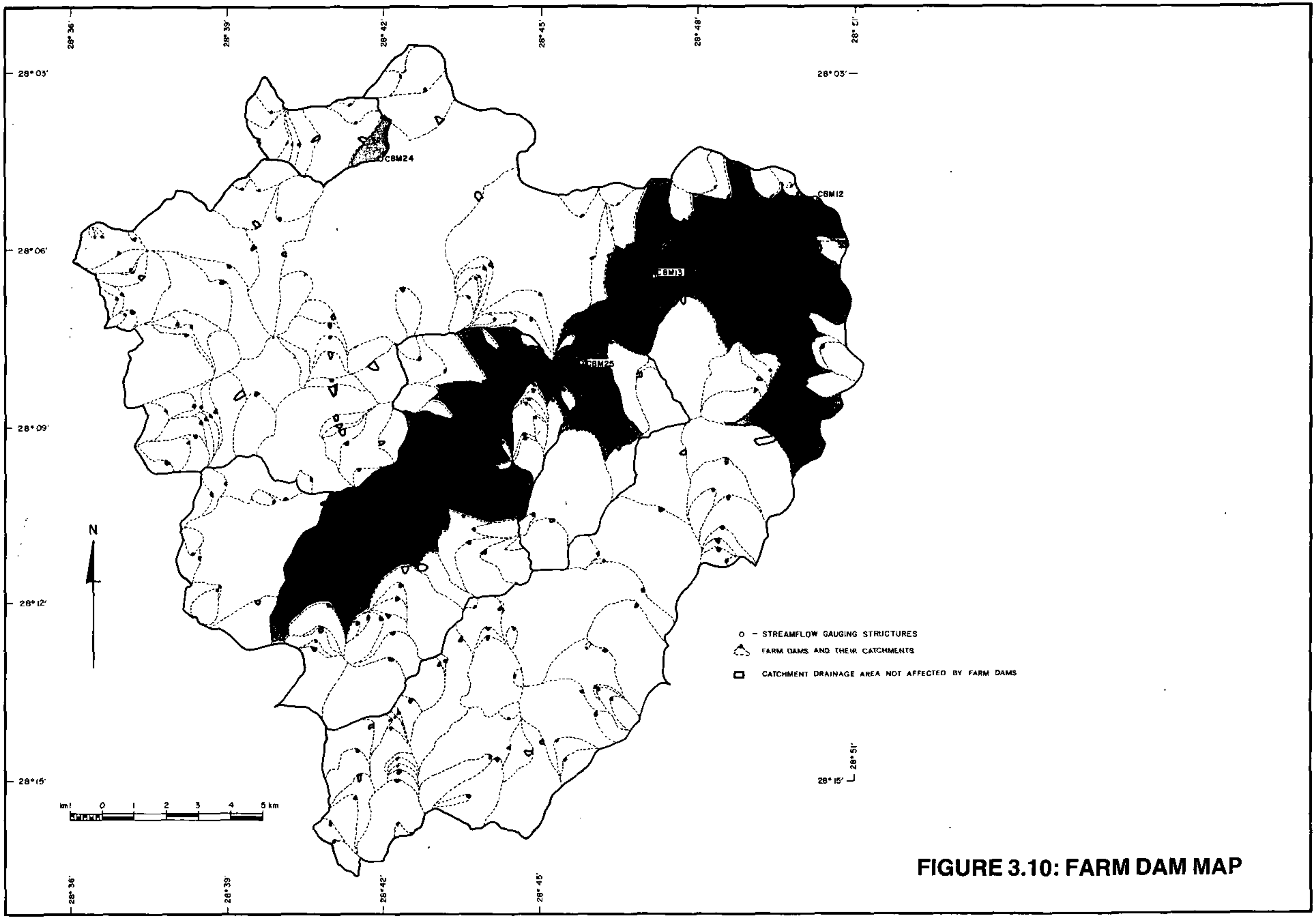


FIGURE 3.10: FARM DAM MAP

PLATE 9: Farm dams in series

PLATE 10: Hillside farm dam

PLATE 11: An example of spillway failure

4. CLIMATIC CHARACTERISTICS

4.1 Rainfall

4.1.1 Annual totals and monthly distribution

The rainfall pattern is typical of the summer rainfall area in South Africa as illustrated in Table 4.1.

TABLE 4.1: Monthly distribution of rainfall at Bethlehem (331/554)

	J	F	M	A	M	J	J	A	S	O	N	D
mm	111	79	90	48	28	9	15	14	26	63	89	104
%	16,4	11,7	13,3	7,1	4,1	1,3	2,2	2,1	3,8	9,3	13,1	15,4

From these data one can see that on average 79,2% of the annual rain falls in the season between October 1st and the end of March. However, rainfall is very unreliable and highly variable.

The average annual total is 676 mm at Bethlehem and shows the following distribution:

TABLE 4.2: Annual rainfall (R) exceeded at given probability levels (P). (Wand, personal communication)

P	R(mm)
0,995	301
0,9	482
0,8	542
0,6	626
0,5	665
0,4	705
0,2	812
0,1	905
0,005	1 273

4.1.2 Type of rainfall and weather situations

Within the context of a rainfall enhancement project the relation between weather situation and rainfall becomes extremely relevant.

Hudak and Steyn (1980) and Harrison <u>et al</u> (1978) designed a classification system for weather situations around Bethlehem. Summary of this classification is given in Table 4.3.

TABLE 4.3: Forecasting classifications of weather situations

Type I:		Days consisting of blue skies, cumulo-humilis or stratus.
Type II:		Days consisting of cumuli with tops warmer than -5°C.
Type III:		Organised squall lines moving into the BEWMEX area overnight (this type is not used in the daily classification but could be used for overnight prediction in the afternoon forecast).
Type IV:		General rain situation
	(IV-A)	Overcast stratus, stratocumulus with little or no precipitation.
	(IV-B)	Overcast skies producing rain for prolonged periods.
	(IV-C)	Broken to overcast low and middle clouds producing some rain but with convective elements present producing heavier showers.
Type V:		Days with cumuli with tops colder than -5°C in which clouds meeting seeding criteria were met.
	(V-S)	Days in which cumuli tops were above -5°C but the seeding criteria were not met (bases too high, tops too warm, rapid early glaciation, tops breaking off, clouds too narrow).
Type VI:		(A) Days in which cumuli formed with tops colder than -5°C and many of the clouds contained hail.
		(B) Days in which cumuli formed with tops colder than -5°C and most contained hail and/or formed into well organised squall lines.

The distribution of the different weather situations during the summer season is illustrated in Table 4.4. Here the occurrence is expressed as a percentage of the days <u>with</u> observations, however, it must be realised that in the last three seasons between 23,6% and 35,8% of the time no observations on weather situations were available.

TABLE 4.4: Relative distribution of different weather situations

Weather situation	1977/78 + 78/79(1)	1979/80	1980/81	1981/82
I	23,6	22,4	19,4	19,8
II	3,3	4,0	5,0	6,9
IV	-	-		3,4
IV-A	-	-	0,7	1,7
IV-B	2,5	0,8	2,2	3,4
IV-C	6,5	4,8	7,2	2,6
V	31,7	33,6	53,2	33,6
V-S	14,1	15,2	5,8	14,7
VI	-	-	1,4	2,6
VI-A	13,0	17,6	5,0	10,3
VI-B	5,8	1,6	-	0,9
NO OBS	-	31,7(2)	23,6(2)	34,8(2)

(1) Court, 1979b

(2) percentage of total days in season

From the table one can see that of the potential rain days (IV, V and VI) the majority of the days is classified as class V. Of the last five years of data collection, the 80/81 season was the wettest (see also Fig. 5.1).

The areal extent and depth of precipitation have been used by Court (1979a, 1979b) to separate rain days into general, scattered and isolated categories.

TABLE 4.5: Rainfall classification*

Dry day	3% or less of stations report rain
Isolated rain	More than 3%, but less than 15% of stations report rain
Scattered rain	15% or more of stations report rain but less than 50% report more than 5 mm
General rain	50% or more of stations report at least 5 mm of rain

* As a measure of the extent of rainfall on a particular day, the number of stations reporting rain on a day was expressed as a percentage of the total number of stations that could have reported within the BEWMEX operational area of some 25 000 km^2.

Court (1979a, 1979b) studied the occurrence of different rainfall patterns during different weather situations. Tentative conclusions were that, in general the type IV and VI weather situations produce the major or general rainfalls and it is the contribution from these days that determines how wet a season is. Also the days of scattered rainfall are largely produced by the type V weather and even in a dry season it is expected that a good number of potentially seedable situations will occur.

4.1.3 Storm characteristics and rainfall intensities

It is known that on the highveld, convective storms generally travel in an approximately north-easterly direction (Heymann and Markham, 1982). Greenacre and Pearce (1979) studying daily rainfall patterns in the BEWMEX operational area also found evidence of this: "Looking at the other regions on the days classified as "scattered rain" days, there are many examples of pairs of stations orientated in a north-easterly direction which are more correleted than expected."

Based on the work of Mader (1979) and Dixon (1977) Heymann and Markham (1982) assumed the following storm characteristics, as illustrated in Table 4.6.

TABLE 4.6: Characteristics of convective storms

	Duration (minutes)	Speed (km/h)	Maximum area (km^2)
Mode	15	10	30
Median	15	22	42
Average	24	30	86
95% pecentile	60	40	140

The median storm can be considered as a "typical" storm. Although these figures must be considered as preliminary estimates, they do show that convective storms, as formed during weather situation V and VI, have a fairly limited areal extent. In order to realistically "measure" storm rainfall at relatively small time intervals of 5 to 15 minutes, one requires fairly dense raingauge networks, probably in the order of one gauge per square kilometre (Heymann and Markham, 1982).

Another indication of storm duration during different weather situations is given by Court (1979b) and illustrated in Table 4.7 derived from the same data set as for the 1977/78 and 1978/79 seasons.

TABLE 4.7: Average duration of precipitation under different weather situations

Weather situation	Mean duration of precipitation (minutes)	Standard deviation
IV-B	140	109
IV-C	90	71
V	26	43
V-S	18	22
VI-A	62	50
VI-B	83	46

Rainfall intensities are closely associated with duration of rain and total depth. Maximum intensities are reported for weather situation VI, especially VI-B. This is illustrated in Table 4.8 also after Court (1979b)

TABLE 4.8: Mean maximum intensities under different weather situations

Weather situations	Mean maximum intensity (mm/hr) in			
	10 min.	20 min.	30 min.	60 min.
IV-B	22	16	14	9
IV-C	35	29	23	15
V	39	25	20	12
V-S	23	17	13	8
VI-A	64	46	37	22
VI-B	69	57	48	27

Again, one can see that rainfall intensities are highest during the type VI weather situation.

With regard to the diurnal rainfall patterns, Court (1979b) also found that type VI-B especially showed a preference for afternoon peaks (single peak between 15h00 and 18h00) while only weather situation IV-B showed multiple peaks between 10h00 and 11h00 and another between 03h00 and 04h00.

With regard to run-off production, rainfall intensities are most important as high intensity rain usually gives rise to more run-off than low intensity rain, given the same storm total. However, total daily depth of precipitation must also be considered.

Fitting the data to a gamma distribution, Court (1979b) obtained the following probabilities of daily falls for each weather situation:

TABLE 4.9: Probabilities that the daily rainfall will be less than or equal to a given threshold

Rainfall (mm)		Weather situation		
	IV	V	V-S	VI
0 - 1	0,18	0,36	0,67	0,06
0 - 2	0,33	0,53	0,88	0,16
0 - 3	0,39	0,69	0,96	0,27
0 - 4	0,50	0,79	0,98	0,37
0 - 5	0,59	0,85	0,99	0,47
0 - 6	0,67	0,90		0,56
0 - 7	0,70	0,93		0,64
0 - 8	0,75	0,95		0,70
0 - 9	0,80	0,97		0,76
0 - 10	0,83	0,98		0,80
0 - 11	0,86	0,98		0,84
0 - 12	0,88	0,99		0,86
0 - 13	0,90			0,88
0 - 14	0,92			0,91
0 - 15	0,93			0,93

To summarise, of the potential rain days (weather situation IV, V and VI), weather situation V occurs most frequently. However, the total volume of actual rainfall is probably relatively lower than for weather situations IV and VI, where rainfall is generally of a longer duration resulting in a larger total depth per day.

This is provisionally comfirmed by the analyses of rainfall over C8M12 during the 1981/82 season as illustrated in Table 4.10.

TABLE 4.10: Weather situation and rainfall depth over C8M12 during 1981/82 season

Weather type	Rainfall (mm)	% of days with observations
IV	52,0	31,1
V	46,2	27,6
VI	69,1	41,3
NO OBS	96,0	-

4.2 Sunshine

Mean fraction of possible sunshine hours per day for each month is given in Table 4.11.

TABLE 4.11: Mean fraction of possible sunshine ($^n/N$) (Bethlehem/Loch Lomond, 1958 - 1975)

J	F	M	A	M	J	J	A	S	O	N	D
0,62	0,67	0,65	0,66	0,75	0,75	0,78	0,80	0,76	0,68	0,64	0,67

n = actual duration of sunshine

N = maximum possible duration of sunshine

4.3 Solar radiation

From the latitude, time of the year and fraction of possible sunshine the following estimates of solar radiation are made: mean daily, clear days (($^n/N$)$\geq$ 0,90) and overcast (($^n/N$)$\leq$ 0,1).

TABLE 4.12: Solar radiation (MJm^{-2})

	J	F	M	A	M	J	J	A	S	O	N	D
Mean+	24,2	23,4	19,9	16,5	14,4	12,5	13,5	16,7	20,2	22,5	24,0	25,7
Clear*	31,9	29,5	25,5	21,0	16,9	14,7	15,5	18,9	23,5	27,8	31,1	32,4
Overcast°	8,1	7,5	6,5	5,3	4,3	3,7	3,9	4,8	6,0	7,0	7,9	8,2

+Estimated as (0,24 + 0,53 $^n/N$) times the extra-terrestrial radiation

*Estimated as 75% of the extra-terrestrial radiation

°Estimated as 19% of the extra-terrestrial radiation

4.4 Temperature

The mean daily maximum, mean daily minimum and average daily temperature data are summarised in Table 4.13.

The average duration of the frost period is 130 days, although frost may occur from April to October.

TABLE 4.13: Temperature data (°C)

	J	F	M	A	M	J	J	A	S	O	N	D
M.d.max	27,0	25,8	24,5	22,1	19,3	16,9	16,5	19,1	22,4	24,3	25,5	26,9
M.d.min	13,1	13,3	11,5	6,4	1,9	-1,7	-2,1	0,9	4,4	8,5	9,9	12,4
Mean	20,1	19,5	18,0	14,3	10,6	7,6	7,2	10,0	13,4	16,4	17,7	19,7

4.5 Evaporation and potential evapotranspiration

Mean daily pan evaporation per month is given in Table 4.14. Measurements are taken with a Class A pan and the Symons pan. Potential evapotranspiration, ET, for a plant cover is given as calculated with the Penman-Monteith equation (Maaren, 1978).

TABLE 4.14: Evaporation data (mm day^{-1})

	J	F	M	A	M	J	J	A	S	O	N	D
ET*	5,7	5,0	4,0	2,9	2,1	1,4	1,5	2,8	4,2	5,2	5,4	6,0
S-pan	5,5	5,4	4,7	3,3	2,4	2,0	2,1	3,0	4,3	5,2	5,2	6,2
A-pan	7,7	7,4	6,3	4,5	3,2	2,6	2,8	4,1	6,2	7,5	7,8	9,0

* Plant characteristics used are: leaf area index, LAI, between 4,0 in summer and 0,8 in winter; plant height between 0,80 m in summer and 0,32 m in winter; minimum canopy resistance 50 sm^{-1} in summer and 120 sm^{-1} in winter.

5. CATCHMENT YIELD

5.1 Streamflow

5.1.1 Annual water yields

An analysis of five seasons, running from October 1, 1977 till March 31, 1982 for the C8M12 catchment whose area is 372,2 km^2 revealed that the percentage run-off as related to rainfall varied from less than 1% in the 78/79 season to 6,3% in the 80/81 season. Detailed information is given in Table 5.1.

TABLE 5.1: Rainfall and run-off in the C8M12 catchment

Season	Run-off ($10^3 m^3$)	Rainfall (mm)	Percentage run-off
77/78	4 303,8	503	2,3
78/79	970,1	308	0,8
79/80	2 282,4	428	1,4
80/81	16 222,1	690	6,3
81/82	1 977,5	390	1,4

The non-linear relation between run-off and rainfall is clearly illustrated in Fig 5.1.

5.1.2 Analysis of quick flow versus delayed flow

The hydrograph analysis is carried out using the technique suggested by Hewlett and Hibbert (1967) whereby quick flow is separated from the delayed flow using the constant slope line of 1,13 mm day^{-1} day^{-1}.

The results for five seasons are given in Table 5.2.

TABLE 5.2: Quick flow and delayed flow in C8M12 catchment, each expressed as a percentage of total flow

Season	77/78		78/79		79/80		80/81		81/82	
Month	D	Q	D	Q	D	Q	D	Q	D	Q
October	100,0	0,0	99,9	0,1	100,0	0,0	100,0	0,0	100,0	0,0
November	100,0	0,0	100,0	0,0	84,1	15,9	53,8	46,2	99,3	0,7
December	82,9	17,1	98,5	1,5	100,0	0,0	88,4	11,6	44,9	55,1
January	76,8	23,2	100,0	0,0	97,3	2,7	96,8	3,2	88,5	11,5
February	95,3	4,7	96,5	3,5	93,4	6,6	43,6	56,4	100,0	0,0
March	100,0	0,0	86,5	13,5	62,9	37,1	84,5	15,5	100,0	0,0
Season	81,1	18,9	91,2	8,8	82,8	17,2	60,6	39,4	67,0	33,0

FIGURE 5.1

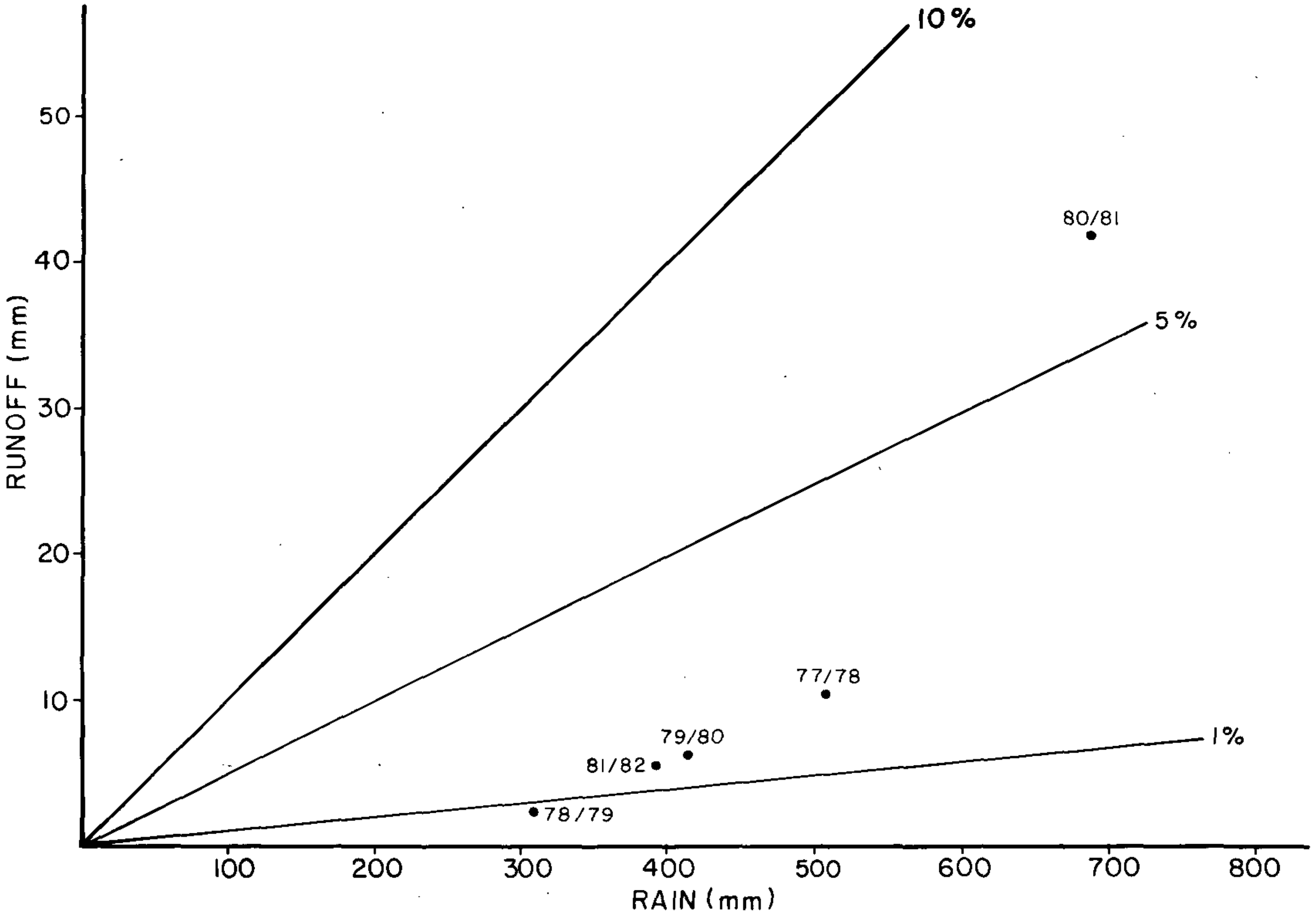


FIG. 5·1 : The rainfall / runoff relationship in C8M12

The maximum amount of quick flow recorded in one month was 56,4% during February 1981.

This way of flood separation is of course rather arbitrary and does not necessarily reflect the origin of the water in terms of overland flow and seepage flow.

Fig. 5.2 shows a typical stream hydrograph for catchment C8M24 (area, 8,9 km^2) resulting from a series of storms. The steepness of the rising limb and initial resession rate seems to be a common feature of the catchment's response to rainfall. However, the response is very dependant on antecedent catchment wetness and this relationship is being studied at present with reference to antecedent rainfall and soil moisture contents.

5.1.3 Recession curve analyses

Cousens (1980) used the technique of recession curve analysis to classify run-off in terms of rain that fell during different weather conditions causing run-off events. Recession curve analysis is based on the concept formulated by Jones and Mefilchrist (1978):

"If no more storm input occurs in the catchment area then the hydrograph should fall according to a model which is constant at each particular gauging station".

As only clouds during weather types V, VS or VI (as described in chapter 4.1.2) have potential for rainfall enhancement, the analysis of run-off weather type relationships becomes extremely important. The main results are repeated in Table 5.3.

TABLE 5.3: Summary of amount of run-off contributed by rainfall which fell on days verified as different weather situations

Weather situation	C8M10		C8M12	
	Run-off volume (10^3m^3)	% of total run-off	Run-off volume (10^3m^3)	% of total run-off
II	1 018,1	2		
IV-A			176,0	3
IV-B	2 326,5	3	547,2	8
IV-C	11 514,8	16	2 275,0	35
V	32 202,9	45	969,0	15
V-S	6 743,8	9	13,1	0
VI-A	7 212,5	10	2 259,5	35
VI-B	11 110,3	15	230,3	4
Total	72 128,8	100	6 470,1	100

This analysis covered 146 run-off events in C8M10 and 93 events for C8M12 during the three seasons between October 1977 and March 1980.

FIGURE 5.2

C8M24

81/82

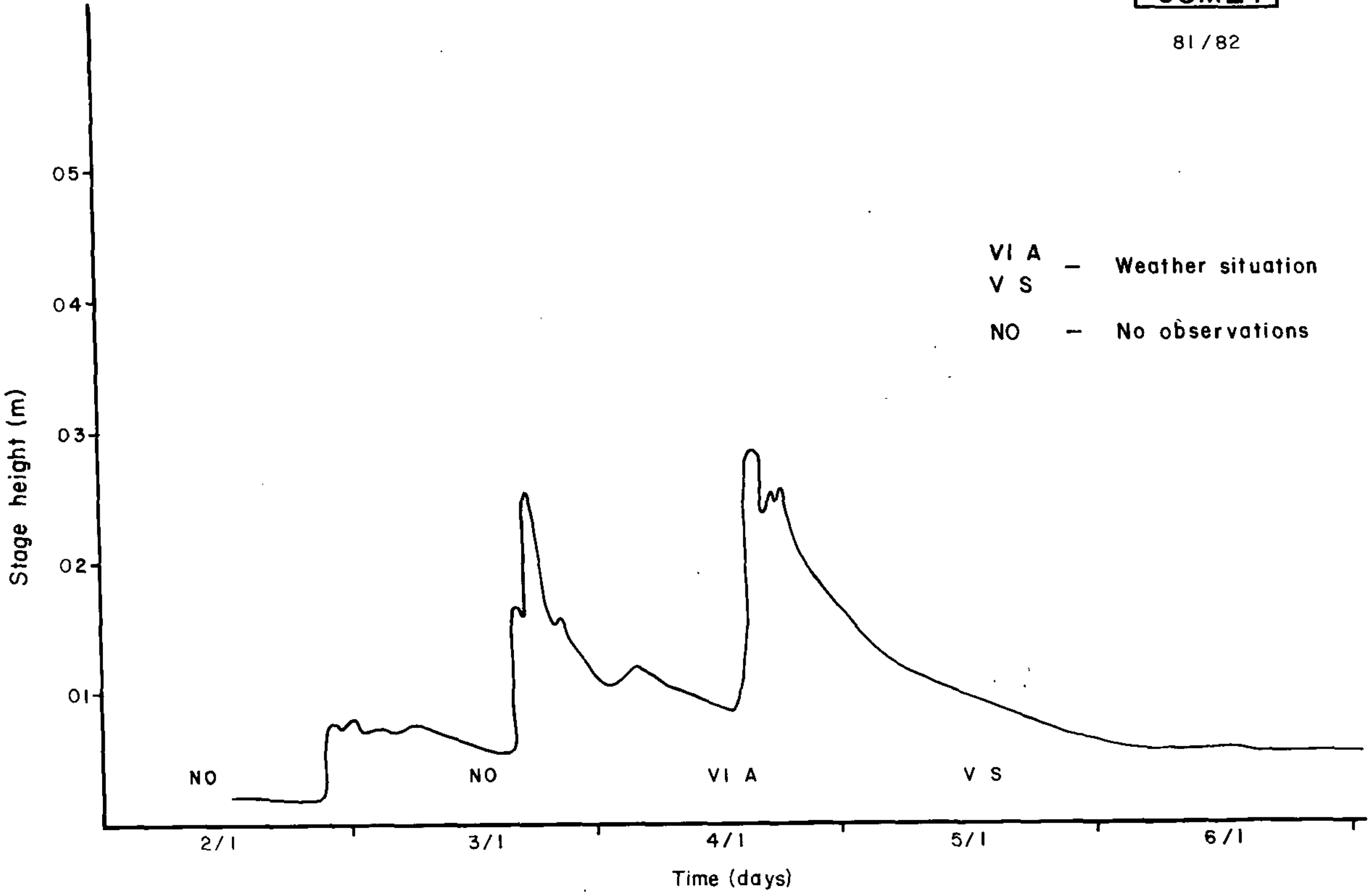


FIG. 5·2 : Example of a stream hydrograph

The fact that run-off was recorded on weather situation II suggests that the classification carried out around Bethlehem is not fully applicable to the C8M10 catchment closer to the escarpment.

The main conclusion tentatively drawn from the above study was that catchment C8M10 showed a much more favourable response to seedable rain than C8M12. However, C8M12 seems to be more representative of the Vaal Dam catchment as a whole and to be especially similar to the sub-catchment of the Wilge River.

Cousens (1980) limited his analysis to days on which observations on weather situations were made. At that time they included most of the weekends. In doing so 76,8% and 85,6% of the total run-off in C8M10 and C8M12 respectively was covered in the analysis for the three seasons. The following analysis takes a look at all the data, including the days with no observations (N.O.) on the weather (weekends and holidays).

A similar analysis was carried out for C8M24, the small catchment within C8M12. The results are given in Table 5.4.

TABLE 5.4: Run-off contributed by rainfall from different weather situations - C8M24

Weather situation	1980/81	1981/82
IV-C	13,3	1,4
V	15,2	5,6
V-S	13,9	5,0
VI-A	20,9	54,7
N.O.	36,7	31,4

N.O. = No observations

Because of the high incidence of run-off events taking place on days without observations on the weather situation, these analyses do not give the full picture. In the 1981/82 season it is quite possible that many of the N.O. days in fact were type V weather situations.

5.2 Groundwater

Groundwater does feature in the catchment, as indicated by numerous productive boreholes (see Fig. 5.3) but its hydrological significance is uncertain. Although a large proportion of the surface area of the catchment consists of impermeable strata (see section 3.2), the presence of dolerite dykes and sills, together with that of interbedded porous sandstone layers indicate regions of potential groundwater recharge (Schultz, 1979).

FIGURE 5.3

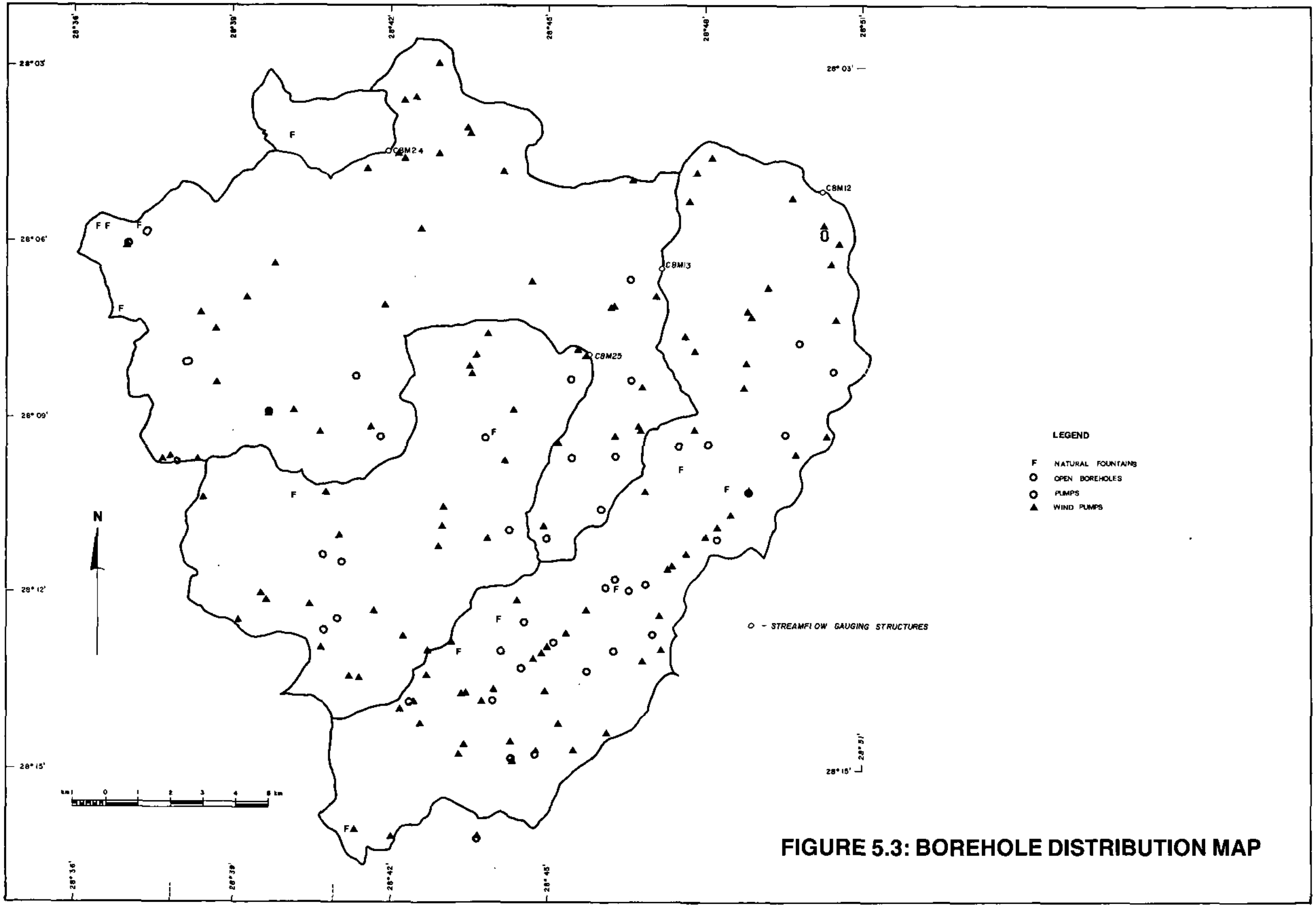


FIGURE 5.3: BOREHOLE DISTRIBUTION MAP

The influence of groundwater yield on catchment discharge is also open to question although, until proved otherwise, it is assumed to be negligible. The geology of the catchment suggests the existence of a series of perched aquifers separated by impermeable mudstones.

Seepage may occur from the sandstone outcrops into the soil and thence into the river as delayed flow. However, in periods of low rainfall, flow is intermittent which suggests low baseflow contributions.

A survey of all boreholes was carried out in catchment C8M12 during March, 1980 (Schultz, 1981). At that time, there were over 200 boreholes (see Fig. 5.3) and the water-table could be accessed at 177 boreholes without dismantling any existing equipment. The level of the water in the borehole was taken to represent the surface of the water-table. The mean depth of the water-table was 8,2 m with values ranging from near surface to over 70 m below the surface. A groundwater contour map drawn up from these data indicates that the subsurface drainage pattern is similar to the surface drainage pattern.

Samples of ground and seepage water were analysed chemically and the results, in the form of a piper diagram, seem to indicate that the groundwater is recent in age (Schultz, 1981).

Continuous logging of groundwater levels on a monthly basis has taken place at seven boreholes since October 1981 (see Plate 2 and Fig. 2.1). These data are being collected for a more detailed investigation into the role of groundwater in the catchment.

6. FUTURE OF THE PROJECT

6.1 Extrapolation of research findings to the Vaal Dam catchment

Ultimately, any results with regard to run-off augmentation will have to be extrapolated from the relatively small research catchments (372 km^2) to the much larger Vaal Dam catchment (over 30 000 km^2). Before this step can be taken, the following points will have to be considered:

(a) problems of scale in hydrological modelling

(b) lumping of input data and model components for the larger catchment without losing vital run-off characteristic information

(c) the much coarser data base of the Vaal Dam catchment

(d) differences in run-off response of small and large catchments

(e) run-off routing

(f) channel losses

Apart from the problems involved in extrapolation with respect to hydrological modelling, further attention must be given to the distribution of weather types and the seeding potential over the larger catchment.

Some of this work will need early attention to ensure proper data collection and to assist in guiding the rainfall augmentation research programme.

6.2 Input data requirements

Initially, there were no clear guidelines for the selection of the size of the research catchments and the density of the input data networks. During the course of the project, experience is gained regarding the typical storms, the expected rainfall characteristic modifications and the sensitivity of run-off response to various inputs. In the light of these findings, the input data requirements will be re-evaluated and network changes considered. The use of radar data to develop storm models and also to compliment the rainfall network for run-off modelling purposes will receive early attention. A distributed evaporation data base will be built up by estimating an "average areal" potential evapotranspiration value using a representative climatic data set rather than pan data. Adjustments will be made for specific sites based on the distributed actual rainfall data.

6.3 Hydrological processes

The methodology adopted by this project i.e. detailed rainfall/run-off modelling is also suited to quantifying the effects of changing agricultural land use on run-off. This research topic enjoys a high priority status in South Africa and much light could be thrown on the subject, using information gained from the BRAR project.

Run-off models required to predict a response to some change in input or process component have to approximate all the critical run-off processes much more closely than the usual semi-black-box models. Even though detailed process studies have, so far, not always improved modelling ability, they are still required to provide greater assurance regarding deductions made from modelling exercises which seldom can be statistically proven.

The evaporation and soil moisture storage components are vital in modelling, especially under the semi-arid conditions of the study region. Here, use can be made of agricultural expertise and existing models. Processes that may need specific attention are infiltration as affected by the soil and run-off pathways, including soil moisture transport.

During the study of run-off pathways, some attention can also be given to the transport of dissolved and suspended material in the water to assist in mineralisation, erosion and nutrient export research.

To conclude, whereas the assessment of the hydrological response to rainfall stimulation will remain the primary objective of this project, hopefully, a better understanding will also be gained of catchment hydrology and modelling in a semi-arid environment.

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1. RAINFALL INSTRUMENTS

1.1 Gauge (see Plate 12)

The manufacturer's specifications are as follows:

Type	- Weather Electronics, type 6011, tipping bucket
Sensitivity	- 0,2 mm
Resolution	- 0,2 mm
Orifice	- 200 mm diameter
Accuracy	- Factory calibrated to less than 1% accuracy at a precipitation rate of 25 mm/h.
Insect protection	- Mesh screens

During each tip of the bucket, a reed switch is momentarily closed by means of a magnet, enabling the tip to be registered in a magnetic cassette tape recorder.

Rainfall intensities exceeding 25 mm/h. are corrected by using the following calibration equation:

$$R_{5A} = 1{,}2\ R_{5M} - 0{,}42 \qquad \text{mm (Schultz, 1980)}$$

where:

R_{5A} and R_{5M} are the actual and measured rainfall during the previous 5 minute period.

1.2 Recorder

The data logger used in conjunction with the raingauge is a S920 manufactured by Diel Electronics according to specifications supplied by the Weather Bureau. This recorder is a microprocessor based instrument with a 24 hour clock.

A contact closure caused by the reed-switch on the gauge results in an increment of 0,2 mm in the raincount which is examined every five minutes at exact multiples of five. If the raincount has incremented since the previous five minute examination, the count plus the time is stored in a CMOS-RAM as a data set. The RAM consists of 32 data sets which are recorded onto the magnetic cassette whenever all of these sets are full or whenever a dump function is performed. No recordings are made if the raincount doesn't increase and unfilled data sets in the RAM are filled with zeros when a dump function is performed.

Digital recording takes place on cassette at 615 bpi. A normal audio cassette recorder is used with a single head and belt drive.

PLATE 12: Raingauge showing tipping bucket mechanism and recorder

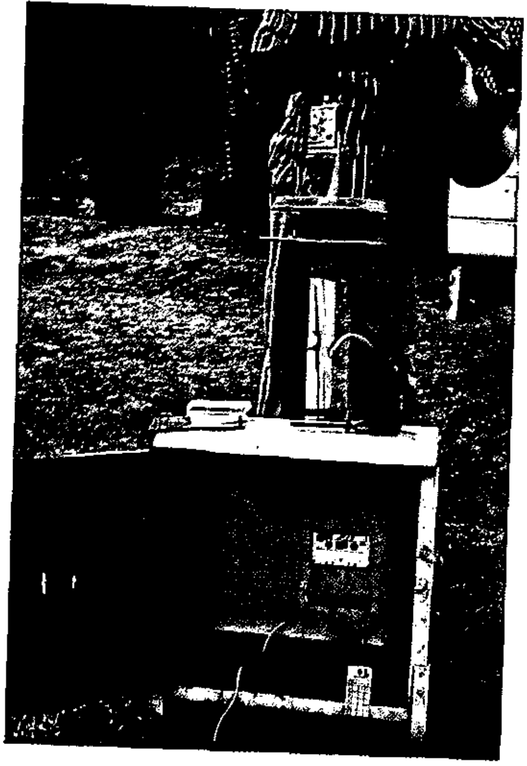
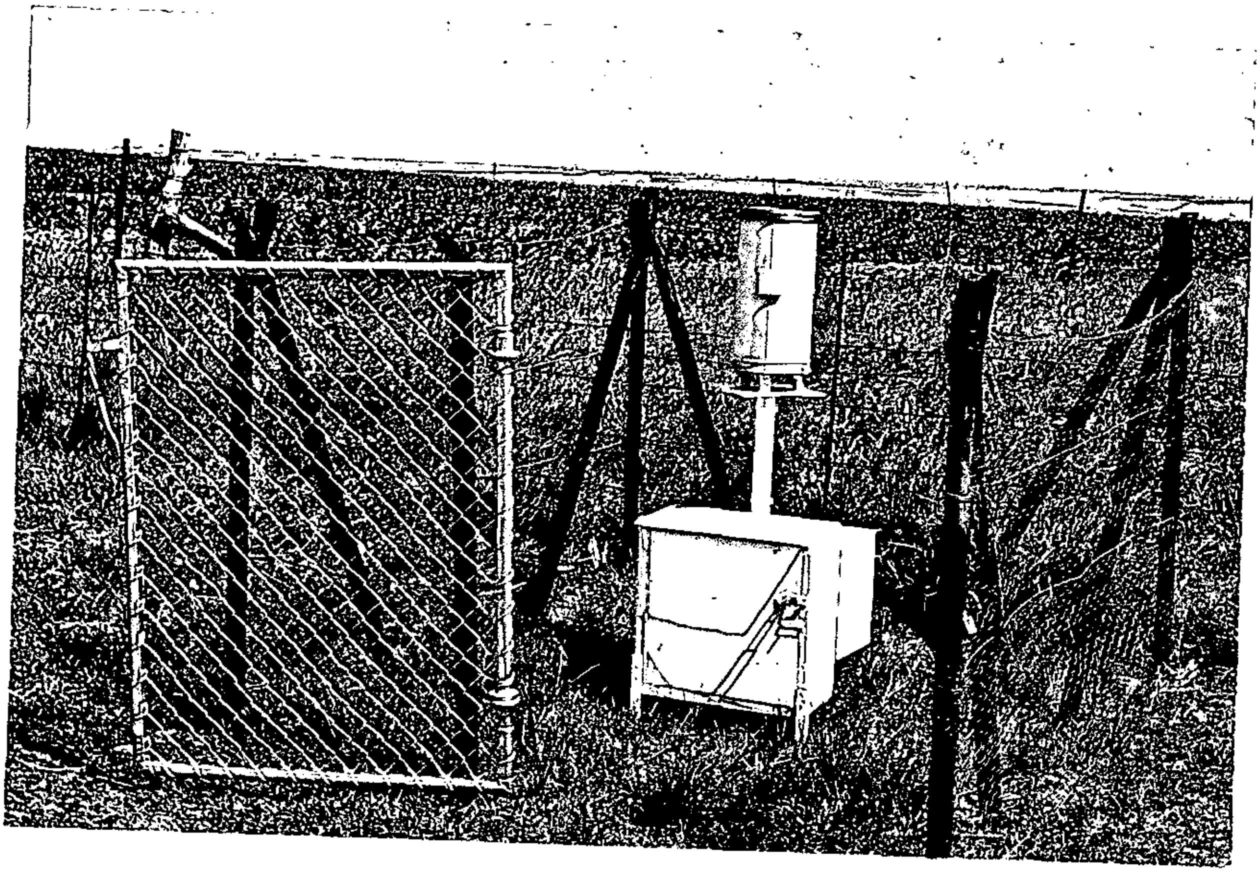


PLATE 13: Raingauge in catchment C8M25



The recorder is powered with a 12V dry cell battery. Power usage over the last season is reflected in the equation.

$$V = 12.17 - 0,0081\ D \text{ (volts)}$$

where:

V = present voltage
D = days after installation of fully charged set of batteries.

More details about performance are given by Maaren and Schultz (1982).

1.3 Installation

The gauge sites were selected as close as possible to a square grid network which concentrates them over the two smallest catchments, C8M25 and C8M24, and gets progressively less dense as catchment area increases. Other factors considered included:

1. accessibility
2. shelter from wind
3. avoidance of obstacles near the gauge
4. permission from the farmer concerned

Each stand was positioned at the preselected sites (Fig. 2.1) in such a manner that the rim of the installed raingauge would be 1,22 m above the ground in accordance with meteorological standards. Each gauge was mounted in a level position on top of its mounting pole. The recorders and batteries were placed in weather proofed, lockable metal boxes attached to the base of the mounting pole. These boxes were lined with an aerolite insulating material and painted white (see Plate 13). The installation of the original network was completed by the end of July, 1980. However, this distribution has been subject to change, due to an increase in the number of BRAR raingauges from 24 to 32 and problems encountered in the field.

2. SOIL MOISTURE

2.1 Instrumentation

Soil moisture is sampled by means of a Wallingford Soil Moisture Probe (Model 225) which consists of a probe, a pulse counter, a cable connecting the two and a transport shield. In use, the probe is lowered into an access tube previously sunk into the ground being studied (see Plate 14). The probe incorporates a sealed radio-active isotope which is a source of fast neutrons. A 'cloud' of slow neutrons is formed when fast neutrons collide with hydrogen atoms, predominantly in the form of soil water, and a detector within the probe detects slow neutrons reflected by the hydrogen atoms in any water present. The electrical pulses from the detector are amplified and shaped before passing up the cable to the counter unit where their mean count rate is displayed. The count rate is translated into soil moisture content (by volume) using an appropriate calibration curve.

PLATE 14: Diagram of neutron probe in use (Bell, 1976)

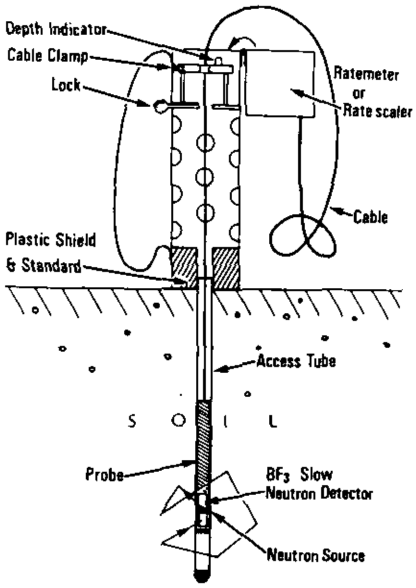


PLATE 15: Carrying the neutron probe in the field (Bell, 1976)

The source is 50 mCi Americium Berylium which has a radioactive half life of 400 years. The slow neutron detector is a boron trifluoride propotional counter which is sited at the lower end of the probe and is surrounded at the centre of its sensitive length by the radioactive source which is sealed into an annular capsule. The total weight of the system as carried in the field (see Plate 15) is 12 kg (Pitman Instruments, 1973). Much more detail concerning the working principles of the probe and procedures for use are given by Bell (1976). Bell's report also gives details about the specifications and installation of access tubes which were followed closely in this project.

Steps are being taken to calibrate the probe in the field but this is a lengthy process as the linear regression must include points spanning the moisture range of the soil. The method used is given by Mason-Williams (1982). Data collected in the meanwhile are calibrated using the calibration curves given by the manufacturer.

2.2 Network

Six sites were chosen to form a stratified random sampling plan with land use and soil type as the main differentiating factors (Mason-Williams, 1980, 1981). Each site is within 1 km of a raingauge.

At each site neutron probe readings are collected at depth intervals of 150 mm from three access tubes located more than 1 m apart.

The median of the three values of each depth is taken to represent 'average' conditions for that site. Sampling takes place on a regular, weekly basis from October-March every year, and began in the 1981/82 season. Prior to that (1979/80, 1980/81) gravimetric samples were taken in triplicate at three depths: 0-100 mm, 300-400 mm and 600-700 mm (Mason-Williams, 1981). Gravimetric samples are also taken when the probe is being repaired, to ensure some continuity of data.

3. STREAM FLOW

TABLE A1: Stream flow recording stations

Station	Weir type	Recorder type	Date opened
C8M09	Compound notch	Ott	1971
C8M10	Compound notch	Ott	1971
C8M12	Compound notch	Ott	1971
C8M13	Compound notch	Ott	1971
C8M24	Crump	Ott	1980
C8M25	Crump	Ott	1980