EFFECTS OF CLIMATIC CHANGE ON WATER RESOURCES FOR IRRIGATION: AN EXAMPLE FROM LESOTHO

(FAO Programme 2111.410.01)

Institute of Hydrology

July 1988

Contents

List of Figures

List of Tables

1. Introduction

1.1 OBJECTIVES

This report explores the consequences of climatic change to one particular activity, irrigation, in one area of Africa, the Lesotho highlands. It has as its focus the identification of computational and conceptual problems encountered in applying information on global climate change to engineering decisions which apply to strictly specified locations. In order to concentrate effort on methodological issues pre-existing results concerning climate change, available climate-runoff transfer functions, and crop water relations were used where practicable. The case study revolves around a hypothetical, although realistic, reservoir feeding an irrigation scheme in Lesotho, southern Africa, a region of known drought propensity.

The project postulated an irrigation scheme fed from a storage reservoir on line to a river. By using a pre-calibrated rainfall-runoff model it would be possible to derive some measures of the scheme performance under the current climate. It was then envisaged that this climate would be perturbed to an extent governed by 2 x CO_2 scenarios from available general circulation models (GCMs). Re-using the calibrated rainfall-runoff model, reservoir dimensions and postulated irrigation scheme, the performance measures would be re-evaluated and hence the impact of climatic change on the scheme performance measured.

The main purpose of this phase of the study is to establish an appropriate methodology using a region where rainfall-runoff data are readily available, and for which a rainfall-runoff model had already been calibrated.

Lesotho was chosen as being a suitable region. The Institute of Hydrology (IH) had recently undertaken part of a water resources study for the Lesotho Highlands, for which the Pitman rainfall-runoff model was used. The Pitman model is described in more detail elsewhere (Pitman, 1973) but one of its advantages is that regionalised estimates of the most important model parameters were available which gave a good starting point for model calibration of the study catchment.

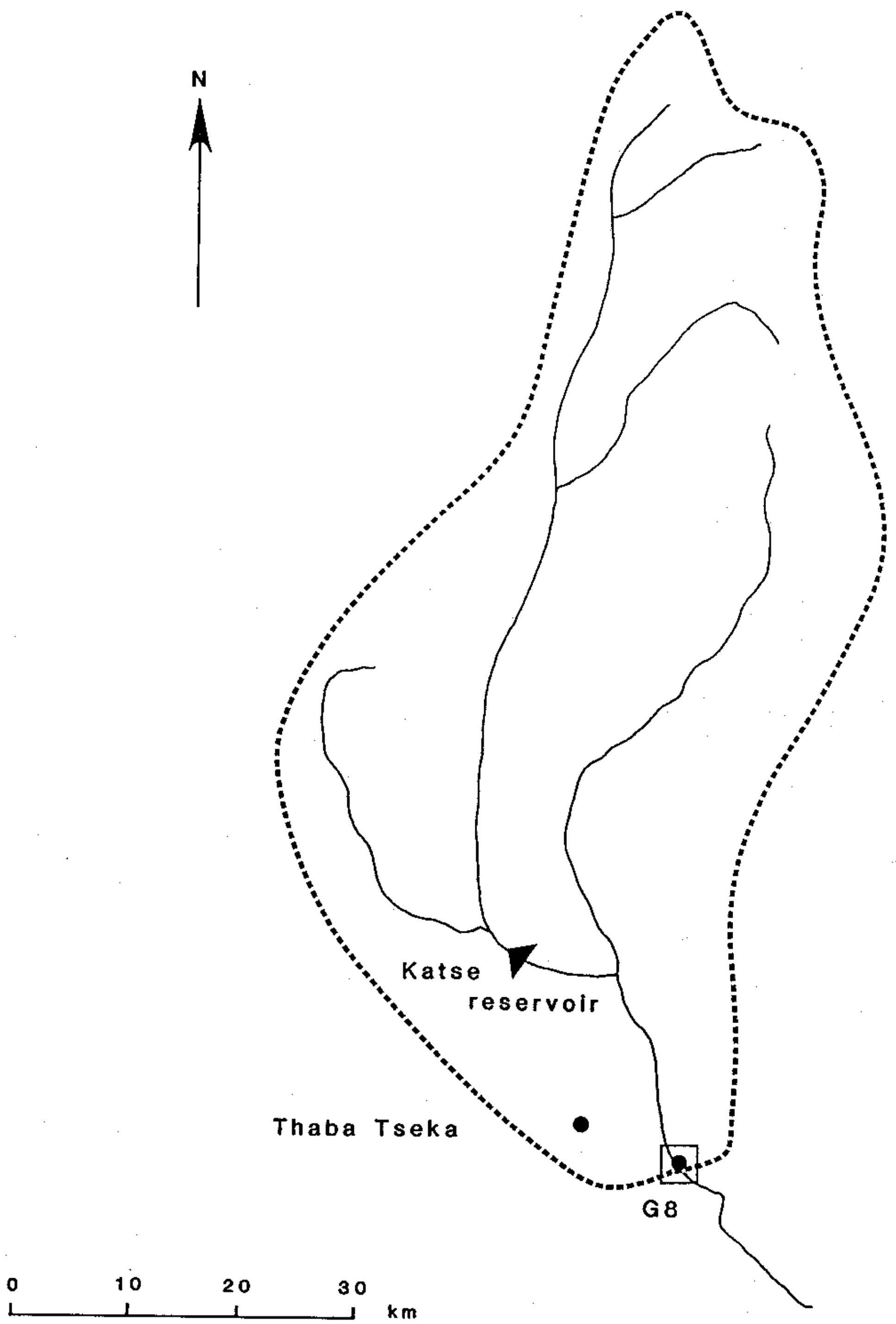
The model was calibrated for the 3,240 km^2 Malibamatso catchment at Paray. The reservoir selected for the study is at Katse, upstream of Paray and with a catchment area of 1,860 km^2. An outline map of the catchment is given as Figure 1.1.

Suggestions are made for further work, including ideas which more directly quantify the uncertainties in scenario construction and model formulation.

1.2 PRESENT CLIMATE OF THE STUDY AREA

Lesotho is a mountainous country with altitudes rising to 3,300 m. Topography is very varied, and the study site lies within the eastern-most mountainous area. The whole of the country lies in the southern African "summer rainfall" zone, with virtually all the annual precipitation falling primarily in convective storms, during the southern hemisphere summer season. Annual totals are as low as 500 mm in the western lowlands, but rise to over 2,400 mm in the eastern mountains. Topography and aspect exert very strong controls on the spatial pattern. Temperatures are also influenced by altitude, and air frost can occur at any point in the country.

Figure 1.1 *Location map*



1.3 ADJUSTED CLIMATE

The evidence and processes of climatic change are still best perceived at the global scale (eg. *Bolin et al., 1986). There is unarguable observational proof that radiatively active trace* components of the atmosphere have been increasing under anthropogenic influence. Carbon dioxide, the best known, has increased as a proportion by volume from 260 ppm in pre-industrial times to 350 ppm currently. Other gases such as methane and chlorofluorocarbons (CFCs) have been increasing at even more dramatic rates.

Given the indisputable rise in concentration and their physical role in the atmosphere, it is difficult to perceive of realistic processes which will not give rise to global temperature increase in the troposhere and at the surface. Palaeoclimatic links between CO_2 concentration and the initiation of glaciations clearly support the contention. Moreover mathematical models, which can incorporate considerable physical and chemical detail, agree in broad terms with the conclusion that global warming must follow CO_2 increase. The fossil record from ice and marine sediment cores suggests that *current CO_2 levels have seldom* been approached and the level expected in the mid 21st Century of 550 ppm may not have been exceeded at any time during the current series of interglacial/glacial cycles, ie. 10^6 years.

Global temperature assemblages are somewhat equivocal about a warming trend but there is a clear visual impression that a global warming has been underway, although not without interruption, throughout this century. The observed rise is compatible with that anticipated from the greenhouse effect although the uncertainties in the impact of transients and ameliorating effects of feedbacks allows for a wide range of permissible compatibilities. Similarly the zonal or regional "footprint" of climate change does not always accord neatly with that anticipated from mathematical models of atmospheric circulation, but once again discrepancies lie within the wide range of variations resulting from model deficiencies and stochastic inputs.

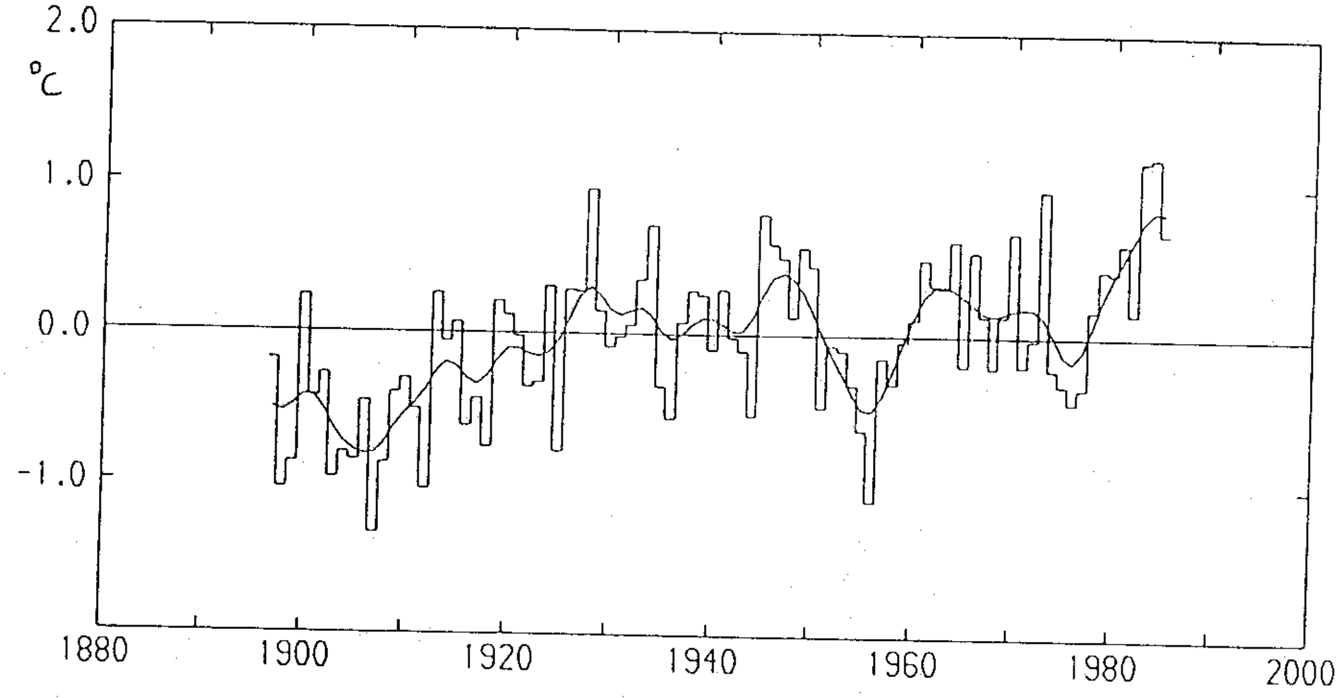
There is evidence of change over time in both temperature and precipitation in the part of southern Africa which includes Lesotho. Figure 1.2 shows mean temperature anomalies for the grid point 30°S, 30°E and although the record from 1973 is less reliable because it is based on just one station, there appears to be evidence of a warming, mirroring the more general southern hemisphere rise (Jones et al., 1986). The precipitation data, however, show no simple trend, but exhibit instead a consistent periodicity (Tyson, 1986). Over much of the summer rainfall area of southern Africa, precipitation data show an 18 year oscillation: the 1980s are in the dry part of the cycle.

1.4 SCENARIO DEVELOPMENT

Scientific debate continues unabated on many aspects of the climate issue but agreement exists *on the general propositions that climate processes are not stationary and some account needs* to be taken in human affairs of the likely global warming due to the greenhouse effect. The Villach statement (in Bolin et al, 1986) underpins such action but does not specify the form it should take. A counterpart debate among those concerned with impacts has also continued, much of it relating to the issue of scenario development.

In the light of the well documented qualitative disagreements between model forecasts at the regional level, the uncertain date at which certain levels of temperature rise is attained, and the paucity of information on future temporal and spatial variabilities, consideration of future

Figure 1.2 *Mean temperature anomaly for July-June (dated by the January) for grid point 30°C, 30° of the Jones et al. (1986) gridded data set for the Southern Hemisphere. The data are anomalies from the reference period 1951-70. The smooth line is a Gaussian filter designed to highlight variations on time scales longer than 10 years.*



conditions have centred on hypothetical accounts of future possibilities. These hypothetical assumptions, termed 'scenarios', must not be confused with 'forecasts' as the technology does not exist to forecast the future with any skill. The basic idea however is familiar to decision makers including design engineers who are faced with the requirement of an objectively stated standard against which the performance of a proposed structure or system is to be tested.

Water resource projects often are able to express such standards in a statistical way, - eg., the frequency of encountering the design conditions - but contingent factors whose effects are less random have to be stated more arbitrarily. This occurs in many structural design cases where the loading is not stochastic and reasonable upper limits are postulated against which the construction must be safe. Even in water resource projects where some of the more critical operating conditions are environmental, and hence random, others such as the integrity of materials, the pattern of future demand, and the human response to the scheme are not; and so arbitrary assumptions must be quoted.

Important characteristics of these assumptions are that they are supportable, are within the realm of possibility, are compatible with external factors, and are internally consistent. In the particular area of climate change impact studies there have been two main avenues for setting standards for scenario development. The first consists of sensitivity analyses where arbitrary changes are made to climate inputs and their effects are traced through a hydrological and water resource model to investigate the change to some final variable of practical interest, such as failure risk to reservoir supply. A study by Nemec and Schaake (1982) is a good example of this in showing particular sensitivities and amplifier effects. In the current study, sensitivity to 10% increases and reductions in precipitation, and increases in temperatures of 1°C, 2°C and 4°C were employed. The second approach has been applied more widely across the entire field of impact studies and consists of the adoption of one or more atmospheric general circulation models (GCM) output climatologies as a scenario for the future. Such an approach addresses more directly the climate change issue but entails many assumptions: it is therefore appropriate to digress here to review in more detail the features of GCMs and the derivation of the secenario used in the current study.

1.5 SCENARIOS BASED ON GENERAL CIRCULATION MODELS

GCMs have been reviewed by Gates (1985) and Schlesinger and Mitchell (1987) and, in general terms, are based on the fundamental dynamical equations describing large scale atmospheric motion. They are often larger scale, simpler, versions of models used for short term weather forecasting, which have increased in complexity dramatically over the last few years. The effect of climatic change - usually an effective doubling of atmospheric CO_2 - is estimated from the differences between model predictions of the equilibrium perturbed climate with the modelled current climate. However, as with all models of physical process, there are some important simplifications and constraints.

GCMs are designed to model global climate, and whilst the overall picture from several models may be very consistent, there may be significant differences at the regional scale. The spatial resolution of GCMs is very coarse (due to computer constraints), with calculations typically made at grid points several hundred kilometres apart. Large scale processes - such as the development and decline of frontal systems - can be modelled physically at this scale, but more local 'sub-grid' behaviour must be estimated using empirical approximations. Model predictions of precipitation will therefore be least accurate where local storms dominate the rainfall process. GCMs use smoothed representations of topography which, whilst being acceptable for global modelling, are inevitably approximations. Model accuracy is therefore greatest in areas with less variable topography. Of the hydrologically significant variables, GCMs are better at modelling temperature than precipitation (Gates, 1985).

It is also important to note that the modelled change in climate based on comparisons of "before" and "after" GCM runs represent equilibrium changes following an effectively instantaneous doubling in greenhouse gas concentrations. These concentrations are in reality increasing gradually, and the end results of this gradual change - even after allowing for time lags in the various components to be made up - may be different to the modelled equilibrium response, which misses out the intermediary stages. Also, whilst some GCMs are capable in principle of exhibiting the inter-annual variability in climate, no studies have presented results on the change in this variability associated with climatic change.

Different GCMs tend to produce different predictions of the effects of climatic change for the same region, and one way of choosing a GCM is to select the one which best models the current climate. Ideally, the model which best describes the change in atmospheric systems through time, as indexed by sea-level pressure, is the most appropriate, but evaluation in practice tends to be based on how well a model reproduces observed temperature and precipitation. Model performance can also be evaluated by comparing predictions of palaeoclimates - such as the postglacial climatic optimum at 5000-9000 years ago - with reconstructions of these climates (Schneider, 1986). However, whilst indications of these climates in southern Africa can be obtained by examining lake levels (Street-Perrott and Roberts, 1983), a lack of time precluded a search for GCM predictions of African palaeoclimates for the present study.

It must also be emphasised that determining local climate from the large-scale averages which constitute GCM output is difficult. The relationship between local and "regional" climate will be strongly determined by local geography, together with the prevailing circulation, and can be estimated by comparing observed local variability with regional averages derived from observed data (Kim et al, 1984). However, the local complexity of Lesotho's topography, the lack of readily available climatic data from a large number of sites, and lack of time meant that this approach could not be pursued in the current study, and point values were obtained by subjective interpolation.

The GCM produced by the U.K. Meteorological Office (UKMO) was used in the current study, partly because grid point data were readily available, but also because the model appears to reproduce closely the current 'average' climate in Lesotho (Table 1.1). Other models - including GFDL, NCAR and GISS (as mapped in Schlesinger and Mitchell, 1987) - are even less accurate in southern Africa (although not necessarily, of course, elsewhere). Southern Africa, and Lesotho in particular, is a difficult area for GCMs because of the rugged topography and the dominance of local convective precipitation. Southern Africa is also at the latitude where tropical and mid-latitude weather systems interact. Most GCMs predict an increase of precipitation in the mid-latitudes, but a decrease - at least for some seasons - in tropical latitudes. Modelled precipitation amounts will depend on the modelled position of these important interaction zones, and the numerical values - or even direction - of change can therefore be expected to vary considerably between models.

Table 1.2 shows the selected GCM-based scenario for Lesotho, indicating temperature and precipitation changes by season. The precipitation changes are represented as percentage differences from the current precipitation, to minimise the effects of the relatively poor modelling of current precipitation. It must be emphasised again that Table 1.2 is not a forecast for the future, it is one of several possible scenarios. Other models, for example, predict a lesser increase in temperature following climatic change.

It is relevant to compare the temperature and precipitation under the scenario with climate in the recent historical past in Southern Africa. The precipitation under the scenario is similar to that experienced in dry spells in the recent past (1905-1915, 1925-1932, 1944-1952 and 1962-1970 (Tyson, 1986)), but the temperature is much higher. Since the beginning of the century no year has been more than approximately 1°C warmer than the long term average (Fig. 1.2), and recent experience cannot therefore be a guide to the possible consequences of climatic change: indeed, figures in Tyson (1986) suggest that the scenario temperatures are considerably higher than temperatures experienced at any time during the Quaternary period.

It is emphasised that this is a general finding, and some have conjectured that at no time since the Cretaceous have global temperatures been experienced that match those expected after CO_2 doubling.

A background summary of climatic change scenarios for Southern Africa, provided for the current study by the Climatic Research Unit of the University of East Anglia, is given in Annex 1.

Table 1.1 Comparison of UKMO GCM model of current climate and regional average data from Lesotho. The 'observed' data are determined by averaging data from eight climate stations in Lesotho (FAO, 1984), excluding data from the highland Oxbow site.

	Season			
	DJF	MAM	JJA	SON
Temperature (°C)				
Observed	19.4	13.7	8.1	15.5
GCM	19.8	13.6	6.9	13.8
Precipitation (mm/day)				
Observed	3.45	1.95	0.41	2.05
GCM	2.8	2.9	1.6	3.1

Table 1.2 Details of scenario for Lesotho region: based on UKMO GCM.

	Season			
	DJF	MAM	JJA	SON
Temperature change (°C)	+6	+6	+6	+6
precipitation change (as a percentage of current total)	-23	-4	+10	+15

2. Data

The hydrological data used for this study were taken directly from Consultant's reports (Lahmeyer MacDonald Consortium, 1983; Lahmeyer MacDonald Consortium, 1986) and from published climatological data.

2.1 RAINFALL

An isohyetal map of mean annual rainfalls for the region had been produced from individual raingauge records. From this map, estimates of the mean annual rainfall of the catchments of interest were calculated.

A series of monthly rainfalls for the region, expressed as percentages of the annual value, was derived using a correlation weighting method. Series of monthly catchment rainfalls are then obtained by multiplying this annual value by the sequence of percentage values. This series covers the period hydrological years 1930 to 1985, giving a total of 56 years of data.

2.2 RIVER FLOWS

Extensive reprocessing of the region's flow records had been carried out by the Consultants for their 1987 report (Lahmeyer MacDonald Consortium, 1986). The flows used in this study are monthly flows measured at gauge G08, the Malibamatso at Paray; the available records cover the period hydrological years 1967 to 1985.

2.3. EVAPORATION

The evaporation data used for calibration of the Pitman model were based on Pitman's published maps of mean monthly Symons pan evaporation isolines.

Estimates of open water evaporation (E_o) for the reservoir area and reference crop evaporation (E_t) for the irrigation scheme area were based on mean monthly climatological data published by FAO (FAO, 1984). Estimates for Thaba Tseka (see Fig. 1.1) are shown in Table 2.1, and were calculated using the version of the Penman equation in the FAO CROPWAT software (FAO, 1987).

Table 2.1 Evaporation Estimates (mm)

	O	N	D	J	F	M	A	M	J	J	A	S	Total
E_t	146	169	179	170	128	110	80	64	44	52	85	116	1342
E_o	183	210	225	215	165	144	105	84	61	71	109	146	1718

3. Analysis

3.1 RAINFALL-RUNOFF MODEL

The Pitman model (Pitman, 1973) has been used for the rainfall-runoff modelling work. An improved version of the model was calibrated for several catchments in the study area using the common period of rainfall and runoff records from 1967 to 1985.

Input to the model is in the form of monthly rainfall totals, expressed as a percentage of the long term mean annual rainfall. The rainfall is broken down into shorter 10-day time-steps using a synthesised mass curve whose parameters are a function of the monthly rainfall.

The model was calibrated for the 3,240 km^2 Malibamatso catchment at Paray in Lesotho. The main observed hydrological characteristics of the catchment are given in Table 3.1.

Table 3.1 Hydrological characteristics of study area

	Mean (mm)	Standard deviation (mm)
Long term annual rainfall	880	170
Fitting period annual rainfall	826	161
Fitting period annual runoff	230	115
Long term annual evaporation (Symons Pan)	1203	

The model was fitted against observed monthly flows for the period 1967 to 1985. The main statistical measures from the calibration are:

correlation coefficient : 0.858
standrard error of estimate : 11.2 mm or 5%

The main components of the water balance are shown in Table 3.2

Table 3.2 Main components of the water balance

Average rainfall	Average annual losses (mm)			Average annual runoff (mm)		
(mm)	Evap.	Interception	Total	Surface	Interflow	Total
826	519	77	596	113	117	230

Given the fitted parameters, it is therefore possible to generate a synthetic series of river flows using input values of monthly rainfall and evaporation. In the current study, fixed monthly evaporation figures were used, based on those given in Table 2.1, together with monthly rainfall data based on the 56 year series described in Section 2.1, to generate 56 year sequences of flows. These input data were perturbed according to the changes detailed in Sections 1.4 and 1.5.

To illustrate the effect of changing climate, Table 3.3 shows the mean water balance components after the model was run with the 56 year sequence of monthly rainfalls increased and decreased by 10%. As expected, a 10% change in precipitation data does not lead to a similar change in runoff: with 10% more precipitation runoff increases by 24%, whilst a 10% fall in annual precipitation lead to a modelled 22% decline in runoff. The greater part of this impact occurs through the agency of the surface runoff component.

Table 3.3 Effect of changing rainfall on water balance components: mean averaged over the fitting period

	Rainfall (mm)	Losses (mm)			Runoff (mm)		
		Evap.	Interception	Total	Surface	Interflow	Total
R + 10%	909	541	81	622	151	134	285
R - 10%	744	493	72	565	80	99	179

4. Irrigation demands

4.1 ALTERNATIVE DEMAND MODELS

Two alternative methods were available for the calculation of crop water requirements and hence irrigation diversion requirements. Both methods, the FAO software CROPWAT written for IBM PC compatibles, and an existing irrigation demand model already available at the IH, use the methodology of FAO Irrigation and Drainage Paper 24.

CROPWAT analyses only one year of data at a time and is written in BASIC, so it is not suitable for simulation studies using longer series of input data. In CROPWAT, the user has to select an effective rainfall function to determine how much of the incoming rainfall is available for use by the crop.

The major difference between CROPWAT and the IH model lies in the way rainfall over the irrigation scheme affects the calculated irrigation requirements. The IH model carries out a simple soil water balance, from which effective rainfall is estimated; it does not therefore rely on assumptions about the form of the effective rainfall function. Consequently the IH model was considered to be the more appropriate for this study. However, the model was modified to incorporate useful features from CROPWAT such as the flexible way in which cropping patterns and planting dates are selected.

4.2 CROP CHARACTERISTICS

Crop characteristics for a number of common crops are given in Table 4.1. The data comprise:

- length of total growing season and individual stages in crop growth (A, B, C and D)
- crop factor for each stage of growth

During execution of the program the user is prompted to select the percentage of the total irrigation area to be planted to each crop and the planting dates. The program then calculates the crop coefficient for each time-step; the values for the initial and mid-season stages are constant as given in the crop data input. Values in the development stage and late season are calculated by linear interpolation.

Table 4.1 Crop characteristics

Crop	Growth stages (days)					Crop factor			
	A	B	C	D	Total	A	B	C	D
Cotton	30	50	55	45	180	.4	.4	1.1	.55
Maize	30	50	60	40	180	.4	.4	1.1	.70
Winter wheat	15	30	65	40	150	.6	.6	1.2	.70
Vegetables	10	30	20	30	90	.5	.5	1.1	.60
Tree crops	90	90	90	90	250	1.0	1.0	1.0	1.0

4.3 CALCULATION OF DEMANDS

The calculation of crop water requirements is carried out on a 10-day basis. For simplicity all months are taken to have 30 days, subdivided into 3 decades of 10 days; the program assumes the year is made up of 36 decade periods.

The transpiration requirement (ETcrop) is calculated from the crop coefficient and decade reference crop evaporation. A field water balance is then carried out. The water balance components are shown schematically in Figure 4.1 and are given by:

R	rainfall (mm) falling on the scheme
ETcrop	crop water requirement (mm)
DRAIN	drainage water (mm) caused by direct runoff
PERC	deep percolation (mm)
SMAX	maximum field water storage (mm)
SNOR	normal or desired field water storage (mm)
SMIN	minimum field water storage (mm)

The field water storage, which represents the storage characteristics of the soil, is divided into three levels. SMIN is the minimum level to which the water can fall before irrigation is necessary, SNOR is the normal or desired storage, and SMAX is the maximum storage.

The field water balance (see Figure 4.2) is calculated as follows:

$$S2 = S1 + R - ETcrop - PERC$$

where S2 is the end of time-step field storage (mm)

Figure 4.1 Schematic diagram of field water balance

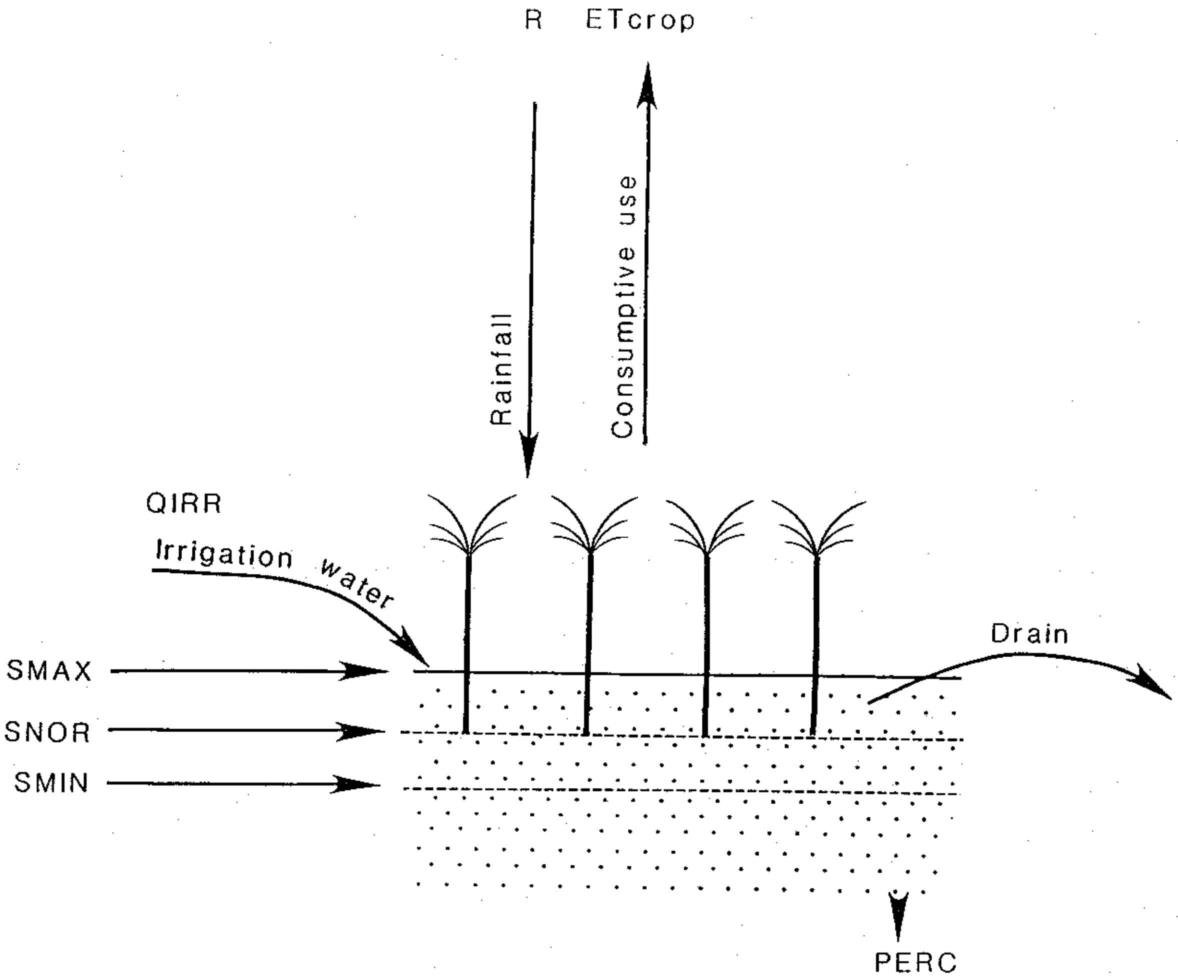
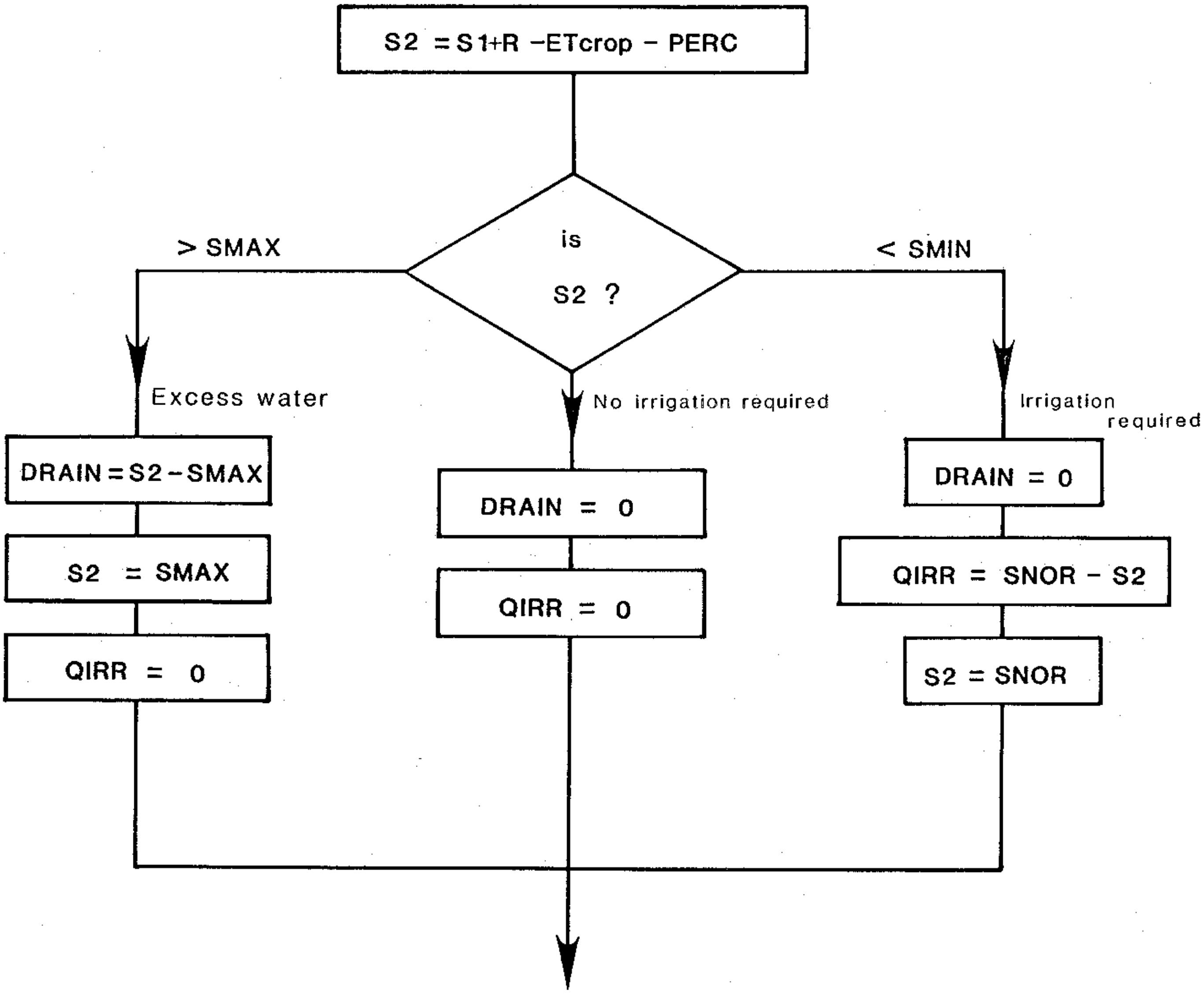


Figure 4.2 Flow chart for field water balance calculation



S1 is the initial field storage (mm)

the other variables have been defined above

Then if	S2 > SMAX	excess water
	DRAIN = S2 - SMAX	
	S2 = SMAX	
	QIRR = 0	no irrigation required
if	SMAX > S2 > SMIN	adequate water
	DRAIN = 0	
	QIRR = 0	no irrigation required
if	S2 < SMIN	insufficient water
	DRAIN = 0	
	QIRR = SNOR - S2	irrigation required
	S2 = SNOR	

Thus irrigation water is applied to bring the field storage up to SNOR.

The irrigation or diversion water requirements (IWR) are greater than the field water requirements due to inefficiencies in the application of water to the field and to losses in the canal and distribution system. Thus:

IWR = QIRR/(EFF/100)

where EFF is an overall irrigation efficiency expressed in percent for each month of the year.

The difference between IWR and QIRR has to be accounted for, as only a proportion will eventually return to the main water course together with part of the excess water (DRAIN) that occurs as direct runoff. The rest will be lost as direct evaporation from standing water, or through transpiration of canal side vegetation, or as deep percolation.

For this work, which is concerned with the ability of a storage reservoir to meet downstream irrigation demands, this component of the water balance is relatively unimportant. However, should the return flow to the river channel be an important addition to the downstream flows then a return factor can be included to account for the reduction in the potential return flow that would occur in practice.

The diversion requirements for each crop are calculated in millimetres on a 10 day basis. These are aggregated into monthly totals and then converted into volumes by multiplying by the total irrigated area of the scheme and the percentage of that area planted to each crop.

4.4 EFFECTS OF CHANGED RAINFALL ON DEMANDS

A comparison of the overall irrigation demands was made for the three rainfall scenarios as discussed in Chapter 3, using the cropping pattern shown in Table 4.2. This pattern is representative of the types of crop grown in the region.

Table 4.2 Cropping pattern used in study

Season	Crop	% Total area	Planting date
Summer	Cotton	50	1 Nov
	Maize	10	1 Nov
Winter	Winter wheat	50	1 June
	Vegetables	10	1 June
Year round	Tree crop	10	

The mean monthly demands for the 56 year period of synthetic record are given in Table 4.3, under different perturbations to the 56 year input rainfall series.

Table 4.3 Mean monthly demands (mm) for different rainfall conditions

Rainfall regime	O	N	D	J	F	M	A	M	J	J	A	S	TOTAL DEMAND
Current	130	33	61	203	190	165	56	16	13	118	208	280	1473
Current + 10%	121	32	53	185	181	161	52	15	12	111	213	267	1403
Current - 10%	143	34	72	235	191	152	68	18	13	122	215	285	1548

There are some surprising results in the Table, for example the mean February irrigation demand for the reduced rainfall case is hardly different for the normal rainfall case. This arises from the representation of the soil moisture store in the model, and the circumstances under which irrigation is required. For example, in a given month under normal rainfall conditions, the incoming rainfall may be sufficient to maintain the soil storage just above the threshold at which irrigation is required. Under reduced rainfall conditions, the storage would have fallen below the threshold, irrigation would have been required, and the soil storage recharged to its normal conditions.

In the following month the balance of rainfall, crop requirements and initial storage may mean that irrigation is required only in the normal case, because the residual soil storage falls below the acceptable threshold. Under the reduced rainfall case the residual storage lies within the acceptable range.

4.5 EFFECTS OF CHANGED EVAPORATION ON DEMANDS

In addition to variations in rainfall caused by a CO_2 doubling, temperatures will also be affected. Table 4.4 gives the mean monthly evaporation for Thaba Tseka for uniform increases in mean monthly temperature of 1°C, 2°C and 4°C respectively. Such a climate change would alter other of the input variables to the Penman equation but for this exercise such effects have been ignored as such changes have not been quantified.

Table 4.4 Effect of temperature changes on evaporation (mm)

Temperature Regime	O	N	D	J	F	M	A	M	J	J	A	S	Total
Current	146	169	179	170	128	110	80	64	44	52	85	116	1342
Current + 1°C	153	178	188	178	135	115	85	68	47	57	90	122	1414
Current + 2°C	159	186	196	185	141	120	90	72	50	61	95	128	1485
Current + 4°C	172	201	212	200	153	130	99	80	57	70	106	140	1621

The irrigation demand model was used with the cropping pattern given in Table 4.2 to investigate the effect of such changes in evaporation. Current rainfall was assumed.

The mean monthly demands under these conditions are given in Table 4.5.

Table 4.5 Mean monthly demands (mm) for different temperature perturbations

Temperature Regime	O	N	D	J	F	M	A	M	J	J	A	S	Total Demand
Current	130	33	61	203	190	165	56	16	13	118	208	280	1473
Current + 1°C	151	37	77	226	198	166	65	18	14	129	238	289	1609
Current + 2°C	164	40	91	259	181	178	93	19	16	140	261	304	1745
Current + 4°C	188	50	120	306	202	190	130	22	19	177	293	346	2044

4.6 EFFECTS OF GCM SCENARIO CHANGES ON DEMANDS

Mean monthly irrigation demands were also determined for the climate indicated by the 2 x CO_2 scenario (Table 1.2), which incorporates both increases in temperature and changes in rainfall. Demands are shown in Table 4.6, and it can be seen that there are very significant increases in the summer season.

Table 4.6 Mean monthly demands (mm) with GCM scenario

	O	N	D	J	F	M	A	M	J	J	A	S	Total Demand
Current	130	33	61	203	190	165	56	16	13	118	208	280	1473
Scenario	200	56	217	384	275	185	134	28	20	223	332	348	2401

5. Reservoir studies

5.1 THE RESERVOIR MODEL

The reservoir model operates on a monthly time step according to a simple water balance. The ability of the reservoir to meet the downstream demands is controlled by a lower rule curve (LRC) that can have different values for each month of the year. An upper rule curve (URC) defines the maximum stored volume in any month. The balance in $m^3 \times 10^6$ is calculated as follows;

$$STOR2 = STOR1 + QIN + (RAIN - EVAP) * AREA - DMND$$

where

STOR2	end of month storage ($m^3 \times 10^6$)
STOR1	start of month storage ($m^3 \times 10^6$)
QIN	reservoir inflows ($m^3 \times 10^6$)
EVAP	open water evaporation (mm)
RAIN	rainfall falling on reservoir surface (mm)
AREA	area of reservoir surface (km^2)
DMND	downstream demand for irrigation ($m^3 \times 10^6$)

Evaporation losses from the reservoir surface can be a significant component of the reservoir water balance. An initial estimate of the area of open water is calculated from STOR1 and the reservoir characteristic curves. The total evaporation loss is then the product of this area and the net evaporation.

If	STOR2 > URC	excess water spilled
	SPILL = STOR2 - URC	demand fully met
	STOR2 = URC	
If	URC > STOR2 > LRC	reservoir in normal range
	SPILL = 0	demand fully met
If	LRC > STOR2	reservoir below LRC
	STOR2 = LRC	demand not fully met

When the reservoir is in the normal range three additional iterations of the balance are completed in order to achieve a better estimate of the average open water area for the month.

The reservoir is operated for the years chosen by the user; tables of key output variables - including water supplied, shortages and reservoir storage - can be produced. The performance of the reservoir is then assessed simply by counting failures, where a failure is defined as a year during which the storage is insufficient to meet demand.

5.2 IRRIGATION SCHEME PERFORMANCE WITH CHANGED CLIMATE

Counting annual failures is the simplest way of assessing irrigation scheme performance. The model was run with different target irrigable areas, and it was found that an irrigable area of 37,500 ha gave an overall failure rate of 1 in 5 years with the unperturbed rainfall and inflow sequences and the cropping pattern given in Table 4.2.

The effects of the postulated perturbations in rainfall and evaporation on irrigable area are shown by the points plotted in Figs. 5.1 and 5.2 respectively, and Fig. 5.3 shows the effect of climate changing according to the GCM scenario. Note that the number of years of failure does not take the severity of failure into account. Table 5.1 shows the areas which could be irrigated with the target failure rate of 1 in 5 years under the various climate scenarios.

Table 5.1 *Irrigable areas with 1 in 5 year failure rate*

CONDITIONS	AREA (ha)
Current rainfall	37500
Sensitivity analysis	
Rainfall + 10%	47500
Rainfall - 10%	30500
Temperature + 1°C	35000
Temperature + 2°C	32000
Temperature + 4°C	27000
GCM scenario	
Changed rainfall and temperature	20000

For the analysis described above, irrigation demands were calculated for the whole period of simulation; the reservoir was then operated over the whole period. The demands in this case are effectively fixed, and are not reduced in line with the water available in storage. Once the reservoir becomes empty a shortage is recorded; no reduction in irrigated area is made for the remaining months of the growing season. No quantification is made of the scale of the shortage.

Whilst this approach is adequate for sizing a scheme it is a very simplistic representation of scheme operation. In practice an attempt to cope with imminent shortages would be made either by progressively reducing the supply of water to the whole area to a proportion of the calculated demand, or by supplying the calculated unit demand to a reduced area. It was decided to adopt the latter approach, so the demand and reservoir models were adapted accordingly.

Figure 5.1 Rainfall perturbations : number of annual failures

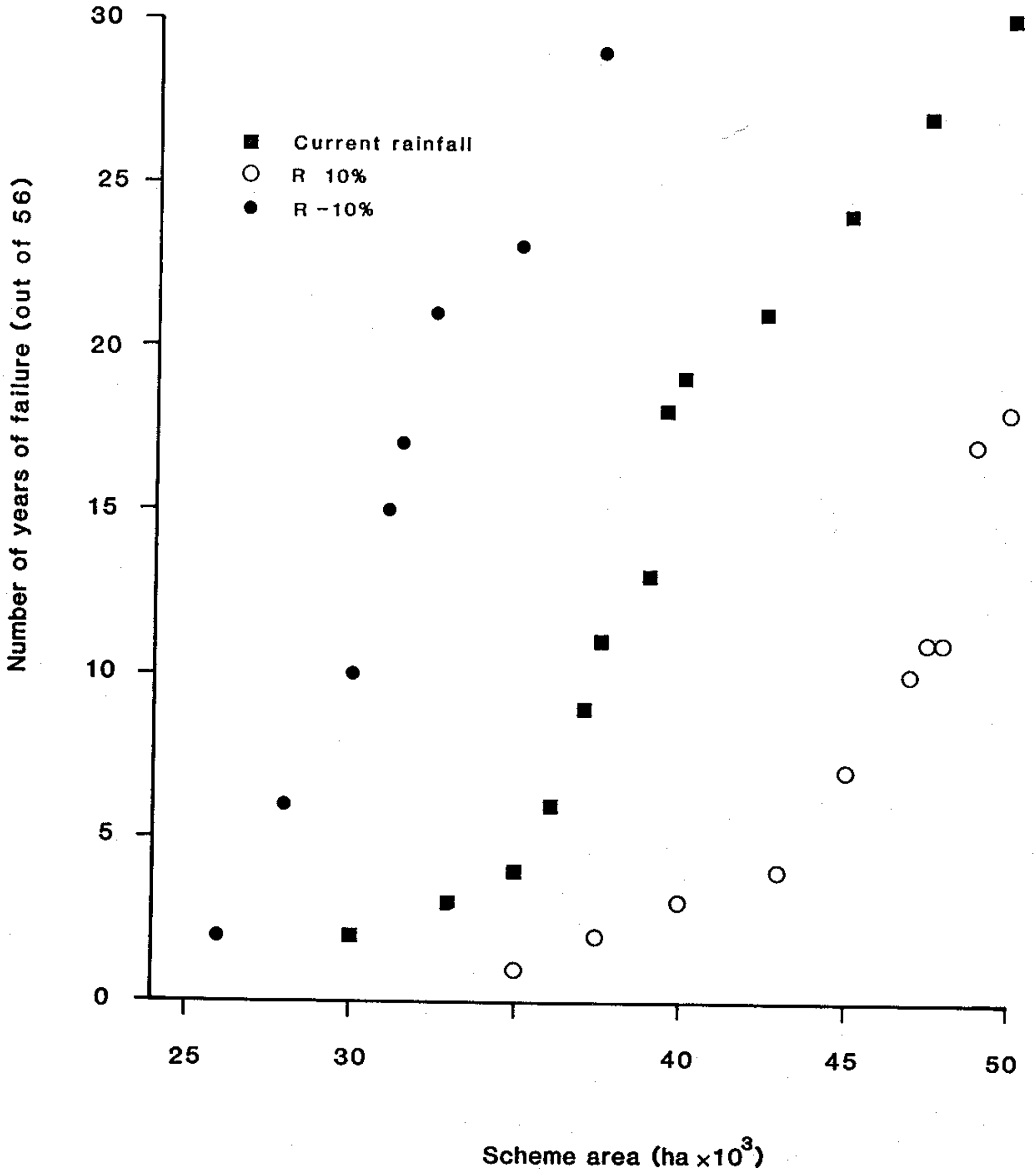


Figure 2 Evaporation perturbations : number of annual failures

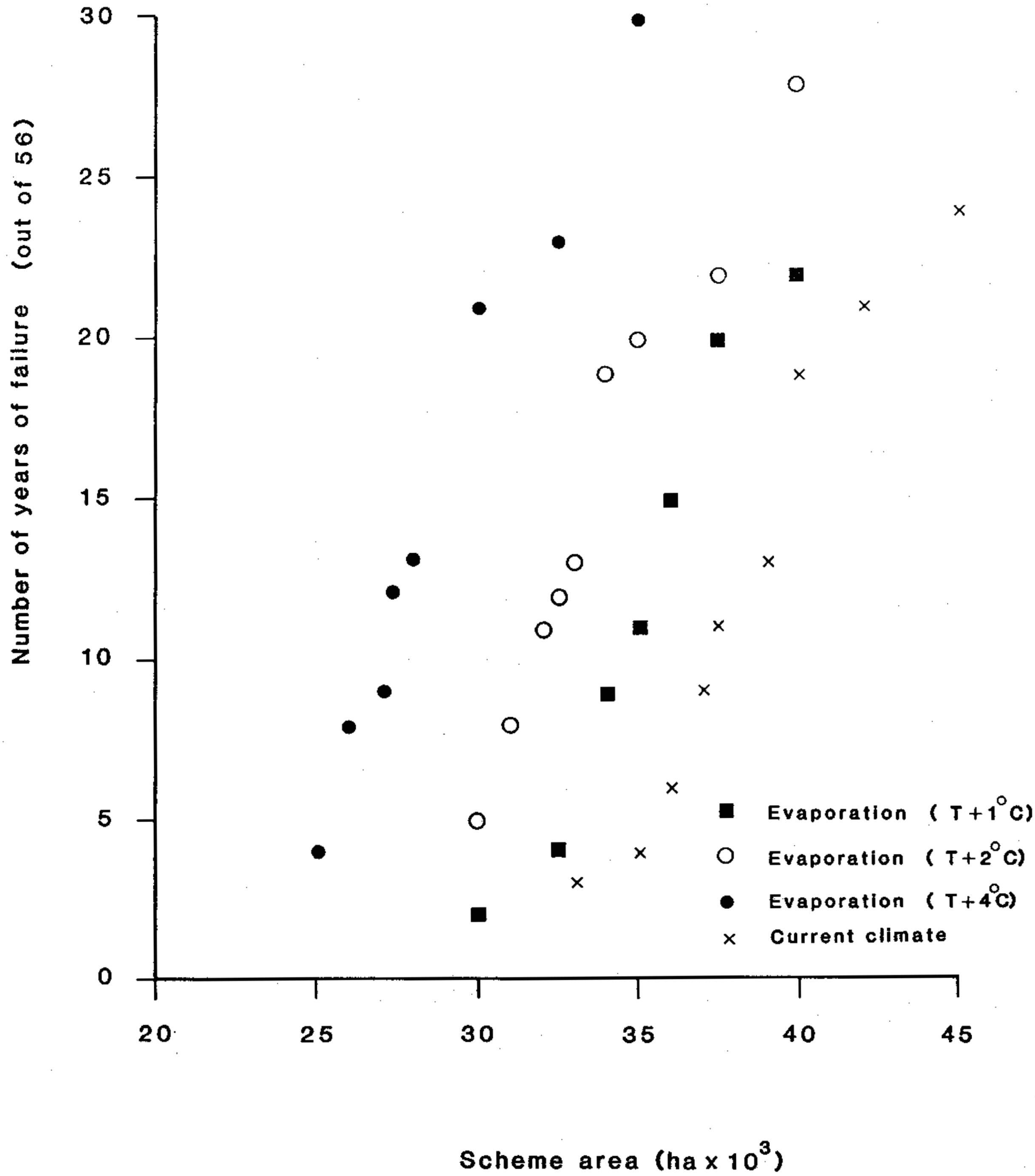
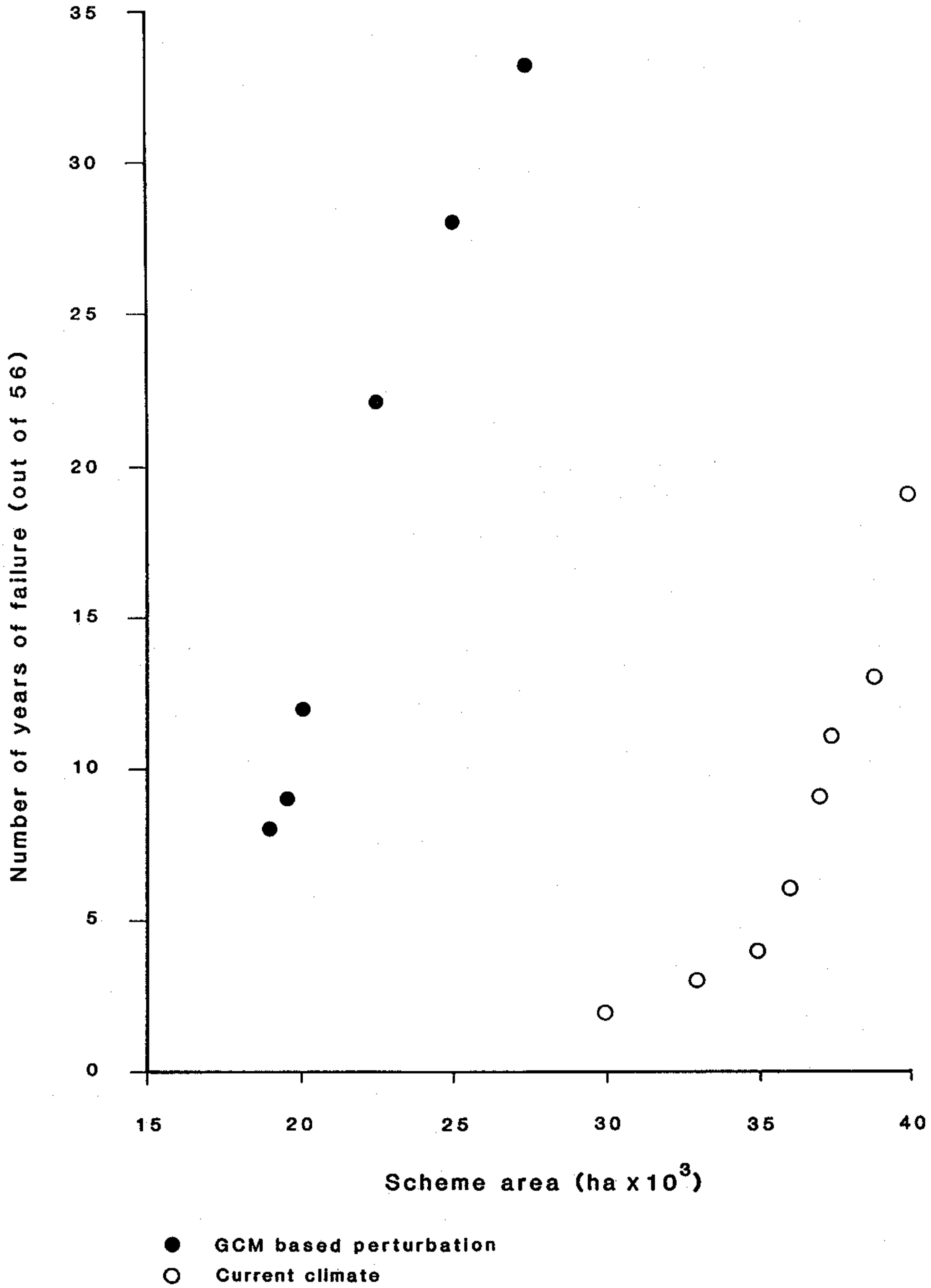


Figure 5.3 GCM based perturbations : number of annual failures



5.3 MORE REALISTIC DEMAND AND RESERVOIR MODELS

In the revised model, the demands for each crop are carried out at the beginning of each month's reservoir simulation. The crops are given an order of priority at the start of the run. The reservoir meets the demand for the highest priority crop first, and then moves on down the order. Should insufficient water be available to meet the full demand, the area of that crop is reduced pro rata. The same reduction in area is carried through to the following months of the growing season. At the start of the next growing season, the cropped area reverts to the target area.

Two categories of failure can be defined:

- shortages that occur when there is insufficient water to satisfy the requirements of the target irrigation area, so the total cropped area is less than target;
- complete failure of the system to deliver water to a given crop, despite reductions in area in previous months of the growing season.

To distinguish between them, these two types are called demand shortages and supply shortages.

Using the irrigated areas for a 1 in 5 year failure rate given in Table 5.1, the revised model was used with the same cropping pattern to simulate the performance of the schemes. Typical results from the simulation run under normal rainfall conditions are given in Table 5.2. The target irrigation area is made up of a permanent crop over the whole year covering 10 per cent of the irrigated area, plus summer and winter crops on a further 60 per cent of the area. Thus the total cropping intensity is 130 per cent.

The crop area statistics show for each type of crop the number of years in which the target area can be achieved. Also given are the number of years and average area for those years when the area has to be reduced progressively as the growing season proceeds, and the number of years when the crop fails completely due to lack of irrigation water. For each crop the average areas cropped over the whole period of simulation are calculated.

The demand shortage statistics show the number of months in which the water supply from the reservoir is insufficient to meet the demands for water from the target areas. The average shortages for those periods of failure are also given as absolute values and as a percentage of the average demand for that period.

The supply shortage statistics record the occasions when the reservoir supply fails despite reductions in target cropped areas.

5.4 EFFECTS OF CLIMATIC CHANGE ON CROPPED AREAS

The reservoir model was run under the different climate conditions implied by both the sensitivity analyses and the GCM scenario. Simulation runs were carried out using the target irrigation areas given in Table 5.1 for a 1 in 5 year failure rate. The results of these runs, expressed in terms of the average area cropped over the 56 year period of simulation, are given in Table 5.3.

A similar set of runs was carried out, using a target around 37,500 ha. The results are shown in Table 5.4, but are not directly comparable with those in Table 5.3, as the number of years in which each crop fails - either due to demand or supply shortages - is very different. A comparison of the number of failures in the 56 year period is given in Table 5.5. If rainfall increases the failure rate of a 37,500 ha target area falls significantly - to once

Table 5.2

Rainfall file : KRAIN.DAT
Inflow file : QKAT.DAT
Evaporation file : EVAP.DAT
Reservoir file : KATSE.DAT

Storage-area data

Water level (m) :	1960.0	1980.0	1990.0	1998.0	2005.0	2012.0	2017.0	2022.0	2027.0	2032.0	2040.0	2050.0
Area (km2) :	7.1	11.6	14.3	16.5	18.7	20.8	22.8	24.6	26.4	27.4	30.4	34.6
Storage (mcm) :	185.0	370.0	494.0	609.0	744.0	868.0	992.0	1117.0	1242.0	1366.0	1616.0	1820.0
Initial storage :	600.0											
Rule curves (mcm)												
Upper :	1616.0	1616.0	1616.0	1616.0	1616.0	1616.0	1616.0	1616.0	1616.0	1616.0	1616.0	1616.0
Lower :	370.0	370.0	370.0	370.0	370.0	370.0	370.0	370.0	370.0	370.0	370.0	370.0

Evaporation (mm)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Et :	146.0	168.0	174.0	171.0	129.0	112.0	81.0	65.0	45.0	53.0	84.0	117.0
Eo :	183.0	210.0	220.0	214.0	165.0	146.0	105.0	84.0	60.0	71.0	109.0	147.0

Irrigation scheme area (ha) : 37500.

% Target areas : ha	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
10. Orchard	3750.	3750.	3750.	3750.	3750.	3750.	3750.	3750.	3750.	3750.	3750.	3750.
50. Winter wheat	18750.	0.	0.	0.	0.	0.	0.	0.	18750.	18750.	18750.	18750.
50. Cotton	0.	18750.	18750.	18750.	18750.	18750.	18750.	0.	0.	0.	0.	0.
10. Vegetables	0.	0.	0.	0.	0.	0.	0.	0.	3750.	3750.	3750.	0.
10. Maize	0.	3750.	3750.	3750.	3750.	3750.	3750.	0.	0.	0.	0.	0.
Total	22500.	26250.	26250.	26250.	26250.	26250.	26250.	3750.	26250.	26250.	26250.	22500.

Crop area statistics	Full crop		Partial Crop		No crop	Overall average area	
Crop	Years	Area(ha)	Years	Area(ha)	Years	(ha)	(%)
Orchard	50	3750.	6	1038.	0	3459.	92.
Winter wheat	49	18750.	3	11778.	4	17037.	91.
Cotton	53	18750.	2	8867.	1	18062.	96.
Vegetables	53	3750.	0	0.	3	3549.	95.
Maize	53	3750.	0	0.	3	3549.	95.
Total		48750.				45657.	94.

Demand shortage statistics

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Demand shortages :	7	3	5	5	5	5	5	4	4	4	6	9	11
Av. shortage (mcm) :	63.4	3.5	15.2	53.9	18.4	27.6	20.3	2.0	3.1	3.4	17.1	43.9	151.2
Shortage (% demand) :	123.7	28.3	66.1	70.5	25.3	44.5	97.0	32.4	62.3	7.7	22.0	41.9	27.2
Area cropped (av. over months of shortages)													
Area cropped (ha) :	7587.	23425.	20138.	14366.	14366.	14366.	14366.	1336.	23836.	23836.	20445.	13669.	
Total (% target) :	34.	89.	77.	55.	55.	55.	55.	36.	91.	91.	78.	61.	

Supply shortage statistics

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Supply shortages :	6	0	2	3	0	0	0	0	0	0	3	6	11
Supply shortage (mcm) :	25.1	0.0	24.5	43.7	0.0	0.0	0.0	0.0	0.0	0.0	23.2	46.3	61.6

in 28 years - but the rate increases greatly if rainfall is reduced or temperature increased. Under the GCM scenario, a target irrigable area of 37,500 ha fails in nearly every year, and average actual cropped areas are therefore well below those attained under current conditions, an area with a target failure rate of 1 = 5 years under perturbed conditions.

Table 5.3 Average cropped areas under different climate conditions : (target annual failure rate : 1 in 5 years)

	CROPPED AREAS (ha)						
Crop	Trees	W.wheat	Cotton	Veg.	Maize	Overall	Scheme Area
Current rainfall	3459	17037	18062	3549	3549	45657	37500
Sensitivity analysis:							
Rainfall + 10%	4382	20750	23112	4411	4496	57150	47500
Rainfall - 10%	2730	13227	14636	2832	2885	36311	30500
Evap. (T + 1°C)	3190	15765	16852	3250	3312	42369	35000
Evap. (T + 2°C)	2941	14683	15402	3087	3029	39140	32000
Evap. (T + 4°C)	2598	12466	12983	2652	2555	33254	27000
GCM scenario:	1857	8725	9676	1857	1893	24008	20000

TABLE 5.4 Average cropped areas under different climate conditions : (target area 37,500 ha)

	CROPPED AREAS (ha)						
Crop	Trees	W.wheat	Cotton	Veg.	Maize	Overall	Scheme Area
Current rainfall	3459	17037	18962	3549	3549	45657	37500
Sensitivity analysis							
Rainfall + 10%	3694	18415	18750	3750	3750	48360	37500
Rainfall - 10%	2586	11128	15681	2596	2925	32917	37500
Evap. (T + 1°C)	3214	14988	17877	3281	3482	42843	37500
Evap. (T + 2°C)	3054	13828	16741	3147	3214	39985	37500
Evap. (T + 4°C)	2442	10243	15578	2488	2879	33629	37500
GCM scenario	1821	5000	9318	1400	1257	18797	37500

Table 5.5 Number of years of failure (out of 56) under different climate conditions. For each changed climate, the table shows the number of failures with a 1 in 5 year reliability irrigated area (top), and an irrigated area of 37,500 ha (bottom).

	Trees		W.Wheat		Cotton		Vegetables		Maize		Overall	
	Partial	Total	Partial	Total	Partial	Total	Partial	Total	Partial	Total	Demand	Supply
Current Climate												
37,500 ha a	6	0	3		4	2	1	0	0	3	11	11
<u>Sensitivity Analysis</u>												
Rainfall + 10%												
47,500 ha	6	0	4	5	3	0	0	4	0	3	11	11
37,500 ha	1	0	0	1	0	0	0	0	0	0	2	2
Rainfall - 10%												
30,500 ha	8	0	3	6	1	2	0	4	1	3	13	13
37,500 ha a	23	0	6	18	7	5	3	15	1	13	27	27
Evap. (T + 1°C)												
35,000 ha	7	0	3	4	2	1	0	4	0	3	11	11
37,500 ha	13	0	3	10	3	1	0	4	0	3	18	18
Evap/ (T + 2°C)												
32,000 ha	6	0	3	4	2	1	2	1	0	3	11	11
37,500 ha	16	0	7	11	6	2	0	9	0	8	21	21
Evap. (T + 4°C)												
27,000 ha	5	0	2	3	2	1	0	1	0	3	8	8
37,500 ha	25	0	5	21	7	6	3	17	0	13	30	30
<u>GCM Scenario</u>												
Changed rainfall and evaporation												
20,000 ha	3	1	5	4	3	0	0	3	0	3	11	11
37,500 ha	34	0	13	32	23	14	2	30	1	37	48	48

6. Discussion

The results of the analyses conducted so far indicate that changes in climate will have significant impacts on irrigation in southern Africa. Considering irrigation demand first, the data show that demand increases almost linearly with temperature when precipitation is held constant (approximately 140 mm for every extra 1°C), and with temperature 4°C higher reach 2000 mm at the hypothesised study site. Demand changes following changes in precipitation alone are less extreme. The annual increase in demand under the GCM scenario (with temperature 6°C higher throughout the year, and rainfall increased from June through November and decreased from December through May) is almost 1000 mm higher than the demand under normal conditions. The rainfall increase in winter and spring to some extent mitigates the overall increase in demand that arises from increases in evaporation. The comparison of average monthly demands under different climate scenarios illustrates the importance of seasonal variation in the direction and magnitude of change.

Changes in rainfall under the GCM scenario also have a significant effect on streamflow. For example the mean annual inflow to the reservoir decreases by almost 15 per cent; there are overall increases in the winter and spring, but the wet season flows are reduced significantly. These reductions in reservoir inflows are compounded by the increases in evaporation loss from the reservoir surface.

The combined effects of these factors are illustrated by the results from the reservoir and irrigation system simulation model. Both versions of the reservoir model - holding cropped area constant and reducing it in conditions of shortage - show that the increasing irrigation demands associated with climatic change would lead to major changes in irrigable areas and scheme reliability. Under the "naive" assumption that no attempt is made to alter crop areas during shortages, the chance of failure for the current "1 in 5 year failure" scheme rises to nearly 1 in 2 years with 10% less precipitation, and to between 1 in 2 and 2 in 3 years with temperature 4°C higher. Under the GCM scenario, such an area would be unsustainable as failure occurs virtually every year and the average area from which some crop is harvested drops from 45,657 ha/year to below 19,000 ha/year.

In practice reservoir and irrigation system managers react to shortages in water supply either by reducing cropped areas, or by changing the cropping pattern and calendar. Moreover there would be greater incentives for increasing the overall irrigation efficiency as water becomes more scarce. Nevertheless this analysis illustrates that the likely GCM based changes in climate will lead to major reductions in cropped area and hence corresponding reductions in crop production. The scheme area would need, in this case, to reduce to 20,000 ha to give continued assurance of harvesting the crops.

7. Conclusions

The objective of this study has been to develop a method for estimating the effects of climatic change on water resource availability and, in particular, on irrigation demands and feasibility.

The method has been tested at a hypothetical irrigation scheme in Lesotho, southern Africa, and uses both both "sensitivity analyses", where climatic inputs are perturbed by fixed, but arbitrary, amounts, and regional results of GCM predictions of global changes in climate following a doubling in the concentration of CO_2 and other radiative trace gases.

Effects on irrigation demand have been modelled, and shown to be significant, and a simple but robust rainfall-runoff model (calibrated on current climate), has been applied with perturbed climatic inputs to produce synthetic series of inflows as inputs to an irrigation reservoir. These results indicate that scheme viability - in terms of areas that can be cropped and the chance of failure - is reduced significantly if temperatures rise and rainfall reduces, as implied in GCM predictions. The results, however, are very sensitive to the degree of change imposed on the climate, and also on the variation in the impact of change through the year.

It is difficult to generalise the numerical results of the study - they depend not just on the hypothesised changes in climate but also on the hypothesised cropping patterns - but several general conclusions and remarks of a methodological nature can be drawn. Firstly, it is important to emphasise that the details of response to climatic change are sensitive to the size and nature of the hypothesised changes. No attempt has been made in the current study to consider the effects of increased atmospheric CO_2 on plant physiological processes. The consequences of changes in characteristics other than temperature on evaporation - such as sunshine time and windspeed - have not been investigated. The method at present also does not consider the effects of changes in extreme event durations on crop productivity, and ignores changes in crop patterns which may be made following repeated irrigation failures. Given the explicitly hypothetical nature of climate change scenarios, these are not felt to be significant omissions of the current method: the method can be revised once more precise predictions of these other effects are available. One inference which can be drawn from the study, however. is that meaningful generalisations of the impacts of climatic change can only be based on general indices of water resource availability. The strong dependence of predictions or irrigation feasibility on the assumed cropping pattern and scheme characteristics (together with the necessary assumption that cropping patterns do not change) means that such assessments will be strictly applicable only to the site under investigation.

Important lessons have also been learnt concerning the development of climatic change scenarios from GCM results. An understanding of current climate processes and controls in a study area - the influence of different circulation systems in different seasons, the relative importance of local convective activity, local variability in topography, for example - is essential when evaluating the performance of alternative GCMs in predicting current and future climates. Techniques for interpolating between GCM grid points are crude, but a 'subjective' element is necessary to incorporate information on local conditions, particularly in areas with variable topography. Palaeoclimatic reconstruction can help with the evaluation of GCM-predicted changes. Long-term instrumental records may provide useful qualitative indications of the directions and types of effects, but modelled changes are in many areas well outside the range of climates measured in the recent past.

Now that this methodology has been developed, the analysis could be extended to other parts of Africa, where appropriate data are available. The data required include:

- complementary rainfall and streamflow data from which a rainfall-runoff model could be derived;
- long-term rainfall data to synthesise a long-term sequence of reservoir inflows;
- data for GCM based predictions;
- information on current irrigation practices.

References

Bolin, B., Döös, B.R., Jaeger, J. and Warrick, R.A. 1986. *The Greenhouse Effect, Climatic Change and Ecosystems.* SCOPE 29; Wiley, Chichester.

FAO, 1984. *Agroclimatological Data for Africa.* Plant Production and Protection Series 22, FAO, Rome.

FAO, 1987. *Manual for CROPWAT* version 4.1. Land and Water Development Division, FAO, Rome.

Gates, W.L. 1985. The use of general circulation models in the analysis of the ecosystem impacts of climatic change. *Climatic Change 7, 267-284.*

Jones, P.D., Raper, S.C.B. and Wigley, T.M.L. 1986. Southern Hemisphere surface air temperature variations, 1851-1984. *J. Climate and Applied Meteorology 25, 1213-1230.*

Kim, J-W, Chang, J-T, Baker, N.L., Wilks, D.S. and Gates, W.L. 1984. The statistical problem of climate inversion: determination of the relationship between local and large scale climate. *Monthly Weather Review, 112, 2069-2077.*

Lahmeyer MacDonald Consortium, 1983. *Lesotho Highlands Water Project, Feasibility Study,* Stage 1 Report. Volume II - Supporting Report A, Hydrology.

Lahmeyer Macdonald Consortium, 1986. *Lesotho Highlands Water Project, Feasibility Study.* Stage 2B. Supporting Report A, Hydrology.

Nemec, J. and Schaake, J.C. 1982. Sensitivity of water resources systems to climate variation. *Hydrological Sciences Journal, 27, 323-343.*

Pitman, W.V. 1973. *A mathematical model for generating monthly river flows from meteorological data in South Africa.* Hydrological Research Unit Report No. 2/73. Univ. of Witwatersand.

Schlesinger, M.E. and Mitchell, J.B. 1987. Climate model simulations of the equilibrium climatic response to increased carbon dioxide. *Review of Geophysics 25, 760-798.*

Schneider, S.H. 1986. Can modelling of the ancient past verify prediction of future climates? *Climatic Change 8, 117-119.*

Street-Perrott, A. and Roberts, N. 1983. Fluctuations in closed basin taken as an indicator of past atmospheric circulation patterns. In: A. Street-Perrott, M. Beran and R. Radcliffe (eds). *Variations in the Global Water Budget.* Reidel, Dordrecht, 331-345.

Tyson, P.D. 1986. *Climatic Change and Variability in Southern Africa.* Oxford University Press, Johannesburg.

Annex 1 Climatic change scenarios for southern Africa

Prepared by the Climatic Research Unit, University of East Anglia, Norwich, U.K.

CLIMATIC CHANGE SCENARIOS FOR SOUTHERN AFRICA

INTRODUCTION

There are a number of different methods for developing regional patterns of climatic change scenarios. The two most important groups of methods are the use of General Circulation Models (GCMs) and the use of past instrumental data. This report concentrates on GCM derived scenarios although it would have been relatively easy to derive instrumentally based scenarios for the region.

Both methods have their weaknesses. The first problem with respect to instrumentally-based scenarios is that they are constrained by the length and availability of data series in a region. The normal method of construction is to consider periods of the instrumental record which were globally warm and compare these to periods which were globally cool. The differences between these periods are then indicators of future regional changes. The second problem is that the range of temperature between the globally-warm and cool periods determines the relevance of the scenario. For example, if the two global periods differ by 0.5°C, how relevant will the scenario be for a possible change in global temperature of 4°C, the value which most GCMs suggest for the response to a doubling of atmospheric CO_2? The change to a doubled CO_2 climate will take place over the next 50-100 years or longer. Change will not happen rapidly but will take place gradually. It may be that instrumentally-based scenarios are most appropriate in the initial stages of the change, say over the next 20 to 30 years.

The GCM approach to scenario construction compares a computer-simulated present climate, in which the equivalent atmospheric concentration of CO_2 is generally about 300 ppmv (the 'control' run) with a second simulation of climate at a higher equivalent CO_2 level (the 'perturbed' run). A common perturbed run is for an equivalent doubling of CO_2 levels to, say, 600 ppmv. This approach provides steady-state or equilibrium climate results for a given CO_2-equivalent level.

Problems with the method relate to differences between the 'control-run' climate and the present day climate. If the 'control-run' climate simulation is poor, there can be little confidence in the 'perturbed-run' climate. The second problem with GCMs is that the scenarios are for steady state climate with 'instantaneously' doubled equivalent CO_2. In the real world, greenhouse gas concentrations are gradually rising and the transient response to this change in forcing may not be related to the steady state or equilibrium response produced by GCMs.

RECENT CLIMATE CHANGE IN SOUTHERN AFRICA

In Figure 1 and 2 we show annual temperature and precipitation series for the 'Lesotho region'. The temperature series is the July-June mean (dated by the January) for the grid point 30°S, 30°E from the gridded data set of Jones et al. (1986). The time series for this grid point is reliable from the 1890s and includes data from four stations in the region 27.5-32.5°S and 25°-35°E (Johannesburg, Bloemfontein, Durban and Pretoria). The precipitation series is the total (Jul-Jun; dated by the January) for the region 28-32°S by 26-30°E. Seventeen stations have been averaged, with the series expressed as normalized anomalies with respect to 1901-80. The series is most reliable for the years 1901-73. Unfortunately, after 1973 the series may be unrepresentative as only one station was available for inclusion in the analysis.

The precipitation series shows quasi-periodic dry periods 1901-1906, 1912-14, 1926-1933 and 1965-1970. Wet periods occur between 1917-24, 1934-44 and 1954-61. There is an apparent periodicity in the series of about 20 years which is just significant at the 5% level when examined by spectral analysis. The correlation between the precipitation and temperature series over the period 1901-73 is -0.28, confirming to some extent the assertion by Tyson (1986) that the wetter spells are associated with cooler temperatures. The relationship is marginally stronger (r = -0.31) if the warming trend in the temperature series from 1901-73 is removed. This linear trend over 1901-73 of the 30°S, 30°E grid point temperature series shows a warming of 0.79°C and explains 20% of the variance. There is no significant trend of the precipitation time series over 1901-73.

GENERAL CIRCULATION MODELS

A number of GCMs have been developed for a variety of tasks. They are modifications of weather forecasting models, with greater spatial resolution and simplified physics in order that they can run for long time periods, typically of the order of 20-30 years. The results from four models were used in this study:

(i) U.K. Meteorological Office (UKMO; Mitchell, 1986)
(ii) Goddard Institute for Space Sciences (GISS; Hansen et al., 1984)
(iii) National Center for Atmospheric Research (NCAR; Washington and Meehl, 1984)
(iv) Geophysical Fluid Dynamics Laboratory (GFDL; Wetherald and Manabe, 1986)

The major characteristics of the four models are listed in Table 1 of Arnell. (Important caveats concerning models have been listed by Arnell.)

When developing scenarios for small regions within southern Africa, the grid resolution of the model must be considered. The region has extremely variable topography with precipitation from both orographic and convective forcing. Thus many of the physical processes which determine the characteristics of the climate take place at the sub-grid scale level. The physical complexity of Lesotho may make GCM-based climate change estimates less accurate than those for an environmentally simpler region. Even if the region under study was less complex, it is still likely that other characteristics of GCMs would call into question their use for the construction of regional climatic change scenarios. The first and most important question that should be asked concerning GCM results is 'How well is the present climate simulated?'. Despite the fact that the modellers say their GCMs predict current climate 'satisfactorily' this is seldom the case from the point of view of those working at the regional level. Models generally simulate most of the major features of the present climate at the global scale. On the regional scale (and many modellers would define the whole of Europe or southern Africa as a region), they do not perform well. The simplest way to compare model output with 'real' data is to examine sea-level pressure data, concentrating on how well the local centres of action and their seasonal cycles are simulated (Santer, 1988). If models do not perform adequately in the simulation of present climate, this must reduce the credibility of the detailed results from perturbed-run simulations of doubled equivalent CO_2.

The modelled climate for Lesotho is derived from two sources. For the UKMO model, grid points around the region have been 'interpolated' to give monthly temperature and precipitation. For the other three models, estimations were made from published maps, generally for the extreme seasons (DJF and JJA).

In Figure 3, we compare the UKMO model current (control-run) rainfall for the region with measured data for Mokhotlong, Lesotho (29°17'S, 29°05'E; Griffiths, 1972). Mokhotlong is only one representative station for the region, and the levels of precipitation should not be compared too rigidly. However, it is clear that the UKMO simulation annual rainfall is too high, and in the dry season (JJA) the modelled rainfall is four times greater than that at Mokhotlong. The UKMO model for this region performs better than the other three models, all of which simulate over 7 times more than the observed rainfall in the dry season (see Table 1 of Arnell). Since the UKMO model control run provides the most realistic simulation of the seasonal cycle of precipitation over the region, it could be inferred that this same model would give the best simulation of the perturbed climate in a doubled CO_2 run. However, it must be stressed that even with the UKMO model, the monthly precipitation levels are not simulated satisfactorily. It is essential that the warm-world scenario change for precipitation should be derived by taking the percentage change over actual, rather than using modelled (perturbed-run) precipitation directly.

CONCLUSIONS/CAVEATS

In conclusion, the UKMO model would appear to give the best simulation of the seasonal cycle of precipitation over this region of southern Africa. The other three models all simulate too much precipitation in the dry season. On these grounds alone, the UKMO model is preferred over the other three models for scenario reconstruction.

However, whichever model is chosen, the problem of reconciling the transient and equilibrium response has not been resolved. The scenario is based on a steady state or equilibrium response model. Future change over Lesotho will result from gradual and continual changes in forcing, the forcing never being in equilibrium with the response, as models assume. Recent climatic change over the region indicates a rise in temperature of 0.8°C since 1900 and no significant change in annual precipitation. Wetter periods this century tend to be colder and this is not in accord with any of the GCM scenarios.

REFERENCES

Griffiths, J.F. (Editor), 1972: Climates of Africa. World Survey of Climatology Volume 10. 604pp.

Hansen, J., Lacis, A., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R. and Lerner, J., 1984: Climate sensitivity: analysis of feedback mechanisms. In: J.E. Hansen and T. Takahashi (Eds.) Climate Processes and Climate Sensitivity. AGU: Washington D.C. Maurice Ewing Series 5.

Jones, P.D., Raper, S.C.B. and Wigley, T.M.L., 1986: Southern Hemisphere surface air temperature variations, 1851-1984. Journal of Climate and Applied Meteorology 25, 1213-1230.

Mitchell, J.F.B., 1986: Simulation of climatic change due to increased atmospheric CO_2. Dynamical Climatology Technical Note 39, U.K. Meteorological Office.

Santer, B.D., 1988: Regional validation of general circulation models. Unpublished Ph.D. Thesis, University of East Anglia, Norwich. 375pp.

Tyson, P.D., 1986: Climatic Change and Variability in Southern Africa. Oxford University Press: Cape Town.

Washington, W.M. and Meehl, G.A., 1984: Seasonal cycle experiment on the climate sensitivity due to a doubling of CO_2 with an atmospheric general circulation model coupled to a simple mixed-layer ocean model. Journal of Geophysical Research 89, 9475-9503.

Wetherald, R.T. and Manabe, S., 1986: An investigation of cloud cover change in response to thermal forces. Climatic Change 8, 5-24.

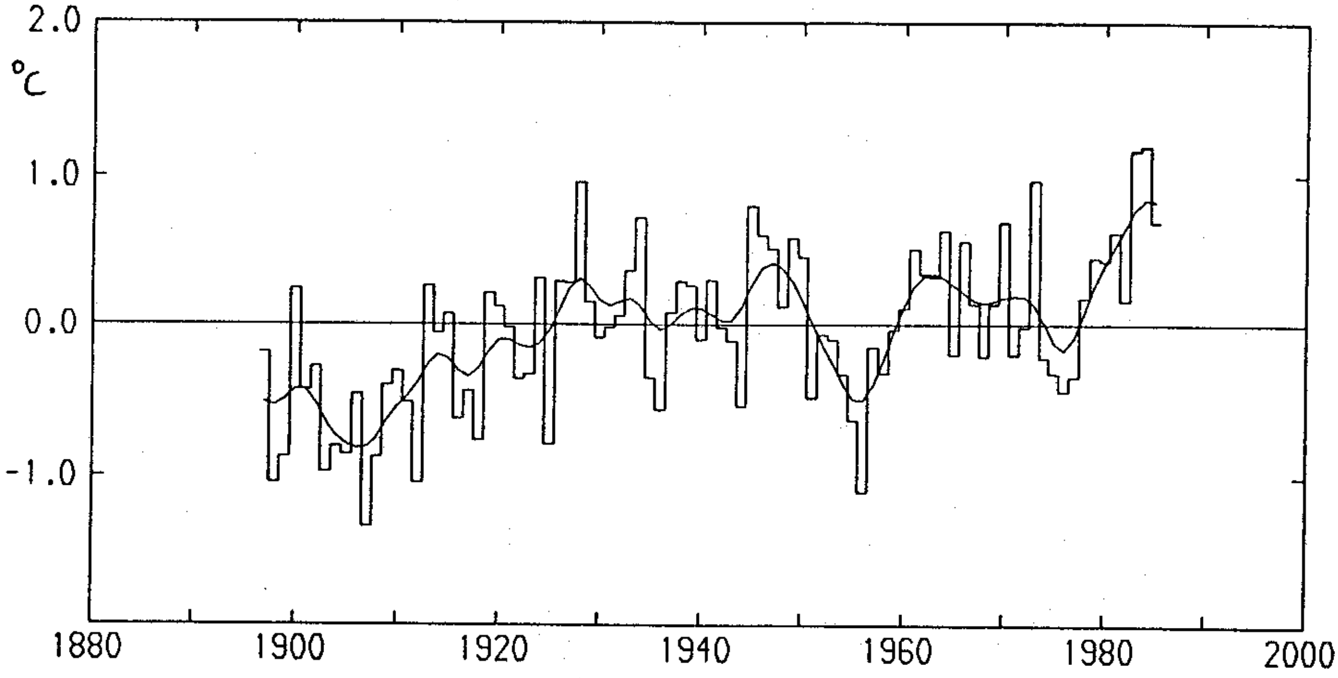


Figure 1: Mean temperature anomaly for July-June (dated by the January) for grid point 30°S, 30°E of the Jones et al. (1986) gridded data set for the Southern Hemisphere. The data are anomalies from the reference period 1951-70. The smooth line is a Gaussian filter designed to highlight variations on time scales longer than 10 years.

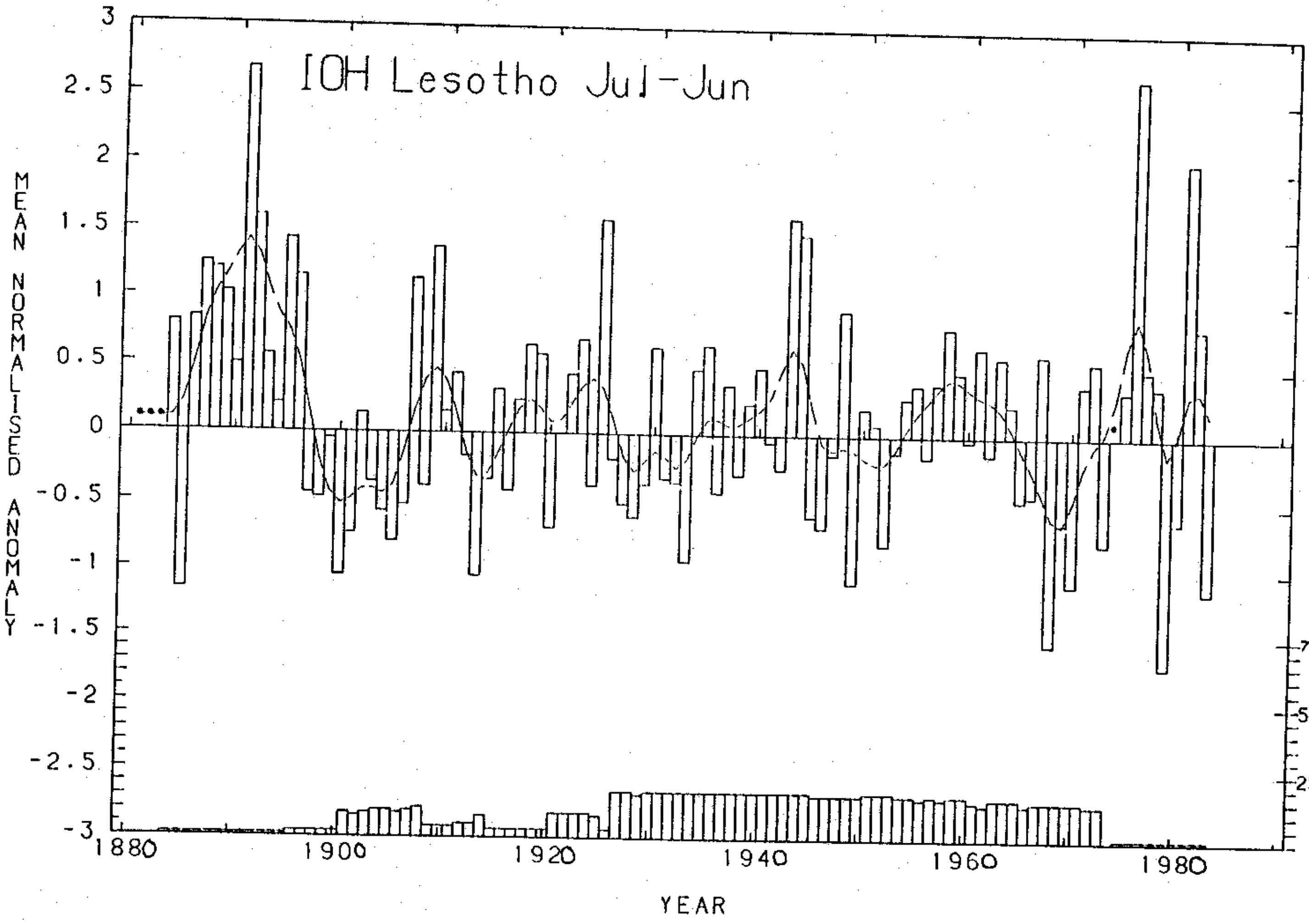


Figure 2: Total precipitation for the region 28-32°S by 26-30°E for the July-June season (dated by January). The data are expressed as the average normalized anomaly for contributing stations. The number of stations used each year is shown as the bottom histogram.

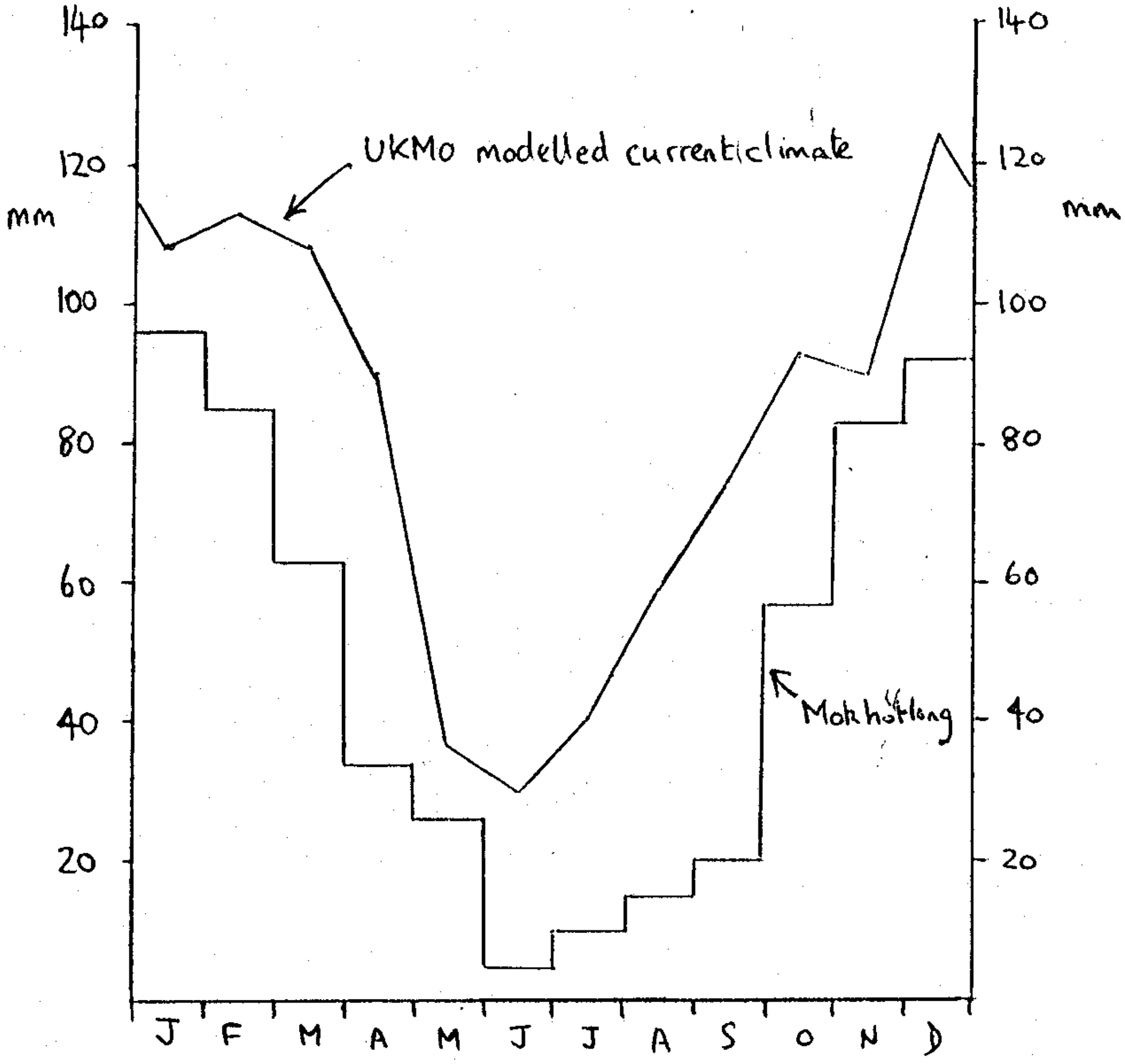


Figure 3: Comparison of Meteorological Office modelled precipitation data for the Lesotho region with measured data for Mokhotlong, Lesotho (data from Griffiths, 1972).