WATER RESEARCH COMMISSION

THE POTENTIAL IMPACTS OF RAINFALL STIMULATION ON WATER RESOURCES AND FORESTRY IN THE NELSPRUIT-BETHLEHEM TARGET ZONE

Compiled by:

G J Howard, A H M Görgens

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EXECUTIVE SUMMARY

INTRODUCTION

During the 1980s research into glaciogenic seeding of convective storms was funded in the Nelspruit-Carolina region by the Water Research Commission (WRC) and in the Bethlehem region by the Weather Bureau. In response to promising findings in these projects of potentially positive seeding effects, the WRC initiated various studies to aid strategic planning for further research into rainfall stimulation and its potential impacts. These studies were identified and prioritised in a research planning report by Görgens and Rooseboom (1990). The research reported here stems directly from this report.

Görgens and Rooseboom (1990) quantified the positive average seeding effects on storm rainfall based on the findings of the Nelspruit project. Subsequently, Seed (1992) developed software to generate seeded daily surface rainfall sequences using these average seeding effects combined with a probability distribution of seeding effect variability. This probability distribution of the increase in mean areal daily rainfall on scattered rain days was found to fit a log-Normal distribution, whereby most seeded days with scattered rainfall (the mode) have a 9% increase in rainfall, with a few seeded events experiencing a minimum 3% and a maximum 27% increase in rainfall. The increase in annual rainfall was found to be 7% (Seed, 1992).

OBJECTIVES

The availability of these augmented "seeded" daily spatial rainfall sequences meant that desk studies of potential impacts by computer models would be possible. This report describes the research undertaken to assess the potential impacts of rainfall stimulation in the "end user" fields of water resources and forestry in the rainfall stimulation target zone located in the Eastern Transvaal. The initial objective was to model the potential augmentation of runoff and increase in timber yield mathematically from selected pilot catchments. Further objectives included the quantification of the statistical dispersion of runoff and timber yield increases using hypothetically augmented rainfall time series by means of Seed's (1992) software and finally

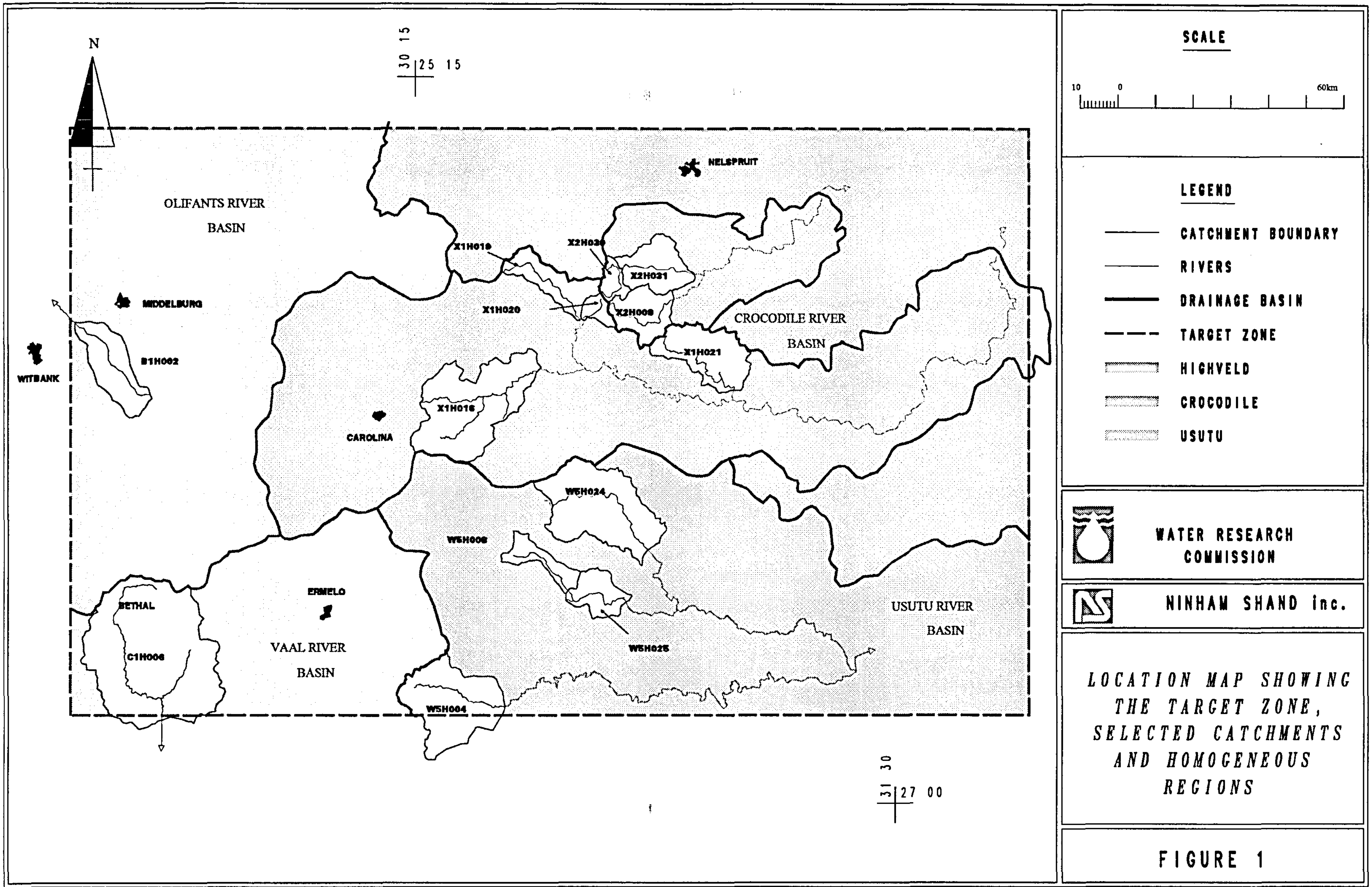
transferring this information from the pilot catchments to the entire target zone.

METHODOLOGY

In this project these impacts were assessed by means of the verified ACRU rainfall-runoff model for both runoff and timber yield using a large number of pairs of stochastically-generated and augmented daily rainfall sequences. Initially, the *ACRU* model was verified on the thirteen selected catchments, shown in Figure 1, by comparing simulated with observed monthly streamflow sequences. These pilot catchments were located in all the major river basins in the region, i.e. the Vaal, Usutu and Crocodile. This task required the collection of historical and current day landuse data, physical data such as soil type and climatic data. Table 1 ranks the catchments in terms of verification acceptability and lists the most important runoff characterstics of each catchment.

Table 1 : Ranking of verification acceptability (and runoff characteristics) of each catchment

CATCHMENT NUMBER	DESCRIPTION OF VERIFICATION	% FORESTED	MAR ($m^3 \times 10^6$)	% RUNOFF
Ranked according to acceptability				
W5H004	A good initial verification (no changes to model variables).	26,0	33,3	9,0
B1H002	A good initial verification (no changes to model variables).	8,2	6,2	3,6
W5H025	A good initial calibration (no changes), although accuracy may be exaggerated by using observed inflows from the upstream catchment.	67,5	36,2	5,1
W5H024	A mediocre initial verification. Minimal changes to variables resulted in a good verification. Accuracy may be exaggerated by using observed flows from an upstream catchment.	46,0	94,9	7,3
C1H006	A mediocre initial verification. Minimal changes to variables resulted in a good verification.	0,0	73,5	9,5
W5H008	A mediocre initial verification. Minimal changes to variables resulted in a good final verification.	24,1	11,1	12,0
X2H008	Mediocre initial verification. Minimal changes to variables resulted in a good final verification.	83,1	17,4	9,4
X2H031	A good initial verification (no changes to model variables). However, a low confidence rating is assigned to this gauge as the verification statistics are dominated by significant observed inflows from an upstream catchment.	50,6	24,1	14,0
X1H016	Poor initial verification. Extensive changes to variables resulted in a good verification. (Accepted due to good final verification).	26,0	79,5	16,0
X1H019	Poor initial verification. Extensive changes to variables resulted in a mediocre final verification.	76,2	56,6	29,1
X1H021	Very poor initial verification. Extensive changes to variables could not improve verification much.	26,3	43,6	12,8
X1H020	Very poor initial verification. Changes to variables could not improve verification.	21,0	5,5	11,4
X2H030	Very poor verification. Extensive changes could not improve verification.	65,0	16,7	25,0



LOCATION MAP SHOWING THE TARGET ZONE, SELECTED CATCHMENTS AND HOMOGENEOUS REGIONS

FIGURE 1

The verified *ACRU* configuration was then adapted to reflect present day development and used to generate a large number (100) of stochastic and augmented runoff and timber yield sequences, each of 30 years duration. A reservoir yield analysis, using the concept of firm yield (no failure) and based on a reservoir full supply capacity equivalent to one MAR (mean annual runoff), was also included to ascertain the effects on water resources in terms of water resources yield. A probabilistic exceedance technique (box-whisker plots) was used to compare the statistical dispersion of the stochastic and augmented sequences.

SENSITIVITY ANALYSIS

A limited sensitivity analysis was undertaken to identify how *ACRU* model parameters or variable choices might affect the findings. A single catchment (C1H006) was used in this analysis and 100 sequences of stochastic and augmented sequences were generated to compare the "altered" reservoir yields with the "base" reservoir yield. Three variables were identified as being sensitive in terms of water resources, namely DEPA (the depth of the A-horizon), SMDDEP (the effective depth of the soil contributing to stormflow production) and VEGINT (the interception loss). Catchment W5H004 was used to test timber yield sensitivity. In addition to the variables identified as being sensitive in terms of water resources, simulated timber yield was also found to be sensitive to rotation period and tree density, which are parameters used in the timber yield sub-routine of *ACRU*. All selected variables and parameters were increased and decreased by 50% above and below the "base" value initially determined. This range in variability reflects the range of values assumed for the 13 verification catchments mentioned before.

The effect of the change to variable values on both the stochastic and augmented yield is presented in Table 5. Results show that DEPA is most sensitive. If DEPA is increased by 50%, both stochastic and augmented reservoir yield drops by 41%.

Conversely, if DEPA is decreased by 50%, the stochastic and augmented yields increase by 120% and 109% respectively. These results show that changes to these variables can result in significant differences in the magnitude of reservoir yield estimation. What is important, however, is that potential errors in variables should not alter the magnitude of the differences between augmented yield and stochastic yield. Table 5 also analyses these differences and shows that the median of the "base" stochastic and "base" augmented sequences is 27 Mm^3

and 32 Mm^3, a difference in yield of 15%. The worst differences in the median of the "altered" stochastic and "altered" augmented sequences is 11% (DEPA decreased by 50%) and 24% (SMDDEP increased by 50%). Therefore, although the magnitude of reservoir yield is sensitive to model variable changes, the relative increase in the augmented median yield over the stochastic median yield is much less sensitive, i.e. the seeding effect is not significantly different. For this reason, all catchments (including those with a poor verification) were included in further analysis.

Timber yield is even less sensitive to parameter changes. There is an increase of 23,8% if the medians of the augmented and stochastic sequences are compared when using the correct or "base" parameters. Changes to DEPA produce the "greatest" variability, although the 26,6% and 20,8% median increases in median timber yield are still very similar to the 23,8% median increase of the base sequence.

RESULTS

Various aspects of the *ACRU* model output were analysed to quantify and explain the impacts of rainfall stimulation on water resources and timber yield. Firstly, the statistical dispersion of the stochastic and augmented sequences using *ACRU* runoff, reservoir yield and timber yield output were compared for each catchment. Table 2 summarises these results using the median of the stochastic and augmented sequences.

MEDIAN INCREASES

Results show that the average median increases in water resources (MAR and reservoir yield) and timber yield (for a 10 year rotation) in all the selected pilot catchments are 32% and 27% for runoff and reservoir yield respectively and 22% for timber yield. Differences in the median percentage increases of catchment runoff, reservoir yield and, to a lesser extent, timber yield are highly variable. Results show the lowest and highest median increases in catchment runoff are 20% in catchment X1H019 and 48% in catchment W5H025 respectively. These increases range from 14% (C1H006) to 42% (W5H008) for reservoir yield and 16% (W5H024) to 30% (X1H020) for timber yield.

Table 2 : Median MAR, Reservoir Yield and Timber (Eucalyptus) Yield of the Stochastic (S) and Augmented (A) Sequences and the Percentage Increase (for Present Day Land-Use)

CATCHMENT NUMBER	MAR ($m^3 \times 10^6$/a)			RESERVOIR YIELD ($m^3 \times 10^6$/a)			TIMBER YIELD (m^3/ha/rotation)		
	S	A	%	S	A	%	S	A	%
B1H006	3,4	4,6	35	2,4	3,1	30	160	190	22
C1H006	48,0	60,0	25	28,0	32,0	14	-	-	-
X1H016	52,0	65,0	25	47,0	58,0	23	320	380	22
X1H019	30,0	36,0	20	28,5	33,8	19	270	320	19
X1H020	3,8	5,3	39	2,5	3,4	36	350	460	30
X1H021	46,0	57,0	24	38,0	46,0	21	430	500	17
X2H008	10,0	13,5	35	8,6	11,4	31	390	465	19
X2H030	8,5	10,4	22	8,1	9,4	16	275	325	18
X2H031	23,0	31,0	35	22,0	28,0	27	280	345	23
W5H004	27,0	35,0	30	21,0	27,5	31	300	370	23
W5H008	6,8	9,9	46	5,0	7,1	42	325	385	29
W5H024	165,0	210,0	27	105,0	122,0	16	430	500	16
W5H025	25,0	37,0	48	17,0	23,8	40	340	430	26
Average	-	-	32	-	-	27,0	-	-	22

DISPERSION OF INCREASES

The range between percentiles provides an index for statistical dispersion. An analysis of the statistical dispersion of data is summarised in Table 3 and indicates a significant variability in water resource results and very little variability with regard to timber yield. For reservoir yield increases, values range from 9% in W5H024 to 46% in X1H020 between the 25 percentile and 75 percentile, and from 0% in W5H024 to 68% in X1H020 using the 5 percentile and 95 percentile. On the other hand, the statistical dispersion of timber yield increases ranges from 16% (using the 25 percentile in X1H021) to 32% (using the 75 percentile in X1H020), and from 14% in W5H024 to 34% in X1H020 using 5 and 95 percentiles respectively.

SPATIAL EXTRAPOLATION OF RESULTS

A further requirement of this project was the extrapolation of these pilot catchment results to the target zone. This was achieved by grouping the pilot catchments into three quasi-homogeneous regions, namely the highveld, the steep sided escarpment conditions of the Crocodile River Basin and the "rolling hill" escarpment conditions associated with the Usutu River Basin. The stochastic and augmented sequences of the pilot catchment water resources and timber yield results were concatenated, producing a single set of stochastic and augmented conditions representative of each

Table 3 : Percentage increase in sub-catchment reservoir firm yield (R) and timber yield (T) for selected percentiles.

Catchment Number	Percentiles							
	5%		25%		75%		95%	
	R	T	R	T	R	T	R	T
B1H002	8	20	30	21	46	23	68	25
C1H006	7	-	12	-	20	-	28	-
X1H016	16	21	21	22	26	23	30	25
X1H019	15	17	18	18	20	20	21	20
X1H020	21	27	27	29	46	32	68	34
X1H021	14	15	17	16	23	17	30	19
X2H008	24	17	30	19	38	21	47	22
X2H030	17	17	19	18	24	19	26	20
X2H031	21	21	25	22	29	23	31	25
W5H004	18	22	26	23	33	24	37	25
W5H008	25	27	39	29	52	30	63	32
W5H024	0	14	9	16	22	17	31	18
W5H025	22	25	34	26	47	27	58	28

region. A summary of the results is presented in Table 4. Results indicate that the Usutu River Basin has the highest median increase in both reservoir yield and timber yield.

Table 4 : Median Percentage Increase in Reservoir Yield and Timber Yield of the Three Quasi-Homogeneous Regions

REGION	RESERVOIR YIELD (%)	TIMBER YIELD (%)
Highveld	25	21,7
Crocodile	23	20,0
Usutu	33	25,0

DOMINANT RAINFALL-RUNOFF PROCESSES

To aid further research planning, a final analysis was carried out to identify the dominant processes in the rainfall-runoff simulation that account for the increases in simulated water resources and timber yield. The investigation included :

i) The relationship between rainfall volume and enhanced rainfall.
ii) The relationship of rainfall volume and enhanced runoff.
iii) Identifying the dominant runoff process (stormflow or baseflow)

For this purpose, a provisional limited analysis using the "seeded" event pairs of the original *ACRU* original historical and augmented 30 year daily sequences were compared for three selected catchments, i.e. all seeded days were compared pair wise.

Table 5 : **Comparison of the Median Reservoir Yield of the "Base" Sequences and "Altered" Sequences for Each Variable Change and the Comparison of Percentage Timber Yield Increases**

Variable Name	"Base" Value	Variable Change %	"Altered" Value	"Base" Sequence Median Reservoir Yield		"Base" Sequence Median % Reservoir Yield Increase	
				Original Stochastic (Mm^3) 27	Augmented (Mm^3) 32	Reservoir Yield	Timber Yield
				"Altered" Sequence Median Reservoir Yield		15	23,8
				Original Stochastic (Mm^3)	Augmented (Mm^3)	"Altered" Sequence Median % Increase	
DEP A (metres)	0,3	+ 50 - 50	0,45 0,15	16 (-41%) 60 (120%)	19 (-41%) 67 (109%)	19 11	26,6 20,8
SMDDEP (metres)	0,3	+ 50 - 50	0,45 0,15	18 (-34%) 55 (103%)	24 (-25%) 61 (91%)	24 11	24,2 22,4
VEGINT (mm/ rainday)	1,6 (for all months)	+ 50 - 50	2,4 0,8	24 (-11%) 32 (18%)	27 (-16%) 37 (16%)	14 16	- -
Rotation Period (mths)	120	- 16 - 33	100 80	- -	- -	- -	23,5 23,2
Density (Stems/ha)	< 1 500		> 1 500	-	-	-	23,8

( ) Denotes the % difference between the "base" and "altered" sequences.

Indications from this investigations are :

i) Rainfall event-days that are small in volume (<5mm/day) occur most frequently (73,8% of the time), yet contribute only 24,5% of the total increase in rainfall. It is the larger rainfall event-days (>15 mm/day) which occur less frequently (26,2% of the time) that contribute the most (75,5%) to the total increase in rainfall. This could have a cost implication by identifying and seeding only those storms with the most potential for enhanced yield.

ii) The lag associated with runoff from the larger events complicates the comparison of same day "seeded" rainfall and "seeded" runoff. A comparison of same day "seeded" runoff explains a 15,8% increase in runoff, compared to a 31,7% increase in runoff if all days are included in the analysis. This indicates that the same-day comparison excludes approximately 50% of the flow increase which, due to runoff lags, exist in the catchment on days after the seeded days. The scope of this investigation was however too limited to explore this interesting result further.

iii) Streamflow increases are mostly a result of baseflow augmentation, with stormflow usually only being relevant for the large rainfall events.

CONCLUSIONS

(i) **MAR and Reservoir Yield** : The average median increase in MAR and reservoir yield is 32% and 27% respectively. Catchment increases in reservoir yield range from 14% to 42%.

(ii) **Timber Yield** : The average median increase in timber yield is 22%. Catchment increases range from 16% to 30%.

(iii) **Statistical Dispersion** : There is a significant variability in water resources. Increases in reservoir yield range from 0% to 68% using the 5 percentile and 95 percentile. The variability in timber is less significant and ranges from 14% to 34% using the 5 percentile and 95 percentile.

(iv) **Spatial Extrapolation** : Extrapolation of pilot catchment results on a regional basis indicated that the Usutu River Basin has the highest median increase in both reservoir yield and timber yield (33% and 25% respectively).

(v) **Sensitivity Analysis** : Potential errors in variables result in significant differences in the *magnitude* of reservoir amd timber yield estimation, but should not alter the *magnitude of the difference* between stochastic yield and augmented yield significantly .

(vi) **Dominant rainfall-runoff processes** : Larger rainfall events (>15 mm/day) occur less frequently (26,2% of the time) and contribute the most (75,5%) to the total increase in rainfall. Runoff from larger events in lagged so that a same day comparison would exclude 50% of the flow increase.

RECOMMENDATIONS

This study has quantified potential cloud-seeding impacts on the basis of 30-year sequences of monthly flows generated by a daily-input model. Further work is recommended to examine the impacts of rainfall stimulation on a daily basis, especially with regard to extreme rainfall events and the flow components most affected. Additional work is also required to compare the economic benefits of enhanced water resources and timber yield with the costs of an operational cloud seeding programme.

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Dr D C Green	WRC
Mr F P Marais	WRC (Secretary)
Mr G Mather	Cloudquest (Pty) Ltd
Dr A W Seed	DWAF
Prof R E Schulze	University of Natal (Department of Agric. Eng.)
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1. INTRODUCTION

1.1 BACKGROUND AND PROJECT AIMS

In 1992, the Water Research Commission (WRC) contracted Ninham Shand Incorporated (NSI) to carry out research into the potential impacts of rainfall stimulation on both water resources and timber yield in the rainfall stimulation target zone located in the Eastern Transvaal (Figure 2.1.1). The concept of rainfall stimulation is rooted in the work of Bergeron in 1933, with the first experiments on glaciogenic seeding being conducted by Schaefer in 1946. Since this time, over 500 operational cloud seeding projects and over 40 precipitation augmentation research experiments have been conducted in over 70 countries under a variety of conditions (Görgens & Rooseboom, 1990). Some of these research projects include assessments of runoff enhancement due to cloud seeding. In South Africa, during the 1980s, two significant projects into glaciogenic seeding of convective storms were executed in the Nelspruit/Carolina (PAWS) and Bethlehem (BPRP) regions respectively. The PAWS project was funded by the WRC, while the BPRP project fell under the auspices of the South African Weather Bureau.

In response to promising findings in these two projects of potentially positive effects of cloud seeding on rainfall, the WRC requested Görgens and Rooseboom (1990) to conduct a research planning study to identify and prioritise further research into the potential impacts of rainfall stimulation. The research reported in this document stems directly from the latter initiative. Görgens and Rooseboom (1990) proposed the derivation of modified rainfall scenarios based on the concept of mean rainflux (mean rainfall intensity x total pixel area), storm area (no. of pixels x representative area), the resultant average rainfall intensity and the use of "time windows since seeding" to assess incremental seeding effects. Table 1.1.1 presents the average seeding effects proposed by Görgens and Rooseboom (1990). These average effects have been incorporated in software developed by Seed (1992), along with a probability distribution of variability of seeding effects, to generate modified daily rainfall sequences based on the available set of historical long-term rainfall records. This is discussed in more detail in Section 1.2. With the availability of these augmented "seeded" daily spatial rainfall time series, it would be possible to model the potential impacts in various "end user" fields such as water resources and timber yield in the target zone.

Table 1.1.1 : Proposed Average Seeding Effects Expressed as Increases over Unseeded Storms

TIME AFTER SEEDING	RAINFLUX % INCREASE	STORM AREA % INCREASE	RAIN RATE % INCREASE
0 - 10	0	0	0
10 - 20	0	0	0
20 - 30	15	5	10
30 - 40	25	5	20
40 - 50	50	35	10
50 - 60	55	40	10

The aims of this research, as identified by Görgens (1991), are listed as follows :

- Mathematically model the potential augmentation of runoff from selected gauged pilot catchments in the rainfall stimulation target zone.

- Mathematically model the potential increase in timber production from selected pilot catchments in the rainfall stimulation target zone.

- Quantify the statistical dispersion of the potential impacts in the pilot catchments for both runoff and timber yield by utilising a large number of alternative rainfall time series which have been hypothetically augmented.

- Transfer results and findings from the pilot catchments to the total target zone, yielding an integrated assessment of water resources and forestry impacts for the target zone.

Credible positive simulated impacts on water resources would be of great help in motivating and planning for a future cloud seeding experiment overfixed catchment areas in the target zone.

1.2 MODIFIED DAILY SPATIAL RAINFALLS

The derivation of augmented spatial rainfall series has been achieved by Seed (1992) by utilising the proposed average seeding effects of Table 1.1.1, PAWS seeding experiment data, radar-derived storm tracks and storm histories, all available rainfall time series in the selected target area, satellite cloud data and synoptic weather data from the national network. This information is used to quantify the effect of weather modification on mean areal daily rainfall. An important finding is that the frequency distribution of the increase in mean areal daily rainfall was found to fit a lognormal distribution, shown in Figure 1.2.1. A model (based on this lognormal distribution) was developed to simulate a weather modification program using daily rain fields derived from gauge measurements.

The procedure used by Seed (1992) is summarised under the following steps :

1. An historical daily rainfall grid is generated on a 3 km x 3 km basis by interpolation of rain gauge data.

2. This daily rainfall grid is classified into seedable events (scattered rain days) which tend to occur in summer, and non-seedable events (no rain or general rain days where more than 50% of the stations report more than 5 mm rainfall on a given day) using an adapted version of a method proposed by Court (1979).

3. The transition probabilities between these three states are calculated.

4. A new stochastic sequence of dry, scattered and general rain days is generated using a Markov chain model.

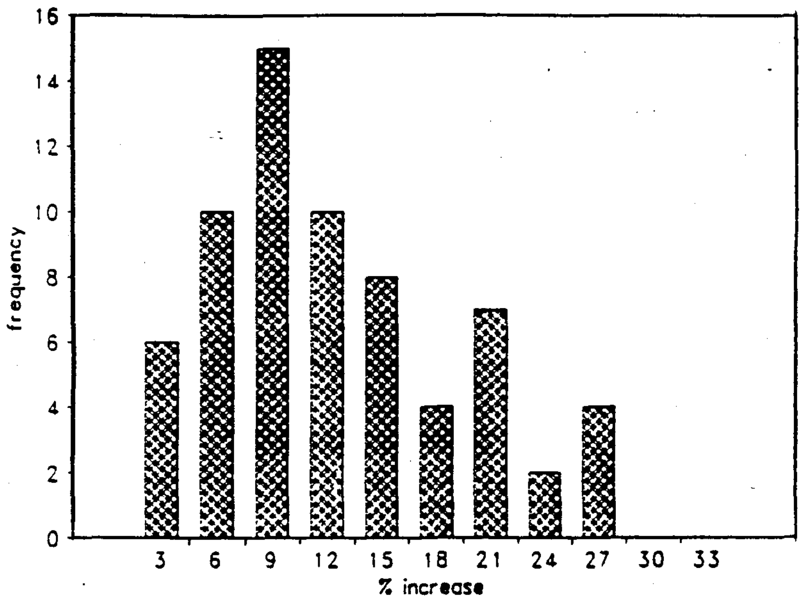


Figure 1.2.1 : **Frequency Distribution of the Seeding Effect on Daily Spatial Rainfall using the Carolina and Bethlehem Data Sets (after Seed, 1992)**

The daily rainfall values are generated by randomly selecting a value corresponding to an appropriate state in the historical record. A seeding effect on the daily spatial rainfall is then generated for each scattered rain day using the lognormal distribution developed by Seed (1992) from the PAWS and BPRP data and incorporating the average seeding effects presented in Table 1.1.1. Figure 1.2.1 shows the frequencies of the daily spatial seeding effect on which Seed bases his lognormal distribution. The final step involves modifying each stochastically generated scattered rain day by its corresponding seeding effect and inserting the modified rainfall value into the modified rainfall database to assess impacts on water resources and timber yield.

1.3 STRUCTURE OF REPORT

Chapter 2 contains a description of the study area with a view to identifying homogeneous regions. Subsequent chapters discuss the data collection, configuration and verification of the model and then quantify the statistical dispersion of the potential impacts on runoff and timber yield utilising a large number of alternative (stochastic) rainfall time series which have been hypothetically augmented. A regionalised procedure is then used to extrapolate the results to quasi-homogeneous regions within the target zone. Furthermore, limited sensitivity tests are undertaken to define the range of possible yields for changing model conditions and to identify sensitive variables in terms of water resources and timber yield. The final chapter investigates the hydrological processess responsible for increased yields.

2. DESCRIPTION OF STUDY AREA

2.1 LOCATION

The general location of the study area is shown in Figure 2.1.1. The study area is located in the Eastern Transvaal and extends roughly from Witbank in the west to Swaziland in the east, and from Nelspruit in the north to Amsterdam in the south. The target zone, within which seeded rainfall scenarios are available, is defined as a rectangular block (Figure 2.1.2). The north west and south east co-ordinates of this block are 25° 23' 25" S, 29° 19' 12" E and 26° 45' 31" S, 30° 52' 04" E respectively. Thirteen catchments were selected in the target zone. These are shown in Figure 2.1.2.

<u>NOTE:</u> The extension of catchment boundaries over the target area boundary is not significant.

2.2 TOPOGRAPHY, DRAINAGE PATTERNS AND LAND USE

The target area covers a large area and includes three distinctive physiographic regions. The highveld is located to the west and includes catchments B1H002 and C1H006. The escarpment consists of two distinctive regions. To the north of the target area the topography is characterised by mountains and steep sided valleys while topography in the south escarpment is less severe and characterised by rolling hills. These homogeneous regions are illustrated in Figure 2.1.2.

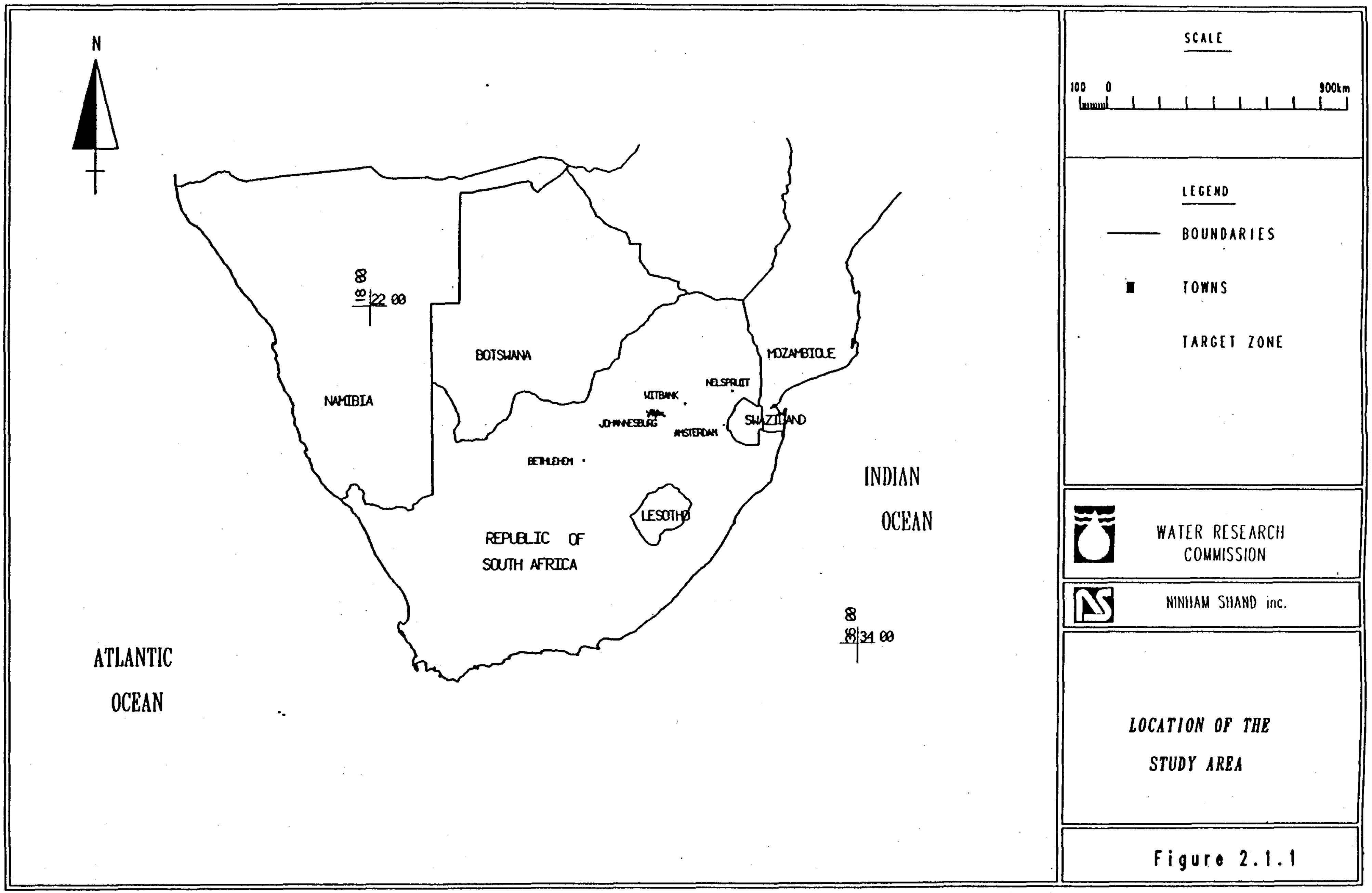
Four major river basins are located in the target zone. The Olifants River Basin drains to the north west and the Vaal River Basin to the south west. The largest portion of the basin is drained by the Crocodile River Basin to the north-east and by the Usutu River Basin to the south-east. The regional physiographic characteristics can be separated according to basin boundaries with the Vaal and Olifants River Basin containing highveld characteristics, the Crocodile River Basin containing steep escarpment characteristics and the Usutu River Basin containing the rolling hill escarpment conditions.

Significant agricultural development has occurred on the highveld. Areas under irrigation (from farm dams) carry mostly fodder crops and pasture to support livestock activities, while maize, potatoes and some vegetables are cultivated. Forestry development is not significant and the natural vegetal cover is grassland (Theron, Prinsloo, Grimsehl & Pullen, 1991).

Intensive agricultural development is found alongside major rivers and dams in the escarpment regions. However, these catchments were excluded from this study in favour of catchments with little or no agriculture to avoid modelling complex water demands. The escarpment region is suitable for exotic afforestation and Eucalyptus grandis and pine plantations are common. The natural vegetal cover is grassland.

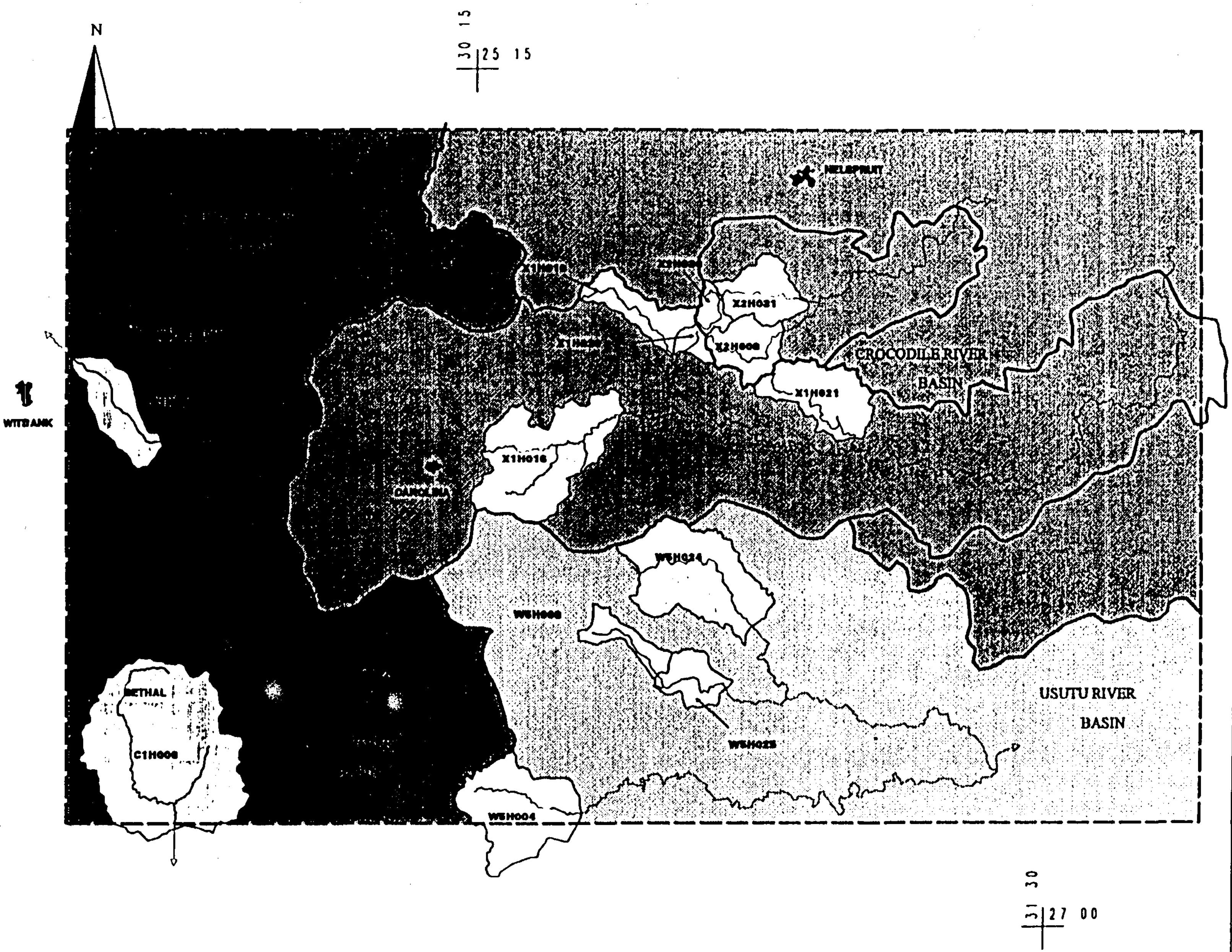
2.3 CLIMATE

The climate of the study region is characterised by mild to hot summers and cold winters. The mean annual precipitation (MAP) is approximately 800 mm on the highveld and varies in the escarpment region from 1 400 mm on the mountains to 600 mm in the valleys. Precipitation is of a convective nature in summer and frontal in winter, with the highest rainfall during December to February. Potential evaporation is most severe from October to March and varies from 1 600 mm/a in the highveld to 1 400 mm/a in the escarpment region.



LOCATION OF THE STUDY AREA

Figure 2.1.1



SCALE

10 0 60km

LEGEND

CATCHMENT BOUNDARY

RIVERS

DRAINAGE BASIN

TARGET ZONE

HIGHVELD

ESCARPMENT (SEVERE)

ESCARPMENT (ROLLING HILLS)

WATER RESEARCH COMMISSION

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LOCATION MAP SHOWING THE TARGET ZONE, SELECTED CATCHMENTS AND HOMOGENEOUS REGIONS

FIGURE 2.1.2

3. MODELLING STRATEGY

A multi-phased modelling strategy was followed to estimate the impacts of rainfall stimulation on both water resources and timber yield in the target zone. The major strategies involved :

(i) The configuration and verification of a suitable catchment model at selected flow-gauging stations
(ii) Use of a daily rainfall surface to prepare the historical sub-catchment rainfall, as well as both the families of stochastic and corresponding modified rainfall scenarios
(iii) Generation of stochastic flow sequences and corresponding modified flow sequences for present day land use conditions in these catchments
(iv) Comparison of the influence of rainfall augmentation on water resources (in terms of yield from a hypothetical dam) and timber yield using the stochastic and modified sequences
(v) Sensitivity tests of the catchment model output to selected model input parameters
(vi) Regionalisation of the results from the selected catchments to the target zone.

These strategies are now examined in detail.

3.1 SELECTION OF AN APPROPRIATE CATCHMENT MODEL

The suggestion to use the *ACRU* daily rainfall-runoff model (Schulze *et al.,* 1989) for this study was initially made in the project proposal (Görgens,1991) and later written into the contract. The acronym *ACRU* is derived from the Agricultural Catchment Research Unit within the Department of Agricultural Engineering of the University of Natal in Pietermaritzburg. The decision to use the *ACRU* model arises primarily out of the necessity to model the seeding effects at a relatively short time resolution (daily), allowing for spatially variable processes in different soil types and caused by different land uses typical of catchments in the target zone.

The need for the daily time step in rainfall stimulation arises because convective storms are the only rainfall systems considered suitable for cloud seeding (Seed, 1992). The *ACRU* model is the only locally developed rainfall-runoff catchment model that uses a daily time step that allows detailed specification of soils patterns and land use patterns. The use of a locally developed model is attractive as it has been developed and used around local conditions and has generally gained acceptability by the local scientific community.

Catchment modelling requires the simulation of both natural processes and land use development effects in a catchment. The most common processes that need to be modelled relate to :

- Precipitation on the catchment which results in streamflow from surface runoff, soilwater interflow and groundwater seepage
- The interception and transpiration of forestry and other types of vegetation
- The retention of water in dams for irrigation and urban needs
- Evaporation from dams, soil and vegetation
- Changes in land use with time.

The *ACRU* model is able to meet the necessary modelling requirements, since it is a physically conceptual model which uses daily, multi-layer soilwater budgeting. Also included is a dynamic input option to facilitate land use changes over time. The general structure of the *ACRU* model, presented in Figure 3.1.1 (Schulze *et al*, 1989), indicates the ability of the model to simulate all the major hydrological processes.

3.2 SURFACE VS POINT RAINFALL

The *ACRU* model requires daily rainfall (in mm) representative of each sub-catchment (discussed in section 4.3.1). Usually this is obtained using a "driver" station - the closest reliable rainfall station. However, this project has made use of the recent software developments by Seed (1992) which generate a daily gridded rainfall surface based on interpolation between rainfall stations. The impact (effect) of cloud seeding is inclusive in this rainfall generation package. The advantages of using these surface data is that a separate rainfall file for each sub-catchment can be used. Using the "driver" station method, most sub-catchments would use the same station, with rainfall adjusted only from long-term trends of MAP with physiography, owing to the sparse distribution of rainfall stations.

The magnitude of rainfall increase as a result of cloud seeding is approximately a 7% increase in long-term MAP (Seed, 1992). Since a large proportion of MAP consists of unseeded (general rain days) the increase in actual convective rainfall events is larger. Increases of between ∞ and 16% were reported in an analysis of all "seeded" events (presented in Chapter 8).

3.3 MODEL CONFIGURATION AND VERIFICATION

3.3.1 Importance of verification

At the outset of this project the intention was to configure and verify the *ACRU* model roughly, with the emphasis being more on the relative difference between natural rainfall than on modified rainfall. However, a decision was made by the project Steering Committee to obtain the best verification possible, as the greater the validity of the model the more plausible the modification results would be. Consequently, a great investment in data[1] collection was made to obtain the most accurate data possible. Spatially related data were captured on a GIS (ARC/INFO). Other data relating to model variable choices were obtained from the *ACRU* User Manual (Schulze *et al.*, 1989) and personal communication with Professor R E Schulze.

Once the configuration phase was complete, the model was run. Initial verification checks were done using the daily water balance and monthly sub-catchment output. Owing to the variability of daily flows, the statistical verification was carried out using the output of monthly totals of daily flows from the *ACRU* model. In addition to using the *ACRU* statistical output, in-house software development enabled the monthly time series and seasonal distributions to be compared graphically. Improvements to poor verification results in certain catchments were achieved using alternative data sources, albeit using only data that improved the fit.

[1]In this report the term data also refers to processed data also called information.

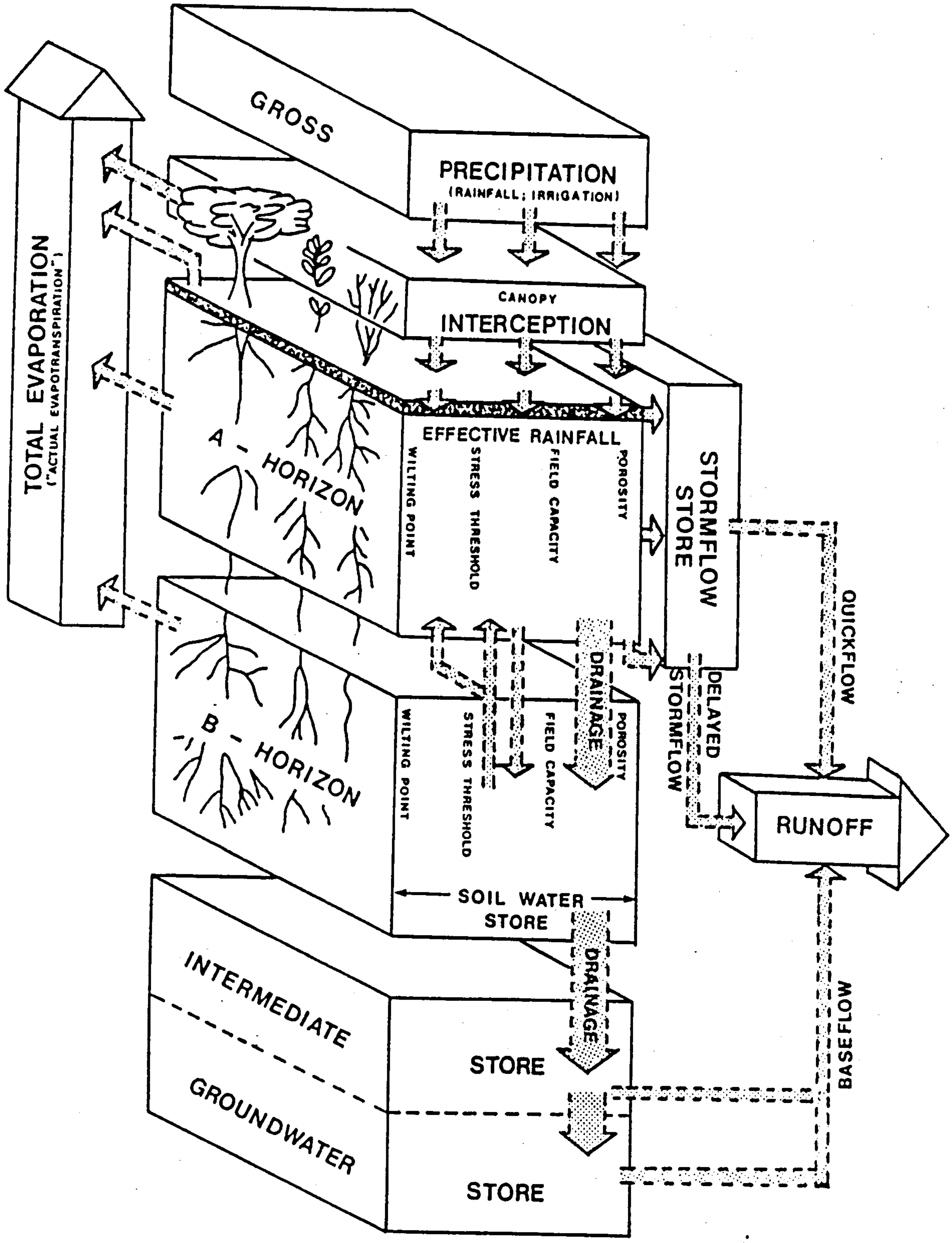


Figure 3.1.1 : The *ACRU* Agrohydrological Modelling System : General Structure (after Schulze *et al.*, 1989)

3.3.2 Simulation of runoff during wet seasons

The seeding effect on large rainfall events is more pronounced than on smaller rainfall events (Seed, 1992). Consequently, the ability of the model to simulate the wettest seasons accurately is important when considering the effects of rainfall stimulation. Should the model over-simulate the long-term water balance, it can be argued that the model will overpredict the effects of enhanced rainfall. Consequently, the annual simulated and observed flows were plotted and checked for their scatter about the 1:1 line.

3.4 HISTORICAL LAND USE VS PRESENT DAY CATCHMENT DEVELOPMENT

When using observed streamflows during model verification, it is important to represent the historical changes over time in land use and catchment development. Great care was taken to incorporate such historical development in the verification phase.

Once an acceptable verification was obtained, a stochastic analysis (discussed in section 3.5) was undertaken to quantify the effects of weather modification. An important consideration when comparing the effects of different hypothetical rainfall scenarios on runoff and timber yield is to maintain constancy in all the other variables. Variables such as agricultural and forestry area, the number of farm dams and irrigation demands that change with time could have a non-linear effect on runoff, thus complicating any attempt to investigate the effect of different rainfall scenarios on runoff and yield. Consequently during investigation of effects of different rainfall scenarios, dynamic data in the *ACRU* model were kept constant at current day (1990) development conditions. So the *ACRU* model simulates the effect of current land use development over an extended simulation period.

3.5 STOCHASTIC RAINFALL SEQUENCES

To quantify the potential effects of rainfall stimulation on runoff, *ACRU* model output using unmodified rainfall must be compared to the output using modified rainfall. Since the modification function developed by Seed (1992) is statistically based, numerous modified rainfall sequences should be analysed to include the statistical variability in the data set.

Modified rainfall sequences with modification limited to scattered raindays giving increases in MAP of approximately 7% were generated initially using the historical rainfall and these modified runoff sequences were then compared to the historical runoff. This method proved unsuitable due to the lack in variability of the modified runoff sequences. Further investigation revealed that while the modified daily rainfall was variable, the variability in modified monthly rainfall is negligible.

To assess the statistical variability of modified rainfall this concept was rejected in favour of generating stochastic rainfall sequences, modifying each stochastic sequence and comparing the modification of each stochastic sequence with the corresponding original. These stochastic sequences are, of course, based on the statistics of the historical rainfall and include extreme wet and dry seasons. This method is therefore likely to ascertain what the effect of rainfall modification will be in these extreme wet and dry seasons.

An analysis of the optimum number of stochastic and modified sequences was carried out. Sequences of 20, 100 and 200 were analysed. Results are summarised in Table 3.5.1. It was found that a small sample of 20 runs may include extreme sequences which greatly affect the statistics. However the larger samples of 100 and 200 runs are not so sensitive and produce similar results. Owing to computer time constraints a sample of 100 sequences was considered sufficiently representative of natural variability.

3.6 YIELDS (WATER RESOURCES AND TIMBER)

This section discusses the methodology used to assess impacts of rainfall stimulation on water resources and timber yield. The water resources component can be assessed using the "hypothetical dam" concept to find the yield from an hypothetical dam using the modelled runoff. Comparisons are made between the yield from a "stochastic based" runoff and corresponding "modified" runoff. The capacity of the hypothetical dam was assumed to equal the MAR of the historical flow at the hypothetical dam site. Other assumptions included using the concept of firm yield (no failure) and both a 10% and 20% monthly failure. A general area/capacity relationship was used so all hydrological yields do not reflect the actual yields of dam built at the outflow from each catchment.

Table 3.5.1 : The Mean 50 and 75 Exceedence Percentile Yield ($m^3 \times 10^6$) for a Variable Number of Runs

NO RUNS	PERCENTILE	YIELD (m^3 X 10^6)		
		FIRM YIELD	10% FAIL	20% FAIL
20	Mean	15,523	15,092	18,326
	50%	15,068	14,953	18,051
	75%	12,025	9,174	10,694
100	Mean	14,001	15,656	16,353
	50%	13,362	15,162	15,498
	75%	9,470	10,227	11,348
200	Mean	15,304	15,810	15,681
	50%	13,656	14,683	14,498
	75%	9,524	11,232	11,348

The timber component is also assessed in terms of yield. In this instance, the yield is calculated by the *ACRU* model by means of a new timber yield (based on Eucalyptus grandis only) sub-routine which has recently been developed (Leenhardt, 1993). The sub-routine estimates a volume of timber (eucalyptus) based on the accumulated transpiration of the tree. Inputs to the sub-routine include the region of interest, available soil water capacity, tree density and the rotation period.

It must be noted that while a distinction was made between pine and eucalyptus in the hydrological component of this study, the timber yield component took eucalyptus into consideration, as the only water use/timber growth information that was available was based on eucalyptus. This was achieved by assuming the current day forest area to be 100% eucalyptus. Consequently, all references to timber yield in this report actually refer to the yield from a eucalyptus plantation.

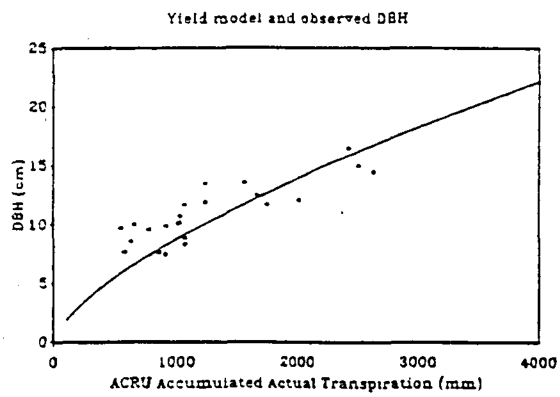


Figure 3.6.1 : *Eucalyptus Grandis* Yield Model Predictions of DBH from Actual Simulated Transpiration (after Leenhardt, 1993)

Figure 3.6.1 shows the relationship on which timber yield is based. There is doubt concerning the prediction of timber volume, as the volume of individual trees has been computed from DBH (diameter at breast height) and HT (height) using the Schönau (1971) equation which has been shown to encompass certain inaccuracies (Leenhaardt, 1993). Consequently, the estimates of actual timber volume should be interpreted with circumspection, while the relative difference between the timber yield from a "stochastically based" rainfall sequence and a corresponding "modified" rainfall sequence is likely to be reasonably realistic.

4. MODELLING PROCEDURE

This chapter describes the tasks undertaken as part of the modelling procedure. The first task discussed is the selection of catchments using criteria such as the reliability of observed flow. Model input collection was then targeted in these catchments followed by the manipulation of these data for the configuration and verification of the model. Final tasks included the generation of thirty years (with "current day development") of both stochastic and corresponding modified flows to compare the water resources and timber yield of both sets of flows. Finally the regionalisation of these findings and model sensitivity is discussed.

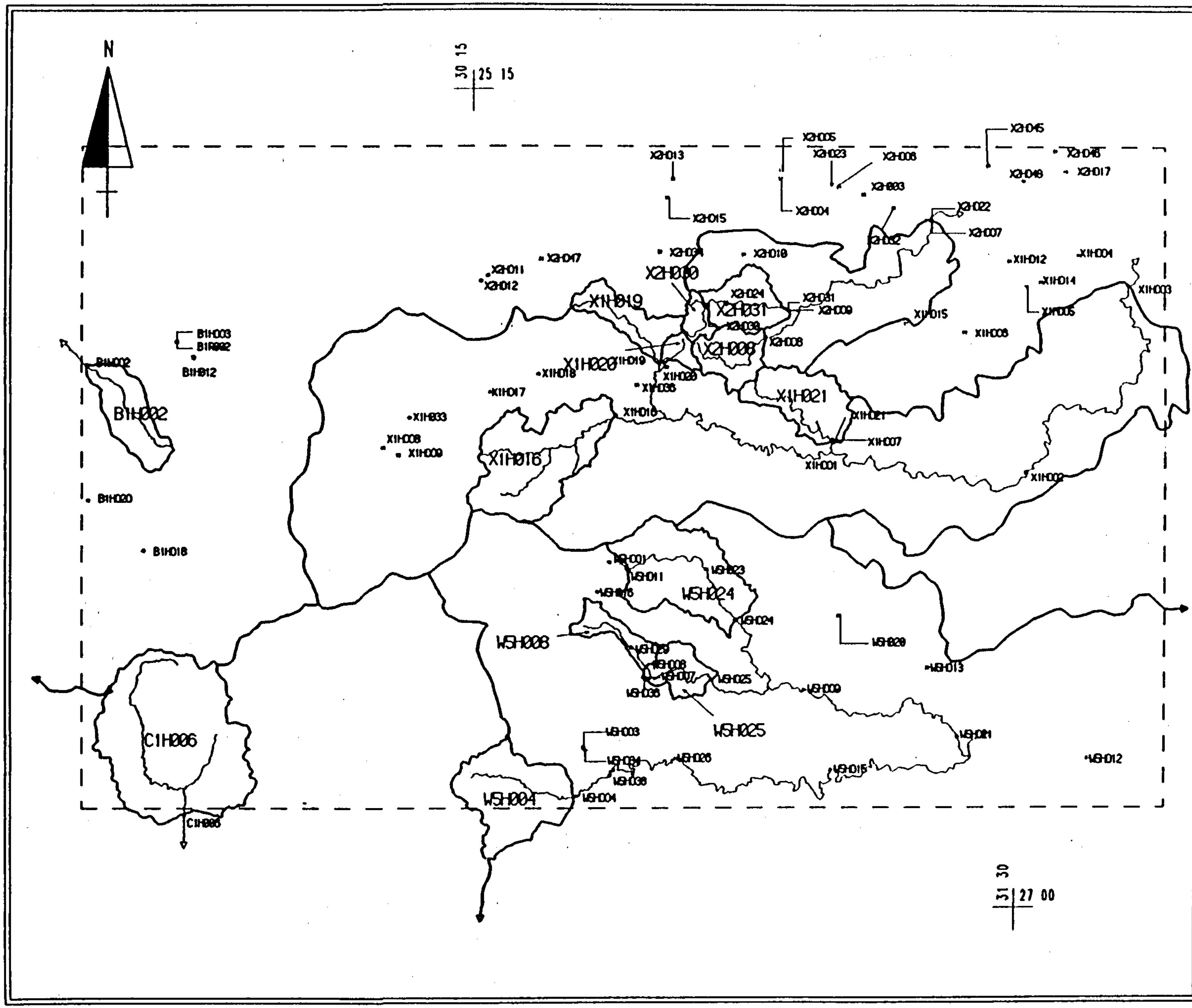
4.1 SELECTION OF CATCHMENTS

Owing to the large areal extent of the target zone and the extensive input requirements of the *ACRU* model, the task of catchment selection was a priority. The locations of all flow gauges in the target zone (Department of Water Affairs and Forestry, 1990) were plotted on 1:250 000 topographic maps and digitised on GIS (Figure 4.1.1).

The best gauges were selected by a process of elimination. Factors taken into account include :

- considering only those gauges with continuous recorders, currently active and with longer than 10 years record length (Department of Water Affairs and Forestry, 1990)
- subjectively selecting those gauges that have few missing data using the DWAF listings of primary data
- disregarding all records representing monthly inflows to reservoirs
- rejecting highly developed catchments with extensive irrigation, urban and industrial water use
- subjectively ensuring that the final selection of catchments is representative of the "geographic variations" within the target zone.

The "geographical variations" considered to be important to this study include afforestation, relative levels of development and three geographically homogeneous regions shown in Figure 2.1.2, viz :



SCALE

10 0 60km

LEGEND

CATCHMENT BOUNDARY

RIVERS

DRAINAGE BASIN

TARGET ZONE

FLOW GAUGES

WATER RESEARCH COMMISSION

NINHAM SHAND inc.

THE LOCATION OF ALL FLOW GAUGES IN THE TARGET AREA

Figure 4.1.1

(i) steepsided escarpment/deep valley type catchments in the Crocodile River Basins to the NE of the target zone draining in a NE direction

(ii) rolling hill escarpment/valley type catchments in the Usutu River Basin draining in a SE direction

(iii) gently, undulating, highveld catchments in the Vaal and Olifants river basins draining in a SE and NE direction, respectively.

Of the original 68 gauges that were considered, only thirteen fulfilled the above-mentioned criteria. The selected gauges and their catchment areas are shown in Figure 2.1.2. Characteristics of the selected gauges are listed in Table 4.1.1.

Table 4.1.1 : Characteristics of Selected Flow Gauges

GAUGE NUMBER	RIVER	LATITUDE (S)	LONGITUDE (E)	DATE OPEN	DATE CLOSED	CATCHMENT AREA (km²)
B1H002	Spookspruit	25° 49' 06"	29° 20' 16"	1964-11-15	Open	252
C1H006	Blesbokspruit	26° 46' 32"	29° 32' 22"	1964-12-11	Open	1 094
X1H016	Buffelspruit	25° 56' 50"	30° 34' 07"	1970-08-21	Open	581
X1H019	Gladdespruit	25° 50' 15"	30° 40' 27"	1973-09-07	Open	186
X1H020	Poponyane River	25° 50' 21"	30° 41' 08"	1973-09-14	Open	48
X1H021	Mtsoli River	26° 00' 30"	31° 04' 45"	1975-10-08	Open	295
X2H008	Queens River	25° 47' 08"	30° 55' 27"	1964-07-26	Open	180
X2H030	Suidkaap River	25° 42' 57"	30° 47' 16"	1966-07-05	Open	57
X2H031	Suidkaap River	25° 43' 45"	30° 58' 44"	1966-06-24	Open	262
W5H004	Ngwempisi River	26° 45' 00"	30° 28' 00"	1968-03-12	Open	460
W5H008	Bonniebrook	26° 28' 58"	30° 38' 05"	1968-03-05	Open	701
W5H024	Mpuluzi River	26° 23' 11"	30° 50' 44"	1976-09-29	Open	1 446
W5H025	Usutu River	26° 30' 45"	30° 47' 11"	1974-10-23	Open	789

4.2 COLLECTION OF DATA AND INPUT INFORMATION

Once the catchment selection process was complete the collection of all relevant data in these areas took place. Data requirements can be defined in four broad categories, namely hydrological, climatic, land use and soil type. Data collection is now summarised for each of these categories.

4.2.1 Hydrological Data

The required hydrological data consist of :

(i) Listings of primary flow data availability and of monthly flow data reliability

(ii) Daily flow data

(iii) Catchment boundaries.

(i) Printouts listing the gaps in the primary data were requested by personal communication with the Department of Water Affairs (DWAF) for all gauges located in the target zone. These data were used in the catchment selection process discussed in section 4.1. In addition, printouts of the monthly flow data for the 13 selected gauges were requested. These summaries included flags of unreliable monthly data which were used in the patching process (discussed in section 4.4).

(ii) Daily flow data for the selected 13 catchments and any upstream catchments or canal abstractions were made available by the DWAF in digital format. These data were converted from DWAF format (m^3/s) to *ACRU* single format (in mm) using software made available via personal communication with the CCWR.

(iii) A GIS coverage of quaternary catchment boundaries was obtained from the DWAF. The coverage was used to check the catchment boundaries digitised by NSI from 1 : 50 000 topographic maps.

4.2.2 Climatic Data

(i) Rainfall data

Rainfall data were obtained from Seed (1992) via personal communication. Sub-catchment boundaries captured on the GIS were exported (to geographic co-ordinates) and processed using software developed by Seed (1992). This process involved intersecting the sub-catchment boundaries with the gridded daily rain surface and estimating the average sub-catchment rainfall. These data were then converted to a single format file for use in the *ACRU* model (same format as the flow file).

(ii) Evaporation data

Evaporation data were obtained from the Department of Agricultural Engineering at the University of Natal. The Department made available a minute by minute grid of mean monthly A-Pan equivalent reference potential evaporation. These data were reformatted and imported to GIS. These data were intersected with the sub-catchment boundaries to produce mean monthly A-Pan values for each sub-catchment. In addition, the maximum and minimum mean monthly temperatures of weather stations located throughout the target area were obtained from the CCWR.

4.2.3 Land use data

Various types of land use data are needed in *ACRU*. These include :

(i) Forestry (includes forest type), agricultural (includes crop type) and natural vegetation (veld type) areas
(ii) Irrigation (includes type of irrigated crop) areas
(iii) Farm dams (functions describing area and capacity).

Since land use data varies over time, data had to be collected at time intervals defining a modelling period from 1961 - 1989 (discussed in section 3.4). Various sources of data were identified and where possible captured on a GIS. This enabled comparisons to be performed using a method of "overlays".

In addition, non-spatial data obtained from consultants were also used either to fill in data gaps or verify the GIS data. Information received from each organisation considered relevant to this project is now outlined.

(i) DWAF
DWAF provided a GIS coverage of forestry based on remote sensing work using 1983/4 Landsat images. These data are presented in Figure 4.2.1.

(ii) Hydrological Research Institute (HRI)
The HRI made available land use maps identifying forestry and agriculture in sections of the Upper Vaal and Komati/Crocodile Basins and based on a 1972

Landsat image. The data from these maps were digitised onto a GIS and are presented in Figure 4.2.2. Note the position of the catchments with respect to land use data.

(iii) FORESTEK

CSIR - Forestek provided a rasterised GIS land use coverage identifying forestry, agriculture (irrigated and non-irrigated) and farm dams based on a 1991 Landsat image. This was converted to polygen format by DWAF. Data are presented in Figure 4.2.3.

(iv) Directorate of Surveys and Mapping

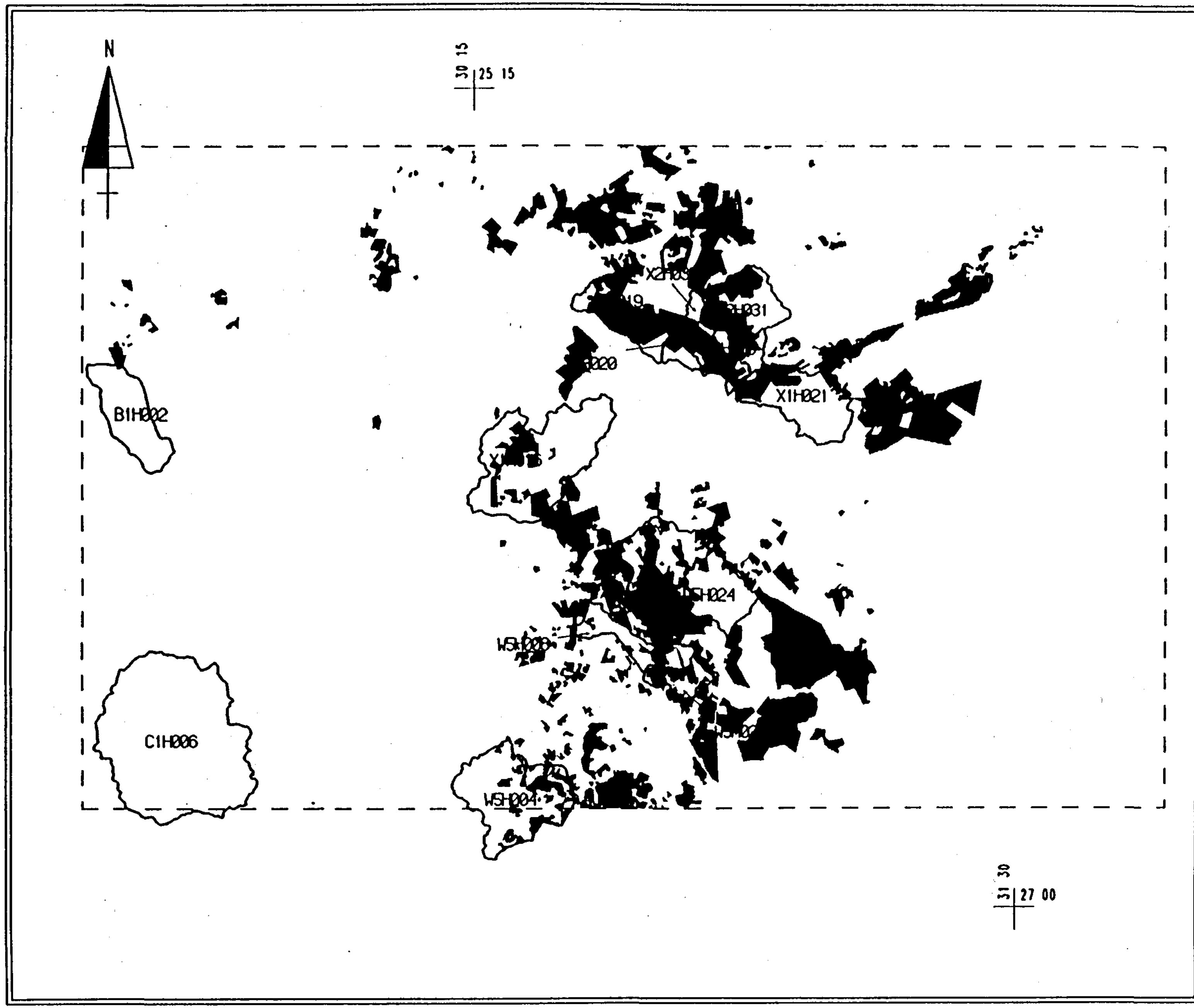
This institution was the source of land use information such as forestry, agriculture and farm dams which NSI digitised from the available topographic maps and aerial photography onto a GIS. In some instances irrigation areas were determined using these data by assuming agricultural land located near farm dams to be irrigated. Map editions vary in date from 1984 to 1988 which is considered a good reflection of current day conditions. Aerial photography was ordered for selected catchments at various time intervals. The data captured are presented in Figures 4.2.4, 4.2.5 and 4.2.6.

(v) Ninham Shand Inc.

Forestry, agriculture and farm dams were digitised onto a GIS from maps based on a field survey. This survey was conducted using a video camera fixed to an aircraft supplied by Cloudquest in March 1992. Only selected catchments considered to be important and lacking recent aerial photography were surveyed. Data captured from the video were mapped on topographic maps and digitised onto a GIS to produce "current day" land use information. These data are presented in Figure 4.2.6.

(vi) Consultants' Reports

Water resource studies have been undertaken by Bruinette, Kruger and Stofberg (BKS, 1988) in the Vaal River Basin; Theron, Prinsloo, Grimsehl and Pullen (TPGP, 1991) in the Olifants River Basin; and Chunnet Fourie and Partners (1991) in the Komati River Basin. These studies were undertaken for the DWAF and are referenced respectively as DWAF, PC000/00/7288; DWAF, PB000/00/0691 and DWAF, PX220/00/0185. Relevant land use data was abstracted from these reports.



SCALE

10 0 60km

LEGEND

CATCHMENT BOUNDARY

FORESTRY

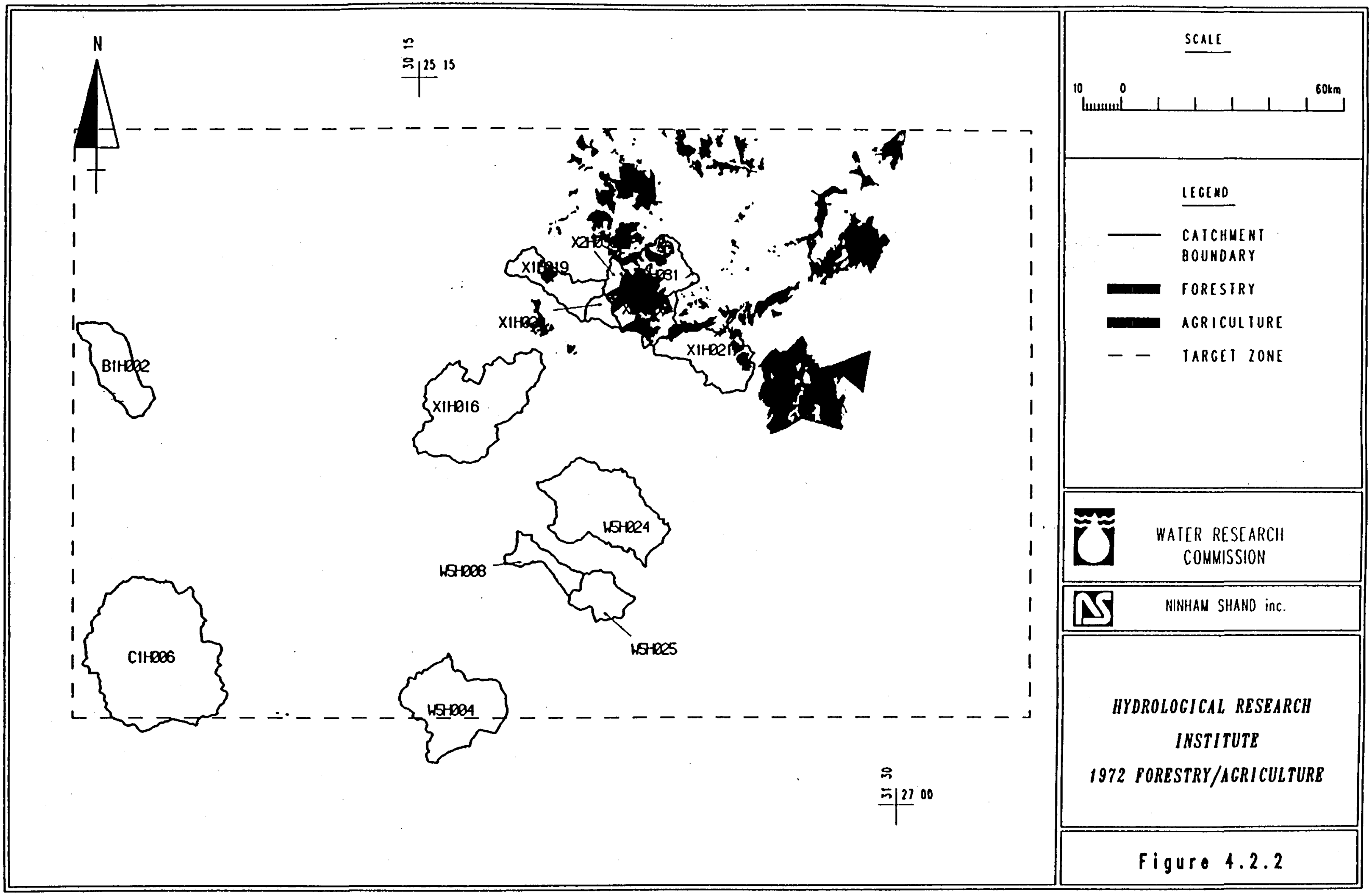
TARGET ZONE

WATER RESEARCH COMMISSION

NINHAM SHAND inc.

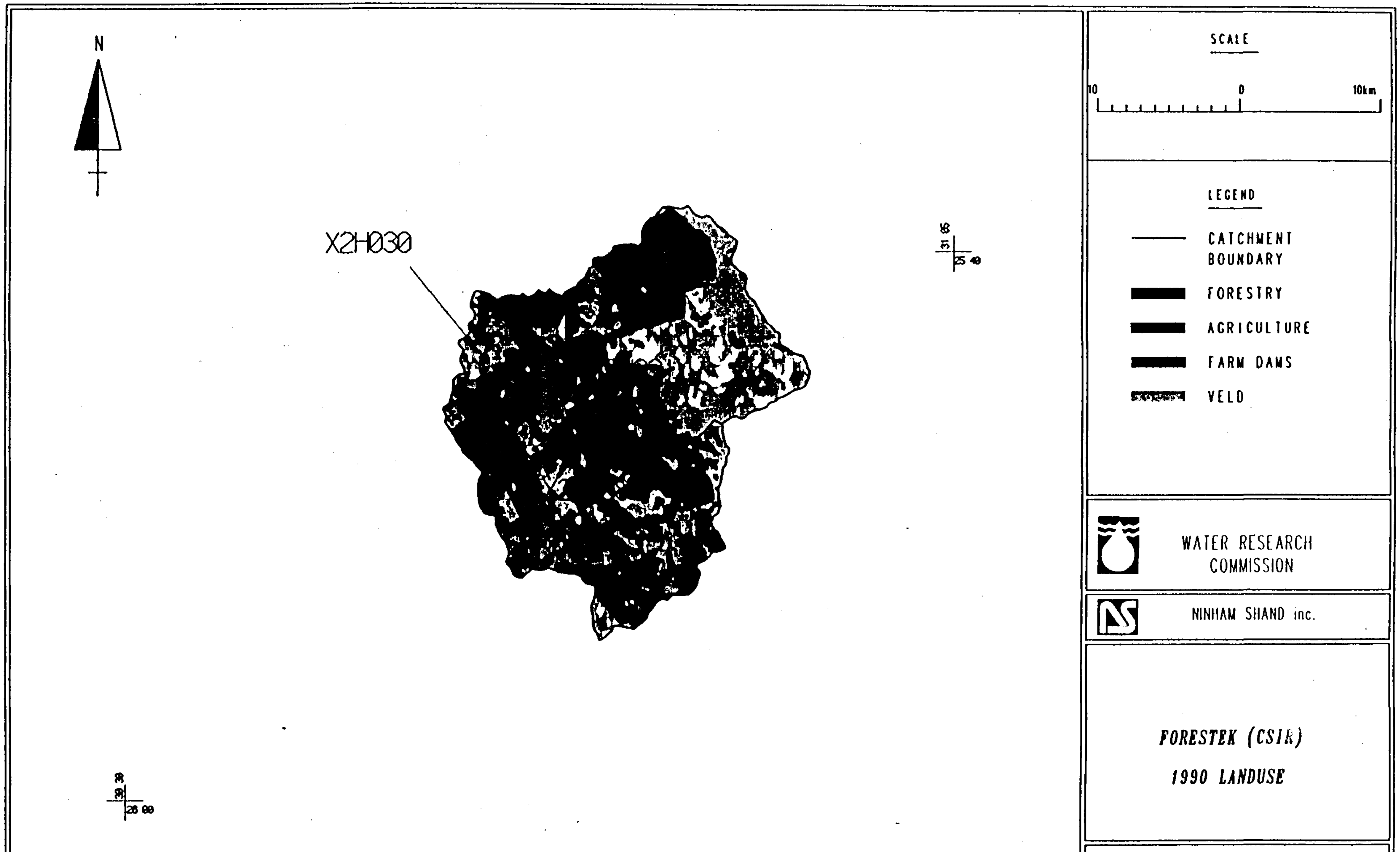
DEPARTMENT OF WATER AFFAIRS & FORESTRY 1989 FORESTRY

Figure 4.2.1



HYDROLOGICAL RESEARCH INSTITUTE
1972 FORESTRY/AGRICULTURE

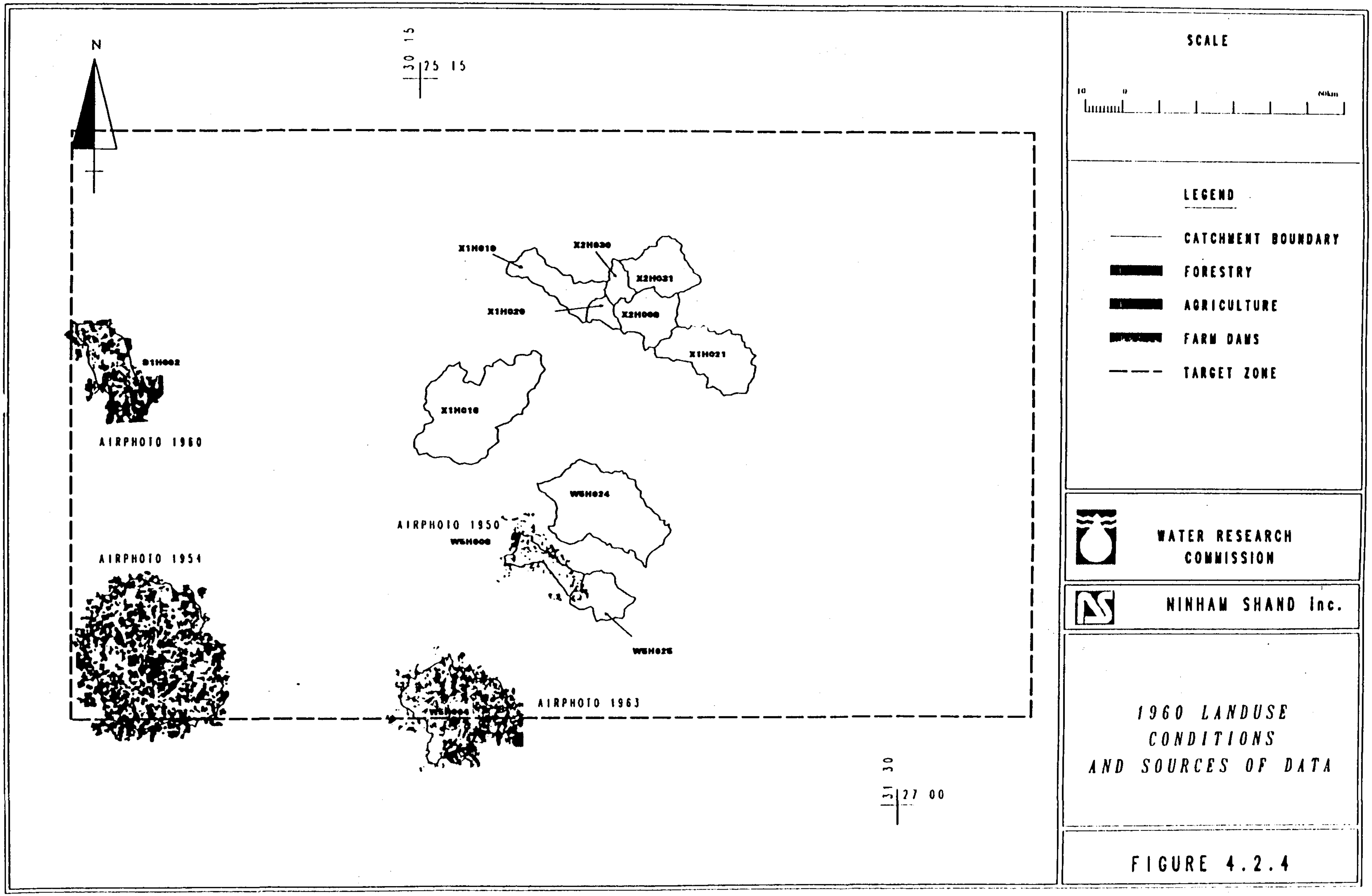
Figure 4.2.2



FORESTEK (CSIR)

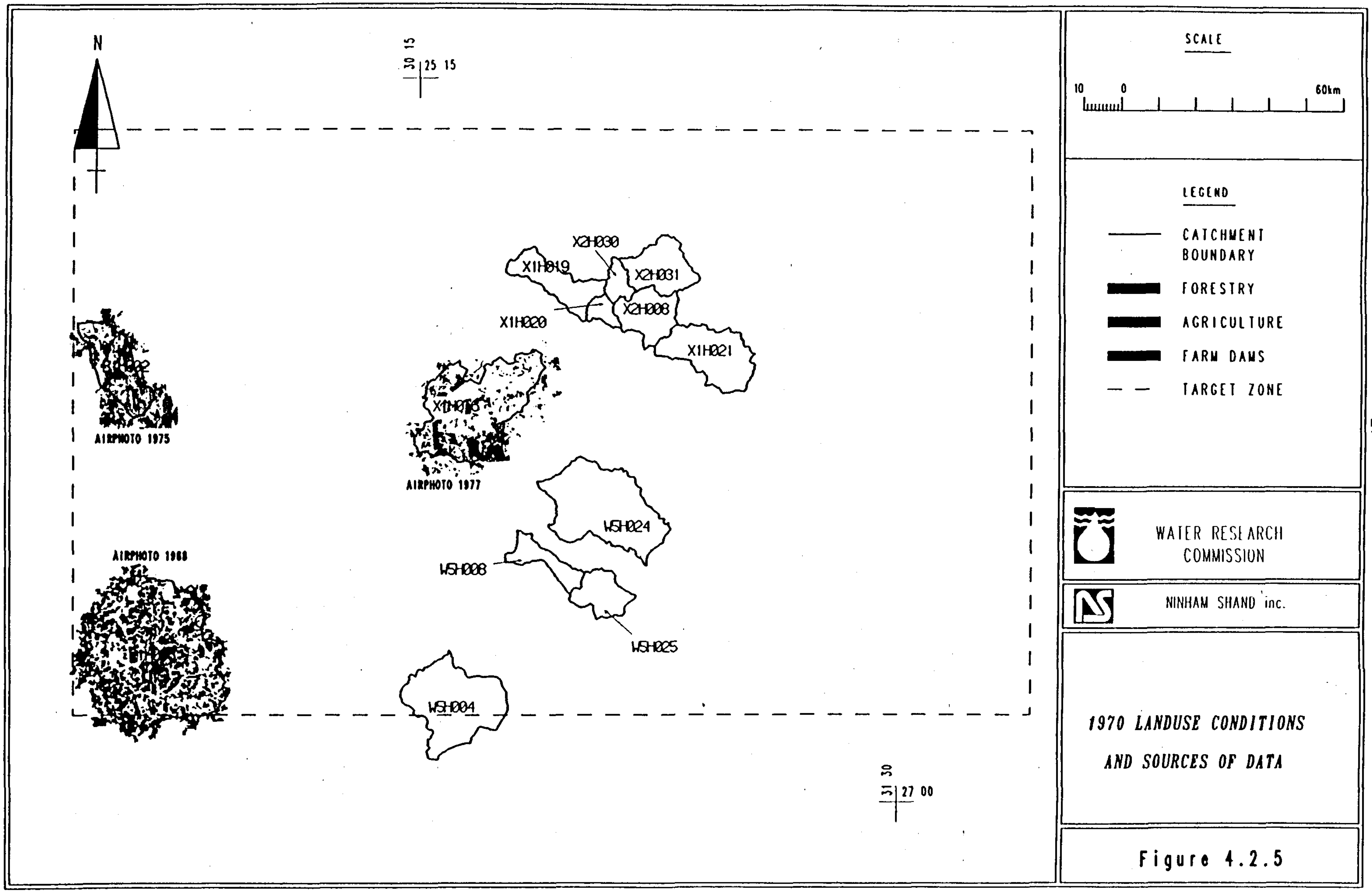
1990 LANDUSE

Figure 4.2.3



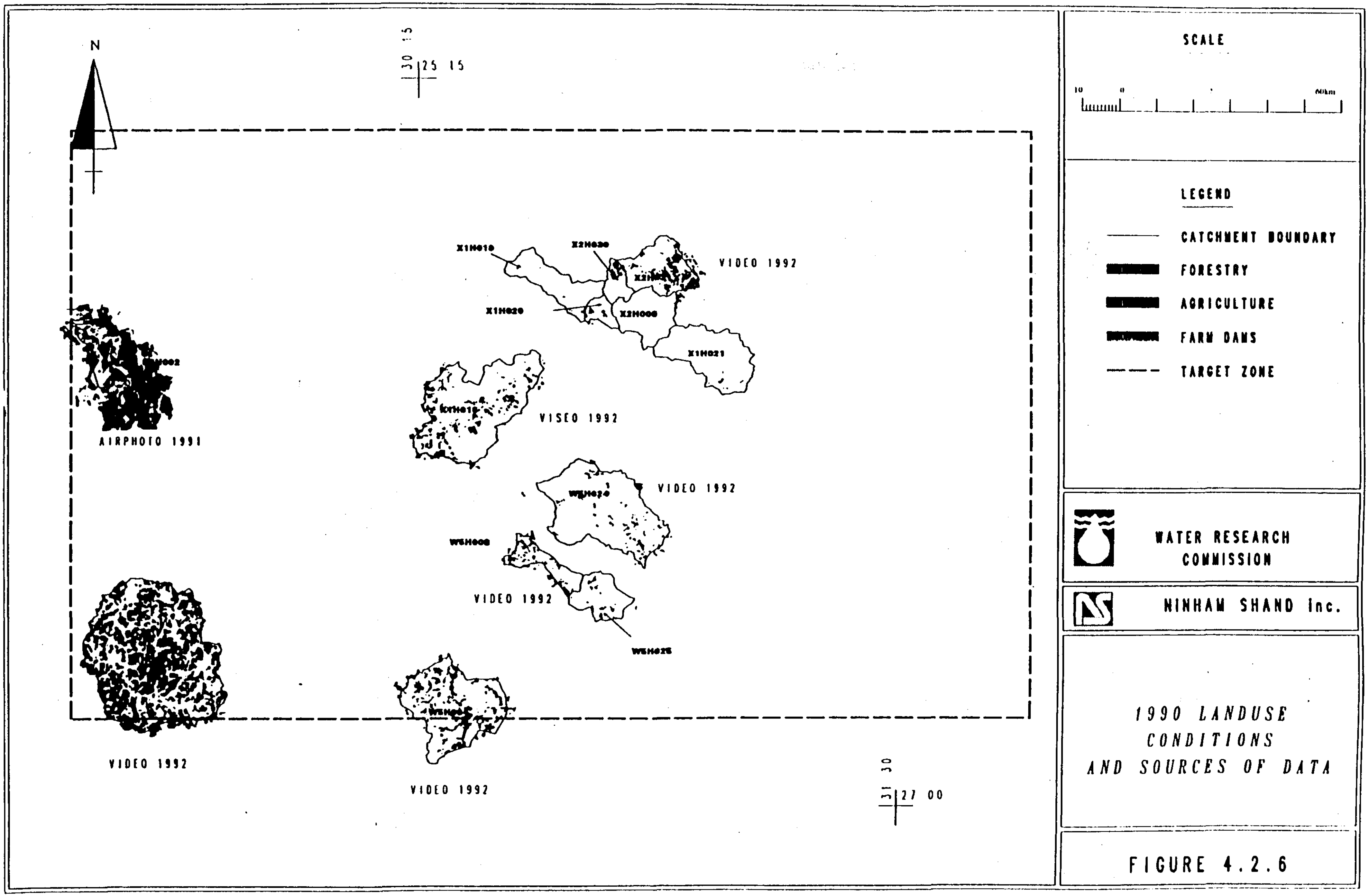
1960 LANDUSE CONDITIONS AND SOURCES OF DATA

FIGURE 4.2.4



1970 LANDUSE CONDITIONS AND SOURCES OF DATA

Figure 4.2.5



1990 LANDUSE CONDITIONS AND SOURCES OF DATA

FIGURE 4.2.6

These data were generally used to estimate historical land use areas/dam capacities and irrigation areas. Data used are presented in the verification appendices of each catchment.

4.2.4 Soils

The *ACRU* model makes use of the land-type maps and manuals published by the erstwhile Soils and Irrigation Research Institute (SIRI, 1989) to estimate soil variables. These land-type maps were obtained and digitised onto a GIS. These data are presented in Figure 4.2.7.

4.2.5 Other Data Requirements

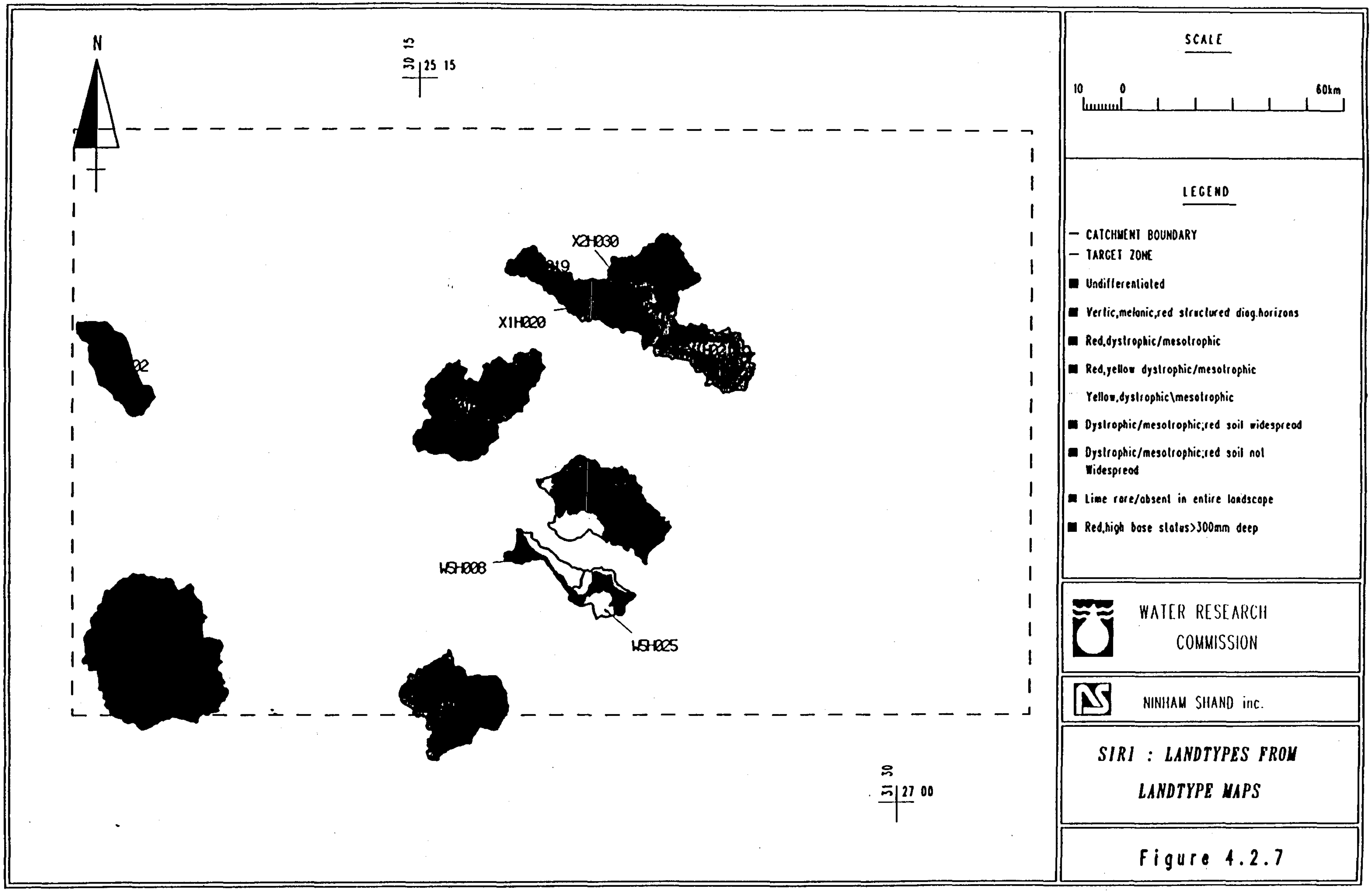
Many other variables need to be estimated for the *ACRU* model. These were obtained from the *ACRU* User Manual (Schulze *et al.*, 1989) and by personal communication with Prof Schulze.

4.3 DATA MANIPULATION AND MODEL CONFIGURATION

4.3.1 Sub-catchment division

A major requirement of the *ACRU* model is to subdivide any complex catchment into sub-catchment which can be considered homogeneous with regards to land use, soil type and catchments draining into farm dams. This task took place taking into account the data captured on a GIS using an overlay system. Ideally the subdivision should take place using land use data of the same "time slice". In reality, however, data inadequacies often resulted in land use and soils data from different "time slices" being used to determine the sub-catchment configuration.

For example, the subdivision of catchment X2H031 presented in Figure 4.3.1 shows the data used for this subdivision. Note how the sub-catchment boundary choice only takes into account a single boundary should two homogeneous divisions be located in close proximity.



SIRI : LANDTYPES FROM LANDTYPE MAPS

Figure 4.2.7

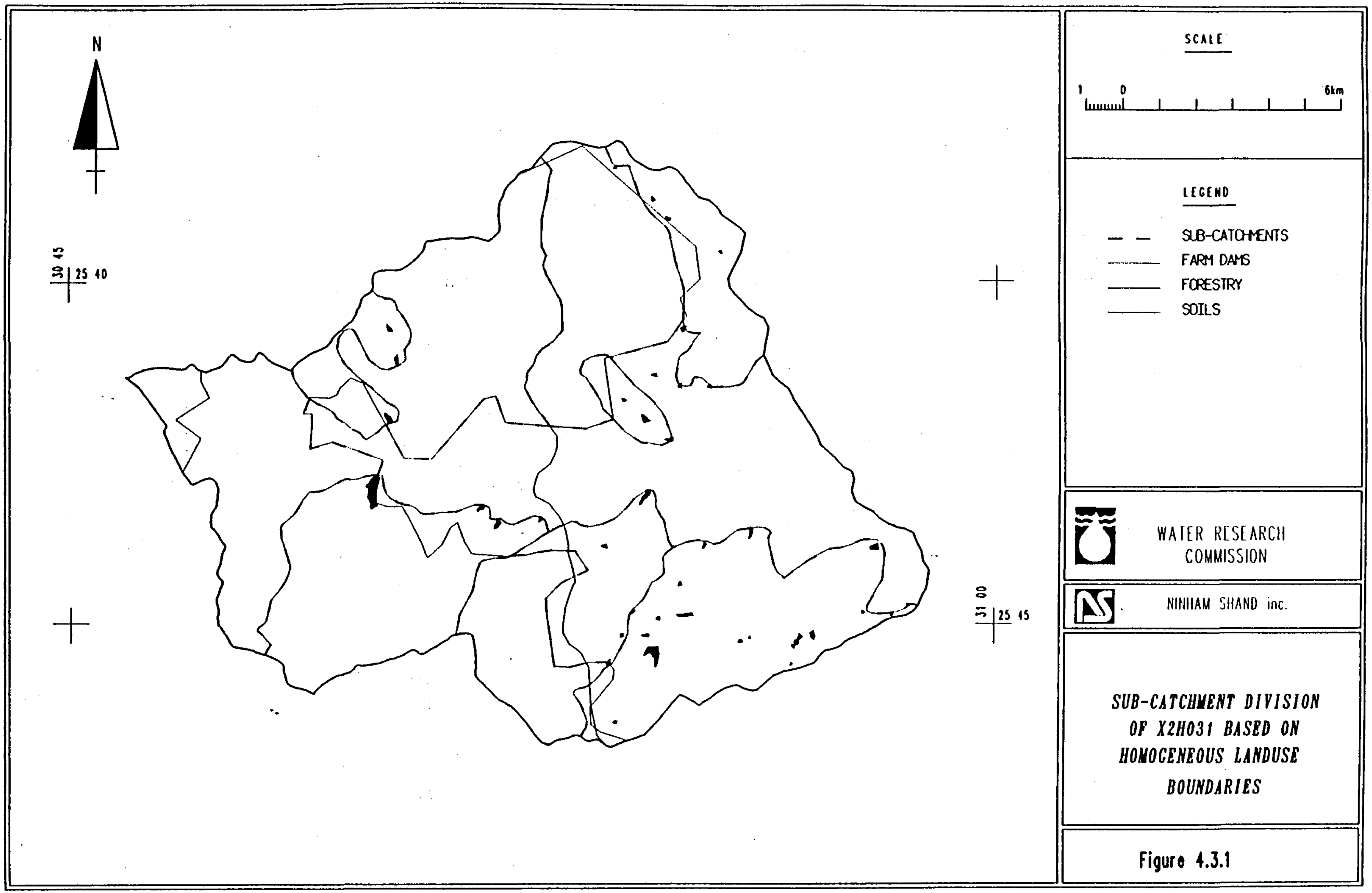
4.3.2 Data Manipulation

Once the sub-catchment division was complete the process of summarising data on a sub-catchment basis could start. All statistical, land use and soils data captured on the GIS could simply be intersected with the sub-catchment configuration to produce values per sub-catchment. Numeric data collected from consultants had to be proportioned on a sub-catchment basis using related GIS data. Using Table 4.3.1 as an example, a catchment irrigation area of 320 ha in catchment X1H016 obtained from a consultant report was proportioned on a sub-catchment basis using the sub-catchment agricultural area obtained from GIS.

In addition, historical land use conditions had to be interpolated to enable the *ACRU* model to account for land use changes. Since the *ACRU* model maintains constant conditions between specified "time slice" values, a period of 5-7 years was considered convenient to reflect changing conditions over time. Table 4.3.2 indicates the way in which sub-catchment hypothetical farm dams areas obtained from the GIS in 1977 and 1990 were interpolated to estimate a 1982 farm dam area and extrapolated to estimate 1972 values.

Numerical data obtained from consultants are often applicable to an entire catchment and at a single historical "time slice". These data have to be proportioned on a sub-catchment basis as in Table 4.3.1, and for various "time slices", as in Table 4.3.2. Table 4.3.3 indicates how Table 4.3.1 and 4.3.2 are used to proportion a catchment irrigation area on a sub-catchment basis using agriculture data and then estimate various "time slices" using farm dams data.

The appendices of each catchment list all the land use (forestry, agriculture, veld), farm dam and soils data on a sub-catchment basis. The land use data were then used in conjunction with software developed by the Department of Agriculture and Engineering, University of Natal (personal communication) to estimate the land use variables used by the *ACRU* model. Similarly, software to average the soils data was also used. The final land use variables are listed in the appendices of each catchment.



SUB-CATCHMENT DIVISION OF X2H031 BASED ON HOMOGENEOUS LANDUSE BOUNDARIES

Figure 4.3.1

Table 4.3.1 : Proportioning a Total Catchment Irrigation Area on a Sub-Catchment Basis using Sub-Catchment Agricultural Areas

SUB-CATCH. NO.	SUB-CATCHMENT. AGRICULTURE AREA (ha) (1992)	RATIO (SUBC/CAT)	CATCHMENT IRRIGATION AREA (ha)	SUB-CATCHMENT. IRRIGATION AREA (ha) (1982)
1	2.101	0.059		19
2	1.476	0.042		13
3	4.499	0.127		41
4	1.461	0.041		13
5	0.418	0.012		4
6	0.007	0.000		0
7	0.026	0.001		0
8	12.075	0.341		109
9a	0.145	0.004		1
9b	0.263	0.007		2
10	0.144	0.004		1
11	12.829	0.362		116
TOTAL	35.447	1.000	320	320

Table 4.3.2 : Estimation of Catchment and Sub-Catchment Farm Dams Areas (ha)

SUB-CATCHMENT NO.	EXTRAPOLATION 1972	AIRPHOTO IN 1977 1977	INTERPOLATION 1982	VIDEO OF 1992 1990
1	0.0	0.0	3.3	8.5
2	0.0	0.0	0.0	0.1
3	0.0	0.0	1.1	2.9
4	7.6	7.6	7.5	7.3
5	0.5	0.7	0.9	1.2
6	0.7	0.7	0.5	0.2
7	0.0	0.0	0.3	0.9
8	5.0	5.2	5.4	5.7
9	0.0	0.0	1.8	4.6
10	2.2	3.1	4.0	5.5
11	3.6	5.5	7.4	10.5
TOTALS	19.6	22.8	32.3	47.4

FDAM factor	0.607	0.707	1.000	1.469

Table 4.3.3 : Estimation of Sub-catchment Irrigation Areas (ha) for different "Time Slices" using Results from Tables 4.3.1 and 4.3.2.

FDAM factor	0.607	0.707	1.000	1.469
SUB-CATCHMENT	1972	1977	1982	1990
NO.	'82*factor	'82*factor		'82*factor
1	12	13	19	28
2	8	9	13	19
3	25	29	41	60
4	8	9	13	19
5	2	3	4	6
6	0	0	0	0
7	0	0	0	0
8	66	77	109	160
9	2	2	3	4
10	1	1	1	1
11	70	82	116	170

4.3.3 Model Configuration

Configuration of the *ACRU* model comprises two tasks. Firstly, the main menu is configured by way of user friendly software which ensures the input is in the correct format. All the starting conditions of the variables used in the *ACRU* model are defined in this menu. The second task involves configuring the dynamic files which define variables that change with time. This is achieved manually using an existing file as a template. In addition to available software, in-house software was developed to simplify the configuration procedure. This software enabled the following tasks to be performed :

(i) Automate the process of configurating dynamic files with land use variables.

(ii) Reformat daily rainfall files produced by the Seed (1992) software to *ACRU* single format

(iii) Add and subtract daily flow files where necessary.

On completion of this configuration phase, all files were transferred electronically to the CCWR where the modelling was undertaken. The remote use of the *ACRU* model in the NSI offices was made possible using a X25 pad.

4.4 MODEL VERIFICATION

Model verification took place in stages. Firstly, the model was run using the data sources discussed in section 4.2. A second verification stage involved using alternative data sources for model variable choices, but only if these data would improve the verification. The third and final stage of verification involved selecting the variables to which the *ACRU* model output is most sensitive, and subjectively changing the values until the best verification result was achieved. These changes are still considered to reflect probable catchment conditions and the justification for their use is discussed in detail.

Verification was based on the following considerations. Firstly, the *ACRU* monthly statistics (i.e. monthly summation totals of daily values) of the simulated and observed flows were compared. This was followed by water balance checks in the daily printout. The monthly printout was checked to ensure the output from each sub-catchment made sense. Because the *ACRU* model did not have user-friendly graphics utilities that could be used remotely, the simulated and observed monthly flows were reformatted and used in conjunction with software developed by NSI to check the 1:1 monthly time series fit and seasonal distribution. Finally, annual observed and simulated flows were plotted to check the model performance during wet seasons.

Mention must be made of the difference between the *ACRU* monthly statistics and the 1:1 time series and seasonal distribution fit. The *ACRU* monthly statistics exclude any "flagged" observed and corresponding simulated data from the analysis. (Flagged data represent incomplete monthly totals.) The time series and seasonal distribution data however include all data. Any flagged observed data were patched by standard procedures.

If an unacceptable verification was obtained, a second verification was attempted by substituting selected data from the sources discussed in section 4.2 with data of a more general nature obtained from the *ACRU* manual (Schulze *et al.*, 1989). These data included suggested interception variables for the Eastern Transvaal and a range of values for soil variables.

A discussion of the verification process, including changing variables to obtain the best verification result, is presented in the sections of Chapter 5 that discuss each catchment, with all variable changes being summarised in Table 5.14.1.

4.5 EFFECTS OF RAINFALL STIMULATION ON WATER RESOURCES AND TIMBER YIELD

The procedure to determine the effects of rainfall stimulation on water resources and timber yield comprised mainly three tasks. The first task involved configuring the *ACRU* model to generate 30 years of flow data with all time related influences kept constant at present-day conditions throughout this period. Secondly, software development was needed to estimate the water resources and forestry yield from the stochastic and modified sequences. Further software was needed for the final task of assessing the difference in stochastic versus modified yield. These tasks are now discussed in more detail.

4.5.1 Model configuration using present day land use development

The concept of using present day development conditions has been discussed in section 3.4. As discussed in section 4.3.3 all time constant variables and initial conditions are defined in the main *ACRU* menu. Any changes in these (land use related) variables are defined using dynamic flies. The procedure of re-configuring the *ACRU* model to simulate present day conditions over the full 30 year period simply requires overwriting those variable values in the verified menu with the present day values in the dynamic file.

4.5.2 Configuration changes for the timber yield model

Several modifications to the menu and dynamic files are necessary to use the timber yield subroutine developed by Leenhardt (1993). Dynamic files must be used to describe the water use of the forest over time. Software has been developed to estimate these variables. The timber yield subroutine assumes a sub-catchment with 100% forest. However, the existing sub-catchment configuration is such that in many instances the area of forestry only covers a proportion of the sub-catchment. This problem was overcome by setting the sub-catchment area equal to the current day forest area. For a sub-catchment with zero forestry, the forestry was set equal to 0,01 km^2 so as not to alter the sub-catchment configuration, which would have been a mammoth task. In addition, the timber yield subroutine uses mean monthly minimum and maximum temperatures to estimate potential evaporation using the 1984 Linacre equation (Schulze *et al.*, 1989). The consequence of these changes was that the water resources analysis and timber yield analysis had to be separated.

4.5.3 Comparison of stochastic versus modified rainfall on water resources and forestry yield

This task involved the development of software to perform the series of operations presented schematically in Figure 4.5.1. Firstly, a stochastic rainfall sequence is generated for each sub-catchment using the sub-catchment historical rainfall and a stochastic model provided by Seed (1992). This stochastic rainfall scenario was then used with the verified *ACRU* model (configured with present day land use development) to produce a "stochastic" simulated flow. The simulated monthly flow is reformatted as the input to a modified reservoir simulation program (RESSIM, Pitman *et al.*, 1982) that estimates the firm (no-failure) yield and yield for an acceptable number of failures for a hypothetical dam with a capacity equal to the historical MAR. These yields are then written to a file. A modified rainfall sequence is then generated for each sub-catchment by superimposing the seeding effect developed by Seed (1992) on the stochastic rainfall sequence. This modified rainfall scenario is then processed in the same manner as the stochastic sequence to produce a "new" reservoir yield. This procedure is repeated a selected number of times and eventually standardised on an optimum number of 100. A similar set of operations was set up to determine the timber volume per rotation from both the stochastic and modified rainfall scenarios. Both rainfall scenarios are used with the *ACRU* model to determine the monthly volume which is averaged and written to a file. This procedure is repeated a selected number of times.

4.5.4 Whisker-box Plots

The stochastic nature of the results is best presented by way of exceedence probability graphs. The whisker-box plots[2] were selected as most suitable for both water resources and timber yield. In-house software was developed and includes comparisons of :

i) The mean, standard deviation and coefficient of variation of both the stochastic and modified scenarios

[2] Referred to as whisker-box plots in this report. Also known as box and whisker plots.

ii) The firm yield, 10% failure and 20% failure for both the stochastic and modified scenarios. This is presented as a volume ($m^3 \times 10^6$) and as a % difference.

iii) A direct comparison of volume (m^3/ha) of stochastic and modified timber yields and their % difference.

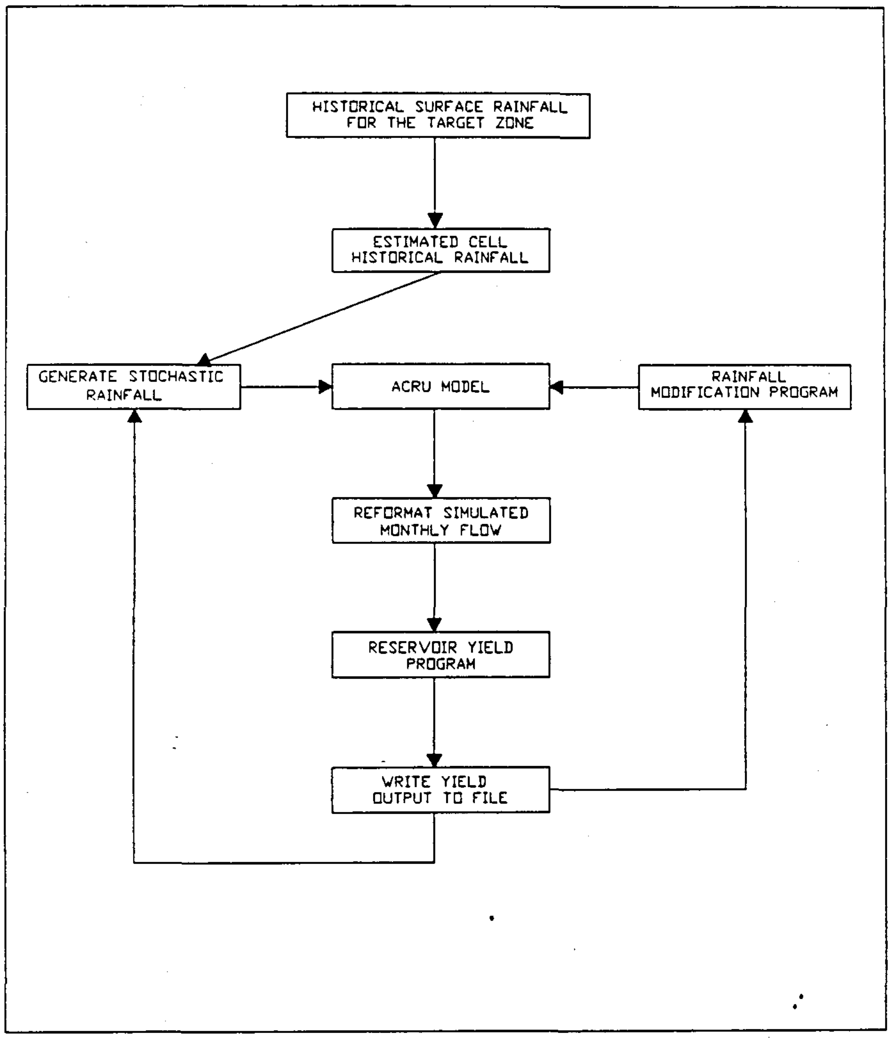


Figure 4.5.1 : Schematic Presentation of Operations to determine Seeding Effects

5. CATCHMENT RESULTS

The data collection, configuration and verification of the *ACRU* model and yield analyses of the 13 selected catchments are now discussed.

5.1 B1H002

5.1.1 Input Information and Preparation

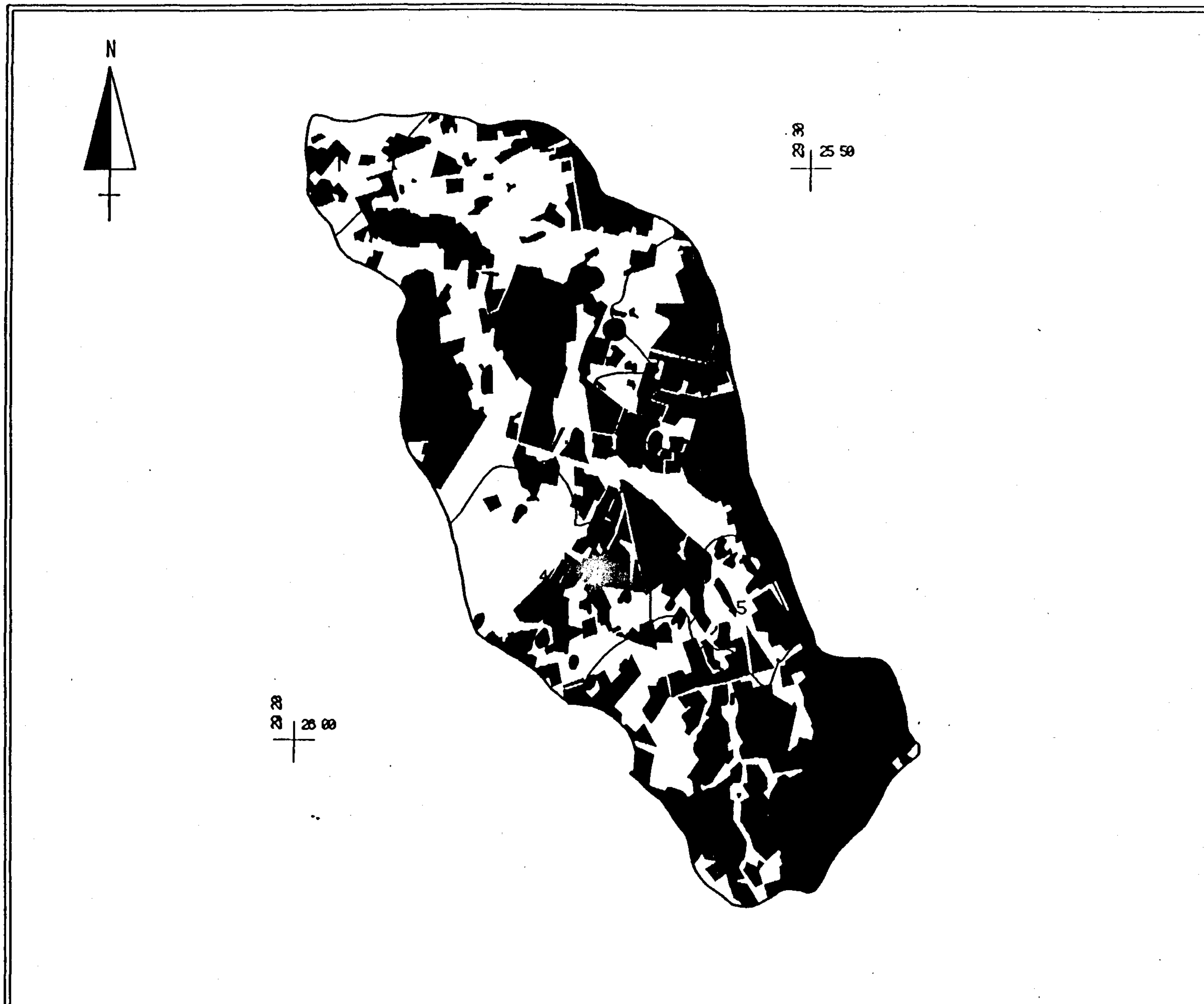
Figure 5.1.1 presents the current day land use in Catchment B1H002. A summary of catchment data is presented in Table 5.1.1.

Table 5.1.1 : Summary of Catchment B1H002 Data

ITEM	VALUE	UNIT
Catchment Area	241,8	km^2
Catchment MAP	700,0	mm
1990 Forest Area	19,8	km^2
1990 Agriculture Area	117,0	km^2
1990 Irrigation Area	104,0	km^2
1990 Dam Capacity	3,68	$m^3 \times 10^6$
Observed MAR	6,2	$m^3 \times 10^6$
Runoff Coefficient	3,6	%
Area per rain gauge	242,0	%

5.1.2 Evaluation of Flow Records

Flow records are available at B1H002 from October 1955 to date. The monthly flow records from October 1961 to September 1989 (the rainfall record period) were checked for unreliable data and patched with simulated flows where necessary.



SCALE

1 0 5km

LEGEND

CATCHMENT BOUNDARY

SUBC BOUNDARY

FORESTRY

AGRICULTURE

FARM DAMS

WATER RESEARCH COMMISSION

NINHAM SHAND inc.

CURRENT DAY LANDUSE IN CATCHMENT B1H002

Figure 5.1.1

5.1.3 Model Output Verification

The initial configuration of the *ACRU* model resulted in an acceptable verification of runoff and no changes to any input variables were made. Figure 5.1.2 and 5.1.3 show a graphical comparison of the simulated versus observed monthly time series and seasonal distribution. Tabie 5.1.2 lists the goodness of fit statistics for monthly totals of daily flows.

The time series shows a mediocre fit with no trend in the monthly residuals, while the seasonal distribution indicates an acceptable fit. The statistics indicate that while an acceptable simulation of the mean is achieved, the correlation of the simulated with the observed flows is very low. The time series highlights this problem. The model both overpredicts and underpredicts, resulting in similar average conditions (mean). A closer investigation of these "problem" months highlights discrepancies with the rainfall/runoff data. Table 5.1.3 shows that in the first two monthly cases, there was serious underprediction of the flow while in the last two cases there was overprediction. Although the monthly rainfall is higher in the last two cases, the preceeding month's rainfall was less, and the simulator is expected to produce similar or slightly lower runoff. A closer investigation reveals that daily rainfall has a significant effect on the model. The first two monthly cases consist of numerous raindays with low rainfall amounts (only one daily rainfall in 4 months greater than 20 mm) while the second two events contain fewer raindays but with larger rainfall amounts (five daily events greater than 20 mm). It is likely therefore that the poor raingauge network recorded the "fringes" of thunderstorm activity in the catchment in the first two monthly cases and then recorded full thunderstorm activity (which only had a partial effect in the catchment) in the last two events.

Apart from these discrepancies that are inherent in the data and therefore unavoidable, the time series and seasonal distribution indicate an acceptable fit. The annual flows in Figure 5.1.4 indicate an acceptable scatter around the 1:1 line with all the wettest years underpredicted. The two others indicate years during which the simulated flow was severely underpredicted as a result of problems with spatial rainfall estimation. The model configuration can therefore be used with confidence for determining yields and in the regionalisation process.

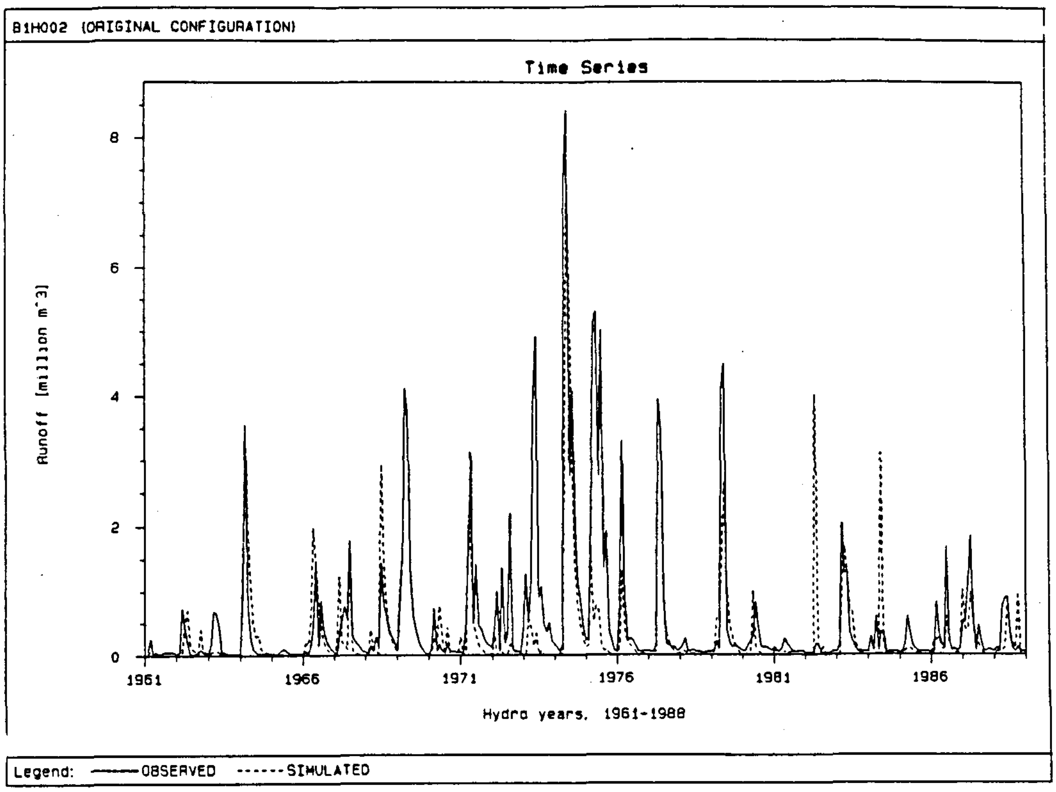


Figure 5.1.2 : Comparison of Observed and Simulated Flows at B1H002 (Original Configuration)

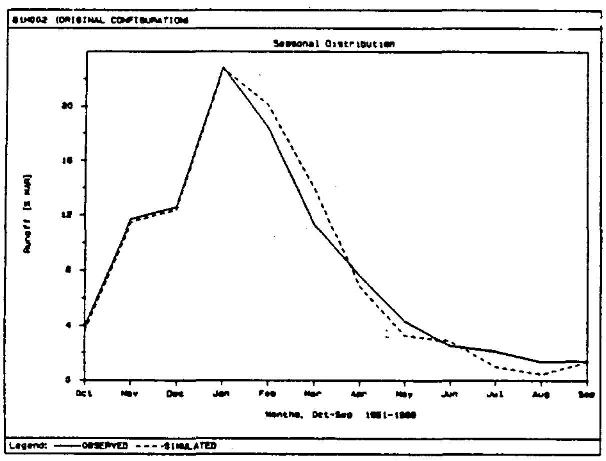


Figure 5.1.3 : Monthly Distribution of Means of Observed and Simulated Flows at B1H002

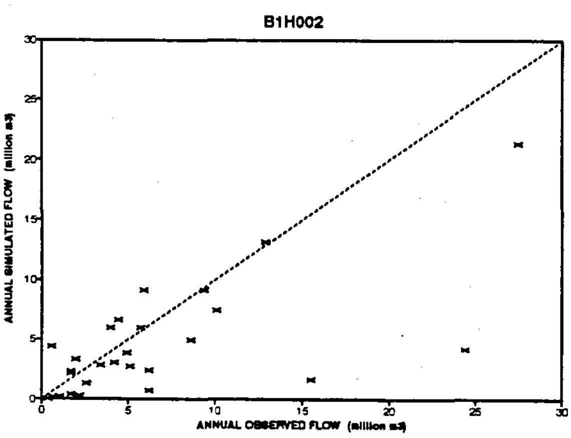


Figure 5.1.4 : Comparison of Annual Totals of Observed and Simulated Flows at B1H002

Table 5.1.2 : A Comparison of Simulated and Observed Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	317,9
Total Simulated Values	288,1
Mean of Observed Values	1,085
Mean of Simulated Values	0,983
Correlation Coefficient	0,631
Regression Coefficient	0,820
Base Constant for Regrn. Eqn.	0,094
Variance of Observed Values	3,5
Variance of Simulated Values	5,8
Standard Deviation of Observed Values	1,9
Standard Deviation of Simulated Values	2,4

Table 5.1.3 : The Monthly Rainfall and Associated Simulated/Observed Runoff Discrepancies in Catchment B1H006

DATE	RAINFALL (mm)	RUNOFF (mm)	
		SIMULATED	OBSERVED
1974 02	(153) 82	1,4	20,3
1976 01	(152) 120	3,2	21,9
1982 01	(44) 152	16,6	0,7
1985 02	(88) 149	12,8	1,5

( ) indicates antecedent monthly rainfall

5.1.4 Water Resources and Timber Yield

Figure 5.1.5 shows the graphical comparison of yields from a hypothetical dam using the "stochastic" based and modified streamflow. Results show that the median MAR increases from 3,4 $m^3 \times 10^6$ to 4,6 $m^3 \times 10^6$ with a similar increase in the range of values. Although there is a slight increase in standard deviation the more significant increase in mean results in a lower coefficient of variation of the modified sequences. Since the modified sequences have less variability, i.e. they are more constant, these sequences result in a higher median yield of approximately 40% for the three failure scenarios.

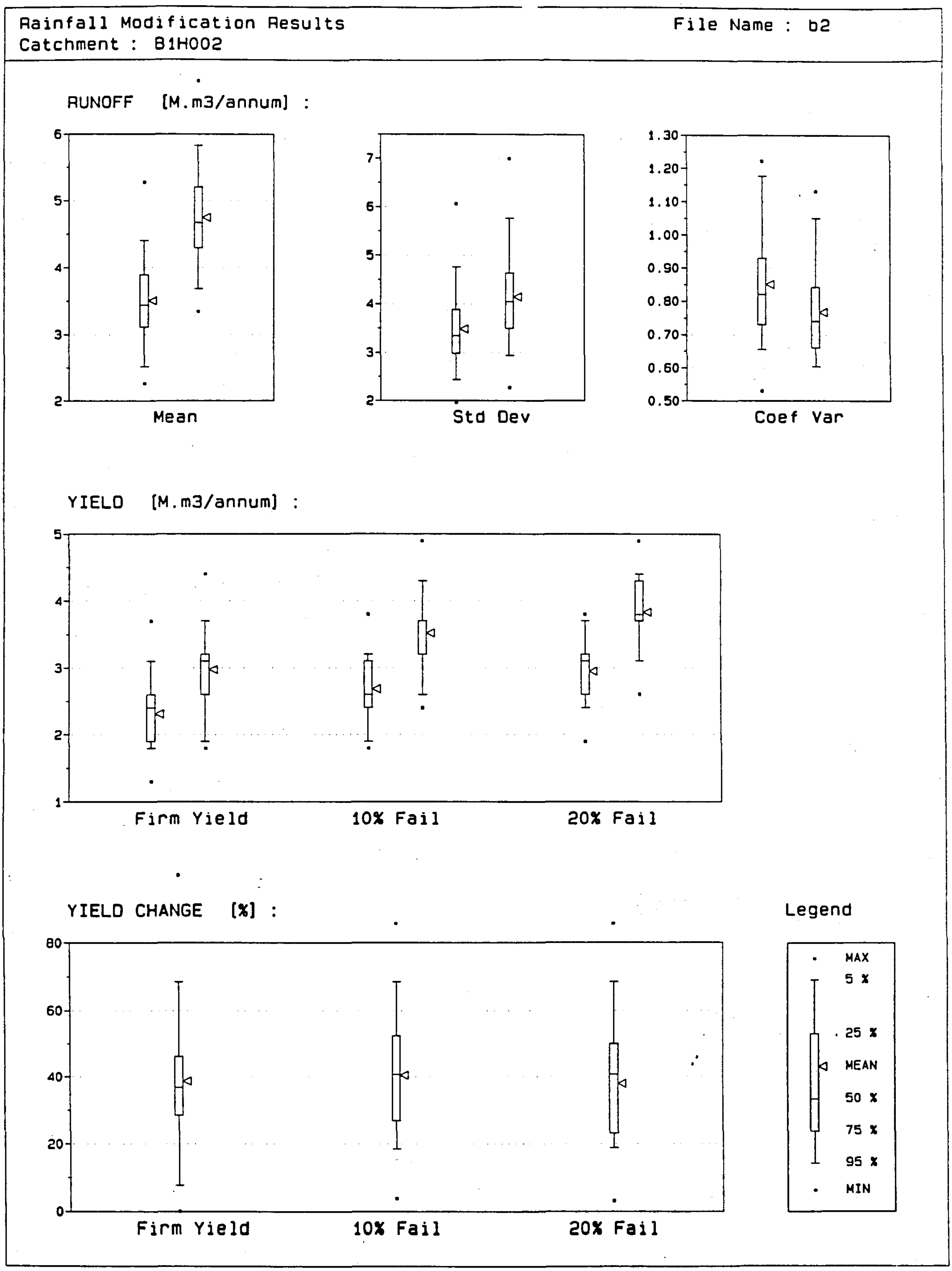


Figure 5.1.5 : Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at B1H002

Figure 5.1.6 shows the timber yield comparisons. Results show an increase in median timber yield from 160 m³/ha/rotation to 190 m³/ha/rotation with a 22% median increase between the two data sets. Also of interest is the small range in values of both the stochastic and modified yields. While the 5 percentile and 95 percentile change in water yield ranges from 10% to 70%, the timber yield only varies from 20% to 24%. This indicates that timber yield is not sensitive to intra-seasonal rainfall changes in the stochastic sequences, i.e. daily variations, but does respond to long-term increases in rainfall associated with modified rainfall.

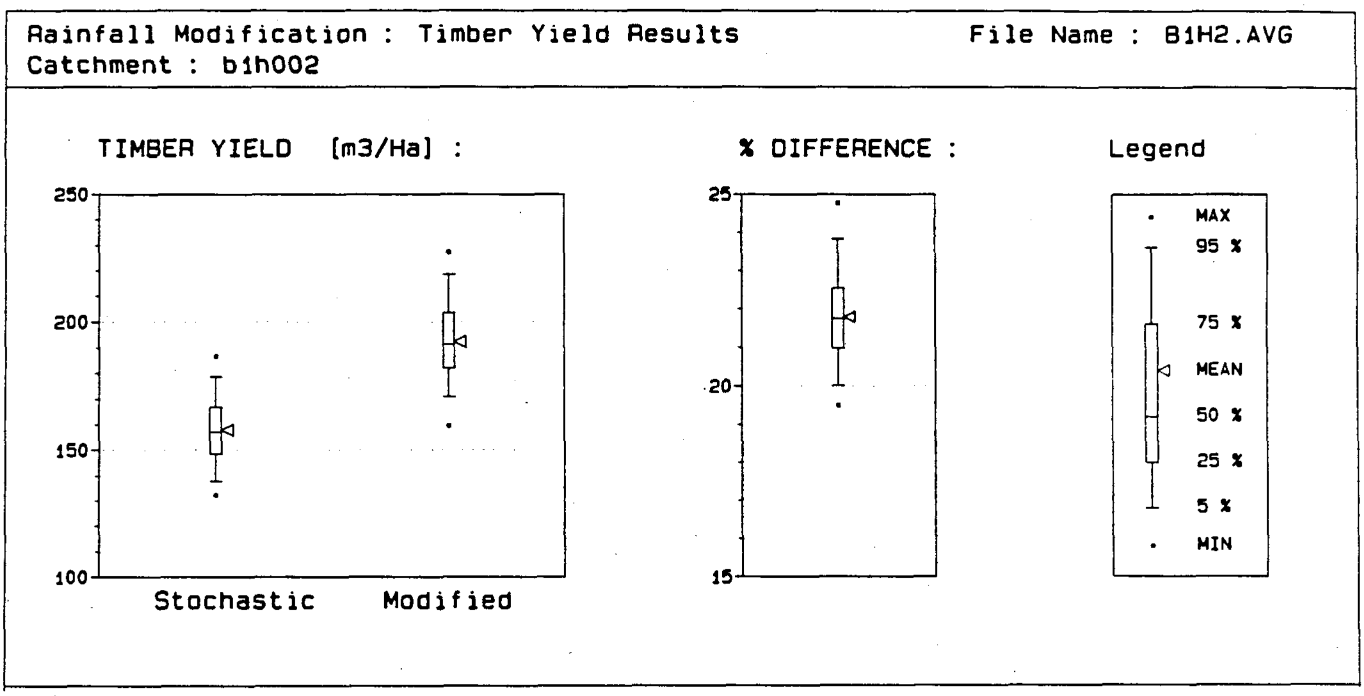


Figure 5.1.6 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at B1H002

5.2 C1H006

5.2.1 Input Information and Preparation

Figure 5.2.1 presents the current day land use in catchment C1H006. Due to the uniformity of data in this catchment the catchment was treated as a single sub-catchment. A summary of catchment data is presented in Table 5.2.1.

Table 5.2.1 : Summary of Catchment C1H006 Data

ITEM	VALUE	UNIT
Catchment Area	1 103,4	km^2
Catchment MAP	700,0	mm
1990 Forest Area	0,0	km^2
1990 Agriculture Area	435,9	km^2
1990 Irrigation Area	49,7	km^2
1990 Dam Capacity	18,8	$m^3 \times 10^6$
Observed MAR	73,5	$m^3 \times 10^6$
Runoff Coefficient	9,5	%
Area per rain gauge	138,0	km^2

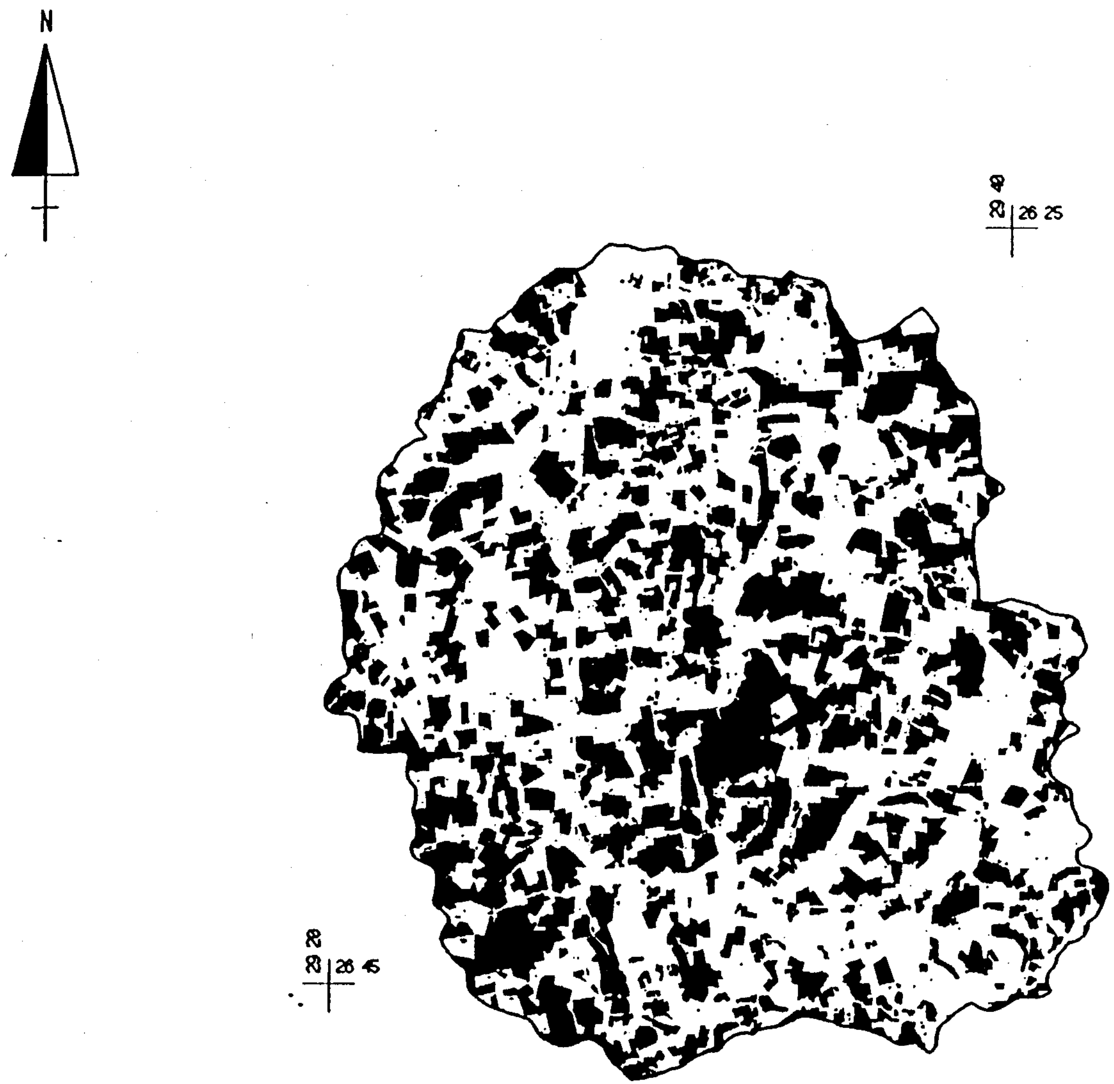
5.2.2 Evaluation of Flow Records

Flow records are available at C1H006 from 1905 to date but contain extensive periods of missing daily data until 1985. The monthly flow record from October 1966 to September 1989 (the rainfall record period) was checked for unreliable data and patched with simulated flows where necessary.

5.2.3 Model Output Verification

The initial configuration of the *ACRU* model resulted in an overestimation of the summer flow especially in the latter part of the verification period from 1979 to 1987 (Figure 5.2.2).

Values for the land use variable "VEGINT" (representing interception loss per rain day) obtained from the *ACRU* Manual (Schulze *et al.*, 1989) were then used instead of data obtained from the GIS. The decrease in this vegetation interception variable improved the fit but did not produce the required result. The 1960 and 1990 variables differ very little and the new estimate was kept constant from 1960 to 1990. The lack of seasonal variability is justified as the large proportion of this catchment is grassland. The grassland interception loss for the Eastern Transvaal is set a constant 1,6 mm/rain day for all months



SCALE

10 0 10km

LEGEND

- CATCHMENT BOUNDARY
- FORESTRY
- AGRICULTURE
- FARM DAMS

WATER RESEARCH COMMISSION

NINHAM SHAND inc.

CURRENT DAY LANDUSE IN CATCHMENT C1H006

Figure 5.2.1

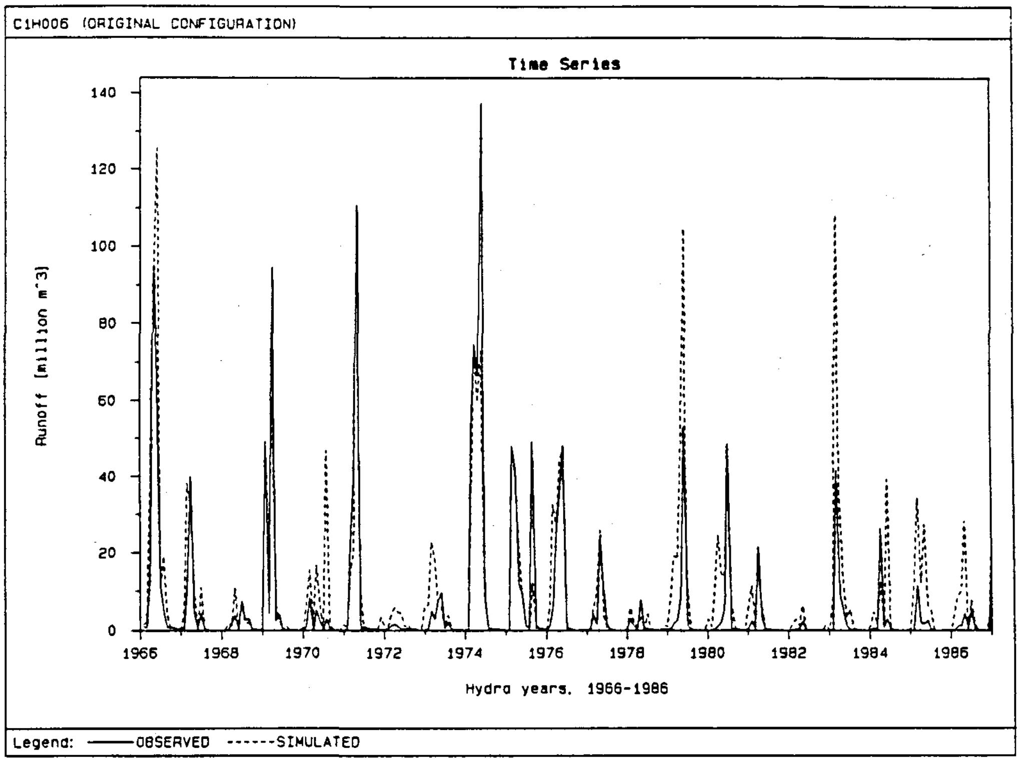


Figure 5.2.2 : Comparison of Observed and Simulated Flows at C1H006 (Original Configuration)

of the year (Schulze *et al.*, 1989). Values from the GIS describing the soil variables which define the depth of the A and B horizon (DEPA and DEPB) were also replaced by values obtained from the *ACRU* Manual (Schulze *et al.*, 1989) and resulted in an acceptable verification.

These changes resulted in an acceptable verification. The *ACRU* monthly statistics in Table 5.2.2 indicate a good simulation of both the mean and variability. The monthly time series and seasonal distribution (Figures 5.2.3 and 5.2.4) identify two problem months (1969 12 and 1974 12) during which the simulated flow is much lower than the observed flow. An investigation of months with similar antecedent monthly rainfall and daily rainfall characteristics indicates the simulator to be fairly constant. It is likely therefore that these discrepancies are the result of the sparse raingauge network recording only a fraction of severe thunderstorm activity that occurred within this catchment. A check on the annual flows (Figure 5.2.5) indicates an acceptable scatter around the 1:1 line.

Table 5.2.2 : A Comparison of Simulated and Observed Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	813,636
Total Simulated Values	842,194
Mean of Observed Values	3,013
Mean of Simulated Values	3,119
Correlation Coefficient	0,801
Regression Coefficient	0,846
Base Constant for Regrn. Eqn	0,569
Variance of Observed Value	77,823
Variance of Simulated Value	86,936
Standard Deviation of Oserved Values	8,822
Standard Deviation of Simulated Values	9,324

5.2.4 Water Resources

Figure 5.2.6 shows the graphical comparison of yields from a hypothetical dam using the "stochastic" based and modified streamflow. Results show the median MAR scenarios from 48 $m^3 \times 10^6$ to 60 $m^3 \times 10^6$. There is only a small decrease in the coefficient of variation of the modified scenarios which results in a low (slightly above 15%) increase in a median yield for the three failure scenarios.

There is no timber grown in this catchment and the timber yield component was therefore ignored.

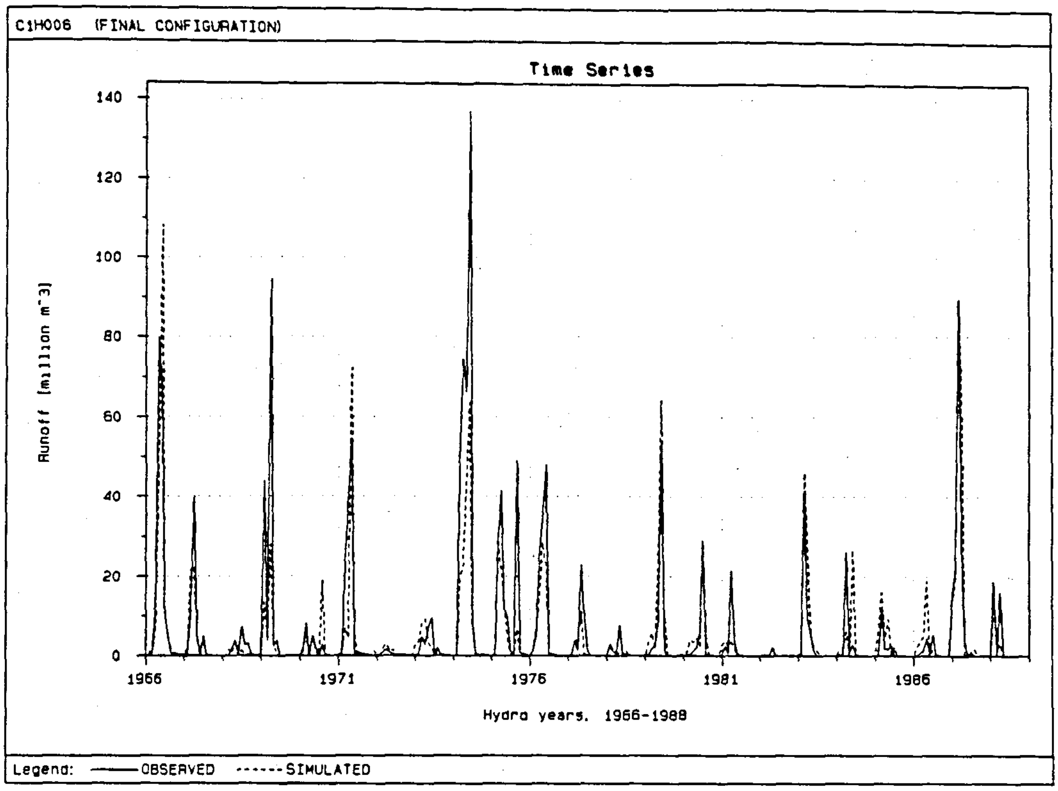


Figure 5.2.3 : Comparison of Observed and Simulated Flows at C1H006 (Final Configuration)

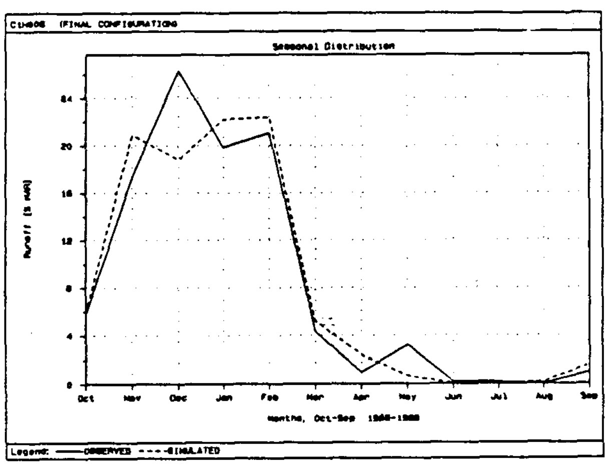


Figure 5.2.4 : Monthly Distribution of Means of Observed and Simulated Flows at C1H006

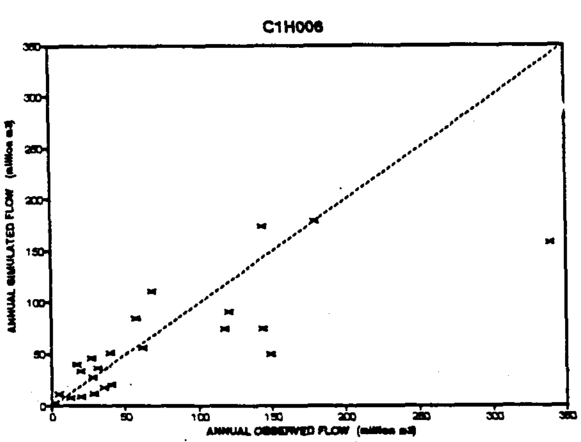


Figure 5.2.5 : Comparison of Annual Totals of Observed and Simulated Flows at C1H006

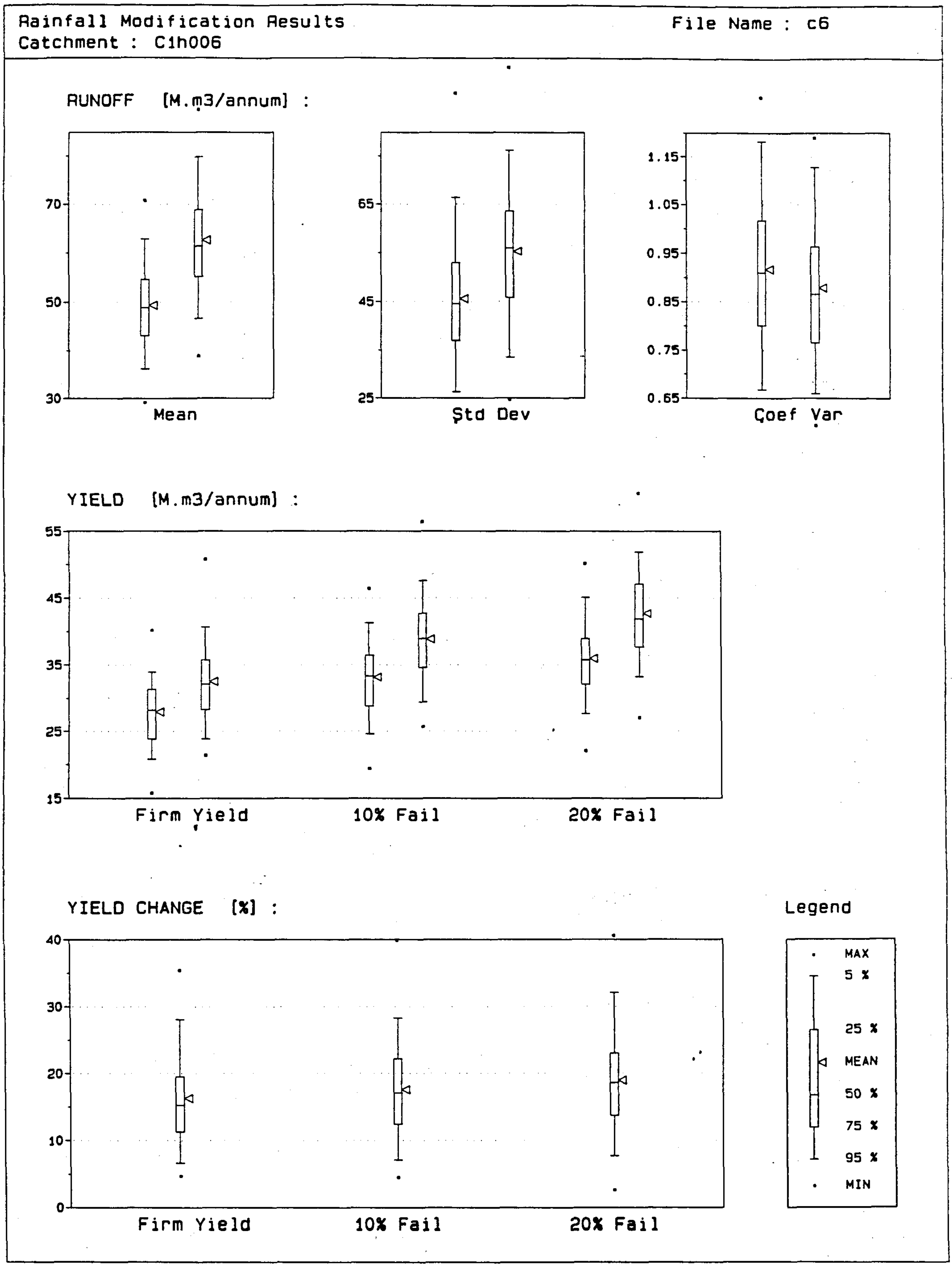


Figure 5.2.6 : **Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at C1H006**

5.3 X1H016

5.3.1 Input Information and Preparation

Figure 5.3.1 presents the current day land use in catchment X1H016. A summary of catchment data is presented in Table 5.3.1.

Table 5.3.1 : Summary of Catchment X1H016 Data

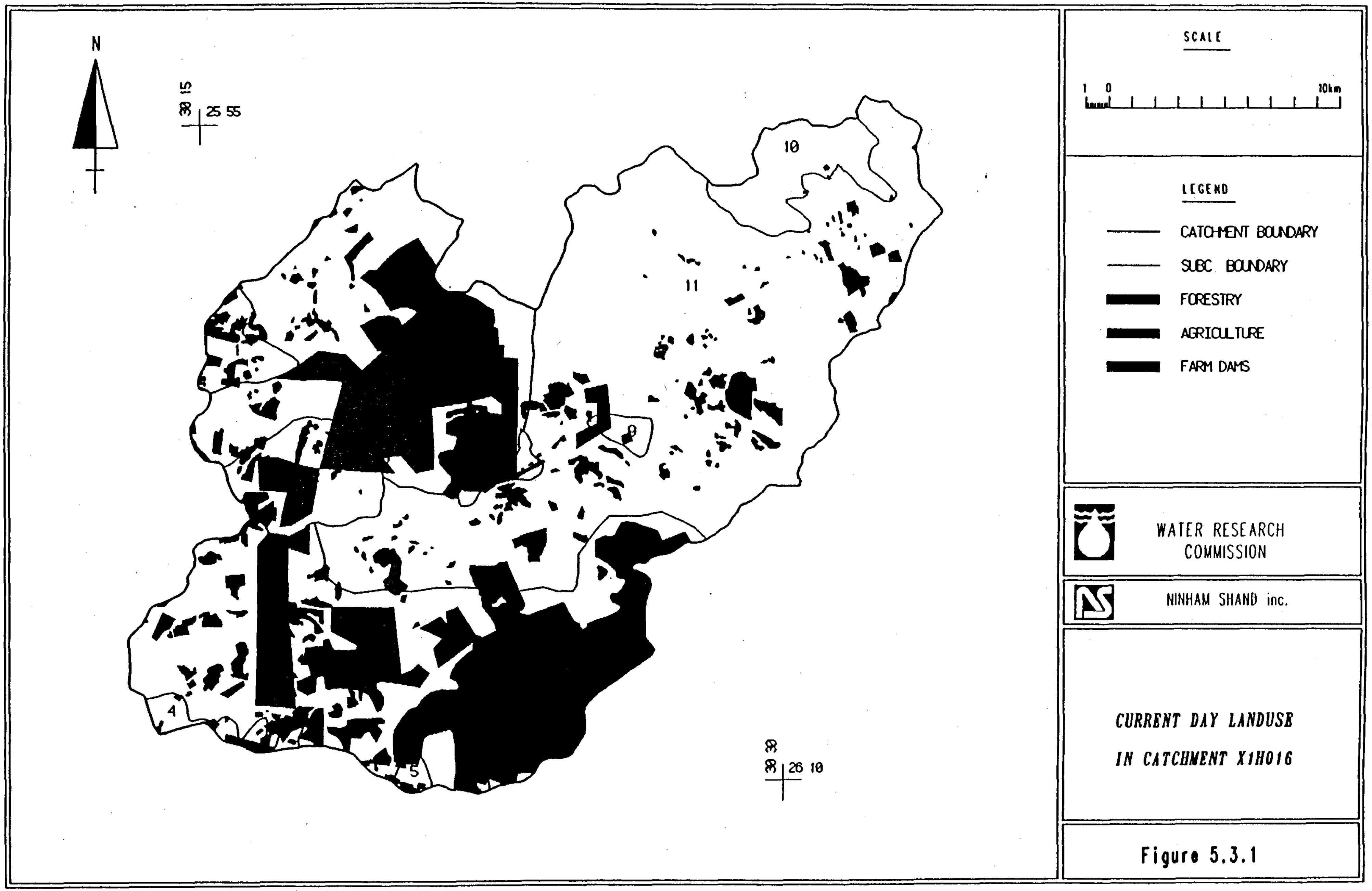
ITEM	VALUE	UNIT
Catchment Area	585,9	km^2
Catchment MAP	852,0	mm
1990 Forest Area	149,8	km^2
1990 Agriculture Area	48,7	km^2
1990 Irrigation Area	4,7	km^2
1990 Dam Capacity	3,0	$m^3 \times 10^6$
Observed MAR	79,5	$m^3 \times 10^6$
Runoff Coefficient	16,0	%
Area per rain gauge	290,0	km^2

5.3.2 Evaluation of Flow Records

Flow records are available at X1H016 from 1970 to date. The monthly flow record from October 1972 to September 1989 was checked for unreliable data. The first two years were rejected due to excessive missing data. Unreliable data in the remaining record were patched with simulated flows.

5.3.3 Model Output Verification

The initial configuration of the *ACRU* model resulted in a marked underestimation of the low flows (Figure 5.3.2). Although the hypothetical dam capacity is small the variables describing seepage and compensation were used during winter in an attempt to model the water use of Badplaas Holiday Resort. The low flow problem was addressed by identifying which variables affect the redistribution of stormflow to ground water flow.



N
30 15
25 55
10
11
8
4
5
30
30
26 10
SCALE
1 0
10km
LEGEND
CATCHMENT BOUNDARY
SUBC BOUNDARY
FORESTRY
AGRICULTURE
FARM DAMS
WATER RESEARCH
COMMISSION
NINHAM SHAND inc.
CURRENT DAY LANDUSE
IN CATCHMENT X1H016

Figure 5.3.1

The initial configuration used variables (from SIRI, 1989) describing a high clay content in the soil. This reflects a situation where surface runoff and little infiltration would predominate. To improve the groundwater contribution, a more sandy soil is required and a soil texture classed loamy sand was assumed for this catchment. The variables (ABRESP/BFRESP) which describe the passage of saturated water through the soil were increased from ∞ 0,3 to ∞ 0,7 using values for a soil texture classed loamy sand (Schulze *et al.,* 1989) and the groundwater contribution to river flow (COFRU) lagged.

This resulted in an improved estimation of low flows except during the early part of the record from 1972 to 1982 which still underestimated low flows. The variables defining vegetation water-use (VEGINT/CAY) were then decreased for the period 1972 to 1982. Only the winter values in the selected sub-catchments with little seasonal variability were reduced by between 2% and 10% to bring these sub-catchment in line with expected winter/summer interception differences.

These changes resulted in an acceptable verification. Figures 5.3.3, 5.3.4 and 5.3.5 show a graphical comparison of the simulated versus observed monthly time series, seasonal distribution and annual flow respectively. Table 5.3.2 lists the *ACRU* monthly statistics.

The statistics indicate a close correlation but with a slight overestimation of the mean. A minor underestimation of low flows is evident in both the time series and seasonal distribution. The time series indicates only a single major monthly discrepancy (February, 1985) where the simulation is double the observed. The most likely explanation is that the sparse raingauge network recorded intense thunderstorm activity not experienced to the same extent within the catchment. The annual flow comparison confirms an accurate simulation of the wettest seasons and the yield results may be used with confidence.

5.3.4 Water Resources and Timber Yield

Figure 5.3.6 shows the graphical comparison of yields from a hypothetical dam using the "stochastic" based and modified streamflow. Results show an increase in median MAR from 52 $m^3 \times 10^6$ to 65 $m^3 \times 10^6$ and very similar increases in median yield of ∞ 23% for the three failure scenarios.

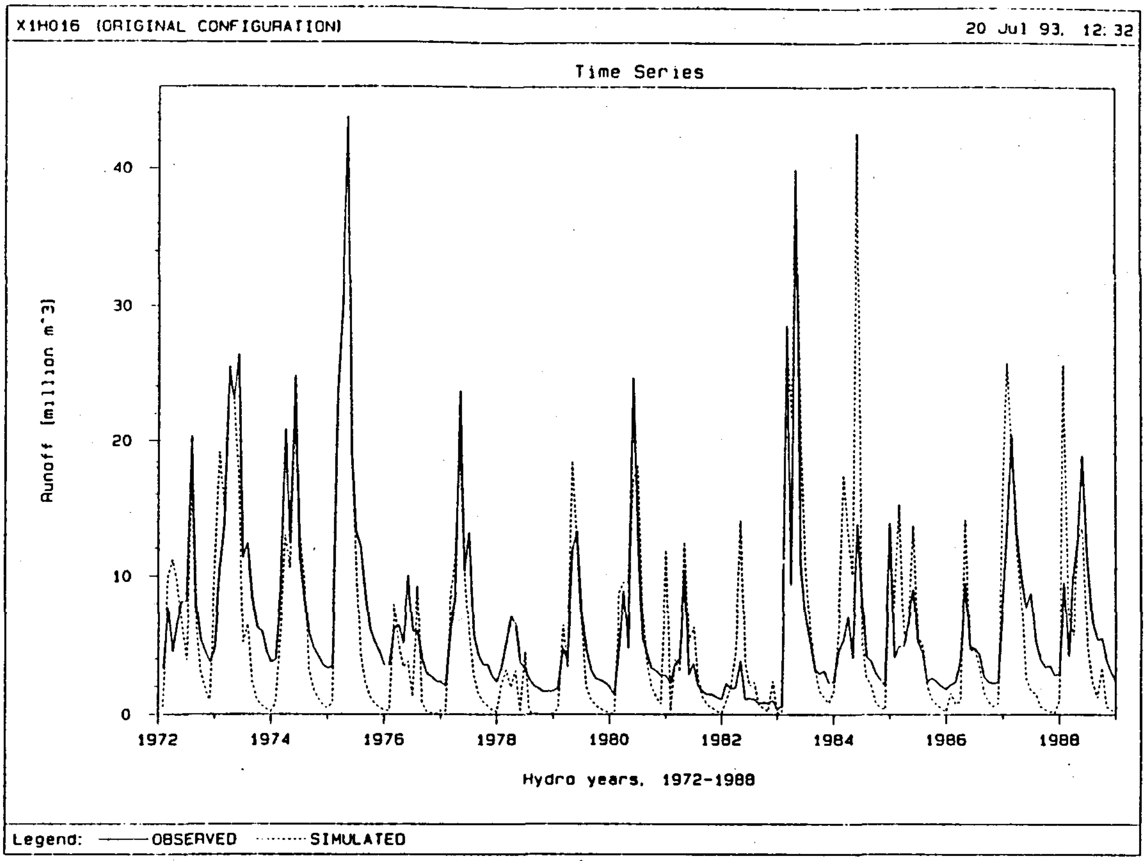


Figure 5.3.2 : Comparison of Observed and Simulated Flows at X1H016 (Original Configuration)

Table 5.3.2 : A Comparison of Simulated and Observed Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	1 937,664
Total Simulated Values	2 257,269
Mean of Observed Values	9,737
Mean of Simulated Values	11,343
Correlation Coefficient	0,822
Regression Coefficient	1,030
Base Constant for Regrn. Eqn	1,310
Variance of Observed Value	58,743
Variance of Simulated Values	92,213
Standard Deviation of Observed Values	7,664
Standard Deviation of Simulated Values	9,603

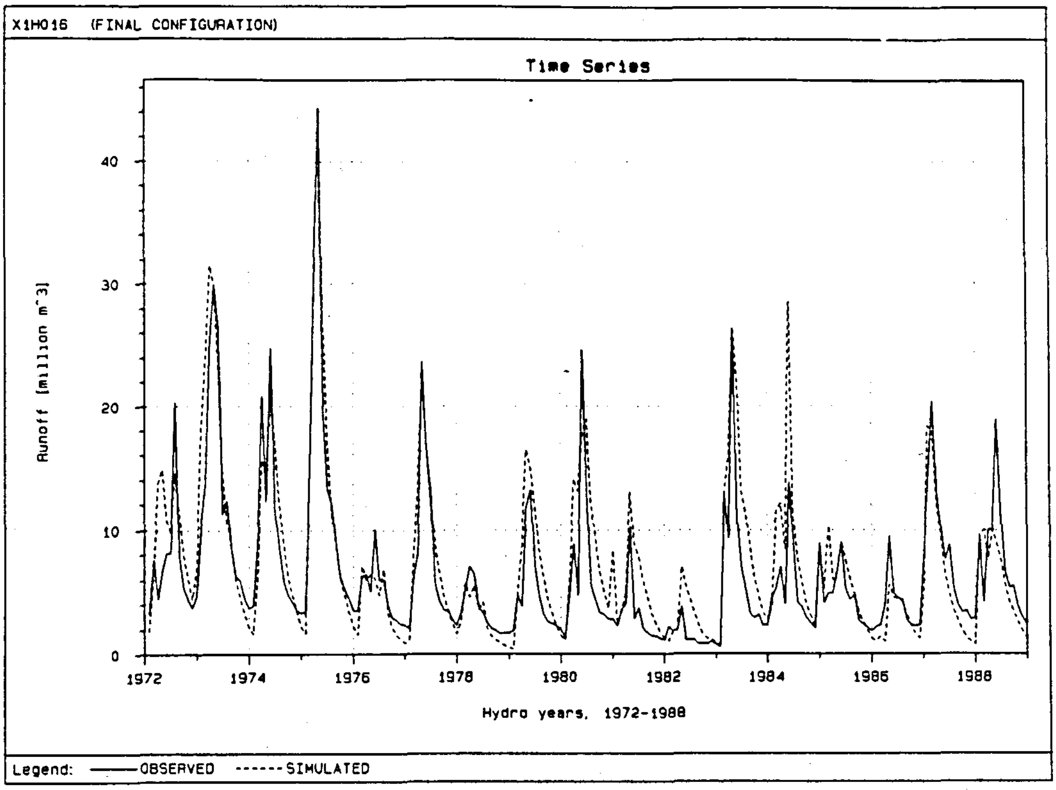


Figure 5.3.3 : Comparison of Observed and Simulated Flows at X1H016 (Final Configuration)

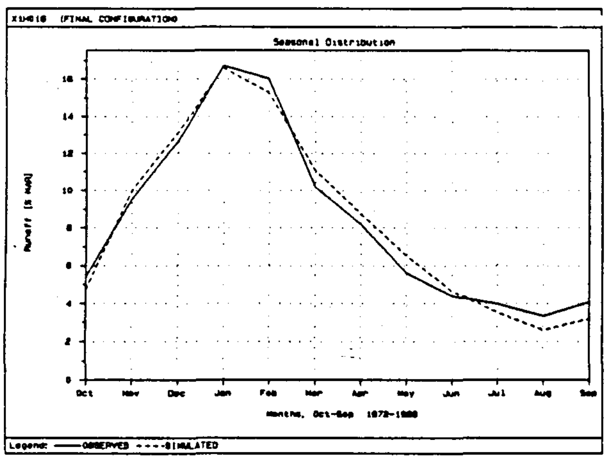


Figure 5.3.4 : Monthly Distribution of Means of Observed and Simulated Flows at X1H016

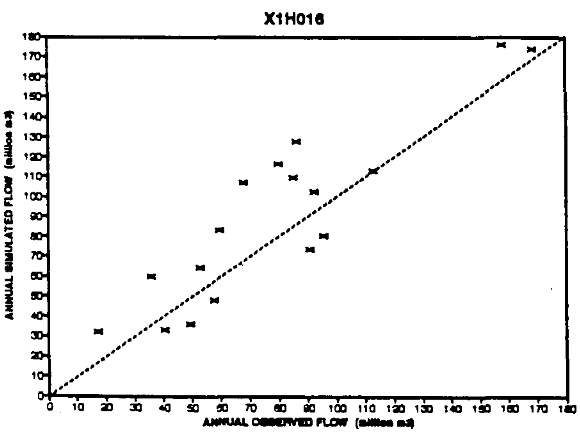


Figure 5.3.5 : Comparison of Annual Totals of Observed and Simulated Flows at X1H016

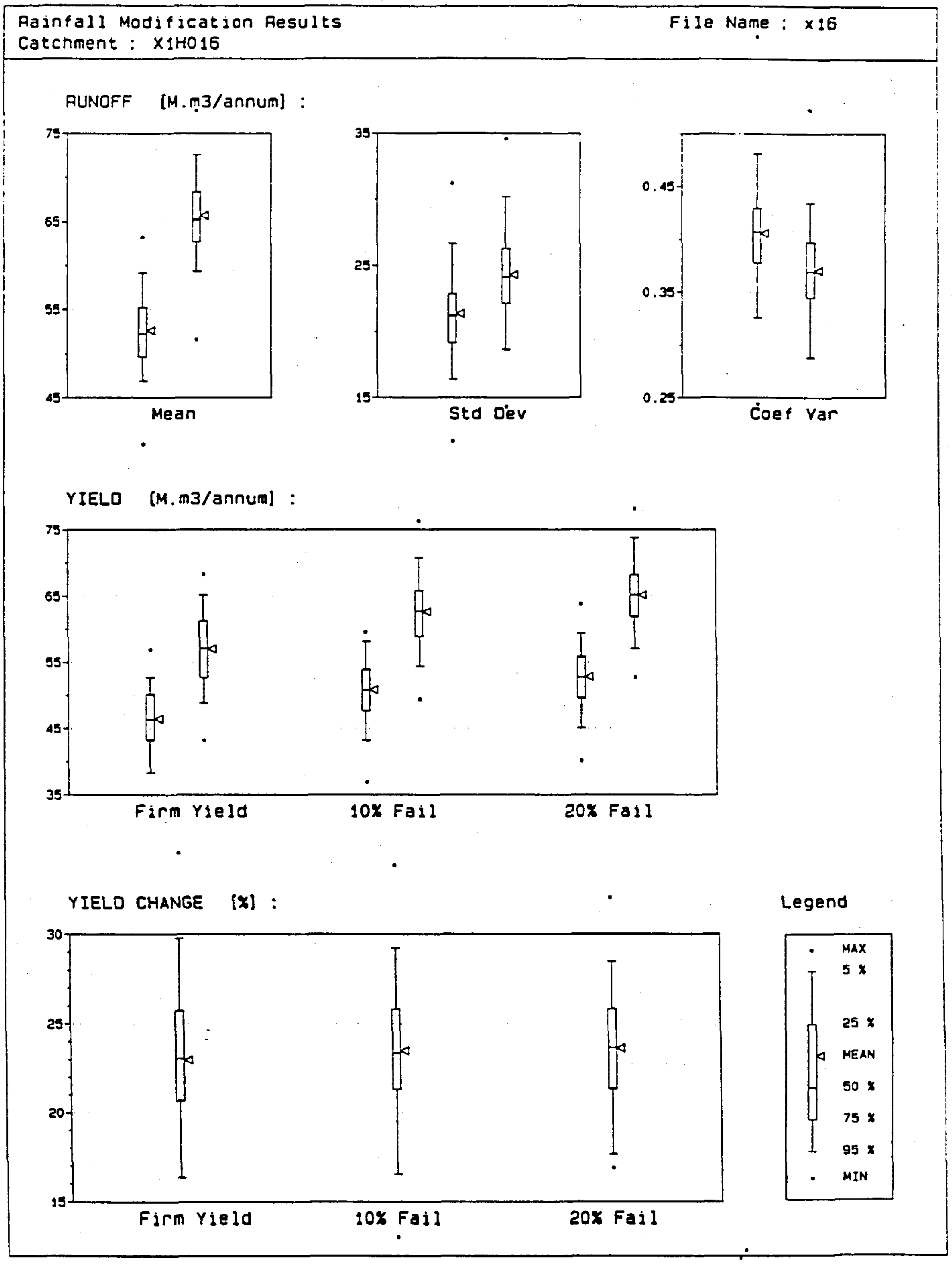


Figure 5.3.6 : **Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at X1H016**

Figure 5.3.7 shows the timber yield comparison. Results show an increase in median timber yield from approximately 320 m^3/ha/rotation to 380 m^3/ha/rotation with a 22% median increase between the two data sets. Again there is little variability about the median when compared to water yield variability.

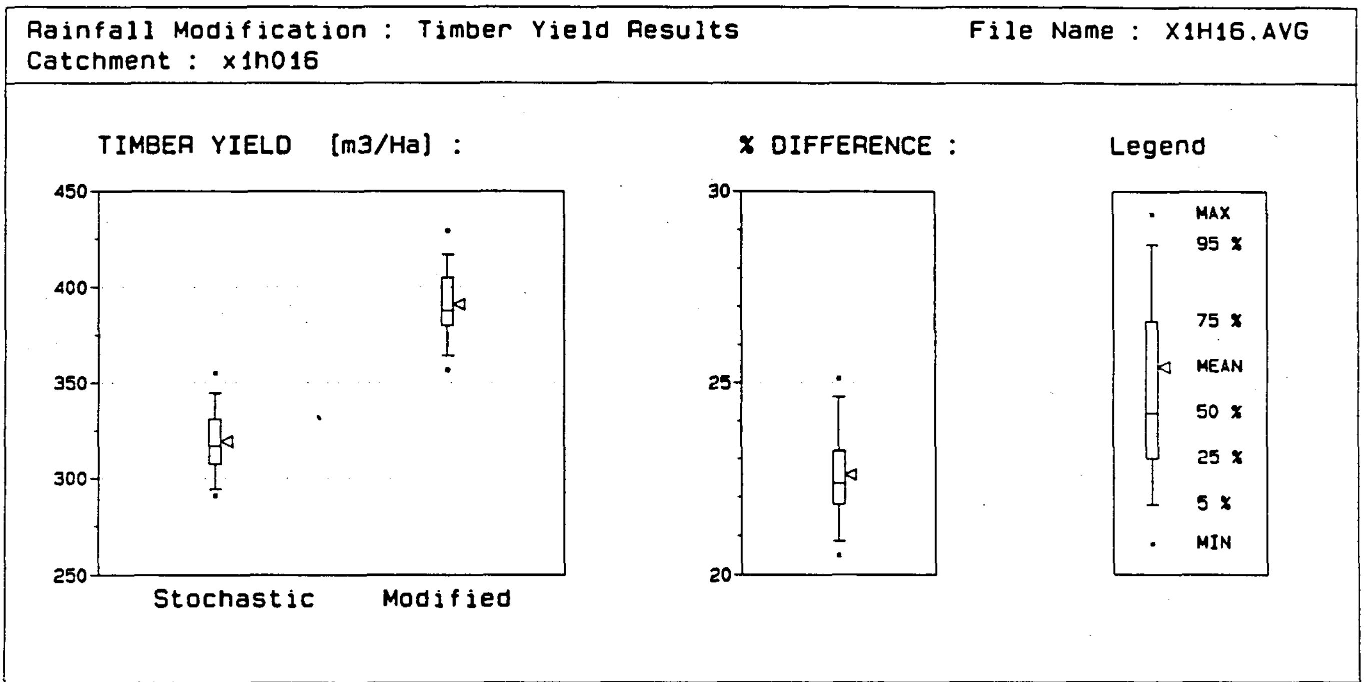


Figure 5.3.7 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at X1H016

5.4 X1H019

5.4.1 Input Information and Preparation

Figure 5.4.1 presents the current day land use in catchment X1H019. A summary of catchment data is presented in Table 5.4.1.

Table 5.4.1 : Summary of Catchment X1H019 Data

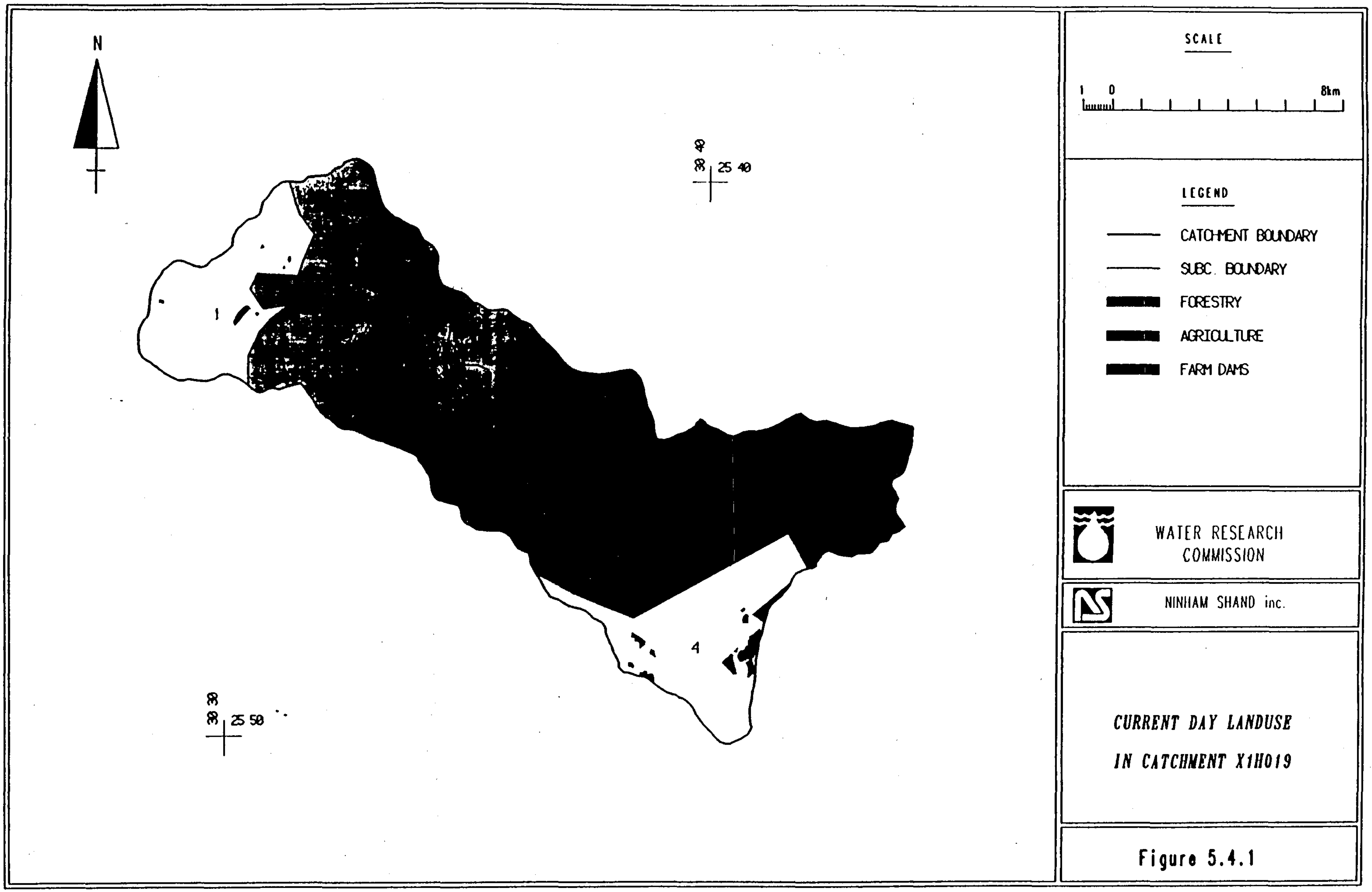
ITEM	VALUE	UNIT
Catchment Area	186,6	km^2
Catchment MAP	1 042,0	mm
1990 Forest Area	142,2	km^2
1990 Agriculture Area	1,3	km^2
1990 Irrigation Area	0,0	km^2
1990 Dam Capacity	0,21	$m^3 \times 10^6$
Observed MAR	56,6	$m^3 \times 10^6$
Runoff Coefficient	29,1	%
Area per rain gauge	62,0	km^2

5.4.2 Evaluation of Flow Records

Flow records are available at X1H019 from 1974 to date. Flow records of two canals were also required. X1H027 (with an available record from 1973 to date) abstracts water upstream of X1H019. X1H029 has an available record from 1975 to date and delivers water upstream of X1H019. The catchment flow at X1H019 is estimated by adding X1H027 and subtracting X1H029. The monthly flow record from January 1975 to December 1989 was checked for unreliable data and found to be suitable for use. Modelling problems, however, resulted in further investigations and communication with DWAF and revealed problems with the rating curve. Consequently, the flow data were rejected as being unsuitable for use.

5.4.3 Model Output Verification

The initial configuration of the *ACRU* model resulted in an unacceptable verification as shown in Figure 5.4.2. The observed flow peaks and low flows are much higher than the simulated flows from the period 1974 to 1982 with only the observed low flow being higher from 1982 to date.



CURRENT DAY LANDUSE IN CATCHMENT X1H019

Figure 5.4.1

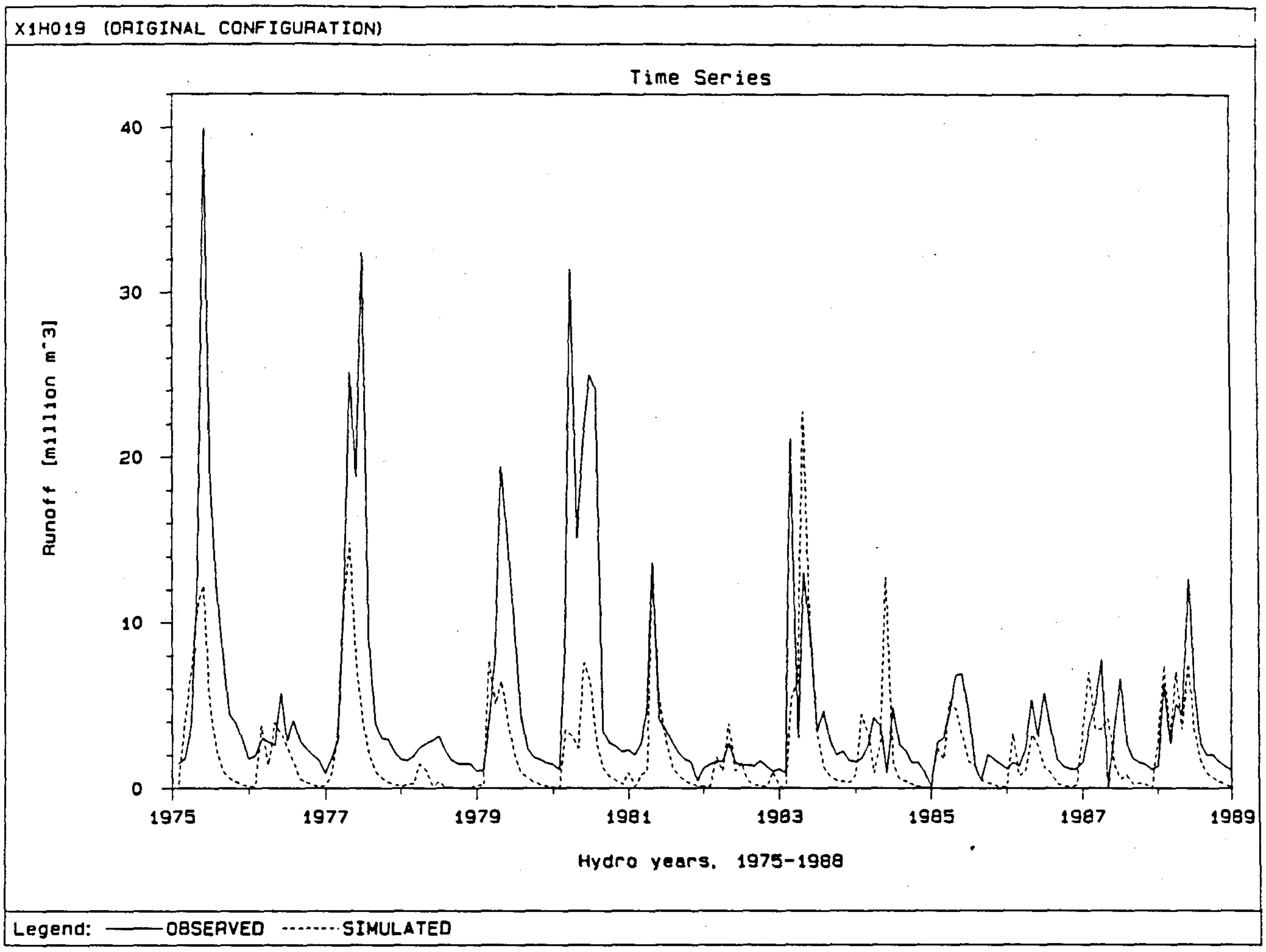


Figure 5.4.2 : Comparison of Observed and Simulated Flows at X1H019 (Original Configuration)

Improvements to the verification were made by decreasing the soil depth to generate the peak flows, increasing the redistribution rate of soil moisture to groundwater, lagging the groundwater contribution and by changing the vegetation variables in the dynamic files to improve the fit before and after 1982. The decrease in soil depth to ∞ 0,15 metres in both horizons corresponds to values for a shallow soil while the soil moisture redistribution variables (ABRESP / BFRESP) corresponds to a sandy loam soil texture (Schulze *et al.,*, 1989). Vegetation wateruse variables (CAY and VEGINT) were decreased in the menu and held constant up to 1982 (instead of 1978) to increase the peaks in the early part of the record.

These changes resulted in an acceptable verification. Figures 5.4.3 and 5.4.4 show the monthly time series and seasonal distribution respectively. Table 5.4.2 lists the *ACRU* monthly statistics.

Results show an underestimation of both the mean and standard deviation which is reflected in the time series and seasonal distribution. The annual scatter in Figure 5.4.5 indicates an underprediction in the wettest seasons so the yield analysis can be accepted with confidence.

Table 5.4.2 : A Comparison of Simulated and Observed Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	3 748,4
Total Simulated Values	3 016,0
Mean of Observed Values	25,2
Mean of Simulated Values	20,2
Correlation Coefficient	0,673
Regression Coefficient	0,400
Base Constant for Regrn. Eqn.	10,175
Variance of Observed Value	1 082,4
Variance of Simulated Values	382,9
Standard Deviation of X Values	32,900
Standard Deviation of Y Values	19,6

Further investigation indicated the likelihood that unreliable flow and/or rainfall data were the cause. Table 5.4.3 compared the monthly rainfall and flow and highlights some discrepancies. The observed rainfall/flow relationship indicates a data problem as the runoff coefficient is over 100%. Communication with DWAF resulted in a reassessment of the primary data. The findings were that the observed flow data were overpredicted. Since the model configuration might be unrepresentative this catchment was not considered representative for the regionalisation process.

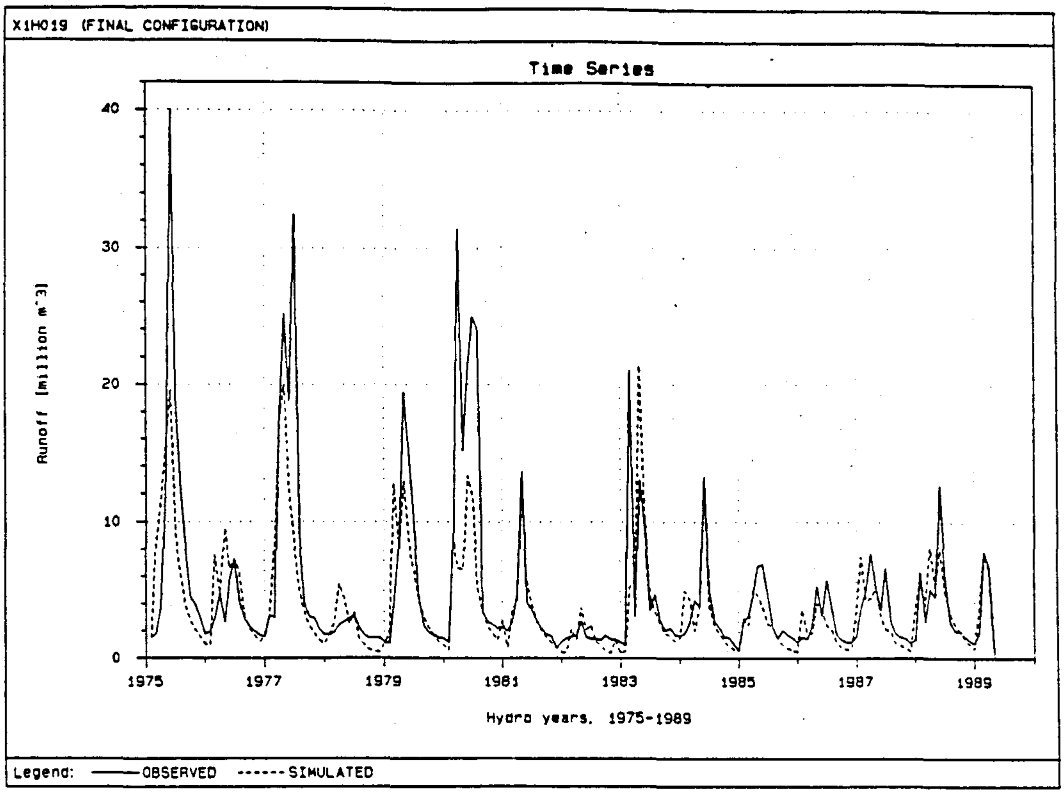


Figure 5.4.3 : Comparison of Observed and Simulated Flows at X1H019 (Final Configuration)

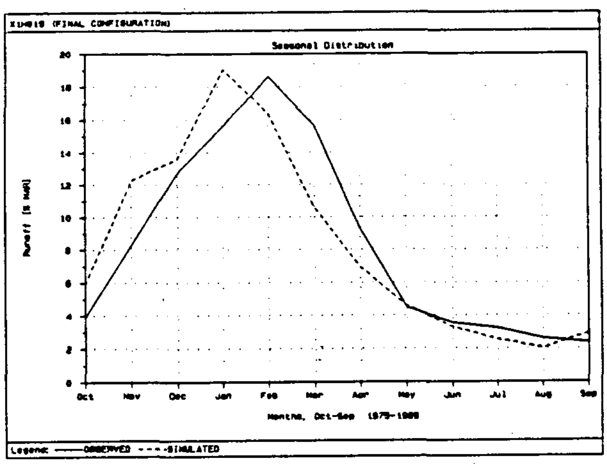


Figure 5.4.4 : Monthly Distribution of Means of Observed and Simulated Flows at X1H019

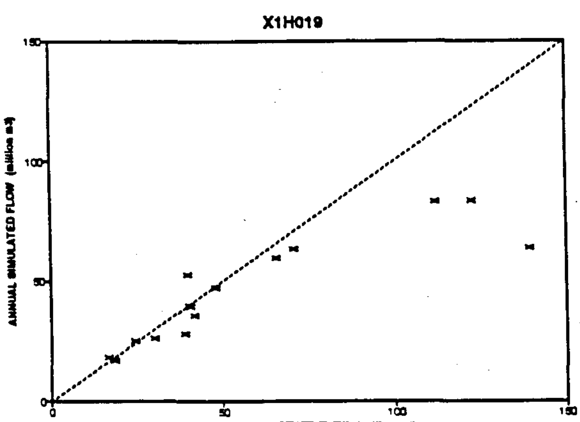


Figure 5.4.5 : Comparison of Annual Totals of Observed and Simulated Flows at X1H019

Table 5.4.3 : Comparison of Monthly Flow and Rainfall

DATE	RAINFALL (mm)	FLOW (mm)	
		SIMULATED	OBSERVED
1976 02	200	105	215
1978 03	69	44	174
1981 04	24	27	129
1986 08	4	3	8

5.4.4 Water Resources and Timber Yield

Figure 5.4.6 shows the graphical comparison of yields from a hypothetical dam using the "stochastic" based and modified streamflow. Results show an increase in median MAR from 30 $m^3 \times 10^6$ to 36 $m^3 \times 10^6$ and corresponding increase in yield of ∞ 18,5% for the three failure scenarios.

Figure 5.4.7 shows the timber yield comparison. Results show a 18,5% increase in median timber yield from over 270 m^3/ha/rotation to close to 320 m^3/ha/rotation.

5.5 X1H020

5.5.1 Input Information and Preparation

Figure 5.5.1 presents the current day land use in catchment X1H020. A summary of catchment data is presented in Table 5.5.1.

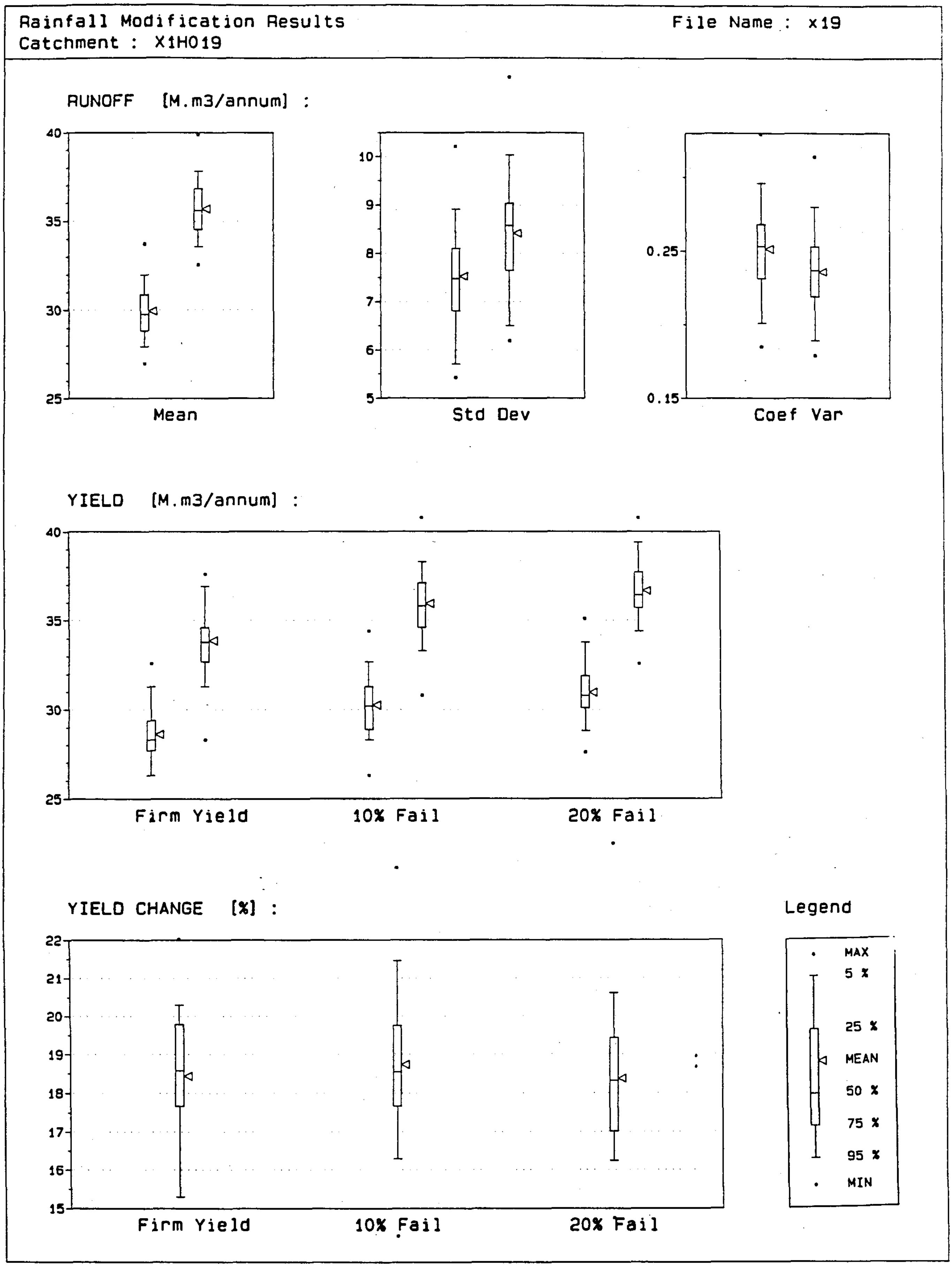


Figure 5.4.6 : Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at X1H019

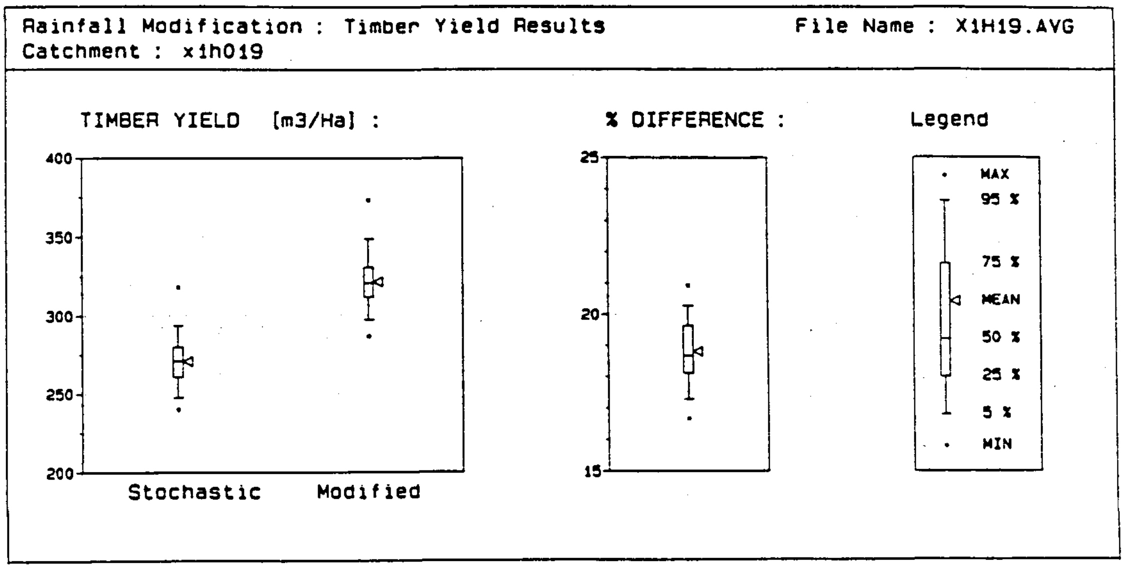


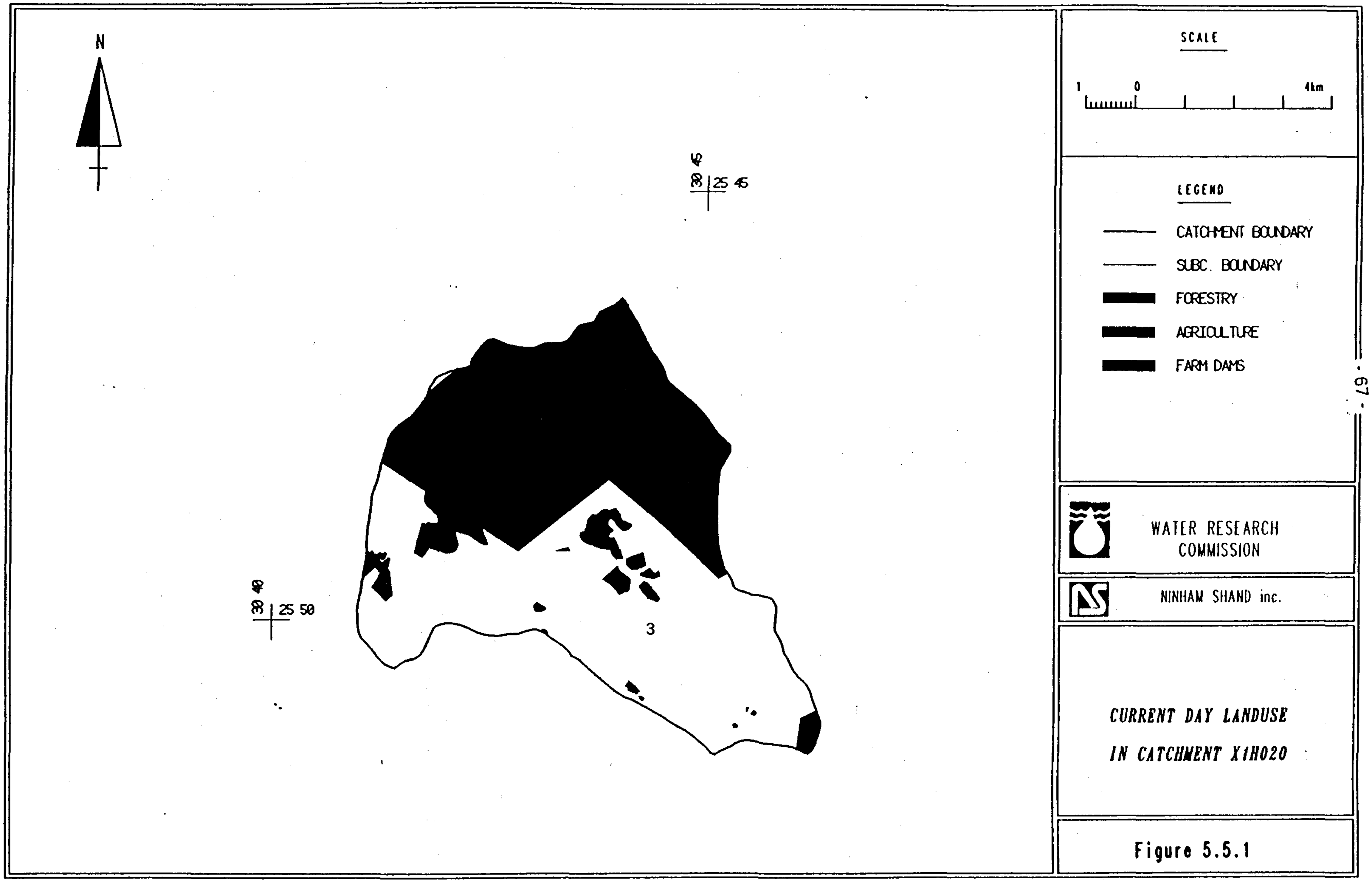
Figure 5.4.7 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at X1H019

Table 5.5.1 : Summary of Catchment X1H020 Data

ITEM	VALUE	UNIT
Catchment Area	48,1	km^2
Catchment MAP	998,0	mm
1990 Forest Area	21,0	km^2
1990 Agriculture Area	2,5	km^2
1990 Irrigation Area	0,0	km^2
1990 Dam Capacity	0,2	m^3 x 10^6
Observed MAR	5,5	m^3 x 10^6
Runoff Coefficient	11,4	%
Area per rain gauge	48,1	km^2

5.5.2 Evaluation of Flow Records

Flow records are available at X1H020 from 1973 to date although the record prior to 1975 contains excessive missing daily data. The flow records of a canal (X1H029) which abstracts water upstream of X1H029 is available from 1975 to date.



CURRENT DAY LANDUSE IN CATCHMENT X1H020

Figure 5.5.1

The catchment flow is estimated by adding X1H029 and X1H020. The monthly flow record from January 1975 to December 1989 was checked for unreliable data and patched with simulated flows where necessary.

5.5.3 Model Output Verification

The initial configuration of the *ACRU* model resulted in an overestimation of simulated peaks in the latter part of the record and an underestimation of the simulated low flows during the early part of the record (Figure 5.5.2). The decrease in observed flows from 1980 indicates a problem with the recorded diversions from the canal (discussed in 5.5.2).

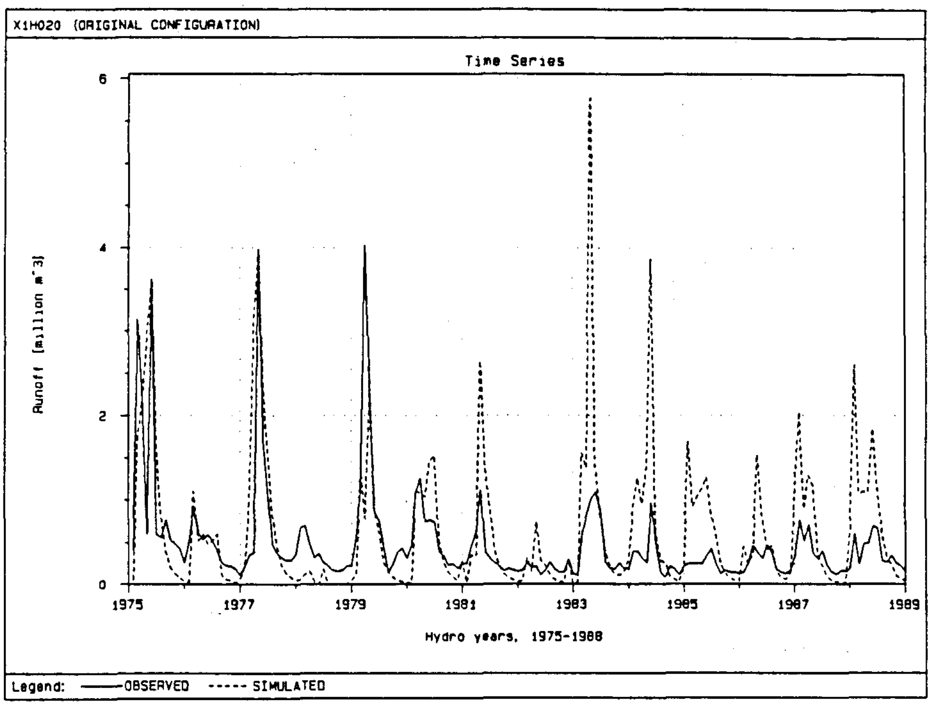


Figure 5.5.2 : **Comparison of Observed and Simulated Flows at X1H020 (Original Configuration)**

Variables (DEPA/DEPB/ABRESP/BFRESP/SMDDP) affecting the redistribution of stormflow to groundwater flow were increased and the groundwater variable (CORFU) lagged to obtain an acceptable verification. The increase in the depth of both the A and B horizons to 0,3 and 0,5 metres respectively and increasing SMDDEP to 0,4 is close to the values used for deep soils while the increase in ABRESP and BFRESP from ∞ 0,35 to ∞ 0,7 corresponds to values for the texture class loamy sand

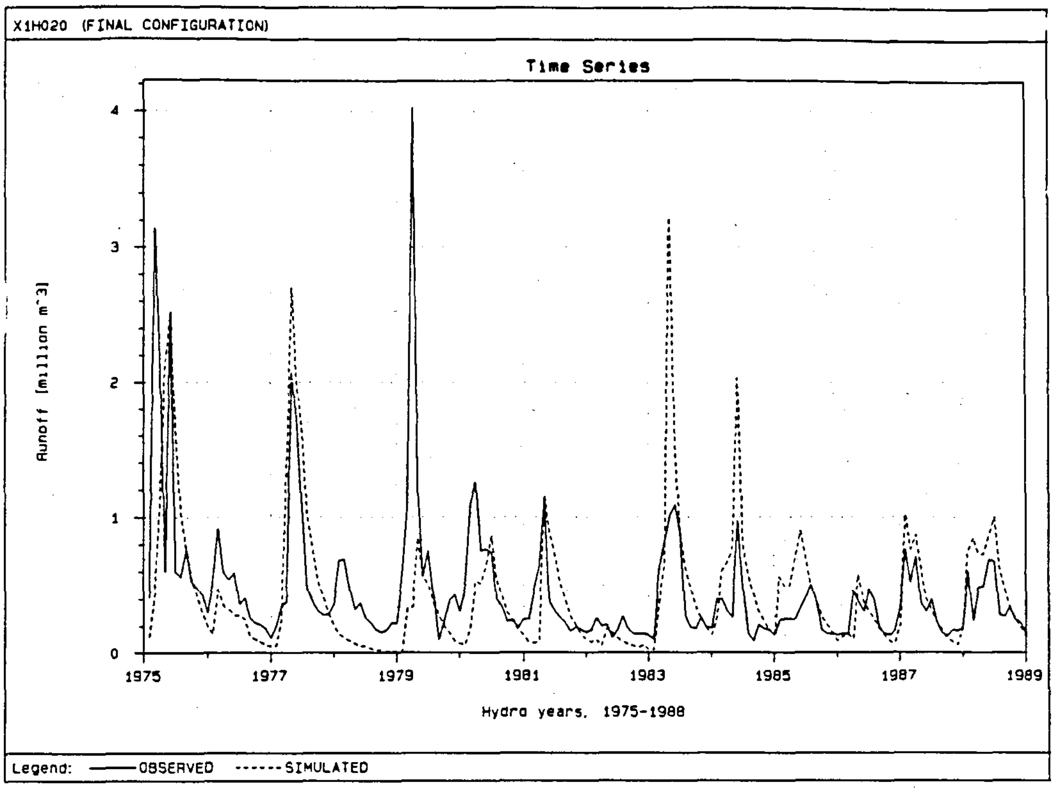


Figure 5.5.3 : **Comparison of Observed and Simulated Flows at X1H020 (Final Configuration)**

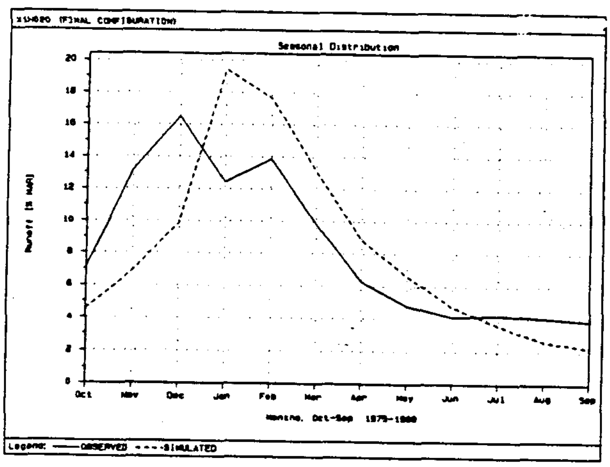


Figure 5.5.4 : Monthly Distribution of Means of Observed and Simulated Flows at X1H020

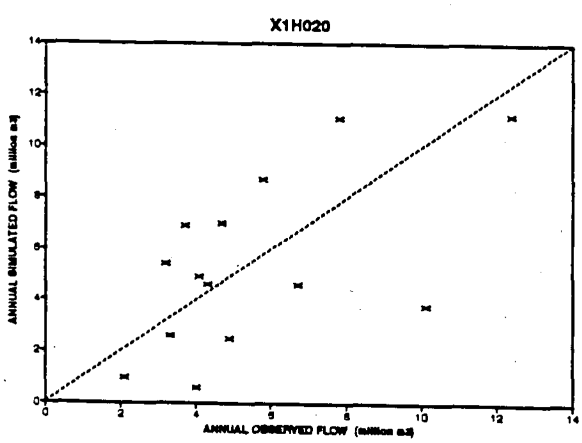


Figure 5.5.5 : Comparison of Annual Totals of Observed and Simulated Flows at X1H020

(Schulze *et al.*, 1989). These changes resulted in the best acceptable fit. Figures 5.5.3 and 5.5.4 present a graphical comparison of the simulated versus observed monthly time series and seasonal distribution respectively. Table 5.5.2 lists the *ACRU* monthly statistics.

Table 5.5.2 : A Comparison of Simulated and Observed Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	1397,7
Total Simulated Values	1378,3
Mean of Observed Values	9,318
Mean of Simulated Values	9,189
Correlation Coefficient	0,379
Regression Coefficient	0,376
Base Constant for Regrn. Eqn	5,687
Variance of Observed Value	99,9
Variance of Simulated Values	98,1
Standard Deviation of Observed Values	9,997
Standard Deviation of Simulated Values	9,903

The statistics show a poor correlation although the mean and standard deviation is preserved. The poor correlation is evident in both the time series and seasonal distribution. Major problems are associated with low flows during the first half of the verification period and with simulating peaks during the latter half of the record. Table 5.5.3 indicates these problems are the result of poor rainfall/runoff data.

Table 5.5.3 : Comparison of Monthly Flow and Rainfall

DATE	MONTHLY RAINFALL (mm)	MONTHLY FLOW (mm)	
		SIMULATED	OBSERVED
1979 Summer	73/60/77/34	1,4/1,0/1,1/0,6	6,6/7,7/5,5/4,5
1979 Winter	6/1/3/28	0,5/0,4/0,3/0,2	3,5/3,2/3,5/4,6
1979 12	91	7	84
1984 01	(231) (137) 289	(8) (13) 67	(13) (17) 21

() indicates antecedent monthly rainfall/runoff

The low flow simulation problem in both the summer and winter of 1979 is most likely the result of an underestimation of rainfall. The low summer rainfall firstly results in underpredicted summer runoff and secondly in little groundwater storage for winter baseflow releases.

By the end of winter the model has a depleted soil moisture status and is unable to respond to the rainfall in December, 1979. However, the magnitude of the observed flow/simulated flow difference also tends to suggest the sparse raingauge network failed to record extensive thunderstorm activity. The overestimation in January 1984 is the result of a saturated soil moisture from antecedent monthly rainfall followed by excessive rainfall in January 1984. The observed flow indicates the January rainfall recorded by the sparse raingauge network was not as severe over the whole catchment.

The scatter of annual flows around the 1:1 line is poor although the wettest seasons are not overpredicted (Figure 5.5.5). Consequently, this catchment was used in the yield analysis but was rejected from the regionalisation process due to the poor verification.

5.5.4 Water Resources and Timber Yield

Figure 5.5.6 shows a graphical comparison of yields from a hypothetical dam using the "stochastic" based and modified streamflow. Results show an increase in median MAR from 3,8 $m^3 \times 10^6$ to 5,3 $m^3 \times 10^6$. The significantly lower coefficient of variation of the modified scenarios results in an dramatic increase in yield of ∞ 38% for the 3 failure scenarios.

Figure 5.5.7 shows the timber yield comparison. Results show an increase in median timber yield of over 30%, from 350 m^3/ha/rotation up to 460 m^3/ha/rotation.

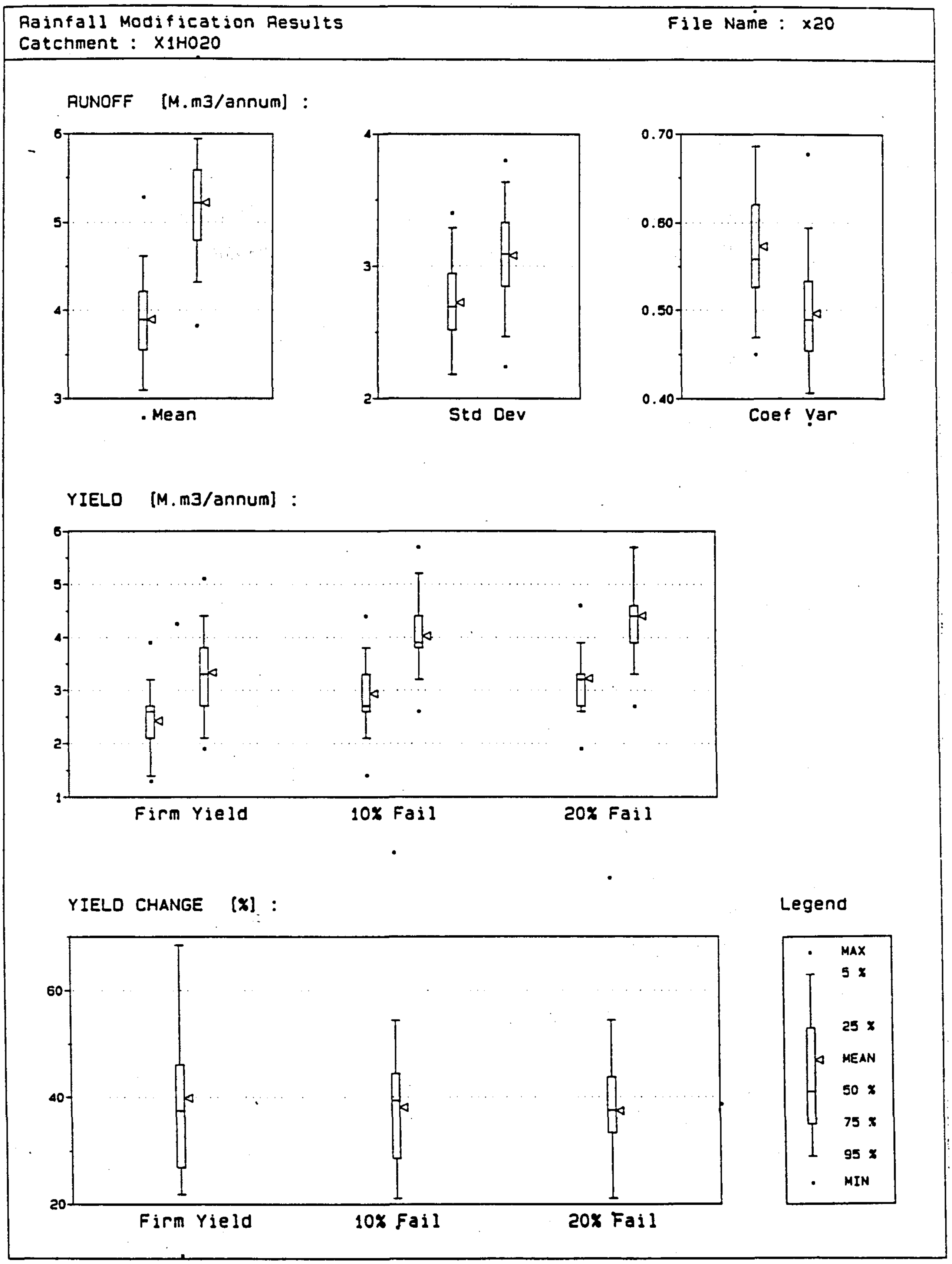
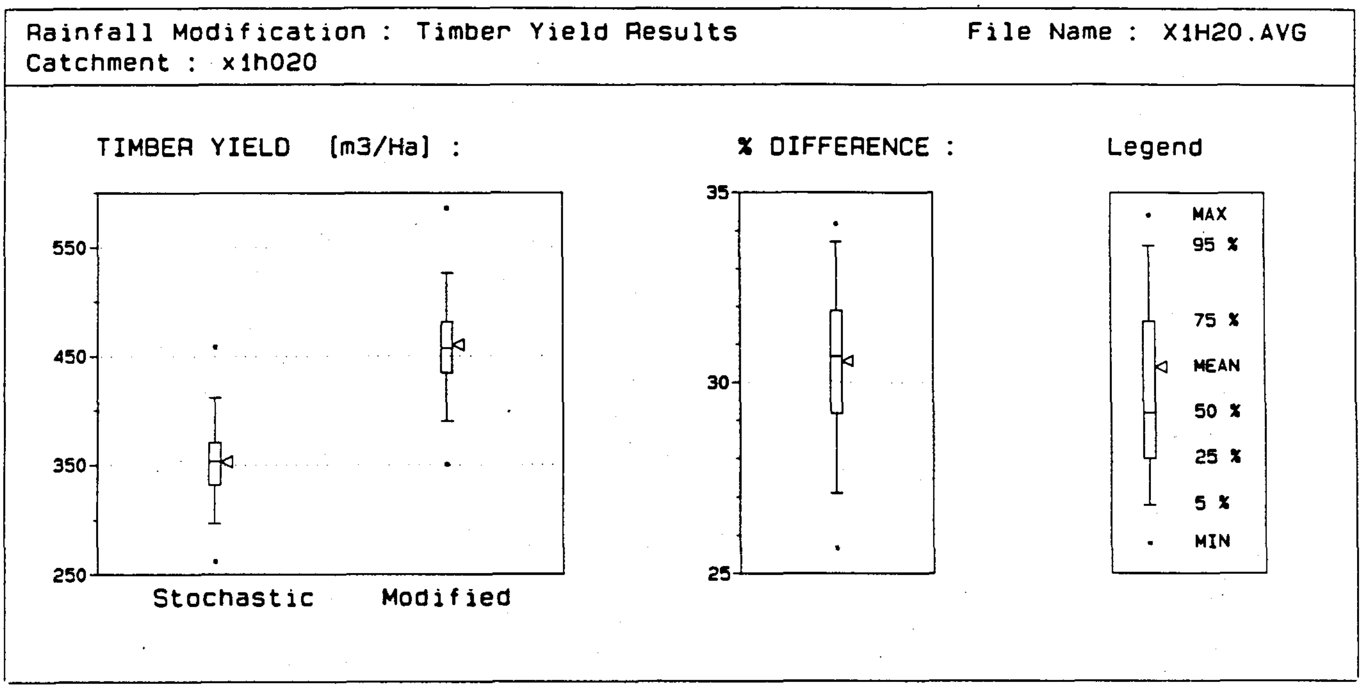


Figure 5.5.6 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at X1H020

Figure 5.5.7 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at X1H020



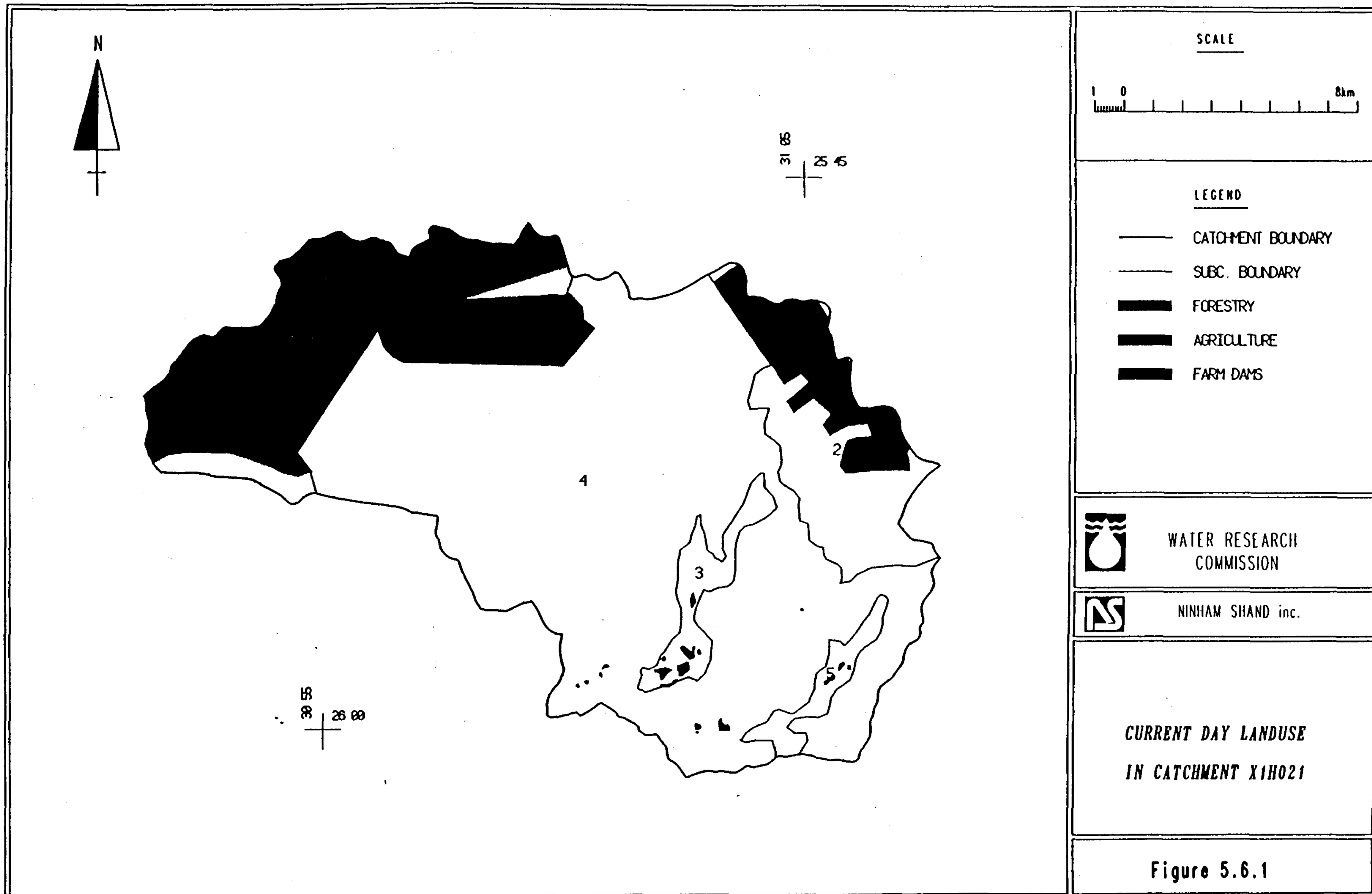
5.6 X1H021

5.6.1 Input Information and Preparation

Figure 5.6.1 presents the current day land use in catchment X1H021. A summary of catchment data is presented in Table 5.6.1.

Table 5.6.1 : Summary of Catchment X1H021 Data

ITEM	VALUE	UNIT
Catchment Area	293,6	km^3
Catchment MAP	1 163,0	mm
1990 Agriculture Area	0,0	km^3
1990 Forest Area	77,3	km^3
1990 Irrigation Area	0,0	km^3
1990 Dam Capacity	0,0	$m^3 \times 10^6$
Observed MAR	43,6	$m^3 \times 10^6$
Runoff Coefficient	12,8	%
Area per rain gauge	293,6	km^2



CURRENT DAY LANDUSE IN CATCHMENT X1H021

Figure 5.6.1

5.6.2 Evaluation of Flow Records

Flow records are available at X1H021 from 1975 to date. The monthly flow records from 1975 to 1989 were checked for unreliable data and found to be suitable for use.

5.6.3 Model Output Verification

The initial configuration of the *ACRU* model resulted in an unacceptable verification of runoff as shown in Figure 5.6.2. The comparison shows that the simulated flows underpredict the low flows over the whole record and overpredict peak flows from 1985 to 1989.

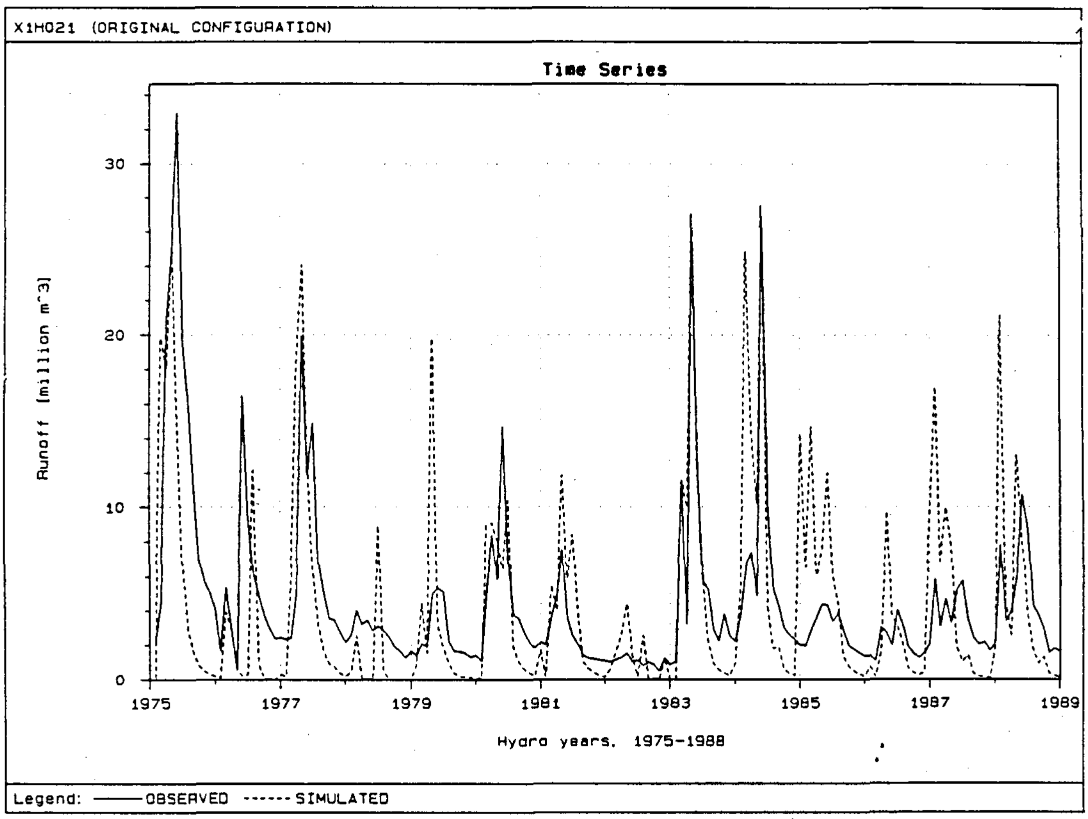


Figure 5.6.2 : Comparison of Observed and Simulated Flows at X1H021 (Original Configuration)

An attempt was made to improve the verification by changing the vegetation, soil and groundwater variables. The soil depth was decreased to 0,2 and 0,3 m in the A and B horizons respectively while the soil moisture redistribution rate (ABRESP/BFRESP) was increased to ∞ 0,8. These values describe a soil with a sandy texture with average depth. The variables describing water loss from vegetation (CAY/VEGINT) were decreased in winter to increase soil moisture during the low flow period. From 1984 they were increased in the summer in an attempt to lower the peaks.

Figures 5.6.3 and 5.6.4 present the series and seasonal distribution comparison. Table 5.6.2 lists the monthly statistics. All indicators reveal a poor verification which is likely to be the result of poor rainfall/runoff data. Table 5.6.3 compares monthly rainfall and observed flow and highlights the worst discrepancies during the latter part of the record.

The first two comparisons indicate that the observed flow data appear to contain inexplicable high winter flows. The last two records compare the influence of two similar rainfall events where the simulator is constant and the observed record varies. This is most likely as a result of the sparse raingauge network not recording the actual catchment rainfall.

Table 5.6.2 : A Monthly Comparison of Simulated and Observed Runoff for Monthly Totals and Daily Flows (mm)

Total Observed Values	2010,998
Total Simulated Values	1550,852
Mean of Observed Values	13,058
Mean of Simulated Values	10,070
Correlation Coefficient	0,592
Regression Coefficient	0,550
Base Constant for Regrn. Eqn.	2,883
Variance of Observed Value	127,326
Variance of Simulated Values	110,188
Standard Deviation of Observed Values	11,284
Standard Deviation of Simulated Values	10,497

Table 5.6.3 : Comparison of Monthly Flow and Rainfall

DATE	RAINFALL (mm)	FLOW (mm)	
		SIMULATED	OBSERVED
1977 06	(0) (0) 2	(4) (3) 2	(13) (10) 8
1979 05	(11) (0) 3	(1) (1) 1	(8) (7) 6
1981 02	(148) 142	(16) 14	(20) 50
1986 01	(156) 152	(16) 12	(12) 15

( ) indicates antecedent monthly rainfall/runoff

The annual flows shown in Figure 5.6.5 indicate an acceptable scatter around the 1:1 line. This catchment was used for the yield assessment but due to the poor verification and "manipulation" of data this catchment was excluded from the regionalisation process.

5.6.4 Water Resources and Timber Yield

Figure 5.6.6 shows a graphical comparison of yields from a hypothetical dam using the "stochastic" based and modified streamflow. Results show an increase in median MAR from 46 $m^3 \times 10^6$ to 57 $m^3 \times 10^6$ with an approximate increase in yield of ∞ 21% for the 3 failure scenarios.

Figure 5.6.7 shows the timber yield comparison. Results show an increase in median timber yield of almost 17%, from 430 m^3/ha/rotation to over 500 m^3/ha/rotation.

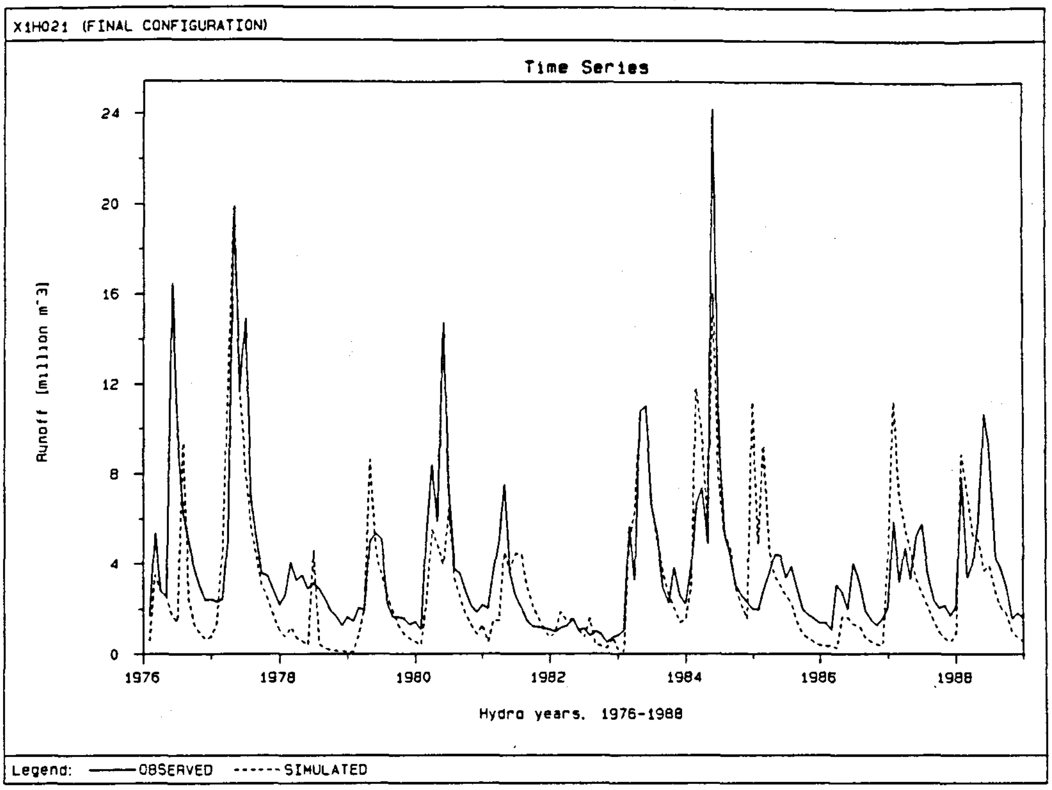


Figure 5.6.3 : **Comparison of Observed and Simulated Flows at X1H021 (Final Configuration)**

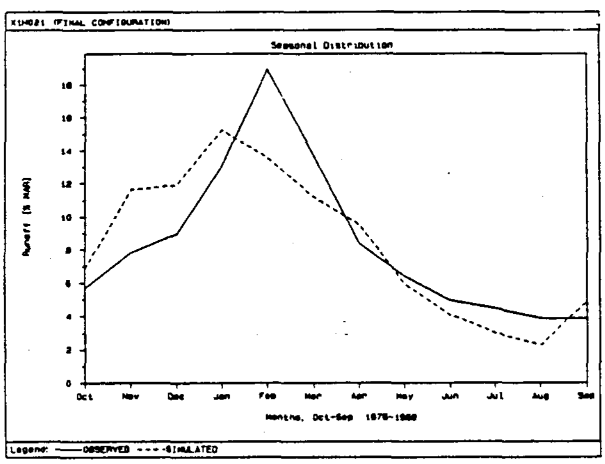


Figure 5.6.4 : Monthly Distribution of Means of Observed and Simulated Flows at X1H021

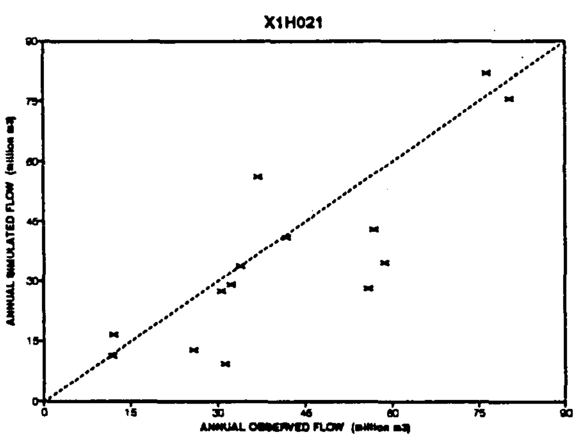


Figure 5.6.5 : Comparison of Annual Totals of Observed and Simulated Flows at X1H021

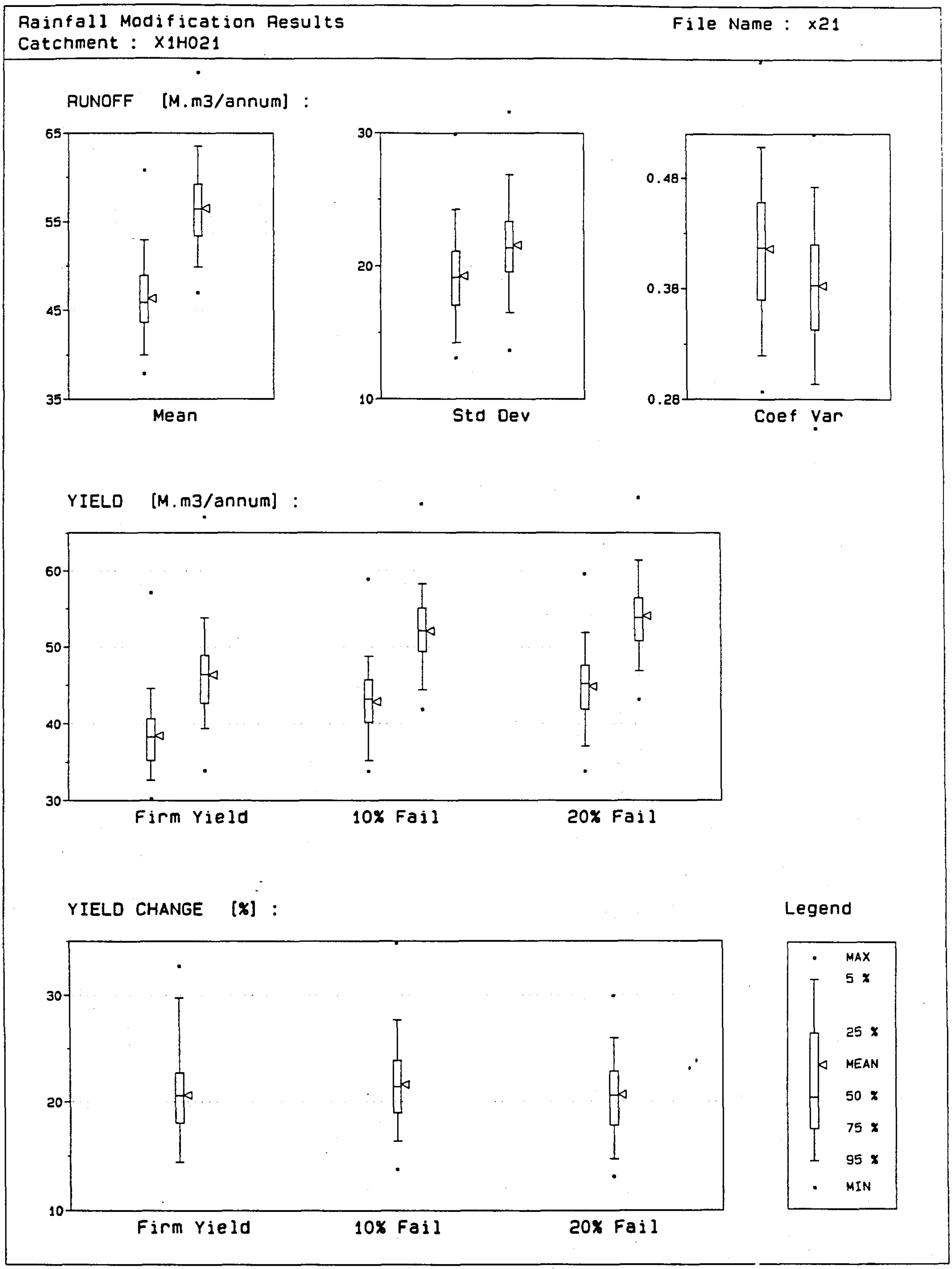


Figure 5.6.6 : Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at X1H021

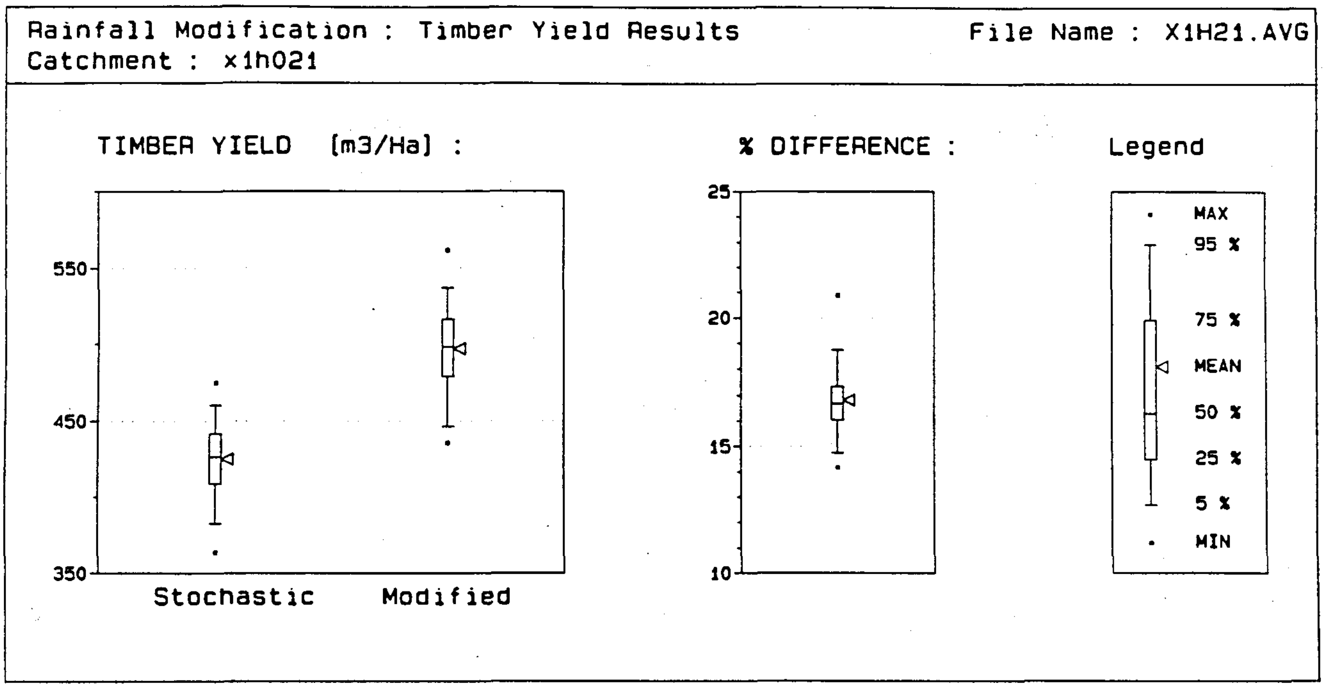


Figure 5.6.7 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at X1H021

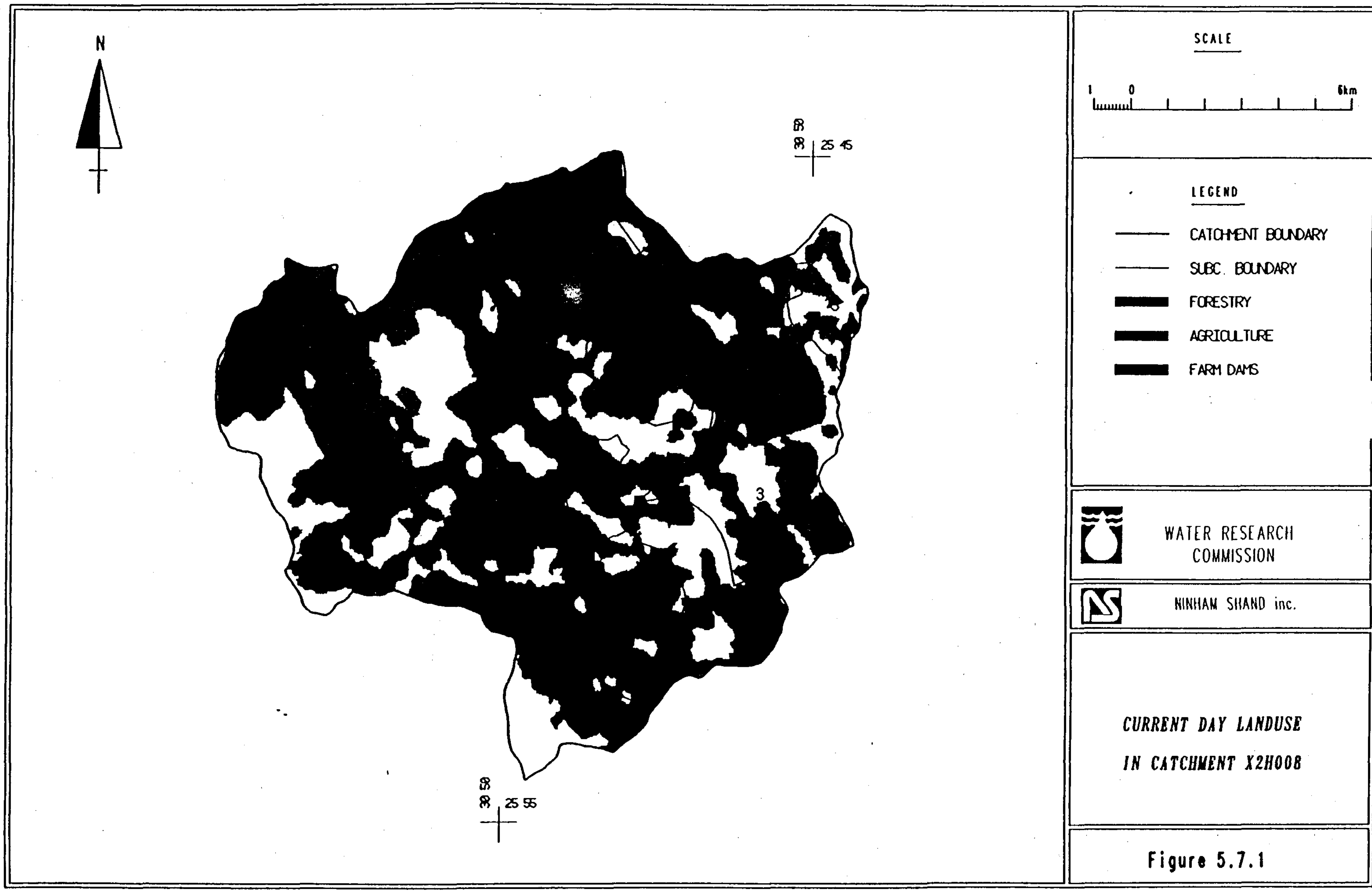
5.7 X2H008

5.7.1 Input Information and Preparation

Figure 5.7.1 presents the current day land use in catchment X2H008. A summary of catchment data is presented in Table 5.7.1.

5.7.2 Evaluation of Flow Records

Flow records are available at X2H008 from 1948 to date. The monthly flow records from January 1961 to December 1989 (the rainfall record period) were checked for unreliable data and patched with simulated flows where necessary.



CURRENT DAY LANDUSE IN CATCHMENT X2H008

Figure 5.7.1

Table 5.7.1 : Summary of Catchment X2H008 Data

ITEM	VALUE	UNIT
Catchment Area	180,4	km²
Catchment MAP	1 023,0	mm
1990 Agriculture Area	0,7	km²
1990 Forest Area	150,0	km²
1990 Irrigation Area	0,06	km²
1990 Dam Capacity	0,38	$m^3 \times 10^6$
Observed MAR	17,4	$m^3 \times 10^6$
Runoff Coefficient	9,4	%
Area per rain gauge	60,0	km²

5.7.3 Model Output Verification

The initial verification of the *ACRU* model resulted in an underestimation of low flows over the whole record and a varied (both over and under) simulation of peaks (Figure 5.7.2).

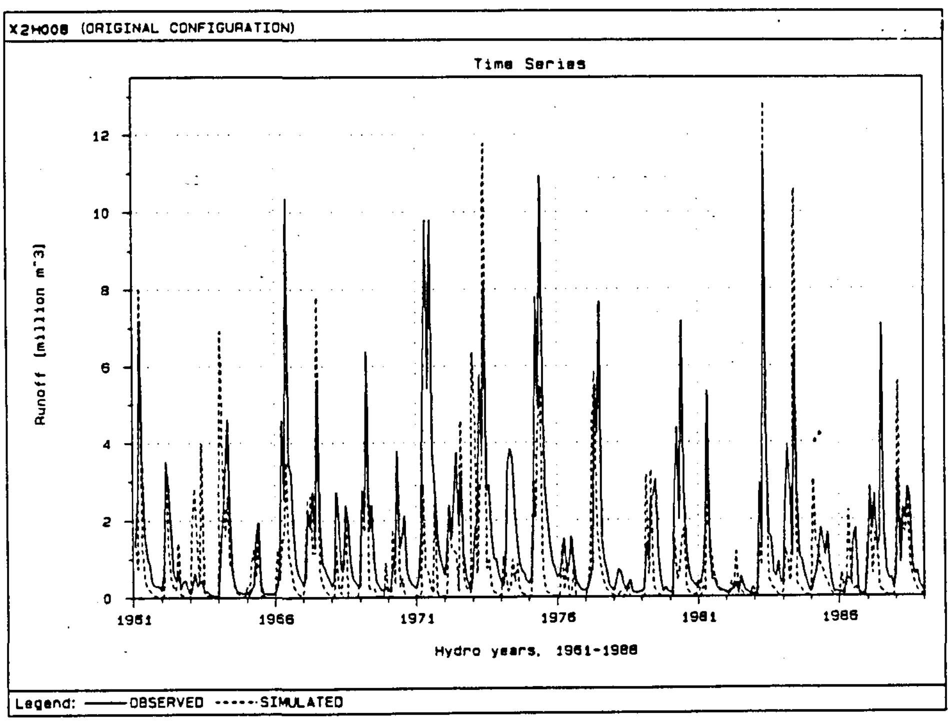


Figure 5.7.2 : Comparison of Observed and Simulated Flows at X2H008 (Original Configuration)

Improvements to the verification were made by changing vegetation, soil and groundwater variables. The depth of the A Horizon (DEPA) was decreased to 0,2 metres and the soil moisture redistribution rate (ABRESP/BFRESP) was increased to ∞ 0,7 to maintain peaks as well as increase low flows. These values correspond to an average soil depth with a sandy soil texture (Schulze *et al.*, 1989). Baseflow was also lagged to increase the low flows. These changes did not result in an acceptable verification and the variables describing vegetation wateruse (CAY/VEGINT) were reduced in the menu and dynamic files. An acceptable fit was achieved by using variables associated with intermediate pines (with intermediate site preparation) instead of mature Eucalyptus (with intensive site preparation).

Figures 5.7.3 and 5.7.4 show a graphical comparison of the simulated versus observed monthly time series and seasonal distribution respectively. Table 5.7.2 lists the *ACRU* statistics.

Table 5.7.2 : A Monthly Comparison of Simulated and Observed Runoff for Totals of Daily Flows (mm)

Total Observed Values	2678,917
Total Simulated Values	2304,249
Mean of Observed Values	8,118
Mean of Simulated Values	6,983
Correlation Coefficient	0,685
Regression Coefficient	0,540
Base Constant for Regrn. Eqn.	2,597
Variance of Observed Value	112,914
Variance of Simulated Values	70,212
Standard Deviation of Observed Values	10,626
Standard Deviation of Simulated Values	8,379

The time series indicates an improvement in the low flow fit although this problem is still evident in the seasonal distribution. The seasonal distribution also indicates that the high flows are slightly underpredicted. The statistics indicate an underestimation of the mean, and an average correlation coefficient. The cause of this average correlation is apparent in the time series where some severe monthly discrepancies are noted. Table 5.7.3 compares the monthly flows and rainfall for two of these cases.

Table 5.7.3 : Comparison of Monthly Flow and Rainfall

DATE	RAINFALL (mm)		FLOW (mm)	
	MONTHLY	DAILY	SIMULATED	OBSERVED
1967 02	232	20/23; 34/7	20	57
1974 02	202	53/58	68	45

Of interest is the similar monthly rainfall in 1967 02 and 1974 02 with distinctly different simulated flows. The reason for this can be found in the difference between the types of daily rainfall. The monthly rainfall in 1967 02 is made up of two mediocre events (each two days) while the monthly rainfall in 1974 02 is made up of a single large event (of two days) which produces more runoff. The consistency of the observed flow indicates that the sparse raingauge network failed to record the nature of the rainfall event in 1967 02. The annual flow comparison in Figure 5.7.5 shows an average scatter around the 1:1 line. Most of the wettest seasons are undersimulated and yield results can therefore be used with confidence.

5.7.4 Water Resources and Timber Yield

Figure 5.7.6 shows the graphical comparison of yields from a hypothetical dam using the "stochastic" and modified streamflow. Results show an increase in median MAR from 10 $m^3 \times 10^6$ to 13,5 $m^3 \times 10^6$ with an approximate increase in yield of ∞ 35% for the failure scenarios.

Figure 5.7.7 shows the timber yield comparison. Results show an increase in median timber yield of over 19%, from 390 m^3/ha/rotation to 465 m^3/ha/rotation.

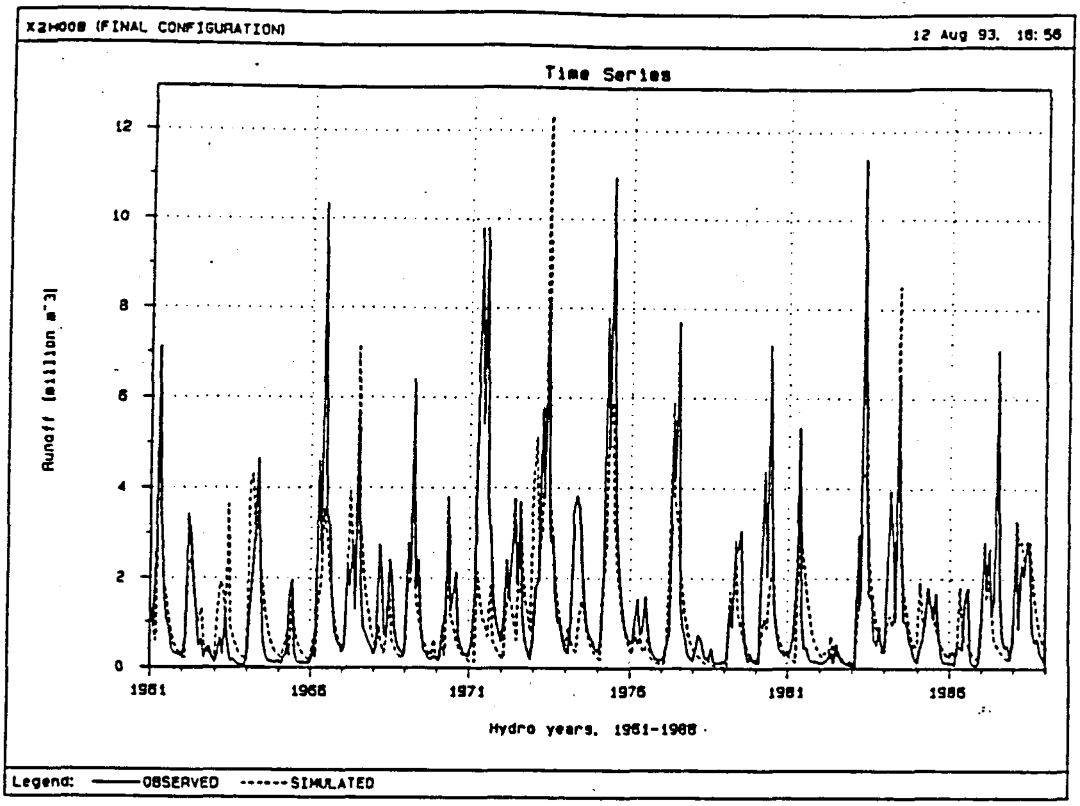


Figure 5.7.3 : Comparison of Observed and Simulated Flows at X2H008 (Final Configuration)

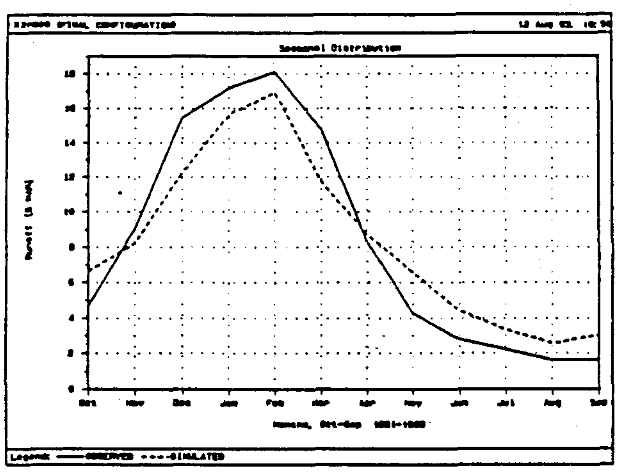


Figure 5.7.4 : Monthly Distribution of Means of Observed and Simulated Flows at X2H008

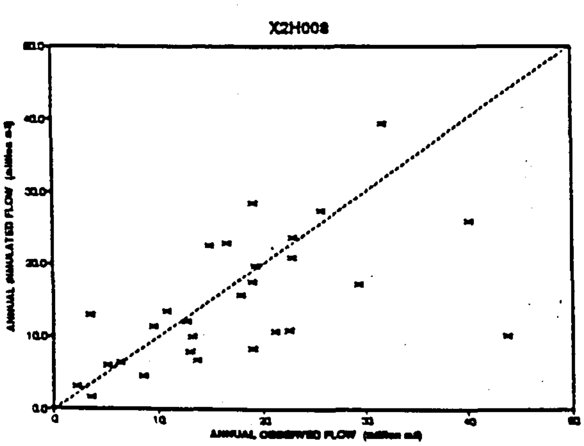


Figure 5.7.5 : Comparison of Annual Totals of Observed and Simulated Flows at X2H008

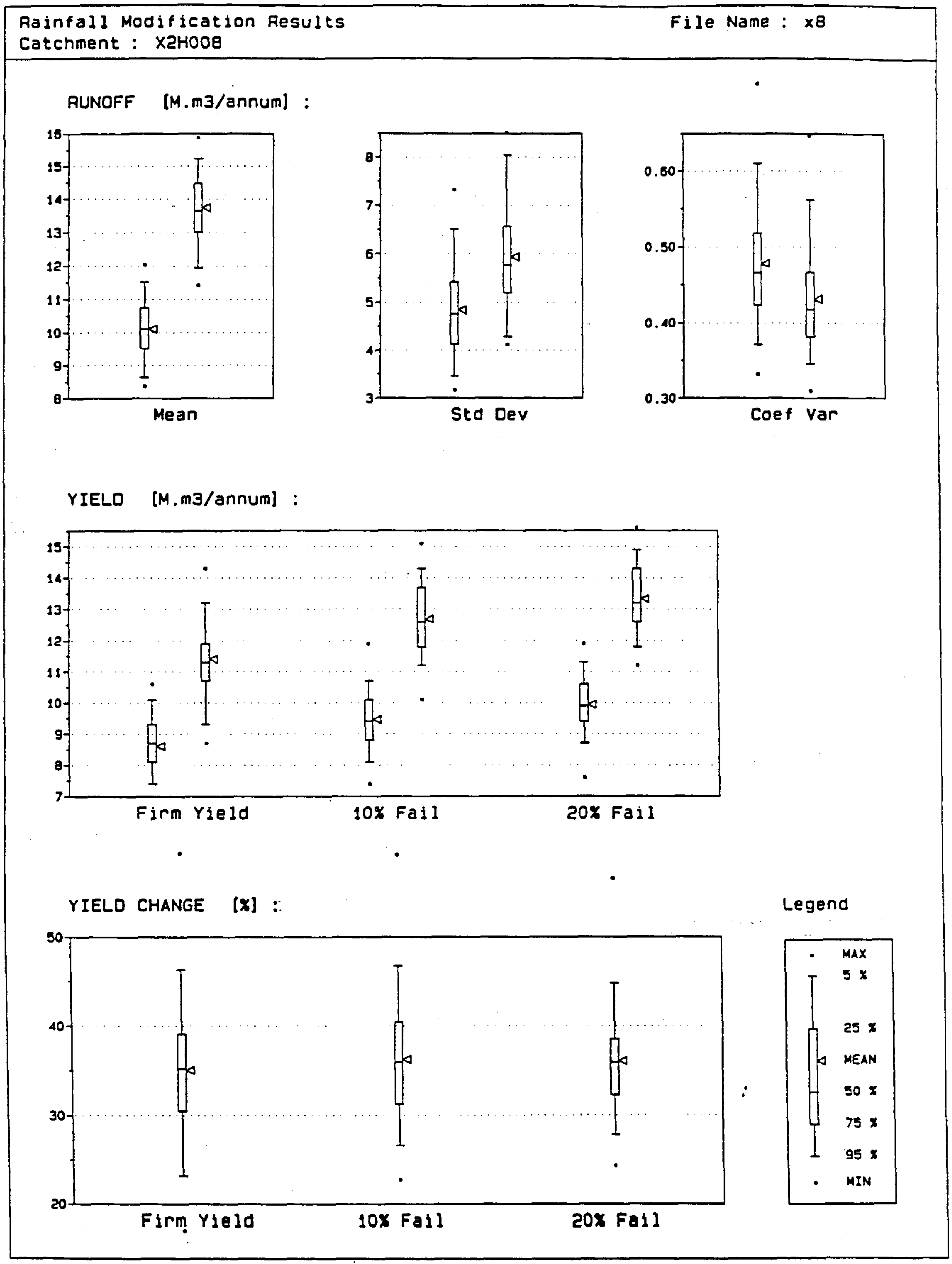


Figure 5.7.6 : Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at X2H008

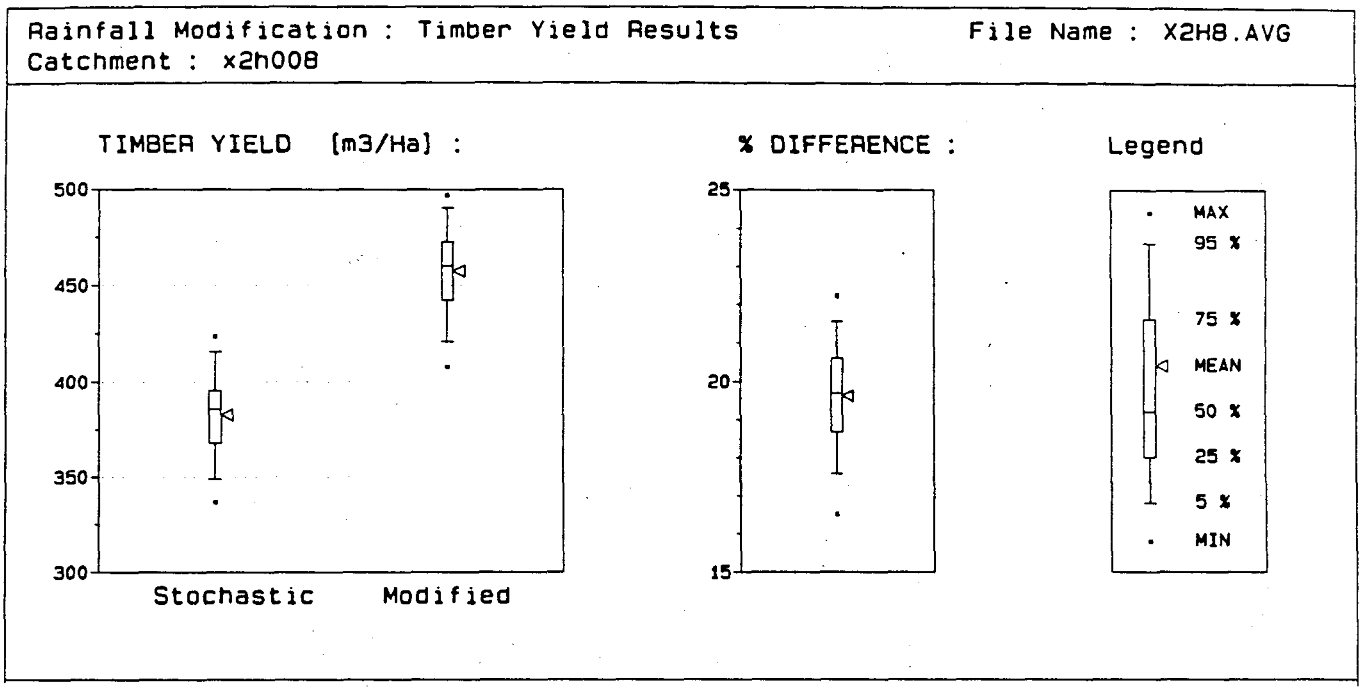


Figure 5.7.7 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at X2H008

5.8 X2H030

5.8.1 Input Information and Preparation

Figure 5.8.1 presents the current day land use in catchment X2H030. A summary of catchment data is presented in Table 5.8.1.

5.8.2 Evaluation of Flow Records

Flow records are available at X2H030 from 1966 to date. The model flow record from 1966 to 1989 was checked for unreliable data and patched with simulated flows where necessary.

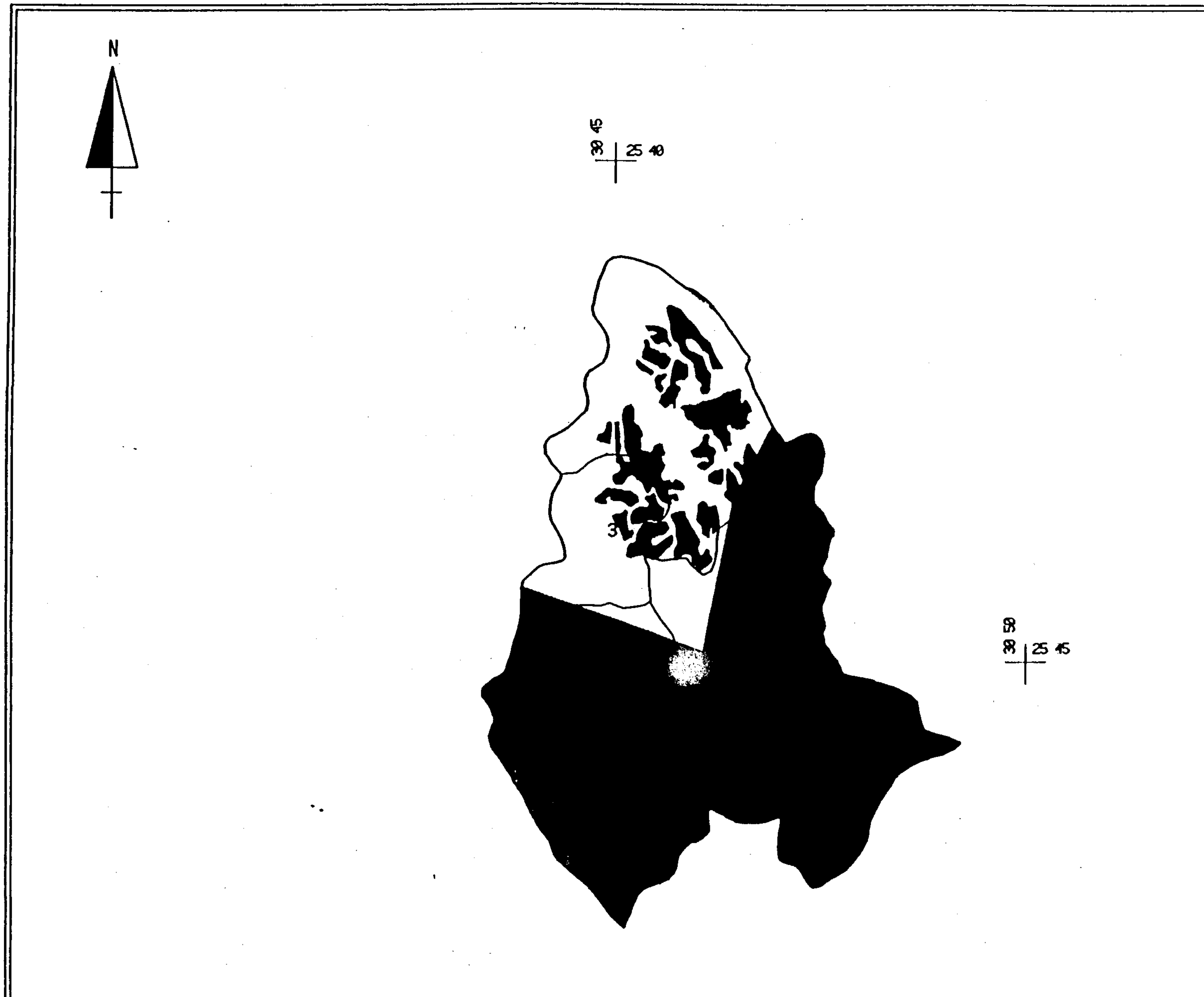
Table 5.8.1 : Summary of Catchment X2H030 Data

ITEM	VALUE	UNIT
Catchment Area	58,5	mm
Catchment MAP	1 133,0	km^2
1990 Agriculture Area	5,0	km^2
1990 Forest Area	38,0	km^2
1990 Irrigation Area	0,0	km^2
1990 Dam Capacity	0,03	$m^3 \times 10^6$
Observed MAR	16,7	$m^3 \times 10^6$
Runoff Coefficient	25,0	%
Area per rain gauge	60,0	km^2

5.8.3 Model Output Verification

The initial configuration of the *ACRU* model resulted in a severe underestimation of flow, particularly the winter low flows (Figure 5.8.2).

Attempts were made to improve the verification by changing soil and groundwater variables. The depths of the A and B horizons were decreased to 0,15 metres and the soil moisture redistribution rate (ABRESP/BFRESP) was increased to ∞ 0,7 to maintain peaks as well as increase low flows. These values correspond to a shallow soil depth with a sandy soil texture (Schulze *et al.*, 1989). Baseflow was also lagged (COFRU changed from 0,02 to 0,01) to increase the low flow. Various other variables were altered but little improvement was achieved.



SCALE

1 0 4km

LEGEND

CATCHMENT BOUNDARY

SUBC BOUNDARY

FORESTRY

AGRICULTURE

FARM DAMS

WATER RESEARCH COMMISSION

NINHAM SHAND inc.

CURRENT DAY LANDUSE IN CATCHMENT X2H030

Figure 5.8.1

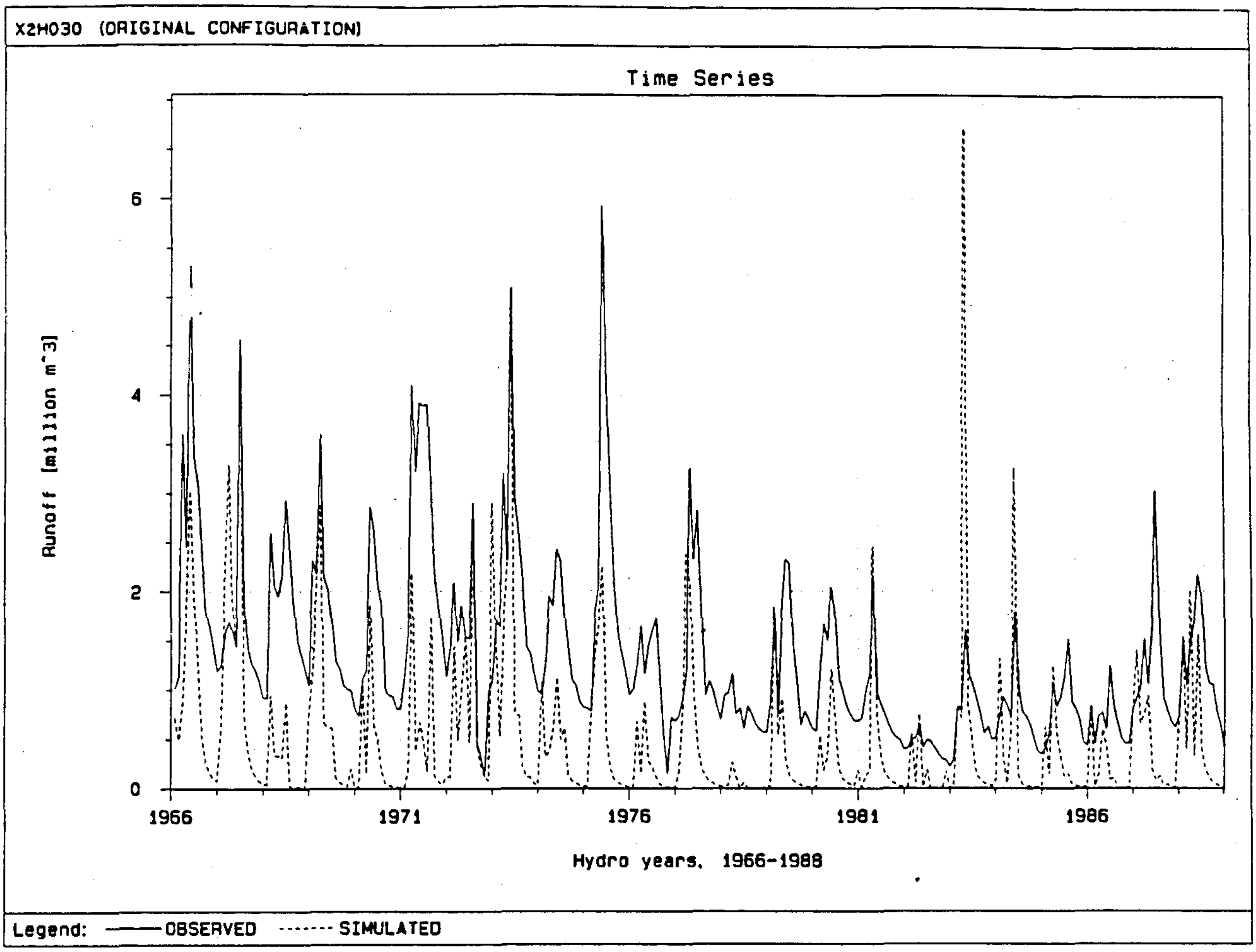


Figure 5.8.2 : Comparison of Observed and Simulated Flows at X2H030 (Original Configuration)

Figure 5.8.3 indicates the marginal improvement to the time series. This low flow problem is highlighted by the seasonal distribution (Figure 5.8.4) and statistics listed in Table 5.8.2. The seasonal distribution also indicates an overestimation peak although this is not a general trend in the time series. This is rather a result of a few months of excessive over-simulation (such as January, 1984). These individual discrepancies are probably caused by the sparse raingauge network recording thunderstorm activity that does not occur to the same extent over the whole catchment. The magnitude of the observed low flows in Table 5.8.3 suggest the occurence of an aquifer located on a phreatic divide as additional winter inputs to this catchment must be occuring. These winter trends listed in Table 5.8.3 occur throughout the record.

Table 5.8.2 : A Monthly Comparison of Simulated and Observed Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	5342,082
Total Simulated Values	3262,074
Mean of Observed Values	22,075
Mean of Simulated Values	13,480
Correlation Coefficient	0,412
Regression Coefficient	0,538
Base Constant Regrn. Eqn.	1,596
Variance of Observed Value	167,050
Variance of Simulated Values	285,014
Standard Deviation of Observed Values	12,925
Standard Deviation of Simulated Values	16,882

Table 5.8.3 : Comparison of Monthly Flow and Rainfall (mm)

DATE	RAINFALL (mm)	OBSERVED FLOW (mm)
1967 06	(10,3) 0,0	(41,6) 30,6
1968 07	(4,7) 8,3	(21,6) 20,3
1969 08	(9,2) 4,9	(23,1) 20,3
1975 08	(0,8) 2,2	(17,7) 15,0
1979 07	(0,5) 1,5	(11,2) 10,3
1985 07	(3,4) 0,0	(11,1) 8,7

( ) antecedent monthly rainfall/flow

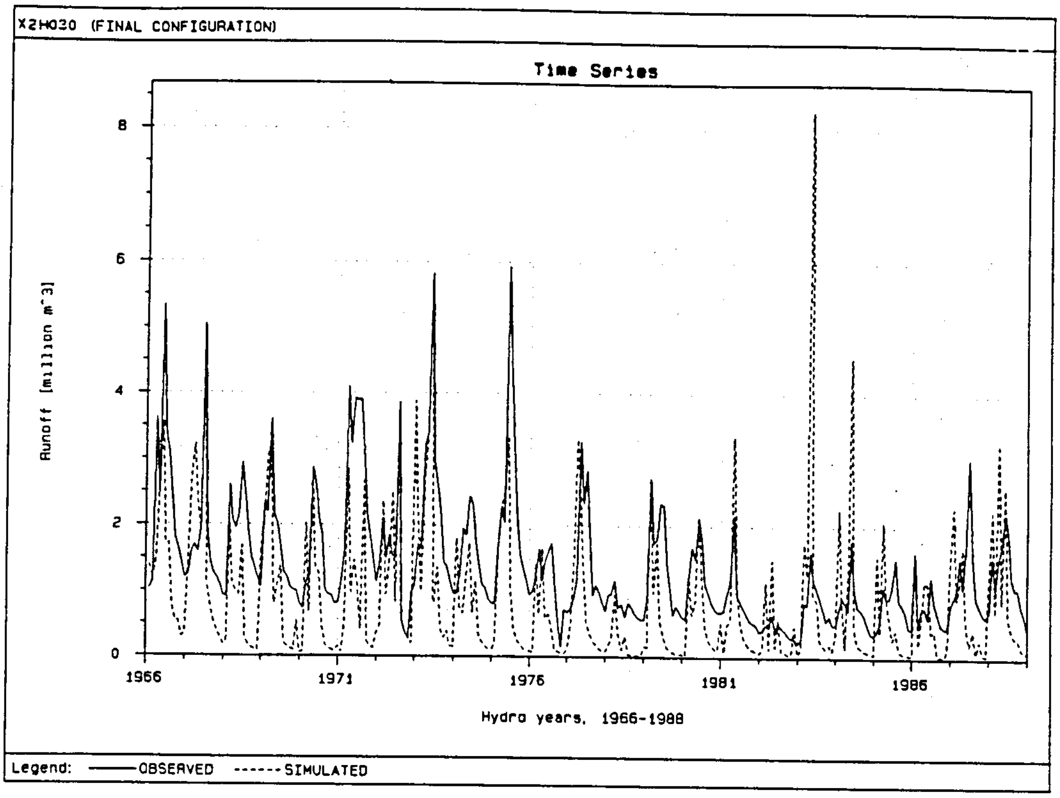


Figure 5.8.3 : **Comparison of Observed and Simulated Flows at X2H030 (Final Configuration)**

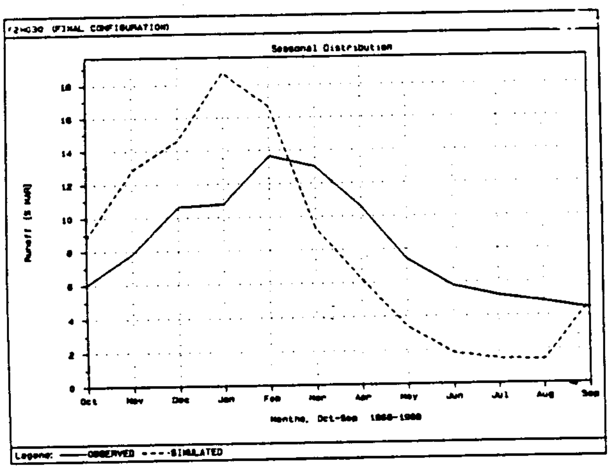


Figure 5.8.4 : Monthly Distribution of Means of Observed and Simulated Flows at X2H030

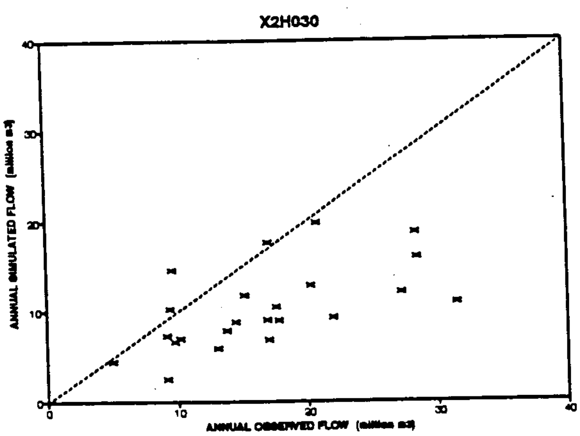


Figure 5.8.5 : Comparison of Annual Totals of Observed and Simulated Flows at X2H030

The scatter of annual flows shown in Figure 5.8.5 also indicate this problem of undersimulation. Since the simulated flows are underestimated this catchment can be used for yield assessments although the poor verification necessitates that this catchment be excluded from the regionalisation process.

5.8.4 Water Resources and Timber Yield

Figure 5.8.6 (see page 94) shows the graphical comparison of yields from a hypothetical dam using the "stochastic" based and modified streamflow. Results show an increase in median MAR from 8,5 $m^3 \times 10^6$ to 10,4 $m^3 \times 10^6$ with an approximate increase in yield of ∞ 23% for the three failure scenarios.

Figure 5.8.7 shows the timber yield comparison. Results show an increase in median timber yield of over 18%, from 275 m^3/ha/rotation to 325 m^3/ha/rotation.

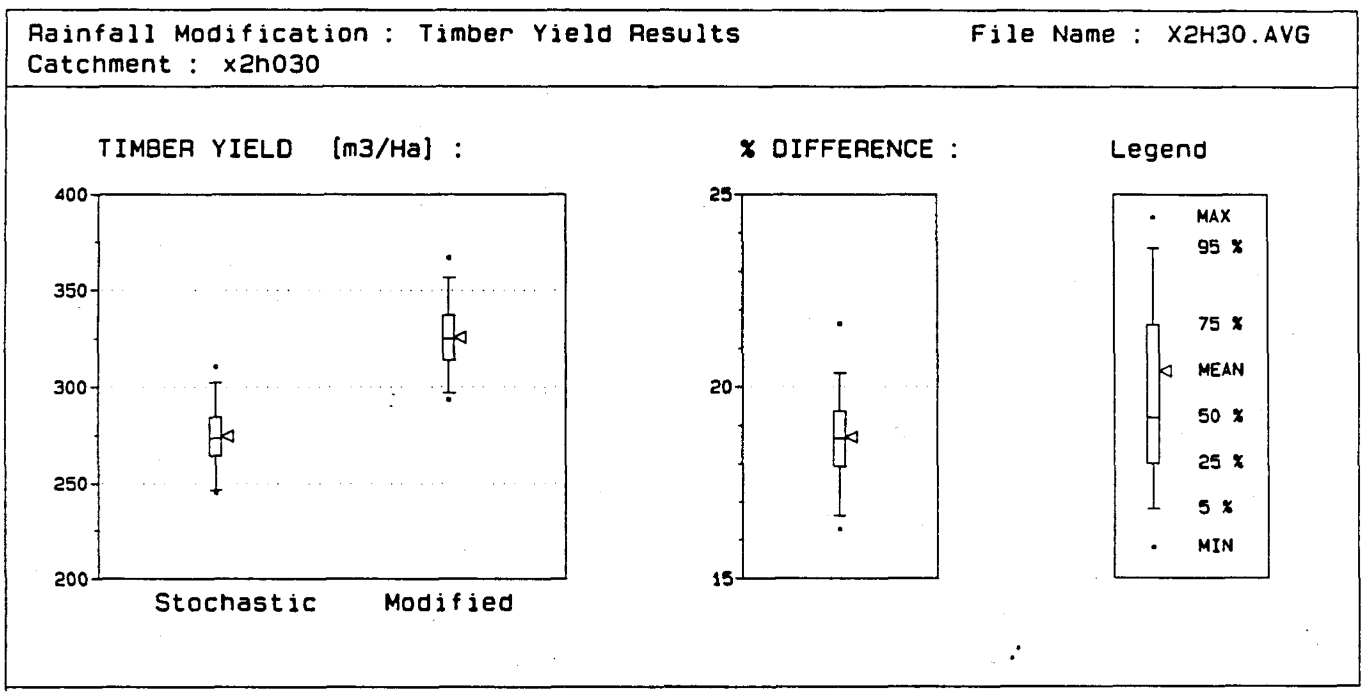


Figure 5.8.7 : Whisker-box Plots comparing Timber Yields Using Stochastic and Modified Rainfall at X2H030

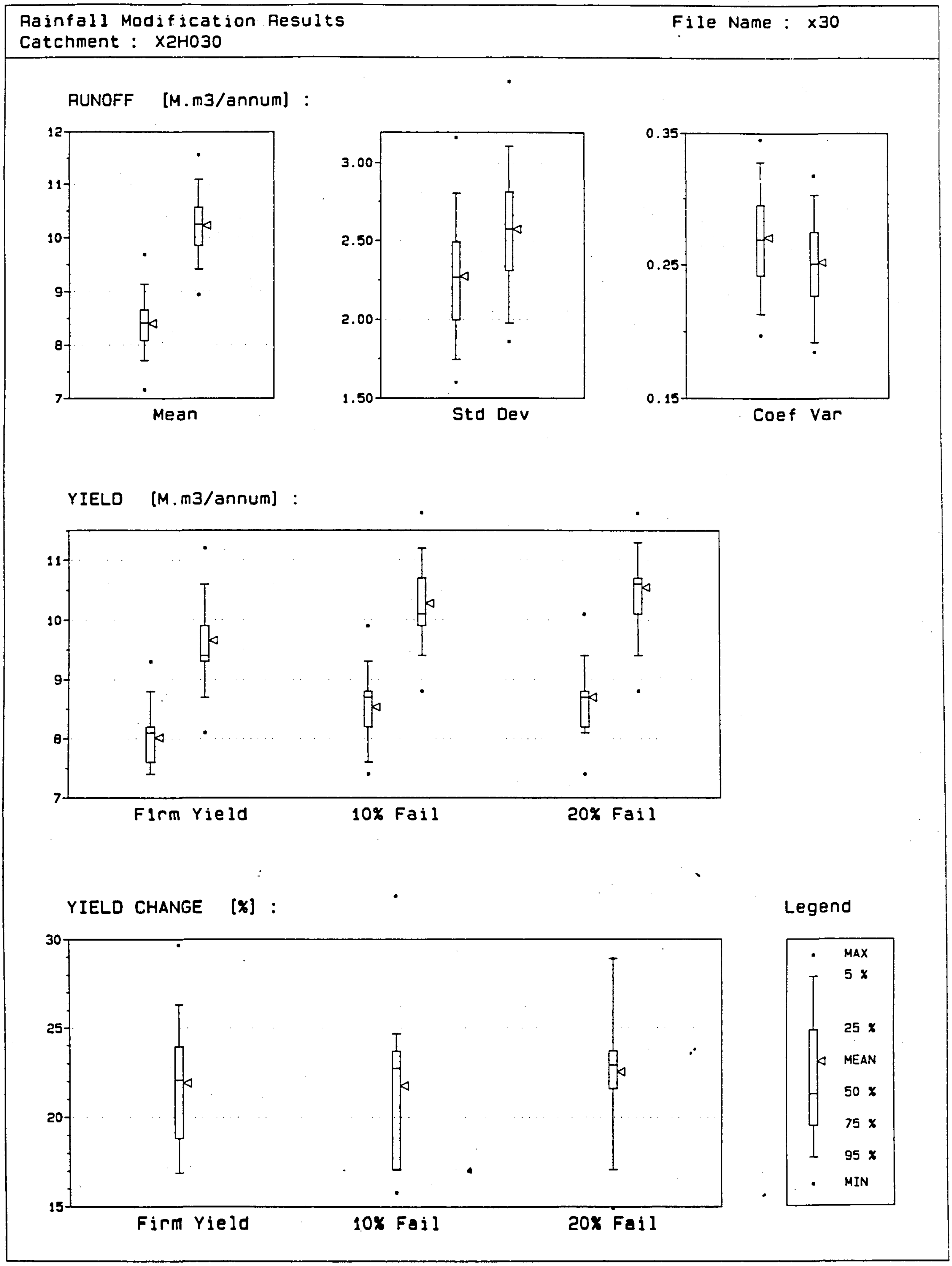


Figure 5.8.6 : **Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at X2H030**

5.9 X2H031

5.9.1 Input Information and Preparation

Figure 5.9.1 presents the current day land use for catchment X2H031. A summary of catchment data is presented in Table 5.9.1.

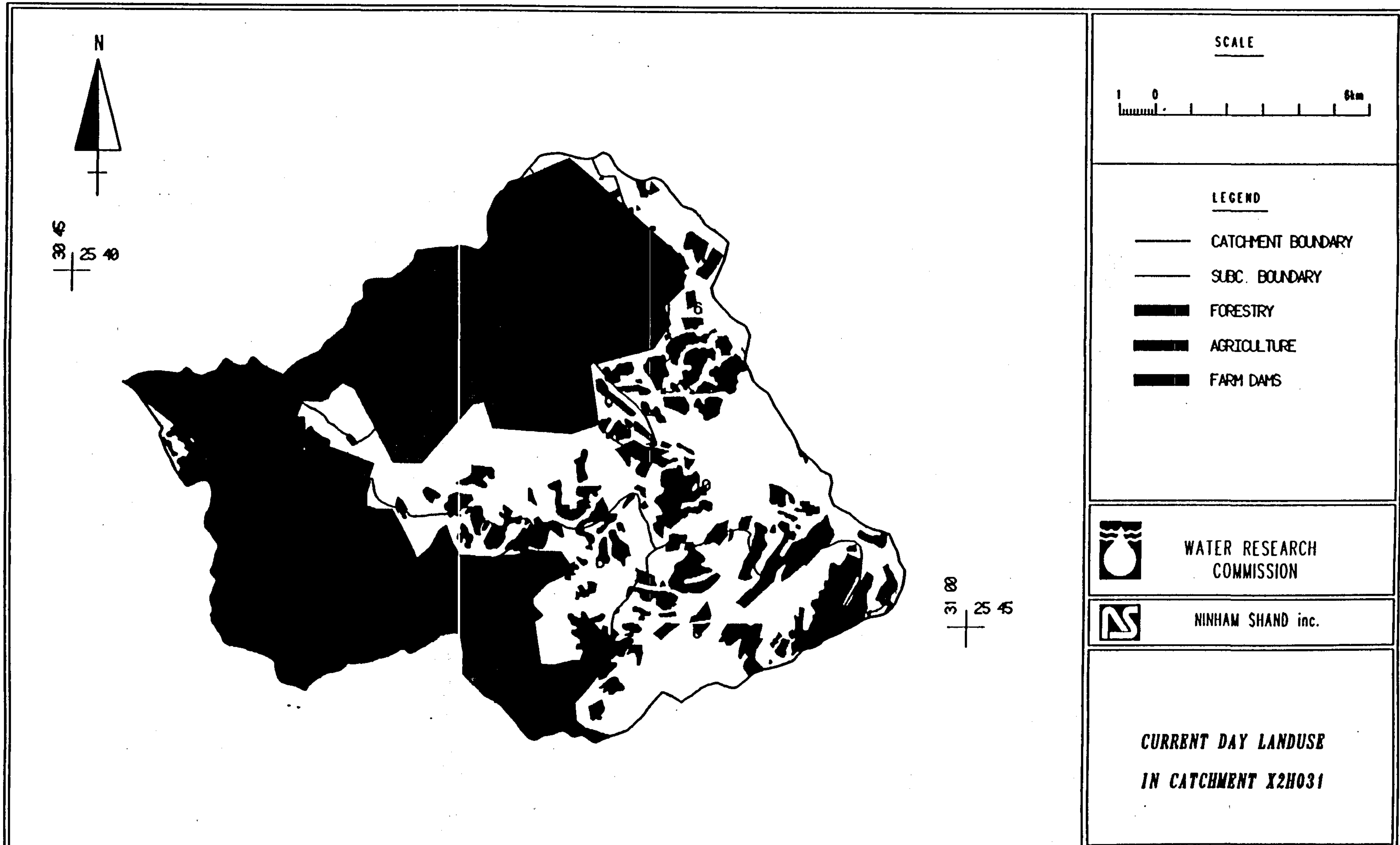
Table 5.9.1 : Summary of Catchment X2H031 Data

ITEM	VALUE	UNIT
Catchment Area (Incremental)	203,9	km^2
Catchment MAP	843,0	mm
1990 Agriculture Area	29,1	km^2
1990 Forest Area	103,1	km^2
1990 Irrigation Area	0,1	km^2
1990 Dam Capacity	1,0	$m^3 \times 10^6$
Observed MAR (Cumulative)	24,1	$m^3 \times 10^6$
Runoff Coefficient	14,0	%
Area per rain gauge	50,0	km^2

<u>Note</u> : Upstream catchment X2H030 data excluded.

5.9.2 Evaluation of flow records

Flow records are available at X2H031 from 1966 to date. This date coincides with the recorded inflow of X2H030 which flows into this catchment. The monthly flow record at X2H031 from 1970 to 1989 was checked for unreliable data and patched with simulated flows where necessary. The data from 1966 to 1970 were excluded owing to the large amount of unreliable data.



CURRENT DAY LANDUSE IN CATCHMENT X2H031

Figure 5.9.1

5.9.3 Model Output Verification

The original configuration of the *ACRU* model resulted in an acceptable fit. This configuration used the observed flows (patched with simulated flows) of the upstream X2H030 catchment which is discussed in section 5.8. Figures 5.9.2 and 5.9.3 show the observed monthly time series and seasonal distribution. Table 5.9.2 lists the *ACRU* monthly statistics.

Table 5.9.2 : A Monthly Comparison of Simulated and Observed Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	1931,2
Total Simulated Values	2161,2
Mean of Observed Values	7,9
Mean of Simulated Values	8,8
Correlation Coefficient	0,691
Regression Coefficient	0,798
Base Constant for Regrn. Eqn.	2,524
Variance of Observed Values	45,223
Variance of Simulated Values	60,216
Standard Deviation of Observed Values	6,725
Standard Deviation of Simulated Values	7,760

The time series indicates an acceptable simulation of the low flows with a variable (both over and under) simulation of peaks. This resulted in an average correlation coeffiecient and a seasonal distribution that indicates this is balanced out over the whole record. The annual flows shown in Figure 5.8.4 indicate an acceptable scatter about the 1:1 fit with the wettest seasons slightly undersimulated. Consequently, both the yield and regionalisation results may be used with confidence.

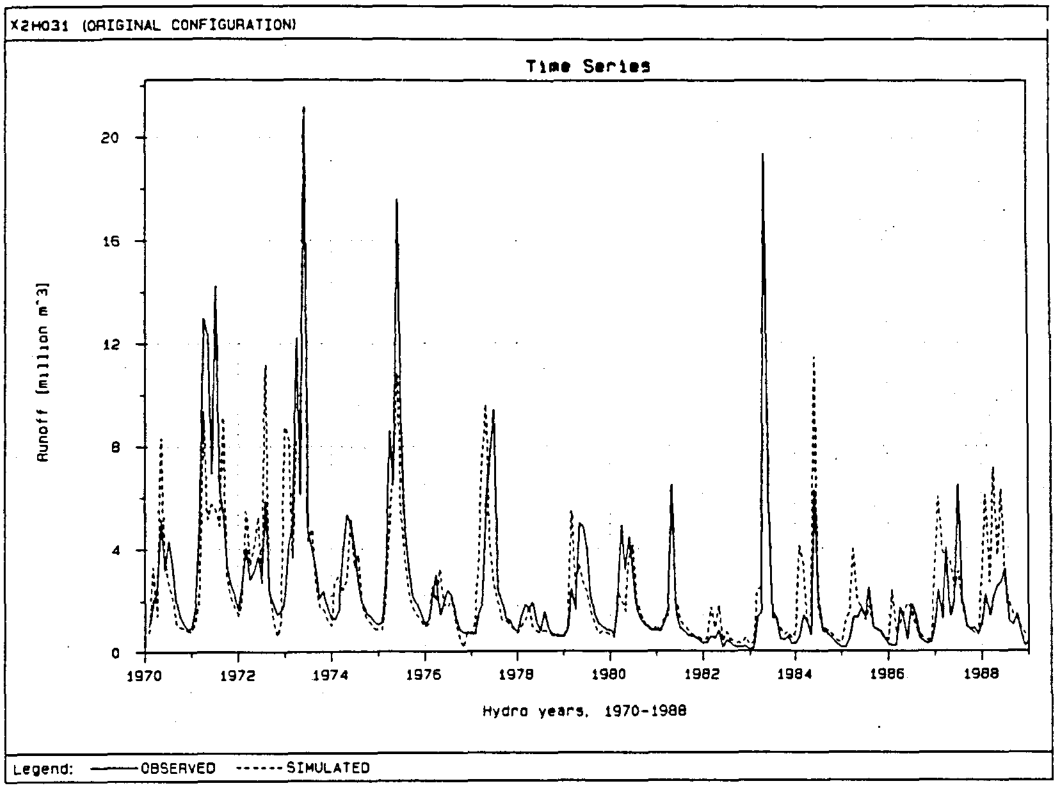


Figure 5.9.2 : Comparison of Observed and Simulated Flows at X2H031 (Original Configuration)

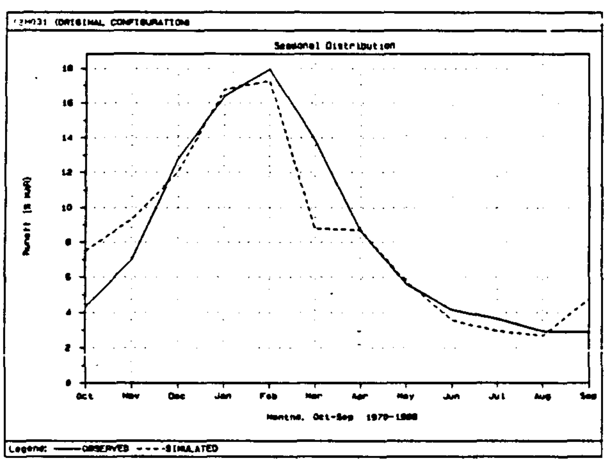


Figure 5.9.3 : Monthly distribution of Means of Observed and Simulated Flows at X2H031

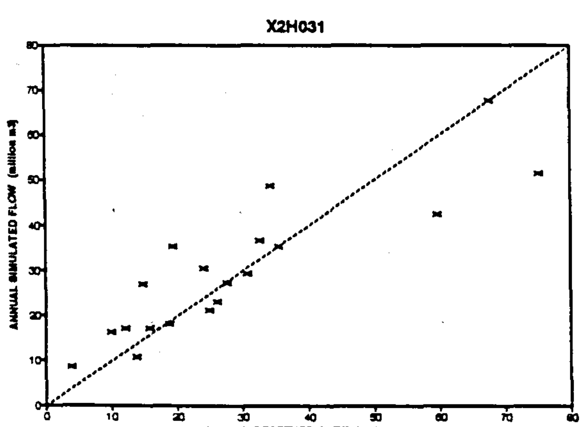


Figure 5.9.4 : Comparison of Annual Totals of Observed and Simulated Flows at X2H031

5.9.4 Water Resources and Timber Yield

Figure 5.9.5 (see page 100) shows the graphical comparison of yields from a hypothetical dam using the "stochastic" and modified streamflow. Results show an increase in median MAR from 23 $m^3 \times 10^6$ to 31 $m^3 \times 10^6$. This substantial increase in runoff and subsequent low coefficient of variability of the modified scenarios result in an increase in yield of ∞ 29% for the 3 failure scenarios.

Figure 5.9.6 shows the timber yield comparison. Results show an increase in median timber yield of 23%, from 280 m^3/ha/rotation to over 345 m^3/ha/rotation. A particularly low variability is associated with this catchment as there is only a 2% variation between the 5 percentile and 95 percentile.

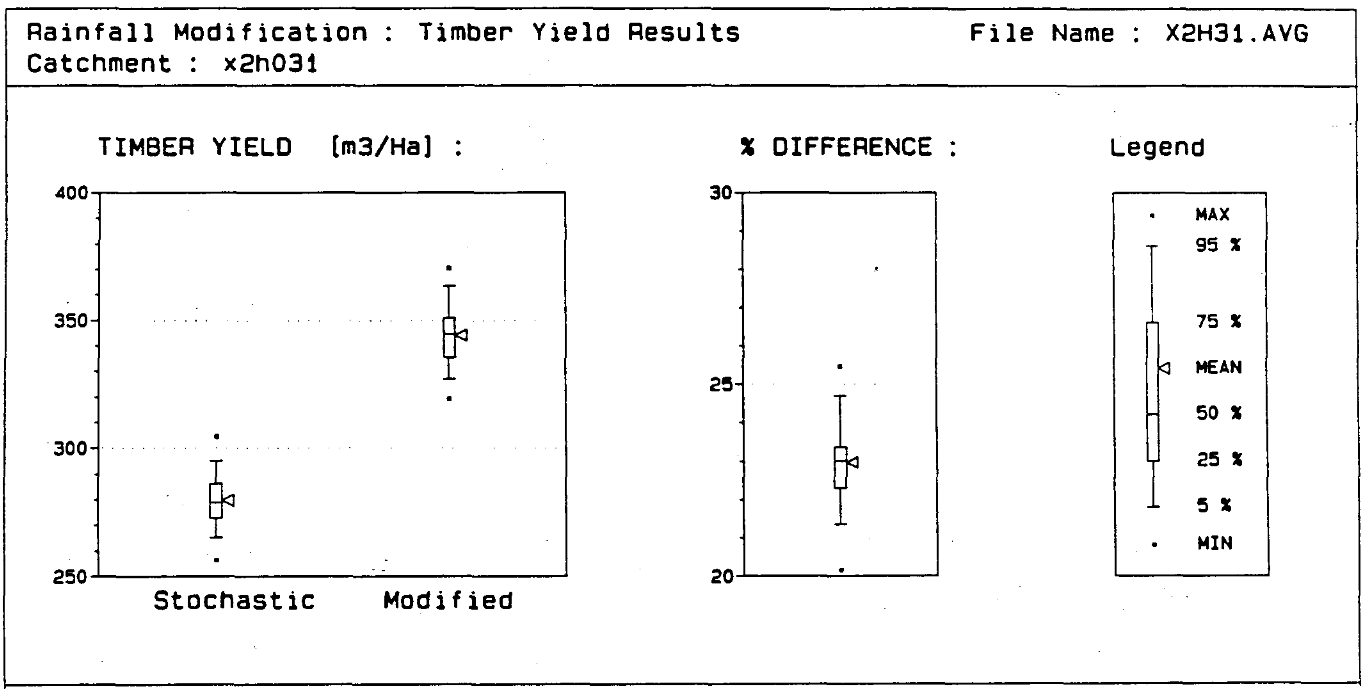


Figure 5.9.6 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at X2H031

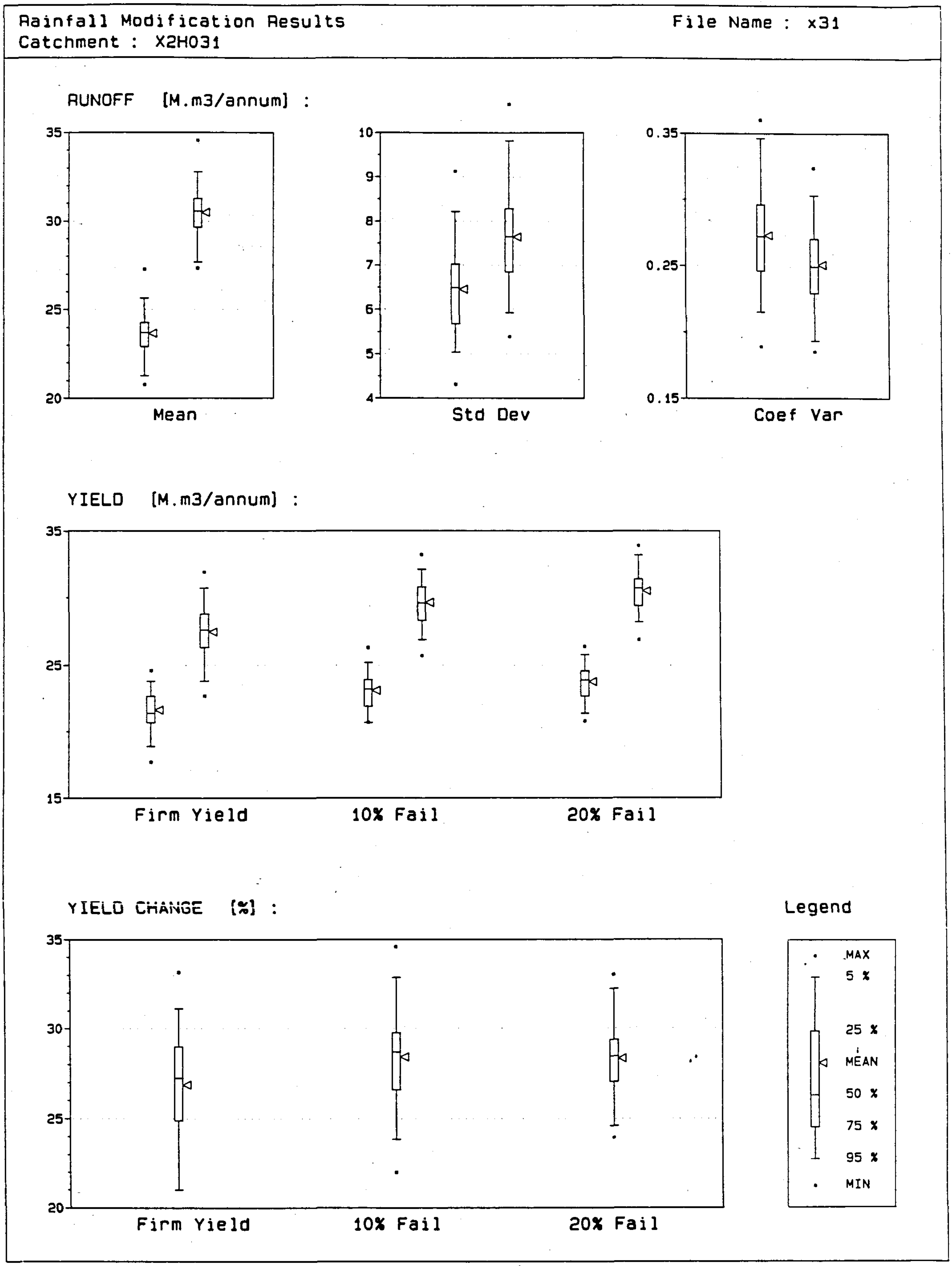


Figure 5.9.5 : Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at X2H031

5.10 W5H004

5.10.1 Input Information and Preparation

Figure 5.10.1 presents the current day land use for catchment W5H004. A summary of catchment data is presented in Table 5.10.1.

Table 5.10.1 : Summary of Catchment W5H004 Data

Item	Value	Unit
Catchment Area	450,6	km^2
Catchment MAP	825,0	mm
1990 Forest Area	117,1	km^2
1990 Agriculture Area	61,2	km^2
1990 Irrigation Area	8,64	km^2
1990 Farm Dam Capacity	13,46	$m^3 \times 10^6$
Obsersed MAR	33,3	$m^3 \times 10^6$
Runoff Coefficient	9,0	%
Area per rain gauge	150,0	km^2

5.10.2 Evaluation of Flow Records

Flow records are available at W5H004 from 1958 to date. The monthly flow records from January 1961 to December 1989 (the rainfall period) were checked for unreliable data and patched with simulated flows where necessary.

5.10.3 Model Output Verification

The original configuration of the *ACRU* model resulted in an acceptable verification (Figure 5.10.2). The seasonal distribution (Figure 5.10.3) indicates that both low flows and peaks are acceptably simulated. The correlation shown in the statistics (Table 5.10.2) is lower than expected as a result of individual monthly discrepancies evident in the time series. Table 5.10.3 lists two of these monthly discrepancies and compares them to a month with a good fit and with a similar rainfall. The simulator is constant so the variability of the observed flow suggests a problem with the observed rainfall/runoff data where thunderstorm activity recorded by the sparse raingauge network has not occurred to the same extent over the catchment surface.

The annual flows shown in Figure 5.10.4 indicate an acceptable scatter around the 1:1 line although a few of the wet seasons are overpredicted. Outliers are due to problems with areal rainfall estimation. Care should be taken when analysing water resources yields from this catchment.

Table 5.10.2 : A Comparison of Monthly Simulated and Observed Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	2226,1
Total Simulated Values	2249,5
Mean of Observed Values	6,5
Mean of Simulated Values	6,6
Correlation Coefficient	0,712
Regression Coefficient	0,796
Base Constant for Regrn. Eqn.	1,389
Variance of Observed Value	91,6
Variance of Simulated Values	114,7
Standard Deviation of Observed Values	9,6
Standard Deviation of Simulated Values	10,7

Table 5.10.3 : Comparison of Monthly Flows and Rainfall

Date	Rainfall (mm)	Runoff (mm)	
		Simulated	Observed
1965 12	244	41	6
1968 11	217	57	16
1978 01	260	48	41

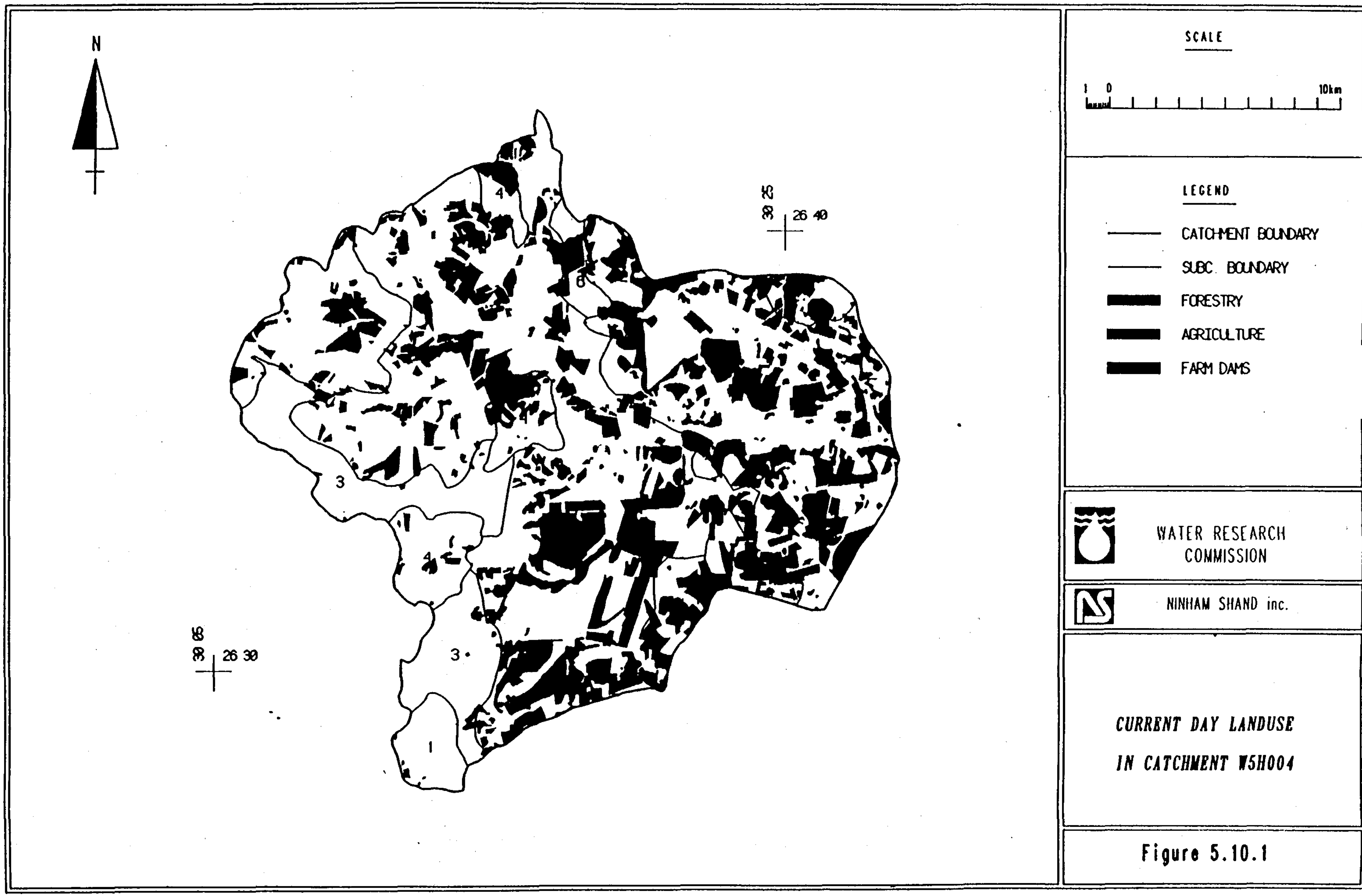

N
26 40
26 30
4
6
3
4
3
1
SCALE
0
10km
LEGEND
CATCHMENT BOUNDARY
SUBC. BOUNDARY
FORESTRY
AGRICULTURE
FARM DAMS
WATER RESEARCH COMMISSION
NINHAM SHAND inc.
CURRENT DAY LANDUSE
IN CATCHMENT W5H004

Figure 5.10.1

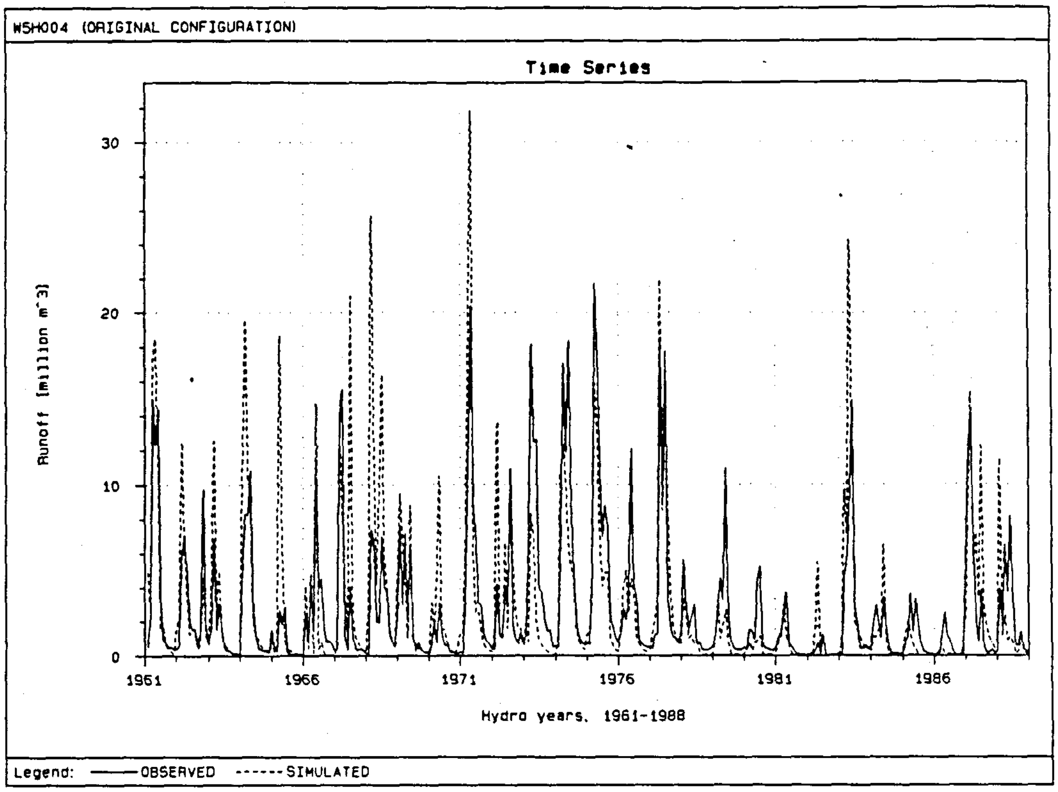


Figure 5.10.2 : Comparison of Observed and Simulated Flows at W5H004 (Original Configuration)

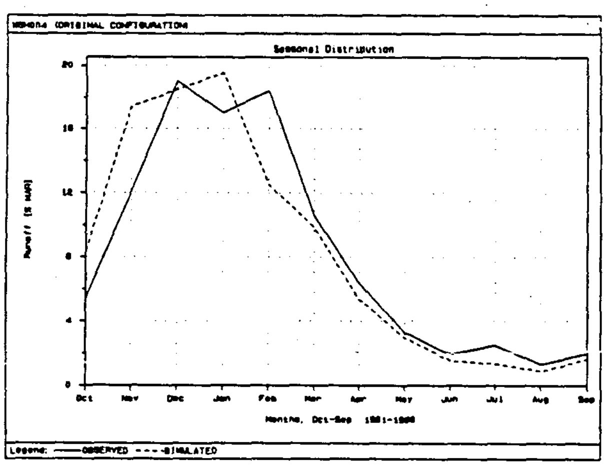


Figure 5.10.3 : Monthly Distribution of Means of Observed and Simulated Flows at W5H004

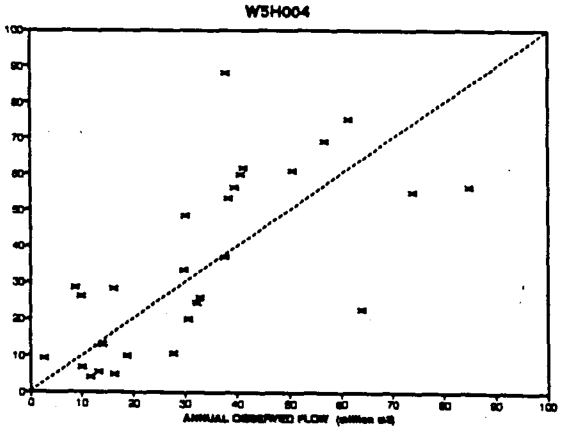


Figure 5.10.4 : Comparison of Annual Totals of Observed and Simulated Flows at W5H004

5.10.4 Water Resources and Timber Yield

Figure 5.10.5 (see page 106) shows the graphical comparison of yield from a hypothetical dam using the "stochastic based and modified streamflow. Results show an increase in median·MAR from 27 m³ x 10⁶ to 35 m³ x 10⁶ and an increase in yield of ∞ 30% for the three failure scenarios.

Figure 5.10.6 shows the timber yield comparison. Results show an increase in median timber yield of 23%, from over 300 m³/ha/rotation to 370 m³/ha/rotation.

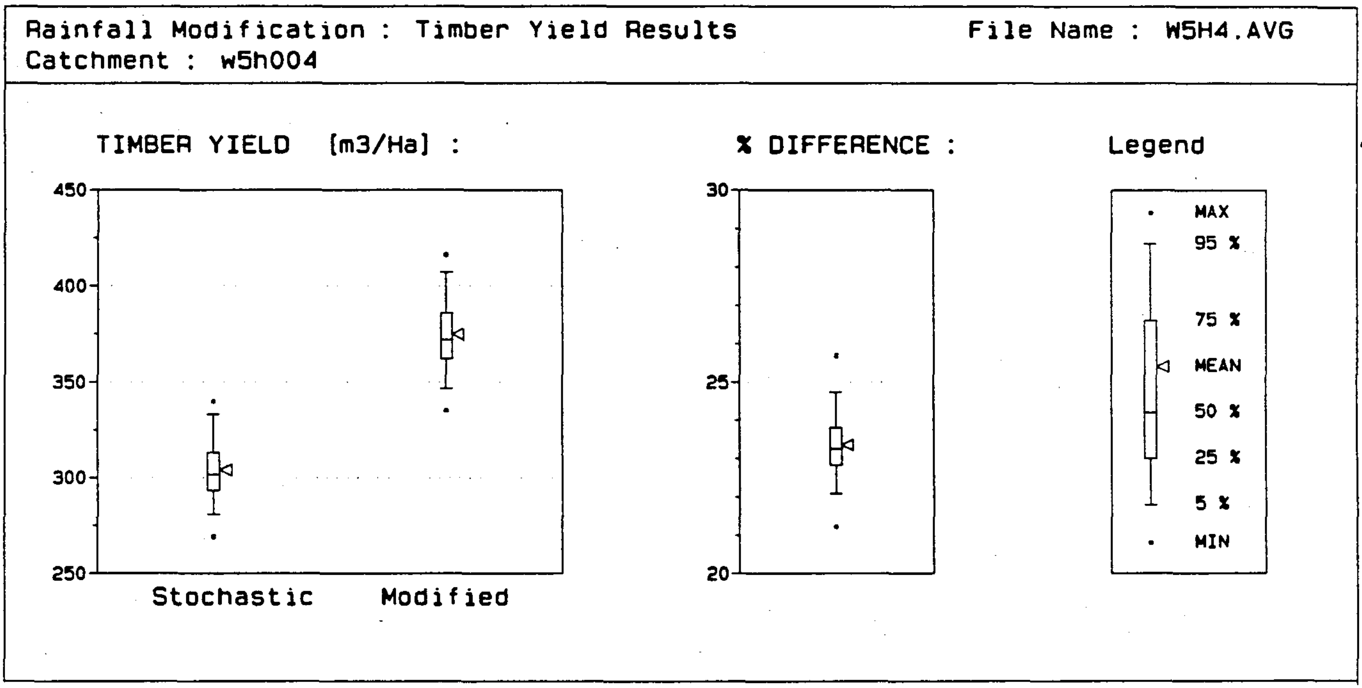


Figure 5.10.6 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at W5H004

5.11 W5H008

5.11.1 Input Information and Preparation

Figure 5.11.1 presents the current day land use in catchment W5H008. A summary of catchment data is presented in Table 5.11.1.

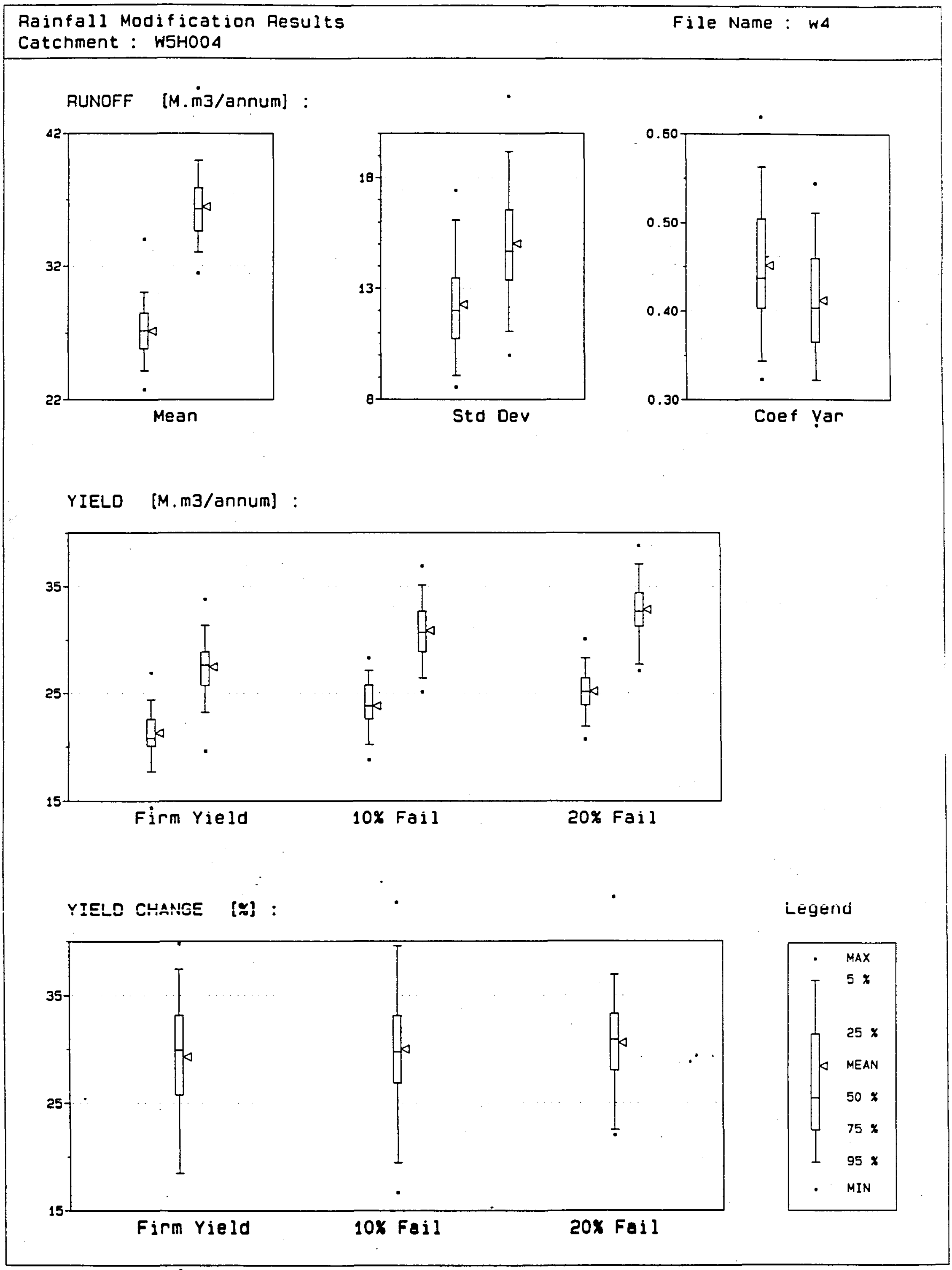


Figure 5.10.5 : **Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at W5H004**

Table 5.11.1 : Summary of Catchment W5H008 Data

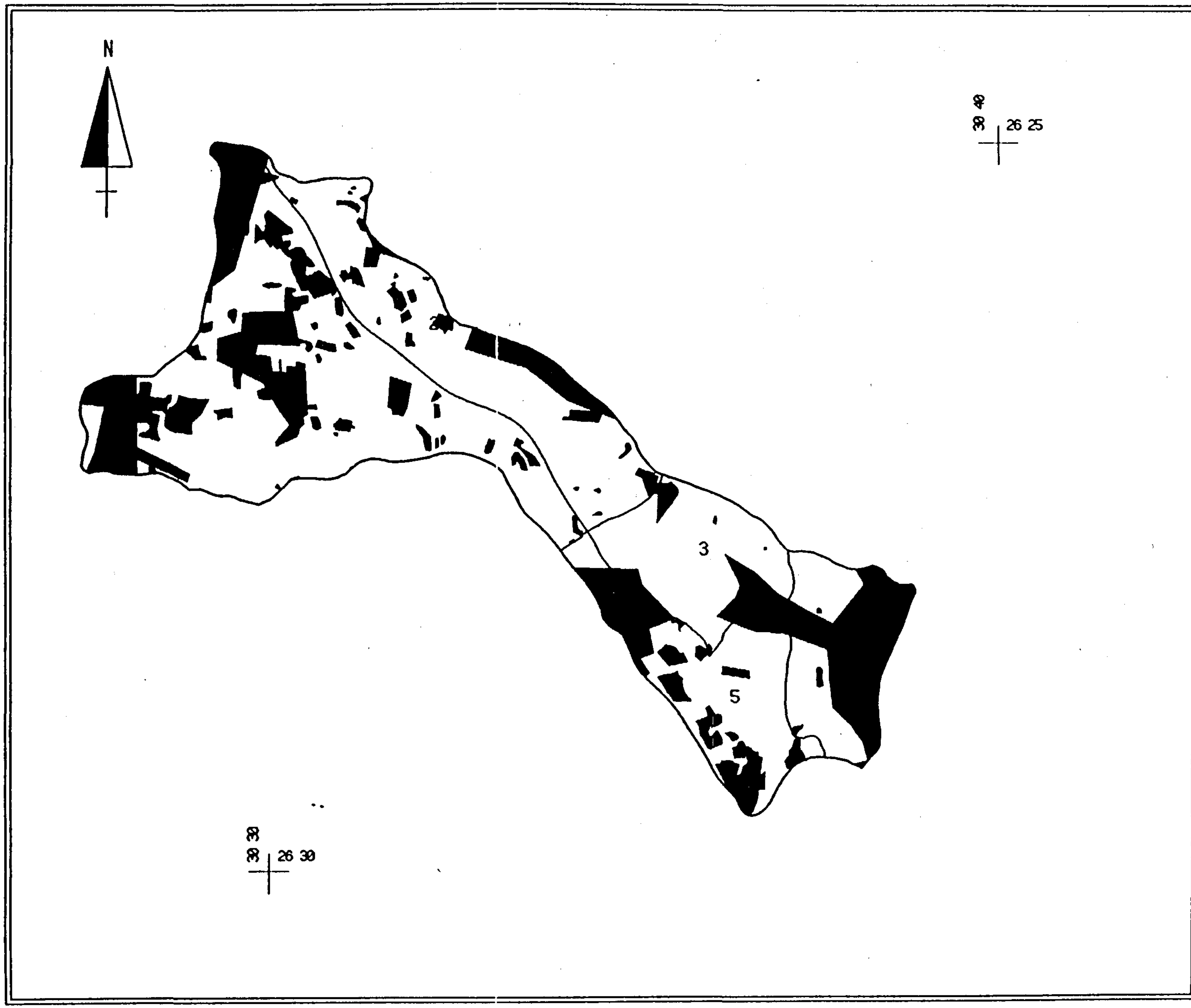
Item	Value	Unit
Catchment Area	109,1	km^2
Catchment MAP	850,0	mm
1990 Forest Area	26,3	km^2
1990 Agriculture Area	11,5	km^2
1990 Irrigation Area	5,13	km^2
1990 Farm Dam Capacity	2,06	$m^3 \times 10^6$
Observed MAR	11,1	$m^3 \times 10^6$
Runoff Coefficient	12,0	%
Area per rain gauge	55,0	km^2

5.11.2 Evaluation of flow records

Flow records are available at W5H008 from 1954 to date. The flow records of a canal (W5H029) which abstracts water upstream of W5H008 is available from 1985 to date. Before 1985 no abstraction took place. The catchment flow is estimated by adding W5H008 and W5H029. The monthly flow from January 1961 to December 1989 (the rainfall period) were checked for unreliable data and patched with simulated flows where necessary.

5.11.3 Model Output Verification

The original configuration of the *ACRU* model resulted in an unacceptable verification (Figure 5.11.2) with an overestimation of the peaks and underestimation of low flow.



CURRENT DAY LANDUSE IN CATCHMENT W5H008

Figure 5.11.1

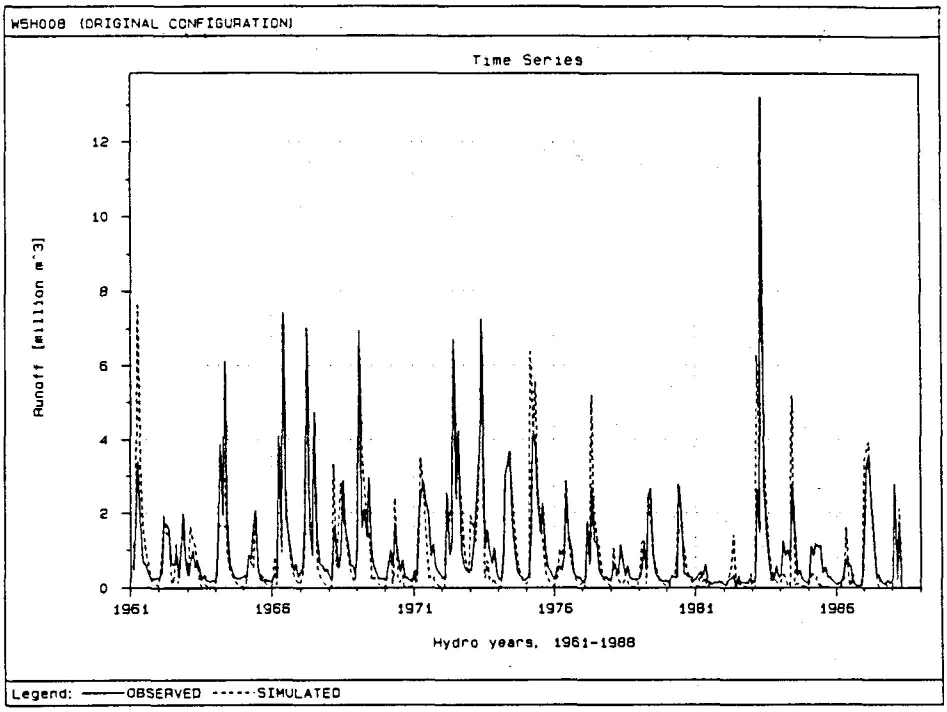


Figure 5.11.2 : Comparison of Observed and Simulated Flows at W5H008 (Original Configuration)

Improvements to the verification were made by changing soil and groundwater variables. The depth of both the A and B horizons was increased by ∞ 10% to lower the summer peaks. In addition the soil moisture redistribution rate (ABRESP/BFRESP) was increased to ∞ 0,7 to increase low flows. These changes correspond to a medium soil depth with a loamy sand texture (Schulze *et al.*, 1989). In addition, the groundwater contribution was lagged.

The time series and seasonal distribution in Figures 5.11.3 and 5.11.4 indicate an acceptable fit. The statistics listed in Table 5.11.2 indicate that the simulated and observed flows have a similar mean and standard deviation and an acceptable correlation. The time series indicates a few monthly discrepancies. As discussed in previous sections, this is most likely caused by the sparse rain gauge network recording non-representative catchments rainfall.

The annual flows shown in Figure 5.11.5 indicates a good scatter around the 1:1 line. The water resource yields results can therefore be used with confidence.

Table 5.11.2 : A Comparison of Monthly Simulated and Observed Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	2194,6
Total Simulated Values	2127,0
Mean of Observed Values	7,1
Mean of Simulated Values	6,9
Correlation Coefficient	0,759
Regression Coefficient	0,770
Base Constant for Regrn. Eqn.	1,418
Variance of Observed Value	60,4
Variance of Simulated Value	62,3
Standard Deviation of Observed Values	7,8
Standard Deviation of Simulated Values	7,9

5.11.4 Water Resources and Timber Yield

Figure 5.11.6 shows a graphical comparison of yields from a hypothetical dam using the stochastic based and modified streamflow. Results show an increase in the median MAR from 6,8 $m^3 \times 10^6$ to 9,9 $m^3 \times 10^6$. This significant increase in runoff and lower coefficient of variability of the modified scenarios result in an increase in yield of ∞ 45% for the three failure scenarios, the highest of all the study catchments.

Figure 5.11.7 shows the timber yield comparison. Results show an increase in median timber yield of 29% which is also a significantly higher increase than the other catchments.

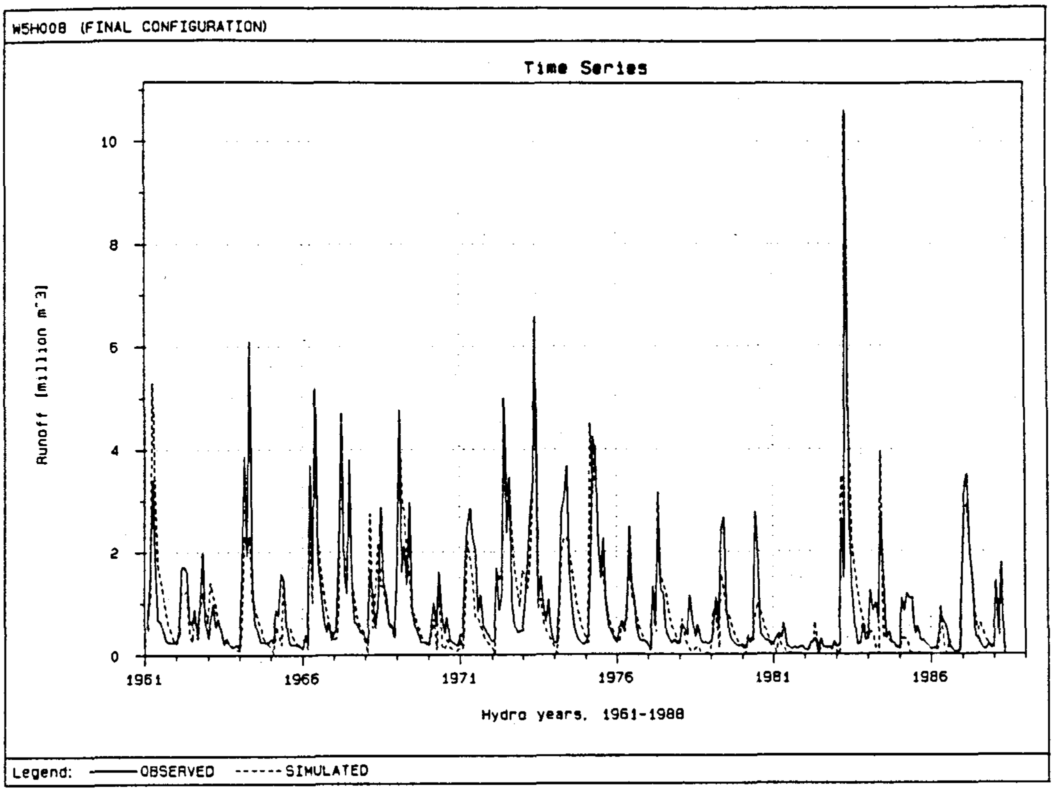


Figure 5.11.3 : Comparison of Observed and Simulated Flows at W5H008 (Final Configuration)

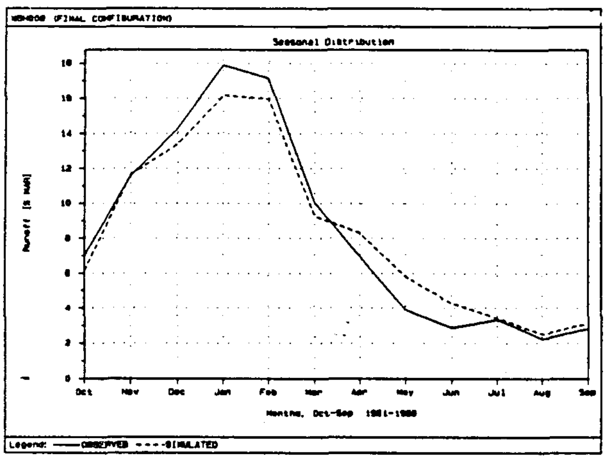


Figure 5.11.4 : Monthly Distribution of Means of Observed and Simulated Flows at W5H008

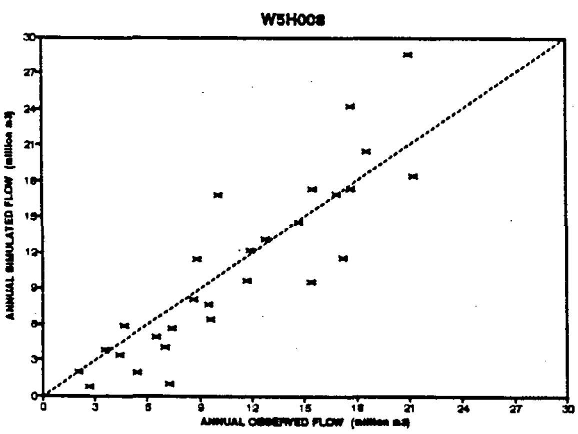


Figure 5.11.5 : Comparison of Annual Totals of Observed and Simulated Flows at W5H008

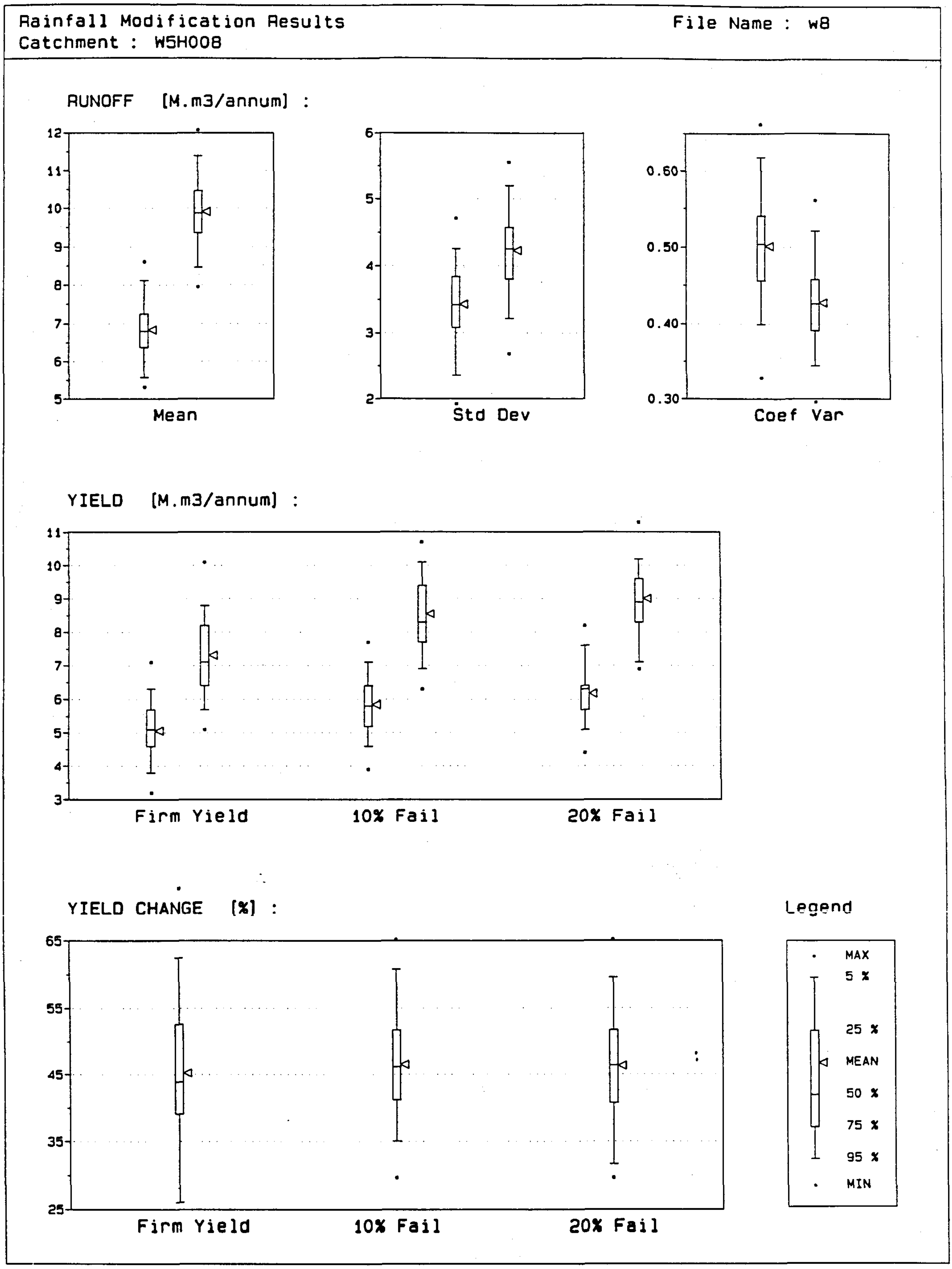
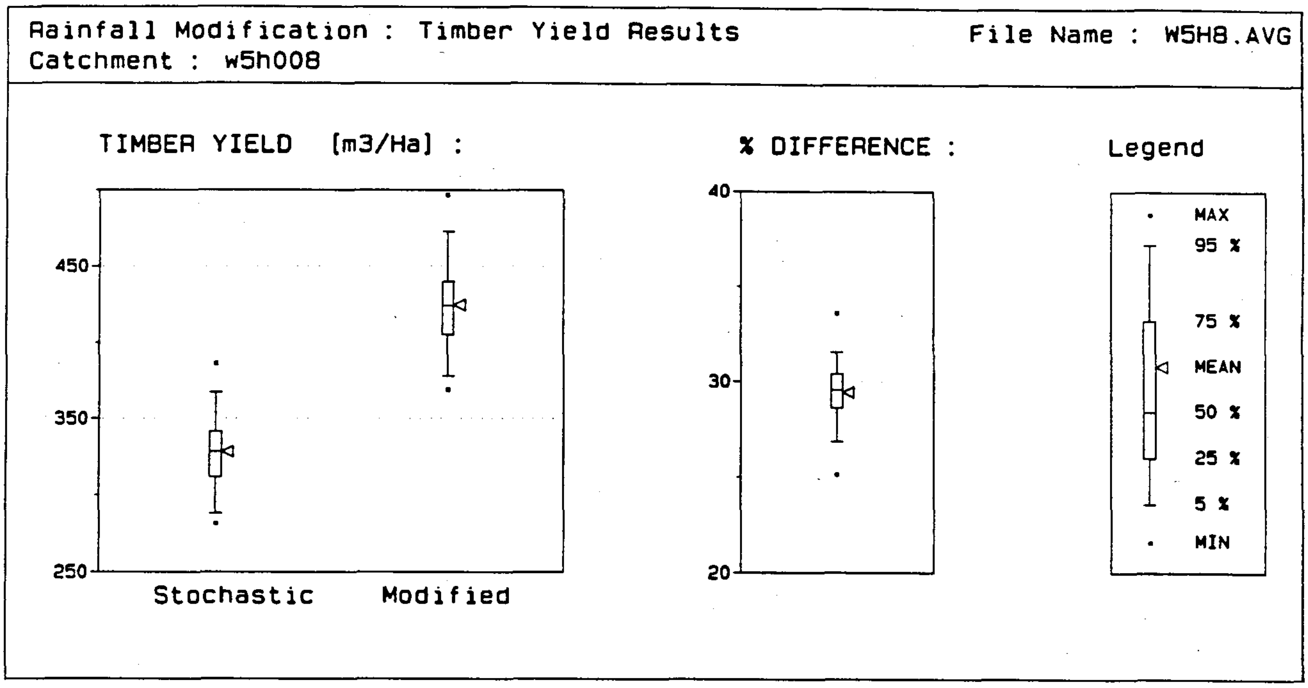


Figure 5.11.6 : **Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at W5H008**

Figure 5.11.7 : Whisker-box Plots comparing Timber Yields and Modified Rainfall at



5.12 W5H024

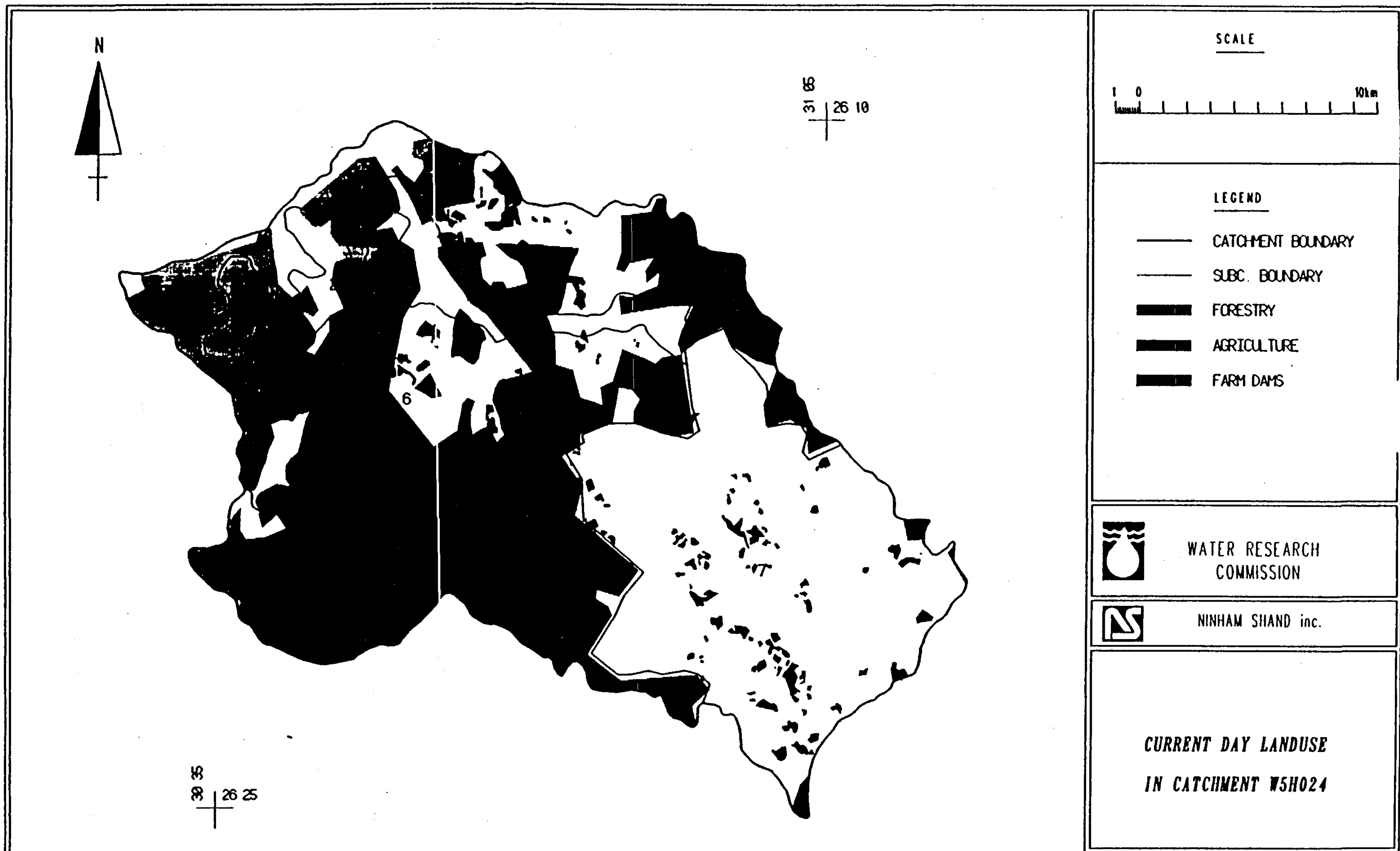
5.12.1 Input Information and Preparation

Figure 5.12.1 presents current day land use for catchment W5H024. A summary of catchment data is presented in Table 5.12.1.

TABLE 5.12.1 : Summary of Catchment W5H024 Data

Item	Value	Unit
Catchment Area (Incremental)	535,4	km^2
Catchment MAP	900,0	mm
1990 Forest Area	246,3	km^2
1990 Agriculture Area	13,6	km^2
1990 Irrigation Area	4,07	km^2
1990 Farm Dam Capacity	3,49	$m^3 \times 10^6$
Observed MAR (Cumulative)	94,9	$m^3 \times 10^6$
Runoff Coefficient	7,3	%
Area per rain gauge	134,0	km^2

Note: Upstream catchment W5H011 ignored.



CURRENT DAY LANDUSE IN CATCHMENT W5H024

Figure 5.12.1

5.12.2 Evaluation of flow records

Flow records are available at W5H024 from 1976 to date. The inflow from an upstream catchment (W5H011) is also applicable and is available from 1963 to date. The monthly flow record from October 1976 to September 1989 at W5H024 was checked for unreliable data and patched with simulated flows where necessary.

5.12.3 Model Output Verification

The configuration used observed flows (patched with simulated flows) of the upstream W5H011 catchment. The original configuration of the *ACRU* model resulted in an unacceptable verification (Figure 5.12.2) with an underestimation of low flows and an underestimation of the mean.

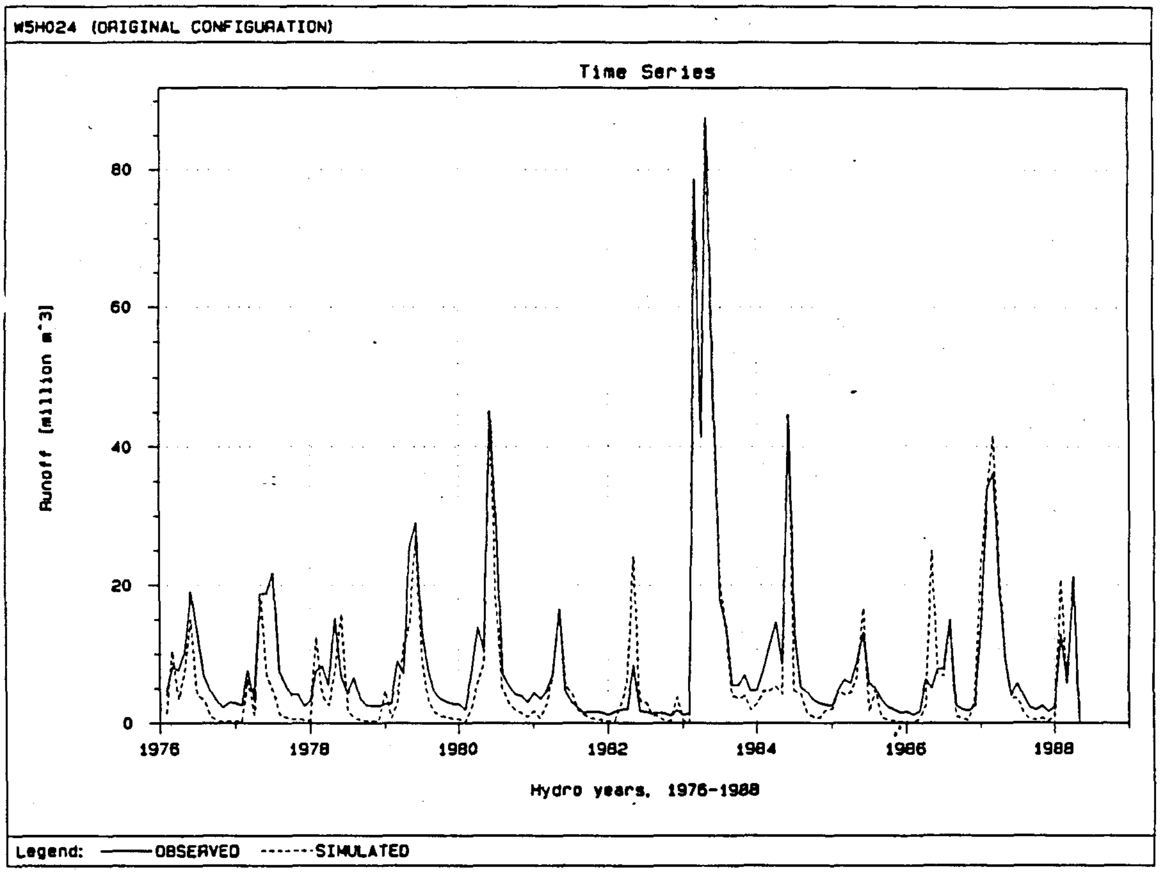


Figure 5.12.2 : Comparison of Observed and Simulated Flows at W5H024 (Original Configuration)

Improvements to the verification were made by changing soil and groundwater variables. The depth of both the A and B horizon (DEPA/DEPB) was decreased by ∞ 10% to improve the mean while the soil moisture redistribution rate (ABRESP/BFRESP) was increased to ∞ 0,7 to increase low flows. These changes correspond to a moderately shallow soil depth with a loamy sand texture (Schulze *et al.,*, 1989). In addition, the groundwater contribution was lagged to improve the later winter low flows. The effective depth of soil contribution to stormflow production (SMDDEP) was increased to 0,4 metres to redistribute peak flow runoff to groundwater.

These changes improved the low flows but lowered peak flows in the early part of the record. The variables describing vegetation water use (CAY and VEGINT) were decreased in the menu by ∞ 10% to improve the water balance until the start of the first dynamic file in 1980.

The time series and seasonal distribution (Figures 5.12.3 and 5.12.4) show an accurate simulation. The statistics listed in Table 5.12.2 reflect an exceptionally accurate simulation. The annual flow shown in Figure 5.12.5 also indicates a close fit around the 1:1 list, and results of further work can be accepted with confidence.

Table 5.12.2 : A Comparison of Monthly Simulated and Seasonal Runoff for Monthly Totals of Daily Flows (mm)

Total Observed Values	481,5
Total Simulated Values	488,5
Mean of Observed Values	4,0
Mean of Simulated Values	4,0
Correlation Coefficient	0,881
Regression Coefficient	0,998
Base Constant for Regrn. Eqn.	0,065
Variance of Simulated Values	14,6
Variance of Observed Values	18,8
Standard Deviation of Observed Values	3,8
Standard Deviation of Simulated Values	4,3

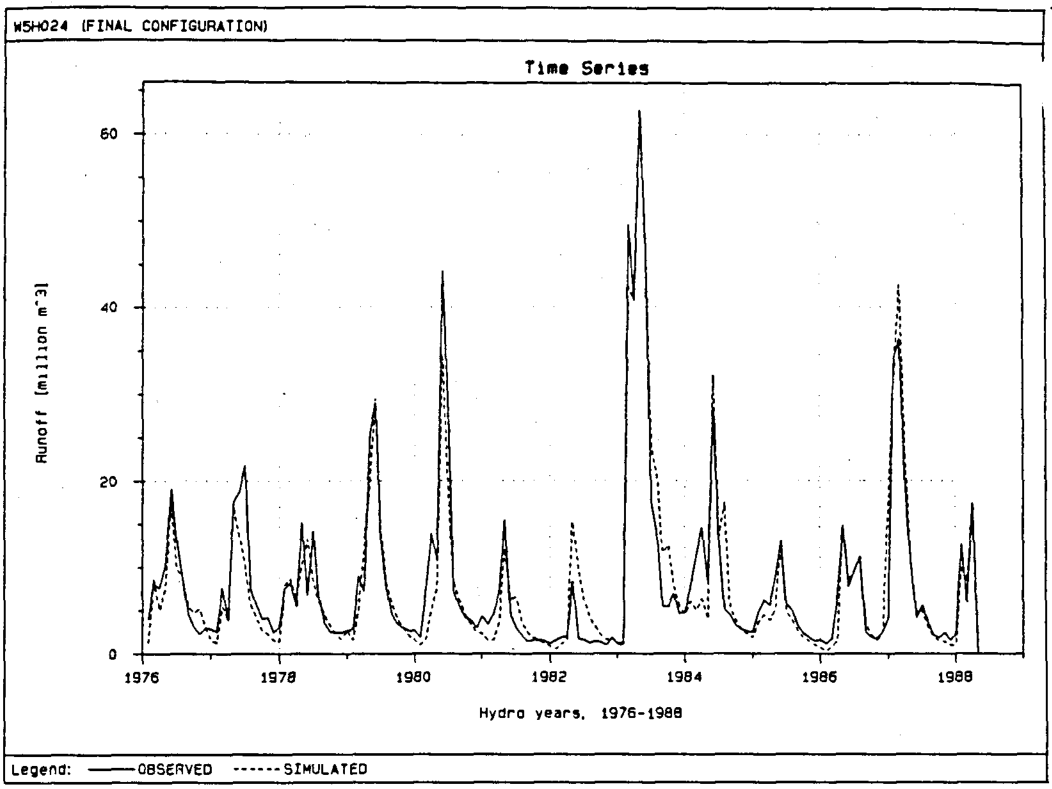


Figure 5.12.3 : **Comparison of Observed and Simulated Flows at W5H024 (Final Configuration)**

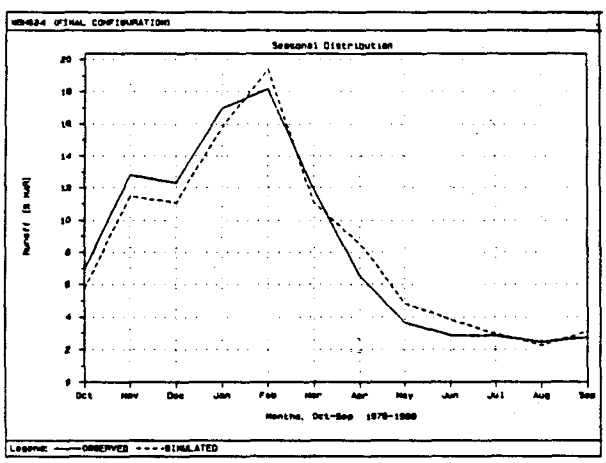


Figure 5.12.4 : Monthly Distribution of Means of Observed and Simulated Flows at W5H024

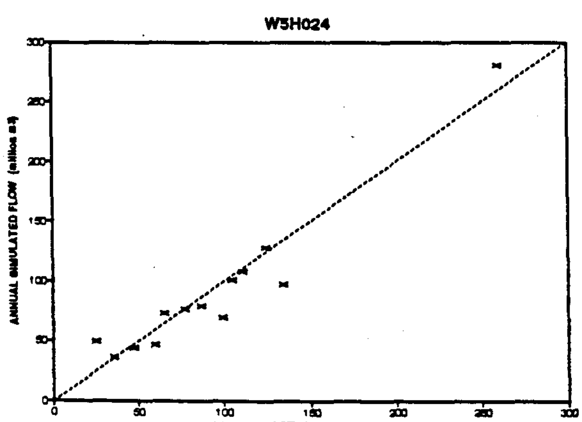


Figure 5.12.5 : Comparison of Annual Totals of Observed and Simulated Flows at W5H024

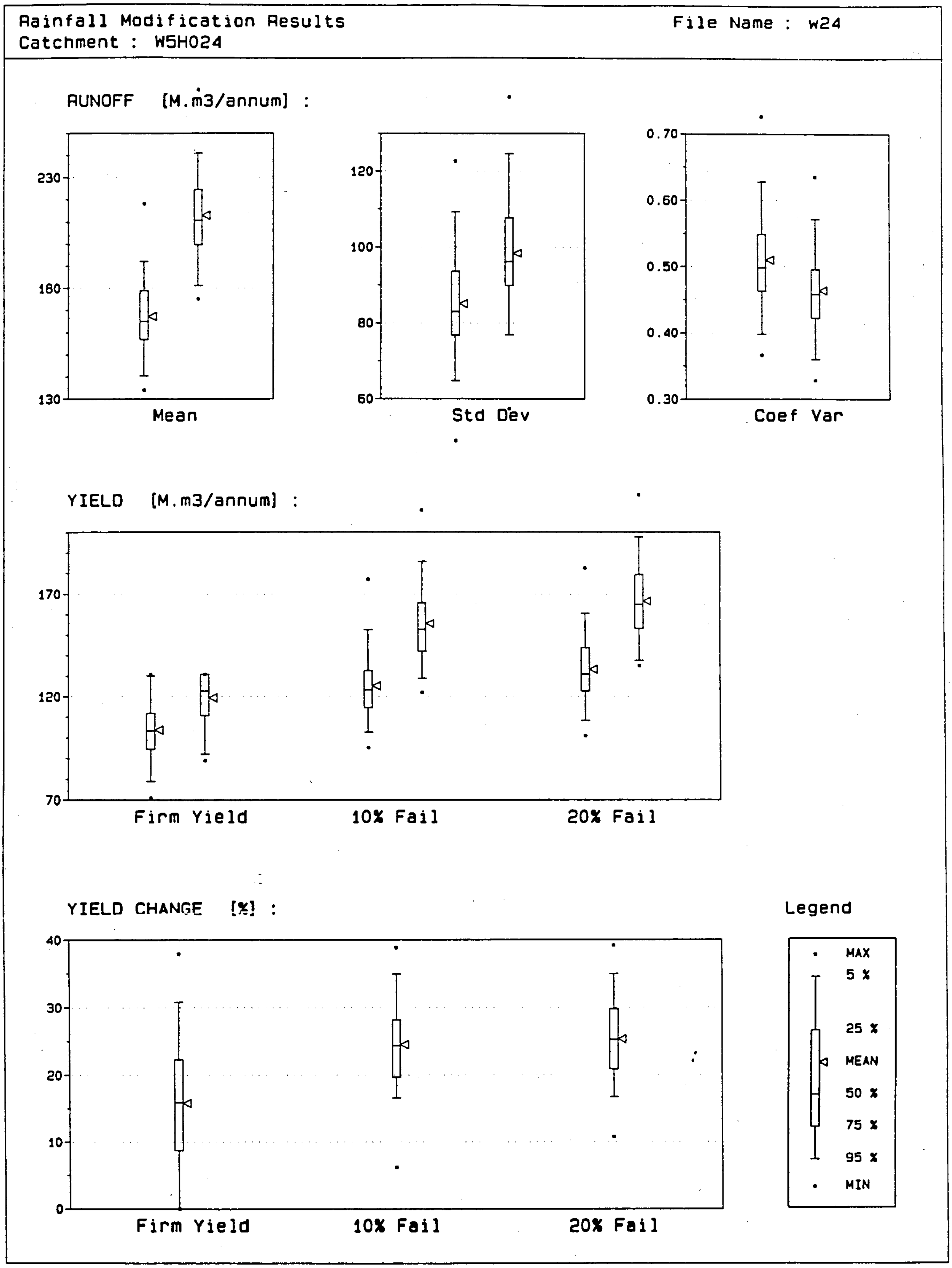


Figure 5.12.6 : Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at W5H024

5.12.4 Water Resources and Timber Yield

Figure 5.12.6 shows the graphical comparison of yields from a hypothetical dam using the "stochastic" based and modified streamflow. Results show an increase in the median MAR from 165 $m^3 \times 10^6$ to 210 $m^3 \times 10^6$ and an increase in yield of between 15% and 25% for the three failure scenarios.

Figure 5.12.7 shows the timber yield comparison. Results show an increase in median timber yield of 16%, from 430 m^3/ha/rotation to 500 m^3/ha/rotation.

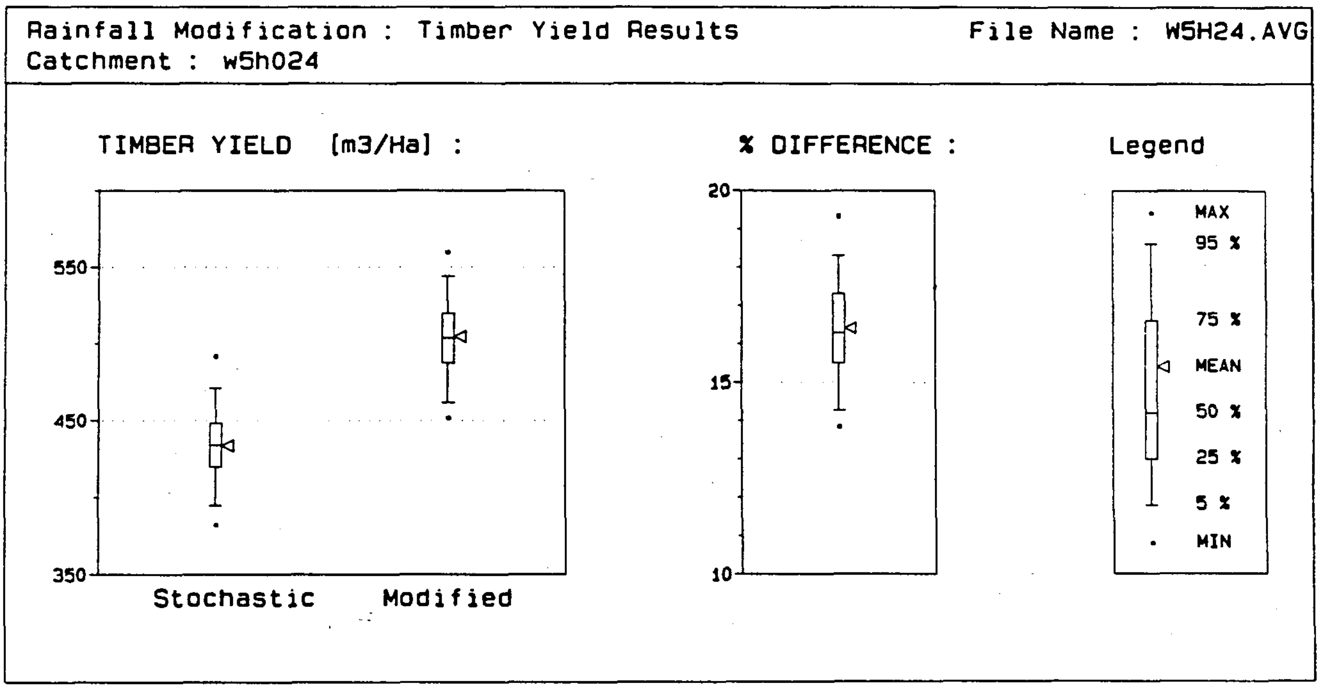


Figure 5.12.7 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at W5H024

5.13 W5H025

5.13.1 Input Information and Preparation

Figure 5.13.1 presents the current day land use in catchment W5H025. A summary of catchment data is presented in Table 5.13.1.

Table 5.13.1 : Summary of Catchment W5H025 Data

Item	Value	Unit
Catchment Area (Incremental)	138,3	km²
Catchment MAP	900,0	mm
1990 Forest Area	93,3	km²
1990 Agriculture Area	4,7	km²
1990 Irrigation Area	4,48	km²
1990 Farm Dam Capacity	4,9	$m^3 \times 10^6$
Observed MAR (Cumulative)	36,2	$m^3 \times 10^6$
Runoff Coefficient	5,1	%
Area per rain gauge	69,0	km²

Note : Upstream catchment W5H008 and W5R002 ignored

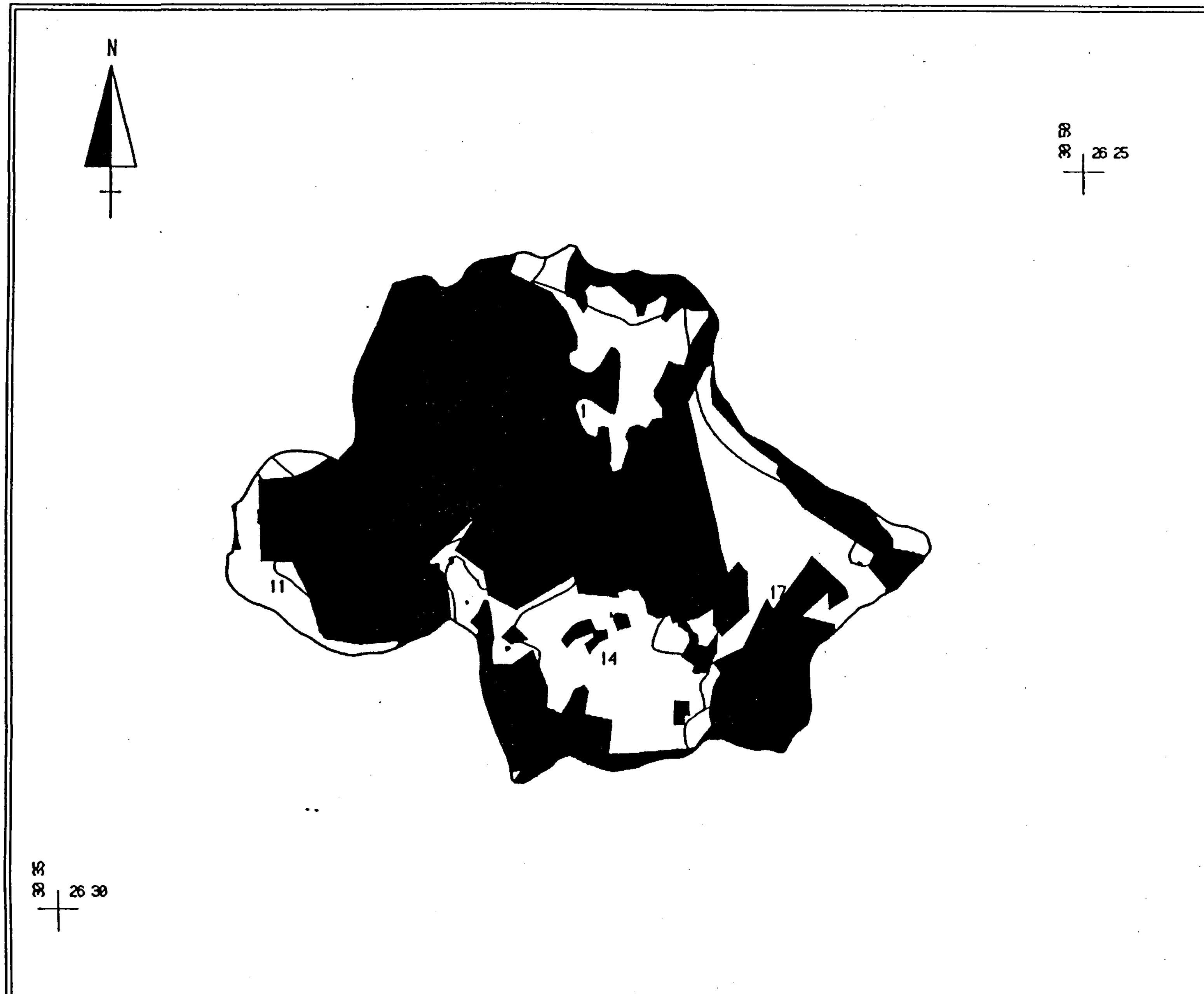
5.13.2 Evaluation of flow records

Flow records are available at W5H025 from 1974 to date. Inflows from two upstream catchments (W5H008 and W5R002) are applicable and have records from 1954 and 1968 respectively. The monthly flows from October 1974 to September 1989 were checked for unreliable data and patched with simulated flows where necessary.

5.13.3 Model Output Verification

The configuration used observed inflows (patched with simulated flows) of both upstream catchments, namely W5H008 and W5R002. Catchment W5H008 is already configured (section 5.11) and variables describing sub-catchment 11 of W5H025 were used to generate flows in the W5R002 sub-catchment (sub-catchment 7).

The initial configuration of the *ACRU* model resulted in an acceptable verification as indicated in the time series (Figure 5.13.2) and seasonal distribution (Figure 5.13.3). The statistics listed in Table 5.13.2 show an underestimation of the mean although all the other statistics indicate an accurate simulation.



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CURRENT DAY LANDUSE IN CATCHMENT W5H025

Figure 5.13.1

The annual flow in Figure 5.13.4 indicates an acceptable scatter around the 1:1 line with all the wettest years underpredicted. Results obtained from this catchment can therefore be used with confidence.

Table 5.13.2 : Comparison of Simulated and Observed Runoff for Monthly Totals of Daily Values (mm)

Total Observed Values	686,8
Total Simulated Values	489,8
Mean of Observed Values	4,2
Mean of Simulated Values	3,0
Correlation Coefficient	0,947
Regression Coefficient	0,782
Base Constant of Regrn. Eqn.	-0,290
Variance of Observed Value	62,8
Variance of Simulated Values	42,8
Standard Deviation of Observed Values	7,9
Standard Deviation of Simulated Values	6,5

5.13.4 Water Resource and Timber Yield

Figure 5.13.5 shows the graphical comparison to yields from a hypothetical dam using the "stochastic" based and modified streamflow. Results show an increase in the median runoff from 25 m^3 x 10^6 to 37 m^3 x 10^6 and an increase in yield of ∞ 40 for the three failure scenarios.

Figure 5.13.6 shows the timber yield comparison. Results show an increase in median timber yield of 26%, from 340 m^3/ha/rotation to 430 m^3/ha/rotation.

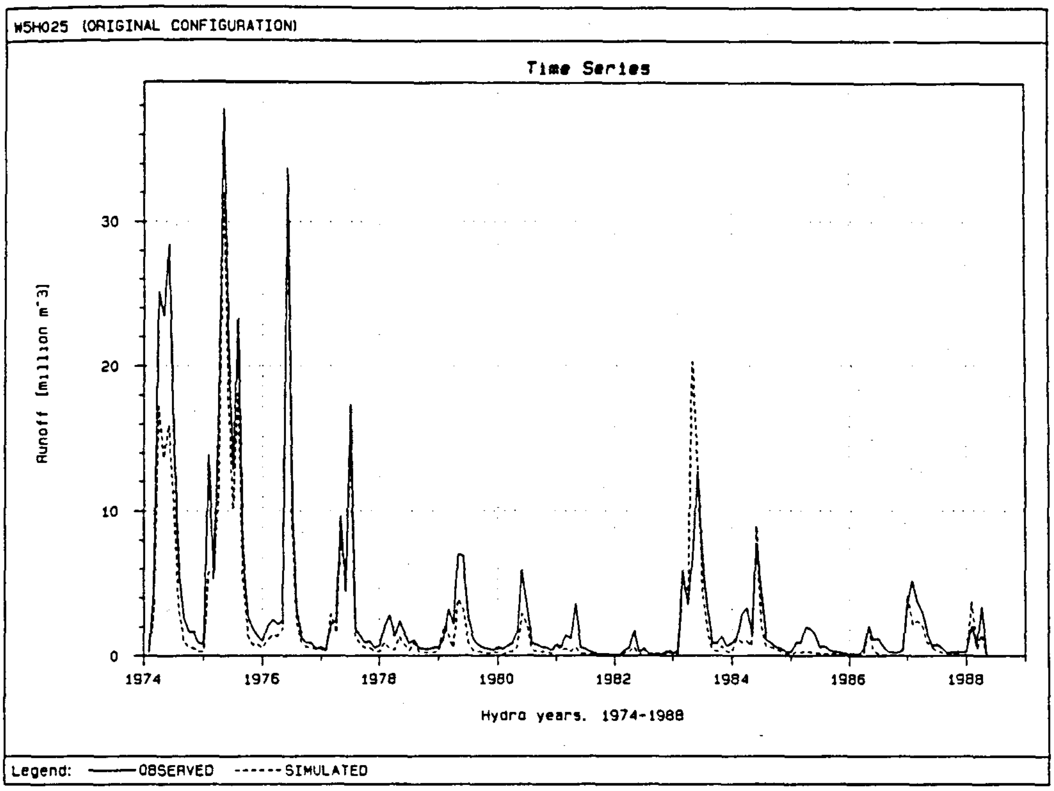

Figure 5.13.2 : Comparison of Observed and Simulated Flows at W5H025 (Original Configuration)

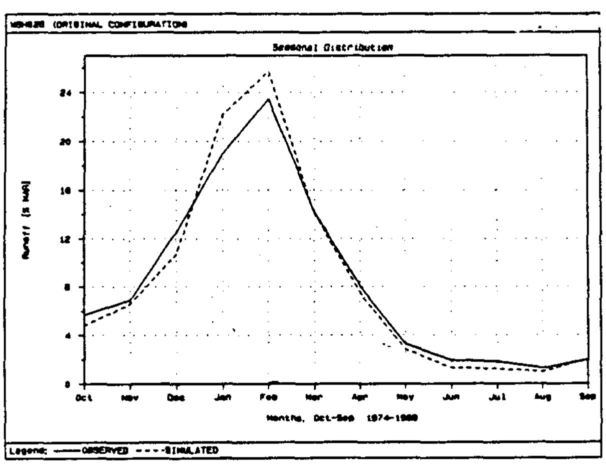

Figure 5.13.3 : Monthly Distribution of Means of Observed and Simulated Flows at W5H025

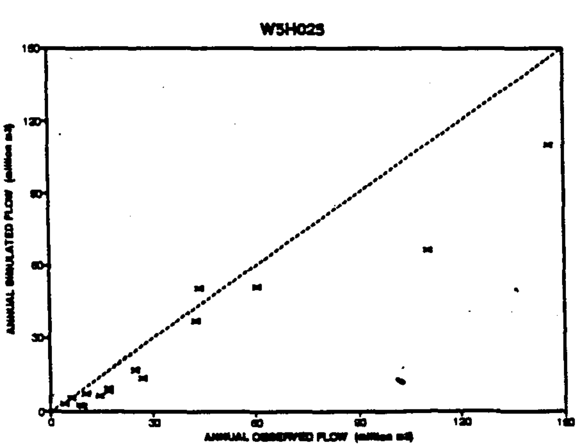

Figure 5.13.4 : Comparison of Annual Totals of Observed and Simulated Flows at W5H025

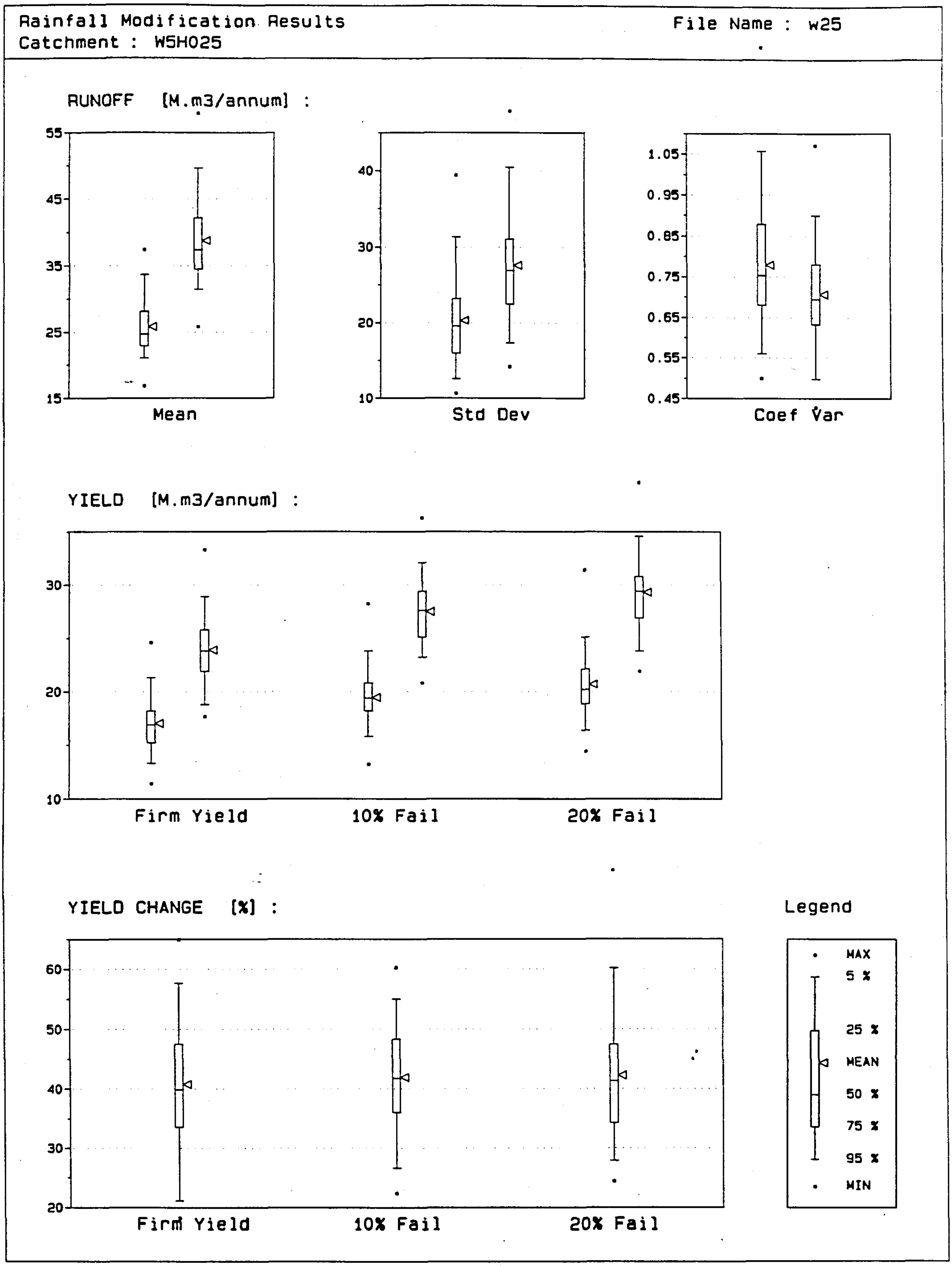

Figure 5.13.5 : **Whisker-box Plots comparing Stochastic and Modified Sequences of Monthly Flow and Yield at W5H025**

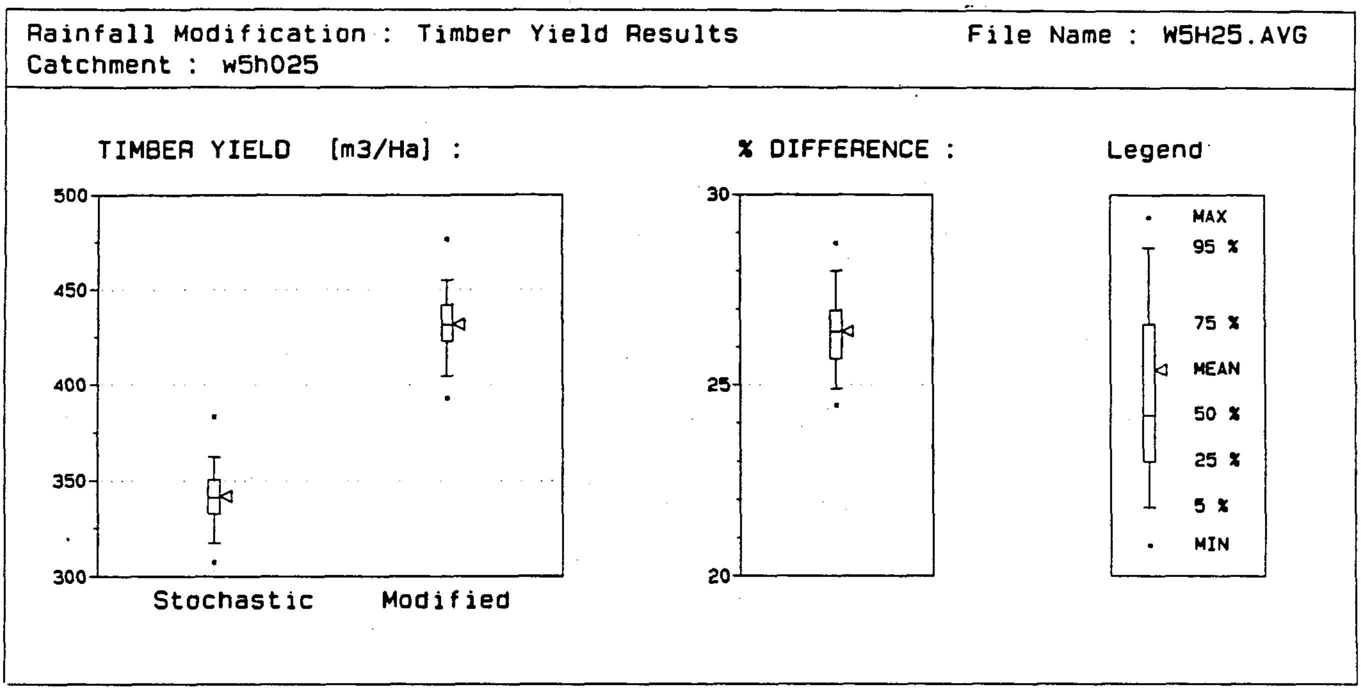

Figure 5.13.6 : Whisker-box Plots comparing Timber Yields using Stochastic and Modified Rainfall at W5H025

5.14 SUMMARY

Table 5.14.1 summarises the soil variable changes that took place as part of the verification process. Also included in Table 5.14 is the area currently forested and runoff characteristics of each catchment.

Table 5.14.1 : Soil Variable Changes and Runoff Characteristics of Each Catchment

CATCHMENT NUMBER	VERSION	VARIABLE CHANGED						% FORESTED	MAR $(m^3 \times 10^6)$	% RUNOFF
		DEP A	DEP B	ABRESP	BFRESP	COFRU	SMDEPP			
B1H002	Original	-	-	-	-	-	-	8,2	6,2	3,6
C1H006	Original	0,2	0,2	0,23	0,23	0,02	0,0			
	Final	0,3	0,5	0,7	0,7	0,01	-	0,0	73,5	9,5
X1H016	Original	-	-	0,3	0,3	0,02	0,0			
	Final	-	-	0,7	0,7	0,01	0,4	26,0	79,5	16,0
X1H019	Original	0,2	0,2	0,3	0,3	0,02	0,0			
	Final	0,1	0,15	0,7	0,7	0,01	-	76,2	56,6	29,1
X1H020	Original	0,2	0,25	0,35	0,35	0,02	0,0			
	Final	0,3	0,5	0,7	0,7	0,01	0,4	21,0	5,5	11,4
X1H021	Original	0,25	0,35	0,4	0,35	0,02	0,0			
	Final	0,2	0,3	0,85	0,85	0,01	0,5	26,3	43,6	12,8
X2H008	Original	0,25	0,35	0,35	0,35	0,02	0,0			
	Final	0,2	0,3	0,7	0,7	0,01	0,35	83,1	17,4	9,4
X2H030	Original	0,25	0,35	0,37	0,37	0,02	0,0			
	Final	0,15	0,15	0,77	0,77	0,01	-	65,0	16,7	25,0
X2H031	Original	-		-	-	-	-	50,6	24,1	14,0
W5H004	Original	-		-	-	-	-	26,0	33,3	9,0
W5H008	Original	0,25	0,35	0,3	0,3	0,02	0,0			
	Final	0,3	0,40	0,7	0,7	0,01	0,30	24,1	11,1	12,0
W5H024	Original	0,22	0,3	0,3	0,3	0,02	0,0			
	Final	0,20	0,25	0,7	0,7	0,01	0,4	46,0	94,9	7,3
W5H025	Original	-	-	-	-	-	-	67,5	36,2	5,1

Table 5.14.2 ranks the catchments in terms of verification acceptability. Two criteria were used :

i) The level of variable adjustment necessary to obtain an acceptable verification.

ii) The "goodness of fit" between simulated and observed flows.

Table 5.14.2 : Ranking of Verification Acceptability for All Catchments

CATCHMENT NUMBER	REASON
Accepted	
W5H004	A good initial verification (no changes)
B1H002	A good initial verification (no changes).
W5H025	A good initial calibration (no changes), although accuracy may be exaggerated by using observed inflows from the upstream catchment.
W5H024	A mediocre initial verification. Minimal changes to variables resulted in a very good verification. Accuracy may be exaggerated by using observed flows from an upstream catchment.
C1H006	A mediocre initial verification. Minimal changes to variables resulted in a good final verification.
W5H008	A mediocre initial verification. Minimal changes to variables resulted in a good final verification.
X2H008	Mediocre initial verification. Minimal changes to variables resulted in a good final verification.
X2H031	A very good initial verification (no changes). However, a low confidence rating is assigned to this gauge as the verification statistics are dominated by significant observed inflows from X1H030.
X1H016	Poor initial verification. Extensive changes to variables resulted in a good final verification. (Accepted due to good final verification).
Rejected	
X1H019	Poor initial verification. Extensive changes to variables resulted in a mediocre final verification.
X1H021	Very poor initial verification. Extensive changes to variables resulted in a poor final verification.
X1H020	Very poor initial verification. Minimal changes to variables resulted in a poor final verification.
X2H030	Very poor verification. Extensive changes resulted in a very poor final verification.

6. REGIONALISATION OF IMPACTS OF RAINFALL STIMULATION

Owing to the escarpment characteristics associated with most of the selected catchments there is a large variation of variable values from sub-catchment to sub-catchment within each catchment. This makes it difficult to characterise or regionalise the catchments based on catchment conditions.

A simple method of regionalising using the findings of the previous chapter is therefore adopted. This method is based on the acceptance of distinctive physiographic regions discussed in section 2.2. The water resources yield results of the 13 selected catchments are then summarised on this regional basis.

6.1 REGIONALISATION PROCEDURE

Catchments were firstly grouped together based on the physiographic region in which they were located (Table 6.1.1).

The water resource results presented in Chapter 5 were then converted from Mm^3 to mm. This enabled the results from all catchments representative of each physiographic region to be concatenated, producing a single set of stochastic and modified conditions representative of the entire region. Sample sizes of 200, 300 and 400 for respectively the Highveld, Crocodile and Usutu regions were produced by this process. The timber yield results were processed in the same manner. Whisker-box plots were then used to identify changes in water resources and timber yield.

Table 6.1.1 : Catchment Location within a Physiographic Region

Physiographic Region	Catchment
Highveld	B1H002; C1H006
Escarpment (Crocodile Basin)	X1H016; X1H019; X1H020; X2H021; X2H008; X2H030; X2H031
Escarpment (Usutu Basin)	W5H004; W5H008; W5H024; W5H025

6.2 RESULTS

The water resource results (expressed as percentage increase in yield) of the three physiographic regions are presented in Figure 6.3.1. Results indicate that the Usutu Basin has the highest median increase in yield (∞33%) with the Highveld and Crocodile regions having the lowest median increase in yield (∞25%). It is also interesting to note the great variability in the results with the Highveld region having the greatest 95 percentile increase in yield (>60%) while the Usutu Basin has the lowest 5 percentile increase in yield of approximately 8%. The Highveld region displays the greatest range of yield increases for the 95 to 5 percentile zone (>50%), while the Crocodile region's corresponding range is the smallest (∞30%).

The timber yield results of the three physiographic regions are presented in Figure 6.3.2. Catchment C1H006 has no forestry so the Highveld region result comprises timber yield results from catchment B1H002. The median increase in timber yield is surprisingly constant with 21,7% values in the Highveld region, a 20,0% increase in the Crocodile Basin and a 25% value in the Usutu Basin. In addition, there is little variability in timber yield with the 5 and 95 percentile range differing from 4% for the Highveld region to ∞15% for the Usutu and Crocodile regions.

6.3 CONCLUSION

These results indicate that catchments located in the Usutu Basin would result in the greatest average increase in water resources and timber yield, albeit that this basin would also occasionally produce the lowest increases. Since this basin seems to react more sensitively to rainfall stimulation than the other basins it seems this region would be most preferable in terms of locating a cloud seeding area experiment over a fixed catchment.

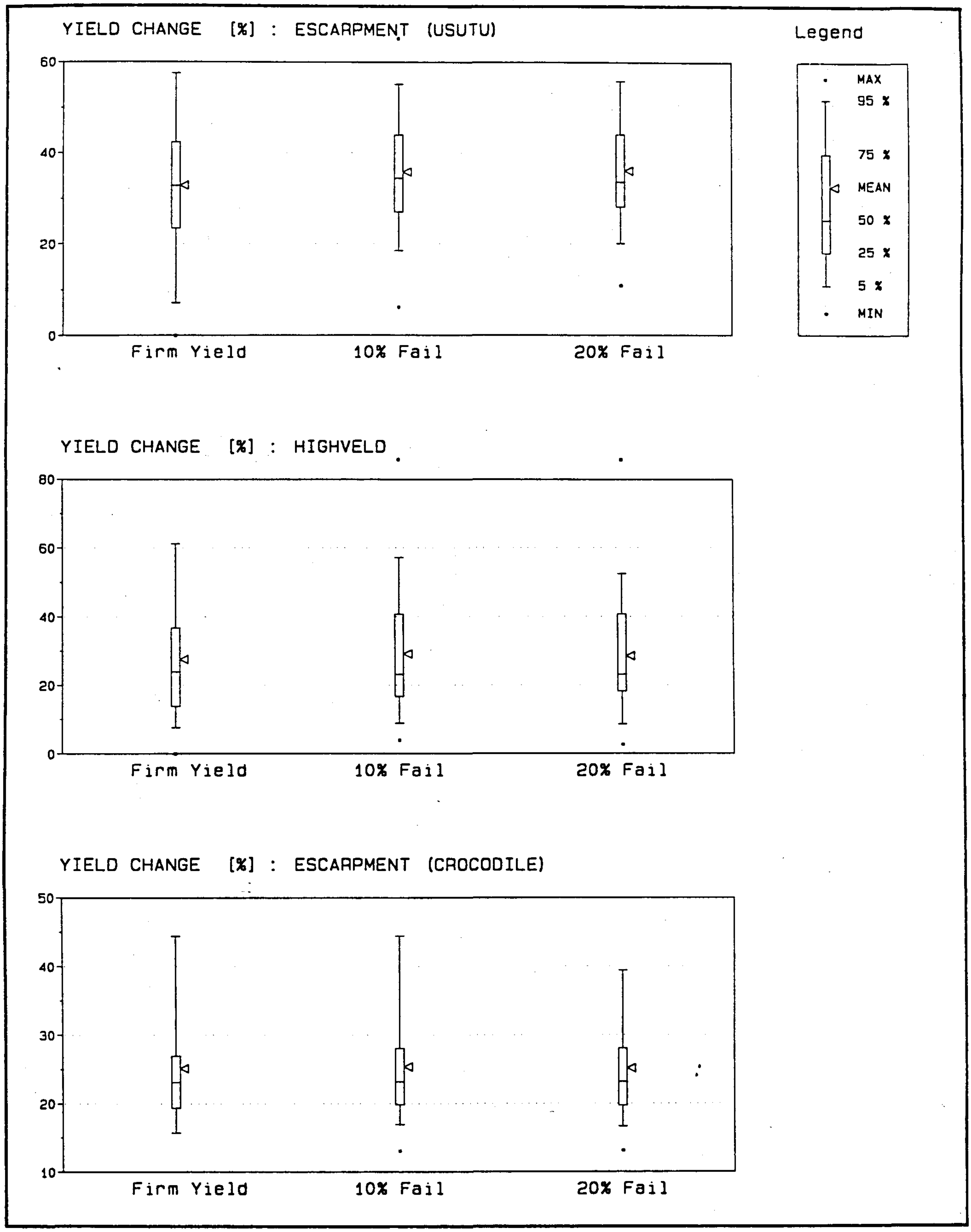

Figure 6.3.1 : Whisker-box Plots comparing the Increase in Modified Yield for the Three Physiographic Regions

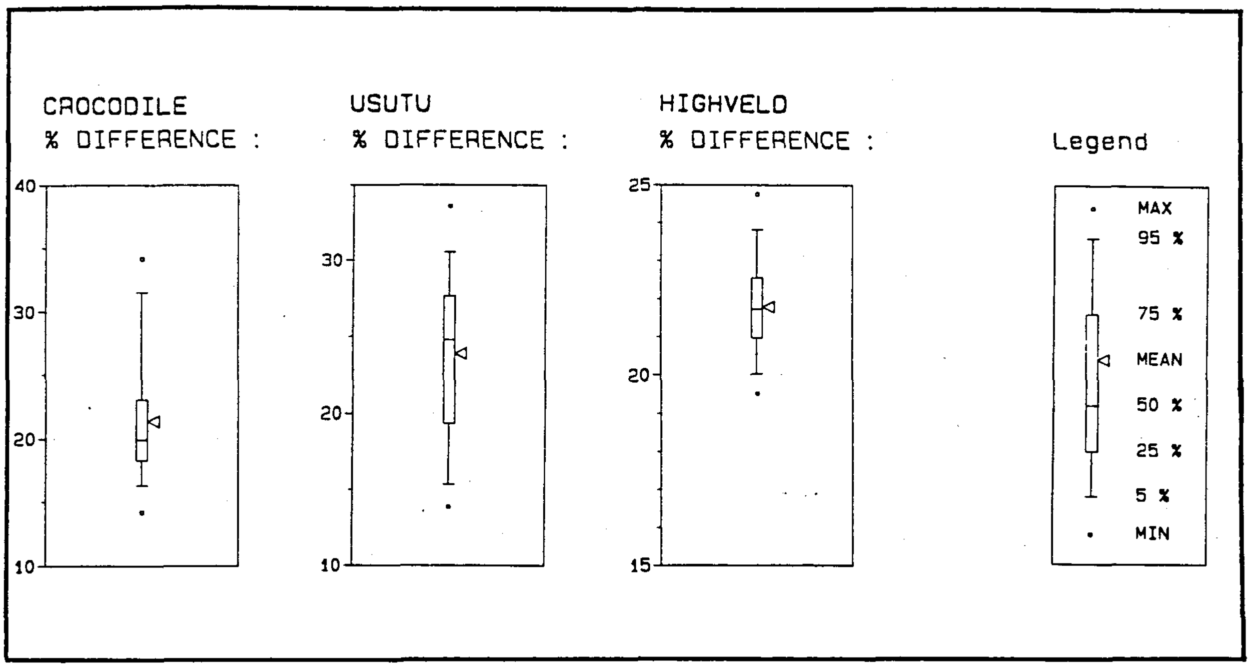

Figure 6.3.2 : Whisker-box Plots comparing the Increase in Modified Timber Yields for the Three Physiographic Regions

7. SENSITIVITY STUDIES OF MODEL INPUT ON MODEL OUTPUT

7.1 INTRODUCTION

Sensitivity is defined as the measure of the effect of change of one factor on another. In terms of hydrological modelling this definition refers to the measure of change in model input and output (Schulze, 1989).

For the purposes of this analysis the sensitivity of two model output components, viz. reservoir yield and timber yield, are considered relevant. In addition, only those variables identified by Schulze (1989) to which outputs were most sensitive were included in the analysis. A further criterion for deciding which variables to include in the analysis was those variables for which different data sources were used in the verification process (as discussed in chapter 5) and the author's finding that outputs were most sensitive to such variables. The variables tend to focus on the core of the *ACRU* model which is the soil water budgeting routine. Although not included in this sensitivity analysis, it was apparent that rainfall has the most dramatic influence on model output and can be considered the most sensitive variable.

7.2 METHOD

For the sensitivity analysis on the reservoir yield component of this project, catchment C1H006 was considered in terms of its importance in the Vaal River Basin. Owing to the negligible area of forest in this catchment it was not possible to use catchment C1H006 for a sensitivity analyses on timber yield. Catchment W5H004 was selected for several reasons :

(i) it has a large catchment area
(ii) it is extensively forested
(iii) although only a mediocre verification was obtained the verification is not influenced by upstream catchment inflows.

An acceptable method for undertaking sensitivity analyses involves adopting a selected set of "base" input parameters and obtaining a "base" output. Thereafter , individual parameters are selected and adjusted and the "altered" output of subsequent runs is compared to the "base" output. This provides a measure of model sensitivity.

For the purposes of this project the "base" values were taken from the verified model but with current day land use. Selected variables (defined in Table 7.2.1) were then increased and decreased by 50%. This variability was selected as the parameter values in the 13 study catchments tend to range to this order of magnitude.

Table 7.2.1 : Definition of Variables Selected for Sensitivity Tests

VARIABLE NAME	DEFINITION
DEPA	Depth (m) of the A-horizon of the soil profile.
DEPB	Depth (m) of the B-horizon of the soil profile.
ABRESP	Fraction of daily soil water to be redistributed from the A-horizon into the B-horizon when the A-horizon is above field capacity.
BFRESP	Fraction of daily soil water to be redistributed from a "saturated" B-horizon into the intermediate/groundwater store.
SMDDEP	Effective depth of the soil (m) contributing to stormflow production.
COFRU	Coefficient of baseflow response (Fraction of the intermediate/groundwater store that becomes runoff on a particular day).
VEGINT	Interception loss (mm/rainday) by land cover.

Schulze (1989) also reports a 50% perturbation in a sensitivity analysis. In addition, unrealistic variations of up to 250% for the parameters ABRESP, BFRESP and VEGINT are also included as values for these parameters occasionally varied by this magnitude.

The modelling procedure for the sensitivity analysis is the same as that used for both the water resource yield and timber yield components, discussed in section 4.5.3. This involved generating 100 stochastic and modified sequences for each variable change to compare the "altered" water resources and timber yields with the "base" yields. The water resources sensitivity analysis was performed on catchment C1H006 as a result of its importance to water resources in the Vaal River Basin. Catchment W5H004 was used for the timber yield analysis due to the extent of afforestation and the confidence in the verification. The whisker-box plots showing the water resources yield of each "altered" scenario are presented in Appendix 1 and can be compared directly to the whisker-box plots of the "base" sequences presented in section 5.2. Table 7.2.2 summarises the mean water resources firm yield comparison between the "base" sequence and "altered" sequences.

Similarly, the "altered" timber yield scenarios are presented in Appendix 2. Also included in this appendix is the "base" sequence. This sequence differs slightly to the sequence presented in section 5.10 as average conditions have been applied to all sub-catchments within the catchment to make a sensitivity analysis possible. A summary of the mean comparison of "altered" and"base" sequences is presented in Table 7.2.2. Included are additional sensitivity tests on parameters of the timber yield sub-routine.

Table 7.2.2 : Comparison of the Median Water Resources Firm Yield of the "Base" Sequences and "Altered" Sequences for Each Variable Change : Catchment C1H006

Variable Name	"Base" Value	Variable Change %	"Altered" Value	"Base" Sequence Median Firm Yield		"Base" Sequence Median % Firm Yield Increase
				Stochastic (Mm^3) 27	Modified (Mm^3) 32	15
				"Altered" Sequence Median Firm Yield		"Altered" Sequence Median % Increase
				Stochastic (Mm^3)	Modified (Mm^3)	
DEP A (metres)	0,3	+ 50 - 50	0,45 0,15	16 (-41%) 60 (120%)	19 (-41%) 67 (109%)	19 11
DEP B (metres)	0,5	+ 50 - 50	0,75 0,25	27 (0%) 30 (11%)	31 (-3%) 35 (9%)	14 16
ABRESP (fraction)	0,23	+ 250 + 50 - 50	0, 8 0,35 0,12	27 (0%) 27 (0%) 29 (7%)	32 (0%) 32 (0%) 33 (3%)	17 14 16
BFRESP (fraction)	0,23	+ 250 + 50 - 50	0, 8 0,35 0,12	25 (-7%) 27 (0%) 27 (0%)	30 (-6%) 33 (3%) 32 (0%)	17 15 16
SMDDEP (metres)	0,3	+ 50 - 50	0,45 0,15	18 (-34%) 55 (103%)	24 (-25%) 61 (91%)	24 11
COFRU (fraction)	0,02	+ 50 - 50	0,03 0,01	27 (0%) 29 (7%)	32 (0%) 34 (6%)	15 16
VEGINT (mm/ rainday)	1,6 (for all months)	+ 50 - 50	2,4 0,8	24 (-11%) 32 (18%)	27 (-16%) 37 (16%)	14 16

( ) Denotes the % difference between the "base" and "altered" sequences.

7.3 RESULTS FROM WATER RESOURCES YIELD

The effect that perturbing each variable has on yield is discussed. The variable DEPA quantifing the depth of the A-horizon has a pronounced effect on yield. A 50% increase in the soil horizon depth causes a 41% decrease in firm median yield while a 50% decrease in soil depth results in over a 100% increase in firm median yield. This is not surprising since the A-horizon depth soil depths will largely determine the fate of rainfall as either runoff to a dam or soil water subject to evapotranspiration losses.

The median % increase of the "altered" sequences (19% and 11% for increasing and decreasing DEPA respectively) is similar to the median increase of the "base" sequence firm yield (15%). So similar increases in median yield can be expected for changes to the variable DEPA. Similar results are reported for all other variabe changes.

The variable DEPB, however, which quantifies the depth of the B horizon has surprisingly little effect on yield. The B horizon should act as intermediate store before groundwater storage and will have an effect on low flow characteristics, which should affect yield. This suggests that yield is dominated by stormflow rather than groundwater or base flow contributions.

The variables ABRESP and BFRESP which describe the rate at which excess water moves from the A to the B horizon and from the B horizon to groundwater have very little effect on runoff and yield when adjusted by 50%. However these variables affected the verification and some very high values were used to increase the low flows in some of the pilot catchment verifications. A sensitivity analysis with a 250% variation was carried out to include the range of values used for the 13 catchments but still had little effect on yield.

The variable SMDDEP defines the effective depth of the soil that contributes to stormflow. Since this variable's function is very similar to DEPA it has a significant effect on yield. This variable has the greatest effect on changing the median % yield increase of the "altered" sequence. The modified sequence is 24% higer than the stochastic sequence for a 50% increase to SMDDEP. However, this is still a relatively minor difference to the median increase of the base sequence (15%).

The variable COFRU (which describes the rate of release of baseflow to the river) has little effect on yield. This variable played an important part in verification by increasing the simulated low flow and could consequently be expected to affect yield. Again, the low sensitivity of this variable suggests the importance of runoff during the rainy season in determining yields.

The variable VEGINT describing the interception of rainfall by vegetation shows a moderate increase and decrease in yield according to the amount of rainfall intercepted.

Although subjective changes to catchment variables during the verification process were based on information from reasonable data sources, it is possible that acceptable verifications could have been obtained by changing variables that are less sensitive to yield.

Therefore *ACRU* model applications to catchments that include significant subjective changes to yield-sensitive variables could either overpredict or underpredict both water resources and timber yield. The firm yield sensitive variables identified by this analysis include DEPA, SMDDEP and to a lesser extent VEGINT. Catchments with significant changes to these firm yield sensitive variables during the verification process include C1H006, X1H019, X1H020, X1H021, X1H008, X2H030, W5H004 and W5H024. Since DEPA has had to be increased in catchments C1H006 and X1H020, this could result in an underprediction in yield in these cases. Decreases in DEPA in the remaining catchments could reflect an overprediction in yield, except for catchment W5H024 where the effect of the decrease in DEPA is balanced by an increase in SMDDEP. However, while changes to these variables might affect the magnitude of the yield, the <u>relative</u> increases in median yield varies little for differing variable values.

7.4 TIMBER YIELD RESULTS

The variables having the greatest effect on water yield also have a significant effect on timber yield. From Table 7.4.1 it can be seen that for W5H004 changes in DEPA and SMDDEP have significant effects on timber yield while the other soil variables have little effect. As DEPA and SMDDEP decreases, the runoff increases and the timber yield decreases. This is due to a reduction in the proportion of available rainfall becoming soil moisture and becoming available to the forest roots. Timber yield is also sensitive to the rotation period parameter used in the timber yield sub-routine.

It is also interesting to note from Table 7.4.1 that there is little difference in the magnitude of change between the "base" vs "altered" stochastic yields and the "base" vs "altered" modified yields. Variable changes appear to affect the stochastic and modified sequences in the same manner.

The analysis comparing the median timber yield increase of the "altered" sequence indicates that changes to variable values produce similar increases in yield to those recorded for the "base" sequence (23,8%). Changes to DEPA produce the greatest sensitivity although the 26,6% and 20,8% median increases in timber yield and are still very similar to the 23,8% median increase of the base sequence.

Table 7.4.1 : Comparison of the Median Timber Yield of the "Base" Sequences and "Altered" Sequences for Each Variable Change : Catchment W5H004

Variable Type	Base Value	Variable Change %	Selected Value	"Base" Sequence Median Timber Yield		"Base" Sequence Median % Timber Yield Increase
				Stochastic (m^3/ha) 310	Modified (m^3/ha) 380	23,8
				"Altered" Sequence Median Timber Yield		"Altered" Sequence Median % Timber Yield Increase
				Stochastic (m^3/ha)	Modified (m^3/ha)	
DEP A (metres)	0,25	+ 50 - 50	0,38 0,13	310 (0%) 262 (-15%)	390 (3%) 318 (-16%)	26,6 20,8
DEP B (metres)	0,40	+ 50 - 50	0,60 0,20	320 (3%) 298 (-4%)	395 (4%) 365 (-4%)	24,5 23,1
ABRESP (fraction)	0,35	+ 230 + 50 - 50	0,80 0,53 0,18	320 (3%) 310 (0%) 305 (0%)	400 (5%) 385 (1%) 375 (0%)	24,0 24,0 24,0
BFRESP (fraction)	0,35	+ 230 + 50 - 50	0,80 0,53 0,18	315 (0%) 310 (0%) 310 (0%)	380 (0%) 380 (0%) 380 (0%)	24,0 24,1 24,1
SMDDEP (metres)	0,25	+ 50 - 50	0,38 0,13	340 (10%) 220 (-29%)	425 (12%) 270 (-29%)	24,3 22,4
COFRU (fraction)	0,02	+ 50 - 50	0,04 0,01	310 (0%) 310 (0%)	385 (0%) 385 (0%)	24,2 24,3
Rotation Period (mths)	120	- 16 - 33	100 80	275 (-11%) 260 (-16%)	335 (-12%) 320 (-16%)	23,5 23,2
Density (Stems/ha)	< 1 500		> 1 500	310 (0%)	385 (0%)	23,8

8. ANATOMY OF SEEDING EFFECT

Results reported in Chapter 5 for the 13 pilot catchments show a potential seeding related increase in total streamflow and yield ranging from 15% to 50% (median values). In Israeli cloud seeding experiments Ben Zri and Langerman (1993) attributed daily runoff increases of between 5 and 75% to the non-linear changes in rainfall-runoff properties as a result of cloud seeding. This suggests the runoff component is enhanced by improved antecedent soil moisture status as well as increased rainfall intensity. A question arises as to which daily rainfall increases contribute how much to daily runoff increases.

In this chapter the contribution of seeded raindays of different magnitudes to total long-term increases in areal rainfall is examined for three pilot catchments. In addition, an initial examination of the link between seeded raindays and corresponding daily runoffs is made. It was hoped that more detailed insight into the "anatomy" of the long-term seeding impact and its spatial variation would aid future planning for areal seeding experiments on fixed catchments.

8.1 METHOD

The daily option of the *ACRU* model quantifies the contribution of stormflow (surface runoff and interflow from the A-horizon) and baseflow (groundwater) to total streamflow, thereby providing a tool for this analysis to take place. Both the historical and modified historical rainfall sequences were run separately with the *ACRU* model to produce historical and "modified" daily runoff. Software was developed to compare all the "seeded" event pairs in each of the 30 year sequences. Consequently this analysis excludes all general raindays and winter rainfall events since only scattered raindays in summer are seeded. Three catchments from each of the homogeneous regions were selected for analysis (C1H006, X2H031 and W5H004), based on reasonable reliability of verification.

8.2 RESULTS

8.2.1 C1H006

The results of catchment C1H006 are presented in Tables 8.2.1, 8.2.2 and Figure 8.2.1.

Table 8.2.1 : The Number of Seeded Events and Percentage of Increase in Rainfall, Same Day Seeded Runoff and Total Runoff for a Range of Seeded Rainfall Events : C1H006

Rainfall Range (mm)	Seeded Events		Percentage of Total Increase		
	Number	%	Rainfall	Same Day Seeded Runoff	Total Runoff
0 - 2,5	1432	60,9	14,5	48,1	24,9
2,6 - 5,0	423	18,0	19,6	13,4	7,0
5,1 - 10,0	320	13,5	29,2	15,3	7,9
10,1 - 15,0	102	4,3	15,7	8,0	4,1
15,1 - 20,0	49	2,1	11,5	6,5	3,3
20,1 - 30,0	25	1,1	8,3	7,7	4,1
30,1 - 40,0	2	0,1	1,2	1,0	0,1
> 40,0	0	0	0,0	0,0	0,0
TOTAL	2353	100	100,0	100,0	51,4

Table 8.2.2 : The Percentage Increase in Total and Seeded Rainfall, Same Day Runoff and Total Runoff

Description	% Increase
Total % increase in rainfall for all days	6,7
Total % increase in rainfall for seeded days	16,7
Total % increase in same day runoff recorded when scattered rain days are seeded	20,7
Total % increase in runoff recorded on all days when scattered rain days are seeded	40,0

An analysis of the effects of rainfall volume in Table 8.2.1 indicates that 1432 of a total of 2353 seeded events (60,9%) have a very low rainfall amount. These contribute only 14,5% of the total increase in rainfall. In comparison, only 320 rainfall events (13,5%) record rainfall between 5,1 and 10,0 mm. These events contribute 29,2% of the total rainfall. This comparison shows that it is the relatively few rainfall events with a greater rainfall volume that are responsible for the increase in rainfall due to seeding. It is expected that these rainfall events should therefore have an even greater contribution to the increase in runoff as a result of the non-linearity of rainfall-runoff properties.

The expected increase in runoff associated with large rainfall volumes is not evident in the analysis of seeded-day runoff. In this analysis only runoff occurring on days in which seeding took place is analysed. The analysis shows that the rainfall events (0 - 2,5 mm) that contribute 14,5% to the total increase in rainfall are responsible for a massive 48,1% increase in runoff. Surprisingly, the larger volumes which contribute 29,2% to the total increase in rainfall only contribute 15,3 % to the total increase in runoff.

Further analysis exposes the problem of attempting to link the daily runoff of larger rainfall events with its seeded-day rainfall. The runoff hydrograph from a single large rainfall event can last several days. By comparing only those days on which seeding took place, a large proportion of runoff from large rainfall events is either ignored or attributed to smaller rainfall events occurring after the large event. This lag effect is clearly of considerable magnitude. Table 8.2.1 indicates that the increase in runoff in each rainfall range is approximately halved when expressed as a percentage of the total increase in runoff, indicating a lag in which 50% of the flow is significant. Table 8.2.2 indicates that this percentage is further emphasised if the total same day seeded runoff increases are expressed as a percentage of the total modified flow and compared to the percentage estimated using all the days in which increases are recorded. Same day seeded runoff comprises 20,7% of the total increase (40,0%) in runoff.

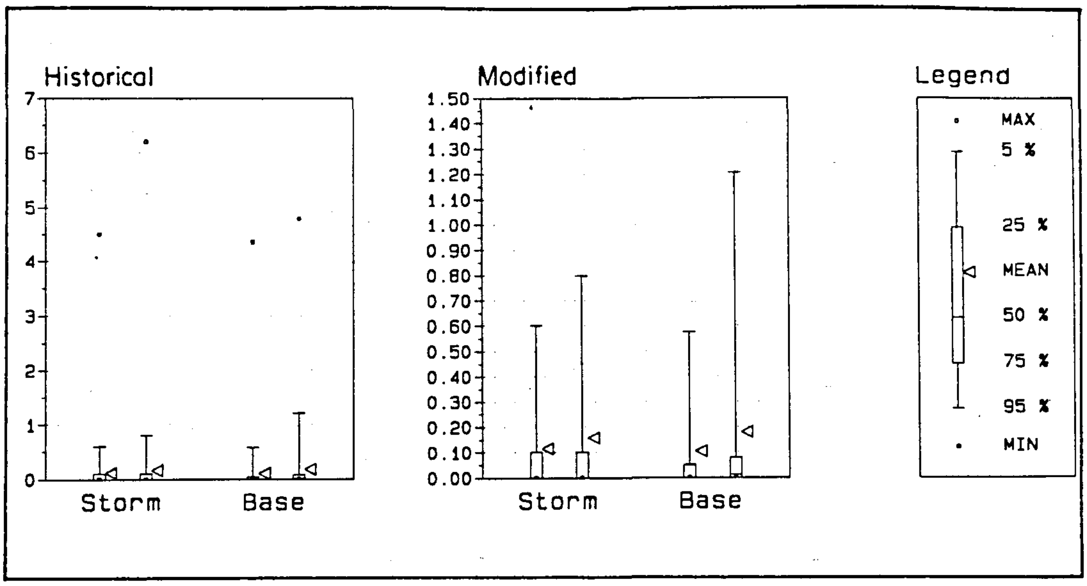

Figure 8.2.1 Whisker-box Plots comparing the Runoff (Stormflow and Baseflow) of Seeded Days in the Historical and Modified Sequences : C1H006

From Figure 8.2.1 it is evident that stormflow is the dominant process, based on a seeded-day comparison. The plot showing the full range of data indicates that there is little increase in stormflow for 75% of all seeded events. Significant increases in stormflow were only recorded for 5% of all events (from 0,6 mm to 0,8 mm) and for the maximum events. The plot with a limit on the y axis shows that the baseflow contribution is less than stormflow at the twenty five percentile (0,05 mm) although an increase in baseflow contributions due to modification is evident at the fifty percentile. Large baseflow increases are evident at the five percentile. These results suggest increases are mostly a result of baseflow with stormflow also relevant for the few large events.

8.2.2 X2H031

The results of catchment X2H031 are presented in Tables 8.2.3, 8.2.4 and Figure 8.2.2.

Table 8.2.3 : The Number of Seeded Events and Percentage of Increase in Rainfall, Same Day Seeded Runoff and Total Runoff for a Range of Seeded Rainfall Events : X2H031

Rainfall Range (mm)	Events		Percentage of total increase		
	Number	%	Rainfall	Same Day Runoff	Total Runoff
0,0 - 2,5	1340	54,4	9,8	34,8	15,5
2,6 - 5,0	381	15,5	12,9	11,7	5,2
5,1 - 10,0	385	15,6	23,8	12,7	5,6
10,1 - 15,0	180	7,3	18,5	9,6	4,3
15,1 - 20,0	83	3,4	11,5	7,8	3,5
20,1 - 30,0	67	2,7	11,8	10,7	4,9
30,1 - 40,0	16	0,6	5,8	5,5	2,4
>40,0	12	0,5	5,9	7,2	3,2
TOTAL	2464	100,0	100,0	100,0	44,6

Table 8.2.4 : The percentage Increase in Total and Seeded Rainfall, Same Day Seeded Runoff and Total Runoff

Description	% Increase
Total % increase in rainfall for all days	7,9
Total % increase in rainfall for seeded days	16,6
Total % increase in same day runoff recorded when scattered rain days are seeded	13,0
Total % increase in runoff recorded on all days when scattered rain days are seeded	29,1

Table 8.2.3 indicates this catchment has a far greater proportion of large rainfall events than catchment C1H006. The smaller rainfall events consist of 54,4% of all events and contribute 9,8% and 34,8% to the increases in rainfall and same day seeded runoff respectively. The 5 to 15 mm rainfall events contribute a higher proportion to the total increase in rainfall although the expected increase to runoff does not occur.

As discussed in section 8.2.1, this is as a result of excluding a large part of the hydrograph. In fact, Table 8.2.4 indicates this lag effect is even more pronounced with same day seeded runoff contributing less than half (13% out of 29%) of the total increase in runoff.

Figure 8.2.2. indicates baseflow to be dominant, based on a same-day comparison process. Increases in stormflow are only evident at the 25 percentile (from 0,2 mm to 0,3 mm) and the mean with significant increases at the maximum (from 15 mm to almost 30 mm), while baseflow increases are evident for the entire data set. Similar to catchment C1H006, enhanced seeded-day streamflow is mostly a result of baseflow increase with stormflow increases relevant for the few large events.

8.3.3 W5H004

The results of catchment W5H004 are presented in Tables 8.2.5, 8.2.6 and Figure 8.2.3.

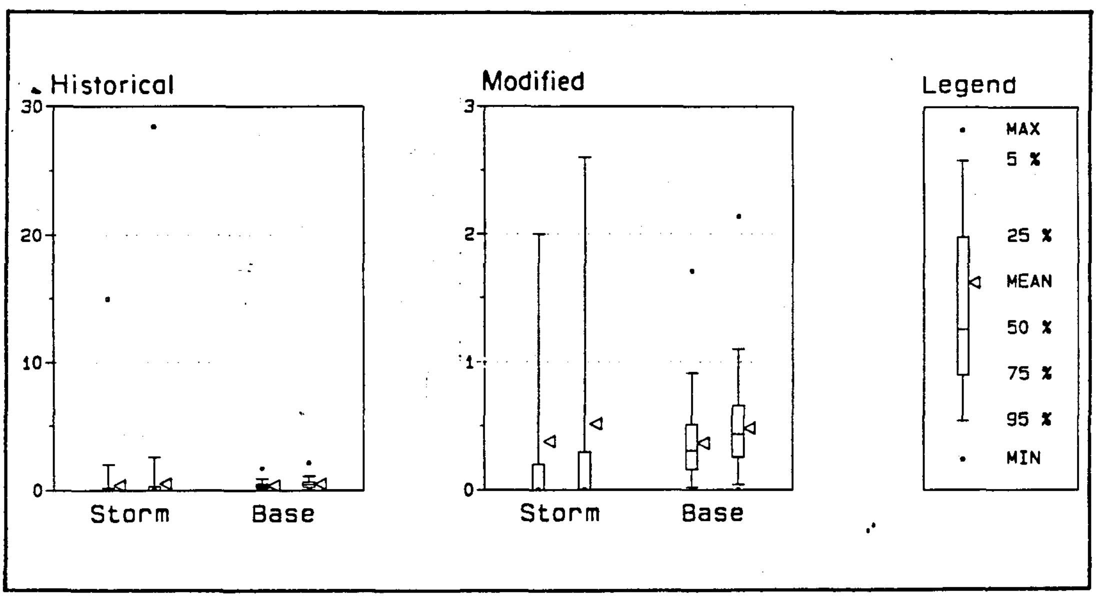

Figure 8.2.2 **Whisker-box Plots comparing the Runoff (Streamflow and Baseflow) of Seeded Days in the Historical and Modified Sequences : X2H031**

Table 8.2.5 : The Number of Seeded Events and Percentage Increase in Rainfall, Same Day Seeded Runoff and Total Runoff for a Range of Seeded Rainfall Events : W5H004

Rainfall Range (mm)	Events		Percentage of Total Increase		
	Number	%	Rainfall	Seeded Same Day Runoff	Total Runoff
0,0 - 2,5	1307	62,2	8,0	40,6	21,3
2,6 - 5,0	229	10,9	8,6	4,8	2,5
5,1 - 10,0	247	11,8	20,1	9,8	5,1
10,1 - 15,0	131	6,2	16,0	3,8	2,1
15,1 - 20,0	76	3,6	12,4	4,3	2,3
20,1 - 30,0	62	2,9	14,8	11,3	6,0
30,1 - 40,0	31	1,5	10,5	11,9	6,4
> 40,1	19	0,9	9,6	14,3	7,6
TOTAL	2102	100	100,0	100,0	53,3

Table 8.2.6 : The Percentage Increase in Total and Seeded Rainfall, Same Day Seeded Runoff and Total Runoff

Description	% Increase
Total % increase in rainfall for all days	7,3
Total % increase in rainfall for seeded days	16,2
Total % increase in same day runoff recorded when scattered rain days are seeded	13,7
Total % increase in runoff recorded on all days when scattered rain days are seeded	25,9

Table 8.2.5 indicates a higher proportion of large rainfall events than the other two catchments with 19 events recording rainfall larger than 40 mm. As with the other two catchments, contributions to the total increased runoff from increases in same day seeded runoff from these large rainfall events are also relatively low. Again this is attributed to the exclusion of delayed runoff from the analysis. Owing to the larger number of large rainfall events in this catchment, this condition is expected to be even more significant than in C1H006 and X2H031. However, Table 8.2.6 indicates that a very similar magnitude (approximately 50%) of lagged flow is excluded (same day seeded runoff contributes 13,7% of the total runoff increase of 25,9%).

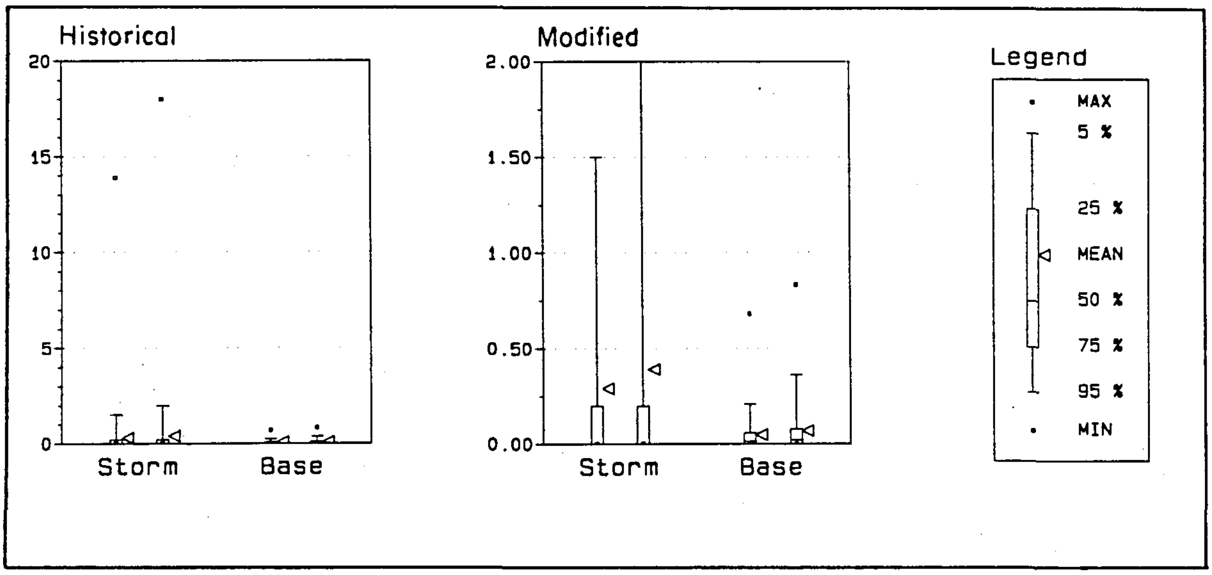

Figure 8.2.3 Whisker-box Plots comparing the Runoff (Stormflow and Baseflow) of the Historical and Modified Sequences : W5H004

Figure 8.2.3 indicates, based on a same-day comparison, that stormflow is the dominant process at the 25 percentile, although the median baseflow is higher. Increases to stormflow are not evident at the 25 percentile, although an increase in the mean indicates an increase in stormflow for the larger events with a maximum increase of 14 mm to 18 mm recorded. Increases to baseflow are evident at both the 50 percentile and the 25 percentile. Again, it is the increases to seeded-day baseflow that improve streamflow for most seeded events with stormflow increases only being relevant for the larger events.

From this analysis the following conclusions are made :

i) Rainfall stimulation results in approximately a 7% increase in long-term rainfall.

ii) It is the fewer rainfall events with greater magnitude (5 - 15 mm) that make the largest contribution to increases in rainfall.

iii) Approximately 50% of the runoff is lagged. Consequently, it is difficult to analyse runoff characteristics using an analysis that takes into account seeded-days only.

iv) Runoff increases are largely a result of additional baseflow contributions although the statistical dispersion of data indicates that stormflow is also relevant for the larger events (at the 5 percentile level).

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 *ACRU* MODEL CONFIGURATION

The first stage of this project involved the determination of input requirements for the *ACRU* model. Thereafter data collection from relevant institutions took place. All relevant spatial data were captured on a GIS and verified with other sources, where possible. This process proved to be time-consuming and costly. The manipulation of these data to calculate variable values for use in the *ACRU* model also proved to be time-consuming, especially :

i) in preparing the dynamic files in catchments where several "time slices" of data were used and
ii) in catchments with a large number of sub-catchment divisions.

Savings in time and cost can be achieved by using only "current day" data and verifying on the latest period of record and by using fewer sub-catchment divisions. This could be achieved by disregarding relatively less sensitive variables and concentrating on sensitive criteria such as changes in soil type when delimiting sub-catchment boundaries.

9.2 *ACRU* MODEL VERIFICATION

Of the 13 catchments selected for verification, 9 verifications were considered acceptable. The major reason for poor verifications are shortcomings in the rainfall and/or runoff data. Although routine runoff screening took place, an intense effort in this regard would have saved significant time spent forcing a good fit with the rejection of catchments containing poor data from the verification process. In addition, catchments with a sparse rain gauge network and/or containing unrepresentative rainfall should be excluded.

A further recommendation is that a larger variety of variables should be changed as part of the verification process. In this study only specific soil and land use variables to which the ACRU Model is sensitive were used. Changes to other variables might result in acceptable verification.

9.3 SEEDING-RELATED IMPACTS

To quantify the potential effects of rainfall simulation on runoff, ACRU model output using unmodified rainfall was compared to the output using modified rainfall. Firstly, stochastic rainfall sequences (based on the statistics of the historical sequence) were generated and used with the ACRU model. The stochastic sequences were then modified and used with the ACRU model. The modified sequences were then compared with their corresponding original stochastic sequences. This comparison included assessing the difference in MAR, yield from a hypothetical dam and timber yield. The hypothetical dam concept uses modelled streamflow to find the firm yield from an imaginary timber dam with a MAR capacity. The yield is calculated by the ACRU model which estimates a volume of timber based on the modelled accumulated transpiration of the tree.

The water resources and timber yield results for the 13 pilot catchments are summarised in Table 9.1. Results show that the increases in both water resources and timber yield are highly significant with an average median increase in water resources of ∞ 30% and a ∞ 20% increase in timber yield.

Table 9.1 : Median Water Resource Firm Yields and Timber Yields of the Stochastic (S) and Modified (M) Sequences and the Percentage Increases

CATCHMENT NUMBER	RUNOFF (Mm^3)			WATER YIELD (Mm^3)			TIMBER YIELD (M^3/ha)		
	S	M	%	S	M	%	S	M	%
B1H002	3,4	4,6	35	2,4	3,1	30	160	190	22
C1H006	48,0	60,0	25	28,0	32,0	14	-	-	-
X1H016	52,0	65,0	25	47,0	58,0	23	320	380	22
X1H019	30,0	36,0	20	28,5	33,8	19	270	320	19
X1H020	3,8	5,3	39	2,5	3,4	36	350	460	30
X1H021	46,0	57,0	24	38,0	46,0	21	430	500	17
X2H008	10,0	13,5	35	8,6	11,4	31	390	465	19
X2H030	8,5	10,4	22	8,1	9,4	16	275	325	18
X2H031	23,0	31,0	35	22,0	28,0	27	280	345	23
W5H004	27,0	35,0	30	21,0	27,5	31	300	370	23
W5J008	6,8	9,9	46	5,0	7,1	42	325	385	29
W5H024	165,0	210,0	27	105,0	122,0	16	430	500	16
W5H025	25,0	37,0	48	17,0	23,8	40	340	430	26
	-	-	32	-	-	27,0	-	-	22

Results presented in Chapter 5 provide a fuller analysis on the statistical dispersion of the data. The range between percentiles provides an index for statistical dispersion.

The water resource yield increases range significantly from a 9% increase (using the 25 percentile in W5H024) to a 45% increase (using the 75 percentile in X1H020). A clear dispersion is evident using the 5 and 95 percentiles, with catchment increases varying from 0% in W5H024 to 68% in X1H020. On the other hand, the statistical dispersion of timber yield increases is less significant, with typically an 16% increase using the 25 percentile in X1H021, to a 32% increase using the 75 percentile in X1H020. Using the 5 and 95 percentiles respectively, these increases range from 14% in W5H024 to 34% in X1H020. This study concludes that rainfall stimulation has a potentially beneficial effect on the long-term yields of both water resources and afforestation.

9.4 REGIONALISATION OF IMPACTS

The extrapolation of these results on a regional basis is presented in Table 9.2 and indicates that rainfall modification in the Usutu basin will have the greatest increase in both water resources and timber yield. Results presented in Chapter 6 indicate a great variability, with the Highveld region having the greatest range of water resource yield increases for the 95 and 5 percentile zone (>50%), while the Crocodile region's corresponding range is the smallest (∞ 30%). There is little variability in timber yield ranging from 4% for the Highveld regions to 15% for the Usutu region using the 5 and 95 percentile range.

Table 9.2 : Median Percentage Increases in Water Resource Firm Yield and Timber Yield of the Three Homogeneous Regions

REGION	FIRM YIELD (%)	TIMBER YIELD (%)
Highveld	25	21,7
Crocodile	25	20,0
Usutu	33	25,0

9.5 SENSITIVITY ANALYSIS

The sensitivity analysis is summarised in Table 9.3 and indicates that the variables describing soil properties are the most sensitive in terms of water resources and timber yield. The soil variables include the depth of the A horizon (DEPA) and the effective depth of the soil contributing to stormflow (SMDDEP), and the only land use variable analysed is the interception loss of vegetation (VEGINT). It is recommended that collection of soil data should be given a higher priority than the collection of land use data. However, although changes to these variables might affect the magnitude of the yield, the relative increases in median yield vary little. An 11% to 24% water resources yield variation for changes to SMDDEP is the most sensitive, with timber yield variations being insignificant.

Table 9.3 : Variable Variation and Percentage Change in Median Yields

VARIABLE NAME	VARIABLE CHANGE	WATER YIELD CHANGE (%)	TIMBER YIELD CHANGE (%)	CHANGE IN % INCREASE	
				WATER	TIMBER
DEPA	+ 50% - 50%	- 41 + 109	+ 3 - 16	19 11	26,6 20,8
SMDDEP	+ 50% - 50%	- 25 + 91	+ 12 - 29	24 11	24,3 22,4
VEGINT	+ 50% - 50%	- 16 + 16	- -	14 16	- -
Rotation Period	- 16% - 33%	- -	- 12 - 16	- -	23,5 23,2
Density	> 1 500 stems/ha	-	+ 0	- -	23,8

9.6 ANATOMY OF THE LONG-TERM SEEDING EFFECT

The analysis, summarised in Tables 9.4 and 9.5, of the break-down of rainfall increases by seeded daily rainfall range and corresponding seeded-day runoffs casts more light on the "anatomy" of the long-term effects of seeding. This analysis averages the results from the 3 catchments reported in Chapter 8 and redefines the range of rainfall volumes analysed.

Table 9.4 : The Number of Events and Percentage Increase in Rainfall and Runoff for a Range of Seeded Rainfall Events

RAINFALL RANGE (MM)	EVENTS		PERCENTAGE OF TOTAL INCREASE		
	NUMBER	%	RAINFALL	SAME DAY SEEDED RUNOFF	TOTAL RUNOFF
0 - 2,5	4079	59,0	10,8	41,2	20,6
2,6 - 5,0	1033	14,8	13,7	10,0	4,9
5,1 - 10,0	952	13,8	24,3	12,3	6,2
10,1 - 15,0	138	2,0	16,7	7,1	3,5
15,1 - 20,0	69	1,0	11,8	6,2	3,0
>20,1	648	9,4	22,7	23,2	11,6
TOTAL	6 919	100,0	100,0	100,0	49,8

Table 9.5 : The Percentage Increase in Total Rainfall, Same Day Seeded Runoff and Total Runoff

Description	% Increase
Total % increase in rainfall for all days	7,3
Total % increase in same day runoff recorded when scattered rain days are seeded	15,8
Total % increase in runoff recorded on all days when scattered rain days are seeded	31,7

Table 9.4 indicates that those rainfall events that are small in volume (0 - 2,5 mm) occur most frequently. However, it is the few rainfall events with a greater rainfall volume (5-15 mm) that make the largest contribution to increases in rainfall. This could have a cost implication by identifying and seeding only those storms with the most potential for enhanced yield (the fewer events with larger rainfall volume). Table 9.5 also indicates that the greatest contribution to the increase in runoff is from the smallest rainfall events. However, this analysis compares rainfall and runoff increases on the same day and ignores any lagged runoff. Table 9.4 also indicates that the seeded-day total increase in runoff, expressed as a percentage of the total increase in

runoff (15,8%), accounts for approximately 50% of the total increase in runoff (31,7%). Assuming that this lag, or tail of the hydrograph (2 - 4 days), is associated with larger rainfall events, the increase in runoff from larger rainfall events is being severely penalised by using a single day comparison. It is strongly recommended that further work is needed to clarify this problem and associated resultant runoff with its rainfall events.

The analysis of the relative streamflow and baseflow contributions to runoff, presented in Chapter 8, indicates that streamflow increases are mostly a result of baseflow, with stormflow also relevant for a few large rainfall events. However, those results could reflect a different scenario with the inclusion of delayed runoff from larger rainfall events.

10. FUTURE WORK

Areas where future work would be of interest have been identified. During the verification process, specific variables were changed to obtain acceptable verifications. Only these variables were included in the sensitivity analysis. Future work is required to assess what effect changes to other variables would have on both the verification results and seeding related impacts.

This study has quantified seeding related impacts on a monthly basis. Further work is recommended to determine the impacts of rainfall stimulation on a daily basis, especially with regard to extreme rainfall events. Additional work is also required to compare the economic benefits of enhanced water resources and timber yield with the costs of operating a cloud seeding programme.

Finally, in this analysis, the use of a single day comparison to compare same day rainfall and runoff ignores all lagged runoff. Results discussed in Section 9.2 indicate that lagged runoff accounts for 50 % of the total increase in runoff. Consequently, additional work is required to clarify this problem and associated resultant runoff with its rainfall events.

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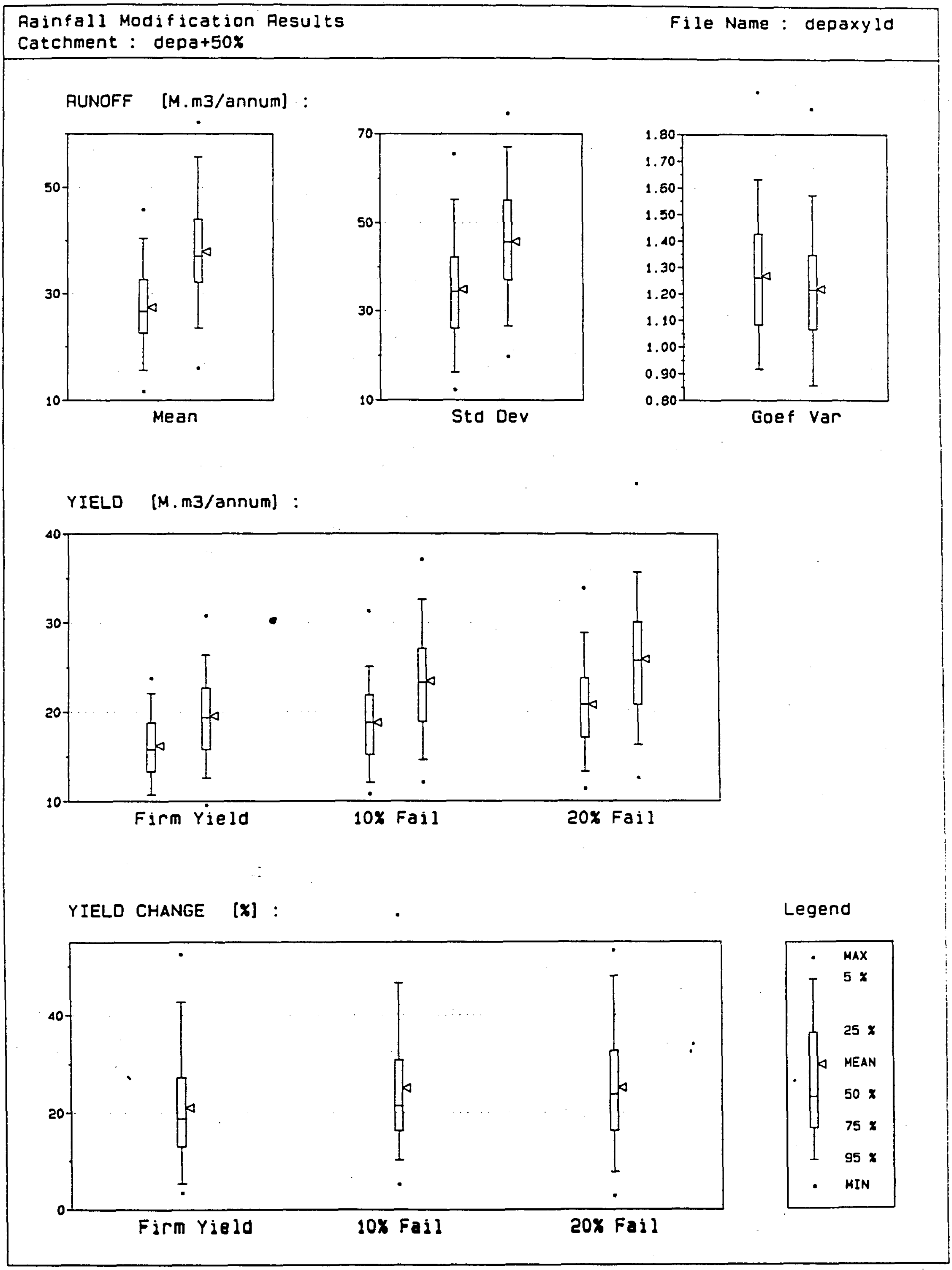
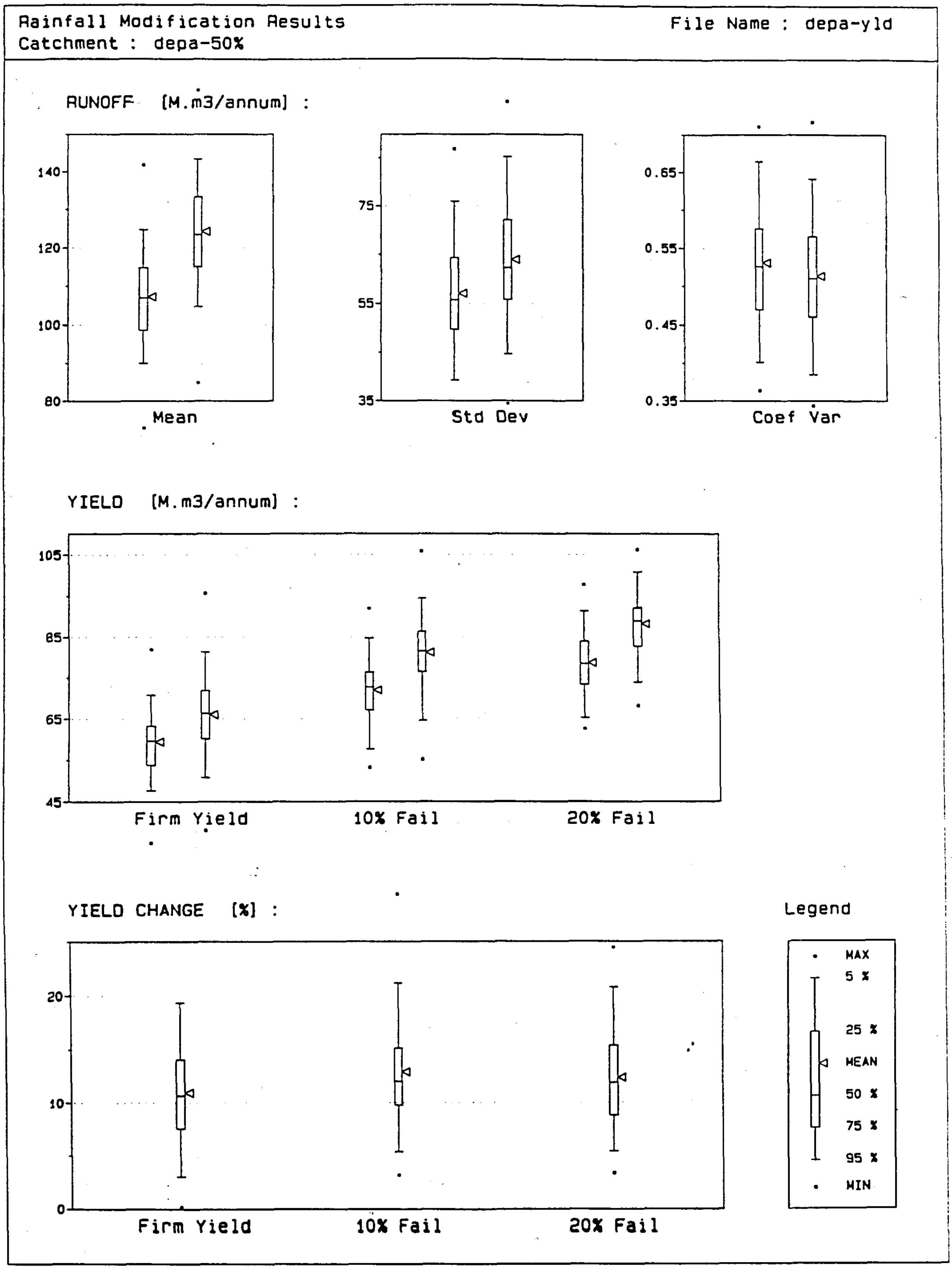
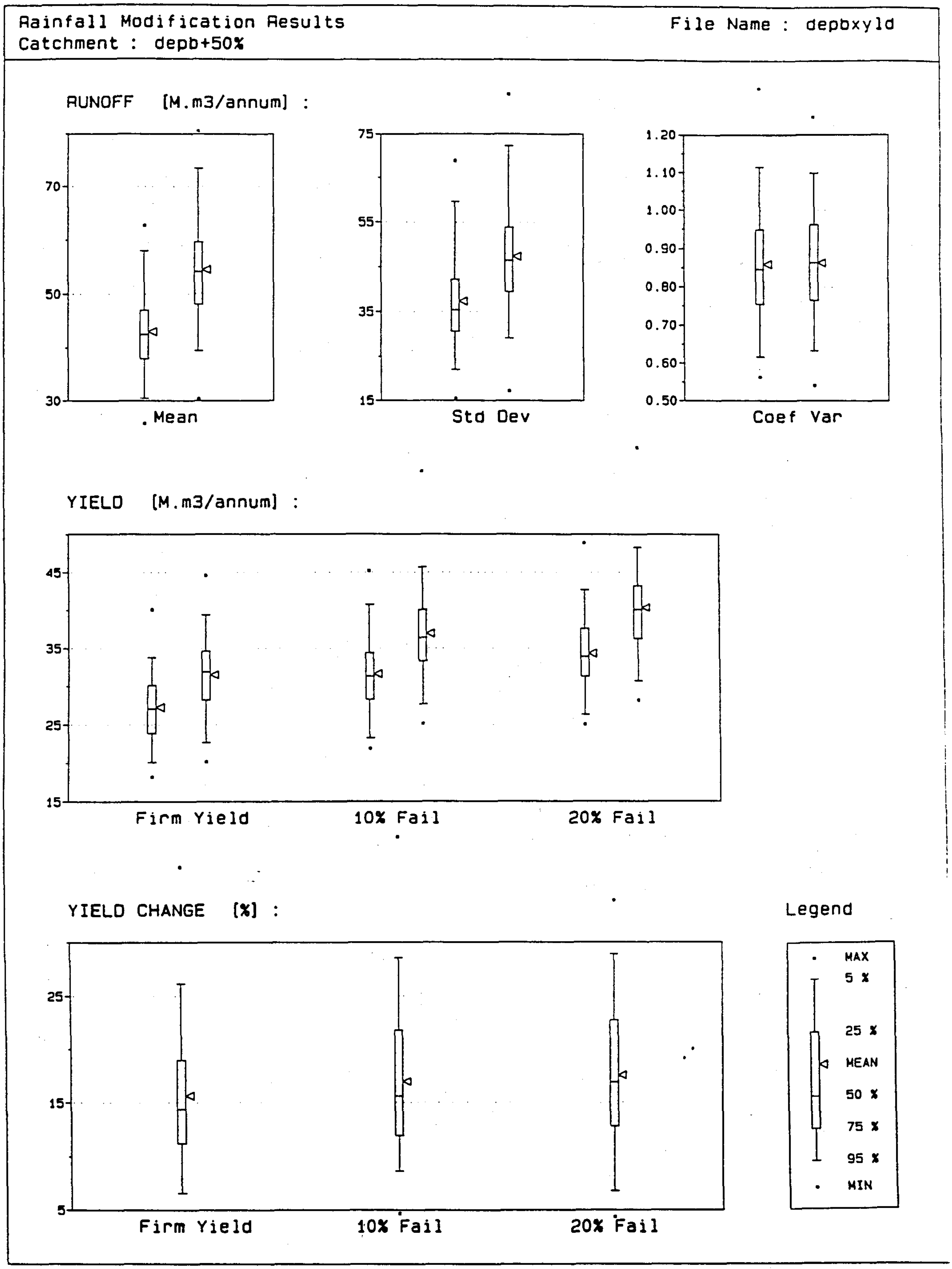


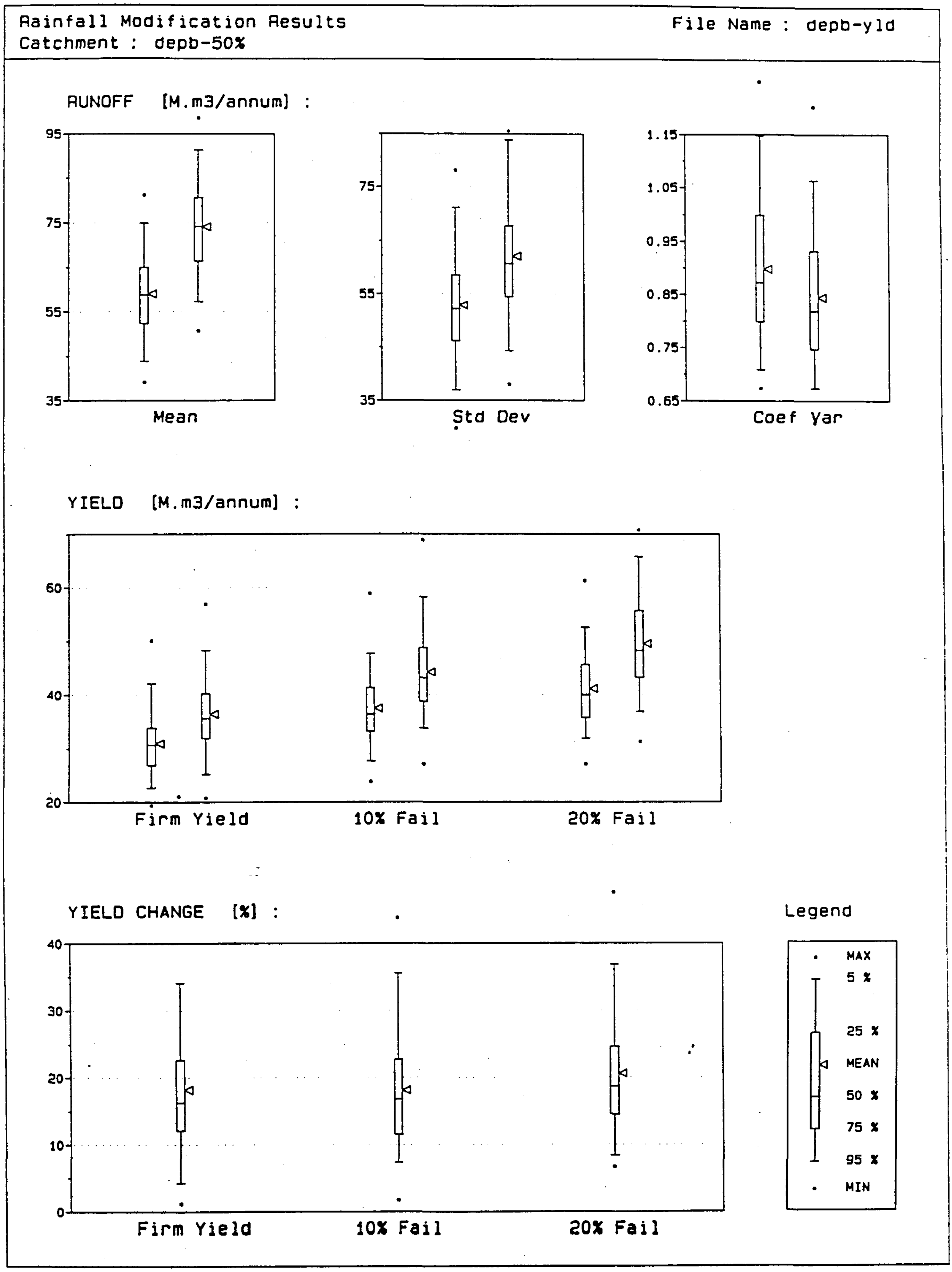
APPENDIX 1 A WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH DEPA INCREASED BY 50%



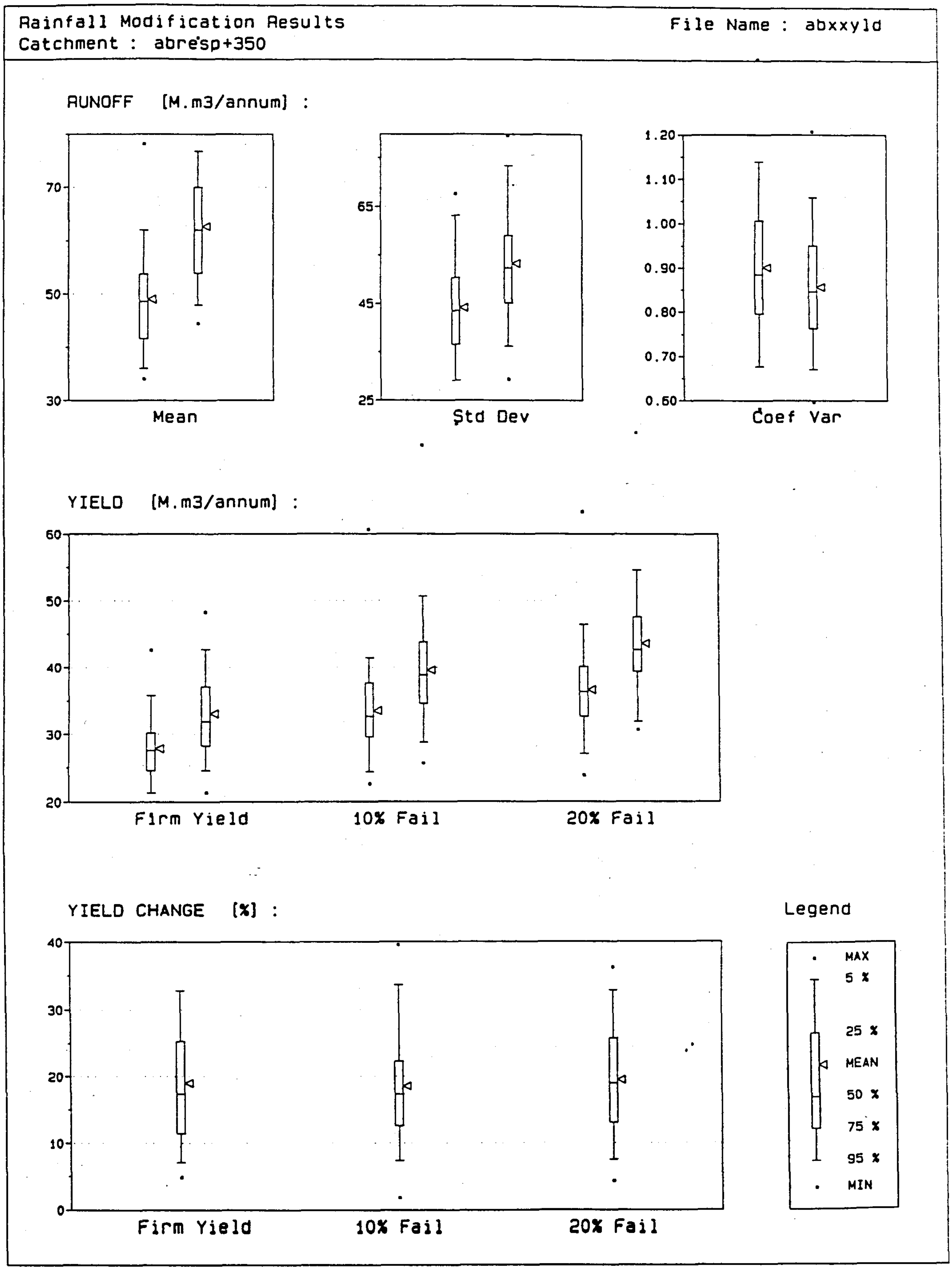
APPENDIX 1 B WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH DEPA DECREASED BY 50%



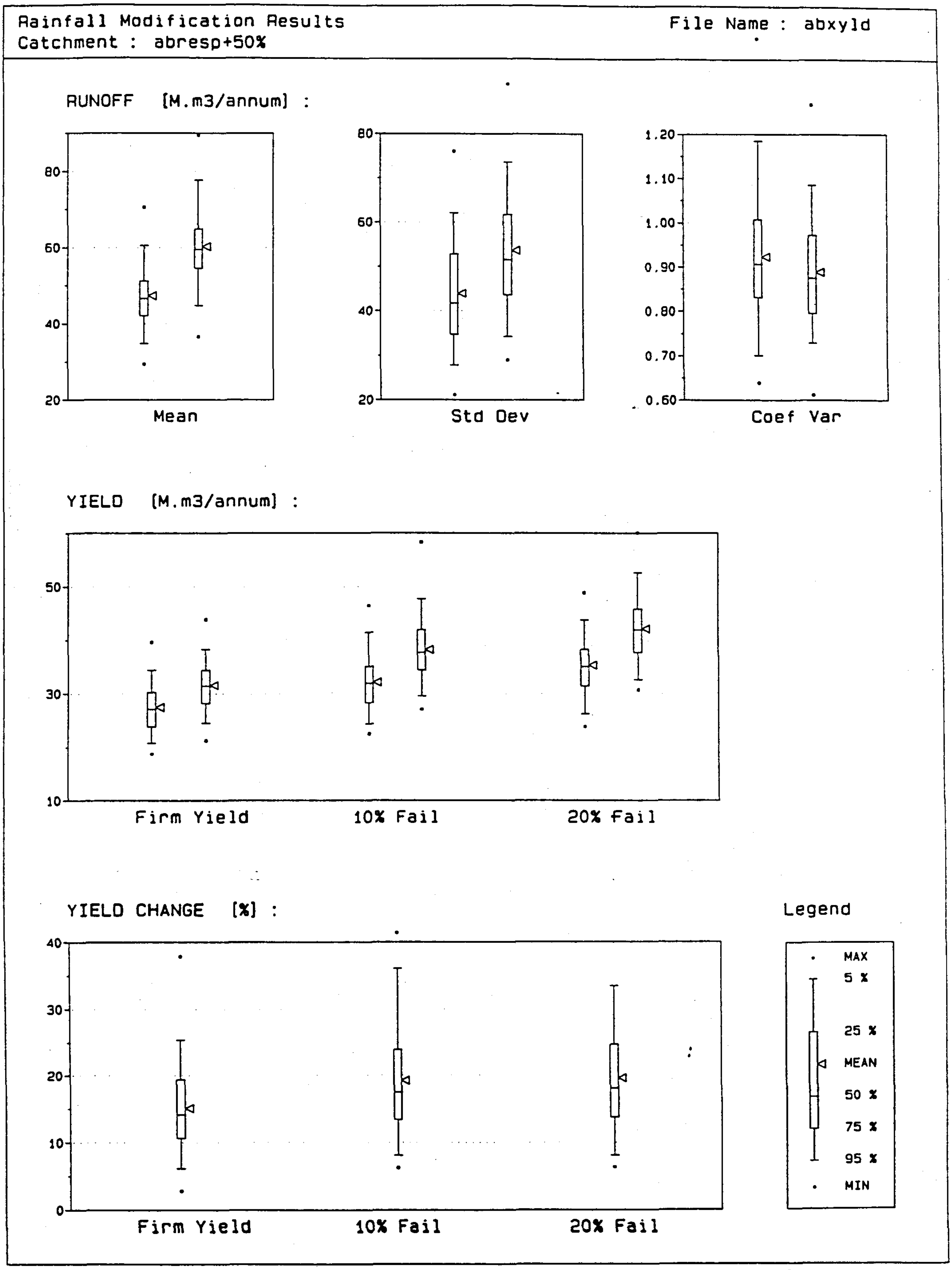
APPENDIX 1 C WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH DEP B INCREASED BY 50%



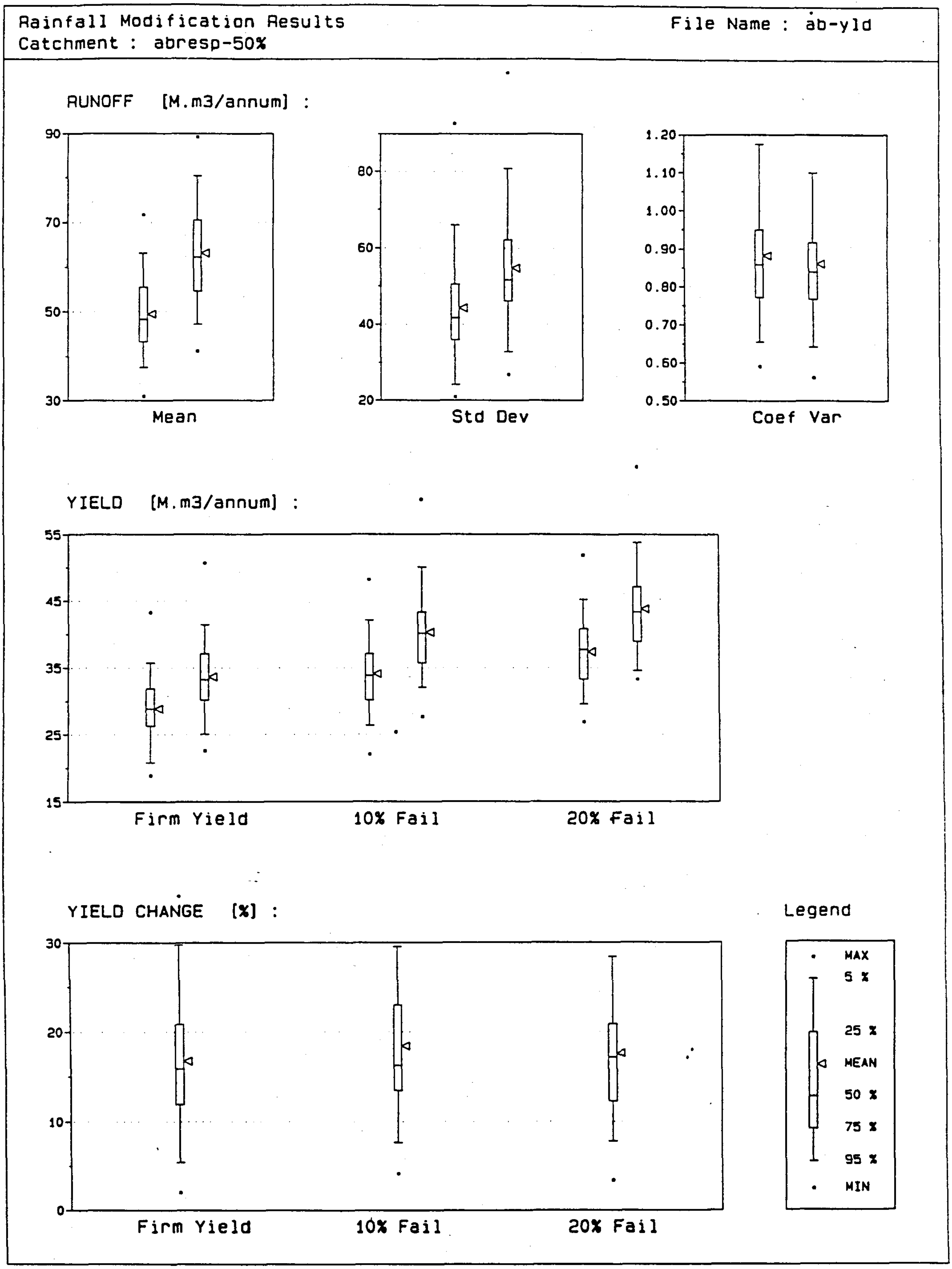
APPENDIX 1 D WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH DEP B DECREASED BY 50%



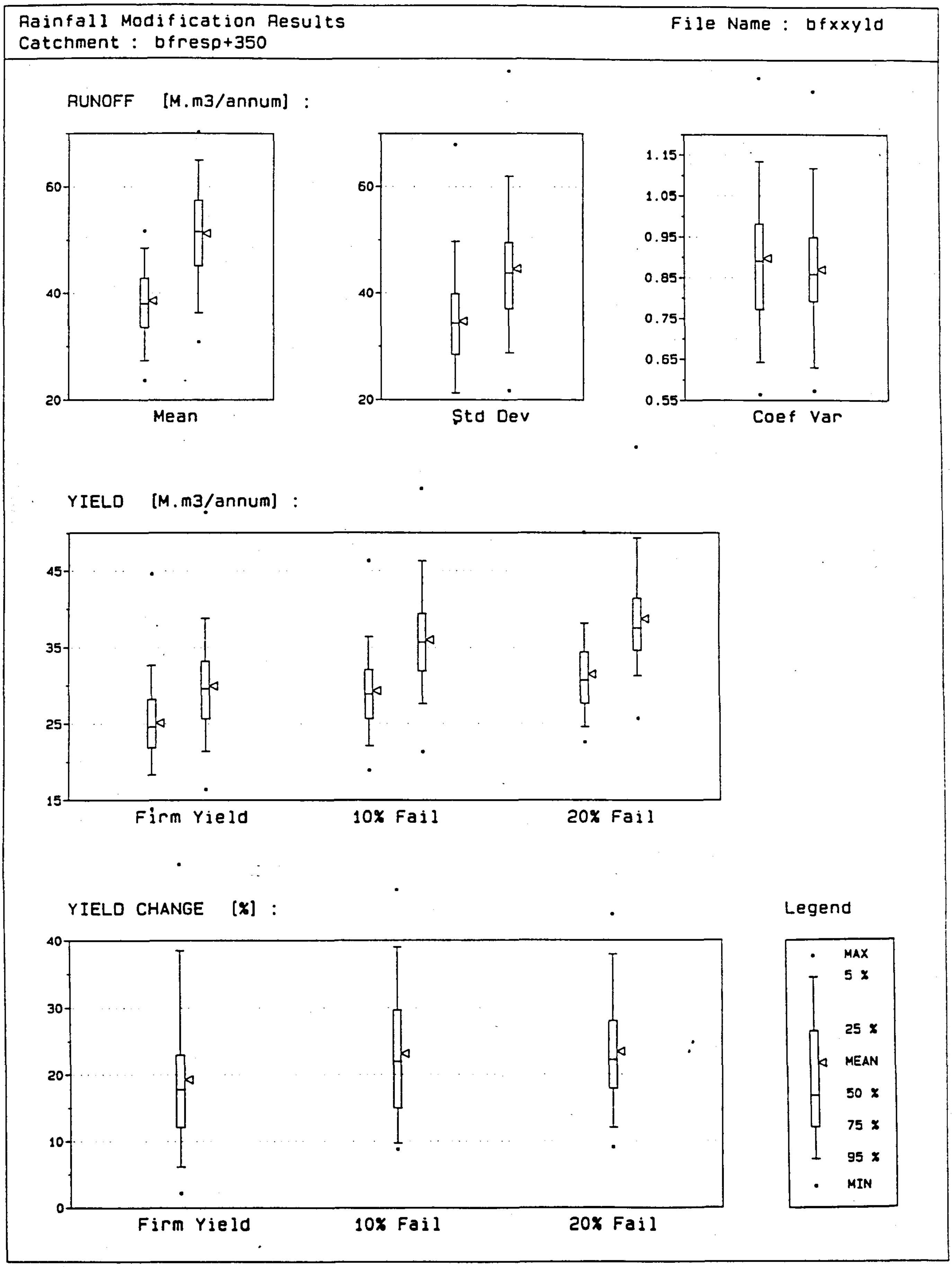
APPENDIX 1 E WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH ABRESP INCREASED BY 350%



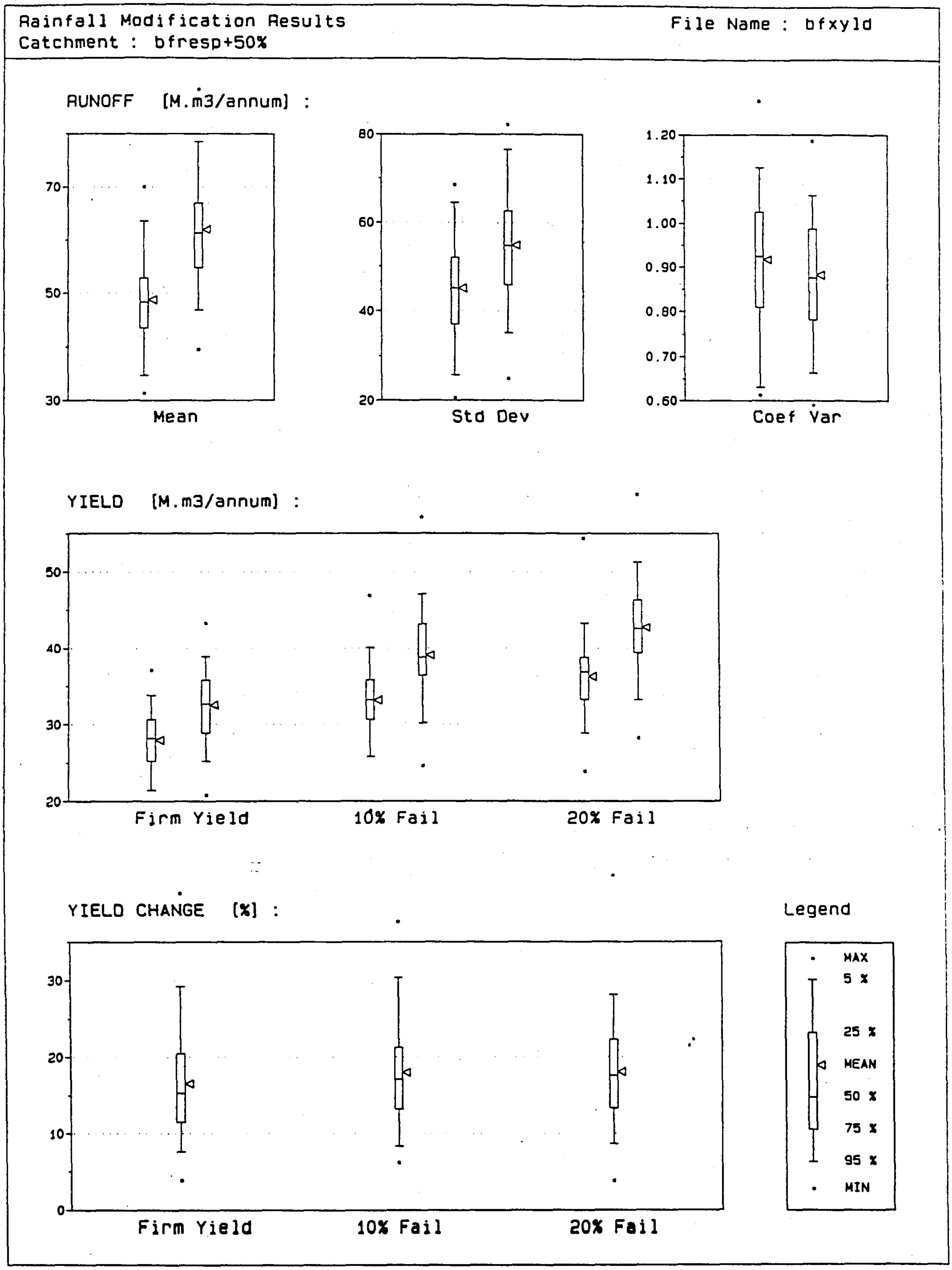
APPENDIX 1 F WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH ABRESP INCREASED BY 50%



APPENDIX 1 G WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH ABRESP DECREASED BY 50%



APPENDIX 1 H WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH BFRESP INCREASED BY 350%



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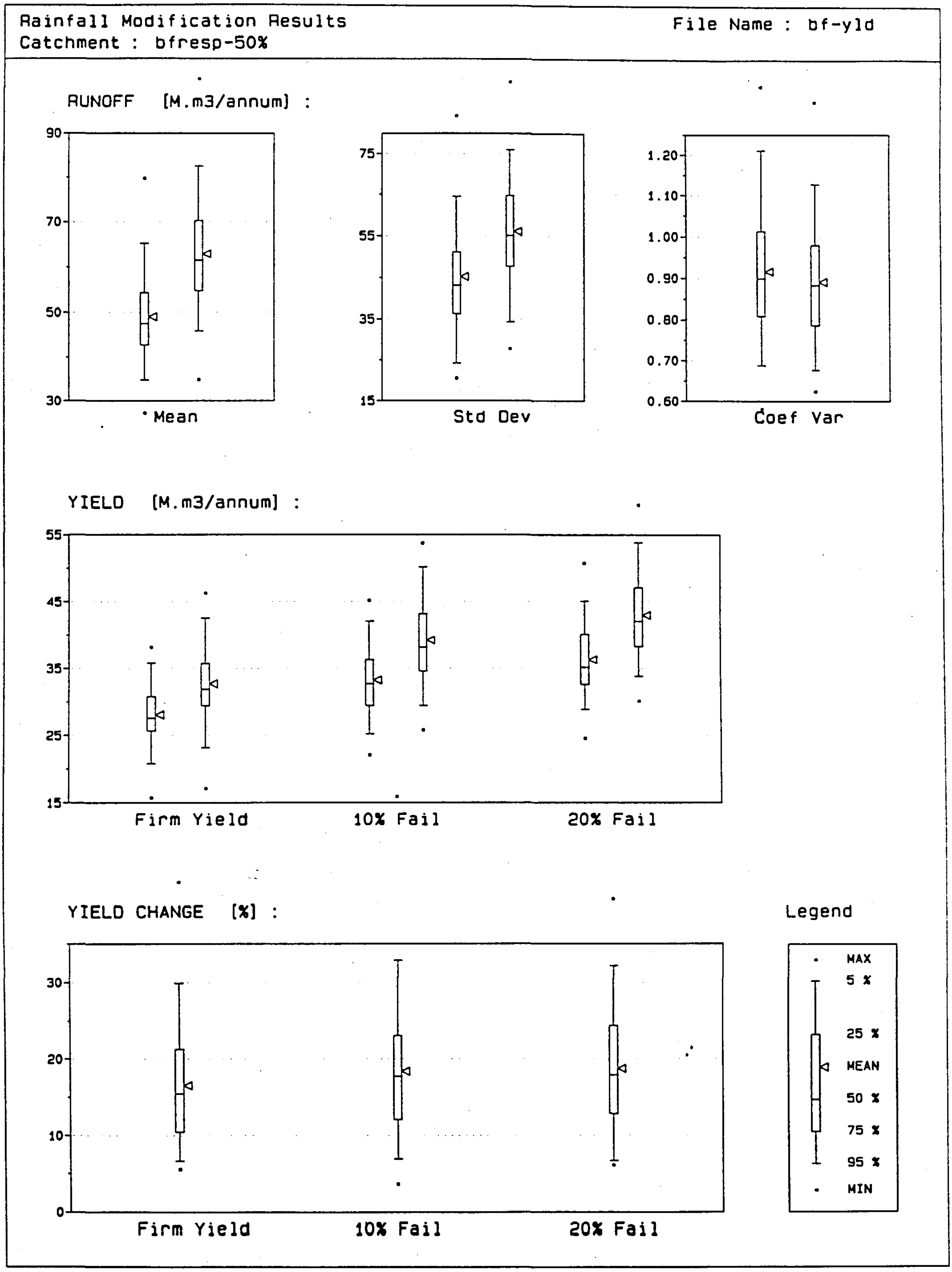

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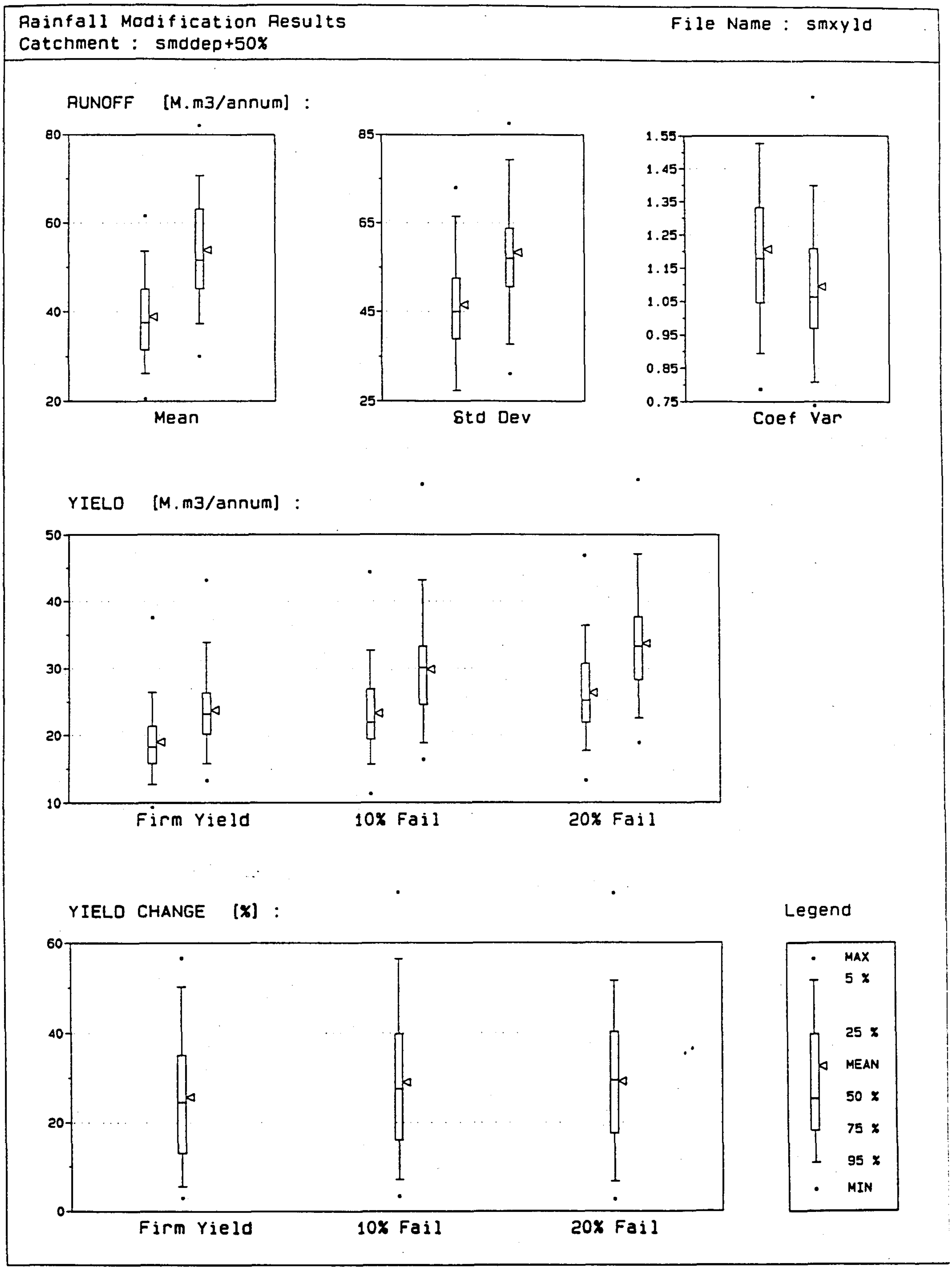
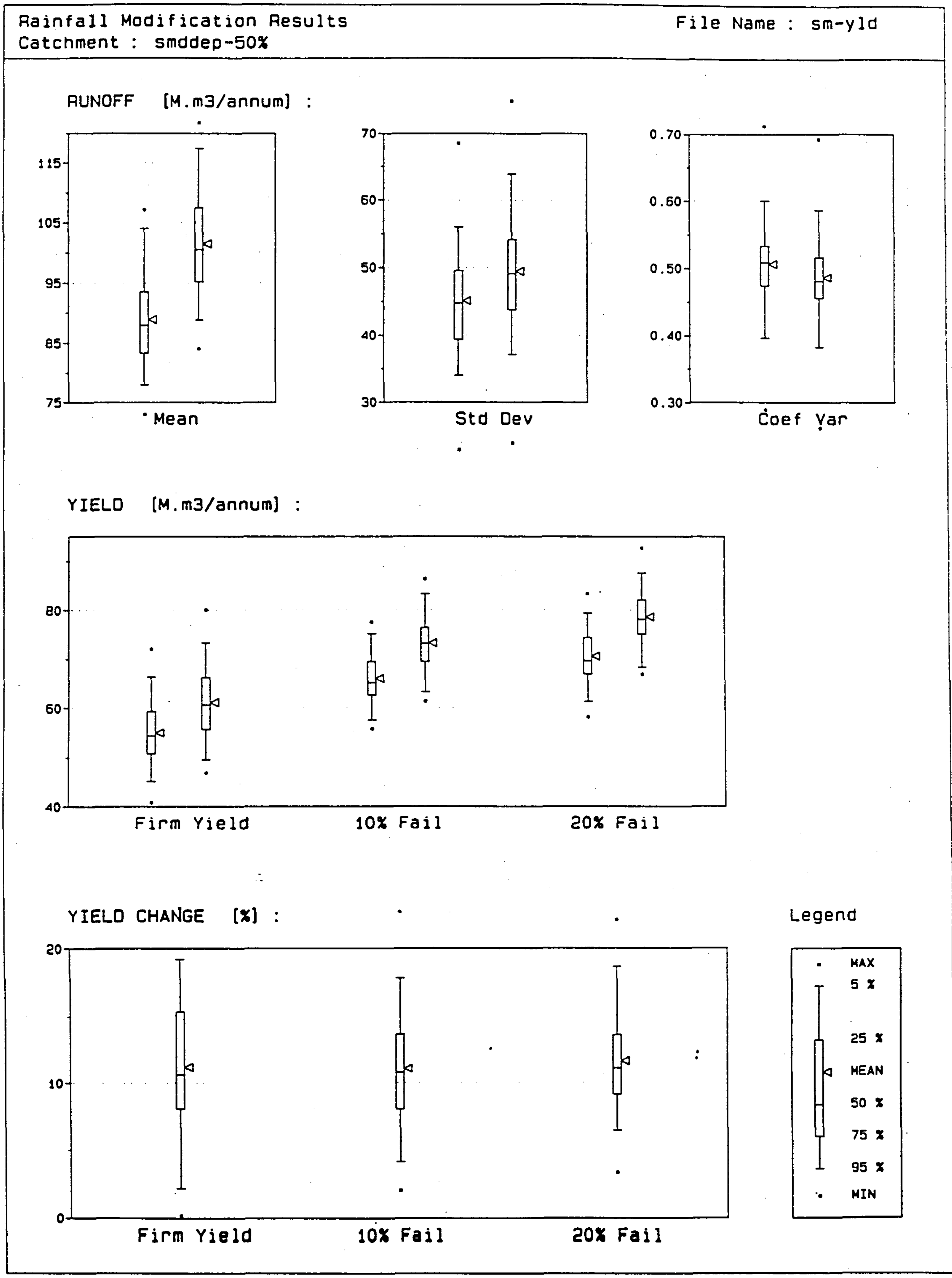


APPENDIX 1 K WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH SMDDEP INCREASED BY 50%



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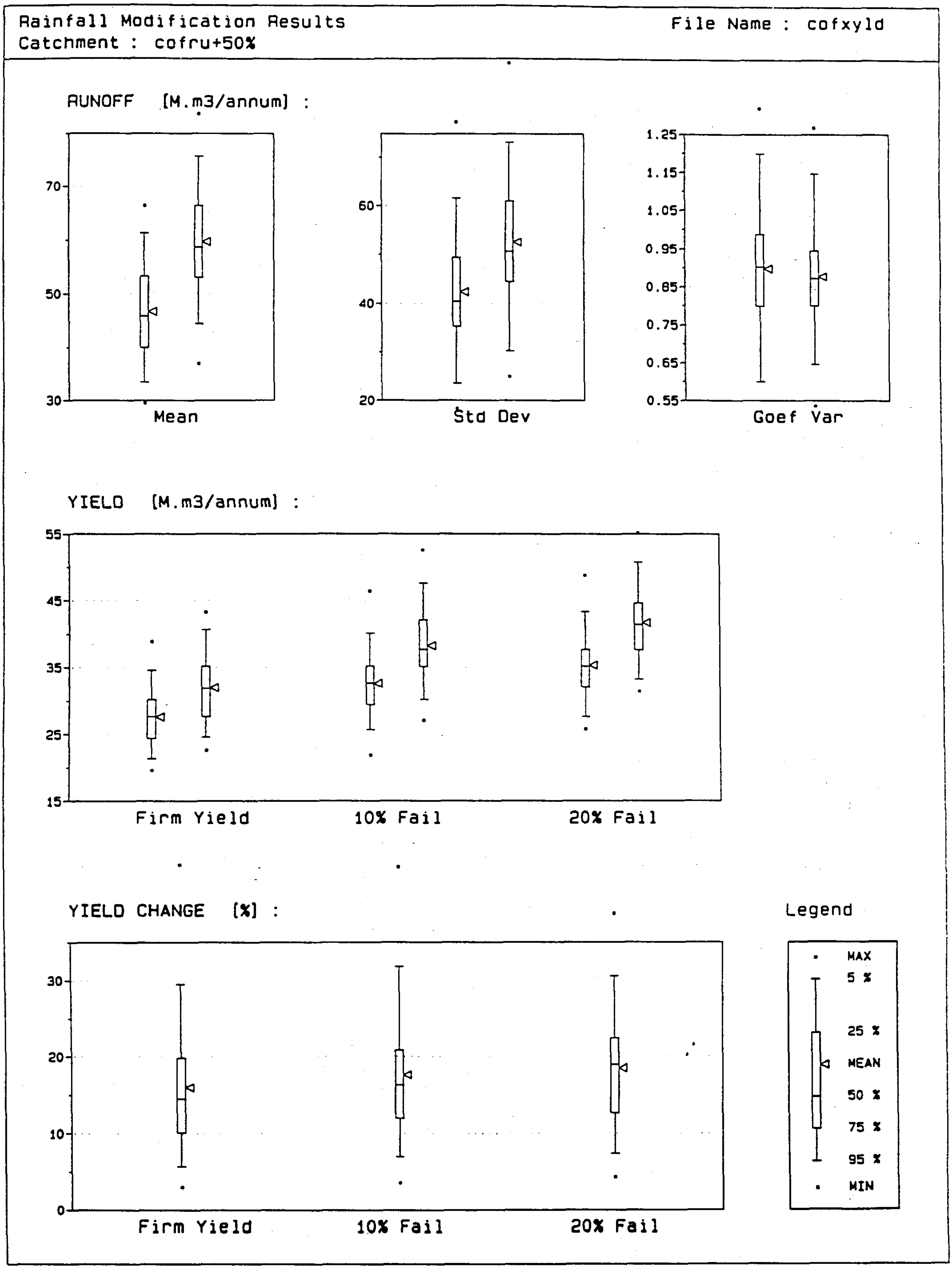
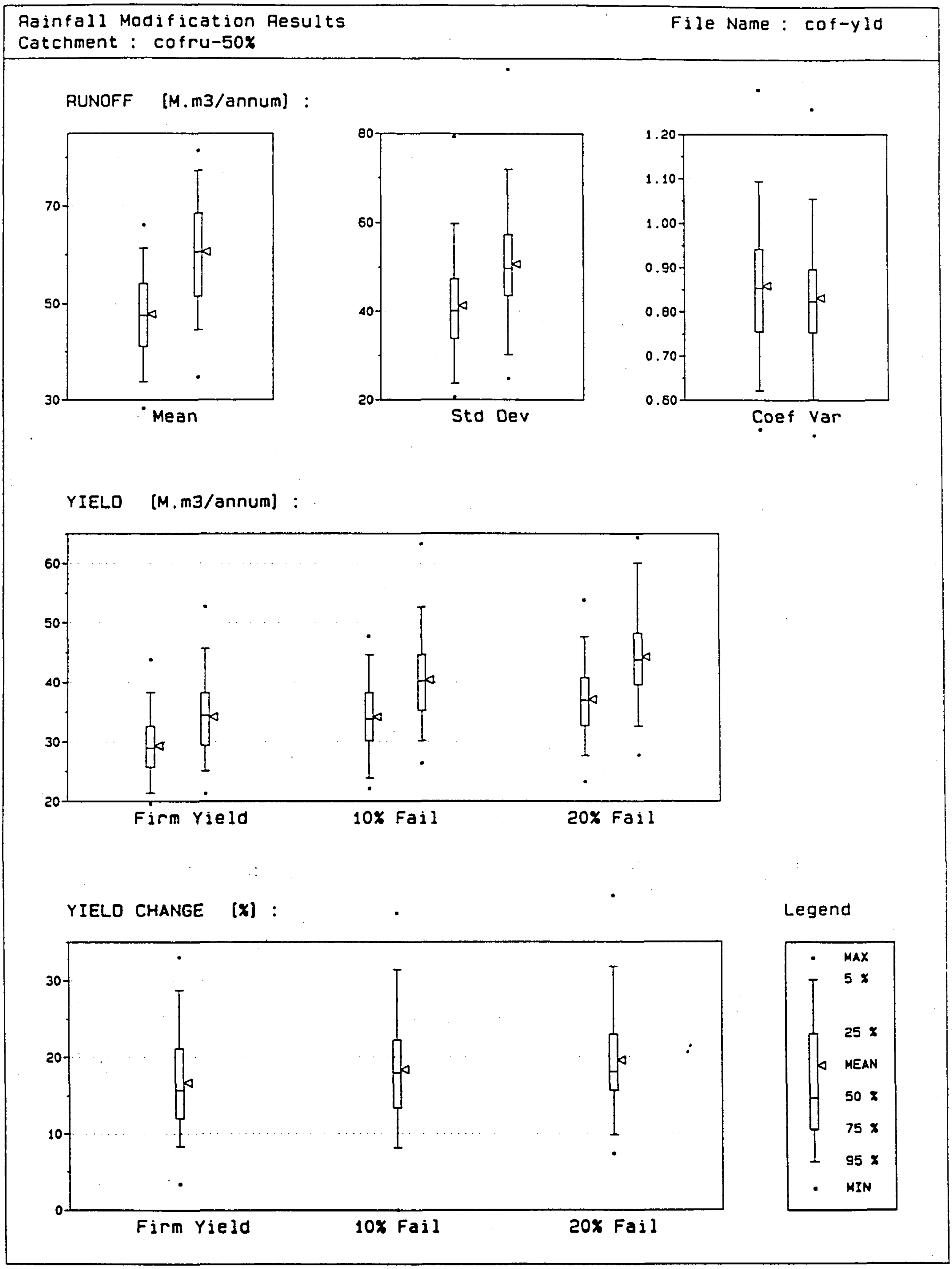


APPENDIX 1 M WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH COFRU INCREASED BY 50%



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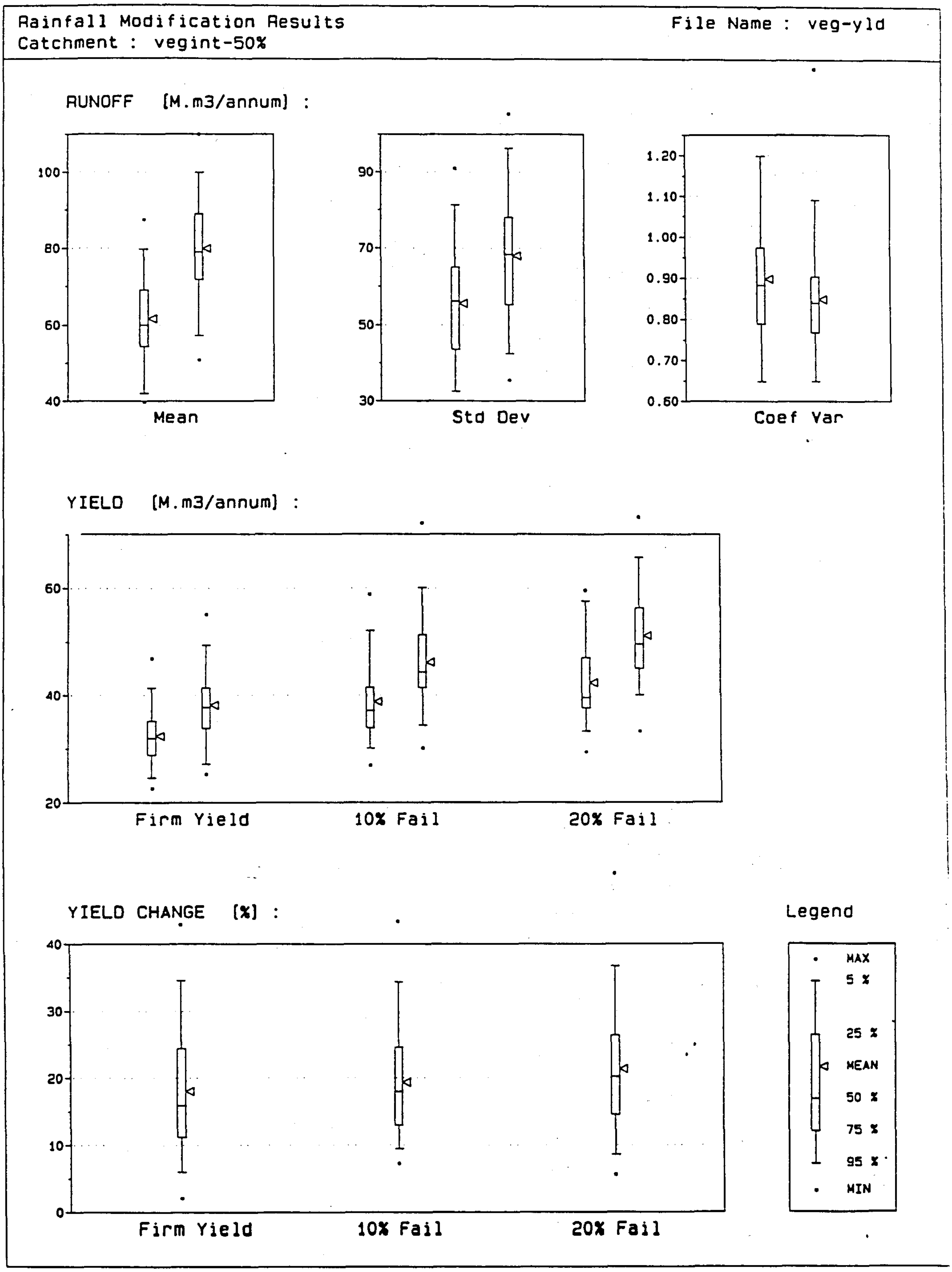
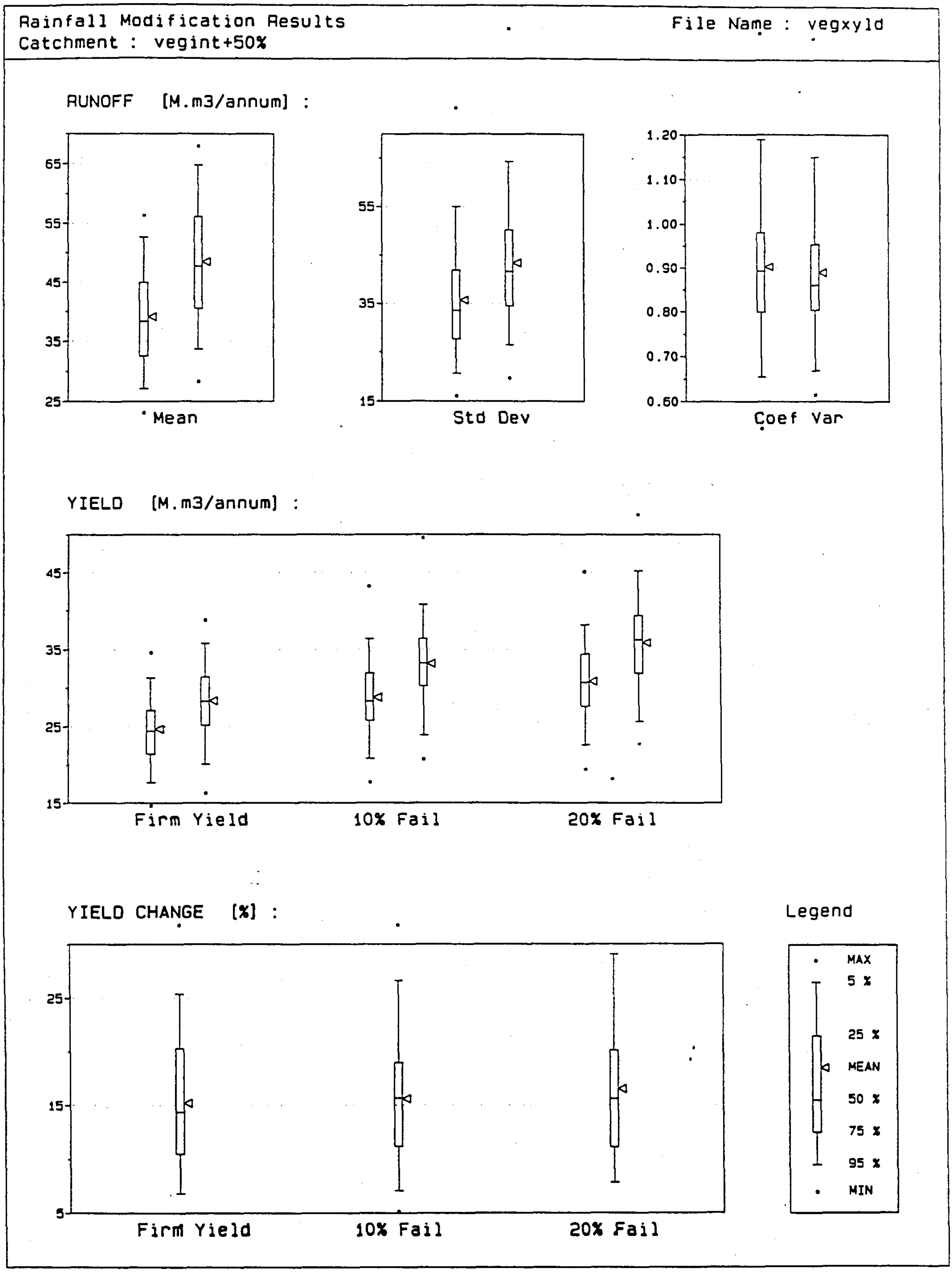
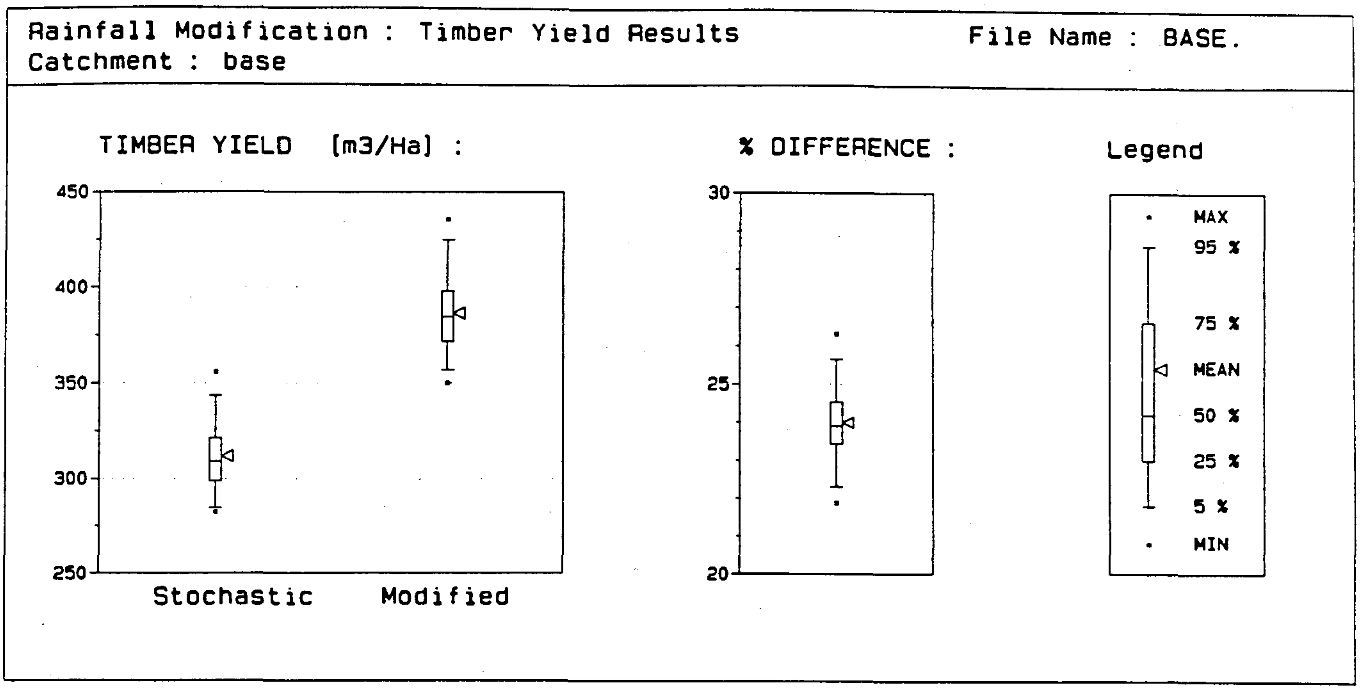


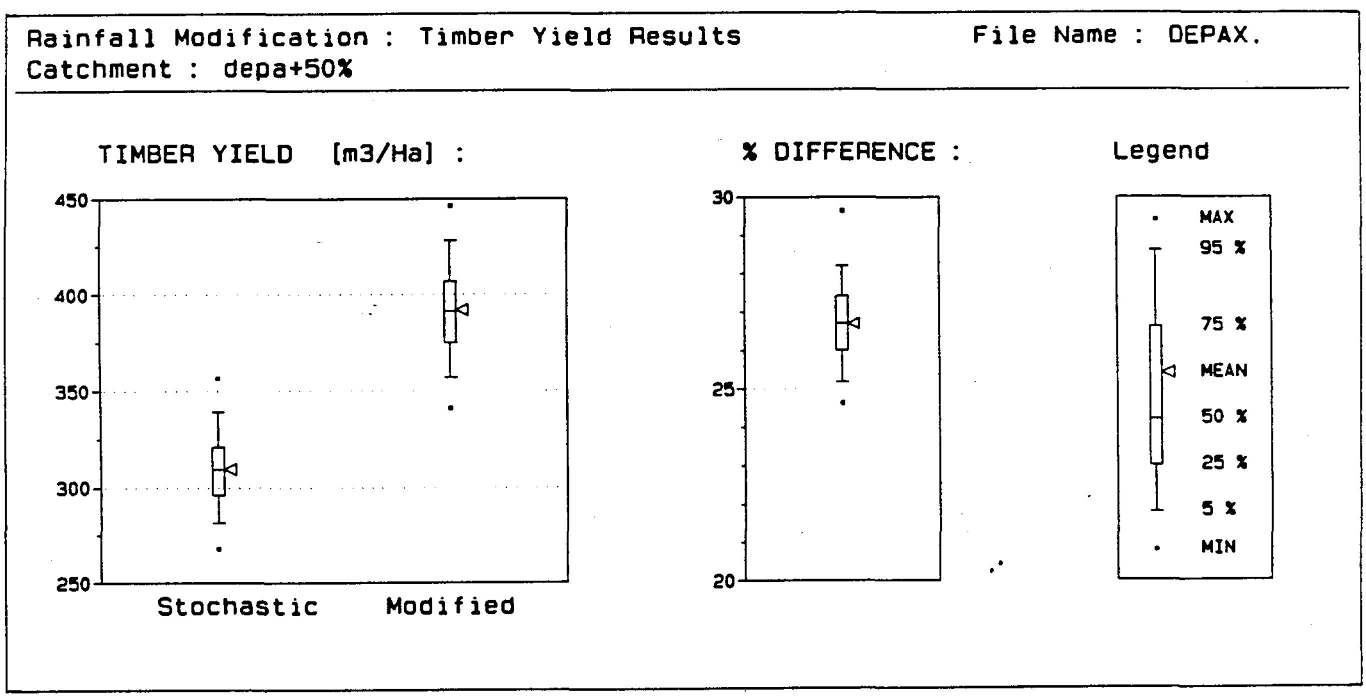
APPENDIX 1 Q WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH VEGINT DECREASED BY 50%



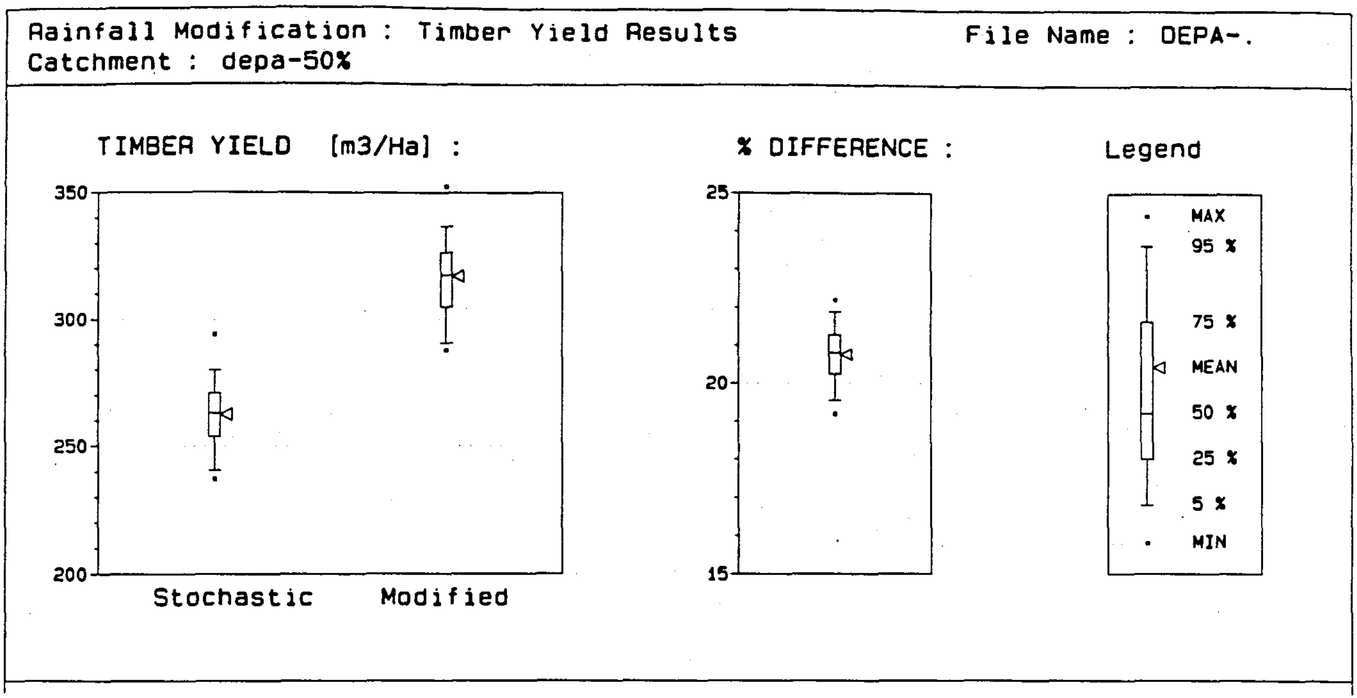
APPENDIX 1 P WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF MONTHLY FLOW AND YIELD WITH VEGINT INCREASED BY 50%



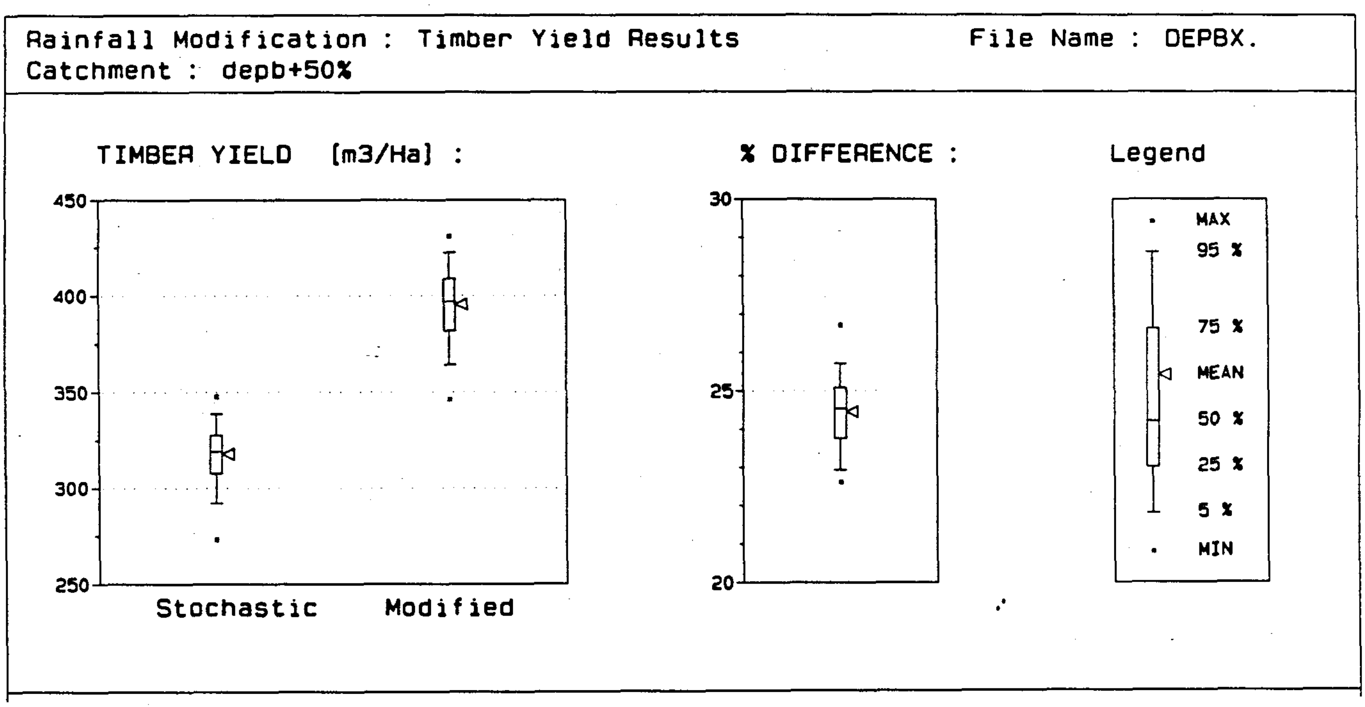
APPENDIX 2 A WHISKER-BOX PLOTS COMPARING TIMBER YIELDS USING STOCHASTIC AND MODIFIED RAINFALL AT W5H004 WITH "BASE" CONDITIONS APPLIED TO ALL SUB-CATCHMENTS



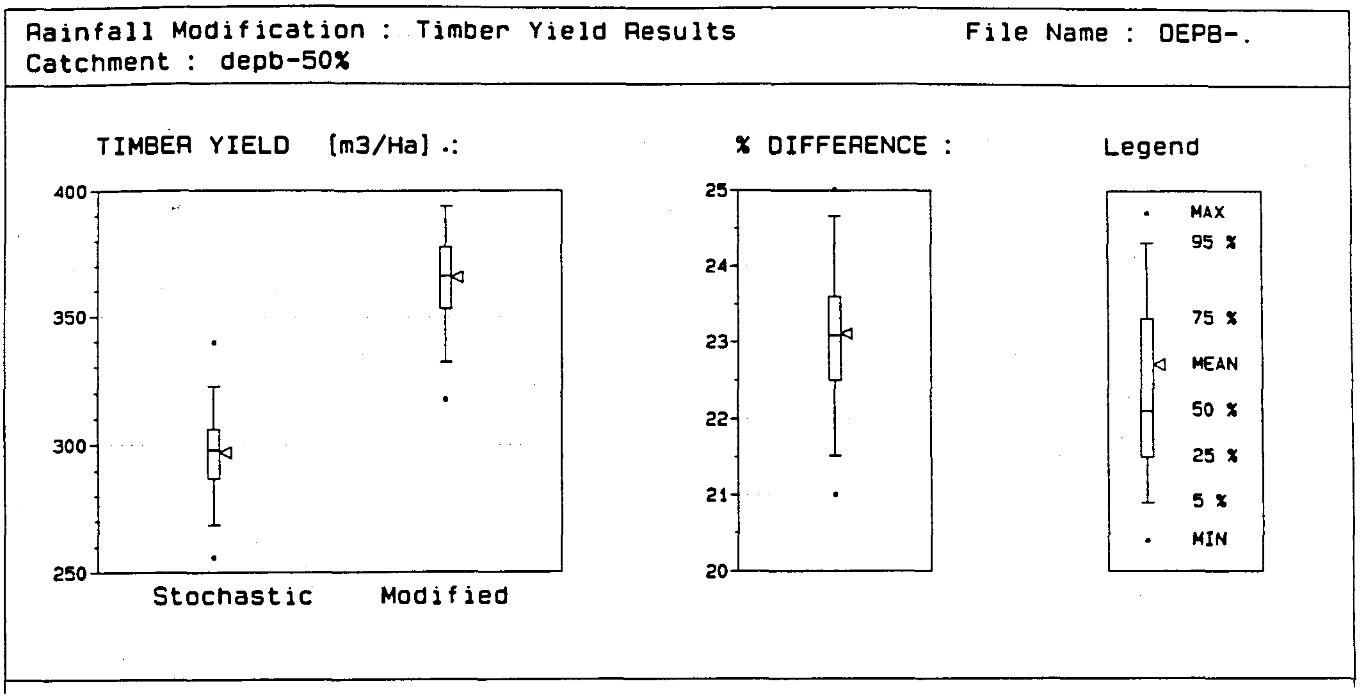
APPENDIX 2 B WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH DEPA INCREASED BY 50%



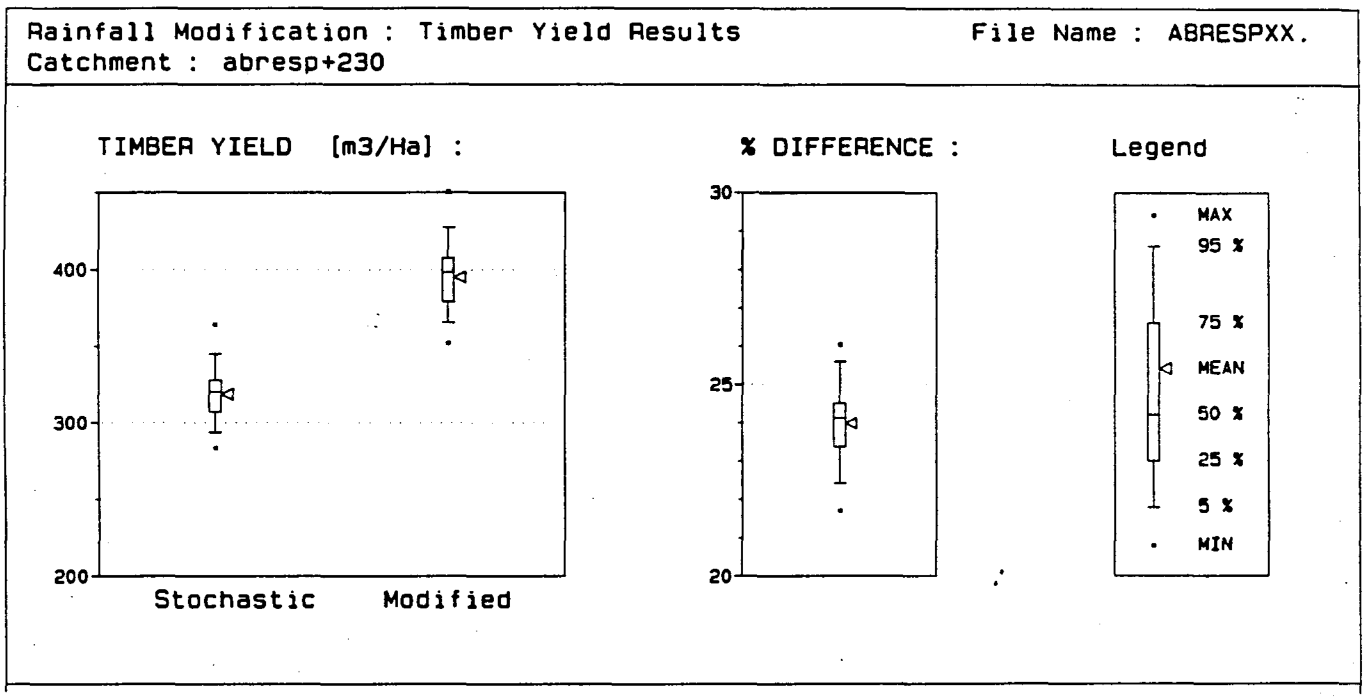
APPENDIX 2 C **WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH DEPA DECREASED BY 50%**



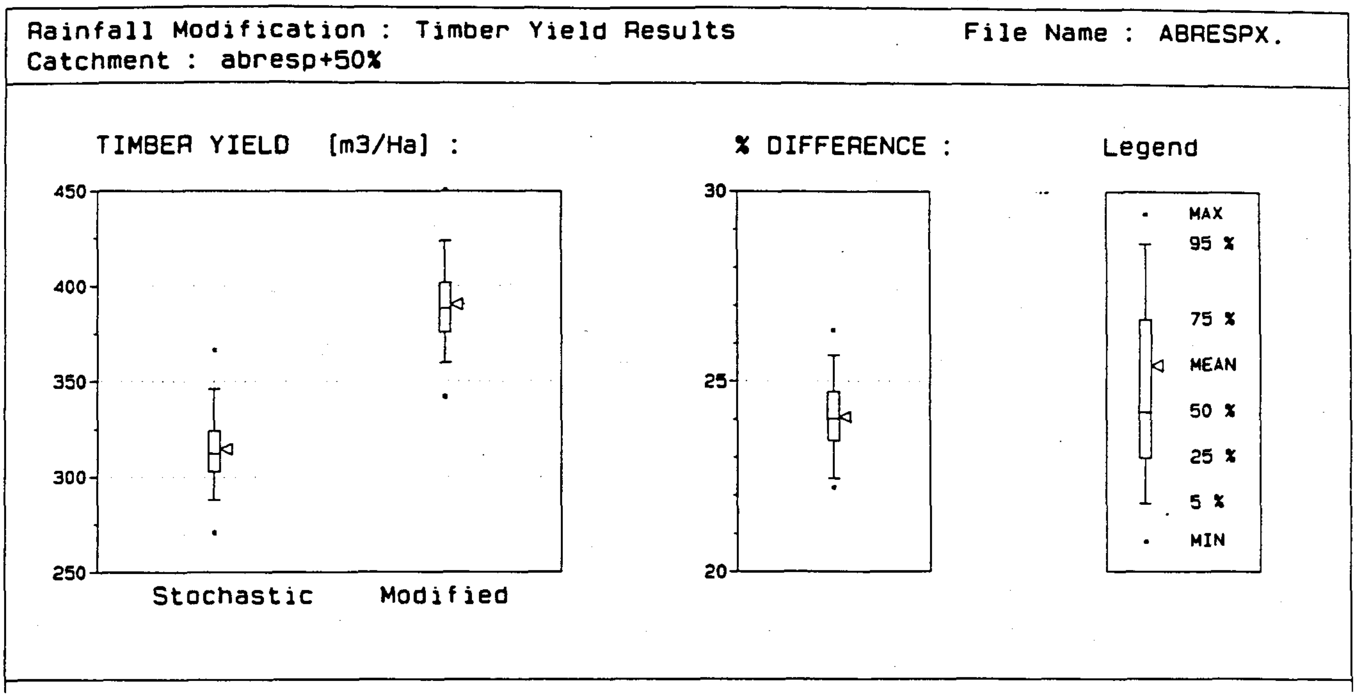
APPENDIX 2 D **WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH DEPB INCREASED BY 50%**



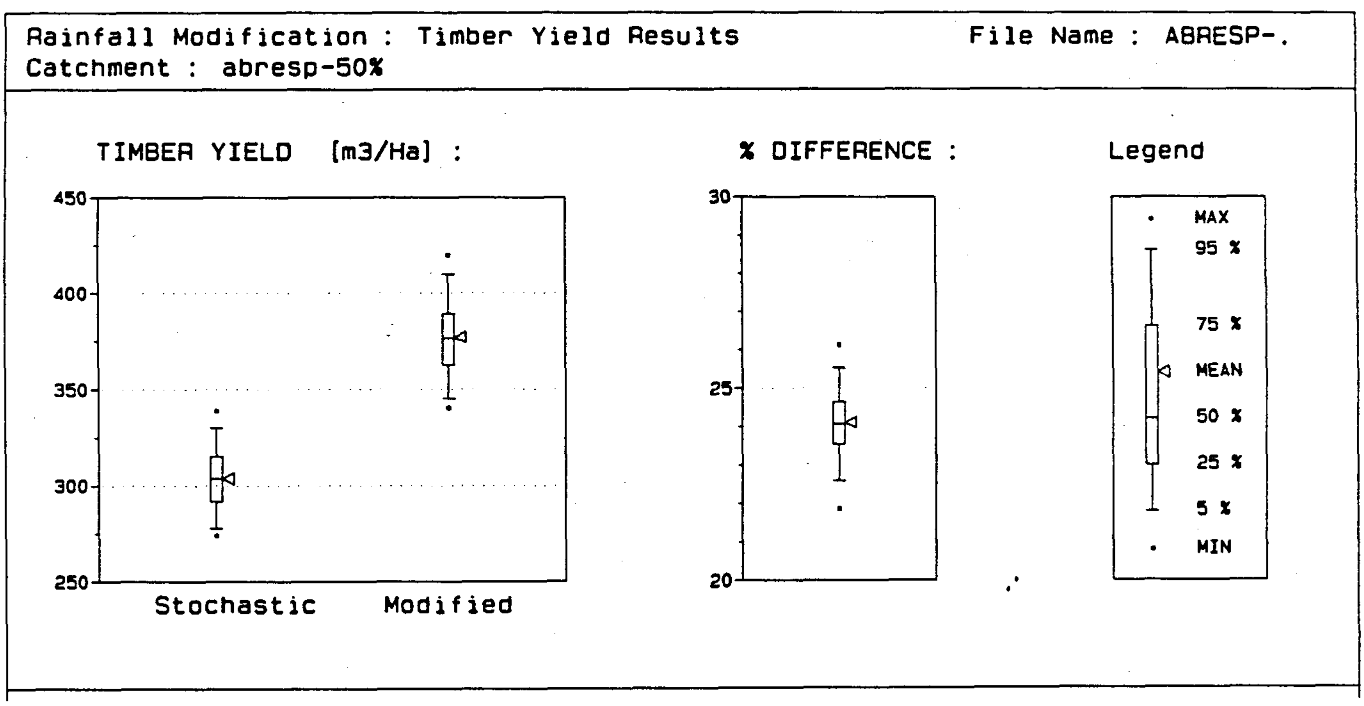
APPENDIX 2 E **WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH DEPB DECREASED BY 50%**



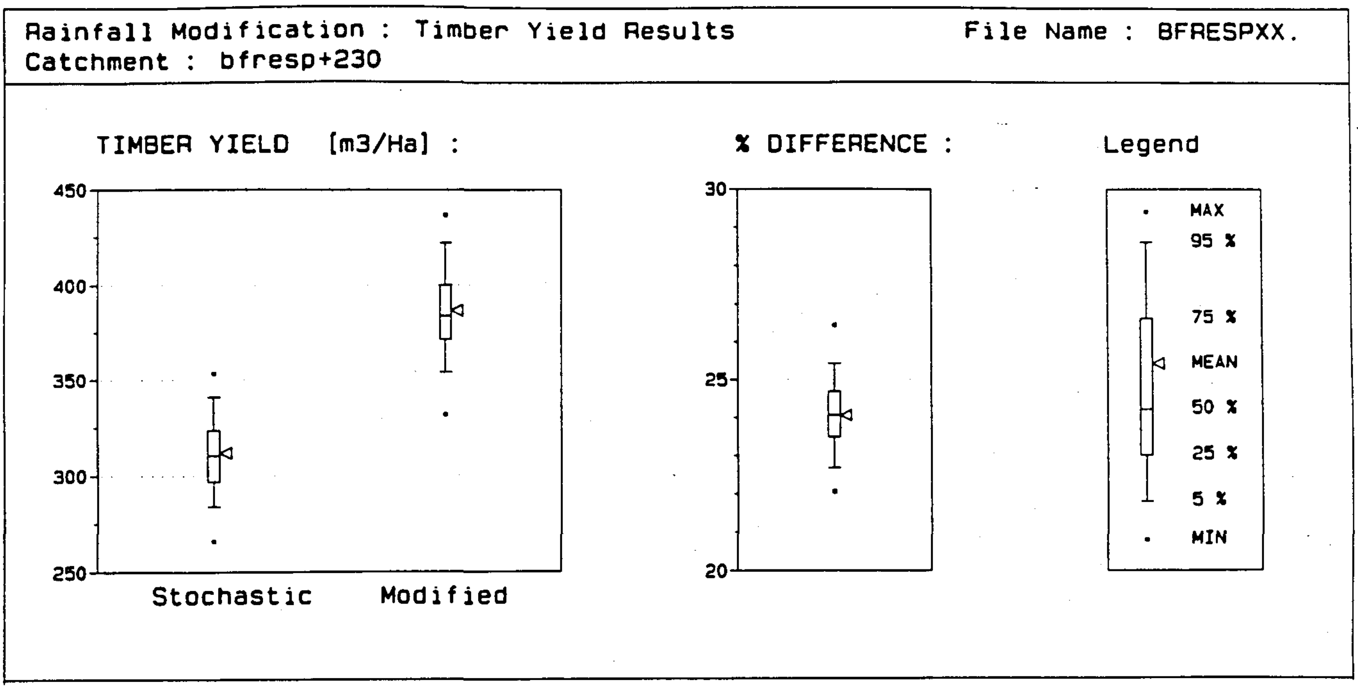
APPENDIX 2 F **WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH ABRESP INCREASED BY 230%**



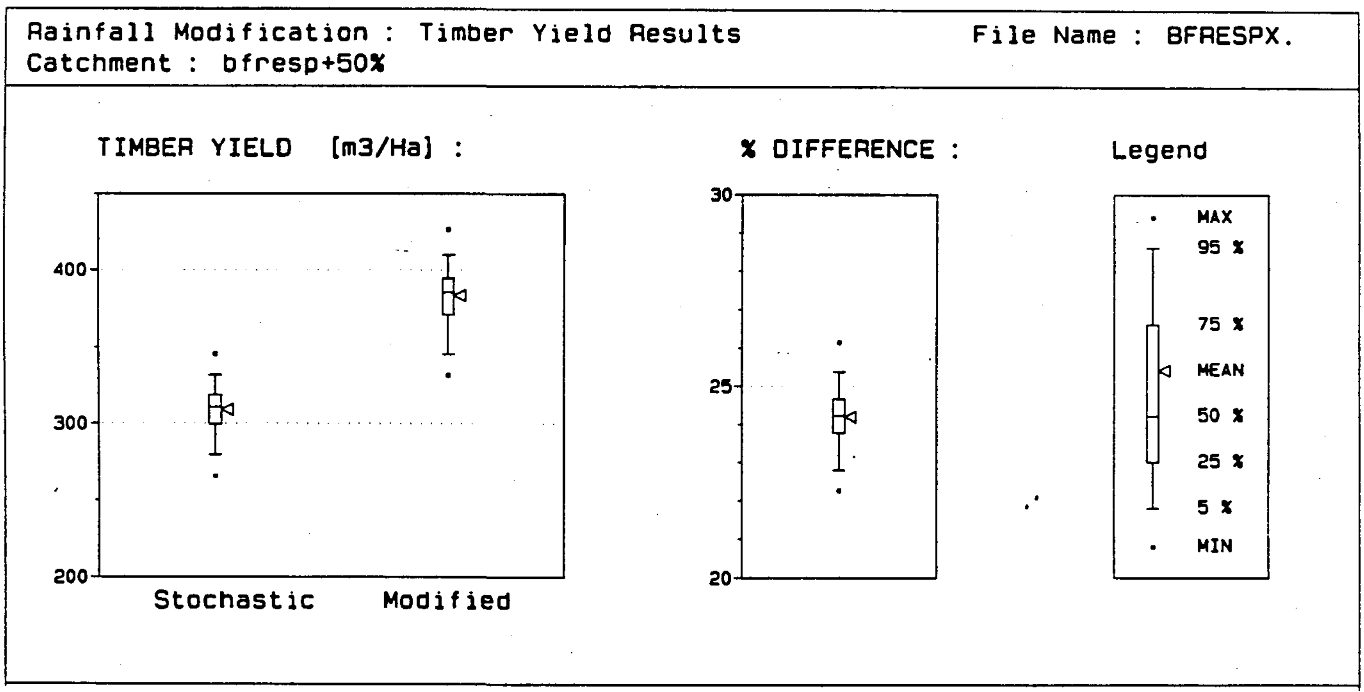
APPENDIX 2 G WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH ABRESP INCREASED BY 50%



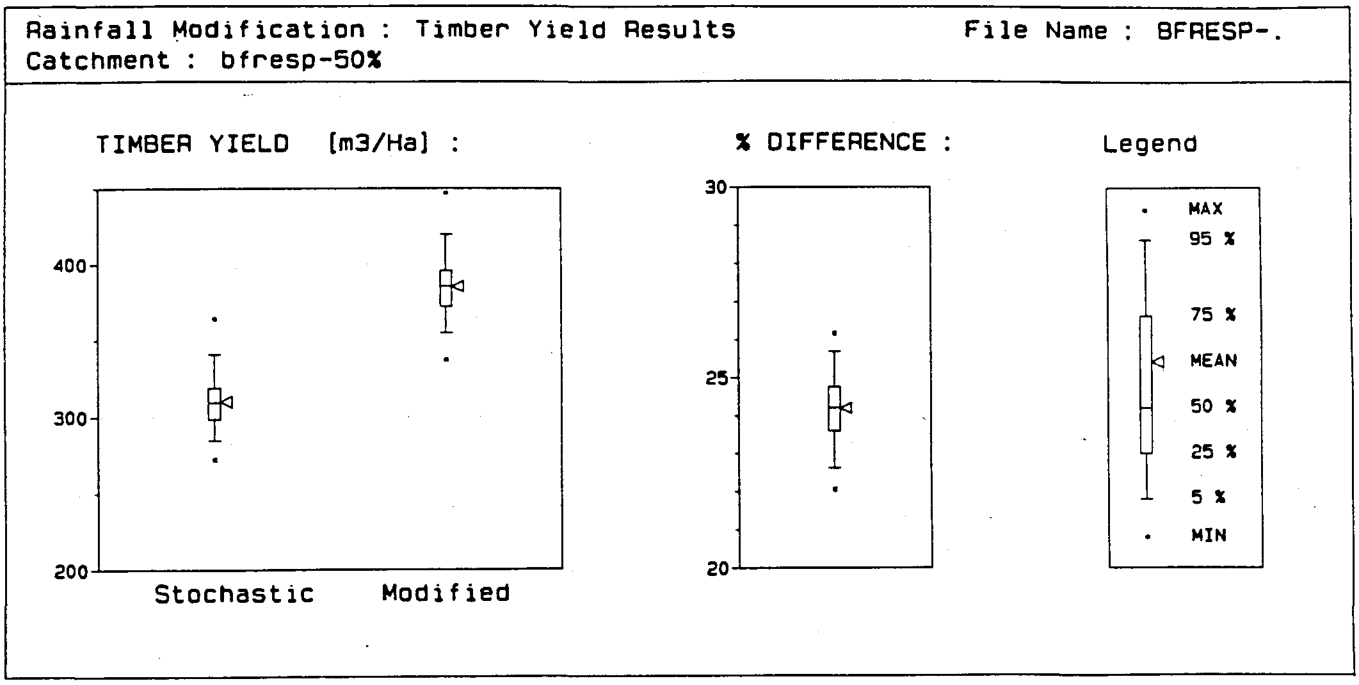
APPENDIX 2 H WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH ABRESP DECREASED BY 50%



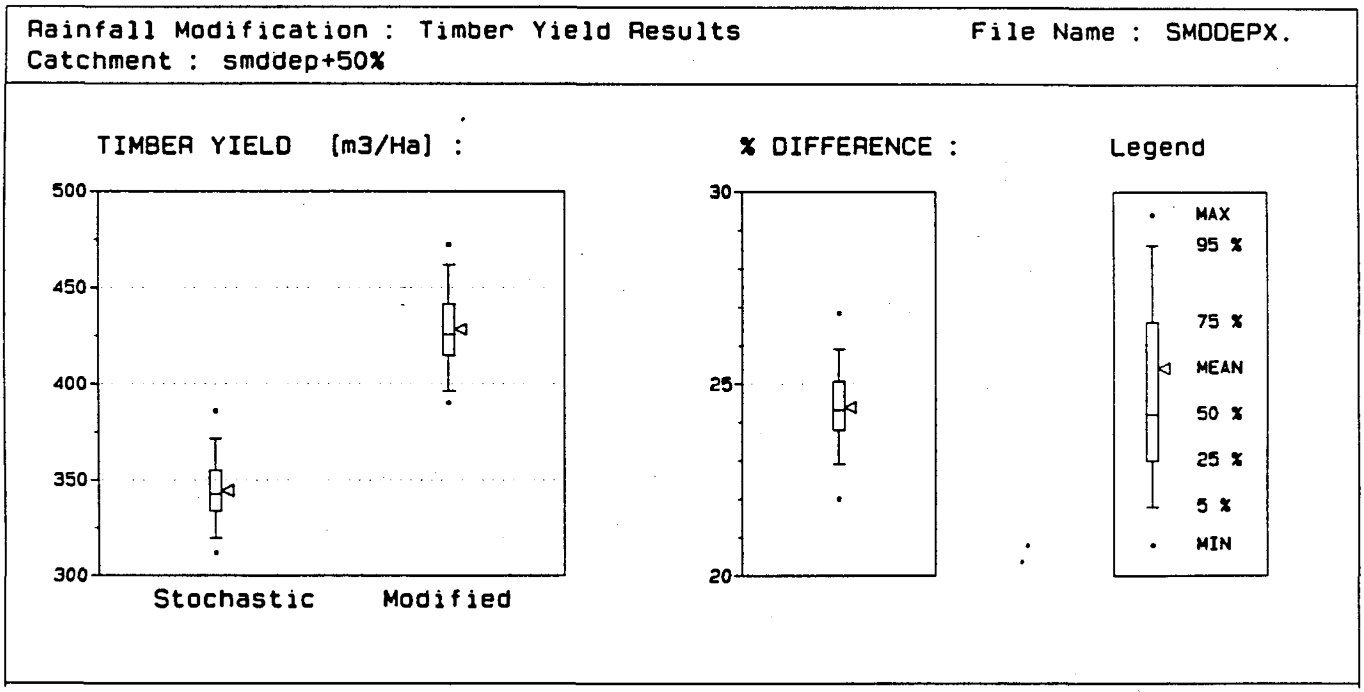
APPENDIX 2 I **WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH BFRESP INCREASED BY 230%**



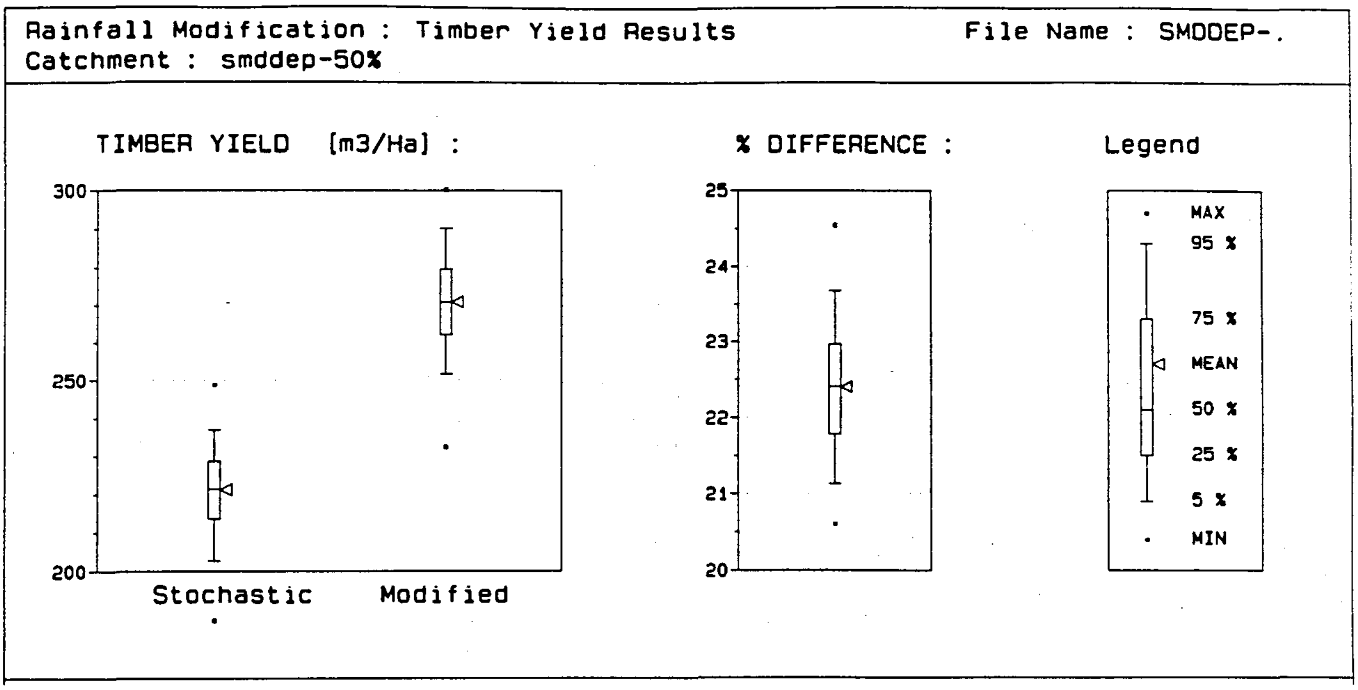
APPENDIX 2 J **WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH BFRESP INCREASED BY 50%**



APPENDIX 2 K WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH BFRESP DECREASED BY 50%



APPENDIX 2 L WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH SMDDEP INCREASED BY 50%



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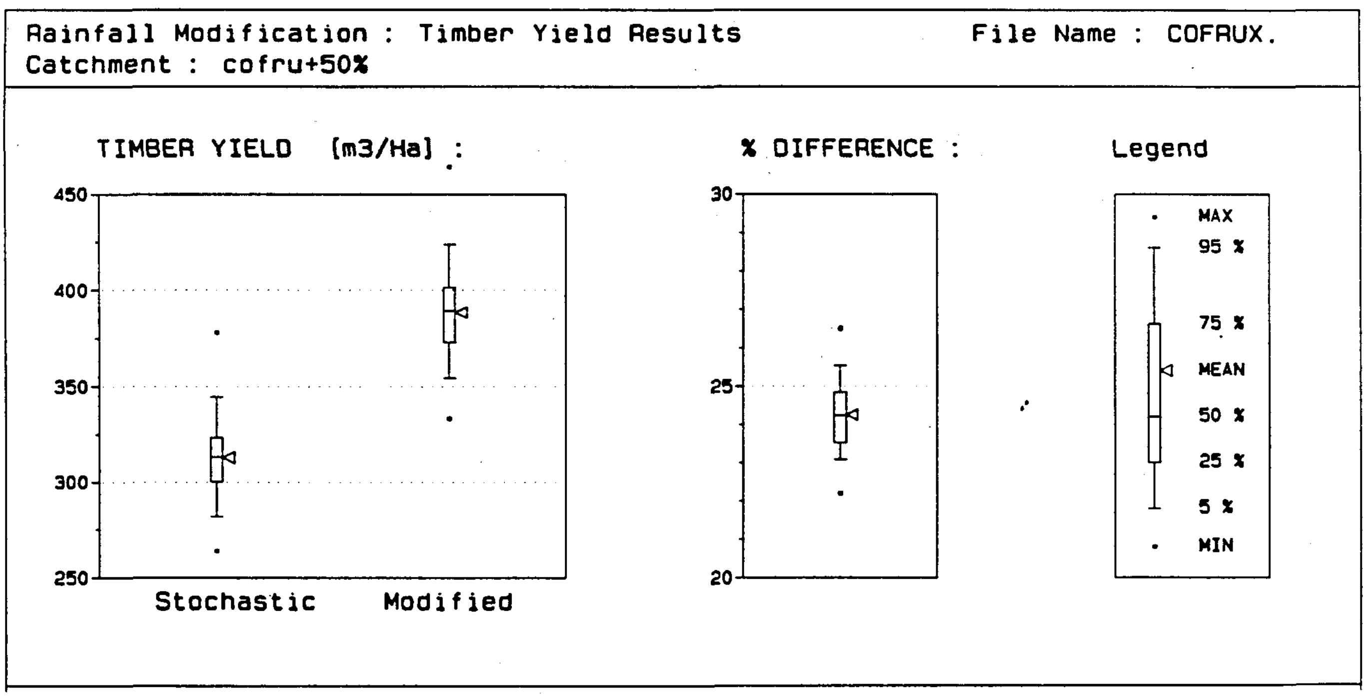
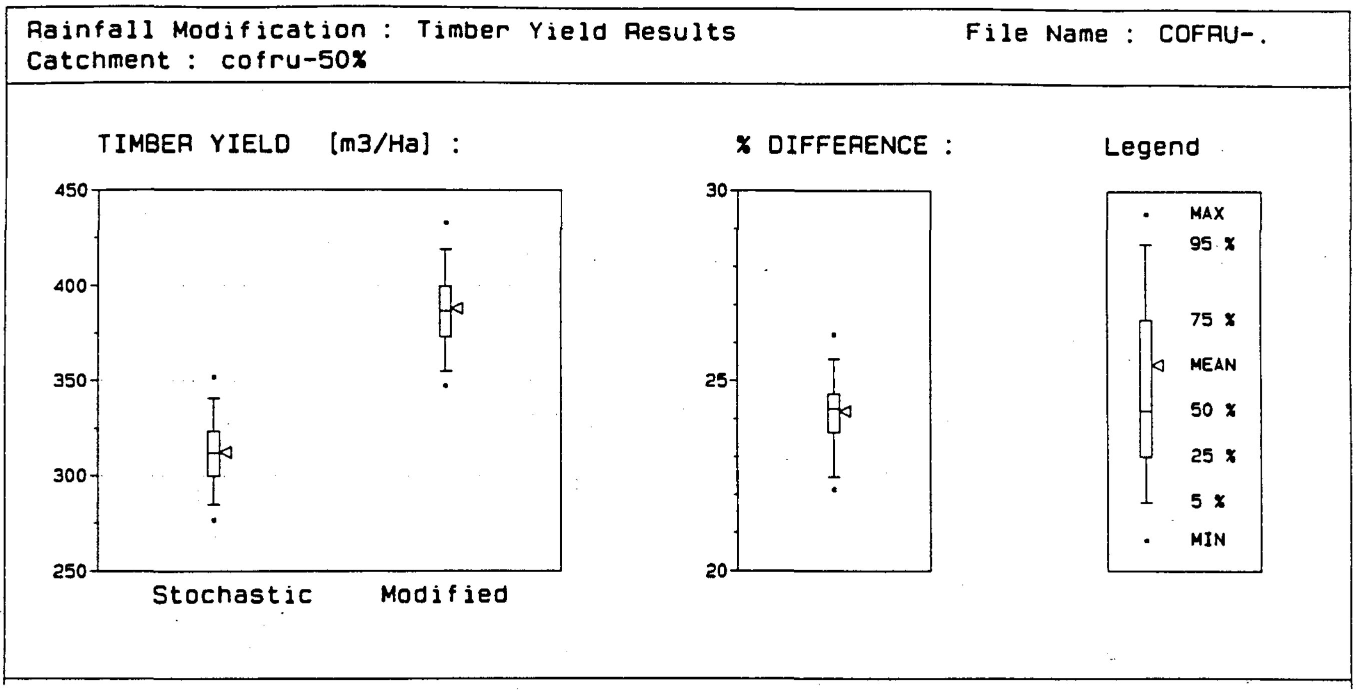


APPENDIX 2 N WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH COFRU INCREASED BY 50%



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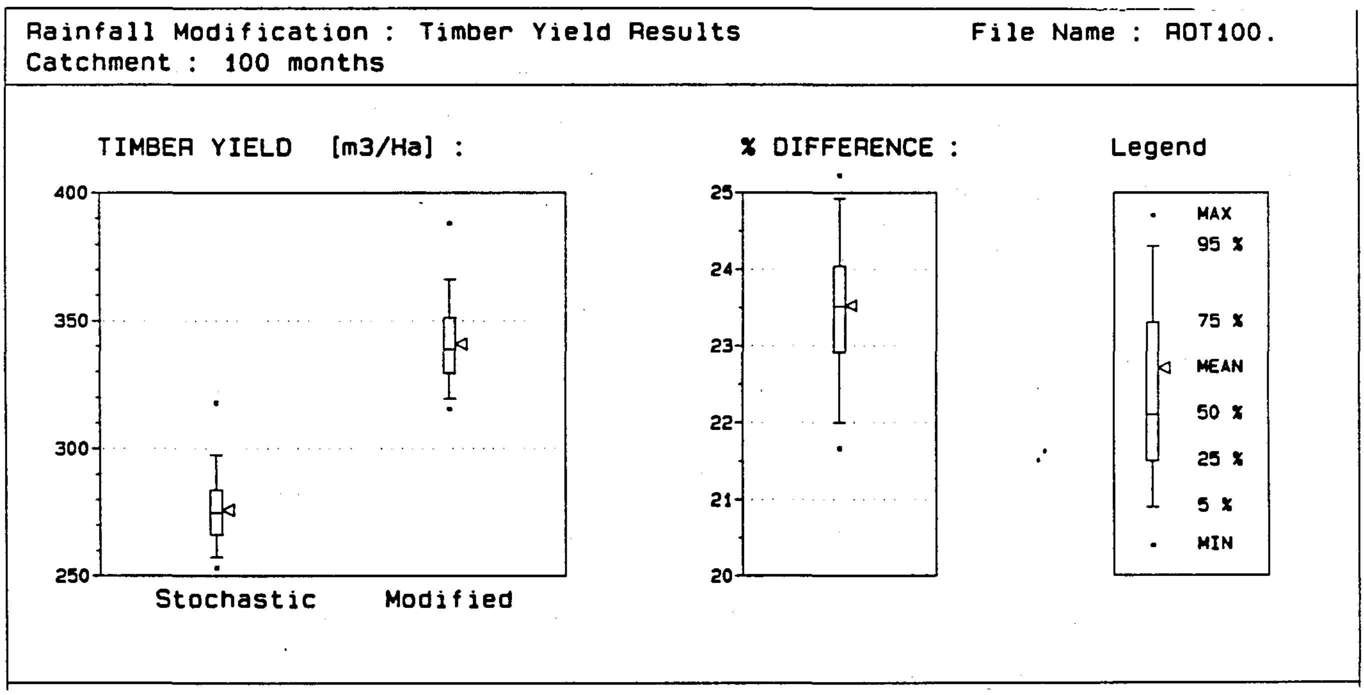
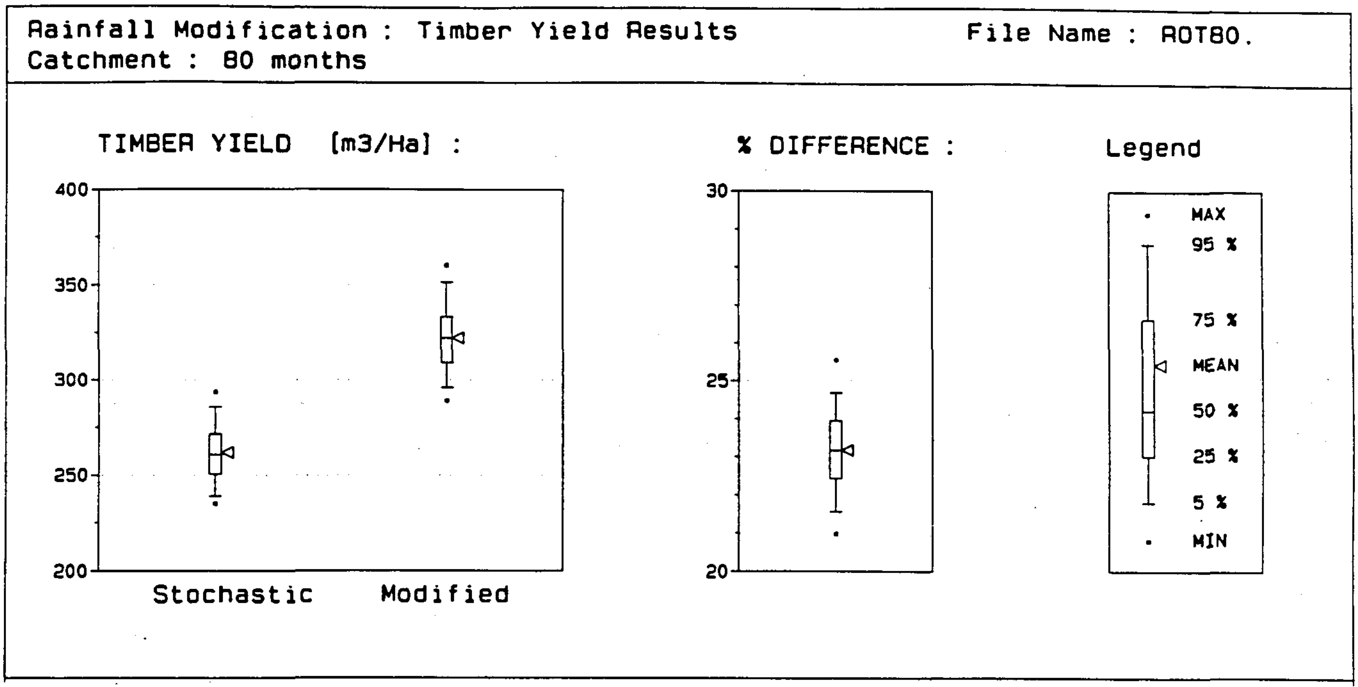


APPENDIX 2 Q **WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH A ROTATION CYCLE OF 100 MONTHS**



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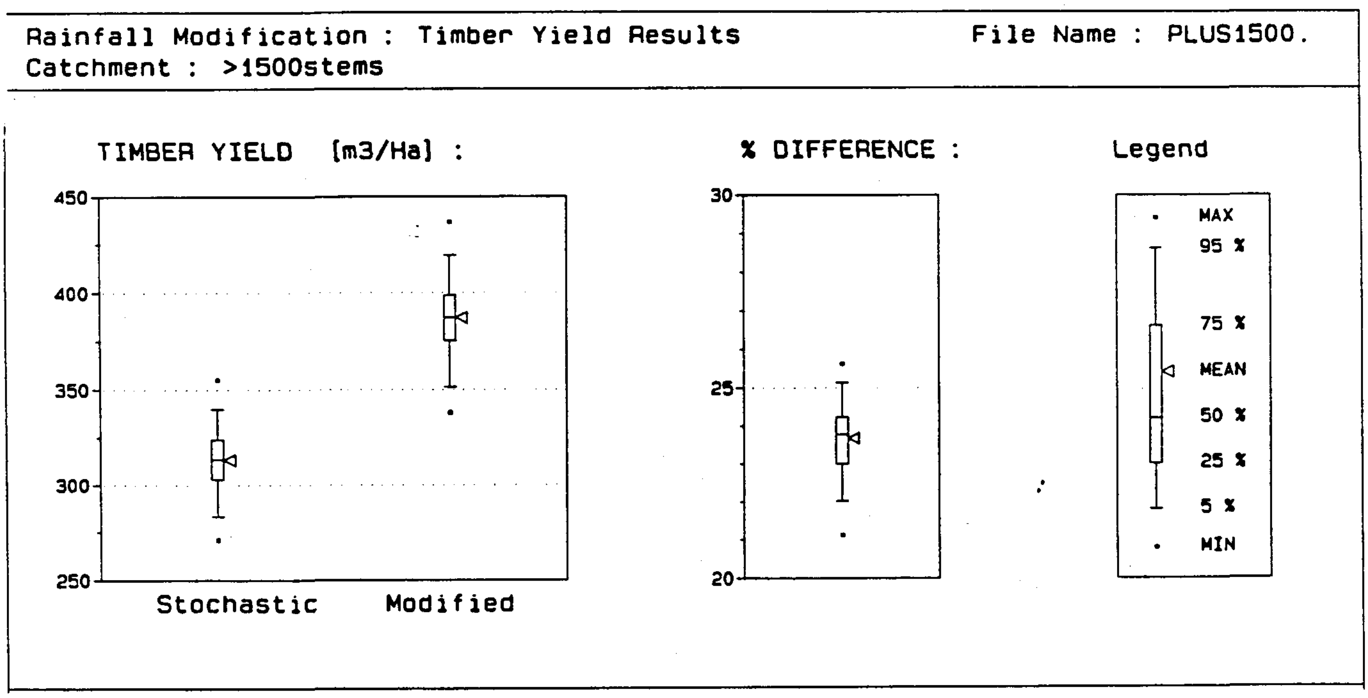

APPENDIX 2 S **WHISKER-BOX PLOTS COMPARING STOCHASTIC AND MODIFIED SEQUENCES OF TIMBER YIELD WITH GREATER THAN 1 500 STEMS/HA**