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Mathematical modelling of some aspects of the water and salt circulation in the Richards Bay—Umhlatuzi system

C.E. Herold

MATHEMATICAL MODELLING OF SOME ASPECTS OF THE WATER AND SALT CIRCULATION IN THE RICHARDS BAY-UMHLATUZI SYSTEM

by

C.E. Herold

A THESIS SUBMITTED TO THE UNIVERSITY OF THE WITWATERSRAND IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENGINEERING

FEBRUARY, 1976

DECLARATION

I, THE UNDERSIGNED, DECLARE THAT
THIS THESIS

1. IS ENTIRELY MY OWN WORK.

2. HAS NOT BEEN SUBMITTED TO ANOTHER UNIVERSITY FOR THE DEGREE M.Sc.(Eng.)

C.E. HEROLD

SYNOPSIS

A harbour is being developed in the northern portion of Richards Bay. Concern has been expressed by ecologists at the possible threat to the ecology of the southern portion of the bay which is to be developed as a nature reserve. The object of this study is to compare by mathematical modelling the behaviour of the proposed new nature reserve with that of the original undeveloped system. It is hoped that the results of this work will make it possible to anticipate any ecological problems that may arise and facilitate the design of remedial measures.

A mathematical catchment model developed by Pitman[8] has been used to synthesise 50 years of monthly runoff into the bay for several conditions of catchment development. The flood hydrographs associated with several recurrence intervals were also constructed by unitgraph technique.

Tidal level fluctuations, velocities and volumes were simulated for the original system and for the proposed nature reserve for extreme and average sea boundary conditions using a one-dimensional mathematical tidal propagation model developed by Hutchison[18]. This model was also applied to the passage of floods through the original bay and new nature reserve.

Long-term water and salt circulations within the two systems were simulated using a lake model developed by Hutchison[22].

It is concluded that the estuary mouth designed by the CSIR for the nature reserve gives rise to unacceptably high tidal fluctuations within the bay. There is also a strong likelihood that over the greater part of the lagoon the bed will be exposed at low tide for some time after the mouth has been scoured out by the passage of a large flood through the system. There is little danger of a salinity build-up in the foreseeable future and flood levels are found to be acceptable.

A satisfactory configuration of the estuary mouth is proposed with the necessary bed and bank protection to minimise scour during floods.

TABLE OF CONTENTS

Chapter No.	Title	Page No.
	List of tables	ii
	List of figures	v
1	Introduction	1
2	Climatology and hydrology of the Richards Bay estuary system	5
3	Modelling of one-dimensional tidal propagation and dispersion in the old Richards Bay and the proposed new nature reserve estuary systems	43
4	Modelling long term water and salt circulation in the original bay and the proposed nature reserve	81
5	Conclusions and recommendations	96
6	Acknowledgements	97
7	References	98
Appendices		
A	Monthly rainfall records expressed as a percentage of each catchment MAP	100
B	Mathematical catchment model	102
C	Estimation of areas of land under sugar cane	105
D	Flood hydrographs for various recurrence interval storms	108
E	Survey datum	109

LIST OF TABLES

Table No.	Title	Page No.
2.1	Details of rainfall stations	9
2.2	Details of D.W.A. evaporation measuring stations	9
2.3	Average monthly evaporation as measured by Symons pan	11
2.4	Details of D.W.A. runoff gauging stations used	12
2.5	Recorded runoff at gauge W1M01	14
2.6	" " " " W1M09	14
2.7	Synthesized runoff at gauge W1M01	14
2.8	" " " " W1M09	14
2.9	Catchment model calibration results	16
2.10	Source data used to synthesize runoffs from catchments	16
	Synthesized runoff for undeveloped conditions	
2.11	Catchment No. 1	18
2.12	" " 2	18
2.13	" " 3	19
2.14	" " 4	19
2.15	" " 1a	20
2.16	" " 1b	20
2.17	Comparison of mean annual runoffs from undeveloped catchment	22
	Synthesized runoff for 1970 conditions	
2.18	Catchment No. 1	23
2.19	" " 2	23
2.20	Estimated water demands as at 1990	24
	Synthesized runoff for 1990 conditions	
2.21	Catchment No. 1	26
2.22	" " 2	26
2.23	" " 3	27
2.24	" " 4	27
2.25	Summary of mean annual runoff values	29
2.26	Summary of approximate median annual runoffs	29
2.27	Parameters used in calibration of catchment indices and lags	33
2.28	Areas enclosed by isohyets of maximum observed 6-day storm	33
2.29	Isohyetal precipitation values for 24-hour duration storms of various recurrence intervals	35

Table No.	Title	Page No.
2.30	Proportions of sub-catchment area represented by each isohyet	35
2.31	Average catchment precipitation for the 24-hour duration storm	36
2.32	Storm rainfall,loss and runoff for various storm durations for the total catchment	37
2.33	Total catchment flood peaks for various storm durations	37
2.34	Peak flood discharges into Richards Bay for undeveloped catchment conditions	39
2.35	Peak flood discharges into Richards Bay from catchment No. 1 for developed conditions	41
2.36	Peak flood discharges into Richards Bay from the total catchment for undeveloped and developed conditions	41
3.1	Hydrographic data used to calibrate the one-dimensional tidal propagation model	57
3.2	Results of convergence tests	57
3.3	Comparison of the tidal propagation model and natural system behaviour	66
3.4	Range of Chézy roughness coefficients extracted from the results of the model calibration runs	67
3.5	Comparison between the one-dimensional tidal propagation in the natural system and that in the proposed new nature reserve	79
3.6	Maximum simulated water levels in the Richards Bay estuary during 5-, 20- and 100-year floods in the Umhlatuzi catchment	80
4.1	Average salinities measured at CSIR salinity measuring stations	90
4.2	Weighted average salinities within each cell on the dates when salinity measurements were made	90
4.3	Level-area relationship for each cell used to model the original Richards Bay system	91
4.4	Level-discharge relationship for the original Richards Bay estuary - July/August 1970 mouth	91
4.5	Results of convergence test simulations - average cell levels and salinities for the period 1921 to 1971 for 1970 catchment conditions	92
4.6	Comparison of the measured and simulated salinities within the original Richards Bay lake system	93
4.7	Level-area relationship for each cell used to model the proposed nature reserve	93
4.8	Level-discharge relationship for the proposed nature reserve estuary - Layout II mouth	93
4.9	Comparison between the long term water and salt circulation in the original natural system and that of the proposed new nature reserve	95

Table No.	Title	Page No.
	Monthly rainfall records expressed as a percentage of each catchment MAP	
A.1	Catchment commanded by gauge W1M01	100
A.2	" " " " W1M09	100
A.3	" downstream of " W1M01	100
A.4	Umhlatuzi catchment (excluding Nsezi catchment)	100
A.5	Nsezi "	101
A.6	North-eastern coastal catchment	101
A.7	South-western " "	101
B.1	Model parameters	104
B.2	Parameters selected after calibration with recorded data	104
C.1	Areas of farms within each sugar producing district	105
C.2	Total area of land under sugar in the Eshowe and lower Umfolozi districts from 1918 to 1961	105
C.3	Areas of land under sugar falling within catchment boundaries during relevant model calibration and simulation periods	107
	Flood hydrographs for various recurrence interval storms	
D.1	5-year R.I. storm	108
D.2	10- " " "	108
D.3	20- " " "	108
D.4	50- " " "	108
D.5	100- " " "	108
D.6	Probable maximum storm	108

LIST OF FIGURES

Figure No.	Title	Page No.
2.1	Richards Bay system - drainage pattern	6
2.2	" " " - topography	7
2.3	" " " - mean annual rainfall	8
2.4	" " " - location of D.W.A. Symons and class A evaporation pan stations	10
2.5	" " " - mean monthly runoff distribution - measured and simulated	17
2.6	Symbolic representation of the model used to simulate 1990 runoff into the Richards Bay estuary system	25
2.7	Catchment boundaries with superimposed isohyets of the maximum observed storm for storm region No. 13 of HRU Report No. 1/72	31
2.8	Longitudinal sections along the main water courses of each catchment	32
3.1	Typical one-dimensional estuary	44
3.2	Views of a typical estuary reach bounded by sections 2 and 2+1	45
3.3	Schematic representation of one-dimensional advection and dispersion process in an estuary channel	47
3.4	Richards Bay estuary showing location of cross-sections and water level recorders	50
3.5	Richards Bay estuary cross-sections (original system)	51
3.6	- do -	52
3.7	- do -	53
3.8	- do -	54
3.9	- do -	55
	Richards Bay system - bathymetry of estuary mouth	
3.10	November 1969	59
3.11	July/August 1970	60
3.12	November 1970	61
	Richards Bay estuary - comparison of measured and modelled water levels for calibration runs	
3.13	October 1969	63
3.14	Early October 1970	64
3.15	Late October 1970	65
3.16	Bathymetry of the new nature reserve after harbour construction showing location of cross-sections	70

Figure No.	Title	Page No.
3.17	Richards Bay estuary cross-sections (proposed new nature reserve)	71
3.18	- do -	72
3.19	- do -	73
3.20	Designed new estuary mouth cross-section	75
	Extreme water levels and maximum advection amplitudes in the estuary systems	
3.21	Original Richards Bay - July/August 1970 mouth	76
3.22	" " " - November 1970 mouth	77
3.23	Proposed new nature reserve	78
4.1	Longitudinal section through a typical flow link (channel)	82
4.2	Longitudinal section through a general flow link, j	85
4.3	Richards Bay-plan of the bay showing locations of cells and salinity measuring stations	88
4.4	Proposed new nature reserve - plan of bay showing locations of cells	88
B.1	Catchment model flowchart	103
C.1	Areas of land under sugar in the Eshowe and Lower Umfolozi magisterial districts	106
E.1	Relationship between LWOST(HRD) at Richards Bay and other datum levels relevant to this study	110

1. INTRODUCTION

1.1 Description of the system

(a) The natural system before harbour development

Before man's activities commenced Richards Bay was a sedimentary basin of area 3 050 ha with a narrow outlet to the Indian Ocean at the north-eastern extremity. The fresh water supply to the bay came mainly from the north-west. The average depth of the bay was approximately one metre.

The banks in the interior of the bay were low-lying and marshy, the northern and western margins being covered by swamp vegetation, while mangroves occupied the southern and eastern margins. The bay was inhabited by large colonies of shrimps, prawns and crabs.

Some 183 species of fish have been identified[1], the the most notable being salmon, grunter, bream and springer. Of particular significance is the fact that nearly all of the fish found were juveniles which depended for their food supply largely on extensive beds of eel grass (*zostera capensis*) in the entrance channel of the bay and on the soft-bodied organisms found in the southern portion of the bay.

(b) Harbour developments

Initial progress has already been made towards the establishment of a harbour which will ultimately be capable of handling ships of up to 250 000 tons d.w.t. The harbour will occupy about two-thirds of the bay area in the north-eastern sector and will be separated from the south-western portion by a 4,5 km long berm wall[2]. The southern portion is to be preserved as a nature reserve.

The entrance to the harbour will be formed by a curved 1,2-km-long southern breakwater and a straight 0,4-km-long northern breakwater. The approach channel is to extend 3,5 km beyond the southern breakwater. The depth of this channel will vary between -24 m LWOST* at the seaward end to -19 m LWOST in the turning basin within the harbour proper. The width of the channel between the breakwaters is to be 300 m.

* The LWOST referred to in this chapter is LWOST(SAR), i.e. 0,900 m GMSL. See figure E.1 of Appendix E.

(c) Proposed nature reserve

The nature reserve in the southern portion of Richards Bay, separated from the harbour by a berm wall, receives the runoff from the entire Umhlatuzi and Nsezi catchments.

An artificial mouth is being provided to open the nature reserve to the sea and will be formed by five channels separated by levees built to heights of approximately 4,5 m LWOST[3]. The central channel, designed to facilitate tidal exchange, is to have a depth of 0,0 m LWOST and a bottom breadth of 285 m. The remaining four channels are to be dredged to -4,5 m LWOST and will be blocked at their seaward side by a 200 m wide sand-berm with crest at +2,0 m LWOST. These channels are intended solely to dispose of flood discharges and are designed to maintain a bay water elevation not higher than 3,1 m LWOST for a flood discharge of 4 300 m^3/s[4]. Tidal gates will be provided in the berm wall to pass part of the discharge through the harbour when the Umhlatuzi is in high flood.

1.2 The problem

When the proposal to develop Richards Bay as a harbour was made public, considerabe concern was expressed at possible adverse effects on the ecology of this natural area. Parameters that are considered of importance by ecologists and that can to a certain degree be manipulated by engineering means are the following:-

(a) The water level regime in the proposed nature reserve
  (i) Tidal fluctuations
  (ii) Tidal velocities and volumes
  (iii) Long term fluctuations in lagoon levels (i.e. over a period of 50 years or more)
  (iv) Flood levels

(b) The salinity regime in the proposed nature reserve
  (i) Salinity fluctuations during a tidal cycle
  (ii) Long term salinity fluctuations (over a period of 50 years or more).

These parameters to a large extent dictate the type of ecosystem that exists. Ideally therefore it would seem advisable to ensure that they are maintained in the newly created nature reserve or at least to ensure that unavoidable changes are relatively small.

If this is not done there is a strong possibility that the nature reserve may degenerate to a different type of ecosystem.

1.3 Previous research on the nature reserve

In 1972 the CSIR[4] developed a simple mathematical model satisfying the continuity and momentum equations in order to simulate the tidal fluctuations and velocities in the lagoon. The model was subject to the following limitations:

(i) In the momentum equation the non-steady and non-uniform terms were neglected. This implies that horizontal inertia is ignored as also Bernoulli effects. Bernoulli effects become especially important in the region of the estuary mouth where constricted flow areas give rise to large changes in velocity.

(ii) The Richards bay system was assumed to consist of a lake connected to the sea by means of a *straight uniform* channel in which the water level varied linearly from the sea to the lake. The model was calibrated by adjusting the Chézy roughness coefficient until the bay levels generated by the model agreed with those recorded in the original Richards bay area. Because of the simplicity of the model the Chézy coefficient compensates for inaccuracies in the modelled channel geometry and as a result the model is applicable only to the particular system and for the specific conditions for which it was calibrated.

Evidence of possible inaccuracies in the model are to be seen in the fact that the two different mouth conditions for which the model was calibrated required Chezy coefficients of 27 $m^{\frac{1}{2}}/s$ and 38 $m^{\frac{1}{2}}/s$ respectively. It would seem to be unrealistic therefore to apply this model to another estuary system such as the nature reserve, which has a totally different geometrical configuration. For these and other reasons the author felt that the simulated tidal ranges and velocities yielded by the CSIR model for the nature reserve would not be sufficiently accurate.

It should be noted also however that the CSIR model tests were carried out only for the nature reserve system, whereas a true comparison between the original untrammeled Richards bay system and the proposed nature reserve system requires that *both* be modelled for similar off-shore tidal conditions.

The CSIR also set up fixed bed[4] and moving bed[3] physical models to establish peak bay flood levels for various mouth conditions in the nature reserve system. Relative levels were established

for a constant discharge in the prototype of 4 300 m^3/s, which was assumed to be a flood of 100-year recurrence interval (R.I.). According to the author's calculations (see chapter 2.5) the 100-year peak discharge is only about 2 800 m^3/s. Additional flood estimates were thus deemed necessary.

No previous work has been carried out to establish the parameters (a) (iii), (b) (i) and (b) (ii) above.

1.4 Aim of this study

The aim of this study is to compare the water circulation regime in the original Richards Bay with that in the new nature reserve lagoon with respect to the parameters listed in 1.2 above. This is accomplished with the aid of existing detailed mathematical models which, once calibrated, can be applied to systems of different geometry (in other words the inadequate information about the geometry is not taken care of merely by adjusting the Chézy coefficient). These models are calibtated on the basis of recorded data from the original system. After calibration of the models, both the old Richards Bay system and the nature reserve are modelled for similar boundary conditions so as to allow direct comparison to be made between the two with respect to the parameters listed in 1.2 above.

2. CLIMATOLOGY AND HYDROLOGY OF THE RICHARDS BAY ESTUARY SYSTEM

2.1 General description of the system

The Richards Bay sy[illegible] shown in figure 2.1, is defined for the purposes of this st[illegible]e bay itself, the two large river catchments feeding [illegible]rom the north-west and two minor coastal catchments feeding it from the north-east and south-west. The two larger catchments are drained by the Umhlatuzi and Nsezi.

The Nsezi and the two minor rivers draining the coastal catchments terminate in fresh water lakes from which some flow enters the bay by way of swamps and groundwater. Topographical features of the system are illustrated in figure 2.2.

2.2 Rainfall

2.2.1 Mean annual rainfall

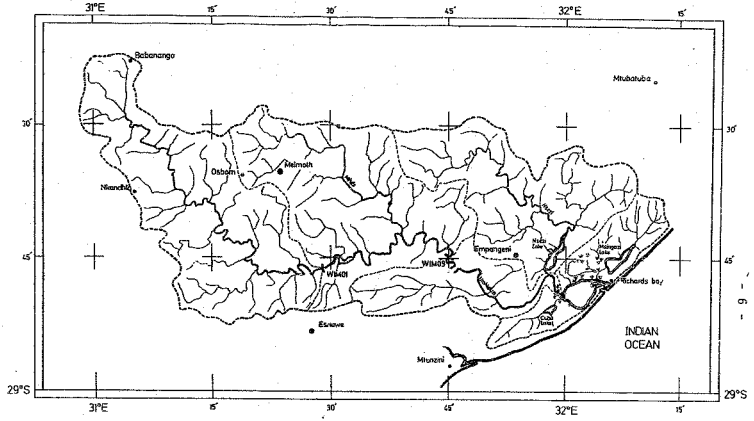
Monthly rainfall records were abstacted from the records of the Weather Bureau, Department of Transport[5]. The locations of the recording stations used, as well as mean annual isohyets, are shown in figure 2.3. These isohyets were drawn among annual precipitation values for the stations indicated. Mean annual precipitation (MAP) decreases from 1 400 mm in the south-eastern coastal region to 800 mm in the north-central region.

Table 2.1 gives the name, position, MAP and length of record for each station (only stations with reasonably long records were used).

2.2.2 Rainfall records

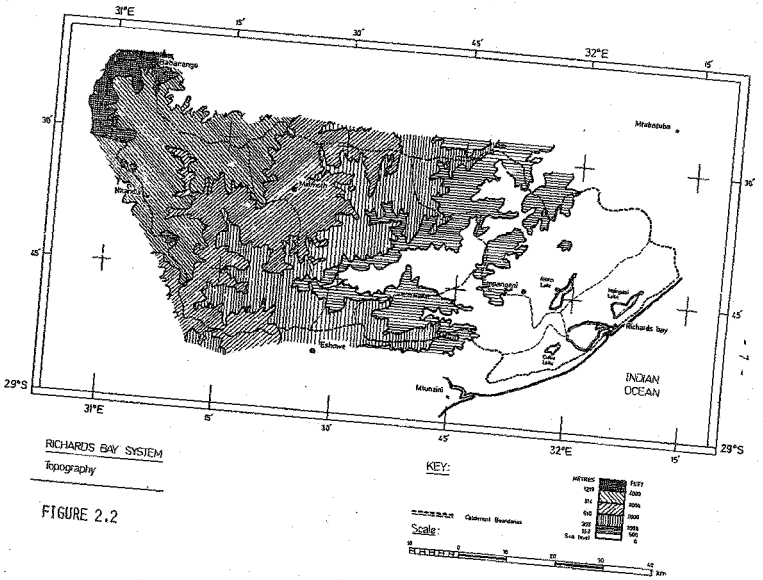
Operation of the mathematical catchment model (see section 2.4) requires as input monthly rainfall and mean monthly evaporation over each catchment. Rainfall histories for all rainfall stations used are expressed as percentages of mean annual precipitation as recorded at each gauge. For each sub-catchment these monthly percental values for selected gauges are averaged out to yield catchment values as percentages of catchment MAP. The mean annual precipitation values for each sub-catchment are taken from figure [illegible].

For each catchment monthly rainfall records expressed as percentages of catchment MAP are reproduced in tables A.1 to A.7 in Appendix A. The precipitation records have been presented in this form for



RICHARDS B
Drainage Pr

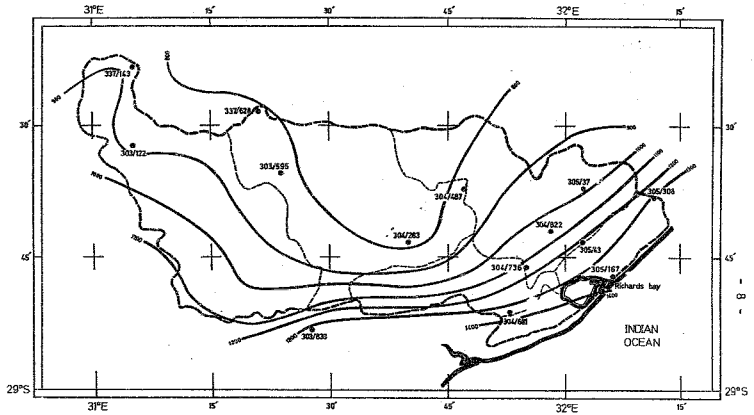
FIGURE 2.1



RICHARDS BAY SYSTEM

Topography

FIGURE 2.2



RICHARDS BAY SYSTEM

Mean Annual Rainfall (mm)

FIGURE 2.3

KEY:

304/736 Weather Bureau Rainfall Gauges

Scale:

10 0 10 20 30 40 km

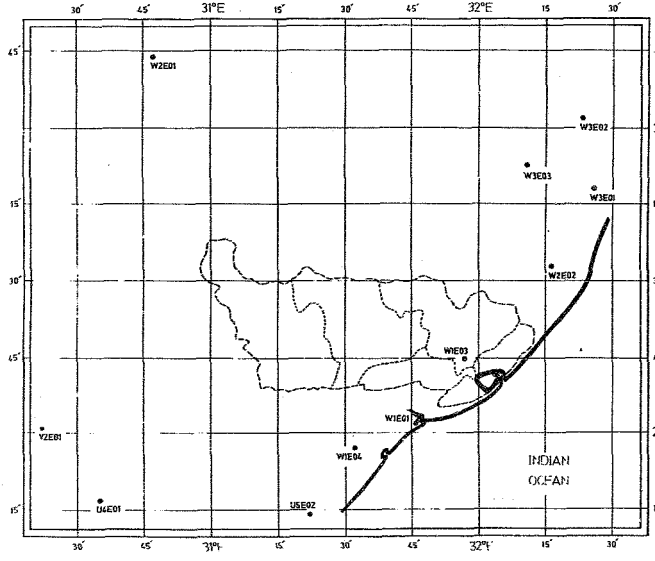
Table 2.1 : Details of rainfall stations

No.	Station		Lat.	Long.	MAP	Period of
	number	name	o '	o '	mm	record-years
1	303/122	Nkandhla	28 32	31 5	886	1901 - 1971
2	303/695	Melmoth	28 35	31 24	809	1899 - 1971
3	303/833	Eshowe	28 53	31 28	1327	1915 - 1971
4	304/283	Kwayaya	28 43	31 40	745	1921 - 1970
5	304/487	Lavoni	28 37	31 47	837	1924 - 1952
6	304/681	Port Durnford	28 51	31 53	1357	1915 - 1970
7	304/736	Empangeni	28 46	31 55	1110	1906 - 1971
8	304/822	Kulu Halt	28 43	31 57	1017	1916 - 1971
9	305/ 37	Fairview	28 37	32 2	997	1926 - 1971
10	305/ 43	Enseleni	28 36	31 52	1213	1931 - 1971
11	305/167	Richards Bay	28 47	32 6	1192	1921 - 1971
12	305/308	Kwa-Mbonahi-Bos	28 38	32 11	1358	1930 - 1971
13	337/143	Babanango	28 23	31 5	892	1928 - 1971
14	337/628	Ntonjaneni	28 28	31 21	814	1937 - 1971

Table 2.2 : Details of D.W.A. evaporation measuring stations

No.	Station		Lat.	Long.	Mean annual Symons pan potential evaporation mm	Date station opened
	number	name	o '	o '		
1	U2E02	Cedara	29 32	30 17	1204	1952
2	U2E03	Midmar Dam	29 30	30 12	1362	1964
3	U3E03	Chakas Kraal	29 27	31 12	1342	1962
4	U4E01	Sevenoaks	29 13	30 35	1160 *	1965
5	U5E02	Darnall	29 16	31 22	1140 *	1965
6	V2E01	Mudan	28 59	30 22	1190 *	1965
7	W1E01	Mtunzini	28 57	31 46	1200 *	1965
8	W1E03	Empangeni	28 45	31 57	1340 *	1967
9	W1E04	Amatikulu	29 03	31 32	1270 *	1966
10	W2E01	Vryheid	27 46	30 47	1466	1952
11	W2E02	Riverview	28 27	32 17	1240 *	1966
12	W3E01	Charter's Creek	28 12	32 25	1416	1950
13	W3E02	Lister's Point	27 58	32 23	1548	1964
14	W3E03	Hluhluwe Dam	28 07	32 11	1705	1963

Note: * Denotes that Symons pan values have been calculated by means of equation 2.1.



RICHARDS BAY SYSTEM

Location of D.W.A. Symons and class A evaporation pan stations.

FIGURE 2,4

the reasons stated below:

(1) Individual rain gauge records are too lengthy to reproduce
(2) Average precipitation values for each catchment are more easily visualised than isolated point values
(3) The mathematical catchment model requires areally averaged monthly rainfall records.

2.3 Symons pan evaporation

Locations of the relevant Symons and Class A evaporation pans of the Department of Water Affairs[5] are shown in figure 2.4. Data pertaining to each station are shown in table 2.2. Most of the stations used have only class A pan data. These class A pan values were converted to equivalent Symons pan values by the equation:

$$Es = 0{,}625\ E_A + 280 \text{ mm} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

where Es = annual Symons pan evaporation (mm)
E_A = annual class A evaporation (mm)

Equation 2.1 was developed by Lund[7].

Because of the low density of measuring stations it was not possible to draw realistic isolines of mean annual evaporation. It was therefore decided to use the monthly evaporation maps produced by Pitman[8]. It is evident from these maps that the evaporation is relativly constant over the entire study area. Mean monthly evaporation values were abstracted and are listed in table 2.3.

Table 2.3 : Average monthly potential evaporation as measured by Symons pan

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation (mm)	150	135	130	95	82	65	70	95	110	130	140	155

Annual total = 1357 mm

2.4 River runoff

2.4.1 Measured runoff

Locations of the Department of Water Affairs (D.W.A.) river flow gauging stations[9] are listed in figure 2.1. Details of the gauging stations used are listed in table 2.4.

Table 2.4 : Details of D.W.A. runoff gauging stations used

Station reference No.	River	Catchment area km^2	Gauge type	Lat. south ° '	Long. east ° '	Period of record (years)
W1M01	Umhlatuzi	1246	weir	26 46	31 29	1921-39
W1M09	"	2293	"	28 45	31 45	1962-70

Measured monthly flows at the two gauges are shown in tables 2.5 and 2.6. These data were abstracted from the D.W.A. records and from reference 9.

For months where the gauge capacities were exceeded, or where data were missing, the runoff volumes were estimated by correlation with catchment rainfall using the mathematical catchment model in an iterative calibration process. Underlined values in the tables are estimates.

2.4.2 Runoff modelling

For hydrological simulation of the estuary system to be meaningful it should extend over a period of about 50 years. The recorded streamflow data, listed in tables 2.5 and 2.6 are thus clearly inadequate as input to the model as they are too short. In addition, the gauges are incapable of monitoring high discharges. It was thus necessary to use a mathematical catchment model to synthesize runoff values from monthly rainfall and potential evaporation records. Average monthly rainfall data for each catchment are available from 1921 to 1971 (tables A.1 to A.7 in Appendix A) and average monthly potential evaporation values appear in table 2.3.

(a) The catchment model and its calibration

A concise description of the mathematical catchment model is to be found in Appendix B. Suffice it to say here that the model synthesizes monthly runoff using monthly rainfall and potential evaporation data and that the key to its application lies in evaluating the twelve model parameters. These parameters are

functions of the geology, topography, soil and vegetal cover and the degree of agricultural and industrial development within the catchment. Calibration can be facilitated by assuming initial values based on Pitman's regional parameters.

The model is then run for the period for which runoff records are available and the synthesized runoff compared with the measured runoff. The model parameters are next adjusted until an "acceptable fit" between model and prototype flows is attained. With the new parameters the model can then be used to extend the runoff record to cover the period of available rainfall record. The same parameters can be used to simulate runoff records from adjoining ungauged catchments, provided the geology, topography and other pertinant catchment features are similar.

In this study the simulated runoffs are required primarily for prediction of the future behaviour of the Richards Bay estuary system. For these conditions an "acceptable fit" should be based upon the following characteristics of model and prototype runoff records:

(1) Mean annual runoff ($m^3 \times 10^6$)

$$= MAR = \frac{1}{n} \sum_{i=1}^{i=n} T_i \quad \text{.....(2.2)}$$

where n = number of years (October to September)

T_i = total runoff for year i ($m^3 \times 10^6$)

(2) Mean log annual runoff

$$= MARL = \frac{1}{n} \sum_{i=1}^{i=n} \log (T_i) \text{.....(2.3)}$$

where log has the base 10.

(3) Standard deviation of the log of annual runoff

$$= SL = \sqrt{\frac{\sum_{i=1}^{n} (\log T_i)^2 - \frac{1}{n} \left(\sum_{i=1}^{n} \log T_i \right)^2}{n - 1}} \text{.....(2.4)}$$

(4) Annual distribution of flow (i.e. the mean October, November ..... September flows - $m^3 \times 10^6$).

Table 2.5 : Recorded runoff at gauge W1M01

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	ACCUMULATED
1921	7.70	11.31	26.39	17.48	13.89	15.00	10.92	8.84	8.66	7.88	8.10	6.44	147.30	147.30
1922	9.28	13.03	15.49	24.49	16.97	14.85	16.91	9.87	7.38	7.86	6.49	8.52	148.84	296.14
1923	7.32	8.16	12.84	9.22	8.51	8.96	7.44	6.44	4.39	4.13	4.34	4.55	96.25	392.44
1924	4.44	23.86	47.51	23.60	22.50	44.64	20.53	22.40	24.00	23.26	14.40	19.81	310.14	1265.00
1925	17.40	12.05	12.66	9.87	10.71	12.60	11.43	10.14	10.47	7.93	8.96	12.44	147.91	1404.96
1926	13.86	16.92	12.66	7.20	8.84	10.62	11.26	9.47	8.91	8.87	7.15	8.56	133.30	1538.26
1927	7.44	8.87	7.44	11.04	7.77	8.28	8.13	6.88	6.74	5.87	4.28	5.20	102.77	1638.17
1928	5.81	8.88	9.35	8.86	9.60	12.74	8.79	6.56	6.68	6.07	4.73	4.61	98.21	1736.44
1929	7.44	14.15	9.44	7.44	14.18	11.23	8.51	6.62	6.62	6.86	5.24	6.24	113.39	1849.83
1930	6.88	9.17	8.30	8.48	8.10	9.18	8.46	7.85	7.61	7.02	5.43	5.48	89.22	1939.10
1931	6.60	8.47	6.77	12.52	11.21	11.95	8.55	6.57	6.19	5.82	4.84	4.84	104.31	2043.41
1932	5.98	10.45	7.12	8.42	6.67	8.41	8.97	7.81	7.76	7.15	5.77	7.69	96.87	2140.34
1933	7.48	9.63	10.21	14.29	11.27	11.82	9.12	8.19	8.05	7.63	5.84	6.52	119.76	2260.61
1934	6.81	8.58	12.16	15.20	13.92	11.76	9.85	7.73	7.72	6.86	5.76	6.13	132.97	2393.58
1935	6.31	15.61	9.67	14.80	12.43	9.84	8.75	7.61	12.20	7.61	6.55	6.54	117.13	2510.71
1936	7.08	19.38	14.67	11.75	13.81	10.34	9.23	8.08	8.84	8.78	6.73	6.88	135.80	2646.51
1937	9.44	9.85	12.72	8.97	11.14	8.47	10.39	7.61	7.41	7.16	6.39	6.56	115.91	2762.42
1938	6.94	9.56	14.28	9.76	12.83	17.90	10.83	8.54	8.80	7.16	6.39	6.61	129.81	2892.23
1939	10.40	14.65	13.83	9.23	9.74	9.11	9.17	7.98	7.81	7.16	6.39	6.61	121.48	3013.71
X TOTAL	8.82	11.38	11.91	11.11	11.03	12.12	10.70	9.46	9.82	9.16	7.14	7.38	130.88	

MEAN/MONTH = 1.142305 STD. DEV.= .383704 MEAN ANNUAL RUNOFF= 130.88 MILLION CUBIC METERS

Table 2.6 : Recorded runoff at gauge W1M09

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	ACCUMULATED
1963	4.43	13.31	9.80	18.41	44.48	38.48	20.53	8.63	4.84	153.08	4.48	4.43	281.45	281.46
1964	4.80	8.36	9.81	45.31	18.43	8.80	7.88	6.48	5.97	5.22	4.79	5.10	115.34	396.80
1965	4.35	5.40	13.84	9.92	9.03	.000	.000	4.23	5.44	4.61	4.17	4.71	65.36	462.16
1966	5.87	14.46	12.79	37.37	13.33	3.63	1.74	1.88	2.30	.86	.26	0.00	104.00	551.16
1967	.000	.000	7.24	6.77	15.12	100.10	65.47	32.62	10.83	4.72	1.80	2.57	236.31	787.46
1968	2.82	10.81	17.67	3.87	8.67	41.46	24.80	.72	.39	.20	4.84	5.33	120.07	907.52
1969	5.73	3.32	20.67	9.84	6.01	61.97	34.82	23.41	7.63	3.11	2.88	2.86	181.45	1088.98
1970	24.07	16.71	9.23	7.61	7.02	8.40	5.24	4.13	4.46	4.25	3.61	3.76	98.28	1227.77
1971	4.44	23.80	14.96	14.84	9.24	8.84	7.85	6.62	6.62	6.86	5.24	6.24	121.40	1349.17
X TOTAL	5.67	9.74	11.73	15.71	14.24	19.84	7.81	10.67	4.13	9.45	3.51	3.98	120.80	

MEAN/MONTH = 1.150118 STD. DEV.= .270314 MEAN ANNUAL RUNOFF= 144.84 MILLION CUBIC METERS

Table 2.7 : Synthesized runoff at gauge W1M01

PE = 2.0 SLP = 0.55 STR =250.KM ST= 28.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %

ZMIN= 8000.MM/MONTH ZMAX= 6000.MM/MONTH PI= 1.2 MM/DAY GL=0.02 MONTHS TL= .25 MONTHS MIN= 4/MONTH

P, EVAP.	104.0	140.0	185.0	150.0	126.0	130.0	95.0	82.0	68.0	56.0	70.0	96.0	MM = MM
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	2.25	10.40	17.19	12.15	7.72	4.26	5.78	5.05	4.54	4.63	5.30	5.92	85.53
1922	7.52	15.54	16.13	32.22	18.11	8.75	5.31	3.12	2.61	1.84	1.57	1.42	102.53
1923	1.05	2.28	6.54	6.11	5.07	4.70	7.11	6.63	5.57	2.27	2.43	2.43	56.97
1924	2.42	24.02	53.45	30.78	31.44	64.63	18.27	18.58	19.85	9.33	5.24	5.24	285.25
1925	10.44	11.72	8.93	8.40	4.24	9.40	8.55	5.76	6.21	8.22	4.54	4.97	86.49
1926	10.13	14.79	14.79	10.27	7.49	14.20	12.87	7.51	6.11	2.98	2.31	2.21	115.84
1927	4.32	6.77	6.52	6.39	11.12	8.74	6.06	4.91	3.95	3.15	2.05	2.24	71.62
1928	3.33	8.32	7.84	7.04	7.07	10.43	10.06	5.48	5.92	3.10	2.81	2.71	73.74
1929	5.97	14.20	11.67	13.54	15.03	13.28	11.42	9.21	9.61	3.73	3.67	4.47	119.71
1930	5.24	8.68	7.58	8.06	7.55	8.06	2.70	2.71	1.93	1.54	1.01	1.02	55.14
1931	3.60	6.30	4.22	2.73	10.47	7.82	20.62	27.78	20.15	10.46	6.79	5.36	115.52
1932	2.69	8.69	4.02	7.57	5.20	5.86	4.68	3.81	3.11	1.98	1.34	1.92	50.74
1933	3.10	8.48	17.48	40.49	33.24	16.23	17.11	15.20	11.44	8.85	8.12	7.52	215.74
1934	3.16	8.05	9.12	13.04	8.85	5.80	5.83	5.04	4.37	4.47	3.71	3.75	84.73
1935	2.79	13.13	3.04	9.58	14.16	10.38	12.30	11.80	17.80	5.44	4.01	3.91	132.58
1936	3.12	15.74	12.20	10.08	14.06	10.32	9.01	8.38	8.84	8.78	6.73	6.88	132.92
1937	3.85	5.48	14.91	10.88	12.46	22.24	17.11	10.49	10.63	11.12	7.03	7.05	133.90
1938	3.06	5.56	16.28	11.76	13.83	47.93	14.83	8.54	8.80	7.16	6.39	6.61	150.15
1939	5.84	20.45	21.28	14.82	9.27	6.08	7.24	17.74	12.72	8.16	8.12	8.12	279.04
X TOTAL	3.01	8.71	9.96	9.76	10.11	24.10	11.17	7.07	6.70	5.06	3.65	3.42	100.68

MEAN/MONTH = 1.118963 STD. DEV.= .338136 MEAN ANNUAL RUNOFF= 121.05 MILLION CUBIC METERS

Table 2.8 : Synthesized runoff at gauge W1M09

PE= 2.0 SLP = 0.55 STR =250.KM ST= 28.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %

ZMIN= 8000.MM/MONTH ZMAX= 6000.MM/MONTH PI= 1.2 MM/DAY GL=0.02 MONTHS TL= .25 MONTHS MIN= 4/MONTH

P, EVAP.	104.0	140.0	185.0	150.0	126.0	130.0	95.0	82.0	68.0	56.0	70.0	96.0	MM = MM
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1963	6.14	12.30	17.35	23.60	18.10	36.78	20.00	14.82	12.74	153.10	99.24	10.40	777.79
1964	8.18	16.61	17.43	17.08	13.31	8.49	8.04	6.78	5.84	5.28	4.44	4.31	114.99
1965	10.76	13.74	15.13	4.78	3.66	1.34	.00	.79	1.93	4.73	4.34	4.76	65.35
1966	10.60	17.30	13.72	25.70	13.11	5.87	6.44	5.84	2.40	1.20	.46	.30	129.14
1967	1.64	8.22	10.30	12.10	120.26	68.84	34.30	21.48	8.78	4.34	1.65	.55	737.75
1968	7.20	9.08	20.66	6.64	6.12	12.68	7.76	2.74	.72	.42	4.60	4.21	90.77
1969	7.20	7.08	23.76	18.82	8.74	83.30	37.58	23.26	12.38	6.86	2.81	2.83	236.73
1970	17.06	16.40	8.46	8.54	.00	1.73	2.48	4.43	4.46	4.10	3.44	3.64	78.54
1971	24.30	26.70	17.00	20.38	10.76	8.84	14.83	40.96	32.46	25.16	18.12	18.48	367.74
X TOTAL	6.43	9.49	7.92	9.17	14.26	12.82	8.27	7.47	6.68	10.86	6.43	5.23	130.88

MEAN/MONTH = 1.150449 STD. DEV.= .377351 MEAN ANNUAL RUNOFF= 171.80 MILLION CUBIC METERS

Assuming that annual runoff follows a log-normal distribution, items (2) and (3) above serve to compare the distribution of the model with that of the natural system. In order to lend meaning to the standard deviation of the log of annual runoff, the range of this quantity can be calculated as follows:

$$T_{max} = \text{antilog}_{10}(MARL + SL) \quad (m^3 \times 10^6) \quad \ldots\ldots\ldots(2.5)$$

$$T_{min} = \text{antilog}_{10}(MARL - SL) \quad (m^3 \times 10^6) \quad \ldots\ldots\ldots(2.6)$$

where T_{max} and T_{min} define the upper and lower limits of the *range within which two-thirds of the annual runoff totals could* be expected to lie if the values were normally distributed.

The log of annual runoff can also be expressed in physical terms by:

$$T = \text{antilog}_{10}(MARL) \quad (m^3 \times 10^6) \quad \ldots\ldots\ldots\ldots\ldots(2.7)$$

The two sub-catchments used for model calibration are both drained by the Umhlatuzi, viz. W1M01 and W1M09.

Gauge W1M01 was in operation from 1921 to 1939 during which period its catchment remained practically undeveloped with respect to agriculture and urbanization. Records for gauge W1M09 are available from 1962 to 1970. It should be noted that considerable agricultural development has since taken place in this catchment and during the period in question approximately 7 600 ha* of land was under irrigated sugar cane. In order to account for irrigation losses the net monthly Symons pan evaporation from an area of 7 600 ha was deducted from the synthesized monthly runoffs. The assumption here is that all of the land is continually irrigated.

Table 2.9 lists the sub-catchments used to calibrate the model and indicates the fit obtained between the model and the natural system with respect to items (1) to (3) listed above. The two calibration simulations are given in tables 2.7 and 2.8. Item (4), the annual distribution of flow for model and natural system, is shown in figure 2.5.

* A detailed explanation of how this figure was reached is presented in Appendix C.

Table 2.9 : Catchment model calibration results

Gauge No.	Period of record	State of catchment	M.A.P. $m^3 \times 10^6$		Antilog (MARL) $m^3 \times 10^6$		Range of standard deviation of log annual runoff $m^3 \times 10^6$			
			natural system	model	natural system	model	natural system		model	
							Tmin	Tmax	Tmin	Tmax
W1M01	1921-39	virgin	180	181	141	132	73	271	62	279
W1M09	1962-70	developed	167	172	141	144	74	269	76	275

Table 2.10 : Source data used to synthesize runoffs from catchments

No.	Catchment			Synthesization components		
	Name	Area km^2	sub-catchments	model parameters used	rainfall	evaporation from
1	Umhlatuzi river	2807	W1M01	as calibrated	Table A.1	Table 2.3
			W1M09	"	" A.2	"
			below W1M01	as for gauges W1M01 and W1M09	" A.3	"
			total	"	" A.4	"
2	Mngeni river	841	total	as for gauges W1M01 and W1M09	Table A.5	Table 2.3
3	North-eastern coastal catchment	197	total	special - see section 2(a)	Table A.6	Table 2.3
4	South-western coastal catchment	101	total	special - see section 2(a)	Table A.7	Table 2.3

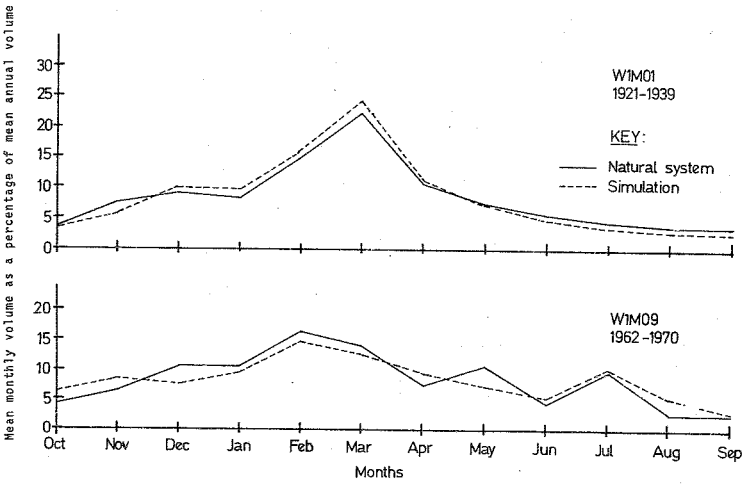


FIG.2.5: Richards bay System
Mean monthly runoff distribution-measured and simulated

Table 2.11 : Synthesized runoff from catchment No. 1 for undeveloped conditions (m^3x10^6)

PDF= 3.9 SE= 0.88 ST= 350.MM PF= 26.0 MM/MONTH GW= 0.8 MM/MONTH AI= 0.0 %

ZONE= 5000.KM/MONTH PE= 1.8 MM/DAY GE=0.00 MM/MONTH TL= .25 MONTH WC= .4/.4/.4

P=.4/.4/.4	104.0	140.0	188.0	130.0	128.0	130.0	98.0	83.0	45.0	56.0	74.0	68.0	MM = MM .4
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	4.04	22.50	47.51	26.64	14.51	13.29	11.84	10.48	13.44	10.97	17.24	13.17	195.47
1922	7.29	30.08	26.22	33.50	18.58	10.77	8.74	8.24	8.16	8.19	32.48	7.83	189.78
1923	5.49	12.39	15.31	9.21	8.44	11.84	14.36	17.35	9.30	7.40	9.54	10.23	130.96
1924	10.83	9.43	16.83	14.87	11.05	9.61	8.66	8.04	7.91	7.91	7.91	7.91	120.16
1925	7.91	7.91	7.91	7.91	7.91	18.44	25.37	11.84	8.16	8.19	8.19	8.19	127.94
1926	19.30	24.40	23.11	17.41	13.69	28.49	28.53	19.25	13.89	13.41	13.24	11.97	276.19
1927	14.32	14.81	15.31	15.64	24.08	28.49	19.25	13.89	9.61	8.16	7.78	6.49	177.82
1928	7.41	6.47	4.54	8.24	8.83	44.26	53.34	29.53	19.01	13.78	13.24	11.63	239.68
1929	9.91	8.16	7.91	7.91	23.97	23.14	17.26	14.19	10.15	8.32	8.19	7.91	146.92
1930	7.91	7.91	12.77	12.90	19.01	7.04	8.24	8.07	8.41	8.32	8.19	7.91	116.59
1931	8.54	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	98.88
1932	7.87	18.61	14.79	11.71	15.33	12.87	7.03	6.82	8.16	8.19	8.19	8.19	127.75
1933	8.07	10.88	24.09	29.33	28.84	23.81	25.13	26.78	23.24	24.53	12.52	8.78	246.12
1934	15.05	14.82	15.82	74.04	24.18	19.73	13.35	11.58	10.01	22.75	15.04	12.85	279.22
1935	8.53	9.14	8.36	13.71	31.79	36.73	25.04	27.67	18.54	38.03	12.45	9.18	270.32
1936	11.44	10.61	17.45	21.31	20.18	24.17	21.15	13.53	8.41	8.19	8.19	8.19	172.73
1937	8.19	15.31	17.20	19.67	121.44	85.70	38.83	23.76	19.49	12.54	23.44	14.84	399.41
1938	14.39	13.33	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	154.80
1939	12.90	12.90	27.43	25.14	15.82	12.48	17.00	16.58	14.82	14.34	17.33	15.73	216.49
1940	14.32	21.24	16.31	49.98	19.16	12.48	11.87	11.49	9.42	8.74	7.11	7.16	189.44
1941	8.19	13.64	12.47	11.31	20.18	49.60	38.74	21.84	16.60	15.73	14.16	11.71	233.91
1942	13.74	23.74	47.41	26.43	14.48	23.22	114.78	103.45	33.15	23.74	19.17	15.84	459.16
1943	12.90	12.90	12.90	40.50	21.78	21.73	28.85	19.44	15.15	14.21	13.98	12.90	230.24
1944	24.47	22.67	15.14	13.74	16.12	141.78	76.35	38.41	19.85	8.48	8.19	8.19	402.69
1945	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	98.88
1946	8.23	14.84	15.32	18.12	28.91	28.53	28.28	19.24	14.48	13.92	11.73	9.77	220.58
1947	11.87	22.14	23.25	27.62	23.14	21.23	21.45	16.82	19.15	8.53	8.19	8.19	241.70
1948	8.19	8.19	8.19	8.19	8.19	20.53	58.62	44.35	19.85	8.48	8.19	8.19	258.05
1949	28.49	28.81	152.97	59.28	28.28	28.70	24.19	15.27	11.26	9.34	8.21	6.77	471.08
1950	5.49	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	54.53
1951	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	54.53
1952	4.59	15.84	18.59	14.79	16.23	14.70	10.01	8.32	8.16	8.19	8.19	8.19	145.19
1953	8.19	10.45	22.14	24.68	17.62	12.90	12.90	12.90	12.90	12.90	12.90	12.90	183.97
1954	198.44	84.20	26.51	23.74	28.35	166.27	47.46	30.73	18.48	11.23	7.41	5.31	657.73
1955	16.20	30.13	31.66	31.85	23.85	151.62	58.08	30.73	18.48	11.23	7.41	5.31	411.19
1956	33.48	34.25	258.41	186.63	41.18	28.11	23.97	28.10	19.41	14.84	24.47	722.92	1386.
1957	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	154.80
1958	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	154.80
1959	14.27	13.48	23.74	23.68	37.95	18.72	34.74	27.38	17.93	13.92	13.69	12.90	272.30
1960	14.32	13.48	23.74	23.68	37.95	18.72	34.74	27.38	17.93	13.92	13.69	12.90	272.05
1961	14.22	23.72	21.49	17.18	12.61	15.01	19.22	19.25	19.15	8.60	8.44	8.19	196.68
1962	8.19	8.19	8.19	8.19	8.19	28.53	28.84	19.38	13.89	26.55	8.44	8.19	174.66
1963	12.90	14.71	17.12	29.48	24.44	16.20	13.84	13.47	19.34	8.24	6.15	6.70	186.84
1964	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	12.90	154.80
1965	23.82	20.72	24.64	31.60	23.85	18.72	13.84	9.71	12.82	14.82	10.13	14.70	253.34
1966	8.23	18.83	15.32	29.38	154.57	75.70	37.46	27.34	6.70	5.47	4.54	4.54	397.24
1967	10.22	21.62	23.61	21.84	11.75	14.20	16.24	9.12	5.81	7.83	13.44	14.70	174.36
1968	13.24	14.72	24.68	27.85	19.23	156.13	44.91	23.74	14.15	10.26	7.41	5.31	351.03
1969	21.67	24.31	17.91	18.43	7.84	7.88	5.76	15.61	13.58	8.31	7.41	5.31	161.24
1970	33.48	34.25	258.41	25.19	20.24	18.49	21.67	192.83	71.86	42.70	29.47	19.00	751.49
1971	8.23	18.83	15.32	35.27	241.61	104.66	23.44	21.66	12.23	10.52	11.42	8.19	514.57
% TOTAL	4.33	4.94	11.55	8.40	10.18	17.34	10.71	7.27	5.18	4.85	3.84	4.76	1.00.18

MEAN(1000)= 2.452201 STD. DEV.= .282221 MEAN ANNUAL RUNOFF= 758.47 MILLION CUBIC METERS

Table 2.12 : Synthesized runoff from catchment No. 2 for undeveloped conditions (m^3x10^6)

PDF= 3.9 SE= 0.88 ST= 350.MM PF= 26.0 MM/MONTH GW= 0.8 MM/MONTH AI= 0.0 %

ZONE= 5000.KM/MONTH PE= 1.8 MM/DAY GE=0.00 MM/MONTH TL= .25 MONTH WC= .4/.4/.4

P=.4/.4/.4	104.0	140.0	188.0	130.0	128.0	130.0	98.0	83.0	45.0	56.0	74.0	68.0	MM = MM .4
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	1.31	27.21	43.47	15.85	6.72	6.19	3.84	3.84	3.48	3.37	6.17	3.81	125.71
1922	1.92	18.77	3.43	20.74	10.42	4.82	2.98	1.26	1.03	1.08	9.32	1.92	77.34
1923	.64	.49	1.98	1.00	2.12	4.25	7.44	6.24	2.98	1.86	1.64	2.30	33.01
1924	10.10	2.86	10.84	14.05	19.81	4.32.11	1.81.66	1.81.66	1.81.66	1.81.66	1.81.66	1.81.66	1.81.66
1925	0.93	0.86	4.81	4.27	4.64	5.48	9.12	5.46	4.67	4.18	5.43	4.69	74.19
1926	3.82	6.34	6.01	3.27	3.44	8.28	9.12	7.78	6.49	4.18	5.43	4.46	77.92
1927	3.82	6.34	6.01	3.27	3.44	8.28	9.12	7.78	6.49	4.18	5.43	4.46	77.92
1928	3.82	1.81	4.81	4.27	4.64	5.48	9.12	5.46	4.67	4.18	5.43	4.46	58.14
1929	3.82	1.81	4.81	4.27	4.64	5.48	9.12	5.46	4.67	4.18	5.43	4.46	58.14
1930	4.06	2.63	3.71	1.02	.98	1.24	1.61	1.48	1.42	1.82	1.42	1.47	21.86
1931	4.06	2.63	3.71	1.02	.98	1.24	1.61	1.48	1.42	1.82	1.42	1.47	21.86
1932	2.39	3.02	6.22	4.84	2.44	3.08	1.72	1.02	.78	.93	1.43	1.19	28.64
1933	2.39	3.02	6.22	4.84	2.44	3.08	1.72	1.02	.78	.93	1.43	1.19	28.64
1934	4.33	4.22	9.33	14.35	7.33	5.33	8.32	7.00	5.17	8.86	6.18	5.14	85.56
1935	4.32	2.04	.81	3.39	10.29	12.61	17.63	16.70	11.58	7.42	4.72	3.54	95.46
1936	4.06	2.63	3.71	1.02	.98	1.24	1.61	1.48	1.42	1.82	1.42	1.47	21.86
1937	3.38	3.77	38.95	30.14	24.71	13.30	6.18	2.84	4.13	3.42	8.84	4.79	152.90
1938	4.06	2.63	3.71	1.02	.98	1.24	1.61	1.48	1.42	1.82	1.42	1.47	21.86
1939	4.32	10.57	1.83	4.30	1.84	2.55	4.14	3.84	34.21	72.02	30.84	12.08	181.21
1940	4.32	10.57	1.83	4.30	1.84	2.55	4.14	3.84	1.44	1.70	1.55	1.76	45.81
1941	1.85	3.21	2.97	2.61	4.90	12.61	9.42	5.31	4.03	3.69	11.38	8.79	70.48
1942	3.38	3.77	38.95	30.14	24.71	13.30	6.18	2.84	4.13	3.42	8.84	4.79	152.90
1943	4.06	2.63	3.71	1.02	.98	1.24	1.61	1.48	1.42	1.82	1.42	1.47	21.86
1944	12.16	13.13	1.85	3.91	4.64	38.83	19.94	9.16	7.34	4.41	3.08	1.97	124.40
1945	1.85	.81	1.85	2.79	2.53	4.15	8.01	4.64	3.97	3.50	1.70	1.53	36.97
1946	2.39	3.02	6.22	4.84	2.44	3.08	1.72	1.02	.78	.93	1.43	1.19	28.64
1947	3.82	6.34	6.01	3.27	3.44	8.28	9.12	7.78	6.49	4.18	5.43	4.46	77.92
1948	4.06	2.63	3.71	1.02	.98	1.24	1.61	1.48	1.42	1.82	1.42	1.47	21.86
1949	4.93	1.46	40.41	21.34	11.05	12.97	10.12	9.16	7.34	4.41	3.08	1.97	127.48
1950	1.85	.81	1.85	2.79	2.53	4.15	8.01	4.64	3.97	3.50	1.70	1.53	36.97
1951	1.85	.81	1.85	2.79	2.53	4.15	8.01	4.64	3.97	3.50	1.70	1.53	36.97
1952	10.23	6.46	2.39	1.97	1.84	1.24	2.49	9.11	5.84	4.92	2.26	2.73	51.17
1953	3.82	6.34	6.01	3.27	3.44	8.28	9.12	7.78	6.49	4.18	5.43	4.46	77.92
1954	52.40	22.24	7.03	6.27	7.49	43.92	12.54	8.12	4.88	2.97	1.96	1.40	173.70
1955	4.28	7.96	8.37	8.41	6.30	40.05	15.34	8.12	4.88	2.97	1.96	1.40	108.63
1956	8.84	9.05	68.27	49.30	10.88	7.43	6.33	7.42	5.13	3.92	6.46	190.92	366.
1957	3.82	6.34	6.01	3.27	3.44	8.28	9.12	7.78	6.49	4.18	5.43	4.46	77.92
1958	3.82	6.34	6.01	3.27	3.44	8.28	9.12	7.78	6.49	4.18	5.43	4.46	77.92
1959	3.77	3.56	6.27	6.26	10.03	4.95	9.18	7.23	4.74	3.68	3.62	3.41	71.90
1960	3.78	3.56	6.27	6.26	10.03	4.95	9.18	7.23	4.74	3.68	3.62	3.41	71.89
1961	3.76	6.27	5.68	4.54	3.33	3.97	5.08	5.09	5.06	2.27	2.23	2.16	51.99
1962	2.16	2.16	2.16	2.16	2.16	7.54	7.62	5.12	3.67	7.02	2.23	2.16	46.18
1963	3.41	3.89	4.52	7.79	6.46	4.28	3.66	3.56	5.11	2.18	1.63	1.77	49.39
1964	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	40.92
1965	6.30	5.48	6.51	8.35	6.30	4.95	3.66	2.57	3.39	3.92	2.68	3.89	66.97
1966	2.18	4.98	4.05	7.77	40.84	20.01	9.90	7.23	1.77	1.45	1.20	1.20	105.04
1967	2.70	5.72	6.24	5.77	3.11	3.75	4.29	2.41	1.54	2.07	3.55	3.89	46.07
1968	3.50	3.89	6.52	7.36	5.08	41.27	11.87	6.27	3.74	2.71	1.96	1.40	92.80
1969	5.73	6.43	4.73	4.87	2.07	2.08	1.52	4.13	3.59	2.20	1.96	1.40	42.63
1970	8.84	9.05	68.27	6.66	5.35	4.89	5.73	50.97	18.99	11.29	7.79	5.02	198.50
1971	2.18	4.98	4.05	9.32	63.85	27.67	6.19	5.73	3.23	2.78	3.02	2.16	135.91
% TOTAL	5.74	4.66	15.87	4.72	9.46	18.47	11.82	9.45	4.86	7.13	4.96	4.70	1.00.00

MEAN(1000)= 1.858012 STD. DEV.= .267184 MEAN ANNUAL RUNOFF= 135.90 MILLION CUBIC METERS

Table 2.13 : Synthesized runoff from catchment No. 3 for undeveloped conditi ns (m^3x10^6)

PWP= 3.0 SL= 0.02 ST= 450.44 FK= 20.0 MM/MONTH GW= 0.9 MM/MONTH AI= 0.4 =

IMAX= 5000.MM/MONTH FMAX= 4000.MM/MONTH FI= 1.5 MM/DAY QI=0.00 MONTHS TL= .25 MONTHS FIFK =FMAX/FK

P.ETAP.	104.0	140.0	182.0	158.0	138.0	98.0	82.0	AI=0.4	76.0	76.0	98.0	WW = W - .4	P.ETAP.	104.0	140.0	182.0	158.0	138.0	98.0	82.0	AI=0.6	76.0	76.0	98.0	WW = W - .6
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1921	.67	6.14	5.81	3.48	2.71	2.79	2.33	5.75	5.24	3.77	3.37	1.43	376.44	1.22	.78	6.23	5.44	3.22	2.39	2.21	1.82	1.14	1.78	1.47	.93	78.77
1922	2.47	2.44	2.25	11.03	5.84	2.38	2.16	1.61	1.25	1.76	1.61	.65	91.41	1.29	4.17	2.82	2.02	2.38	2.16	1.61	1.25	1.76	1.61	.65	91.41
1923	.66	.65	1.11	.43	1.67	10.53	10.01	4.88	3.49	2.55	2.31	.71	69.77	1.23	.64	.64	.32	.79	1.31	6.87	2.38	1.78	1.42	1.48	1.04	54.14
1924	2.44	15.66	6.24	4.74	22.02	98.84	49.96	33.94	19.23	9.45	3.39	3.12	747.46	1.81	4.32	4.68	3.26	14.12	98.27	36.16	20.80	8.14	4.83	1.39	1.72	155.74
1925	1.77	2.91	2.53	1.51	1.22	2.43	2.26	1.81	2.04	1.78	1.34	1.47	16.68	1.44	1.72	.81	.52	.96	.85	.62	.48	.42	.45	.41	.48	16.68
1926	1.25	1.32	.93	1.45	.95	1.71	1.18	2.55	1.94	1.81	1.34	1.71	16.84	1.25	.32	.22	.15	.20	.30	.41	.32	.19	.16	.11	.11	6.97
1927	1.53	.77	1.43	1.80	1.42	1.25	1.23	1.93	1.98	1.78	1.34	1.47	16.93	1.53	.77	1.43	1.80	1.42	1.25	1.23	1.93	1.98	1.78	1.34	1.47	16.93
1928	2.14	2.35	1.41	2.16	1.41	1.74	1.81	1.73	2.53	2.27	2.09	1.76	22.15	1.29	1.11	.61	1.01	.65	2.82	2.27	2.09	1.76	1.44	1.38	1.17	16.71
1929	2.14	2.35	1.41	2.16	1.41	1.74	1.81	1.73	2.53	2.27	2.09	1.76	22.15	1.29	1.11	.61	1.01	.65	2.82	2.27	2.09	1.76	1.44	1.38	1.17	16.71
1930	2.14	2.41	1.45	1.72	1.76	1.78	1.83	1.74	2.74	2.49	2.31	1.83	22.50	1.29	1.15	.65	1.07	.69	1.18	1.49	1.27	1.02	1.74	1.76	1.55	16.61
1931	2.37	3.07	1.71	2.79	6.77	19.62	22.89	24.04	9.64	3.31	2.45	2.93	96.91	1.29	1.34	1.10	1.06	11.46	11.92	22.81	19.04	6.48	1.62	1.34	1.50	79.45
1932	2.37	3.03	2.52	2.52	5.22	5.45	5.87	3.44	1.34	1.78	1.62	1.02	93.45	1.29	1.34	1.10	1.06	3.86	2.81	.72	.56	.48	.41	.47	.49	16.49
1933	1.84	1.85	1.40	2.09	2.65	4.47	5.82	3.40	6.30	11.42	4.99	2.49	47.94	1.84	.78	.47	2.15	2.14	4.76	3.44	1.73	4.43	2.13	2.34	1.41	74.27
1934	2.02	1.14	2.48	2.78	5.23	4.81	3.26	5.14	4.45	2.36	2.37	1.41	45.14	1.11	.81	1.13	1.31	5.21	4.24	1.31	1.29	2.46	2.73	1.99	1.17	74.27
1935	2.02	1.14	2.48	2.78	5.23	4.81	3.26	5.14	4.45	2.36	2.37	1.41	45.14	1.11	.81	1.13	1.31	5.21	4.24	1.31	1.29	2.46	2.73	1.99	1.17	74.27
1936	2.02	2.16	2.01	2.45	2.46	15.81	5.62	2.24	1.83	2.02	1.74	1.41	49.41	1.29	1.34	1.10	1.06	3.86	2.81	.72	.56	.48	.41	.47	.49	16.49
1937	1.25	1.00	2.61	2.63	2.11	2.92	2.00	2.16	2.00	2.16	1.80	1.25	23.09	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1938	2.63	4.11	2.04	1.74	3.67	4.04	4.37	15.18	6.45	2.77	1.49	0.49	64.31	1.27	.79	.84	.92	1.26	2.11	3.11	10.00	5.11	2.64	1.92	2.51	34.32
1939	2.63	4.11	2.04	1.74	.98	2.51	2.52	14.54	12.61	3.51	1.49	0.49	64.31	1.82	2.77	1.83	1.10	1.16	2.02	4.19	11.31	21.38	8.46	2.92	1.92	76.46
1940	2.28	5.79	3.81	3.02	1.43	1.41	1.35	.92	1.62	1.46	.97	1.22	39.19	1.29	1.34	1.10	1.06	1.75	1.34	.98	.93	.97	.97	.90	.91	19.24
1941	1.75	1.44	2.48	1.87	3.16	17.40	15.43	7.04	2.63	1.34	1.26	0.89	75.69	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1942	1.75	1.44	2.48	1.87	3.16	17.40	15.43	7.04	2.63	1.34	1.26	0.89	75.69	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1943	2.33	2.24	1.57	.66	1.00	1.36	1.18	1.12	2.13	2.31	.66	1.75	19.24	1.84	1.37	1.13	.82	1.02	1.22	1.26	1.07	1.07	2.30	2.32	1.78	19.24
1944	2.58	3.42	1.69	1.48	2.24	8.31	4.36	2.72	2.22	2.29	2.06	1.17	35.17	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1945	1.32	.84	1.46	2.21	.89	1.89	2.54	2.89	2.39	2.48	1.89	1.22	19.44	1.29	1.34	1.10	1.06	.44	.37	.98	1.24	1.22	1.11	.87	.77	9.80
1946	1.32	.84	1.46	2.21	.89	1.89	2.54	2.89	2.39	2.48	1.89	1.22	19.44	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1947	2.77	2.79	3.32	2.65	2.82	3.7.	3.10	2.42	1.66	2.79	1.34	1.78	29.47	1.84	1.37	1.09	1.38	1.62	1.74	1.38	1.32	1.32	1.32	1.40	1.25	16.98
1948	2.77	2.79	3.32	2.65	2.82	3.7.	3.10	2.42	1.66	2.79	1.34	1.78	29.47	1.84	1.37	1.09	1.38	1.62	1.74	1.38	1.32	1.32	1.32	1.40	1.25	16.98
1949	3.18	1.79	2.24	2.68	2.18	2.25	2.68	2.19	2.75	2.48	2.31	1.83	26.36	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1950	1.81	.68	2.23	1.82	.62	1.41	1.17	1.48	1.24	1.77	1.32	1.37	17.34	1.29	1.34	1.10	1.06	.44	.37	.98	1.24	1.22	1.11	.87	.77	9.80
1951	3.12	1.24	2.44	.66	.98	1.41	1.17	1.48	1.24	1.77	1.32	1.37	17.34	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1952	.84	2.28	.87	.61	.89	1.54	1.30	1.28	1.14	1.56	1.26	1.69	16.74	1.82	.74	1.02	.93	1.02	1.31	1.48	1.40	.92	.88	.87	.61	11.98
1953	2.84	2.28	2.87	2.44	2.58	2.42	2.27	2.33	2.54	2.37	2.09	1.76	27.70	1.85	1.84	1.61	1.27	2.39	2.57	2.39	2.37	2.33	2.13	1.60	1.32	23.65
1954	1.86	2.27	2.04	2.58	2.47	2.53	2.53	2.58	2.54	2.39	2.14	1.81	26.67	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1955	2.86	2.27	2.04	2.58	2.47	2.53	2.53	2.58	2.54	2.39	2.14	1.81	26.67	1.84	1.37	1.09	1.38	1.62	1.74	1.38	1.32	1.32	1.32	1.40	1.25	16.98
1956	3.09	5.57	4.46	3.40	2.76	7.46	30.91	15.46	6.45	2.77	1.49	0.49	64.31	1.84	1.37	1.09	1.38	1.62	1.74	1.38	1.32	1.32	1.32	1.40	1.25	16.98
1957	10.50	4.72	3.30	38.85	15.67	3.72	3.42	3.28	3.81	2.92	2.59	3.15	93.43	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1958	2.34	2.34	2.72	1.52	1.11	.76	.72	1.00	1.42	1.78	1.54	1.41	19.71	1.84	1.37	1.21	1.07	.44	.37	.98	1.24	1.22	1.11	.87	.77	9.80
1959	2.28	2.22	2.72	6.63	3.42	3.48	2.98	2.38	2.17	2.43	2.06	1.71	34.61	1.84	1.37	1.09	1.38	1.62	1.74	1.38	1.32	1.32	1.32	1.40	1.25	16.98
1960	2.28	2.22	2.72	6.63	3.42	3.48	2.98	2.38	2.17	2.43	2.06	1.71	34.61	1.84	1.37	1.09	1.38	1.62	1.74	1.38	1.32	1.32	1.32	1.40	1.25	16.98
1961	2.37	2.01	2.61	2.63	2.11	2.92	2.00	2.16	2.00	2.16	1.80	1.25	23.09	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1962	2.37	2.01	2.61	2.63	2.11	2.92	2.00	2.16	2.00	2.16	1.80	1.25	23.09	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1963	2.84	2.28	2.87	.61	.89	1.54	1.30	1.28	1.14	1.56	1.26	1.69	16.74	1.82	.74	1.02	.93	1.02	1.31	1.48	1.40	.92	.88	.87	.61	11.98
1964	2.84	2.28	2.87	2.44	2.58	2.42	2.27	2.33	2.54	2.37	2.09	1.76	27.70	1.85	1.84	1.61	1.27	2.39	2.57	2.39	2.37	2.33	2.13	1.60	1.32	23.65
1965	1.86	2.27	2.04	2.58	2.47	2.53	2.53	2.58	2.54	2.39	2.14	1.81	26.67	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1966	2.86	2.27	2.04	2.58	2.47	2.53	2.53	2.58	2.54	2.39	2.14	1.81	26.67	1.84	1.37	1.09	1.38	1.62	1.74	1.38	1.32	1.32	1.32	1.40	1.25	16.98
1967	10.50	4.72	3.30	38.85	15.67	3.72	3.42	3.28	3.81	2.92	2.59	3.15	93.43	1.29	1.34	1.10	1.06	1.75	1.34	1.31	1.40	1.40	1.25	1.23	1.31	16.98
1968	2.34	2.34	2.72	1.52	1.11	.76	.72	1.00	1.42	1.78	1.54	1.41	19.71	1.84	1.37	1.21	1.07	.44	.37	.98	1.24	1.22	1.11	.87	.77	9.80
1969	2.28	2.22	2.72	6.63	3.42	3.48	2.98	2.38	2.17	2.43	2.06	1.71	34.61	1.84	1.37	1.09	1.38	1.62	1.74	1.38	1.32	1.32	1.32	1.40	1.25	16.98
1970	2.28	2.22	2.72	6.63	3.42	3.48	2.98	2.38	2.17	2.43	2.06	1.71	34.61	1.84	1.37	1.09	1.38	1.62	1.74	1.38	1.32	1.32	1.32	1.40	1.25	16.98
1971	4.37	2.47	1.56	9.94	21.18	10.31	4.48	2.63	2.20	12.56	13.33	5.82	190.80	4.37	2.47	1.56	9.94	21.18	10.31	4.48	2.63	2.20	12.56	13.33	5.82	190.80
X TOTAL	4.43	6.41	6.07	5.84	6.63	13.92	13.32	13.49	10.11	8.51	6.41	5.04	160.58	X TOTAL	2.78	3.14	2.74	4.48	6.43	8.20	12.56	13.33	5.82	6.52	6.32	100.89

SKAMLOOP= 1.520461 STD. DEV.= .3384842 MEAN ANNUAL RUNOFF= 214.84 MILLION CUBIC METRES

SKAMLOOP= 1.257680 STD. DEV.= .2823324 MEAN ANNUAL RUNOFF= 134.42 MILLION CUBIC METRES

Table 2.14 : Synthesized runoff from catchment No. 4 for undeveloped conditions (m^3x10^6)

PWP= 3.0 SL= 0.02 ST= 450.44 FK= 20.0 MM/MONTH GW= 0.9 MM/MONTH AI= 0.4 =

IMAX= 2000.MM/MONTH FMAX= 4000.MM/MONTH FI= 1.5 MM/DAY QI=0.00 MONTHS TL= .25 MONTHS FIFK =FMAX/FK

Table 2.15 : Synthesized runoff from catchment No. 1a for undeveloped conditions (m^3x10^6)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	2.24	10.30	14.44	17.81	4.43	4.05	4.21	4.77	4.57	6.23	8.34	4.42	91.46
1922	3.29	3.89	4.52	5.57	11.40	12.41	12.41	12.41	12.41	12.41	12.41	12.41	123.35
1923	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	148.94
1924	4.44	24.06	25.04	30.62	31.26	251.62	193.34	19.74	19.49	6.24	4.58	4.47	576.49
1925	18.34	11.61	7.95	9.26	5.74	5.59	5.59	5.59	5.59	5.59	5.59	5.59	91.03
1926	10.14	14.42	11.14	9.21	7.21	14.92	12.41	9.61	2.40	3.95	5.71	4.99	116.11
1927	4.27	9.22	5.71	9.07	12.41	9.37	6.41	2.61	2.61	2.61	2.61	2.61	71.51
1928	2.62	2.61	2.62	2.62	2.61	10.29	13.92	7.46	4.49	4.31	4.24	4.18	71.57
1929	4.12	5.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	143.34
1930	4.78	5.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	143.34
1931	2.47	3.41	3.94	5.24	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	134.37
1932	2.47	3.41	3.94	5.24	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	134.37
1933	2.47	3.41	3.94	5.24	12.41	12.41	12.41	12.41	12.41	12.41	12.41	12.41	134.37
1934	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1935	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1936	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1937	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1938	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1939	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1940	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1941	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1942	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1943	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1944	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1945	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1946	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1947	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1948	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1949	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1950	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1951	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1952	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1953	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1954	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1955	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1956	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1957	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1958	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1959	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1960	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1961	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1962	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1963	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1964	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1965	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1966	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1967	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1968	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1969	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1970	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1971	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1972	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1973	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1974	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1975	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1976	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1977	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1978	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1979	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1980	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1981	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1982	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1983	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1984	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1985	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1986	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1987	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1988	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1989	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1990	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1991	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1992	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1993	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1994	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1995	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1996	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1997	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1998	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
1999	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2000	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2001	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2002	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2003	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2004	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2005	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2006	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2007	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2008	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2009	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2010	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2011	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2012	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2013	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2014	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2015	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2016	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2017	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2018	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2019	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2020	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2021	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2022	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2023	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2024	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2025	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2026	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2027	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2028	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2029	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2030	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2031	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2032	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2033	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2034	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2035	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2036	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2037	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2038	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2039	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2040	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2041	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2042	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2043	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2044	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2045	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2046	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2047	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2048	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2049	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28
2050	4.34	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	4.44	53.28

Table 2.16 : Synthesized runoff from catchment No. 1b for undeveloped conditions (m^3x10^6)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	4.17	19.83	27.46	34.17	8.58	4.88	4.16	4.23	4.04	4.01	7.98	4.14	123.65
1922	3.02	3.58	4.16	5.13	10.50	11.43	11.43	11.43	11.43	11.43	11.43	11.43	113.58
1923	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	137.16
1924	4.09	22.16	23.06	28.21	28.80	231.70	178.01	18.18	17.95	5.75	4.22	4.12	530.95
1925	16.89	10.69	7.32	8.53	5.29	5.15	5.15	5.15	5.15	5.15	5.15	5.15	83.82
1926	9.34	13.28	10.26	8.48	6.64	13.74	11.43	8.85	2.21	3.64	5.26	4.59	106.92
1927	3.93	8.49	5.26	8.35	11.43	8.63	5.90	2.40	2.40	2.40	2.40	2.40	65.86
1928	2.41	2.40	2.41	2.41	2.40	9.47	12.82	6.87	4.14	3.97	3.90	3.85	65.90
1929	3.80	4.98	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	132.00
1930	4.40	4.98	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	132.00
1931	2.27	3.14	3.63	4.82	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	123.72
1932	2.27	3.14	3.63	4.82	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	123.72
1933	2.27	3.14	3.63	4.82	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	123.72
1934	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1935	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1936	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1937	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1938	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1939	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1940	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1941	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1942	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1943	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1944	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1945	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1946	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1947	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1948	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1949	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1950	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1951	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1952	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1953	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1954	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1955	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1956	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1957	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1958	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1959	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1960	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1961	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1962	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1963	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1964	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1965	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1966	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1967	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1968	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1969	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1970	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1971	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1972	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1973	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1974	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	49.08
1975	4.00	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09

The model parameters used for the calibration simulations are shown in table B.2 of Appendix B. It will be noticed that identical parameters were used for gauges W1M01 and W1M09.

The model parameters for the two small coastal catchments to the north-east and south-west of the bay, which are extremely flat and sandy, were chosen so as to cause the runoff to appear mostly as ground-water seepage. The model parameters adopted are identical to those used by Hutchison and Pitman[7] for similar St. Lucia Lake catchments. In the absence of quantitative measurements calibration was not possible but the mean annual runoffs from these catchments were checked against the rainfall-runoff relationships presented in reference 10 and the resulting comparisons are given in table 2.17.

(b) Synthetic runoff from the undeveloped catchments

Using the model parameters referred to in (a) above, extended monthly runoffs were synthesized for the following catchments:

(1) Umhlatuzi catchment (excluding that part of the catchment drained by the Nsezi)

'1a) Umhlatuzi catchment commanded by gauge W1M01

(1b) Umhlatuzi catchment excluding those portions commanded by gauge W1M01 and drained by the Nsezi river.

(2) Nsezi catchment (to confluence with the Umhlatuzi)

(3) North-eastern coastal catchment feeding into the estuary via the Mzingazi and groundwater flow

(4) South-western coastal catchment feeding directly into the bay via interflow and groundwater seepage.

Table 2.10 indicates source data pertaining to the synthesization process for each of the catchments listed above.

The resulting synthetic monthly flows for the four total catchments in undeveloped condition are presented in tables 2.11 to 2.14, while those for the Umhlatuzi sub-catchments upstream and downstream of gauge W1M01 are listed in tables 2.15 and 2.16.

The MAR's for the undeveloped catchments arrived at by this process are compared in table 2.17 with those shown in HRU report No. 2/69[10].

Table 2.17 : Comparison of mean annual runoffs from undeveloped catchments

catchment		MAR $m^3 \times 10^6$	
No.	name	this sudy	HRU 2/69
1	Umhlatuzi (excluding Nsezi)	358	344
2	Nsezi (to confluence with Umhlatuzi)	126	131
3	North-eastern coastal catchment	55	65
4	South-western coastal catchment	33	37
Total		572	577

(c) Modelling of water usage to simulate 1970 conditions

The only change of significance to be accounted for is that resulting from abstraction of water for irrigation. For conditions prevailing in 1970 the estimated areas of land under sugar in the Umhlatuzi and Nsezi catchments were respectively 12 300 and 11 100 ha*. To simulate the conditions prevailing at that time flows corresponding to net evaporation from the land under cultivation in each catchment were deducted from the simulated monthly runoffs for undeveloped catchments. The resulting monthly flows are listed in tables 2.18 and 2.19.

The monthly flows from the two coastal catchments were assumed to be unaltered from the virgin conditions (i.e. as in tables 2.13 and 2.14 in (b) above).

(d) Modelling of water usage to simulate year 1990 conditions

The major developments that have to be accounted for within the catchments are:

(1) Increased abstraction of water for sugar cane irrigation

(2) The construction of a storage dam[1] on the Umhlatuzi

(3) Abstractions from the Umhlatuzi at its mouth and from the three coastal lakes for industrial and urban usage in the Richards bay area.

These water usages are summarized in table 2.20.

* see Appendix C.

Table 2.18 : Synthesized runoff from catchment No. 1 for 1970 conditions (m^3x10^6)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1901	1-31	35.78	11.46	19.35	6.84	7.84	4.35	3.46	4.81	5.16	12.12	6.44	121.37
1902	1-30	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1903	1-29	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1904	1-28	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1905	1-27	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1906	1-26	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1907	1-25	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1908	1-24	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1909	1-23	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1910	1-22	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1911	1-21	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1912	1-20	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1913	1-19	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1914	1-18	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1915	1-17	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1916	1-16	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1917	1-15	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1918	1-14	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1919	1-13	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1920	1-12	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1921	1-11	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1922	1-10	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1923	1-9	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1924	1-8	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1925	1-7	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1926	1-6	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1927	1-5	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1928	1-4	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1929	1-3	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1930	1-2	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26
1931	1-1	36.84	12.13	33.27	22.89	8.87	5.24	6.02	5.00	5.00	5.00	5.00	150.26

Table 2.19 : Synthesized runoff from catchment No. 2 for 197Q conditions (m^3x10^6)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1931	1-31	37.91	13.47	8.18	0.00	.44	0.00	0.00	0.00	0.00	0.00	0.00	59.99
1932	1-30	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1933	1-29	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1934	1-28	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1935	1-27	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1936	1-26	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1937	1-25	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1938	1-24	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1939	1-23	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1940	1-22	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1941	1-21	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1942	1-20	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1943	1-19	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1944	1-18	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1945	1-17	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1946	1-16	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1947	1-15	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1948	1-14	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1949	1-13	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1950	1-12	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1951	1-11	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1952	1-10	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1953	1-9	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1954	1-8	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1955	1-7	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1956	1-6	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1957	1-5	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1958	1-4	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1959	1-3	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1960	1-2	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16
1961	1-1	38.57	2.91	20.57	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.16

Table 2.20 : Estimated water demands as at 1990

catchment	use		source
Umhlatuzi - downstream of gauge W1M01 *	agricultural		
	Nkwaleni settlement	6 500 ha	dam
	Ntambanana valley **	5 200 ha	"
	Bantu reserve	2 000 ha	"
	Ntambanana valley	2 900 ha	Mfule ***
	urban and industrial		
	Richards bay	$0,77 \times 10^6$ m /month	dam
	" "	$7,93 \times 10^6$ m /month	coastal lakes
Umhlatuzi - upstream of gauge W1M01 *	agricultural		
	sugar cane	600 ha+	Umhlatuzi
Nsezi	agricultural		
	sugar cane	14 100 ha+	Nsezi

* Gauge W1M01 is located at the site of the proposed dam.

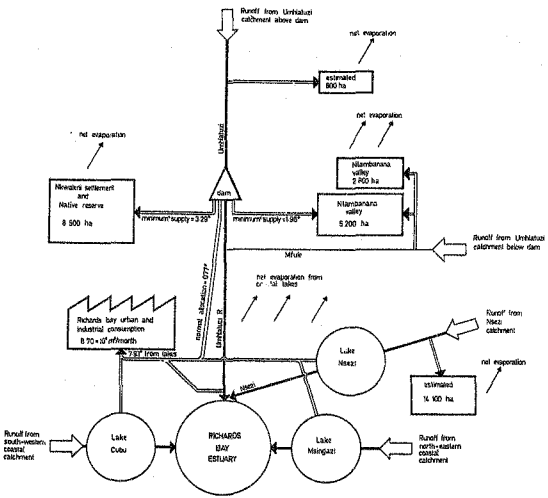
** It is proposed to supply this area from dam storage only when direct pumping from the Mfule proves inadequate.

*** The Mfule is a tributary of the Umhlatuzi.

\+ These estimates are based on results from Appendix C.

According to reference 11 minimum water requirements for the Nkwaleni Settlement and the Nature Reserve have been set at 108 000 m^3/d ($3,29 \times 10^6$ m^3/month) while those for the Ntambonana valley have been set at 65 00 m^3/d ($1,98 \times 10^6 m^3$/month).

From table 2.20 it may be noted that to satisfy a highly reliable continuous demand of $7,93 \times 10^6$ m^3 per month the three coastal lakes are needed. As the total surface area of these three lakes is about 2 010 ha, it follows that abstraction of $7,93 \times 10^6$ m^3 per month for any three-month period during which there is negligible runoff into the lakes will cause the water level to drop by 1,2 metres. As such a lowering of the water level might be damaging both to the local ecology and to recreational facilities, it was decided to assume that the lake levels will be maintained at a constant level, i.e. during any one month abstraction from the lakes may not exceed the runoff into the lakes for that month. It was assumed that any shortfall in supply



KEY:

\+ assured irrigation allocation- maximum supply = net evaporation

* 10 m /month

river channel

water transport

agricultural consumption

urban and industrial consumption

lake storage

FIGURE 2.6 Symbolic representation of the model used to simulate 1990 runoff into the Richards bay estuary system

Table 2.21 : Synthesized runoff from catchment No. 1 for 1990 conditions (m^3x10^6)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	0.00	15.63	23.26	10.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.24
1922	0.00	7.34	0.00	17.48	12.47	.57	0.00	0.00	0.00	0.00	0.00	0.00	37.86
1923	0.00	0.00	0.00	0.00	0.00	0.00	7.45	1.28	1.13	.11	0.00	0.00	9.97
1924	0.00	1.97	14.18	15.46	14.48	197.71	420.44	42.72	19.48	72.07	24.35	12.43	775.29
1925	21.42	14.61	0.00	0.00	0.00	2.14	.00	0.00	0.00	2.64	0.00	.44	41.25
1926	7.36	0.00	0.00	0.00	0.00	15.74	2.62	6.76	0.00	0.00	0.00	0.00	32.49
1927	0.00	0.00	0.00	0.00	3.62	0.70	0.00	0.00	0.00	0.00	0.00	0.00	4.32
1928	0.00	0.00	0.00	0.00	4.26	0.00	82.34	31.84	7.82	10.45	0.00	0.00	136.71
1929	0.00	0.00	2.07	0.00	10.10	6.44	1.71	0.00	0.00	.47	0.00	0.00	20.79
1930	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1931	0.00	0.00	0.00	0.00	0.00	182.46	95.00	66.00	76.65	36.11	0.72	0.00	454.94
1932	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1933	0.00	0.00	0.00	0.00	14.89	23.44	24.78	19.82	19.23	14.13	14.47	0.00	130.96
1934	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.12	0.00	0.00	0.00	19.12
1935	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1936	1.73	26.74	1.21	5.14	18.18	17.70	20.44	9.00	6.42	21.67	10.64	12.61	151.48
1937	0.00	0.00	0.00	40.18	6.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	46.62
1938	4.81	0.00	6.43	.21	182.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	194.08
1939	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1940	0.00	17.61	117.14	40.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	175.03
1941	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1942	.49	7.09	59.03	40.86	11.42	24.84	204.74	98.62	22.23	13.11	69.94	22.22	573.77
1943	62.52	8.42	29.13	0.00	11.43	12.64	2.45	0.00	0.00	0.00	0.00	0.00	126.59
1944	22.73	24.81	0.00	0.00	0.00	0.00	148.98	59.18	19.82	0.00	0.00	0.00	275.52
1945	0.00	0.00	0.00	0.00	3.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.21
1946	0.00	0.00	0.00	0.00	0.00	14.18	16.84	12.74	6.87	0.00	0.00	0.00	51.61
1947	0.00	0.00	0.00	0.00	0.00	4.65	5.39	14.39	0.00	0.00	0.00	0.00	24.43
1948	0.00	0.00	0.00	0.00	0.00	7.09	1.27	76.97	19.44	17.68	1.11	0.00	0.00
1949	0.00	0.00	13.48	61.42	47.25	21.73	28.85	0.00	0.00	0.00	0.00	0.00	172.74
1950	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1951	14.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.12
1952	0.00	0.00	0.00	0.00	3.22	.00	0.00	0.00	0.00	0.00	0.00	0.00	3.22
1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1954	113.34	43.71	0.00	0.00	0.00	.42	79.26	41.71	20.85	5.73	0.00	0.00	304.86
1955	0.00	0.00	19.47	23.93	0.00	141.16	70.74	19.42	2.48	2.13	0.00	0.00	279.33
1956	4.26	25.46	245.70	135.15	38.52	26.37	32.43	13.57	1.69	11.51	6.39	581.43	963.17
1957	240.08	76.23	0.43	4.45	15.16	28.12	35.71	6.69	4.71	1.28	0.00	0.00	412.86
1958	2.00	0.00	3.81	14.52	24.43	0.00	0.00	0.00	0.00	0.00	0.00	2.79	47.55
1959	7.22	0.00	0.12	2.76	20.78	24.70	37.26	19.41	3.44	2.72	0.00	0.00	118.60
1960	0.00	0.00	81.14	257.15	113.84	38.74	15.74	83.55	24.31	21.00	8.14	2.17	0.00
1961	0.00	12.47	12.70	.41	7.82	1.24	3.71	0.00	0.00	0.00	0.00	0.00	38.34
1962	0.00	0.00	6.72	2.81	14.62	6.81	31.33	55.38	9.56	21.32	19.14	93.35	0.00
1963	0.00	0.00	1.72	0.00	0.00	0.00	7.76	0.00	3.23	0.00	0.00	0.00	206.04
1964	1.23	0.00	1.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.89
1965	1.23	0.00	0.00	14.27	0.00	0.00	0.00	0.00	0.00	2.72	1.16	0.00	2.39
1966	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.43
1967	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1968	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1969	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1970	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1971	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1972	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1973	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1974	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1975	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1976	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1977	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1978	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1979	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1980	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1981	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1982	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1983	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1984	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1985	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1986	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1987	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1988	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1989	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1990	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1991	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1992	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1993	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1994	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1995	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1996	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1997	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1998	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1 TOTAL	5.89	5.47	12.27	9.47	13.06	20.41	12.58	9.58	4.46	6.48	4.37	3.54	100.06

MEAN ANNUAL RUNOFF = 1.668308 STD. DEV.= .964130 SKEW ANNUAL RUNOFF= 2.19.58 MILLION CUBIC METERS

Table 2.22 : Synthesized runoff from catchment No. 2 for 1990 conditions (m^3x10^6)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	0.00	31.62	48.07	1.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	81.11
1922	0.00	0.00	15.66	35.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	51.38
1923	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1924	0.00	14.54	24.41	19.24	19.21	422.11	1434.44	49.81	13.71	7.65	0.00	0.00	1005.12
1925	0.00	.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1926	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1927	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1928	0.00	0.00	0.00	0.00	0.00	0.00	60.46	30.82	1.84	0.00	0.00	0.00	0.00
1929	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1930	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1931	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1932	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1933	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1934	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1935	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1936	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1937	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1938	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1939	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1940	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1941	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1942	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1943	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1944	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1945	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1946	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1947	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1948	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1949	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1950	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1951	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1955	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1956	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1957	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1958	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1959	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1960	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1961	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1962	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1963	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1964	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1965	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1966	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1967	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1968	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1969	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1970	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1971	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1972	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1973	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1974	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1975	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1976	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1977	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1978	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1979	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1980	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1981	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1982	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1983	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1984	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1985	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1986	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1987	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1988	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1989	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1990	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1991	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1992	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1993	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1994	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1995	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1996	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1997	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1998	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1 TOTAL	4.43	5.06	12.28	8.98	14.74	19.96	14.79	10.19	6.17	4.74	3.91	3.11	108.00

MEAN ANNUAL RUNOFF = .901767 STD. DEV.= 1.802842 SKEW ANNUAL RUNOFF= 11.96 MILLION CUBIC METERS

Table 2.23 : Synthesized runoff from catchment No. 3 for 1990 conditions (m^3x10^6)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	0.00	0.00	2.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.42
1922	0.00	0.00	0.00	11.02	1.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.04
1923	0.00	0.00	0.00	0.00	0.00	0.71	0.00	0.00	0.00	0.00	0.00	0.00	0.71
1924	0.00	0.00	0.00	0.00	0.00	23.93	38.84	49.25	30.54	14.22	0.00	0.00	0.00	156.78
1925	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1926	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1927	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1928	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1929	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1930	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1931	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1932	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1933	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1934	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1935	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1936	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1937	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1938	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1939	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1940	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1941	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1942	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1943	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1944	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1945	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1946	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1947	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1948	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1949	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1950	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1951	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1955	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1956	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1957	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1958	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1959	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1960	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1961	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1962	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1963	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1964	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1965	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1966	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1967	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1968	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1969	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1970	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1971	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1972	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1973	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1974	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1975	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1976	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1977	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1978	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1979	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1980	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1981	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1982	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1983	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1984	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1985	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1986	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1987	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1988	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1989	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1990	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1991	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1992	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1993	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1994	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1995	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1996	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1997	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1998	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2002	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2003	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2004	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2005	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2007	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2008	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2011	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2012	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2013	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2014	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2016	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2018	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2019	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2020	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2021	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2022	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2023	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2024	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2025	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2026	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2027	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2028	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2031	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2032	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2033	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2034	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2035	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2036	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2037	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2039	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2040	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2041	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2042	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2043	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2044	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2046	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2047	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2048	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2049	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2050	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2051	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2052	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2053	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2054	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2055	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2056	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2057	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2058	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2059	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2060	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2061	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2062	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2063	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2064	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2066	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2067	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2068	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2069	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2070	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2071	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2072	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2073	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2074	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2075	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2076	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2077	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2078	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2079	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2080	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2081	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2082	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2083	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2084	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2085	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2086	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2087	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2088	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2089	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2090	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2092	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2094	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2095	0

would be made good from the Umhlatuzi dam.

Operating rule for the dam

To model water usage for 1990 conditions it was necessary to assume an operating rule for the proposed dam[11] on the Umhlatuzi. The proposed capacity is 295 x 10^6 m^3. From table 2.15, it is evident that the MAR of the catchment commanded by the dam is 168 x 10^6 m^3. The draft that should be sustained by the reservoir at a high degree of assurance is 6,04* x 10^6 m^3 (i.e. 43% MAR). From the draft-storage-frequency relationship for the relevant region in Appendix E of reference 10, in order to sustain a draft of 43% MAR in the face of a drought of RI 100 years the storage must exceed 23% MAR, i.e. 40 x 10^6 m^3. Thus for the purposes of simulation it was assumed that whenever the storage dropped below 40 x $10^6 m^3$, the monthly irrigation supplies to the Nkwaleni Settlement and the Ntombonana Valley were restricted to 3,29 and 1,98 x $10^6 m^3$ respectively.

A mathematical model was set up to simulate the water usage appropriate to 1990 conditions as described above. A symbolic representation of the modelled conditions is given in figure 2.6. Output from the model takes the form of monthly runoffs from the four catchments into the Richards Bay estuary. These runoffs are listed in tables 2.21 to 2.24.

(e) Comparison of virgin, 1970 and 1990 runoffs

A comparison of the mean annual runoffs for undeveloped, present day and projected 1990 conditions is given in tables 2.25 and 2.26.

* The figure of 6,04 x $10^6 m^3$ per month is broken down as follows:

Richards Bay and Eshowe urban and industrial demand	0,77 x $10^6 m^3$/month
Minimum irrigation requirement for Ntambonana valley	1,98
Minimum irrigation requirement for Nkwaleni Settlement and Bantu Reserve	3,29
Total	6,04 x $10^6 m^3$/month

Table 2.25 : Summary of mean annual runoff values

catchment		time period					
No.	name	undeveloped		1970		1990	
		$m^3 \times 10^6$	mm	$m^3 \times 10^6$	mm	$m^3 \times 10^6$	mm
1	Umhlatuzi	358	128	301	107	220	78
2	Nsezi	126	150	94	112	82	98
3	north-east coastal	55	278	55	278	29	146
4	south-west coastal	33	326	33	326	7	69

Table 2.26 : Summary of approximate median annual runoffs

catchment		time period					
No.	Name	undeveloped		1970		1990	
		$m^3 \times 10^6$	mm	$m^3 \times 10^6$	mm	$m^3 \times 10^6$	mm
1	Umhlatuzi	284	101	203	72	77	27
2	Nsezi	91	108	35	42	8	10
3	north-east coastal	43	218	43	218	1	5
4	south-west coastal	25	248	25	248	0	0

2.5 Flood discharges from the catchments feeding Richards Bay

2.5.1 Design flood criteria

Although, strictly speaking, the catchment is not of sufficient size (4 000 km²) to be classified as a "large catchment"*, there is no hard and fast rule. On the other hand the flood response of the Richards Bay estuary system could not be treated as an intermediate-sized catchment as more than one sub-catchment is involved, each with a different response time. Thus meaningful flood responses can be obtained only by designing for a single storm pattern over the entire catchment. It would be illogical to use the most severe storm pattern for each sub-catchment independently and then combine these to obtain design flood discharges into the Bay system.

2.5.2 Sub-catchment lags

From a comparison of figure 2.7 with figure F.1 in HRU Report No. 1/72[12], it may be observed that almost the entire catchment area falls within Veld Zone 8. For each of the sub-catchments, the profile of the main drainage line was plotted and the average slope line drawn as shown in figure 2.8. The lengths of the main watercourse and distance from catchment outlet to centre of area of catchment, L and Lc respectively, were measured from 1:250 000 relief maps. From these values the Catchment Index,

$$\frac{L.Lc}{\sqrt{S}}$$

was calculated and the catchment lag, Tl,then estimated for each sub-catchment by referring to figure F.2 of HRU report No. 1/72. The relevant parameters are listed in table 2.27.

2.5.3 Design storm

In order to estimate the extreme flood conditions realistically, a single storm must be synthesized for the entire catchment. As the critical storm duration was unknown, the 2-, 4-, 8-, 12-, 18- and 24-hour storms were synthesized.

* HRU Report No. 1/72[12] describes a "large catchment" as being greater than 5000 km² in area.

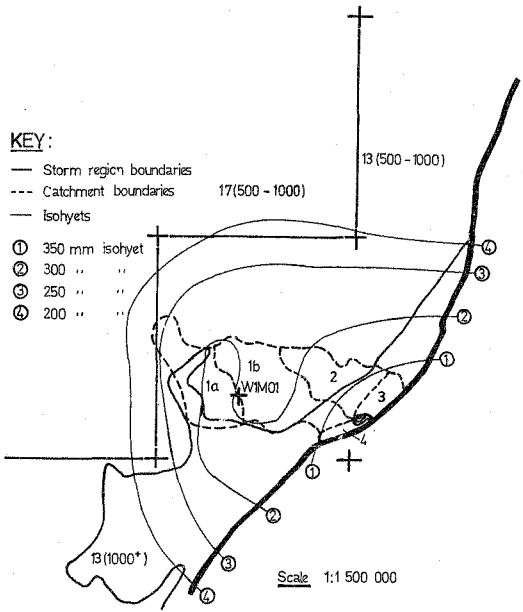


FIG. 2.7:
Catchment boundaries with superimposed isohyets of the maximum observed storm for storm region No. 13 of HRU Report No. 1/72

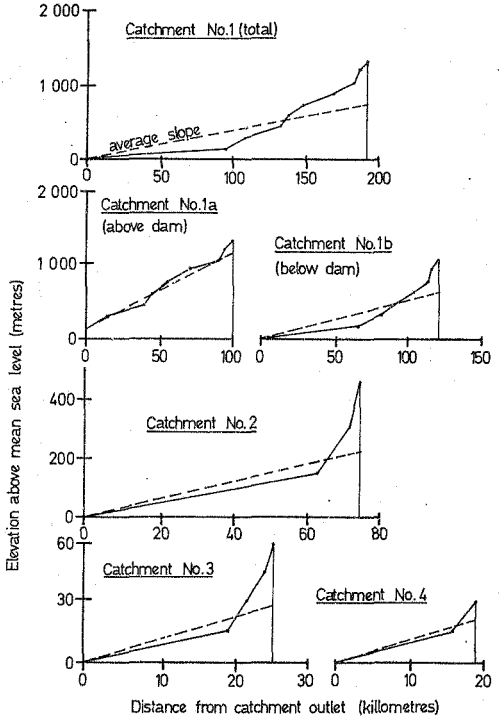


FIGURE 2.8: Longitudinal sections along the main water courses of each catchment

Table 2.27 : Parameters used in calculation of catchment indices and lags

sub-catchment		area	L	Lc	S	catchment index	lag,T
No.	description	km²	km	km			hours
1a	Umhlatuzi above gauge W1M01	1246	99	46	0.0120	41 500	9
1b	Umhlatuzi below gauge W1M01	1561	120	66	0.0044	119 000	13
1	total Umhlatuzi	2807	188	96	0.0043	275 000	18
2	Nsezi	841	75	30	0.0020	41 700	9
3	north-eastern coastal	197	25	10	0.0011	7 530	5
4	south-western coastal	101	18	8	0.0011	4 340	4

Table 2.28 : Areas enclosed by isohyets of maximum observed 6-day storm (km²)

Isohyet		storm region 13(1000+)		storm region 13(500-1000)	
No.	mm	catchment area enclosed	total area enclosed	catchment area enclosed	total area enclosed
1	350	615	880	-	-
2	300	906	3 360	1 427	2 360
3	250	1 120	5 180	2 740	8 550
4	200	1 120	6 220	2 780	11 400

(a) 24-hour duration storm

By comparing figure 2.7 with figure D.1 of HRU report No. 1/72 it is seen that the catchment lies within the boundaries of storm region 13. The isohyets of the maximum observed storm for storm region 13 are shown in figure 2.7*. For the sake of convenience these isohyets have been numbered from 1 to 4 as indicated in table 2.28.

The total areas enclosed by each design storm isohyet within each storm region are listed in table 2.28 along with the corresponding areas embraced by isohyet and catchment boundaries.

Using the total area enclosed by each isohyet contained in table 2.28 along with the maximum depth-area-duration curves presented in figures D.20 and D.21 of HRU report No. 1/72, the corresponding maximum one-day duration rainfall values were obtained for each isohyet in each of the two storm regions. The isohyetal precipitation values for storms of various recurrence intervals were interpolated from the corresponding depth-area-duration-frequency curves. The one-day duration isohyetal values for the two storm regions are presented in table 2.29.

The values underlined are those adopted to construct the design storm inputs. From figure 2.7 and table 2.28 it is seen that for isohyets 2, 3 and 4 storm region 13(500-1000) dominates, while the area enclosed by isohyet number 1 falls entirely within storm region 13(1000+).

The proportions of each catchment embraced by the isohyets were obtained by planimetry and are shown in table 2.30.

These proportions, applied to the adopted 24-hour duration rainfall values for each isohyet contained in table 2.29, yielded the average sub-catchment precipitation values for various recurrence intervals of the 24-hour storm. The resulting values, expressed in millimetres and as proportions of total catchment average precipitation, are listed in table 2.31.

The rainfall values for the total catchment were used in conjunction with figure G.2 of HRU report No. 1/72 to interpolate the percentage runoff for each of the recurrence intervals listed. For the probable maximum event the maximum runoff efficiency was

* These were obtained from figures D.20 and D.21 of HRU report No. 1/72.

Table 2.29 : Isohyetal precipitation values for 24-hour duration storms of various recurrence intervals

storm recurrence interval	storm region	Isohyet number			
		1	2	3	4
5	13(1000+)	120	90	75	70
	13(500-1000)	-	75	55	45
10	13(1000+)	155	120	100	95
	13(500-1000)	-	100	75	65
20	13(1000+)	190	150	135	130
	13(500-1000)	-	125	95	85
50	13(1000+)	235	195	175	170
	13(500-1000)	-	150	115	100
100	13(1000+)	265	225	205	200
	13(500-1000)	-	165	130	120
probable maximum	13(1000+)	390	320	270	260
	13(500-1000)	-	270	220	210

Table 2.30 : Proportions of sub-catchment area represented by each isohyet

sub-catchment		Isohyet number			
No.	name	1	2	3	4
1	total Umhlatuzi excluding Nsezi catchment	0.228	0.474	0.286	0.012
1a	Umhlatuzi catchment above gauge W1M01	0.200	0.470	0.300	0.039
1b	Umhlatuzi catchment below gauge W1M09	0.242	0.477	0.281	0.000
2	Nsezi catchment	0.554	0.392	0.054	0.000
3	north-eastern coastal catchment	1.000	0.000	0.000	0.000
4	south-western coastal catchment	1.000	0.000	0.000	0.000
total catchment		0.367	0.415	0.209	0.009

Table 2.31 : Average catchment precipitation for the 24-hour duration storm

recurrence interval	units	sub-catchment							storm runoff	storm loss
		1	1a	1b	2	3	4	total	mm	mm
5	mm	79	77	80	98	120	120	87	16	71
	proportion	0.91	0.89	0.92	1.13	1.38	1.38	1		
10	mm	105	103	106	129	155	155	115	25	90
	proportion	0.92	0.90	0.93	1.12	1.35	1.35	1		
20	mm	131	128	132	158	190	190	142	34	108
	proportion	0.92	0.90	0.93	1.12	1.34	1.34	1		
50	mm	159	155	161	194	235	235	173	48	125
	proportion	0.92	0.89	0.93	1.12	1.35	1.35	1		
100	mm	177	173	179	218	265	265	194	56	138
	proportion	0.92	0.89	0.92	1.12	1.37	1.37	1		
probable maximum	mm	283	277	285	334	390	390	303	261	42
	proportion	0.93	0.92	0.94	1.10	1.29	1.29	1		
average	proportion	0.92	0.90	0.93	1.12	1.35	1.35	0.995		
adopted	proportion	0.92+	0.91	0.93	1.12	1.39	1.39	1.000*		

* The proportion for the whole catchment, given by $\frac{p_i \cdot A_i}{A}$ ....(2.8), must equal unity.

where p_i = proportion of sub-catchment i
A_i = area of sub-catchment i
A = area of total catchment

+ The upper and lower portions of of the Umhlatuzi catchment must also conform to the requirements of equation 2.8 with respect to catchment number 1.

Table 2.32 : Storm rainfall, loss and runoff for various storm durations for the total catchment (mm)

recurrence interval	storm duration hours	2	4	8	12	18	24
years	proportion of 24-hour storm	0.69	0.76	0.84	0.90	0.96	1.00
5	rainfall	59	66	73	78	83	87
	loss	51	56	61	65	69	72
	runoff	8	10	12	13	14	15
10	rainfall	78	87	98	103	110	115
	loss	64	72	78	83	87	90
	runoff	14	15	18	20	23	25
20	rainfall	97	109	120	128	136	142
	loss	79	87	93	98	104	108
	runoff	18	22	27	30	32	34
50	rainfall	118	132	146	156	166	173
	loss	94	103	111	117	123	126
	runoff	24	29	35	39	43	47
100	rainfall	133	148	163	175	186	194
	loss	102	112	121	127	134	138
	runoff	31	36	42	48	52	56
probable maximum event	rainfall	209	231	256	275	290	303
	loss	29	32	36	38	40	42
	runoff	180	199	220	237	250	261

Table 2.33 : Total catchment flood peaks for various storm durations (m^3/s)

recurrence interval years	storm duration - hours					
	2	4	8	12	18	24
5	760	861	860	817	701	614
10	1 159	1 237	1 227	1 221	1 132	1 008
20	1 467	1 621	1 727	1 774	1 608	1 364
50	1 879	2 048	2 195	2 284	2 087	1 873
100	2 295	2 422	2 619	2 774	2 513	2 225
probable maximum	11 367	12 006	12 371	12 759	11 632	10 173

obtained from figure G.1 of the same report. From these percentages the total catchment runoffs and losses in millimetres were calculated and are listed in the last two columns of table 2.31.

(b) Storms of duration other than 24 hours

The method outlined in HRU report No. 1/72 was used to obtain the rainfalls and runoffs for storms of duration other than 24 hours. These appear in table 2.32.

2.5.4 Design flood synthesization

Design flood hydrographs were synthesized using a computer program developed by Pitman[13]. This program follows the unitgraph method outlined in HRU report No. 1/72 and can also be modified to lag-and-route flood hydrographs from the various sub-catchments.

(a) Critical storm duration

Flood hydrographs from each sub-catchment were synthesized in this way for 2-, 4-, 8-, 12-, 18- and 24-hour storm durations. The resulting hydrographs were summed to yield total catchment discharges into Richa . Bay. The flood hydrographs thus obtained appe..r in table 2.33 in which the maximum flood peaks for each recurrence interval are underlined.

To simplify the following calculations a critical storm duration of 12 hours was adopted ill recurrence intervals.

(b) Flood hydrograph synthesization for undeveloped catchments

From figures 2.1 and 2.7 it is noted that catchments 2, 3 and 4 are controlled at their outlets by the Nsezi, Mzingazi and Cubu lakes respectively. Accordingly, to simulate flood discharges from these catchments, the floods derived in section (a) above, for storms of 12-hour duration must be routed through these lakes.

For the purposes of this investigation it was deemed sufficient to adopt level-pool routing. The following discharge formula for a broad crested weir[14] was assumed to apply at the outlet to the lakes:

$$Q = 1{,}65\ L\sqrt{g}h^{3/2} \qquad \text{.....(2.9)}$$

where L = spillway length (m)

$g = 9{,}81\ m^3/s$

h = head on crest (m).

A spillway length of 500 m was adopted as a rough estimate

based on the end widths of the lakes.

The flood hydrographs for virgin conditions for each sub-catchment appear in columns 2, 4, 5 and 6 of tables D.1 to D.6 in Appendix D. The peak discharges for floods of various recurrence intervals appear in table 2.34.

Table 2.34 : Peak flood discharges into Richards Bay for undeveloped catchment conditions (m^3/s)

sub-catchment		recurrence interval - years					
No.	name	5	10	20	50	100	pmf*
1	Umhlatuzi	281	488	821	1102	1413	8039
2	Nsezi	358	519	729	929	1111	4358
3	north-east coastal	179	277	336	422	493	1475
4	south-west coastal	103	158	191	239	278	828

* Probable maximum flood

(c) Flood hydrograph synthesization for developed catchment conditions

For developed catchment conditions the main catchment change to be accounted for is that resulting from the construction of a dam on the Umhlatuzi[11]. For purposes of simulation the Umhlatuzi catchment (No. 1 in figure 2.7) was treated as two separate sub-catchments - one upstream, and one downstream of the dam, numbered 1a and 1b respectively (see figure 2.7).

To ensure that the results could be compared with those obtained for undeveloped conditions, flood hydrographs from sub-catchments 1a and 1b were constructed in such a way that the sum of the hydrograph from the lower part and that from the upper part routed down the Umhlatuzi should equal the hydrograph obtained in (b) above for undeveloped conditions.

The method adopted is elaborated below:

(1) First, the 12-hour duration storm flood hydrograph was constructed for the catchment upstream of the dam.

(2) This flood hydrograph was then Muskingum-routed from the upper catchment outlet (at the dam) to the lower catchment outlet (which is also the total catchment outlet at Richards Bay.

The form of the equation used is as follows:

$$O_2 = C_0 I_2 + C_1 I_1 + C_2 O_1 \quad \text{.....(2.10)}$$

where O_2 = discharge at lower end of channel section at end of time step Δt

O_1 = discharge at lower end of channel section at beginning of time step Δt

I_2 = discharge at upstream end of channel section at end of time step Δt

I_1 = discharge at upstream end of channel section at beginning of time step Δt

and C_0, C_1 and C_2 are constants defined as follows:

$$C_0 = \frac{-(Kx - 0{,}5\Delta t)}{(K - Kx + 0{,}5\Delta t)} \quad \text{.....(2.11)}$$

$$C_1 = \frac{(Kx + 0{,}5\Delta t)}{(K - Kx + 0{,}5\Delta t)} \quad \text{.....(2.12)}$$

$$C_2 = \frac{(K - Kx - 0{,}5\Delta t)}{(K - Kx + 0{,}5\Delta t)} \quad \text{.....(2.13)}$$

where K = storage constant with dimension of time.

x = dimensionless constant which varies between 0,0 and 0,5. For rivers it is usually taken as 0,3.

Δt = time step of computation (in this case taken as 2 hours).

The lag K was estimated as follows:

Length of stream from dam to bay = 89 km. Assuming the flood hydrograph velocity to be 3 m/s, then the time lag = 8,24 hours (say 8 hours).

For purposes of routing the river was divided into four equal reaches of lag time 2 hours.

(3) This routed 12-hour hydrograph from the upper catchment was then subtracted from the total Umhlatuzi catchment hydrograph obtained in section (b) above. The resulting hydrograph was then smoothed graphically and adopted as the lower catchment flood hydrograph.

(4) The flood hydrograph for the upper catchment was then routed through the dam. Equation 2.9 for a broad-crested weir was

assumed to apply to the dam spillway. The dam characteristics[11] are as follows:

Spillway length = 150 m
Lake surface area when full = 8 km²

Level-pool routing was used, the dam assumed to be full at the onset of the flood.

(5) The flood hydrograph thus generated was then routed to the Umhlatuzi mouth using equation 2.10 and added to the lower catchment hydrograph obtained in step (⁴) above to yield the total Umhlatuzi (catchment 1) flood hydrograph.

The resulting hydrographs for catchment 1 for various recurrence intervals are given in Appendix D and the peak discharges are listed in table 2.35.

Table 2.35 : Peak flood discharges into Richards Bay from catchment No. 1 for developed conditions (m^3/s)

recurrence interval years	5	10	20	50	100	pmf
flood peak - m^3/s	228	409	708	964	1251	8407

Peak discharges for the total catchment draining into Richards Bay both for developed and for undeveloped catchment conditions are given in table 2.36.

Table 2.36 : Peak flood discharges into Richards Bay from the total catchment for developed and undeveloped conditions (m^3/s)

catchment condition	recurrence interval - years					
	5	10	20	50	100	pmf
undeveloped	799	1236	1746	2250	2747	13000
developed (with dam)	762	1174	1644	2119	2573	12164

It should be noted that, in calculating flood hydrographs for conditions prevailing after construction of the dam, the assumption was made that the critical storm duration would remain 12 hours. The time lag introduced by the dam could well modify the critical storm duration. Any errors thus introduced must be small, however, as the differences between flood peaks for the total catchment before and after construction of the dam are

small (see table 2.36). Should 12 hours not be the critical storm duration for developed conditions, then by definition the true peak discharges must be *higher* than those calculated, and must therefore render the difference between the developed and undeveloped peaks even *smaller*.

The result of this reasoning is that the flood response of the catchment for developed conditions may, for purposes of simulating flood responses in the Richards Bay estuary, be assumed to be essentially the same as that for the undeveloped catchment.

3. MODELLING OF ONE-DIMENSIONAL TIDAL PROPAGATION AND DISPERSION IN THE OLD RICHARDS BAY AND THE PROPOSED NEW NATURE RESERVE ESTUARY SYSTEMS

3.1 Description of programs used (HCSP03, HCSP04 and HCSP05)

Three separate FORTRAN IV programs developed by Hutchison[18], HCSP03, HCSP04 and HCSP05, were used to simulate tidal propagation and dispersion in the Richards bay estuary. These programs are discussed below:

3.1.1 HCSP03

This program simulates unsteady, spatially varied flow in a one-dimensional channel. Estuary geometry is defined by means of cross-sections at specified chainages from the mouth. Each cross-section is represented by a depth-area curve.

For any specified ocean tidal stage-time curve and upstream water level- or discharge-time relationship, the program calculates the corresponding stage-time and discharge-time relationship for all defined sections within the estuary.

The estuary is sub-divided into interconnected one-dimensional reaches as depicted in figure 3.1. A generalised reach is shown in figure 3.2. Cross-sectional characteristics of the estuary are specified at the ends of each reach. Each flow cross-section is divided into two regions:

(1) A shallow storage region where velocities are negligible
(2) A flow region through which most of the water transport takes place.

The flow simulation is accomplished by a simultaneous implicit finite difference solution of the continuity and momentum or energy equation within each estuary reach:

(a) Continuity equation

$$\frac{\partial Q}{\partial x} + B\,\frac{\partial z}{\partial t} = \frac{q}{\partial x} \quad \text{.....(3.1)}$$

where Q = discharge in x-direction (m^3/s)

x = longitudinal axis of flow; positive in the upstream or landward direction (m)

B = total water surface width (m)

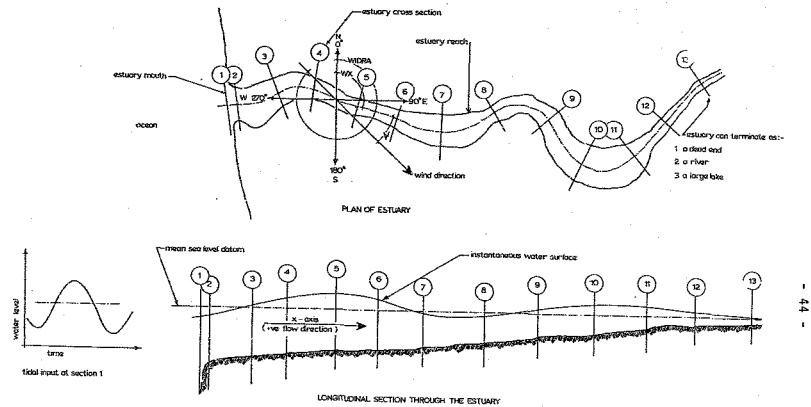


FIGURE 3.1 Typical one-dimensional estuary

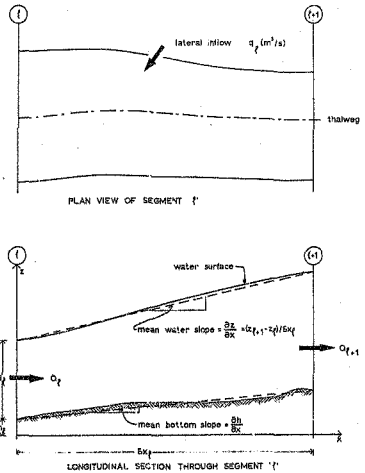


FIGURE 3.2 Views of a typical estuary reach bounded by sections ℓ and $\ell+1$

z = water level (m)
t = time (s)
q = lateral inflow of water over distance δx (m^3/s)

(b) Momentum equation

$$\frac{\partial z}{\partial x} + \frac{Q|Q|}{C^2a^2H} + \frac{\beta}{ga}\frac{\partial Q}{\partial t} - \frac{\partial z}{\partial t}\left(\frac{\alpha Q}{ga^2}(b+H\frac{\partial b}{\partial z})\right) + j\frac{(\beta-b)_{Q^2}}{ga^2} + \frac{\alpha Q}{ga^2}\frac{\partial Q}{\partial x}$$

$$-\frac{\alpha Q}{ga^3}\frac{\partial a}{\partial x} + \frac{H}{2\gamma}\frac{\partial \gamma}{\partial x} + \frac{\beta qQ}{ga^2\delta x} - \frac{W}{\gamma H} + \frac{k_3Q|Q|}{2ga^2\delta x} = 0 \quad \ldots\ldots\ldots\ldots(3.2)$$

where C = Chezy coefficient of roughness ($m^{\frac{1}{2}}/s$)
a = cross-sectional area of flow region (m^2)
H = hydraulic depth (m) = a/b
β = momentum correction factor (dimensionless)
α = energy correction factor (dimensionless)
b = water surface width of flow region (m)
$\frac{\partial b}{\partial z}$ = rate of change of water surface breadth of flow region with z (dimensionless)
g = gravitational acceleration (m/s^2)
W = wind shear stress factor (N/m^2)
γ = specific weight of water (N/m^3)
k_3 = headloss coefficient (dimensionless)
j = storage region inflow momentum factor

(c) Energy equation

$$z_\ell - z_{\ell+1} = \frac{1}{2g}\left\{\alpha_{\ell+1}\left(\frac{Q_{\ell+1}}{a_{\ell+1}}\right)^2 - \alpha_\ell\left(\frac{Q_\ell}{a_\ell}\right)^2\right\} + \frac{Q_\ell|Q_{\ell+1}|}{a_\ell a_{\ell+1}}\left\{\frac{2\delta x_\ell}{(H_\ell+H_{\ell+1})C^2} + \frac{k_3}{2g}\right\} \quad \ldots\ldots\ldots(3.3)$$

where H_ℓ = hydraulic depth at section ℓ (m)
$H_{\ell+1}$ = hydraulic depth at section $\ell+1$ (m)
k_3 = contraction or expansion headloss coefficient (dimensionless)
$\alpha_\ell, \alpha_{\ell+1}$ = energy correction factors at sections ℓ and $\ell+1$ respectively.

The energy equation is usually specified only for estuary reaches that exhibit sudden constrictions where Bernoulli effects dominate. A detailed derivation of the above equations is given in reference 18.

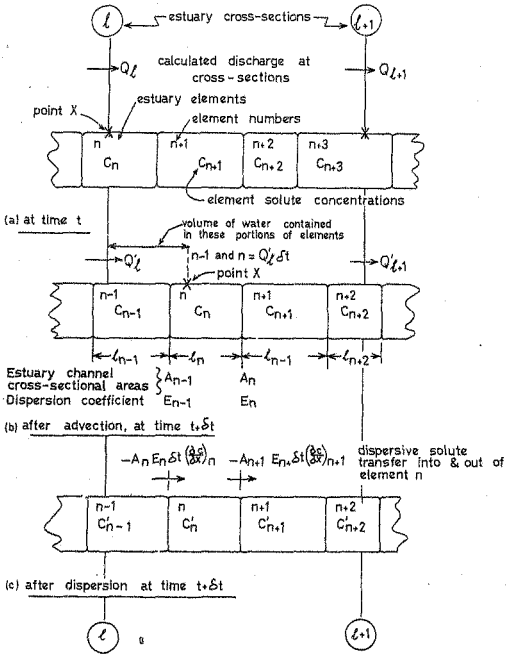


FIGURE 3.3 Schematic representation of one-dimensional advection & dispersion process in an estuary channel.

3.1.2 HCSP04

HCSP04, the plotting program, reads in the output of HCSP03 and the natural system water levels and discharges (if required). Output takes the form of stage-time and discharge-time curves in the model, or model and natural system.

3.1.3 HCSP05

HCSP05 reads in the output from HCSP03 and models solute dispersion using a Lagrangian-type advection process and a dispersion equation. It simulates the movement of sea water into the estuary or that of an artificial tracer introduced at any point in the estuary.

Computation proceeds in two separate stages:

(1) Advection

The estuary is divided into a series of interconnected elements, each assigned an initial solute concentration. Advection is simulated by moving the elements up or down the estuary channel according to the discharges at each cross-section. The discharge-time relationship is obtained from the output of the one dimensional estuary flow model, HCSP03.

Inflow of water across the upstream or downstream boundaries of the estuary is accomplished by creating new elements of specified solute concentration. Outflow of water across these boundaries is dealt with by removing elements, or portions thereof, from the system.

(2) Dispersion

Solute dispersion across element boundaries is computed after the advection step has been completed. Equation 3.4 is a simplified form of the dispersion equation. This equation uses a Fickian-type dispersive law and merely reflects the change in storage of element n due to dispersive fluxes across it's two ends.

$$C'_{n-1}(-T_{n-1}) + C'_n(V_n + T_{n-1} + T_n) + C'_{n+1}(-T_n)$$
$$= C_{n-1}(T_{n-1}) + C_n(V_n - T_{n-1} - T_n) + C_{n+1}(T_n) \quad \ldots\ldots\ldots\ldots (3.4)$$

where C = the solute concentration in the element

subscripts n-1,n,and n+1 = element numbers

the prime ' indicates that the solute concentration applies to conditions after the dispersion step (i.e. the unknown values)

and $T_{n-1} = \frac{A_{n-1} \cdot E_{n-1} \cdot \delta t}{(z_n + z_{n-1})}$ ..... (3.5)

$T_n = \frac{A_n \cdot E_n \cdot \delta t}{(z_n + z_{n+1})}$ ..... (3.6)

where A_{n-1} = total cross-sectional area between elements n-1 and n (m^2)

A_n = total cross-sectional area between elements n and n+1 (m^2)

E_{n-1} = dispersion coefficient between elements n-1 and n (m^2/s)

E_n = dispersion coefficient between elements n and n+1 (m^2/s)

z_{n-1}, z_n, z_{n+1} = lengths of elements n-1, n, and n+1 (m).

Figure 3.3 illustrates these terms.

3.2 Calibration of the one-dimensional tidal propagation and dispersion models using hydrographic data measured in the original Richards Bay system prior to harbour construction

3.2.1 Richards Bay natural system data

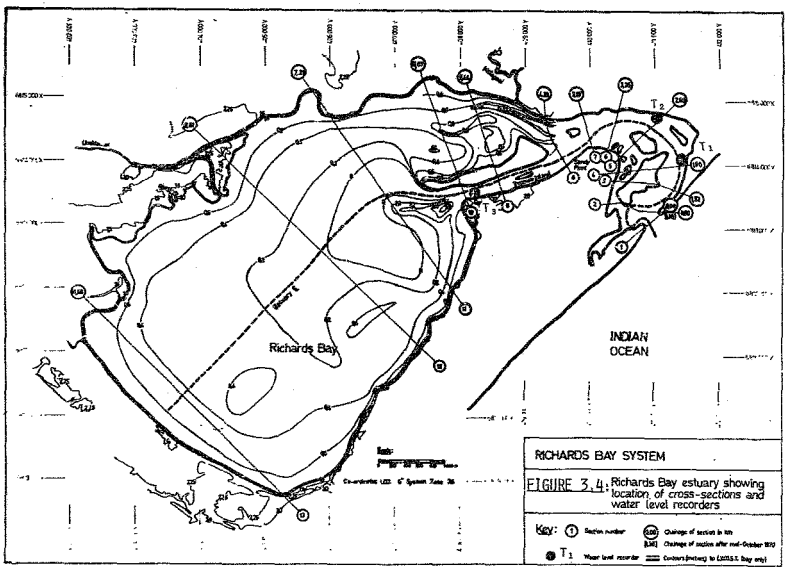
The location of the Richards Bay estuary system is shown in figure 2.1. A plan of the estuary is given in figure 3.4. The survey datum for all the hydrographic data presented in this chapter is LWOST(HRD) as defined in Appendix E.

(a) Estuary geometry

The locations of all the cross-sections used to calibrate the model are indicated in figure 3.4. These cross-sections were derived from depth surveys carried out between September 1969 and November 1970 by the CSIR[19]. The cross-sections are plotted in figures 3.5 to 3.9.

(b) Water level and discharge measurements

The locations of the three CSIR water level recording stations in the bay are illustrated in figure 3.4. A breakdown of the water level and velocity measurement data used to calibrate the model is given in table 3.1. Unfortunately measurement of sea level at Richards Bay did not take place concurrently with level measurements within the estuary. It was therefore necessary to use Durban sea tide records for model calibration. Durban sea tide


Richards Bay
INDIAN
OCEAN
RICHARDS BAY SYSTEM
FIGURE 3.4: Richards Bay estuary showing location of cross-sections and water level recorders
Key:

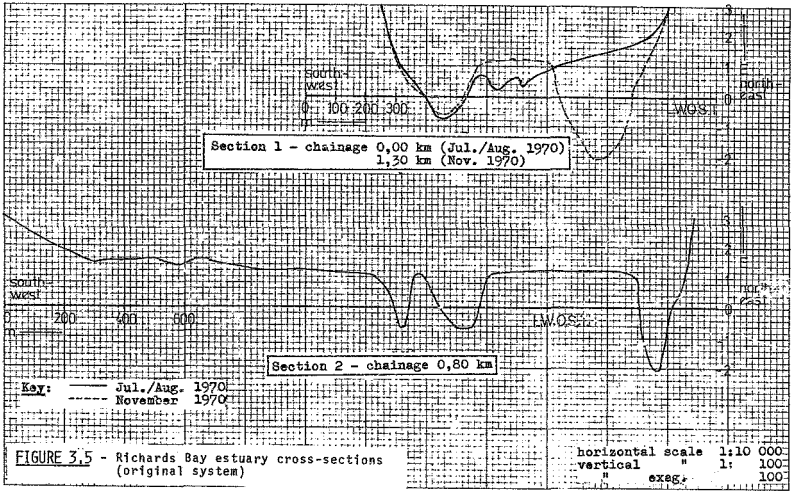


FIGURE 3.5 - Richards Bay estuary cross-sections (original system)

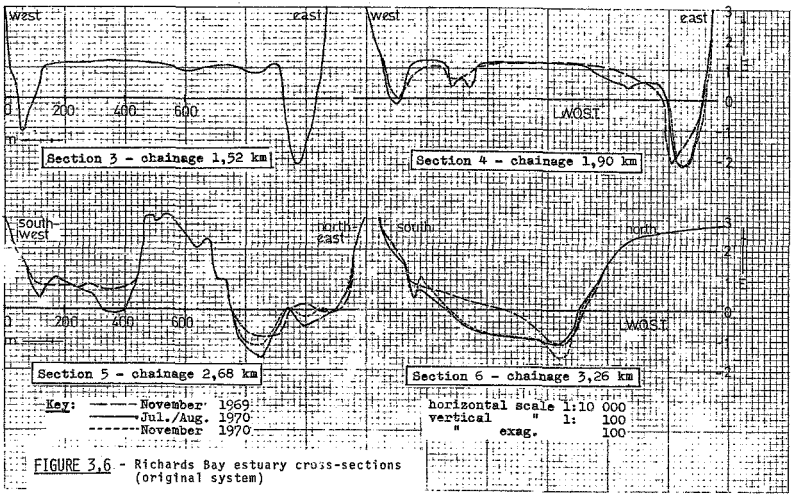


FIGURE 3,6 - Richards Bay estuary cross-sections (original system)

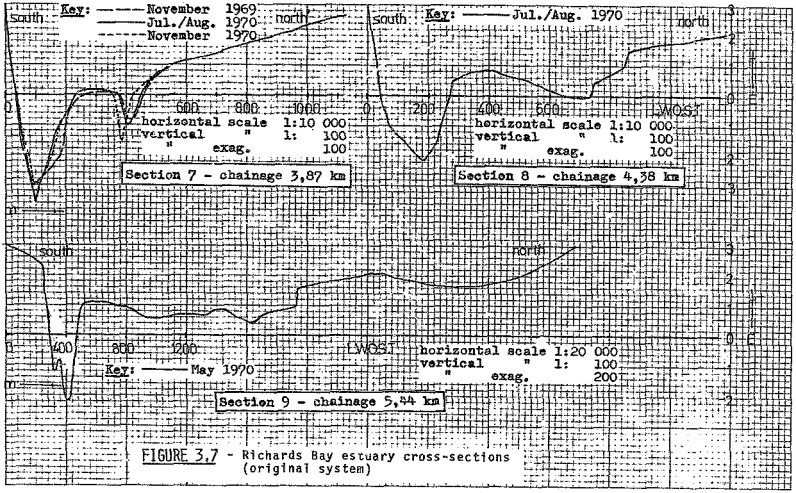


FIGURE 3.7 - Richards Bay estuary cross-sections (original system)

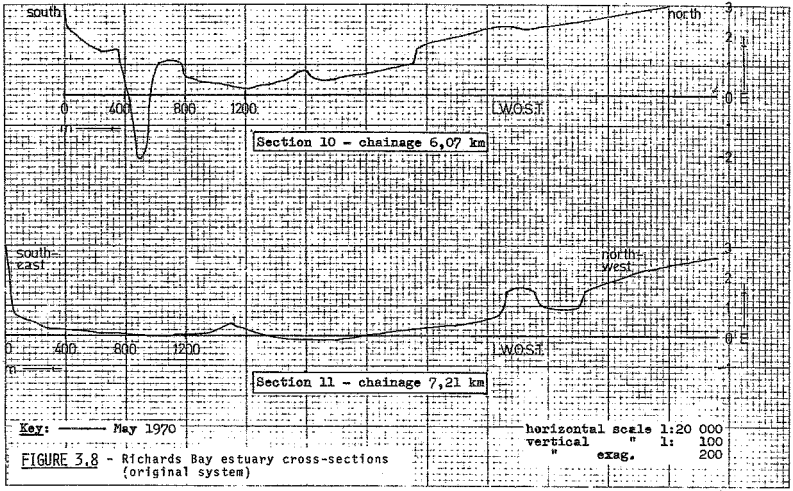


FIGURE 3,8 - Richards Bay estuary cross-sections (original system)

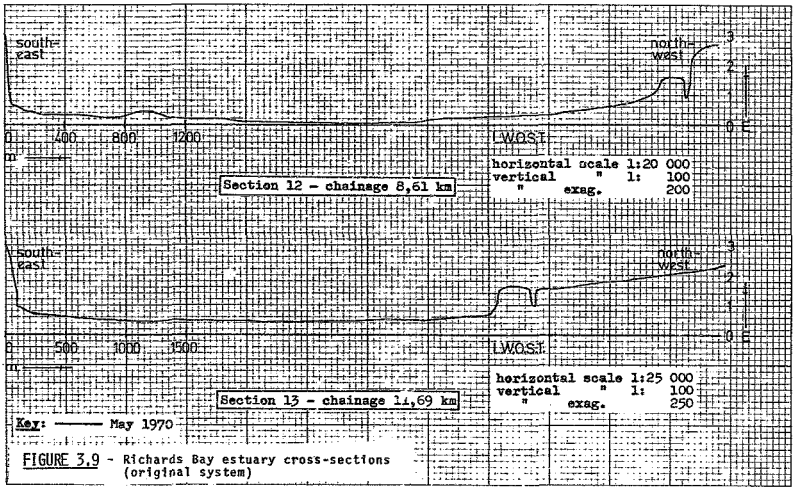


FIGURE 3.9 – Richards Bay estuary cross-sections (original system)

records prior to October 1970 are considered by the Navy hydrographer to be unreliable. This places a further restraint on the selection of suitable data for calibration. Runoff from the Umhlatuzi has been recorded by the CSIR on a daily basis. This coarse time resolution renders simulating floods extremely inaccurate. For this reason the data chosen for calibration of the model have been selected during periods when flows from the Umhlatuzi were low and daily changes small.

Discharge measurements were carried out at the estuary mouth on the 20 th November 1970 by the CSIR. These could not be used for model calibration purposes because at the cross-section used there were two tidal channels, one on either side of Pelican Island. The one-dimensional model proved incapable of simulating accurately the discharges at this point because of the two-dimensional effect. (This is due to the fact that ebb and flow tides favour diffent channels).

Model runs demand elevations at time resolution shorter than one hour which is the interval associated with the data in table 3.1. Water levels therefore had to be interpolated linearly between the hourly values except at the tidal peaks and troughs where a parabolic interpolation was employed.

3.2.2 Convergence test runs

Tests were carried out to study the convergence of the finite difference solution in HCSP03 and consequently to select an appropriate simulation time increment. A zero inflow at the upstream boundary (cross-section 13) and a sinusoidal tide of 1,2 m range (cross-section 1) were specified. These runs were performed for five time increments varying from 225 to 3600 seconds. In each case sufficient "running-in"* time was allowed. The results are listed in table 3.2. For all model runs initial conditions constituted a level water surface throughout the estuary and zero discharge at all cross-sections. From table 3.2 it is evident that a time increment of 900 seconds and a running-in period of 24 hours yields satisfactory results, i.e. the

* Running-in period, required to eliminate the effect of wrongly assumed starting levels and discharges, is defined as the period after which the differences in the water levels and discharges at corresponding stages in the tidal cycle were less than 1%.

Table 3.1 : Hydrographic data used to calibrate the one-dimensional tidal propagation model

Period	Type of data	Measuring station	Cross-section NO.	Measurement period			
				day	h	day	h
October 1969	water level	Estuary : T1	4	1	0 to	29	13
		Estuary : T2	5	1	0 to	29	9
		Estuary : T3	10	7	12 to	29	13
	discharge	Umhlatuzi:mouth	13	1	0 to	29	13
October 1970	water level	Durban :sea	-	1	12 to	11	0
		Estuary : T1	4	5	16 to	9	6
		Estuary : T3	10	1	12 to	11	0
	discharge	Umhlatuzi:mouth	13	1	12 to	11	0
October 1970	water level	Durban :sea	-	20	0 to	30	0
		Estuary : T1	4	20	0 to	30	0
		Estuary : T3	10	20	0 to	29	12
	discharge	Umhlatuzi:mo. th	13	20	0 to	30	0

Note: The levels referred to above are stored at hourly intervals and discharges from the Umhlatuzi at daily intervals.

Table 3.2 : Results of convergence tests

Cross-section number	Model output	Levels and discharges as % of the "correct" values*					Running-in time (No. of 12-hour tidal cycles)
		time increment (Δt) in seconds					
		3600	1800	900	450	225	
2	high tide	100,0	100,0	100,0	100,0	100,0	1
	low tide	97,6	98,9	99,6	99,8	100,0	2
	peak inflow	109,8	98,3	99,8	100,0	100,0	2
	peak outflow	115,2	119,9	100,3	100,0	100,0	2
10	high tide	99,2	99,8	99,8	99,9	100,0	2
	low tide	98,1	98,6	99,7	99,9	100,0	2
	peak inflow	102,8	94,7	97,3	99,1	100,0	2
	peak outflow	107,5	110,1	98,7	99,4	99,8	2
12	high tide	98,0	98,4	99,3	99,7	99,9	2
	low tide	98,6	99,3	100,0	100,0	100,0	2
	peak inflow	95,8	90,7	95,5	98,1	99,4	2
	peak outflow	106,2	104,1	98,5	99,5	100,0	2

* The "correct" values were obtained by extrapolation to zero δt on plots of the values of peak high or low tide inflow or outflow against time.

majority of errors are less than 1% and all are below 5%.

3.2.3 Model calibration for the period 7 to 17 October 1969

As no reliable sea levels are available for this period, the recorded levels at gauge T_1 were used as the downstream boundary conditions. The data recorded at stations T_2 and T_3 (sections 5 and 10) were used to calibrate the model between sections 4 (measuring gauge T_1) and section 13 (upstream end of bay).

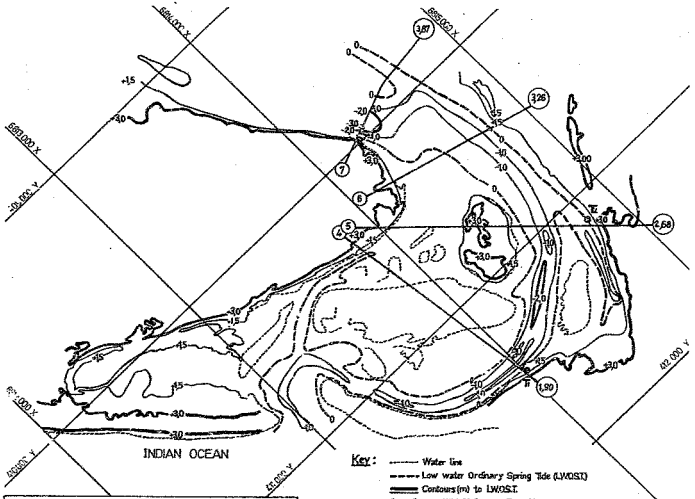
Estuary mouth geometry used for this simulation was obtained from the depth survey carried out by the CSIR[19] during November 1969 and is shown in figure 3.10.

Table 3.3 demonstrates the correlation achieved between model and natural system behaviour, Figure 3.13 illustrates the comparison between model and natural system water levels for the model runs which produced the "best fit" at sections 5 and 10. In determining the "best fit" in this case, as well as in those of chapter 3.2.5, greater emphasis was placed on correspondence between model and natural system average levels and tidal ranges than on the correlation coefficient, which could easily be distorted by an error in average sea level.

3.2.4 Model calibration for the period 5 to 8 October 1970

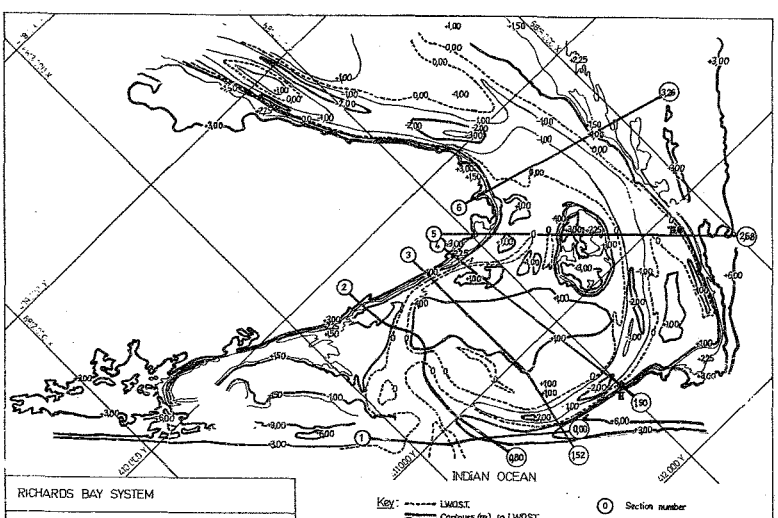
The data recorded during this period were used to calibrate the model between the estuary mouth (section 1) and the upstream end of the bay (section 13). Sea level data at Richards Bay were not available for this period. Durban sea level data were used for the downstream boundary condition. Water levels recorded at gauges T_1 and T_3 (sections 4 and 10) were used to calibrate the model. Estuary mouth geometry was taken from the depth survey carried out by the CSIR[19] during July and August of 1970, given in figure 3.11.

The correlation achieved between model and natural system is indicated in table 3.3. Model and natural system water levels at gauges T_1 and T_3 are plotted in figure 3.14.



RICHARDS BAY SYSTEM

FIGURE 3.10: Bathymetry of estuary mouth - November 1969


INDIAN OCEAN
RICHARDS BAY SYSTEM
FIGURE 3.11: BATHYMETRY OF ESTUARY MOUTH- JULY/AUGUST 1970
Key:
LWOST.
Contours (m) to LWOST.
Water level recorder
Section number
Chainage of section in km
Scale:
Co-ordinates UTM 6° System Zone 36

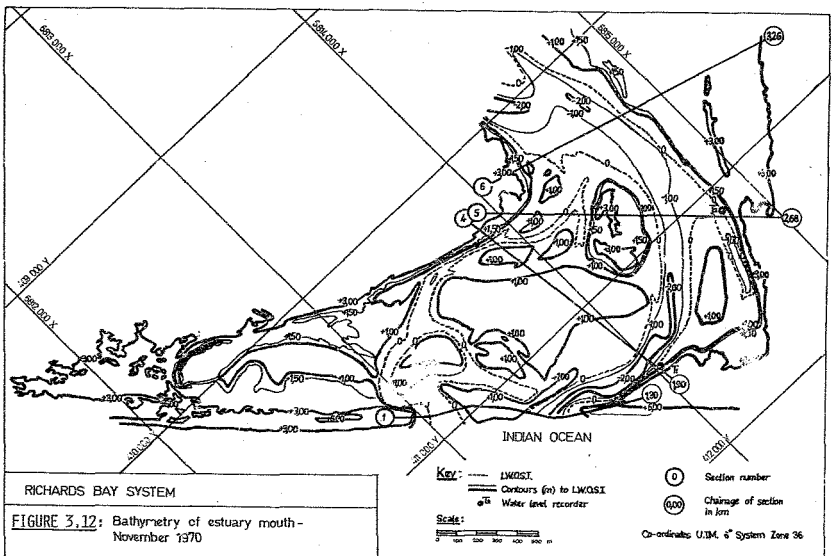


FIGURE 3.12: Bathymetry of estuary mouth - November 1970

3.2.6 Model calibration for the period 20 to 29 October 1970

Data recorded during this period were used to calibrate the model between the estuary mouth (section 1) and the upstream boundary (section 13). Downstream boundary conditions were provided by Durban sea level records. Model calibration was facilitated by comparison between simulated and recorded levels at gauges T_1 and T_3 (sections 4 and 10).

The estuary mouth geometry used for simulation purposes was obtained from the depth survey carried out by the CSIR during November 1970. This is shown in figure 3.12.

The correlation achieved between model and natural system is indicated in table 3.3. Model and natural system water levels at gauges T_1 and T_3 are plotted in figure 3.15. Two model simulations were carried out for this period as described below:

(a) Initial calibration simulation

The initial calibration simulation was carried out for conditions as described above. From figure 3.15 it is seen that the tidal range at gauge T_1 is too large. Moreover the discrepancy between model and natural system tidal ranges becomes more pronounced towards the end of the simulation period. Closer examination of the available natural system data reveals the following facts:

(1) Depth surveys of the mouth geometry carried out in September and November 1969, and March and July 1970 bear striking similarity, suggesting that these represent equilibrium conditions for periods of low flow from the Umhlatuzi.

(2) On the 14 th October 1970 a flood (12-14 October) opened up a new esuary mouth.

(3) The simulation period commences six days after the above mentioned flood when runoff from the Umhlatuzi is steadily decreasing.

(4) The depth surveys carried out to establish the mouth geometry used in the simulation were carried out on 10, 13 and 16 November, while a flood similar in magnitude to that which opened the new mouth occured during the period 10-11 November[13].

(5) The equilibrium mouth geometry (i.e. corresponding to that prevailing in September and November 1969, and March and July

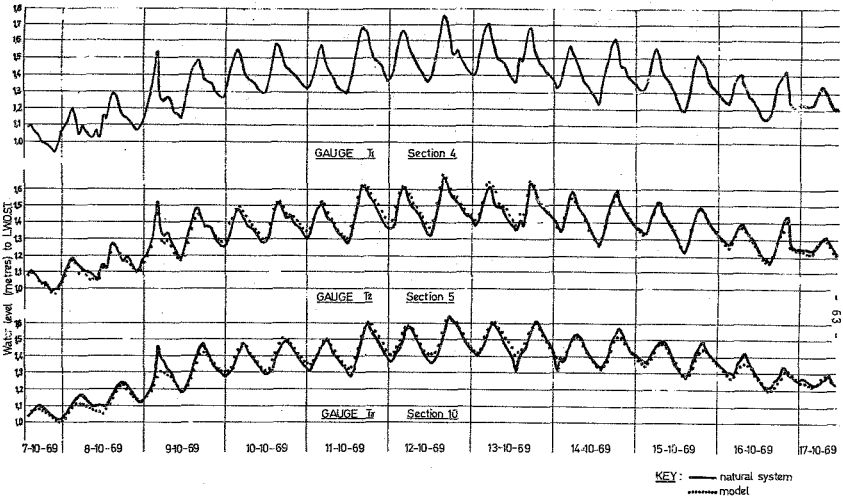


FIGURE 3.13 - Richards Bay estuary- comparison of measured and modelled water levels for the October 1969 calibration run

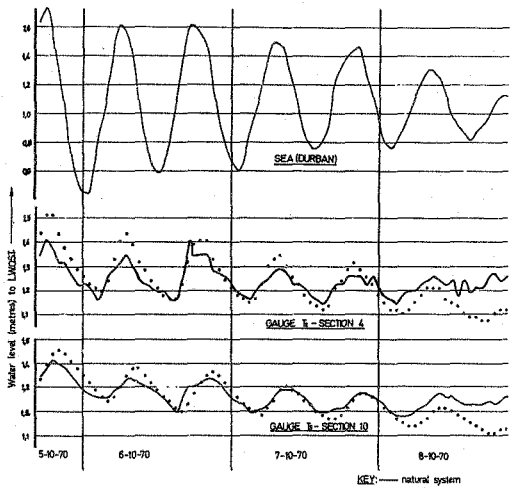


FIGURE 3.14: RICHARDS BAY ESTUARY - Comparison of measured and modelled water levels for early October 1970 calibration run

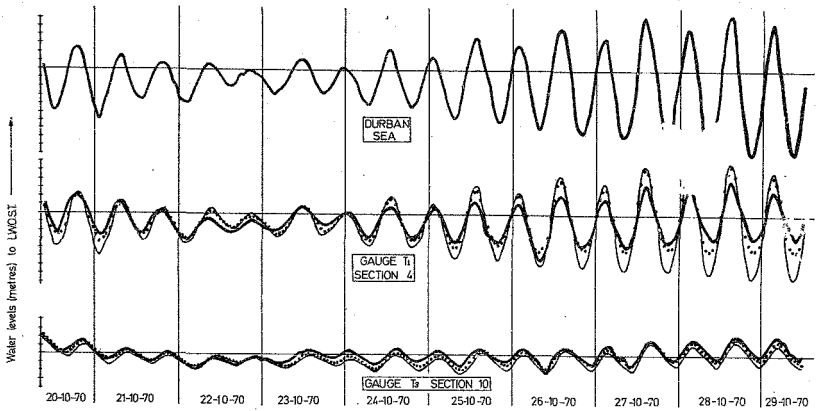


FIGURE 3.15: Richards Bay estuary - comparison of measured and modelled water levels for late October 1970 calibration runs

KEY:
—— natural system
—— calibration run with November 1970 estuary geometry
•••••• sensitivity run - November 1970 estuary geometry and July 1970 mouth section

Table 3.3 : Comparison of the tidal propagation model and natural system behaviour

calibration period	description of simulation	station	section number	water levels (m)			
				natural system mean	model mean	diff.	correlation coeff. %
November 1969	T1 as downstream boundary	T1	4	1,363	-	-	-
		T2	5	1,358	1,362	-0,004	97,7
		T3	10	1,361	1,357	0,004	96,7
5-8 October 1970	Before formation of new mouth-Jul./Aug. 1970 geometry	sea	1	1,001	-	-	-
		T1	4	1,241	1,234	0,007	-
		T3	10	1,260	1,247	0,013	26,2
20-29 October 1970	After formation of new mouth-Nov. 1970 geometry	sea	1	0,838	-	-	-
		T1	4	0,913	0,859	0,054	27,2
		T3	10	1,003	0,942	0,061	50,2
	Sensitivity run	sea	1	0,838	-	-	-
		T1	4	0,913	0,911	0,002	85,5
		T3	10	1,003	0,960	0,043	77,0

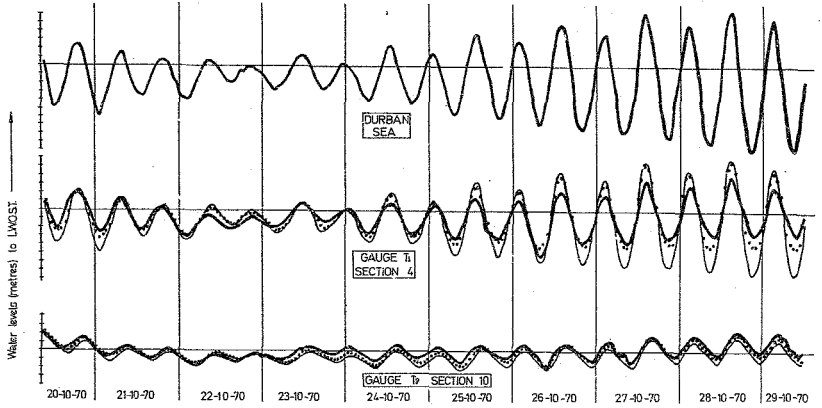


FIGURE 3.15: Richards Bay estuary - comparison of measured and modelled water levels for late October 1970 calibration runs

KEY:
- natural system
- calibration run with November 1970 estuary geometry
- sensitivity run - November 1970 estuary geometry and July 1970 mouth section

1970) is much more constricted than that measured in November 1970.

It is thus reasonable to assume that the mouth geometry used in the model simulation is not sufficiently constricted to represent the conditions prevailing during the period simulated.

In order to confirm this belief the following simulation was performed:

(b) Sensitivity run

The only change introduced was that mouth geometry similar to that prevailing in July, ugust 1970 was used. Only section 1, the sea boundary, was altered.

The improvement to the fit between model and natural system levels at sections 4 and 10 is apparent from figure 3.15 and table 3.3.

3.2.7 Results of the model calibration simulations

The momentum equation was used throughout and the mouth Bernoulli equations were not applied. The best fit between model and natural system water levels illustrated above was achieved after trying several values of effective roughness of the channel. The roughness height finally adopted for all sections was 100 mm for all three runs.

Table 3.4 lists the range of Chézy roughness coefficients associated with the model calibration runs for several estuary cross-sections.

Table 3.4 : Range of Chézy roughness coefficients extracted from the results of the model calibration runs

section number		1	2	3	4	5	6	7	8	10	12
Chézy cofficient $m^{1/2}/s$	maximum	48,3	46,9	47,2	51,1	50,6	51,3	51,8	48,4	48,2	48,8
	minimum	38,5	44,5	46,9	46,4	46,4	48,3	49,6	45,9	43,4	41,7

3.3 Simulation of one-dimensional tidal propagation and advection in the original system and in the proposed new nature reserve

The model simulations described below were performed in order to compare the natural system with the nature reserve in regard to points (a) (i),(ii) and (iv),and (b)(i) discussed in chapter 1. It should be noted that in making this comparison it was assumed that the calibration parameters obtained in chapter 3.2 for the natural system could be used to simulate conditions in the new nature reserve.

In order to study changes in average water level, tidal range, tidal prism and advection amplitude the upstream boundary river inflow was set at zero while the downstream boundary sea levels were represented by a sine curve of period 12,5 hours (i.e. the average sea tidal frequency). A running-in period of 200 hours was allowed.

Three average mean sea levels were used in the simulation runs:

(a) 0,940 m LWOST, the present actual mean sea level (AMSL)

(b) 1,060 m LWOST, the highest monthly MSL recorded

(c) 0,820 m LWOST, the lowest monthly MSL recorded.

Sea tidal ranges of 1,900, 1,200 and 0,450 m were used in the simulations. 1,200 m is the average tidal range, while 90 percent of all tidal ranges fall between 1,900 and 0,450 m[20].

In each case advection amplitudes* during a complete tidal cycle were obtained by simulating the movement of solute samples injected into the estuary channel at various distances from the estuary mouth.

3.3.1 Simulation of one-dimensional tidal propagation and advection in the original system

Simulations were carried out for two distinct conditions of estuary mouth:

(a) Mouth geometry prevailing during normal conditions (i.e. prior to October 1970). The bathymetric survey of July/August 1970 was taken as representing these conditions.

* The advection amplitude at a particular chainage is defined as the total length of estuary channel traversed during a tidal cycle by a particle placed in the estuary at that chainage at peak inflow velocity.

(b) Mouth geometry occurring immediately after the passage of a flood through the estuary. The depth survey carried out during November 1970 is taken as being representative of these conditions.

The geometry used in (a) and (b) above is similar to that given in figures 3.10 and 3.12. The results of these simulations are summarised in table 3.5 and in figures 3.21 and 3.22.

3.2.2 Simulation of one-dimensional tidal propagation and advection in the proposed new nature reserve system

The layout of the new nature reserve after completion of the harbour works is presented in figure 3.15. The locations of the cross-sections used in the one-dimensional hydraulic model are shown in figure 3.16. The cross-sections are plotted in figures 3.17 to 3.19.

The following estuary mouth conditions were used:

(a) Mouth design accepted by the SAR & H
(layout II of CSIR report No. C/SEA/74/11/3)
The mouth geometry, which is presently being dredged for the nature reserve, is given in figure 3.16. This mouth consists of one tidal channel with invert level at chart datum (0 m LWOST) which is open to the sea, and four flood channels with invert level at -4,5 m LWOST which are blocked at their seaward ends by a 200 m wide sand-bar with a crest height of +2,00 m LWOST.

(b) Mouth similar to that of the natural system during July/ August 1970
In this simulation sections number 1 and 2 were altered to conform with the cross-sectional characteristics of the natural system during normal conditions. Although the tidal prism in the new nature reserve is different from that in the natural system the river runoff into the bay remains similar. It is possible therefore, that the dredged mouth may tend towards this configuration.

(c) Layout II mouth with the sand-bar eroded to -4,5 m LWOST
Extreme bay tidal conditions after the passage of a flood were simulated assuming the sand-bar blocking the four flood channels to have been washed out by a flood.

(d) Layout II mouth with the sand-bar eroded to -2,0 m LWOST
As there is no way of knowing how severely the sand-bar will be eroded by a flood, this other assumption was made for comparative purposes.

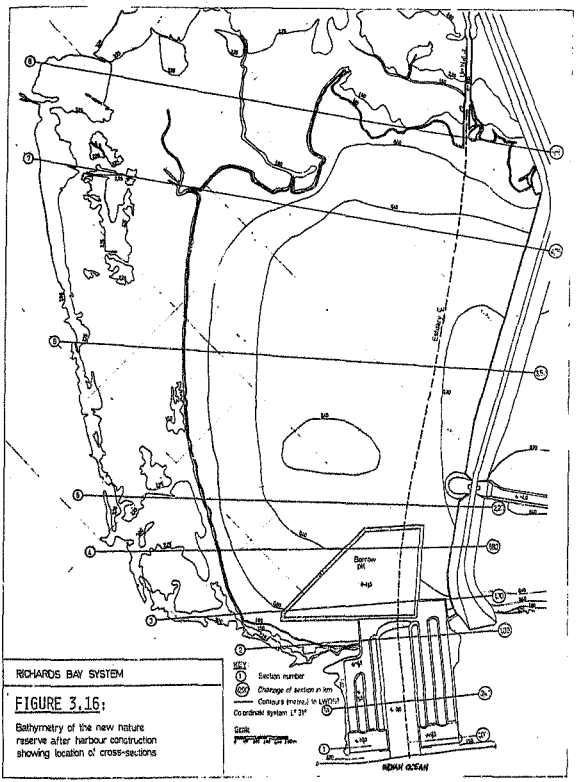


FIGURE 3.16:

Bathymetry of the new nature reserve after harbour construction showing location of cross-sections

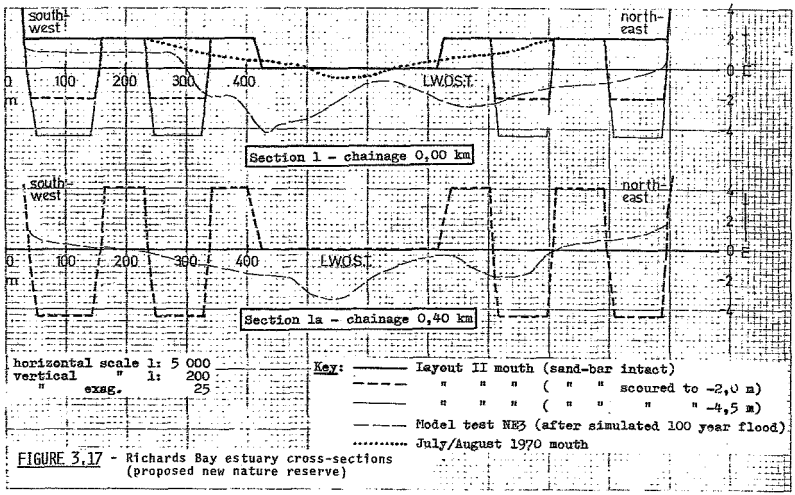


FIGURE 3.17 - Richards Bay estuary cross-sections (proposed new nature reserve)

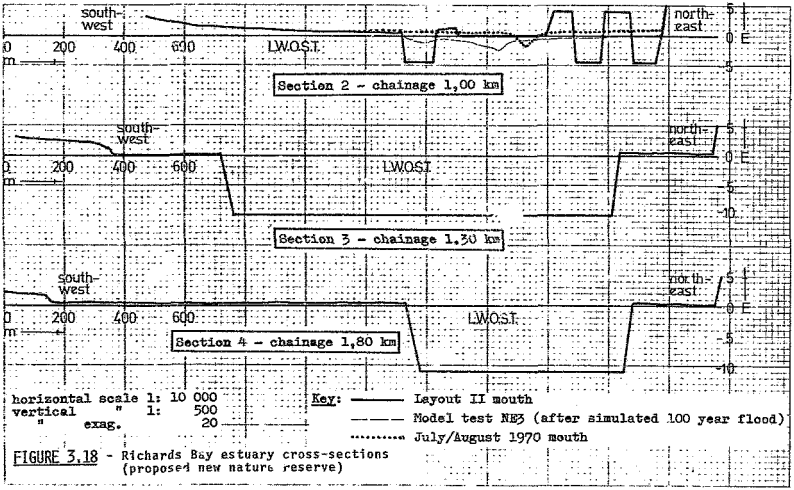


FIGURE 3.18 - Richards Bay estuary cross-sections (proposed new nature reserve)

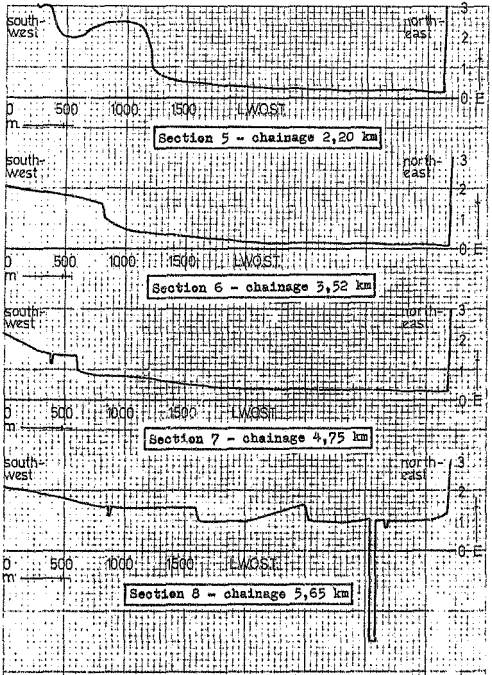


FIGURE 3.19 - Richards Bay estuary cross-sections (proposed new nature reserve)

(e) Mouth geometry recorded in moving-bed model tests after the passage of a large flood

Simulations of conditions prevailing after a flood were carried out using the geometry obtained by the CSIR in the moving-bed model test NE3[21] after the passage of what was considered by the CSIR to be the 100-year flood (i.e. 4 300 m^3/s). This geometry is probably very extreme as the flood modelled corresponded to what was something like a 1-in-1 000-year event (see chapter 1). It should also be noted that in the model test the peak discharge was sustained for a period equivalent to 24 hours in the real system. Table D.5 of Appendix D indicates that the peak discharge should last only from 6 to 8 hours.

(f) Design mouth

A tidal channel was designed such as to bring tidal fluctuations in the bay within acceptable limits. This consists of a 1 km long channel with invert level at -0,5 m LWOST and bottom width 30 m. A cross-section is given in figure 3.20.

The results of these simulations are summarised in table 3.5 and figure 3.23.

3.3.3 Comparison of the one-dimensional tidal propagation and advection in the natural system with that of the proposed new nature reserve

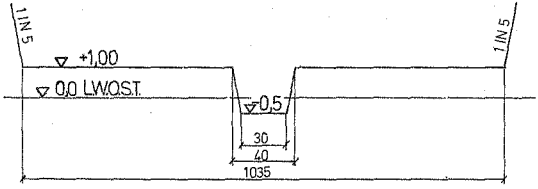
Table 3.5 gives the mean and extreme bay levels and the tidal prisms for each of the simulations. Figures 3.21 to 3.23 show the maximum and minimum water levels and the maximum tidal advection occurring at each estuary cross-section. From table 3.5 and figure 3.23 it is seen that in all of the runs simulating conditions existing in the proposed nature reserve after the passage of a large flood the water levels in the bay fall below invert level.

In order to make these simulations effective it became necessary to assume the existence of a small channel in the bottom of each of the affected estuary cross-sections. The dimensions of the channel were chosen such as to ensure that the water level remains above invert level and that the water velocities remain within reasonable limits without adversely effecting the accuracy of the tidal simulation.

Comparison of these water levels with figure 3.16 shows that, over

90 percent of the bay, the bed would become exposed at low tide (i.e. the entire bay except the borrow pit). Tidal simulations within the harbour proper indicate that full sea tide,with negligible phase shift, occurs on the harbour side of the tidal control gates in the berm wall. Thus operation of these gates will not prevent this bed exposure at low tide. From table 3.5 it is noted that the maximum tidal range occurring in the original system is 0,42 m, whereas in the new nature reserve, with layout II mouth, the maximum tidal range is as high as 0,75 m.

Very little improvement is effected by using a tidal channel of cross-section similar to that of the original system. This is due to the fact that the tidal channel of the new nature reserve is only 1 km long, whereas that of the original system was nearly 7 km long. Thus in order to reduce the tidal range a mouth of smaller cross-section than that of the original system is required. From table 3.5 it is seen that the mouth configuration used in simulation (f) of chapter 3.3.2 results in a maximum tidal range similar to that of the original system (0,52 m). It should be noted, however, that such a mouth would probably not develop naturally. It is possible that the tidal channel will tend towards the cross-sectional characteristics of the original system (simulated in chapter 3.3.2 b). To maintain a mouth similar to that designed would probably require some form of bank and bed protection or the provision of an artificial constriction (such as a weir). Any such constriction would also have to block the four flood channels to prevent the bay from draining completely at low tide after the passage of a large flood.



Not to scale

FIGURE 3.20: DESIGNED NEW ESTUARY MOUTH CROSS-SECTION

Dimensions in metres
Datum LWOST

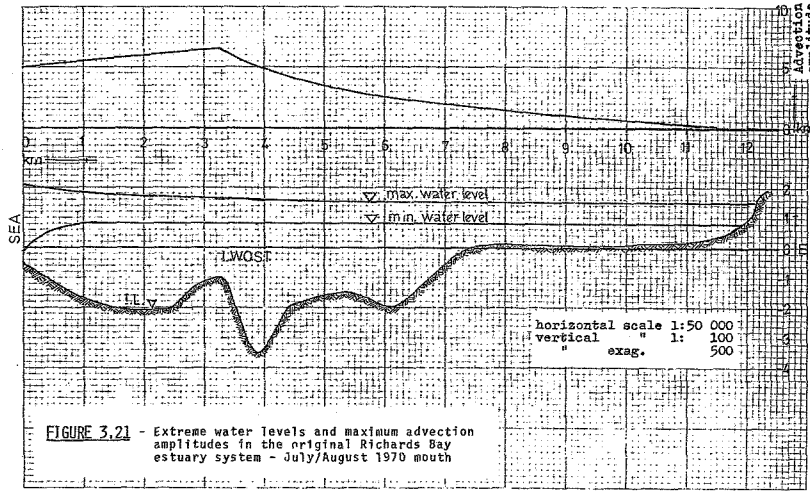


FIGURE 3.21 - Extreme water levels and maximum advection amplitudes in the original Richards Bay estuary system - July/August 1970 mouth

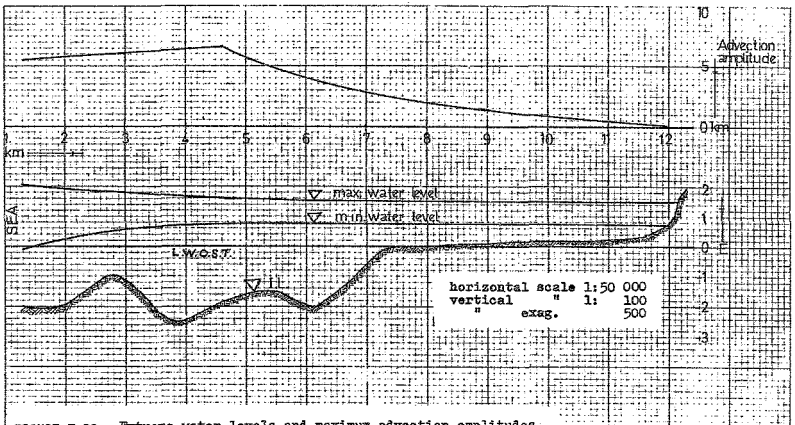


FIGURE 3.22 - Extreme water levels and maximum advection amplitudes in the original Richards Bay estuary system - November 1970 mouth (after flood)

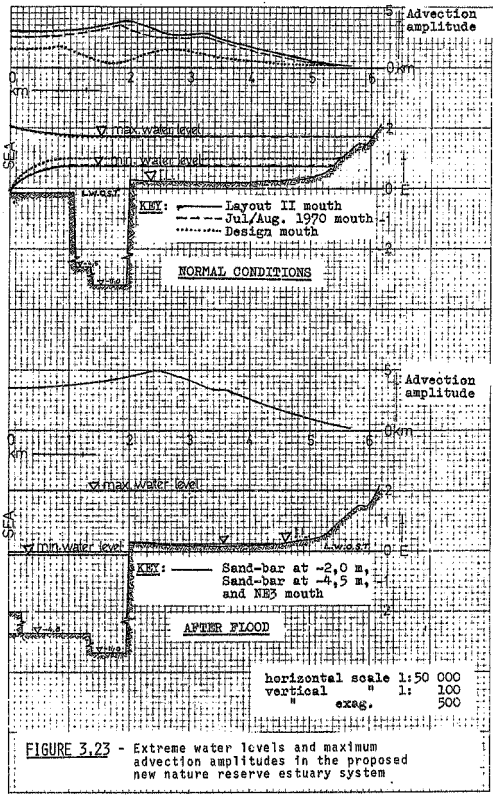


FIGURE 3.23 - Extreme water levels and maximum advection amplitudes in the proposed new nature reserve estuary system

Table 3.5 : Comparison between the one-dimensional tidal propagation in the original system and that in the proposed new nature reserve

system	mouth condition	water levels (m)					model tidal prism
		sea		modelled bay levels			
		mean	range	mean	max.	min.	range	10^6 m^3
old	July/August 1970	1,06	1,90	1,43	1,57	1,30	0,26	7,8
		1,06	0,45	1,09	1,43	1,04	0,10	2,9
		0,94	1,20	1,11	1,20	1,04	0,16	4,5
		0,82	0,45	0,84	0,89	0,80	0,09	2,0
		0,82	1,90	1,20	1,31	1,11	0,20	5,6
	November 1970	1,06	1,90	1,30	1,54	1,12	0,42	12,3
		1,06	0,45	1,08	1,17	1,00	0,17	4,7
		0,94	1,20	1,05	1,19	0,92	0,27	7,1
		0,82	0,45	0,84	0,91	0,76	0,15	3,4
		0,82	1,90	1,08	1,25	0,92	0,34	9,0
new	layout II	1,06	1,90	1,35	1,76	1,01	0,75	10,6
		1,06	0,45	1,07	1,24	0,92	0,32	4,0
		0,94	1,20	1,07	1,35	0,84	0,50	6,3
		0,82	0,45	0,84	0,97	0,72	0,25	2,9
		0,82	1,90	1,18	1,51	0,92	0,59	7,5
	July/August 1970	1,06	1,90	1,40	1,76	1,10	0,65	9,6
		0,82	0,45	0,84	0,94	0,75	0,18	2,0
		0,82	1,90	1,20	1,47	0,99	0,48	6,3
	design	1,06	1,90	1,43	1,73	1,21	0,52	2,8
		0,82	0,45	0,84	0,87	0,81	0,06	0,6
		0,82	1,90	1,20	1,40	1,10	0,30	4,0
	sand-bar eroded to -4,5m	1,06	1,90	1,11	2,06	0,37*	1,69	22,6
		0,82	1,90	0,92	1,82	0,25*	1,57	19,3
	sand-bar eroded to -2,0m	1,06	1,90	1,14	2,06	0,38*	1,68	22,6
		0,82	1,90	0,93	1,83	0,26*	1,57	19,3
	model test ME3	1,06	1,90	1,13	2,05	0,40*	1,65	22,6
		0,82	1,90	0,93	1,80	0,28*	1,52	19,1

* These levels are below the average bottom level of the bay, viz. 0,5 m

3.4 Simulation of the flood response of the Richards Bay original system and the new nature reserve system

Maximum flood water levels were obtained by carrying out simulations with HCSP03 for the original and new estuary systems using the flood hydrographs derived in chapter 2 as upstream boundary conditions. Average sea tidal conditions were used at the downstream (sea) boundary (i.e. a sinusoidal sea level hydrograph with mean 0,940 m LWOST and tidal range 1,200 m). The geometry data files used in the flood simulations are similar to those used in chapter 3.3. The simulated maximum water levels obtained for 5-, 20- and 100-year recurrence interval floods in the Umhlatuzi catchment are given in table 3.6.

Table 3.6 : Maximum simulated water levels in the Richards Bay estuary during 5-, 20- and 100-year floods in the Umhlatuzi catchment (metres to LWOST)

estuary system	mouth condition	recurrence interval flood		
		5	20	100
original natural system	July/August 1970	1,7	2,4	2,9
	November 1970	1,5	2,1	2,6
new system (after harbour construction)	layout 2	1,7	2,0	2,5
	layout 2 with sand-bar at -4,5m	-	-	2,1
	layout 2 with sand-bar at -2,0m	-	-	2,1
	Ne3 model test	-	-	2,1
	July/August 1970	-	-	3,1
	designed channel	-	2,5	3,0

In no case modelled did the 100-year flood level exceed 3,1 m LWOST (i.e. the design criterion proposed by the CSIR[4]).

4. MODELLING LONG TERM WATER AND SALT CIRCULATION IN THE ORIGINAL BAY AND THE PROPOSED NATURE RESERVE

Salinity measurements (see table 4.1 and figure 4.3) suggest that the main body of the original bay was spatially well mixed except for localised regions at the river mouths. This implies that the large scale two-dimensional (in plan) currents generated by wind action and Coriolis forces and smaller scale turbulent mixing processes are sufficiently vigorous to produce a uniform salinity.

Salt is transported into the bay by the dispersive action of the tides. During the incoming tide sea water flows into the bay (see figure 4.3). Due to turbulence this water mixes with bay water. Diluted water thus flows out of the bay during the outgoing tide. Part of the salt remains in the bay. If there were no freshwater inflow to the bay this tidal dispersion would eventually fill the entire bay with sea water. Any net inflow of freshwater to the system sets up an advective current out to sea which flushes out some of the salt. The salinity of the bay therefore depends on the balance between the tidal dispersion and the freshwater advection.

The one-dimensional tidal model used in chapter 3 has been used to approximate the tidal intrusion process discussed above. This model could be used to simulate the dispersion/advection process for the entire lake. The mixing effect of the large scale two-dimensional currents in the bay could be dealt with by specifying a suitable one-dimensional dispersion coefficient. However it would prove completely unmanageable for simulating the long term (say 50 years) salinity fluctuations in the bay at say ½ hour increments.

It was therefore decided to use a cell type monthly lake model developed by Hutchison[22]. Briefly the lake or bay is represented as a series of interconnected cells. The bay/ocean boundary is represented by a lake stage-discharge curve. In this model the tidal dispersive process discussed above is treated as pure dispersion, the rate of salt influx being dependent on the salinity gradient between the bay and the sea, the cross-sectional area of the channel linking the bay to the sea and a dispersion constant. A brief discription of this lake model follows.

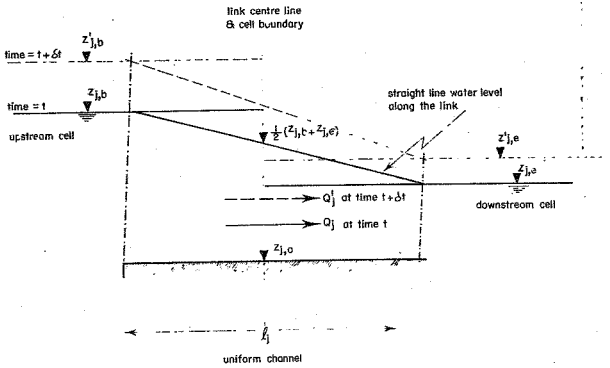


FIGURE 4.1 LONGITUDINAL SECTION THROUGH A TYPICAL FLOW LINK (channel)

4.1 Description of the programs used

4.1.1 HDYP05

This program is designed to simulate long-term water circulation within the lake, i.e. for periods of 50 years or more. The lake system is represented as a series of interconnected storage cells each having a horizontal water surface (see figure 4.3). Water enters the system by way of estuaries, which connect the lake to the sea, rivers and direct rainfall and leaves the system via the estuaries and evaporation. Discharges in the flow links connecting the cells are governed by continuity*. From a glance at the bay geometry it is obvious that the friction losses are negligible. The continuity solution is given below:

(a) Continuity equation for general cell i

A typical flow link is illustrated in figure 4.1. For this solution all the cell levels at the end of the time period, i.e. z_i, are equal and set at zz' (i.e. there are no friction losses in the links).

From the fundamental continuity equation:

$$I = \Delta S + O \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

where, during time increment Δt, I = inflow
O = outflow
ΔS = change of storage

we get:

$$zz'\left(-\frac{x_i A_i}{\delta t} + 0{,}0432 \sum_{k=1}^{k=m_i} \frac{\partial QE_k}{\partial z_i}\right) + \sum_{j=1}^{j=n_i} f_{i,j} 0{,}0864 Q_j' =$$

$$-\frac{x_i A_i}{\delta t} z_i - \frac{V_i}{\delta t} - 0{,}0864 \sum_{k=1}^{k=m_i} \left(QE_k - \frac{1}{2}\frac{\partial QE_k}{\partial z_i} z_i\right) + e_i x_i A_i \quad \ldots (4.2)$$

where zz' = cell water level at time t + δt (m)
z_i' = cell water level at time t (m)
x_i = cell surface area correction factor
A_i = cell water surface area (km^2)
δt = time increment (days)
0,0864 = seconds x 10^6/day

* The program can handle friction losses if necessary.

m_i = number of estuaries entering cell i

k = general estuary

QE_k = discharge in estuary at time t (m^3/s)

$f_{i,j}$ = factor defining direction of flow in link j
= -1 if positive direction of flow in the link is out of the cell
= 1 if positive direction of flow in the link is into the cell

Q_j^t = link discharge at time t + δt (m^3/s)

n_i = number of flow links connected to cell i

j = general flow link

V_i = river inflow ($m^3 \times 10^6$)

e_i = net evaporation from cell (m/day)

Thus for ℓ cells and p flow links, the number of unknowns at the end of time period δt will be p+1 (i.e. flow link discharges and final lake level) while the number of cell continuity equations will be ℓ.

(b) Solution procedure

For a configuration of ℓ cells and p links a set of ℓ cell continuity equations is set up and solved for the p+1 unknowns, viz. the final lake level and average link discharges.

Program HDYPO5 is described in detail in reference 22.

4.1.2 HDYPO6

This program simulates salinity circulation within the lake system. Both advective and dispersive processes are considered. The storage cells are assumed to be well mixed and thus have a uniform salinity distribution. All salt transport takes place within the flow links. A typical salinity distribution within the model is illustrated in figure 4.2.

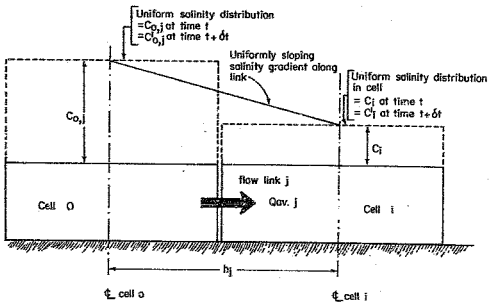


FIGURE 4.2 LONGITUDINAL SECTION THROUGH A GENERAL FLOW LINK, j

(a) Advection

The advective currents in the flow links are averages obtained from the program HDYPO5. Salt advection over the monthly time increment is approximated as the product of the average link discharge and the average salinity of the cell from which the water is flowing. This implies a constant discharge and a linear variation in cell salinity over the time period. The advection equations used are given below:

Advection into cell via flow link j:-

$$\text{Advection} = \text{LAI} = 0{,}0864\ r_{i,j}\ \tfrac{1}{2}(C'_{o,j} + C_{o,j})Qav_j\delta t$$

$$-0{,}0864\ s_{i,j}\ \tfrac{1}{2}(C'_i + C_i)Qav_j\delta t \quad \ldots\ldots\ldots\ldots(4.3)$$

where $r_{i,j} = 1$ and $S_{i,j} = 0$ if Qav_j is into cell i

and $r_{i,j} = 0$ and $S_{i,j} = 1$ if Qav_j is out of cell i

Qav_j = average discharge in link during period δt (m^3/s)

Advection into cell via estuary k:-

$$\text{Advection} = \text{EAI} = 0{,}0864\ r_k C_s QEav_k\delta t - s_k\ \tfrac{1}{2}(C'_i + C_i)QEav_k\delta t$$

$\ldots\ldots\ldots(4.4)$

where r_k and s_k have the same meaning as before but with respect to $QEav_k$.

$QEav_k$ = average estuary discharge for period δt (m^3/s)

(b) Dispersion

The dispersive process is assumed to be governed by a Fickian-type law, i.e. the rate of transport is proportional to the salinity gradient. This gradient is evaluated in terms of the salinities of the cells at the beginning and end of the channel and the channel dispersive length (see figure 4.2). The dispersion length is the distance between the cell centroids. The dispersion rate is also dependent upon the average channel cross-sectional area between cell centroids. The dispersive length of an estuary is taken as the distance from the centroid of the cell to that edge of the cell which is linked to the sea. The dispersion equations used are given below:

Dispersion into cell via flow link j:-

$$\text{Dispersion} = \text{LDI} = \frac{Dg_j}{2h_j}(C'_{o,j} + C_{o,j} - C'_i - C_i)\delta t \quad \ldots\ldots\ldots(4.5)$$

where D = link dispersion coefficient; assumed to be the

same for all links (km^2/day)

g_j = link dispersive cross-sectional area (m^2)

h_j = link dispersion distance (m)

δt = time increment (days)

C_i, C_i^t = average salinity of cell i at time t and t+δt (ppt)

$C_{o,j}, C'_{o,j}$ = average salinity of cell at other end of flow link at time t and at time t+δt (ppt).

Dispersion into cell via estuary k :-

$$\text{Dispersion} = \text{EDI} = \frac{Dg_k}{2h_k}(2.C_s - C_i^t - C_i)\delta t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.6)$$

where g_k and h_k have the same meaning as before but with respect to the estuary

and C_s = sea water salinity (ppt).

The increase in cell salt content during the period δt is given by:-

$$\Delta s = Vs_i^t C_i^t - Vs_i C_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.7)$$

where Vs_i, Vs_i^t = cell i volumes at time t and t+δt ($m^3 \times 10^6$)

The cell salt conservation equation is:-

$$\Delta s = \text{net inflow of salt} = \Sigma\text{LDI} + \Sigma\text{LAI} + \Sigma\text{EDI} + \Sigma\text{EAI} \quad \ldots(4.8)$$

Substitution of equations 4.3 to 4.7 into 4.8 and re-arrangement of the terms yields:-

$$C_i^t\{Vs_i^t + \frac{\delta t}{2}\sum_{j=1}^{j=n_i}(\frac{Dg_j}{h_j} + 0{,}0864\, s_{i,j}Qav_j) + \frac{\delta t}{2}\sum_{k=1}^{k=m_i}(\frac{Dg_k}{h_k} + 0{,}0864\, s_kQEav_k)\} - \frac{\delta t}{2}\sum_{j=1}^{j=n_i}C'_{o,j}(\frac{Dg_j}{h_j} - 0{,}0864\, r_{i,j}Qav_j) =$$

$$C_i\{Vs_i - \frac{\delta t}{2}\sum_{j=1}^{j=n_i}(\frac{Dg_i}{h_j} + 0{,}0864\, s_{i,j}Qav_j) - \frac{\delta t}{2}\sum_{k=1}^{k=m_i}(\frac{Dg_k}{h_k} + 0{,}0864\, s_kQEav_k)\} + C_s\{\delta t\sum_{k=1}^{k=m_i}\frac{Dg_k}{h_k} + 0{,}0864\, r_kQEav_k\}$$

$$+ \frac{\delta t}{2}\sum_{j=1}^{j=n_i}C_{o,j}(-\frac{Dg_j}{h_j} + 0{,}0864\, r_{i,j}Qav_j) \quad \ldots\ldots\ldots\ldots\ldots\ldots(4.9)$$

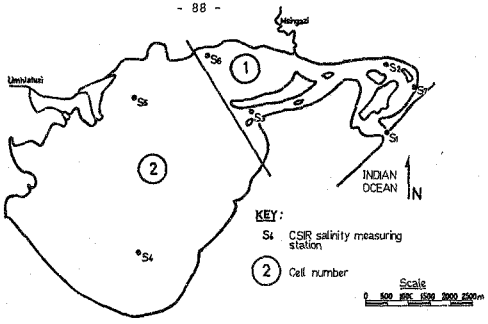


FIGURE 4.3 Richards bay – plan of the bay showing locations of cells and salinity measuring stations

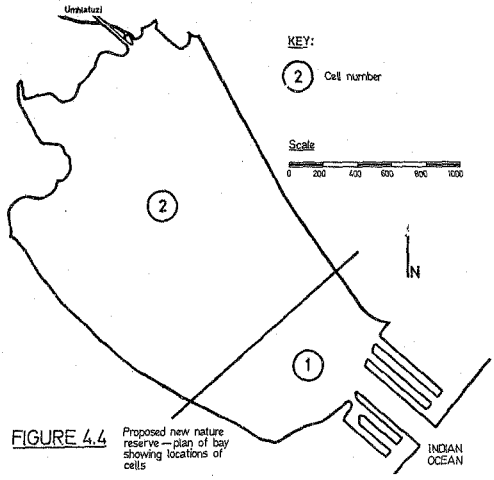


FIGURE 4.4 Proposed new nature reserve – plan of bay showing locations of cells

(c) Solution procedure

Flow link dispersion geometry, dispersion coefficient and sea water salinity must be specified. Equation 4.9 is set up for each of the ℓ cells, thus providing ℓ equations with ℓ unknowns, viz. final average cell salinities. At any time t cell levels and salinities are known from the previous time step while average link and estuary discharges and final cell levels are generated by the simulation program. The set of ℓ equations is then solved simultaneously to yield the cell salinities at the end of the time period. The solution thus continues in a stepwise manner.

Programs HDYP05 and HDYP06 can be run at monthly time increments or fractions thereof.

4.2 Calibration of the water and salt circulation models

4.2.1 Richards Bay natural system data

Salinity measurements were carried out by the CSIR during the period February 1969 to March 1971. These salinities are tabulated in table 4.1. The locations of the salinity measuring stations are given in figure 4.3. It should be noted that this data is subject to the following limitations:

(i) Very few measurements were taken within the bay proper,
(ii) Station S4 was inoperative for most of the observations,
(iii) These salinity readings are point measurements carried out on a specific day. They may not, therefore accurately represent the average bay salinity for that day. It is also difficult to extrapolate month-end salinities for purposes of comparison with simulated values.

As the bay is spatially well mixed, it was decided to model it as one cell. The estuary channel was represented by a second cell because there is a consistent difference between the bay and estuary channel salinities (see table 4.2). The cell configuration is shown in figure 4.3.

The spatially weighted average salinity within each cell for the months during which salinity measurements were made by the CSIR are given in table 4.2. The level-area relationship for each cell is given in table 4.3. The level-discharge relationship for the estuary was established by running the one-dimensional tidal

Table 4.1 : Average salinities measured at CSIR salinity measuring stations (ppt)

date			station number						
year	month	day	1	2	3	4	5	6	7
1969	Feb.	26	35	35	34	-	34	35	35
	Mar.	14	34	20	12	-	8	9	17
	May.	5	34	24	18	-	17	22	32
	Jun.	23	34	30	22	-	20	23	29
	Jul.	9	34	27	22	-	25	25	30
	Sep.	29	34	32	33	-	32	30	34
	Nov.	25	33	26	24	-	20	26	29
1970	Jan.	9	33	32	31	-	29	32	33
	Jul.	28	34	33	32	32	30	32	34
	Sep.	11	34	33	34	31	30	32	34
	Oct.	14	32	28	22	21	16	-	30
	Dec.	11	30	27	21	18	19	24	32
1971	Mar.	3	34	34	34	28	27	27	34

Note : These are spot measurements. The values given above are averages of top and bottom salinities measured at one point in time.

Table 4.2 : Weighted average salinities within each cell on the dates when salinity measurements were made

date			cell number	
year	month	day	1	2
1969	Feb	26	35	34
	Mar	14	15	8
	May	5	21	17
	Jun	23	25	21
	Jul	9	26	25
	Sep	29	33	32
	Nov	25	25	21
1970	Jan	9	32	30
	Jul	28	33	31
	Sep	11	34	31
	Oct	14	25	19
	Dec	11	24	19
1971	Mar	3	34	28

Note: The above average cell salinities were weighted by Thiessen's Polygon method.

propagation model discussed in chapter 3 for the original system for one tidal cycle with various fixed bay levels. A sinusoidal sea tide of 1,2 m range (Durban mean) and 0,940 m MSL (Durban mean) was specified at the downstream boundary. Simulations performed by Hutchison[20] indicate that use of a mean or median tidal range and the long term mean sea level gives an accurate average estuary inflow or outflow.

July/August 1970 mouth geometry was taken as being representative of normal conditions within the original bay system. The resulting level-discharge relationship is given in table 4.4.

Table 4.3 : Level-area relationship for each cell used to model the original Richards bay system

cell 1		cell 2	
level m	area km^2	level m	area km^2
-3,00	0,006	-0,10	0,409
-1,00	0,574	0,20	5,011
-0,50	0,943	0,40	14,065
0,00	1,428	0,60	19,072
0,50	3,261	0,70	20,948
1,00	6,017	1,00	22,389
1,50	7,142	1,50	23,364
2,25	10,333	2,25	31,078
3,00	13,597	3,00	38,937

Table 4.4 : Level-discharge relationship for the original Richards bay estuary - July/August 1970 mouth (+ve direction into the bay)

level m	discharge m^3/s
0,70	97,0
1,11	0,0
2,00	-553,3
3,00	-1 411,8

4.2.2 Convergence test runs

These runs were used in order to select an appropriate simulation time increment. The period 1961 to 1971 was simulated in the original system for calculation time increments varying between 1 and 8 calculations per month. Boundary river runoffs were provided by the monthly runoffs simulated in chapter 2 for 1970 catchment conditions (i.e. tables 2.13, 2.14, 2.18 and 2.19). The dispersion coefficient, D, was set at 10 km^2/day. The results of

the convergence tests are given in table 4.5, from which it is seen that a calculation time increment of ¼ month (i.e. 4 calculations per month) yields satisfactory results, i.e. the *error in average cell levels and salinities are less than 2% and* in no single month do these errors exceed 10%.

Table 4.5 : Results of convergence test simulations - average cell levels and salinities for the period 1921 to 1971 for 1970 catchment conditions

number of calculations per month	lake level	salinity ppt	
	m	cell 1	cell 2
1	1,13	25,6	22,7
2	1,13	25,8	22,7
4	1,12	25,6	22,6
8	1,14	25,7	22,7

4.2.3 Model calibration for the period February 1969 to July 1971

The level-discharge curve given in table 4.4 was used for the estuary boundary (i.e. a MSL and tidal range of 0,940 and 1,200 m respectively, and July/August 1970 mouth conditions were assumed). The monthly runoffs into Richards Bay simulated in chapter 2 for 1970 catchment conditions were used for the river boundaries. The model was calibrated by varying the dispersion coefficient, D, and the evaporation pan coefficient until a reasonable agreement was achieved between measured and simulated salinities. The evaporation pan coefficient was found to have very little effect and was set at 1,1. The discontinuous nature of the available salinity data precluded any attempt at accurate calibration of the model. Table 4.6 demonstrates the correlation achieved between model and natural system behaviour. The final value of D adopted was 13 km^2/day.

Table 4.6 : Comparison of the measured and simulated salinities within the original Richards Bay lake system (ppt)

date			cell number 1		cell number 2	
year	month	day	measured	simulated	measured	simulated
1969	Feb	26	36	30	34	28
	Mar	14	15	23	8	20
	May	5	21	18	17	13
	Jun	23	25	25	21	22
	Jul	9	26	26	25	24
	Sep	29	33	30	32	29
	Nov	25	25	27	21	24
1970	Jan	9	32	30	30	28
	Jul	28	33	31	31	29
	Sep	11	34	31	31	30
	Oct	14	25	27	19	24
	Dec	11	24	24	19	20
1971	Mar	3	34	27	28	23

Note: The above simulated cell salinities were interpolated linearly between the month end values obtained from the lake model.

Table 4.7 : Level-area relationship for each cell used to model the proposed nature reserve

cell 1		cell 2	
level m	area km²	level m	area km²
-11,16	0,718	0,20	0,588
-4,66	1,069	0,40	3,465
-0,16	1,670	0,60	7,250
0,40	2,465	1,00	8,888
0,60	3,437	1,50	9,345
1,00	3,853	2,25	16,012
1,50	3,976	3,00	17,859
3,00	5,281		

Table 4.8 : Level-discharge relationship for the proposed nature reserve estuary - Layout II mouth

level m	discharge m³/s
0,70	132,3
1,00	44,7
2,00	-767,5
3,00	-1 594,1

4.3 Simulation of the long term water and salt circulation in the original Richards Bay system and in the proposed new nature reserve

These simulations were run for a period of 51 years using the synthesized monthly runoffs into Richards Bay discussed in chapter 2 as boundary conditions. Corresponding monthly net potential evaporations from the bay are also available for the simulation period. The dispersion coefficient used is 13 km^2/day.

4.3.1 Original natural system

Conditions in the original Richards Bay system were simulated only for the 1970 catchment conditions. The discharge-level relationship of table 4.4 was used as the estuary boundary condition while the river inputs were abstracted from tables 2.13, 2.14, 2.18 and 2.19. The results of this simulation are given in table 4.9.

4.3.2 Proposed new nature reserve

The cell configuration is shown in figure 4.4 and the level-area relationship for each cell is given in table 4.7. The level-discharge relationship for the estuary was determined as before, using layout II mouth, and is shown in table 4.8.

Simulations were performed for two catchment conditions:

(a) 1970 catchment conditions - the river boundaries specified as in 4.3.1 above for the original system simulations,

and

(b) 1990 catchment conditions - here the river inputs were provided by tables 2.21 to 2.24.

The results of these simulations are given in table 4.9.

4.3.3 Comparison between the long term water and salt circulation in the original natural system and that of the proposed nature reserve

From table 4.9 it is seen that at no time does the salinity exceed 36 ppt in any of the systems modelled. For the catchment conditions prevailing in 1970 there is very little difference between the average salinities and water levels obtained in the original system and those of the proposed nature reserve.

It is thus clear that there is little cause for concern with

respect to long term average water levels and salinities within the proposed nature reserve.

Table 4.9 : Comparison between the long term water and salt circulation in the original natural system and that of the proposed new nature reserve

parameter	units	estuary system					
		original system		proposed nature reserve			
		1970 catchment		1970 catchment		1990 catchment	
		cell 1	cell 2	cell 1	cell 2	cell 1	cell 2
mean annual							
net evaporation	$m^3 \times 10^6$	0,90	2,39	0,38	1,08	0,38	1,08
river runoff	"	54,96	503,99	0,00	503,99	0,00	232,93
mean annual							
estuary inflow	$m^3 \times 10^6$	0,53	-	0,00	-	4,41	-
estuary outflow	"	556,11	-	502,48	-	235,82	-
water levels							
average	m	1,14	1,14	1,08	1,08	1,07	1,07
maximum monthly	"	1,42	1,42	1,12	1,12	1,10	1,10
minimum monthly	"	1,04	1,04	1,01	1,01	1,01	1,01
standard dev.	"	0,04	0,04	0,01	0,01	0,01	0,01
salinity							
average	ppt	26,6	23,9	24,5	22,1	30,5	29,6
maximum monthly	"	34,3	34,0	33,4	32,9	35,9	36,0
minimum monthly	"	5,5	6,7	6,0	6,6	6,9	7,8
standard dev.	"	6,2	1,1	3,8	0,7	3,9	0,7

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

For all the model simulations performed it was found that the mean bay level averaged over a tidal cycle within the proposed nature reserve were not significantly different from those experienced in the original system. The tidal prism was found to differ markedly depending upon the mouth conditions ascribed to the new system. Tidal ranges within the proposed nature reserve with layout II mouth were found to be two to three times larger than those of the original system. It was also established that should a flood wash out the sand-bar which blocks the seaward ends of the four flood channels, there is a strong likelihood that the bed of nearly the entire nature reserve will become exposed at low spring tide. The design is offered of a tidal channel that will cause acceptable tidal ranges within the nature reserve.

Maximum flood levels for all of the mouth configurations modelled were found to be acceptable (i.e. not higher than 3,1 m LWOST* for a 100-year flood). Proposed developments within the Umhlatuzi catchment make very little difference to the flood response of Richards Bay.

Tidal advection amplitudes along the thalweg of each of the estuary systems have been plotted and from these the extent of tidal sea water intrusion can be inferred.

Very little difference was found between the long term water levels and salinity fluctuations within the original system and those in the proposed nature reserve. Even for projected 1990 catchment conditions the average monthly salinity never exceeds 36 ppt (i.e. 1 ppt above average sea salinity).

5.2 Recommendations

(a) It is strongly recommended that the four flood channels in the new estuary mouth be permanently blocked so as to prevent unacceptably shallow water at low tide after a flood has scoured out the narrow sand-bar at present temoparily obstructing the seaward outlet. This could be effected by:

(i) filling in the flood channels with material borrowed from the dykes separating the flood channels,

or (ii) constructing an erosion-resistant weir across the flood channels.

It is suggested that the finished level of the flood plain (case (i)) or the crest level of the weir (case (ii)) should be set at 1,0 m LWOST (see figure 3.33 of chapter 3).

(b) A 30 m wide tidal channel with invert level at -0,5 m LWOST is recommended in order to keep tidal water level fluctuations within the nature reserve similar to those that were experienced in the original Richards Bay system.

(c) It is suggested that suitable bed and bank protection be provided for the tidal channel to prevent scour during floods.

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APPENDIX A - Monthly rainfall records expressed as a percentage of each catchment MAP

Table A.1

AVERAGE RAINFALL ON CATCHMENT (EXPRESSED AS PERCENTAGE OF MEAN) =MONTHLY RATIO

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD	
3E07/12	1951	TO 1971
3E16/02	1950	TO 1971
3E16/03	1950	TO 1971
3E16/03	1950	TO 1971
3E25/03	1951	TO 1971
3F07/01	1950	TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL RAINFALL
1950-51	2	72	210	143	64	53	58	24	41	89	13	74	18	860
1951-52	2	102	164	71	64	23	29	29	15	28	15	15	20	621
1952-53	2	44	161	124	121	102	66	16	28	3	0	33	72	710
1953-54	2	64	71	141	151	64	39	28	43	8	1	45	72	715
1954-55	2	157	34	43	72	54	148	49	22	40	2	11	74	755
1955-56	2	87	84	83	75	84	108	54	16	4	0	17	34	646
1956-57	2	49	177	78	58	58	96	41	9	27	28	70	71	765
1957-58	2	72	41	71	98	68	101	28	7	26	17	83	93	753
1958-59	2	76	84	71	104	48	51	39	14	8	0	27	58	580
1959-60	2	76	76	71	104	48	51	39	14	8	0	27	58	580
1960-61	2	51	93	75	74	273	61	52	61	24	0	1	28	1004
1961-62	2	84	140	71	75	59	77	39	7	39	0	37	47	676
1962-63	2	82	156	245	231	89	109	84	82	20	46	12	153	1329
1963-64	2	82	156	245	231	89	109	84	82	20	46	12	153	1329
1964-65	2	44	74	71	74	89	57	216	4	0	0	45	268	842
1965-66	2	84	188	87	122	188	62	20	1	24	15	15	49	861
1966-67	2	84	188	87	122	188	62	20	1	24	15	15	49	861
1967-68	2	84	188	87	122	188	62	20	1	24	15	15	49	861
1968-69	2	53	282	114	92	98	41	211	54	0	10	98	90	1050
1969-70	2	53	282	114	92	98	41	211	54	0	10	98	90	1050
1970-71	2	53	282	114	92	98	41	211	54	0	10	98	90	1050
1971-72	2	64	31	75	108	104	133	28	37	26	0	11	68	687
1972-73	2	64	31	75	108	104	133	28	37	26	0	11	68	687
1973-74	2	134	144	169	98	98	89	87	15	5	17	1	100	1057
1974-75	2	54	81	64	157	102	71	40	3	1	0	15	75	664
1975-76	2	54	81	64	157	102	71	40	3	1	0	15	75	664
1976-77	2	152	189	184	171	153	109	61	11	6	1	41	77	1075
1977-78	2	152	189	184	171	153	109	61	11	6	1	41	77	1075
1978-79	2	152	189	184	171	153	109	61	11	6	1	41	77	1075
1979-80	2	126	188	182	119	84	109	30	20	18	14	7	8	905
1980-81	2	126	188	182	119	84	109	30	20	18	14	7	8	905
1981-82	2	112	19	102	87	77	49	47	5	0	0	19	72	591
1982-83	2	74	110	133	104	141	61	28	8	0	0	0	37	708
1983-84	2	65	160	157	79	114	107	70	0	0	0	0	37	793
1984-85	2	220	141	9	157	102	103	49	24	11	1	0	30	1049
1985-86	2	220	141	9	157	102	103	49	24	11	1	0	30	1049
1986-87	2	109	124	249	115	144	84	15	5	9	20	21	101	1000
1987-88	2	109	124	249	115	144	84	15	5	9	20	21	101	1000
1988-89	2	109	124	249	115	144	84	15	5	9	20	21	101	1000
1989-90	2	47	164	274	74	74	115	74	0	0	0	0	72	820
1990-91	2	47	164	274	74	74	115	74	0	0	0	0	72	820
1991-92	2	47	164	274	74	74	115	74	0	0	0	0	72	820
1992-93	2	132	142	158	167	43	188	99	0	0	176	4	0	1156
1993-94	2	132	142	158	167	43	188	99	0	0	176	4	0	1156
1994-95	2	132	142	158	167	43	188	99	0	0	176	4	0	1156
1995-96	2	113	154	101	84	111	104	0	0	0	0	0	0	1132
1996-97	2	113	154	101	84	111	104	0	0	0	0	0	0	1132
1997-98	2	113	154	101	84	111	104	0	0	0	0	0	0	1132
1998-99	2	43	38	93	144	64	29	38	0	0	0	0	0	1132
1999-00	2	43	38	93	144	64	29	38	0	0	0	0	0	1132
2000-01	2	43	38	93	144	64	29	38	0	0	0	0	0	1132
2001-02	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2002-03	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2003-04	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2004-05	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2005-06	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2006-07	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2007-08	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2008-09	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2009-10	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2010-11	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2011-12	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2012-13	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2013-14	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2014-15	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2015-16	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2016-17	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2017-18	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2018-19	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2019-20	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2020-21	2	64	84	102	68	102	84	15	5	9	20	21	101	1000
2021-22	2	64	84	102	68	102	84	15	5	9	20	21	101	1000

MEANS %%	26	103	124	124	104	111	88	73	30	20	34	47	850
ANNUAL STAN	30	38	54	53	53	6	4	2	2	2	6	6	100

Table A.2

AVERAGE RAINFALL ON CATCHMENT (EXPRESSED AS PERCENTAGE OF MEAN) =MONTHLY RATIO

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD	
3E07/12	1951	TO 1971
3E16/02	1950	TO 1971
3E16/03	1950	TO 1971
3E16/03	1950	TO 1971
3E25/03	1951	TO 1971
3F07/01	1950	TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL RAINFALL
1950-51	2	77	208	135	65	52	60	25	36	86	16	74	19	857
1951-52	2	109	162	67	65	23	30	29	14	27	16	15	21	618
1952-53	2	47	159	117	123	103	68	17	27	3	0	33	73	717
1953-54	2	68	70	133	154	65	40	29	42	8	1	45	73	716
1954-55	2	167	34	41	73	54	148	49	21	40	2	11	74	755
1955-56	2	92	83	78	76	85	108	54	15	4	0	17	34	648
1956-57	2	52	175	74	59	59	96	41	9	27	28	70	72	764
1957-58	2	76	41	71	99	68	101	28	7	26	17	83	94	716
1958-59	2	81	83	71	105	48	51	39	14	8	0	27	58	585
1959-60	2	81	75	71	105	48	51	39	14	8	0	27	58	585
1960-61	2	54	92	75	75	273	61	52	61	24	0	1	28	1004
1961-62	2	89	139	71	76	59	77	39	7	39	0	37	47	676
1962-63	2	87	154	245	233	89	109	84	82	20	46	12	154	1329
1963-64	2	87	154	245	233	89	109	84	82	20	46	12	154	1329
1964-65	2	47	73	71	75	89	57	216	4	0	0	45	268	842
1965-66	2	89	186	87	123	188	62	20	1	24	15	15	49	861
1966-67	2	89	186	87	123	188	62	20	1	24	15	15	49	861
1967-68	2	89	186	87	123	188	62	20	1	24	15	15	49	861
1968-69	2	56	279	114	93	98	41	211	54	0	10	98	90	1050
1969-70	2	56	279	114	93	98	41	211	54	0	10	98	90	1050
1970-71	2	56	279	114	93	98	41	211	54	0	10	98	90	1050
1971-72	2	68	31	76	109	104	133	28	37	26	0	11	68	687
1972-73	2	68	31	76	109	104	133	28	37	26	0	11	68	687
1973-74	2	142	142	171	99	98	89	87	15	5	17	1	100	1057
1974-75	2	57	80	65	159	102	71	40	3	1	0	15	75	664
1975-76	2	57	80	65	159	102	71	40	3	1	0	15	75	664
1976-77	2	161	187	186	173	153	109	61	11	6	1	41	77	1075
1977-78	2	161	187	186	173	153	109	61	11	6	1	41	77	1075
1978-79	2	161	187	186	173	153	109	61	11	6	1	41	77	1075
1979-80	2	133	186	184	120	84	109	30	20	18	14	7	8	905
1980-81	2	133	186	184	120	84	109	30	20	18	14	7	8	905
1981-82	2	118	19	103	88	77	49	47	5	0	0	19	72	591
1982-83	2	78	109	135	105	141	61	28	8	0	0	0	37	708
1983-84	2	69	158	159	80	114	107	70	0	0	0	0	37	793
1984-85	2	232	140	9	159	102	103	49	24	11	1	0	30	1049
1985-86	2	232	140	9	159	102	103	49	24	11	1	0	30	1049
1986-87	2	115	123	252	116	144	84	15	5	9	20	21	101	1000
1987-88	2	115	123	252	116	144	84	15	5	9	20	21	101	1000
1988-89	2	115	123	252	116	144	84	15	5	9	20	21	101	1000
1989-90	2	49	163	277	75	74	115	74	0	0	0	0	72	820
1990-91	2	49	163	277	75	74	115	74	0	0	0	0	72	820
1991-92	2	49	163	277	75	74	115	74	0	0	0	0	72	820
1992-93	2	139	141	160	169	43	188	99	0	0	176	4	0	1156
1993-94	2	139	141	160	169	43	188	99	0	0	176	4	0	1156
1994-95	2	139	141	160	169	43	188	99	0	0	176	4	0	1156
1995-96	2	119	153	102	85	111	104	0	0	0	0	0	0	1132
1996-97	2	119	153	102	85	111	104	0	0	0	0	0	0	1132
1997-98	2	119	153	102	85	111	104	0	0	0	0	0	0	1132
1998-99	2	45	38	94	145	64	29	38	0	0	0	0	0	1132
1999-00	2	45	38	94	145	64	29	38	0	0	0	0	0	1132
2000-01	2	45	38	94	145	64	29	38	0	0	0	0	0	1132
2001-02	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2002-03	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2003-04	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2004-05	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2005-06	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2006-07	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2007-08	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2008-09	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2009-10	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2010-11	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2011-12	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2012-13	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2013-14	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2014-15	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2015-16	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2016-17	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2017-18	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2018-19	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2019-20	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2020-21	2	67	84	103	69	102	84	15	5	9	20	21	101	1000
2021-22	2	67	84	103	69	102	84	15	5	9	20	21	101	1000

MEANS %%	27	102	126	124	104	111	88	73	30	20	34	47	850
ANNUAL STAN	30	38	54	53	53	6	4	2	2	2	6	6	100

Table A.3

AVERAGE RAINFALL ON CATCHMENT EXPRESSED AS PERCENTAGE OF MEAN =MONTHLY RATIO

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD	
3E07/12	1951	TO 1971
3E07/A4	1964	TO 1971
3E16/02	1950	TO 1971
3E16/03	1950	TO 1971
3E16/03	1950	TO 1971
3E25/03	1951	TO 1971
3F07/01	1950	TO 1971
3F07/A1	1964	TO 1971
3F07/A2	1964	TO 1971
3F07/A3	1964	TO 1971
3F07/A4	1964	TO 1971
3F07/05	1964	TO 1971
3F07/06	1964	TO 1971
3F07/07	1964	TO 1971
3F07/08	1964	TO 1971
3F07/09	1964	TO 1971
3F07/10	1964	TO 1971
3F07/11	1964	TO 1971
3F07/12	1964	TO 1971
3F07/13	1964	TO 1971
3F07/14	1964	TO 1971
3F07/15	1964	TO 1971
3F07/16	1964	TO 1971
3F07/17	1964	TO 1971
3F07/18	1964	TO 1971
3F07/19	1964	TO 1971
3F07/20	1964	TO 1971
3F07/21	1964	TO 1971
3F07/22	1964	TO 1971
3F07/23	1964	TO 1971
3F07/24	1964	TO 1971
3F07/25	1964	TO 1971
3F07/26	1964	TO 1971
3F07/27	1964	TO 1971
3F07/28	1964	TO 1971
3F07/29	1964	TO 1971
3F07/30	1964	TO 1971
3F07/31	1964	TO 1971
3F07/32	1964	TO 1971
3F07/33	1964	TO 1971
3F07/34	1964	TO 1971
3F07/35	1964	TO 1971
3F07/36	1964	TO 1971
3F07/37	1964	TO 1971
3F07/38	1964	TO 1971
3F07/39	1964	TO 1971
3F07/40	1964	TO 1971
3F07/41	1964	TO 1971
3F07/42	1964	TO 1971
3F07/43	1964	TO 1971
3F07/44	1964	TO 1971
3F07/45	1964	TO 1971
3F07/46	1964	TO 1971
3F07/47	1964	TO 1971
3F07/48	1964	TO 1971
3F07/49	1964	TO 1971
3F07/50	1964	TO 1971
3F07/51	1964	TO 1971
3F07/52	1964	TO 1971
3F07/53	1964	TO 1971
3F07/54	1964	TO 1971
3F07/55	1964	TO 1971
3F07/56	1964	TO 1971
3F07/57	1964	TO 1971
3F07/58	1964	TO 1971
3F07/59	1964	TO 1971
3F07/60	1964	TO 1971
3F07/61	1964	TO 1971
3F07/62	1964	TO 1971
3F07/63	1964	TO 1971
3F07/64	1964	TO 1971
3F07/65	1964	TO 1971
3F07/66	1964	TO 1971
3F07/67	1964	TO 1971
3F07/68	1964	TO 1971
3F07/69	1964	TO 1971
3F07/70	1964	TO 1971
3F07/71	1964	TO 1971
3F07/72	1964	TO 1971
3F07/73	1964	TO 1971
3F07/74	1964	TO 1971
3F07/75	1964	TO 1971
3F07/76	1964	TO 1971
3F07/77	1964	TO 1971
3F07/78	1964	TO 1971
3F07/79	1964	TO 1971
3F07/80	1964	TO 1971
3F07/81	1964	TO 1971
3F07/82	1964	TO 1971
3F07/83	1964	TO 1971
3F07/84	1964	TO 1971
3F07/85	1964	TO 1971
3F07/86	1964	TO 1971
3F07/87	1964	TO 1971
3F07/88	1964	TO 1971
3F07/89	1964	TO 1971
3F07/90	1964	TO 1971
3F07/91	1964	TO 1971
3F07/92	1964	TO 1971
3F07/93	1964	TO 1971
3F07/94	1964	TO 1971
3F07/95	1964	TO 1971
3F07/96	1964	TO 1971
3F07/97	1964	TO 1971
3F07/98	1964	TO 1971
3F07/99	1964	TO 1971
3F07/100	1964	TO 1971
3F07/101	1964	TO 1971
3F07/102	1964	TO 1971
3F07/103	1964	TO 1971
3F07/104	1964	TO 1971
3F07/105	1964	TO 1971
3F07/106	1964	TO 1971
3F07/107	1964	TO 1971
3F07/108	1964	TO 1971
3F07/109	1964	TO 1971
3F07/110	1964	TO 1971
3F07/111	1964	TO 1971
3F07/112	1964	TO 1971
3F07/113	1964	TO 1971
3F07/114	1964	TO 1971
3F07/115	1964	TO 1971
3F07/116	1964	TO 1971
3F07/117	1964	TO 1971
3F07/118	1964	TO 1971
3F07/119	1964	TO 1971
3F07/120	1964	TO 1971
3F07/121	1964	TO 1971
3F07/122	1964	TO 1971
3F07/123	1964	TO 1971
3F07/124	1964	TO 1971
3F07/125	1964	TO 1971
3F07/126	1964	TO 1971
3F07/127	1964	TO 1971
3F07/128	1964	TO 1971
3F07/129	1964	TO 1971
3F07/130	1964	TO 1971
3F07/131	1964	TO 1971
3F07/132	1964	TO 1971
3F07/133	1964	TO 1971
3F07/134	1964	TO 1971
3F07/135	1964	TO 1971
3F07/136	1964	TO 1971
3F07/137	1964	TO 1971
3F07/138	1964	TO 1971
3F07/139	1964	TO 1971
3F07/140	1964	TO 1971
3F07/141	1964	TO 1971
3F07/142	1964	TO 1971
3F07/143	1964	TO 1971
3F07/144	1964	TO 1971
3F07/145	1964	TO 1971
3F07/146	1964	TO 1971
3F07/147	1964	TO 1971
3F07/148	1964	TO 1971
3F07/149	1964	TO 1971
3F07/150	1964	TO 1971
3F07/151	1964	TO 1971
3F07/152	1964	TO 1971
3F07/153	1964	TO 1971
3F07/154	1964	TO 1971
3F07/155	1964	TO 1971
3F07/156	1964	TO 1971
3F07/157	1964	TO 1971
3F07/158	1964	TO 1971
3F07/159	1964	TO 1971
3F07/160	1964	TO 1971
3F07/161	1964	TO 1971
3F07/162	1964	TO 1971
3F07/163	1964	TO 1971
3F07/164	1964	TO 1971
3F07/165	1964	TO 1971
3F07/166	1964	TO 1971
3F07/167	1964	TO 1971
3F07/168	1964	TO 1971
3F07/169	1964	TO 1971
3F07/170	1964	TO 1971
3F07/171	1964	TO 1971
3F07/172	1964	TO 1971
3F07/173	1964	TO 1971
3F07/174	1964	TO 1971
3F07/175	1964	TO 1971
3F07/176	1964	TO 1971
3F07/177	1964	TO 1971
3F07/178	1964	TO 1971
3F07/179	1964	TO 1971
3F07/180	1964	TO 1971
3F07/181	1964	TO 1971
3F07/182	1964	TO 1971
3F07/183	1964	TO 1971
3F07/184	1964	TO 1971
3F07/185	1964	TO 1971
3F07/186	1964	TO 1971
3F07/187	1964	TO 1971
3F07/188	1964	TO 1971
3F07/189	1964	TO 1971
3F07/190	1964	TO 1971
3F07/191	1964	TO 1971
3F07/192	1964	TO 1971
3F07/193	1964	TO 1971
3F07/194	1964	TO 1971
3F07/195	1964	TO 1971
3F07/196	1964	TO 1971
3F07/197	1964	TO 1971
3F07/198	1964	TO 1971
3F07/199	1964	TO 1971
3F07/200	1964	TO 1971
3F07/201	1964	TO 1971
3F07/202	1964	TO 1971
3F07/203	1964	TO 1971
3F07/204	1964	TO 1971
3F07/205	1964	TO 1971
3F07/206	1964	TO 1971
3F07/207	1964	TO 1971
3F07/208	1964	TO 1971
3F07/209	1964	TO 1971
3F07/210	1964	TO 1971
3F07/211	1964	TO 1971
3F07/212	1964	TO 1971
3F07/213	1964	TO 1971
3F07/214	1964	TO 1971
3F07/215	1964	TO 1971
3F07/216	1964	TO 1971
3F07/217	1964	TO 1971
3F07/218	1964	TO 1971
3F07/219	1964	TO 1971
3F07/220	1964	TO 1971
3F07/221	1964	TO 1971
3F07/222	1964	TO 1971
3F07/223	1964	TO 1971
3F07/224	1964	TO 1971
3F07/225	1964	TO 1971
3F07/226	1964	TO 1971
3F07/227	1964	TO 1971
3F07/228	1964	TO 1971
3F07/229	1964	TO 1971
3F07/230	1964	TO 1971
3F07/231	1964	TO 1971
3F07/232	1964	TO 1971
3F07/233	1964	TO 1

Table A.5

AVERAGE RAINFALL IN SOUTH-EASTERN CATCHMENT

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD	
3044/87	1924	TO 1952
3045/34	1918	TO 1952
3046/31	1916	TO 1971
3047/37	1904	TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	MM	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL RAINFALL
1921-22	2	119	216	145	57	44	89	39	44	30	20	49	20	1012
1922-23	2	101	142	48	162	49	81	52	16	3	32	7	11	701
1923-24	2	49	49	120	26	260	125	36	215	92	31	27	127	992
1924-25	2	55	163	177	122	162	115	64	143	13	72	7	21	1062
1925-26	2	104	55	76	16	158	169	37	17	36	64	11	72	935
1926-27	2	41	54	127	111	76	140	36	76	32	61	19	46	815
1927-28	2	14	49	74	137	152	56	94	64	21	17	58	24	980
1928-29	2	41	21	64	126	24	192	62	27	65	27	70	65	1035
1929-30	2	30	76	27	244	54	171	35	21	27	38	44	46	988
1930-31	2	35	91	74	27	67	66	14	18	35	7	24	5	508
1931-32	2	67	76	93	71	134	264	161	119	24	3	11	17	1236
1932-33	2	14	59	117	162	58	28	10	11	3	10	26	25	663
1933-34	2	25	101	113	134	124	94	44	47	51	38	22	34	853
1934-35	2	74	34	110	14	74	76	106	132	15	34	15	46	781
1935-36	2	38	35	42	142	202	183	80	158	26	44	14	49	953
1936-37	2	79	201	14	157	211	196	94	61	31	7	40	31	1126
1937-38	2	24	114	24	111	163	57	41	35	42	39	33	100	763
1938-39	2	37	51	74	24	24	150	102	43	20	20	50	15	610
1939-40	2	21	22	44	75	89	150	100	160	30	143	44	32	1052
1940-41	2	41	54	78	137	27	81	29	73	34	16	14	43	672
1941-42	2	49	232	61	75	25	212	64	52	38	56	45	77	1009
1942-43	2	44	110	154	61	52	204	210	38	24	115	82	24	1154
1943-44	2	143	158	47	27	121	96	28	14	28	42	18	185	893
1944-45	2	45	140	41	72	124	234	28	28	14	3	24	5	764
1945-46	2	21	27	112	111	45	121	61	25	10	9	15	25	623
1946-47	2	72	45	101	52	226	145	45	51	26	58	39	74	1007
1947-48	2	43	150	114	54	110	92	43	5	20	3	16	7	659
1948-49	2	40	119	48	102	137	41	247	12	49	15	15	45	917
1949-50	2	110	76	24	107	196	126	62	25	32	38	45	31	867
1950-51	2	46	28	144	91	28	87	48	26	42	37	130	42	708
1951-52	2	15	5	102	81	67	40	46	126	19	52	3	16	572
1952-53	2	62	114	107	132	64	74	17	28	2	27	26	25	712
1953-54	2	30	142	158	74	98	232	67	36	46	108	15	28	1064
1954-55	2	222	25	16	114	51	214	93	42	16	3	47	40	828
1955-56	2	63	132	74	28	102	132	58	23	42	16	4	23	741
1956-57	2	118	145	91	152	119	126	26	19	5	5	36	134	1008
1957-58	2	114	34	114	71	115	112	18	35	32	14	5	34	748
1958-59	2	49	15	44	13	53	34	11	43	5	1	24	11	343
1959-60	2	142	84	113	4	152	74	47	12	22	22	59	32	763
1960-61	2	42	25	282	82	129	5	72	24	47	9	12	27	726
1961-62	2	42	114	107	132	64	74	17	28	2	27	26	25	712
1962-63	2	30	142	158	74	98	232	67	36	46	108	15	28	1064
1963-64	2	222	25	16	114	51	214	93	42	16	3	47	40	828
1964-65	2	63	132	74	28	102	132	58	23	42	16	4	23	741
1965-66	2	118	145	91	152	119	126	26	19	5	5	36	134	1008
1966-67	2	114	34	114	71	115	112	18	35	32	14	5	34	748
1967-68	2	49	15	44	13	53	34	11	43	5	1	24	11	343
1968-69	2	142	84	113	4	152	74	47	12	22	22	59	32	763
1969-70	2	42	25	282	82	129	5	72	24	47	9	12	27	726
1970-71	2	47	91	45	71	127	94	25	48	30	14	19	46	667
1971-72	2	14	41	77	161	213	46	49	54	39	30	14	19	767
MEAN	##	59	77	104	86	113	123	72	56	41	34	38	53	1000
ANNUAL MEAN	%	5	7	10	8	11	12	7	5	4	3	4	5	100

Table A.6

AVERAGE RAINFALL IN SOUTH-EASTERN COASTAL CATCHMENT

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD	
3044/861	1918	TO 1924
3045/341	1916	TO 1952
3046/31A	1916	TO 1971
3047/37A	1904	TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	MM	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL RAINFALL
1921-22	2	148	261	175	93	57	144	52	66	44	28	101	30	1404
1922-23	2	127	170	59	255	63	134	71	25	5	49	12	17	1,003
1923-24	2	62	84	161	42	334	178	145	46	25	41	25	172	1297
1924-25	2	68	204	216	146	204	144	107	200	21	74	10	109	1967
1925-26	2	146	123	95	41	88	214	54	24	38	13	40	100	1956
1926-27	2	58	84	164	146	61	72	53	38	30	15	14	68	1204
1927-28	2	24	68	103	172	167	124	108	224	37	43	27	41	1178
1928-29	2	57	31	84	154	32	240	84	124	102	35	142	84	1989
1929-30	2	40	95	39	305	82	220	58	42	48	59	65	132	1144
1930-31	2	51	134	95	41	104	95	24	32	48	9	34	8	645
1931-32	2	78	89	118	95	167	334	195	154	35	4	15	24	1,509
1932-33	2	16	69	146	434	228	101	160	84	26	26	35	34	1361
1933-34	2	30	127	128	45	154	130	57	58	74	44	24	46	1,017
1934-35	2	86	42	138	20	94	108	134	123	122	138	107	68	1209
1935-36	2	52	48	54	191	281	241	101	195	33	59	23	76	1,305
1936-37	2	96	241	20	198	264	244	114	69	43	9	57	38	1,393
1937-38	2	29	147	28	141	203	72	52	44	54	49	42	124	985
1938-39	2	46	64	94	30	30	190	129	54	25	25	63	19	769
1939-40	2	26	28	56	94	111	190	126	202	38	180	55	40	1,326
1940-41	2	52	68	98	173	34	102	36	92	43	20	18	54	850
1941-42	2	62	293	77	94	31	268	81	66	48	71	57	97	1,274
1942-43	2	56	139	195	77	66	258	265	48	30	145	104	30	1,456
1943-44	2	181	200	59	34	153	121	35	18	35	53	23	234	1,126
1944-45	2	57	177	52	91	157	296	35	35	18	4	30	6	964
1945-46	2	27	34	142	140	57	153	77	32	13	11	19	32	787
1946-47	2	91	57	128	66	286	183	57	65	33	73	49	94	1,273
1947-48	2	54	190	144	68	139	116	54	6	25	4	20	9	834
1948-49	2	50	151	61	129	173	52	312	15	62	19	19	57	1,160
1949-50	2	139	96	30	135	248	159	78	32	40	48	57	39	1,097
1950-51	2	58	35	182	114	67	173	54	67	31	47	164	53	1,004
1951-52	2	19	6	129	102	84	50	58	159	24	66	4	20	724
1952-53	2	31	144	135	168	81	94	21	35	3	34	33	100	901
1953-54	2	38	180	200	94	124	293	85	45	58	137	19	35	1,348
1954-55	2	281	32	20	144	64	271	118	53	20	4	59	51	1,049
1955-56	2	80	167	94	35	129	167	73	29	53	20	5	29	938
1956-57	2	149	184	115	192	151	159	33	24	6	6	46	170	1,276
1957-58	2	144	43	144	90	146	142	23	44	41	18	6	43	946
1958-59	2	62	19	56	16	67	43	14	54	6	1	30	14	434
1959-60	2	180	106	143	5	192	94	59	15	28	28	75	41	966
1960-61	2	53	32	356	104	163	6	91	30	59	11	15	34	918
1961-62	2	53	144	135	168	81	94	21	35	3	34	33	100	901
1962-63	2	38	180	200	94	124	293	85	45	58	137	19	35	1,348
1963-64	2	281	32	20	144	64	271	118	53	20	4	59	51	1,049
1964-65	2	80	167	94	35	129	167	73	29	53	20	5	29	938
1965-66	2	149	184	115	192	151	159	33	24	6	6	46	170	1,276
1966-67	2	144	43	144	90	146	142	23	44	41	18	6	43	946
1967-68	2	62	19	56	16	67	43	14	54	6	1	30	14	434
1968-69	2	180	106	143	5	192	94	59	15	28	28	75	41	966
1969-70	2	53	32	356	104	163	6	91	30	59	11	15	34	918
1970-71	2	47	91	45	71	127	94	25	48	30	14	19	46	667
1971-72	2	14	41	77	161	213	46	49	54	39	30	14	19	767
MEAN	##	79	104	106	113	123	142	94	62	42	34	42	67	1,106
ANNUAL MEAN	%	7	9	10	10	11	13	8	6	4	3	4	6	100

Table A.7

AVERAGE RAINFALL IN SOUTH-EASTERN CATCHMENT

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD	
3047 44	1921	TO 1971
3047/37	1921	TO 1971
3047/38A	1,920	TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	MM	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL RAINFALL
1921-22	1	142	305	214	80	116	135	52	76	44	31	96	31	1,443
1922-23	1	151	226	77	279	79	97	77	31	7	54	15	17	1,041
1923-24	1	79	81	196	58	357	170	152	69	31	46	28	144	1,410
1924-25	1	89	259	265	183	242	176	115	234	25	101	15	112	2,021
1925-26	1	148	123	95	41	88	214	54	24	38	13	40	100	1,001
1926-27	1	58	84	164	146	61	72	53	38	30	15	14	68	1,204
1927-28	1	66	73	145	167	189	157	119	243	39	43	27	41	1,309
1928-29	1	57	31	84	154	32	240	84	124	102	35	142	84	1,089
1929-30	1	40	95	39	305	82	220	58	42	48	59	65	132	1,144
1930-31	1	51	134	95	41	104	95	24	32	48	9	34	8	645
1931-32	1	78	89	118	95	167	334	195	154	35	4	15	24	1,509
1932-33	1	92	130	92	114	206	198	101	152	38	25	38	34	1,061
1933-34	1	84	102	146	121	147	130	46	57	22	76	24	21	1,076
1934-35	1	66	112	119	201	142	91	123	122	138	107	68	38	1,346
1935-36	1	96	82	278	19	74	82	169	274	25	12	31	1,305	
1936-37	1	28	71	247	215	218	147	44	179	47	54	27	1,393	
1937-38	1	122	200	25	172	206	246	44	32	28	9	57	38	1,129
1938-39	1	87	141	234	123	197	197	60	69	43	54	63	152	1,424
1939-40	1	77	32	142	224	167	72	106	61	74	46	46	146	1,474
1940-41	1	74	262	52	126	30	266	152	296	104	34	101	45	1,664
1941-42	1	81	224	182	73	28	34	22	72	26	22	24	80	1,071
1942-43	1	34	135	35	153	45	259	40	82	67	137	1,106		
1943-44	1	36	112	274	55	27	238	18	24	28	42	18	185	1,057
1944-45	1	140	70	69	29	84	126	52	24	114	28	24	178	1,052
1945-46	1	87	122	87	52	124	121	61	25	10	9	15	25	1,023
1946-47	1	67	38	25	152	28	212	196	74	21	9	52	48	975
1947-48	1	54	150	114	68	124	92	43	6	25	4	20	9	734
1948-49	1	40	119	48	102	137	41	247	12	49	15	15	45	917
1949-50	1	110	76	24	107	196	126	62	25	32	38	45	31	867
1950-51	1	46	28	144	91	28	87	48	26	42	37	130	42	708
1951-52	1	15	5	102	81	67	40	46	126	19	52	3	16	572
1952-53	1	62	114	107	132	64	74	17	28	2	27	26	25	712
1953-54	1	30	142	158	74	98	232	67	36	46	108	15	28	1064
1954-55	1	222	25	16	114	51	214	93	42	16	3	47	40	828
1955-56	1	63	132	74	28	102	132	58	23	42	16	4	23	741
1956-57	1	118	145	91	152	119	126	26	19	5	5	36	134	1008
1957-58	1	114	34	114	71	115	112	18	35	32	14	5	34	748
1958-59	1	49	15	44	13	53	34	11	43	5	1	24	11	343
1959-60	1	142	84	113	4	152	74	47	12	22	22	59	32	763
1960-61	1	42	25	282	82	129	5	72	24	47	9	12	27	726
1961-62	1	42	114	107	132	64	74	17	28	2	27	26	25	712
1962-63	1	30	142	158	74	98	232	67	36	46	108	15	28	1064
1963-64	1	222	25	16	114	51	214	93	42	16	3	47	40	828
1964-65	1	63	132	74	28	102	132	58	23	42	16	4	23	741
1965-66	1	118	145	91	152	119	126	26	19	5	5	36	134	1008
1966-67	1	114	34	114	71	115	112	18	35	32	14	5	34	748
1967-68	1	49	15	44	13	53	34	11	43	5	1	24	11	343
1968-69	1	142	84	113	4	152	74	47	12	22	22	59	32	763
1969-70	1	42	25	282	82	129	5	72	24	47	9	12	27	726
1970-71	1	47	91	45	71	127	94	25	48	30	14	19	46	667
1971-72	1	14	41	77	161	213	46	49	54	39	30	14	19	767
MEAN	##	79	104	106	113	123	142	94	62	42	34	42	67	1,106
ANNUAL MEAN	%	7	9	10	10	11	13	8	6	4	3	4	6	100

APPENDIX B - Mathematical catchment model

Brief description of the model*

A gaphical description of the model is given in figure B.1. Data input for the model consists of monthly rainfall and evaporation. Some of the precipitation is intercepted, while some is kept in depression and soil moisture storage from where losses to evapotranspiration occur. The remainder appears as surface runoff. Part of the soil moisture reaches surface channels via interflow. Each component contributing to the outflow from the catchment has to be suitably lagged. To improve the sensitivity, monthly rainfall data is broken down into quarter-monthly units and computations are carried out at quarter-monthly time steps.

Evaporation losses from intercepted water is modelled as a function of interception storage (PI), monthly rainfall and total interception loss. The remaining rainfall is then split into surface runoff and absorbed rainfall. AI, the proportion of the catchment that is impervious, and Zmin and Zmax, the minimum and maximum absorbtion rates for the remaining catchment, determine the surface runoff.

The quantity of soil moisture lost to evaporation is controlled by the potential evaporation for the month, the soil moisture storage, S, the total soil moisture storage capacity, ST, and the factor R (that determines the rate at which evaporation decreases from potential at S=ST to zero at a storage defined by R) and the potential evaporation. The soil moisture storage, S, is determined at each time step by satisfying the water balance of the catchment.

The quantity of soil moisture reaching the channel system depends on S and ST, as well as on SL (the soil moisture level below which no runoff from soil moisture occurs) and FT (the runoff from soil moisture at S=ST) and POW (the power of the assumed soil moisture-runoff curve).

TL is the time delay of runoff, while GL is the soil moisture lag. GW provides an upper limit to groundwater runoff.

The twelve catchment parameters are listed in table B.1.

* A detailed description can be found in reference 8.

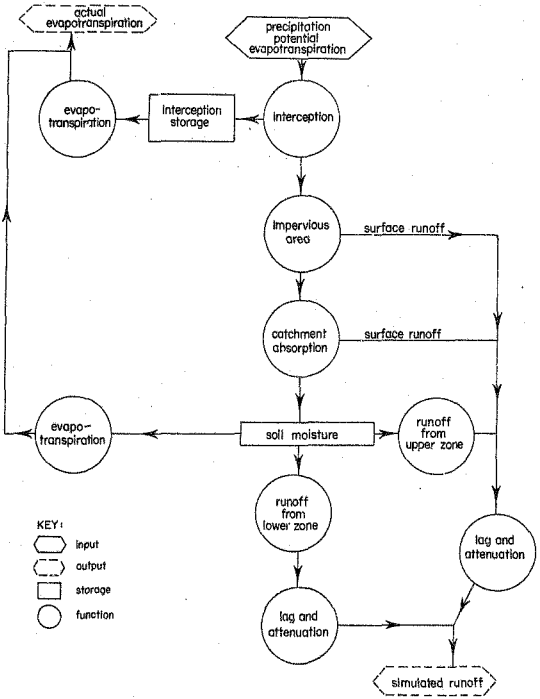

FIGURE B.1 CATCHMENT MODEL FLOWCHART

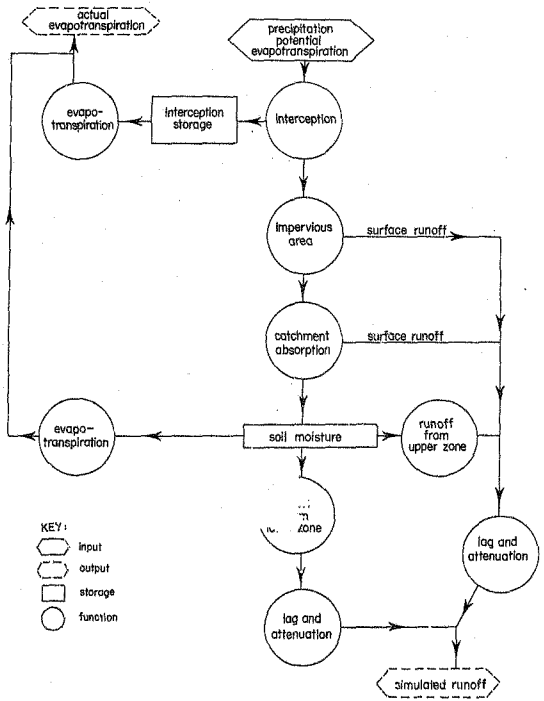

FIGURE B.1 CATCHMENT MODEL FLOWCHART

Table B.1 : Model parameters

parameter	units	description
POW	-	power of the soil moisture - runoff curve
SL	mm	soil moisture storage below which no runoff occurs from soil storage.
ST	mm	maximum soil moisture capacity.
FT	mm/month	runoff from soil moisture at full capacity.
GW	mm/month	maximum runoff from soil moisture.
AI	-	impervious proportion of catchment.
Z-min	mm/month	minimum absorbtion rate.
Z-max	mm/month	maximum absorbtion rate.
PI	mm	interception storage.
TL	months	lag of surface runoff.
GL	months	"groundwater" lag.
R	-	parameter determining evaporation - soil moisture storage relationship.

Table B.2 : Parameters selected after calibration with recorded data

gauge	POW	SL	ST	FT	GW	AI	Zmin	Zmax	PI	TL	GL	R
W1M01	3.0	0	250	25	0	0	5000	6000	1.8	.25	0	.5
W1M09	3.0	0	250	25	0	0	5000	6000	1.8	.25	0	.5
coastal * catchments	2.0	0	650	20	0	0	5000	6000	1.5	.25	0	.5

* The "coastal catchments" comprise the two small catchments north-east and south-west of Richards bay. (see figure 2.1)

APPENDIX C - Estimation of areas of land under sugar cane

Areas of farm lands falling within the Eshowe and Lower Umfolozi magisterial districts were measured from the relevant 1 : 50 000 topographical survey maps. The areas of farm land within these districts falling within the various catchment boundaries were also ascertained. It was thus possible to calculate the proportion of farm land falling within the catchment boundaries within each district. These areas and proportions are given in table C.1.

Table C.1 : Areas of farms within each sugar producing district

Area bounded by	District			
	Eshowe		Lower Umfolozi	
	ha	proportion	ha	proportion
catchment commanded by gauge W1M01	50	0.00	-	-
catchment commanded by gauge W1M09	3 510	0.18	8 450	0.16
Umhlatuzi catchment	4 090	0.21	14 310	0.27
Nsezi catchment	-	-	16 890	0.32
total district	19 530	1.00	52 650	1.00

The following data pertaining to areas of land under sugar in the two magisterial districts were abstracted from reference 15.

Table C.2 : Total area of land under sugar in the Eshowe and Lower Umfolozi districts from 1918 to 1961 (ha)

district	year				
	1918	1926	1930	1952	1961
Eshowe	286	2 501	6 285	7 008	12 540
Lower Umfolozi	4 978	19 080	21 710	23 450	29 890

These figures, along with projected future areas, are represented in figure C.1.

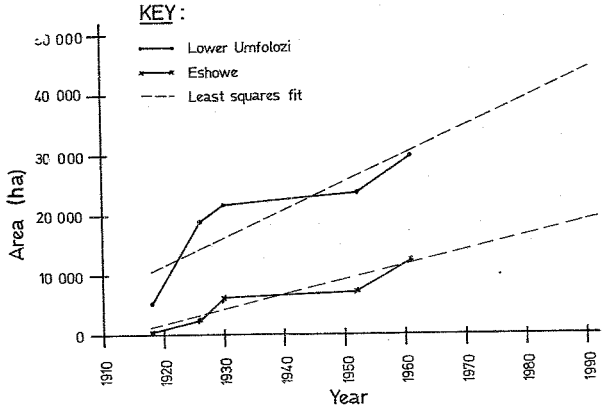

FIGURE C.1: Areas of land under sugar in the Eshowe and Lower Umfolozi magisterial dis icts

Table C.3 : Areas of land under sugar falling within catchment boundaries during relevant model calibration and simulation periods (ha)

catchment	district	simulation period			
		1921-39	1962-70	1970	1990
above W1M01	Eshowe	40			600
	Lower Umfolozi	-	n.a.	n.a.	-
	total	40			600
above W1M09	Eshowe		2 300		
	Lower Umfolozi	n.a.	5 300	n.a.	n.a.
	total		7 600		
Umhlatuzi	Eshowe			2 300	4 000
	Lower Umfolozi	n.a.	n.a.	9 500	12 000
	total			12 300	16 000
Nsezi	Eshowe			-	-
	Lower Umfolozi	n.a.	n.a.	11 100	14 100
	total			11 100	14 100
total	Eshowe	4 700	13 100	14 000	19 000
"	Lower Umfolozi	19 600	33 400	35 100	44 500

It was assumed that the areas of land under sugar in each sub-catchment would remain in the same proportions as those of the cultivated lands shown in table C.1. Table C.3 was compiled using the proportions in table C.1 along with projected future areas in figure C.1.

APPENDIX D - Flood hydrographs for various recurrence interval storms

APPENDIX E - Survey datum

All topographical heights and water levels in this report have as datum the LWOST defined by the Hydraulics Research Division of the Council for Scientific and Industrial Research[16]. This is the datum that was used by the CSIR in all reports prior to 1971.

All sea levels used in this study were obtained from the S.A. Navy tide recorder located at Salisbury Island inside Durban Bay. These records are considered by the Navy to be unreliable prior to October 1970. For the period October - November 1970 the tide recorder datum at Salisbury Island was 0,370 metres below that of the SAR & H recorder at Durban[17]. It should be noted that this correction cannot be applied to other time periods as the positions of these recorders relative to each other has varied in the past.

All datum levels at Richards Bay pertinant to this study are shown in figure E.1. It should be noted that all SAR & H working drawings and CSIR reports subsequent to 1971 are relative to LWOST (SAR) which is -0,900 m GMSL.

∇ +0,200 m GMSL	Actual MSL Durban (AMSL). Average for period September 1970 to January 1974.
∇ 0,000 m GMSL	Geodetic MSL Durban (GMSL).
∇ -0,741 m GMSL	LWOST (HRD).
∇ -0,831 m GMSL	SAR & H tide recorder datum at Durban.
∇ -0,900 m GMSL	Chart datum ≈ LWOST (SAR).
∇ -1,201 m GMSL	S.A. Navy tide recorder datum at Salisbury Island inside Durban Bay.

Scale 1 : 10

FIGURE E.1 : Relationship between LWOST (HRD) at Richards Bay and other datum levels relevant to this study

Author Herold C E
Name of thesis Mathematical Modelling Of Some Aspects Of The Water And Salt Circulation In The Richards Bay - Umhlatuzi System. 1976

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