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

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

LIST OF TABLES

LIST OF FIGURES

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-bar 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. shown in figure 2.1, is defined for the purposes of this st e bay itself, the two large river catchments feeding from 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

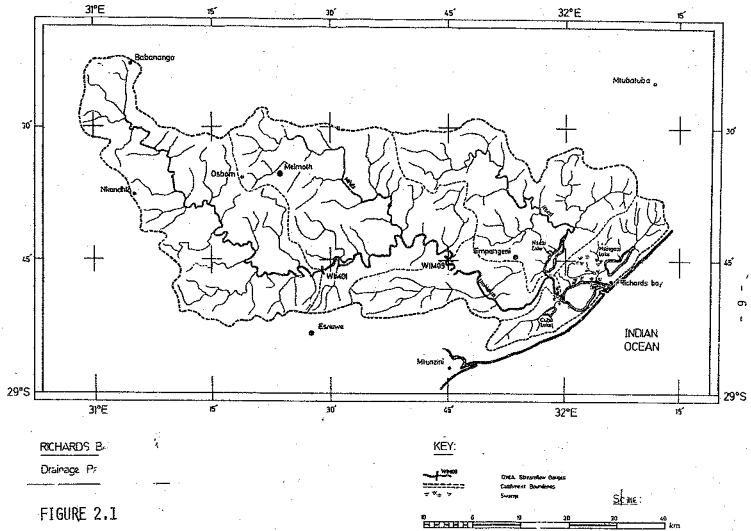
Monthly rainfall records were abstacted from the records of the Weather Bureau, Department of Transport[5]. The locations of the recording stations used, as well as mean annual isohyets, are shown in figure 2.3. These isohyets were drawn among annual precipitation values for the stations indicated. Mean 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 2.3.

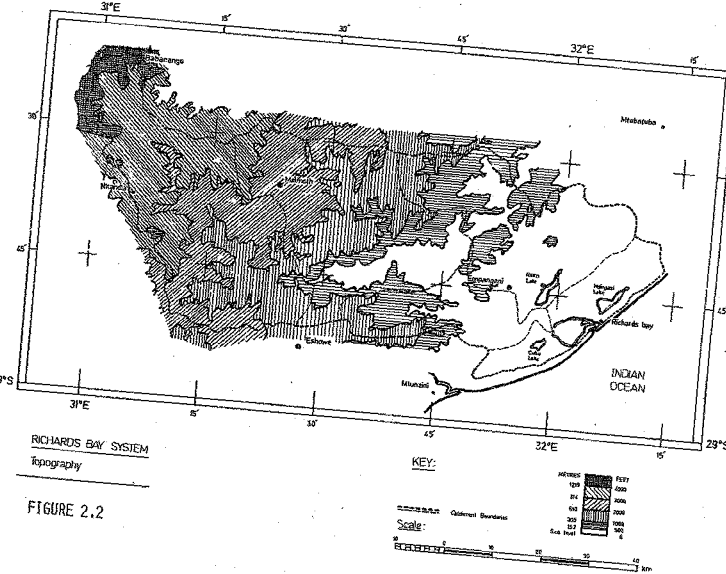
For each catchment monthly rainfall records expressed as percentages of catchment MAP are reproduced in tables A.1 to A.7 in Appendix A. The precipitation records have been presented in this form for



RICHARDS B

Drainage P

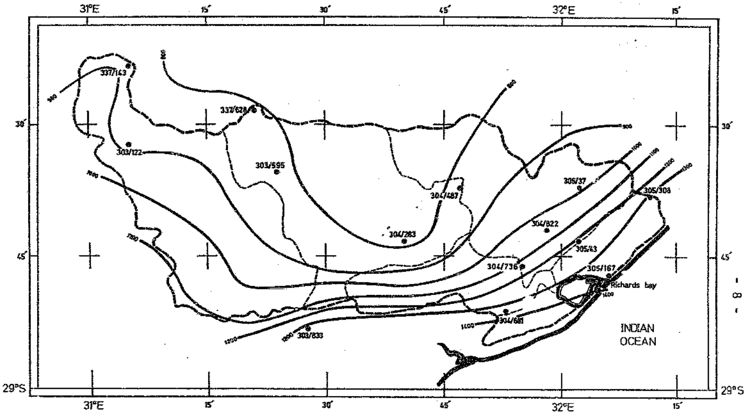
FIGURE 2.1



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

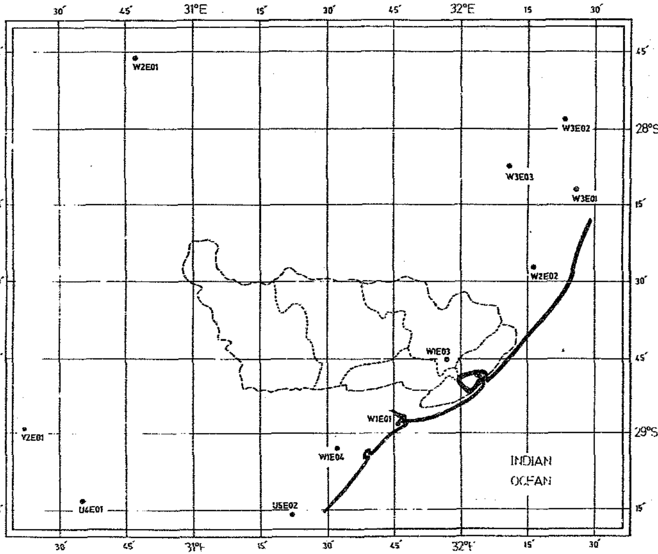
Table 2.1 : Details of rainfall stations

No.	Station number	Station name	Lat. ° '	Long. ° '	MAP mm	Period of 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-Mbonabi-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 number	Station name	Lat. ° '	Long. ° '	Mean annual Symons pan potential evaporation mm	Date station opened
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	Muden	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.



KEY:

W1E01 D.W.A. Evaporation pan

Scale:

10 0 10 20 30 40

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[6] 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:

$$E_s = 0{,}625\ E_A + 280\ \text{mm} \qquad \text{.....................(2.1)}$$

where E_s = 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 tabl s 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 ($m^3 \times 10^6$)

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

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

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

where log has the base 10.

(3) Standard deviation of the log of annual runoff

$$= SL = \sqrt{\frac{\sum_{i=1}^{n} (\log T_i)^2 - \frac{1}{n} (\sum_{i=1}^{n} \log T_i)^2}{n - 1}} \quad \ldots\ldots (2.4)$$

(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	20.29	17.40	13.09	15.00	10.92	9.86	8.56	7.88	8.10	6.44	167.30	167.30
1922	8.28	18.03	15.40	24.49	16.87	14.55	10.91	8.87	7.30	7.86	6.40	5.50	148.96	316.26
1923	4.35	8.19	13.04	7.13	9.51	8.98	7.44	5.44	4.30	4.18	4.24	4.55	59.38	375.64
1924	6.34	21.88	27.81	22.00	22.50	441.44	203.33	26.00	25.00	22.09	14.40	19.41	868.76	1265.00
1925	17.00	16.05	12.66	9.87	10.71	12.60	11.47	10.14	13.67	7.67	6.84	12.59	145.81	1405.96
1926	13.30	16.53	12.66	7.30	8.84	16.82	11.35	6.67	5.82	5.87	7.15	5.56	117.30	1523.30
1927	5.64	6.87	9.16	27.10	14.14	7.77	8.75	6.12	4.88	4.76	5.04	4.20	102.07	1625.37
1928	5.03	3.88	3.25	8.86	3.60	12.74	6.59	4.56	6.58	5.07	4.33	4.43	66.31	1691.68
1929	7.06	14.16	7.64	14.88	7.16	14.10	11.33	8.31	5.62	5.17	5.46	5.20	110.49	1801.37
1930	6.55	6.14	5.33	8.46	4.10	3.18	3.46	3.85	2.61	3.02	2.43	2.45	50.72	1852.19
1931	4.00	4.47	6.77	2.53	131.60	74.18	11.00	26.50	13.19	8.82	6.68	6.06	296.30	2148.49
1932	5.50	15.45	7.13	6.43	4.07	5.41	3.87	3.81	2.78	3.10	2.77	2.40	56.87	2205.36
1933	2.84	10.43	16.31	55.32	11.37	18.00	11.03	8.18	8.65	5.65	8.48	4.53	160.25	2365.61
1934	4.01	8.58	23.18	15.10	13.92	11.76	8.35	7.72	7.72	6.06	8.75	4.53	170.97	2536.58
1935	3.21	15.61	3.07	14.80	10.20	8.80	10.42	13.38	7.61	6.68	8.04	6.19	115.13	2651.71
1936	7.08	18.78	14.87	11.73	13.81	13.34	7.32	4.80	4.88	4.70	4.73	4.09	109.89	2761.60
1937	3.44	4.86	13.72	8.07	111.13	83.87	10.30	7.61	8.13	8.16	6.22	3.38	237.96	2999.56
1938	4.94	2.56	14.33	9.76	82.88	17.30	10.52	8.54	6.60	7.10	4.38	3.41	177.81	3177.37
1939	10.40	26.88	12.83	8.32	12.65	6.02	7.71	26.77	40.80	13.70	8.57	6.23	298.40	3475.77
% TOTAL	3.83	5.38	8.01	8.11	14.83	22.12	10.70	7.40	5.83	4.15	3.54	3.28	100.00	

MEAN LOG= 2.148208 STD. DEV.= .283704 MEAN ANNUAL RUNOFF= 180.30 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
1962	4.33	13.31	8.80	18.42	64.68	30.68	20.33	5.03	4.06	101.05	5.35	5.82	285.96	285.96
1963	4.50	5.34	3.61	63.31	12.42	2.80	7.80	6.48	3.87	3.22	1.39	1.10	111.34	397.30
1964	4.25	5.40	10.84	8.52	9.81	.53	.08	.03	2.31	2.44	1.17	1.71	45.56	442.86
1965	5.87	14.05	13.70	37.27	28.33	3.60	1.74	1.08	2.20	.99	.26	0.00	108.99	551.85
1966	.84	7.24	16.77	12.13	103.10	46.27	38.42	15.83	4.73	1.05	2.31	1.66	248.31	800.16
1967	7.83	10.81	17.67	2.67	8.67	41.46	3.88	.92	.55	.30	4.06	1.77	100.47	900.63
1968	2.72	3.38	80.57	3.64	6.01	61.87	34.03	22.41	7.63	4.11	2.00	3.60	231.86	1132.49
1969	24.07	16.71	9.32	1.41	7.82	5.40	1.24	6.13	4.10	1.85	2.61	0.70	95.28	1227.77
1970	.64	25.80	15.65	16.84	5.24	3.79	10.46	108.18	31.75	24.05	13.89	2.55	274.00	1501.77
% TOTAL	3.67	4.74	11.73	10.71	16.24	13.04	7.61	10.87	4.15	9.45	2.02	2.18	100.00	

MEAN LOG= 2.180110 STD. DEV.= .270314 MEAN ANNUAL RUNOFF= 166.86 MILLION CUBIC METERS

Table 2.7 : Synthesized runoff at gauge W1M01

FO = 3.0 SL= 0.MM ST= 250.MM FT= 25.0 MM/MONTH OT= 0.0 MM/MONTH AI= 0.0 %

ZMIN= 5000.MM/MONTH ZMAX= 6000.MM/MONTH PI= 1.2 MM/DAY GL=0.00 MONTHS TL= .25 MONTHS HI= 4/MONTH

P.EVAP.	104.0	140.0	185.0	150.0	135.0	130.0	95.0	82.0	65.0	56.0	74.0	98.0 MM = MM .8	
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	2.25	10.40	13.10	13.12	7.92	4.38	5.75	6.05	4.54	4.63	5.80	5.02	87.32
1922	7.60	15.04	14.11	22.80	18.11	8.75	5.22	3.10	3.01	1.66	1.57	1.42	102.58
1923	1.59	3.20	4.24	6.15	8.37	6.70	7.11	6.63	3.85	2.67	2.21	3.42	84.52
1924	5.13	26.06	23.62	20.76	21.46	504.82	184.57	18.02	10.89	8.33	4.89	6.83	836.06
1925	10.44	11.70	8.98	5.80	4.24	3.60	9.55	5.76	8.28	8.88	4.06	4.87	84.65
1926	10.27	14.70	15.77	6.43	7.40	14.20	12.80	7.01	4.11	3.88	4.31	4.21	109.36
1927	6.33	6.77	4.58	2.30	11.13	0.74	4.05	4.80	2.89	3.19	2.10	3.20	71.42
1928	3.23	3.20	2.56	3.04	3.37	10.42	13.46	9.40	6.58	7.10	4.89	6.19	71.56
1929	0.57	14.30	11.67	13.84	15.03	12.26	11.47	8.51	5.61	3.73	3.57	4.57	115.07
1930	6.84	6.65	7.88	8.66	7.98	6.06	3.70	2.71	1.93	1.04	1.81	1.43	56.74
1931	2.63	4.26	4.32	3.72	104.47	71.53	23.46	27.78	30.12	10.65	5.79	3.98	312.78
1932	3.60	4.62	7.57	8.20	8.06	6.89	4.45	3.81	1.80	1.05	2.14	1.05	54.28
1933	2.10	8.40	17.45	68.40	33.33	16.23	17.11	16.38	11.44	8.85	8.13	7.62	218.74
1934	8.36	7.12	33.30	39.16	13.12	8.05	6.04	5.32	8.64	5.87	4.61	3.20	147.75
1935	2.70	3.13	3.04	7.66	16.18	10.35	13.29	11.80	11.83	7.64	4.48	3.36	104.58
1936	5.13	13.74	12.26	10.08	14.00	12.33	7.01	3.88	2.88	2.47	2.06	2.41	88.32
1937	3.85	2.40	65.01	58.80	133.40	82.24	27.11	18.40	10.83	11.10	8.30	6.70	406.50
1938	7.18	7.14	11.57	13.68	93.88	47.03	16.65	15.36	7.11	6.43	5.33	4.52	233.88
1939	8.56	30.45	22.28	14.58	8.37	6.05	7.36	77.74	42.88	16.72	8.00	6.13	249.01
% TOTAL	3.01	5.71	8.86	9.76	14.11	24.10	11.17	7.07	4.70	3.30	2.48	2.42	100.00

MEAN LOG= 2.118043 STD. DEV.= .328126 MEAN ANNUAL RUNOFF= 181.06 MILLION CUBIC METERS

Table 2.8 : Synthesized runoff at gauge W1M09

FO = 3.0 SL= 0.MM ST= 250.MM FT= 25.0 MM/MONTH OT= 0.0 MM/MONTH AI= 0.0 %

ZMIN= 5000.MM/MONTH ZMAX= 6000.MM/MONTH PI= 1.8 MM/DAY GL=0.00 MONTHS TL= .25 MONTHS HI= 4/MONTH

P.EVAP.	104.0	140.0	155.0	150.0	135.0	130.0	95.0	82.0	65.0	56.0	74.0	98.0 MM = MM .8	
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1962	4.14	12.30	17.36	23.60	18.10	26.80	30.00	14.82	13.76	105.10	50.28	10.80	330.70
1963	8.10	10.00	1.43	17.00	15.55	6.48	8.04	4.78	3.06	3.28	.84	.71	81.80
1964	10.70	13.78	13.32	4.56	3.58	1.34	.60	.78	4.93	4.73	.65	5.86	66.80
1965	13.60	17.30	13.73	26.70	31.13	12.80	8.44	5.04	2.82	1.30	.68	.78	135.35
1966	1.64	6.21	12.30	32.00	100.30	68.04	36.80	31.60	8.78	6.34	1.40	.88	318.19
1967	7.80	18.80	14.56	6.64	4.18	13.60	7.80	3.70	.72	.63	6.60	6.13	91.16
1968	7.20	9.03	23.70	18.52	5.74	83.50	37.58	23.36	13.80	8.08	3.02	4.34	238.77
1969	17.00	16.40	6.20	1.74	.02	1.73	2.48	6.62	8.38	3.10	3.44	0.59	76.77
1970	44.30	30.70	17.00	30.20	10.76	8.06	14.82	40.80	52.80	25.10	18.12	10.48	303.84
% TOTAL	6.15	9.43	7.92	8.17	14.36	12.82	9.27	7.67	5.63	10.06	5.63	3.22	100.00

MEAN LOG= 2.158467 STD. DEV.= .277031 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:

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

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

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:

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

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	273

Table 2.10 : Source data used to synthesize runoffs from catchments

No.	Catchment			Synthesization components		
	Name	Area km²	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	Msezi 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

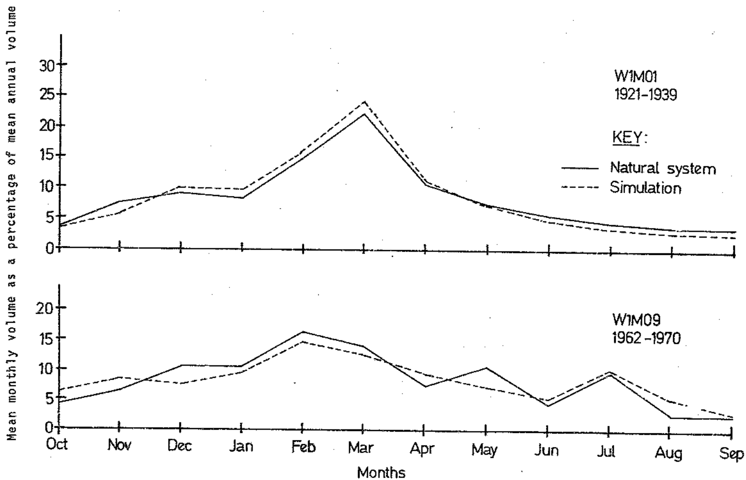


FIG.2.5: Richards bay System
Mean monthly runoff distribution-measured and simulated

Table 2.11 : Synthesized runoff from catchment No. 1 for undeveloped conditions ($m^3 \times 10^6$)

PORW 3.0 SL= 0.82 ST= 250.MM FT= 25.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %
ZMIN= 5000.MM/MONTH ZMAX= 6000.MM/MONTH PI= 1.5 MM/DAY GL=0.00 MONTHS TL= .25 MONTHS R= 4/MONTH

P-EVAP=	104.0	140.0	155.0	150.0	126.0	130.0	95.0	82.0	45.0	56.0	74.0	98.0 MM = PM .5
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	4.06	22.59	42.51	35.04	16.51	13.25	11.84	10.49	10.46	10.07	13.24	13.52	203.57
1922	17.29	30.00	36.22	33.03	32.50	10.89	10.77	4.74	4.66	4.25	4.19	3.49	193.29
1923	3.37	5.13	15.31	9.81	8.48	11.84	54.28	12.35	9.30	7.49	4.40	9.04	109.05
1924	13.83	33.40	46.25	46.88	47.26	1215.81	442.42	46.33	33.52	25.46	20.23	19.56	1987.58
1925	24.45	25.35	15.08	11.19	7.81	15.76	18.65	13.47	11.91	12.56	9.38	8.05	177.54
1926	19.30	26.40	21.13	13.41	15.58	20.69	28.53	18.32	12.89	13.63	13.24	11.37	275.57
1927	16.22	16.51	13.85	16.44	24.08	30.65	15.28	12.52	9.72	7.44	4.90	4.31	169.18
1928	7.41	6.67	4.56	8.34	9.85	66.26	50.34	25.55	18.01	17.75	15.21	15.50	245.54
1929	20.33	14.43	15.41	33.07	33.46	21.42	17.36	14.19	10.10	8.22	8.17	10.30	214.15
1930	11.54	11.81	12.77	12.90	18.03	7.04	5.84	4.87	3.61	4.09	4.09	3.78	97.66
1931	5.34	8.97	5.08	8.54	394.36	133.97	54.13	45.34	51.20	25.48	13.01	9.44	600.11
1932	7.47	10.01	14.78	15.71	18.50	12.53	7.95	4.03	3.48	3.58	4.21	4.19	104.91
1933	5.07	10.88	34.08	39.33	38.54	33.06	19.13	25.78	22.38	20.53	21.34	17.15	283.40
1934	12.05	14.92	151.62	74.36	24.18	17.72	13.75	11.80	14.01	22.75	19.49	14.85	391.53
1935	8.53	3.34	5.36	13.71	32.58	39.37	27.06	37.57	28.54	20.03	12.51	9.15	239.02
1936	11.60	30.04	27.40	21.31	38.68	34.17	31.15	11.23	8.11	8.12	9.32	8.07	226.45
1937	8.45	10.61	50.30	52.62	221.44	83.73	28.83	23.75	19.49	22.58	23.46	14.64	606.96
1938	14.38	15.22	16.29	32.44	214.75	107.40	36.14	25.30	20.42	19.42	16.84	15.40	537.79
1939	20.60	22.01	47.83	36.14	13.60	13.82	17.25	145.30	104.45	47.58	24.63	17.33	551.97
1940	14.33	21.34	18.31	49.98	19.38	13.48	11.87	11.18	9.42	8.76	7.33	7.16	258.06
1941	8.10	12.64	13.47	21.21	25.04	22.00	30.86	21.54	18.03	15.96	11.73	15.10	227.67
1942	17.74	33.74	83.63	55.61	34.68	33.33	316.75	103.45	33.19	33.36	56.17	45.05	785.84
1943	28.08	62.01	40.30	21.78	23.39	25.88	18.48	11.45	16.21	21.75	16.03	24.73	362.10
1944	34.67	25.80	15.54	43.26	16.12	161.78	76.35	30.61	12.88	9.60	6.07	4.61	403.68
1945	4.85	4.50	6.12	20.61	24.73	19.06	14.45	10.40	7.35	5.38	4.13	3.74	175.52
1946	2.23	14.96	13.37	18.12	30.31	30.53	30.28	18.16	15.14	14.88	12.57	11.71	221.40
1947	31.37	23.14	22.25	27.42	22.16	21.23	21.65	16.83	10.15	6.83	4.35	4.92	202.47
1948	4.50	12.11	13.09	15.26	22.24	25.22	68.62	46.88	24.15	14.16	58.43	9.75	268.07
1949	18.40	28.61	102.07	59.34	29.28	28.70	24.19	15.77	11.08	9.34	8.21	6.77	343.70
1950	6.13	6.10	15.33	14.60	10.47	8.45	8.57	8.53	6.48	5.96	15.50	25.12	[illegible]
1951	28.08	18.50	13.43	13.56	11.74	10.33	8.75	9.25	9.39	11.04	10.97	7.47	159.77
1952	6.55	11.86	36.61	18.70	21.37	18.20	14.08	7.89	6.04	5.24	5.28	6.51	174.34
1953	9.17	19.01	25.52	20.06	21.56	27.29	19.80	21.43	21.66	15.57	10.54	15.35	232.88
1954	150.64	51.28	26.63	22.74	25.25	114.27	67.46	30.73	58.48	11.13	7.40	6.31	497.79
1955	14.30	30.12	36.46	21.88	151.62	60.80	27.13	14.79	10.57	8.30	6.90	8.45	411.39
1956	13.49	36.25	265.41	186.63	41.10	38.11	33.80	28.09	36.41	14.86	14.83	209.47	972.82
1957	346.34	60.32	36.87	33.44	142.65	64.40	35.34	22.57	15.27	10.04	7.73	6.76	491.64
1958	9.62	33.36	16.30	39.04	30.72	18.71	8.16	9.81	10.36	7.47	8.58	15.02	177.20
1959	14.27	13.48	22.76	22.60	32.56	30.18	34.74	28.68	17.62	11.30	8.53	8.55	235.59
1960	10.83	67.45	265.47	126.73	41.33	30.06	36.31	37.26	27.21	19.30	12.11	11.91	720.00
1961	16.72	22.72	21.40	17.16	13.81	16.01	18.22	15.89	19.13	6.69	7.08	6.49	173.71
1962	9.56	20.70	26.89	30.55	26.93	23.84	38.78	26.55	21.17	198.03	93.44	20.20	546.39
1963	13.50	16.71	13.12	20.48	34.44	16.07	13.86	13.47	10.56	8.36	5.16	4.95	166.66
1964	15.30	21.65	20.37	14.04	9.54	6.35	5.80	5.42	9.71	12.83	14.65	16.31	147.79
1965	43.05	20.71	24.64	31.60	39.52	25.25	12.58	8.38	8.48	7.34	6.79	7.45	235.98
1966	8.22	18.83	15.70	25.38	134.67	39.86	82.60	48.30	19.91	12.74	9.97	6.97	455.59
1967	10.28	22.82	23.61	15.46	11.75	16.30	15.36	9.13	5.51	4.43	7.83	11.46	154.65
1968	13.26	14.72	25.08	27.85	26.23	106.11	54.81	22.74	24.15	15.98	9.88	9.96	387.19
1969	21.67	26.05	17.91	10.48	7.04	7.08	7.94	10.61	11.68	8.31	7.96	11.75	149.95
1970	28.43	42.21	26.56	25.19	23.86	19.49	21.67	132.53	71.90	33.22	76.07	18.20	277.03
1971	19.83	18.02	21.16	35.07	241.61	104.66	23.64	21.66	22.39	16.73	11.48	9.10	545.57
% TOTAL	6.33	6.36	11.75	8.40	13.18	17.34	10.71	7.37	5.10	4.55	3.86	4.26	100.00

MEAN LOG= 2.452501 STD. DEV.= .283231 MEAN ANNUAL RUNOFF= 358.47 MILLION CUBIC METERS

Table 2.12 : Synthesized runoff from catchment No. 2 for undeveloped conditions ($m^3 \times 10^6$)

PORW 3.0 SL= 0.82 ST= 250.MM FT= 25.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %
ZMIN= 5000.MM/MONTH ZMAX= 6000.MM/MONTH PI= 1.5 MM/DAY GL=0.00 MONTHS TL= .25 MONTHS R= 4/MONTH

P-EVAP=	104.0	140.0	155.0	150.0	126.0	130.0	95.0	82.0	45.0	56.0	74.0	98.0 MM = PM .5
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	1.81	37.81	42.43	15.60	4.70	4.10	3.86	3.86	3.48	3.27	4.17	3.51	128.71
1922	6.43	10.77	7.63	36.72	13.42	4.02	2.06	1.38	1.03	1.39	1.26	.87	76.94
1923	.64	.48	1.69	1.50	2.12	4.48	5.66	45.28	25.88	11.69	8.32	10.82	117.78
1924	10.18	14.54	26.94	16.04	38.01	432.11	151.09	40.61	20.18	10.04	7.60	6.94	760.09
1925	2.32	5.86	6.01	4.27	4.44	3.60	9.13	5.60	4.67	6.15	5.41	4.00	77.15
1926	6.22	6.68	6.26	6.50	8.64	8.17	7.76	4.94	4.10	4.49	5.65	4.66	77.98
1927	6.40	4.26	3.62	2.70	5.64	4.72	4.12	4.13	6.82	8.65	5.11	4.29	55.24
1928	3.08	1.61	.68	8.80	6.25	60.46	30.78	19.87	8.10	4.92	7.10	5.24	149.66
1929	8.38	6.23	2.84	8.51	8.80	10.37	9.59	5.93	4.34	5.14	5.01	8.30	91.11
1930	4.36	3.43	3.72	1.32	.88	1.24	1.61	1.45	1.42	1.04	1.62	1.67	23.86
1931	1.81	3.21	2.58	1.88	92.26	41.91	96.80	57.80	18.31	8.48	4.65	2.60	331.87
1932	2.12	3.13	6.35	4.86	4.66	3.08	1.73	1.05	.78	.92	1.15	1.39	29.44
1933	3.70	3.70	3.82	4.78	8.46	8.36	3.40	6.80	7.59	9.17	8.06	6.28	80.18
1934	4.29	4.07	6.20	7.80	4.45	3.66	3.33	5.32	17.63	14.50	11.60	8.55	93.46
1935	4.70	2.06	.81	2.38	10.69	12.83	8.34	10.78	11.06	9.90	6.60	4.69	88.54
1936	4.74	14.36	4.22	7.78	44.65	23.46	11.58	7.63	4.73	4.70	6.54	4.94	145.61
1937	3.36	3.77	35.90	10.16	24.71	13.30	4.10	2.84	4.13	7.43	8.56	5.78	122.90
1938	4.30	2.50	3.74	3.87	50.61	44.79	15.48	10.53	11.83	10.79	7.80	9.16	194.41
1939	8.33	13.87	6.63	4.20	1.84	5.60	8.14	34.92	72.08	30.84	12.00	8.86	211.45
1940	6.25	12.34	18.73	5.30	2.31	2.05	1.98	1.44	1.70	1.95	1.70	1.78	48.41
1941	1.48	2.11	3.71	5.07	4.51	12.60	11.65	9.61	9.69	11.26	8.79	9.77	90.06
1942	6.83	8.24	6.36	8.41	5.60	19.72	72.44	30.77	7.72	8.69	13.87	10.75	203.48
1943	10.28	11.37	8.62	4.06	3.86	4.84	4.08	2.41	6.01	8.74	7.52	10.76	94.10
1944	12.16	13.13	7.60	3.91	4.66	39.83	19.96	9.65	7.86	4.81	3.06	1.97	126.60
1945	1.01	.83	1.46	2.77	3.52	4.15	5.01	4.54	3.57	2.50	1.75	1.37	32.07
1946	2.83	1.73	2.17	3.44	12.88	15.13	11.88	8.83	7.83	8.70	8.10	7.56	90.40
1947	6.04	8.87	5.72	4.80	5.36	5.81	6.46	5.10	3.34	3.36	1.64	1.51	54.60
1948	2.08	3.67	2.72	3.50	4.87	5.92	58.68	26.68	7.75	5.77	3.91	7.06	137.40
1949	4.83	5.46	40.48	31.34	11.08	12.07	10.13	7.18	5.22	4.57	3.99	7.92	130.14
1950	3.58	1.86	3.73	3.50	3.55	3.41	3.74	3.96	3.82	3.91	7.50	10.71	50.67
1951	10.33	8.64	3.10	1.57	1.36	1.98	2.65	5.11	5.84	5.09	2.56	3.71	81.17
1952	1.66	2.65	3.77	5.51	5.61	3.81	2.59	1.81	1.38	1.84	1.57	3.10	34.71
1953	6.25	11.82	5.50	5.26	46.78	22.62	10.78	13.67	14.72	11.40	7.21	9.94	170.23
1954	77.44	31.19	3.83	4.60	5.33	24.78	18.52	11.36	7.09	4.08	3.03	3.97	195.81
1955	6.06	5.25	6.47	2.58	38.51	57.30	21.44	4.37	5.44	4.61	3.81	4.32	164.68
1956	7.04	11.00	264.83	79.84	13.65	11.93	18.07	11.55	6.55	5.76	8.74	25.12	460.27
1957	49.89	20.62	5.43	43.40	13.60	7.51	6.83	6.36	4.85	4.43	3.59	4.12	178.83
1958	6.25	4.43	3.34	3.07	2.13	.78	.29	1.46	1.74	1.81	3.13	5.42	32.57
1959	7.62	6.21	4.73	2.53	4.80	7.47	11.66	13.27	9.47	6.47	4.60	7.99	82.94
1960	3.27	45.60	162.83	48.88	9.02	7.60	10.87	10.83	8.80	8.17	6.68	4.86	344.08
1961	8.03	6.18	3.14	1.02	.86	1.43	2.36	2.78	2.19	1.72	1.81	1.93	36.85
1962	1.88	2.54	1.77	1.66	1.63	3.28	5.02	3.85	7.38	142.50	55.70	6.74	233.36
1963	3.88	3.64	2.44	3.48	2.01	1.55	2.36	2.31	2.83	2.65	2.79	2.74	38.47
1964	4.35	4.61	2.62	.82	.33	.57	.32	.78	3.42	3.33	4.39	5.79	28.39
1965	8.63	8.12	3.56	4.69	5.41	2.81	1.66	1.40	1.40	1.46	2.11	2.57	41.08
1966	1.44	1.45	.42	.43	1.13	3.08	37.71	18.91	6.17	4.84	4.51	3.13	85.24
1967	2.66	3.70	1.68	.86	2.46	4.45	2.23	1.56	1.68	1.80	2.40	2.71	28.01
1968	3.06	3.57	1.77	.60	6.00	8.04	11.28	9.12	6.64	4.67	2.78	2.78	57.10
1969	4.67	4.40	2.00	.82	.72	1.18	1.45	3.95	3.12	2.61	1.67	1.75	37.96
1970	4.31	6.53	3.83	2.34	2.33	4.86	7.07	150.80	44.98	11.37	9.40	6.77	273.04
1971	4.20	4.48	2.62	3.64	42.81	20.97	6.38	4.31	6.44	5.67	4.14	2.19	111.97
% TOTAL	5.76	6.66	16.57	6.72	8.46	15.47	11.86	9.45	6.86	7.13	4.95	4.20	100.00

MEAN LOG= 1.858012 STD. DEV.= .347184 MEAN ANNUAL RUNOFF= 125.50 MILLION CUBIC METERS

Table 2.13 : Synthesized runoff from catchment No. 3 for undeveloped conditions ($m^3 x 10^6$)

POW= 3.0 RL= 0.KM ST= 630.KM FT= 30.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %

ZMIN= 5000.MM/MONTH ZMAX= 6000.MM/MONTH PI= 1.5 MM/DAY GL=0.00 MONTHS TL= .30 MONTHS KITE 4/MONTH

P.EVAP.	104.0	140.0	155.0	150.0	135.0	130.0	96.0	82.0	65.0	56.0	76.0	88.0	
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	.47	4.16	5.01	3.43	2.71	2.75	2.23	2.51	2.24	1.93	2.37	1.07	29.38
1922	2.47	3.44	2.55	11.03	5.94	3.38	2.10	1.61	1.33	1.74	1.83	.65	36.51
1923	.40	.62	1.21	.42	1.87	10.23	10.31	4.88	3.40	3.33	2.12	3.31	43.72
1924	3.44	16.66	6.34	4.71	23.05	93.84	49.25	33.54	14.33	3.41	2.79	2.11	257.46
1925	3.27	3.20	2.53	1.62	1.27	2.13	2.26	1.81	2.08	1.78	1.35	1.54	24.68
1926	1.03	1.22	.28	1.45	.88	1.72	1.19	1.55	1.54	1.81	1.34	1.21	14.86
1927	1.20	.58	3.31	1.70	1.51	1.74	3.14	3.41	3.08	2.82	2.55	2.07	23.58
1928	1.43	.74	.53	.89	.42	5.27	4.25	3.52	10.75	6.85	8.53	8.07	50.90
1929	3.14	2.25	1.47	2.18	1.41	1.74	1.81	1.72	2.32	2.57	3.97	7.18	27.15
1930	2.18	2.62	1.44	.83	1.73	1.92	2.28	1.83	2.43	3.76	2.49	2.37	34.52
1931	2.37	3.37	1.76	1.79	4.77	19.82	33.89	24.86	7.44	3.51	2.49	1.73	96.51
1932	2.03	2.02	2.33	2.12	2.23	2.48	1.87	1.44	1.36	1.78	1.87	1.82	31.07
1933	1.46	1.51	1.40	2.08	2.65	2.47	2.83	3.10	5.90	11.03	5.87	2.49	47.55
1934	2.80	1.85	2.80	2.44	2.13	1.85	5.85	2.40	18.93	8.79	3.58	3.77	52.76
1935	2.02	1.54	2.45	2.73	5.52	4.81	3.09	8.14	4.05	3.36	2.53	2.93	40.13
1936	2.88	4.16	2.01	2.63	2.88	15.82	8.62	2.34	1.93	2.02	1.76	1.41	49.43
1937	2.26	1.90	2.51	2.65	3.15	3.02	2.80	2.66	2.88	3.41	4.41	2.99	42.24
1938	2.62	1.25	2.94	1.78	2.57	6.24	4.27	20.18	6.45	3.77	3.19	8.09	54.33
1939	5.81	6.61	3.40	2.44	.98	2.51	3.33	16.54	23.61	8.51	5.54	2.99	91.39
1940	2.58	5.75	3.81	3.02	1.68	1.61	1.25	.82	1.58	1.40	.89	1.22	35.19
1941	.57	1.17	.51	1.49	.62	1.82	2.27	2.52	2.28	2.28	2.27	3.48	20.31
1942	1.71	2.84	3.85	1.87	2.16	17.45	15.63	9.54	3.62	4.24	8.35	4.79	87.06
1943	3.32	2.36	1.57	.60	1.00	1.30	1.14	1.12	2.17	3.21	2.45	15.76	37.28
1944	8.50	3.45	3.94	1.60	2.24	8.28	4.35	2.72	2.42	2.29	2.01	1.37	39.17
1945	1.31	.36	.68	2.21	.88	1.84	2.54	2.86	2.38	1.85	1.50	1.52	19.48
1946	1.78	.73	1.33	1.74	3.45	7.	8.99	5.60	7.48	19.85	7.10	7.06	60.57
1947	2.72	2.75	3.18	2.65	3.30	2.7	2.40	2.42	1.80	2.79	1.26	1.50	29.47
1948	1.31	2.17	.77	1.08	1.34	1.10	2.14	2.11	2.14	2.12	1.75	1.81	19.17
1949	2.18	1.74	2.50	2.44	2.95	3.17	2.83	2.75	2.73	2.33	2.48	1.80	30.83
1950	1.61	.48	1.23	1.00	.62	1.45	1.17	1.48	1.24	1.77	2.29	2.87	17.35
1951	3.12	2.36	1.62	.64	.46	.84	1.51	1.01	1.97	2.27	1.71	1.22	19.35
1952	.66	1.39	.87	.44	.99	1.56	1.24	1.28	1.14	1.06	1.06	1.65	14.26
1953	1.91	3.68	2.88	2.88	4.43	4.02	10.17	15.78	7.66	3.27	2.91	3.24	62.79
1954	34.86	21.64	1.67	3.39	1.95	2.21	3.48	3.53	3.68	2.44	2.87	3.14	66.27
1955	3.28	3.50	2.45	.93	12.75	32.32	14.10	8.44	9.82	5.26	10.14	11.46	114.64
1956	5.77	4.36	42.33	19.40	3.78	7.44	23.50	11.14	3.06	3.22	3.19	14.57	149.79
1957	18.80	6.75	3.20	28.85	15.87	3.23	3.10	3.28	3.81	2.92	2.59	3.19	93.63
1958	3.30	2.11	1.73	1.53	1.11	.78	.72	1.42	1.04	1.42	1.79	1.94	19.01
1959	3.29	2.22	2.42	2.63	3.43	2.65	3.09	3.38	3.17	3.35	3.41	3.45	39.87
1960	1.95	5.77	36.35	15.82	3.32	3.17	28.86	12.68	18.05	16.04	6.11	3.52	151.40
1961	3.34	3.48	2.81	3.00	2.08	3.81	3.26	3.55	3.81	3.19	3.38	2.50	36.05
1962	2.95	3.13	2.80	2.73	1.68	2.60	3.19	2.39	24.31	78.15	13.68	2.17	91.23
1963	2.60	2.04	1.54	2.23	1.78	1.89	2.78	2.43	2.47	2.67	2.33	2.36	27.73
1964	2.65	2.74	2.44	1.35	2.38	.95	1.51	1.31	2.55	2.82	4.63	5.94	32.92
1965	19.23	8.57	1.73	2.38	2.38	1.32	2.26	2.23	2.30	2.10	2.46	2.75	48.90
1966	2.28	1.76	.88	1.78	1.53	2.57	38.26	15.27	2.80	2.06	2.09	2.36	79.64
1967	2.45	1.86	1.65	1.80	2.37	3.97	2.64	2.10	2.42	2.18	2.40	7.37	34.54
1968	2.21	2.62	1.78	.73	.64	17.42	19.83	10.12	4.34	3.15	2.70	2.94	66.15
1969	3.07	2.20	1.57	1.82	1.48	1.86	1.58	2.08	2.30	2.02	1.57	1.95	21.65
1970	2.52	4.74	3.55	2.00	2.33	3.72	3.28	46.65	30.49	16.63	8.75	3.47	153.34
1971	3.41	3.35	3.66	2.83	23.46	14.45	9.31	16.73	8.83	3.80	2.87	1.47	94.41
% TOTAL	6.53	5.41	6.57	5.84	9.53	12.93	13.32	12.49	10.14	8.51	6.41	6.06	100.00

MEANLOG = 1.632451 STD. DEV. = .284843 MEAN ANNUAL RUNOFF= 54.86 MILLION CUBIC METRES

Table 2.14 : Synthesized runoff from catchment No. 4 for undeveloped conditions ($m^3 x 10^6$)

POW= 3.0 RL= 0.KM ST= 150.KM FT= 30.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %

ZMIN= 5000.MM/MONTH ZMAX= 6000.MM/MONTH PI= 1.5 MM/DAY GL=0.00 MONTHS TL= .30 MONTHS KITE 4/MONTH

P.EVAP.	104.0	140.0	156.0	150.0	135.0	130.0	95.0	82.0	65.0	56.0	76.0	88.0	
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	.27	.78	4.24	3.44	1.32	1.39	1.21	1.32	1.14	1.05	1.17	.73	20.77
1922	1.26	4.17	2.36	8.02	3.94	1.18	.89	.74	.58	.74	.48	.32	24.72
1923	.36	.32	.64	.32	.78	1.31	4.07	2.58	1.70	1.41	1.48	1.64	16.74
1924	1.81	6.22	4.68	3.20	14.12	98.37	30.10	20.00	8.14	1.83	1.39	1.52	150.38
1925	1.64	1.72	1.26	.81	.34	.86	.88	.62	.48	.43	.45	.45	10.40
1926	.32	.19	.01	.06	0.00	.12	.12	.16	.30	.24	.10	.11	1.97
1927	.08	.03	.41	.42	.61	.87	1.00	1.38	2.81	2.21	1.46	1.23	12.79
1928	.98	.56	.44	.47	.35	2.98	2.82	3.27	13.40	9.46	6.26	3.13	44.21
1929	1.60	1.11	.81	1.01	.48	5.07	.98	1.01	1.32	1.72	1.82	1.44	18.20
1930	1.34	1.48	1.00	.78	1.52	2.19	1.45	1.37	1.52	1.74	2.73	1.36	19.93
1931	1.39	1.36	1.10	1.06	11.45	12.93	23.11	15.06	4.48	1.62	1.36	1.00	78.85
1932	.85	1.03	.98	.85	1.06	1.08	.91	.73	.65	.83	.71	.47	10.39
1933	.86	.75	.47	1.10	2.14	1.76	1.64	1.73	4.43	5.13	2.66	1.41	24.27
1934	1.34	1.08	1.36	10.23	5.67	1.34	1.21	1.39	6.49	3.73	1.95	1.51	36.77
1935	1.11	.81	1.12	1.31	1.53	1.72	1.47	4.23	3.12	1.88	1.50	1.60	21.28
1936	1.56	2.69	1.53	1.47	3.51	12.81	5.45	1.33	1.22	1.14	.94	.84	38.45
1937	.88	1.12	2.64	2.46	2.37	1.75	1.39	1.31	1.45	1.70	3.11	3.14	23.65
1938	1.37	.75	.96	.93	1.30	5.12	3.11	10.09	5.21	2.44	1.92	2.91	36.37
1939	1.92	3.77	1.92	1.30	1.10	6.02	4.20	11.31	21.38	8.44	1.89	1.65	65.40
1940	1.40	4.57	2.56	1.08	.82	1.01	.74	.75	.93	.97	.70	.76	15.24
1941	.54	.76	.46	.88	.88	1.36	1.60	1.61	1.53	1.49	1.43	1.44	14.74
1942	1.18	1.17	2.94	1.81	1.32	9.82	16.81	6.44	1.46	2.18	4.61	2.61	52.52
1943	1.68	1.37	1.13	.83	1.09	1.35	1.07	1.07	3.30	5.37	2.78	6.24	27.06
1944	3.68	4.89	3.64	1.02	1.24	1.87	1.81	1.36	1.17	1.07	.94	.65	22.93
1945	.62	.23	.21	.44	.37	.98	1.26	1.32	1.11	.87	.87	.70	9.09
1946	.78	.36	.78	.82	2.72	7.23	7.11	3.08	3.46	5.76	3.09	1.48	36.79
1947	1.43	1.30	1.09	1.38	1.44	1.62	1.74	1.35	1.82	1.03	1.43	1.46	16.69
1948	1.37	1.23	.78	.89	1.05	.92	2.12	1.71	1.37	1.30	1.06	1.30	15.01
1949	1.07	1.03	1.34	1.24	1.42	1.34	1.46	1.46	1.35	1.12	1.12	.99	14.75
1950	.80	.40	.77	.63	.52	.87	.85	.83	.84	.59	1.22	1.59	10.31
1951	1.47	1.02	1.22	.44	.78	.74	.84	1.17	1.32	1.51	1.24	1.01	13.48
1952	.74	.88	1.03	.83	1.03	1.31	1.08	1.02	.82	.89	.87	.49	11.59
1953	1.06	2.16	1.43	1.62	3.27	2.39	3.87	8.81	4.45	1.76	1.57	1.44	34.44
1954	10.87	8.17	.68	1.22	1.08	3.48	2.81	2.13	1.60	1.33	1.43	1.45	32.58
1955	1.54	1.64	1.40	.74	2.44	18.84	8.30	2.83	3.39	2.28	3.49	3.99	50.76
1956	6.01	4.90	25.00	16.20	7.40	6.45	14.67	6.66	1.65	1.67	1.73	10.26	107.60
1957	12.92	4.66	1.64	19.33	9.62	1.56	1.54	1.23	1.41	1.46	1.45	1.62	58.66
1958	1.25	1.37	1.21	1.07	.46	.55	.43	.75	.57	.60	.90	.88	10.77
1959	1.06	1.06	1.04	.71	1.11	1.36	8.59	5.18	1.71	1.66	1.43	1.30	27.20
1960	1.15	10.47	19.02	5.63	4.33	2.57	9.19	4.72	11.28	10.54	3.46	1.86	80.40
1961	2.17	1.91	1.26	2.38	.84	1.36	1.58	1.77	1.46	1.54	1.50	1.73	17.93
1962	1.40	1.59	1.14	1.37	1.01	1.35	1.62	1.19	7.92	24.42	8.80	1.57	54.17
1963	1.24	1.01	1.00	1.17	.82	.85	1.29	1.23	1.18	1.38	1.00	1.07	13.74
1964	1.28	1.37	1.34	.84	.65	.56	.67	.82	1.14	1.34	2.77	2.39	15.66
1965	1.88	3.85	1.00	1.27	1.64	1.16	1.32	1.22	1.18	1.19	1.24	1.17	26.27
1966	1.10	.86	.52	.78	.91	1.13	14.26	8.78	1.82	1.53	1.57	1.55	35.37
1967	1.43	1.37	.73	.05	1.33	3.41	3.13	1.17	1.27	1.11	1.26	1.19	17.21
1968	1.28	1.31	.56	.41	.30	2.17	9.49	5.23	2.16	1.40	1.13	1.32	32.35
1969	1.46	1.25	1.67	1.31	2.06	1.10	1.15	1.34	1.39	1.39	1.00	1.07	16.38
1970	2.14	4.76	3.36	1.26	1.43	4.74	7.67	42.13	16.27	3.25	2.17	1.72	92.70
1971	4.37	2.47	1.56	5.04	21.18	19.21	6.48	9.34	4.71	2.06	1.48	1.55	70.81
% TOTAL	5.39	5.14	6.48	6.42	8.30	12.84	12.33	13.37	9.83	7.82	6.50	5.02	100.00

MEANLOG= 1.397480 STD. DEV.= .218324 MEAN ANNUAL RUNOFF= 31.42 MILLION CUBIC METRES

Table 2.15 : Synthesized runoff from catchment No. 1a for undeveloped conditions ($m^3 x 10^6$)

[illegible] ST= 250.MM PI= 25.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %

AREA 5000.MM/MONTH [illegible] PI= 3.0 MM/DAY [illegible] MONTHS TL= .25 MONTHS [illegible]

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
P.EVAP.	104.0	145.0	155.0	180.0	135.0	130.0	95.0	42.0	65.0	59.0	76.0	[illegible]	
1921	2.24	10.39	[illegible]	17.46	[illegible]	6.36	5.21	5.77	4.87	4.21	5.76	5.17	[illegible]
1922	7.62	14.83	12.47	21.67	17.41	8.17	4.78	2.84	1.87	1.14	1.16	.44	[illegible]
1923	1.21	[illegible]	6.15	6.45	5.12	6.52	6.75	5.20	3.45	3.12	1.10	1.30	[illegible]
1924	4.45	24.96	22.05	20.61	21.26	301.12	143.24	17.74	10.47	4.28	4.44	4.77	[illegible]
1925	10.36	11.41	6.45	5.26	3.74	8.50	5.76	5.29	5.21	5.14	3.45	[illegible]	98.61
1926	10.15	14.32	11.10	[illegible]	7.31	14.00	12.11	[illegible]	3.65	3.74	3.11	7.90	[illegible]
1927	6.27	6.24	4.71	5.07	10.44	9.37	6.54	4.12	3.44	4.91	5.46	1.51	67.77
1928	4.01	2.65	2.03	2.68	2.56	10.30	12.94	7.46	4.49	6.31	5.46	6.69	66.40
1929	2.76	14.12	11.02	14.75	15.61	12.36	11.65	4.97	5.25	3.46	3.24	4.74	114.67
1930	3.24	6.42	2.57	4.43	7.16	4.56	3.19	2.22	1.55	1.22	1.04	1.30	43.44
1931	2.47	3.43	3.6	3.23	132.76	70.39	23.36	37.12	10.59	16.36	4.77	3.55	[illegible]
1932	3.45	4.21	3.44	7.64	7.79	4.37	4.17	2.30	1.42	1.73	1.74	1.51	[illegible]
1933	1.76	6.46	17.25	67.28	32.55	36.13	14.72	15.00	11.10	8.65	5.07	3.17	221.17
1934	5.01	7.01	61.57	34.32	11.76	8.58	6.58	4.91	3.56	3.51	4.27	3.21	152.77
1935	2.44	2.71	3.49	7.56	15.04	19.04	12.66	11.77	11.08	7.31	4.08	3.07	100.14
1936	3.03	11.76	12.34	[illegible]	13.47	11.07	6.54	3.35	3.37	3.17	1.92	3.16	54.71
1937	3.06	5.22	67.54	52.75	101.14	51.55	26.36	17.79	10.75	11.06	7.40	6.44	[illegible]
1938	7.23	6.50	31.74	13.37	93.42	47.09	36.11	10.10	4.73	6.42	5.06	6.84	271.75
1939	0.35	25.1	21.25	14.32	8.72	8.75	7.09	76.45	42.10	14.35	4.47	4.1	[illegible]
1940	0.54	6.43	52.60	10.23	8.08	5.43	5.72	6.53	4.59	5.41	3.44	3.82	[illegible]
1941	4.42	5.24	4.72	9.6	13.39	15.41	13.24	4.77	7.06	5.90	5.10	4.47	[illegible]
1942	6.35	13.05	73.35	34.84	13.26	13.41	45.21	41.94	14.43	15.46	47.63	74.78	[illegible]
1943	45.61	34.44	16.70	10.17	12.67	15.21	11.45	5.97	7.04	4.50	5.94	10.09	196.56
1944	14.12	12.02	7.18	6.19	7.52	46.59	31.93	9.23	5.62	3.52	2.10	1.44	147.94
1945	2.07	1.44	2.70	26.12	19.08	10.16	6.64	4.24	2.64	1.97	1.77	1.22	[illegible]
1946	4.20	3.46	10.60	10.38	15.01	17.49	13.24	7.61	6.63	5.10	4.49	3.66	[illegible]
1947	4.55	12.37	15.60	17.48	13.71	13.28	12.36	7.30	4.74	2.04	1.92	1.66	113.04
1948	3.31	6.21	4.25	8.63	33.64	16.64	22.67	17.53	10.36	4.37	3.42	3.25	119.64
1949	7.24	14.75	46.37	26.62	13.64	13.41	10.86	7.02	4.70	7.53	3.92	2.66	157.60
1950	2.44	2.16	6.13	8.80	5.13	3.87	3.59	2.77	2.11	1.71	5.46	9.71	53.70
1951	12.05	2.13	3.01	5.14	7.05	6.44	5.27	4.85	3.34	[illegible]	4.41	3.49	77.57
1952	3.23	8.51	5.25	9.12	11.36	10.26	8.35	3.35	2.74	2.74	2.15	7.50	69.57
1953	3.42	7.57	16.35	8.34	10.55	9.74	7.45	4.87	5.41	5.93	3.98	6.11	97.27
1954	66.35	40.45	15.26	13.44	15.27	36.23	24.11	12.53	7.32	4.60	2.59	2.13	277.31
1955	6.04	14.23	15.15	31.72	92.16	43.82	21.03	5.69	3.63	3.85	2.79	7.74	214.54
1956	6.74	16.16	81.74	41.66	14.58	12.99	13.12	11.16	6.46	4.72	7.79	96.44	327.78
1957	125.74	40.62	19.53	20.36	23.67	17.04	13.12	10.49	5.98	3.37	1.94	1.47	315.70
1958	2.51	4.05	8.16	10.22	49.17	22.63	7.16	9.69	5.74	3.71	2.97	1.90	126.72
1959	4.80	6.97	41.12	22.26	11.27	13.39	16.00	12.19	6.45	4.34	3.01	2.44	144.64
1960	6.16	34.21	130.26	54.62	16.76	19.76	14.19	11.32	8.25	5.31	2.97	3.47	265.07
1961	3.06	2.21	11.13	6.73	7.64	6.70	9.33	7.05	4.11	2.85	3.14	2.45	99.58
1962	5.62	13.54	14.76	16.26	12.51	15.60	16.09	11.71	9.01	52.10	30.45	6.50	213.99
1963	5.53	5.01	6.73	12.13	13.58	7.34	5.81	5.47	4.17	3.35	2.57	2.10	73.57
1964	6.21	8.31	11.92	9.01	5.66	2.96	2.15	2.16	7.66	4.72	5.50	5.40	69.70
1965	5.64	12.63	32.11	45.24	20.73	12.62	6.11	4.46	3.61	2.65	2.19	2.47	149.69
1966	3.17	5.37	6.15	35.29	86.53	44.51	21.52	14.57	7.54	4.85	3.36	3.21	234.00
1967	4.07	11.06	12.61	8.38	6.40	2.36	6.84	4.45	2.60	1.84	3.73	5.54	70.05
1968	4.27	4.12	14.63	13.63	5.56	35.27	23.86	13.71	7.53	4.11	3.64	7.70	137.74
1969	10.42	12.35	6.60	5.62	4.02	3.80	3.92	4.65	4.47	3.62	3.44	4.45	73.96
1970	14.30	21.76	13.66	13.57	12.15	8.88	8.25	46.42	36.21	12.27	4.32	[illegible]	[illegible]
1971	8.26	7.71	16.10	24.01	111.64	47.57	10.66	9.65	9.56	7.13	4.42	3.82	194.04
% TOTAL	6.13	6.3	12.63	18.65	15.07	16.53	9.76	6.40	4.34	3.40	3.21	3.77	100.00

MEAN LOG= 3.128545 STD. DEV.= .273601 MEAN ANNUAL RUNOFF= 166.21 MILLION CUBIC METERS

Table 2.16 : Synthesized runoff from catchment No. 1b for undeveloped conditions ($m^3 x 10^6$)

[illegible] ST= 250.MM PI= 25.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %

AREA 5000.MM/MONTH [illegible] 4000.MM/MONTH PI= 3.0 MM/DAY [illegible] MONTHS TL= .25 MONTHS [illegible]

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
P.EVAP.	104.0	140.0	155.0	180.0	135.0	130.0	85.0	42.0	65.0	56.0	76.0	[illegible]	
1921	2.17	15.83	31.46	14.17	5.58	4.88	4.10	4.27	4.36	4.00	7.88	5.24	105.40
1922	9.52	16.20	11.23	17.49	15.93	8.05	4.30	1.90	.97	1.52	.60	0.36	84.54
1923	0.00	.30	3.76	3.35	3.50	4.68	5.78	4.44	3.65	2.82	2.42	4.32	34.49
1924	6.06	16.10	32.96	27.13	14.06	494.62	251.44	76.42	17.69	15.10	8.95	18.15	1132.11
1925	13.14	13.00	6.38	3.19	1.58	8.14	7.77	4.76	4.19	5.25	3.19	4.44	76.46
1926	9.26	11.57	5.57	6.31	6.57	14.41	12.30	3.02	5.78	7.40	4.17	5.79	107.30
1927	8.94	6.61	5.06	8.17	10.92	8.13	4.79	5.72	4.04	1.35	2.49	1.82	71.44
1928	2.64	.23	6.57	8.20	3.37	52.35	32.71	11.72	10.61	8.53	7.98	9.00	146.34
1929	10.02	8.35	[illegible]	15.11	14.73	6.16	4.94	3.51	3.30	3.01	3.28	5.07	96.54
1930	6.08	4.28	4.75	3.71	3.07	1.29	1.24	.29	.34	1.32	.09	.64	34.71
1931	3.14	2.52	2.19	1.40	152.46	47.55	45.14	49.38	25.58	11.19	5.38	7.36	360.01
1932	3.84	3.85	5.34	5.65	7.04	3.82	1.81	.23	.05	.64	.70	.09	31.45
1933	1.49	6.83	11.67	16.53	17.51	14.57	12.33	11.11	11.00	10.55	11.15	7.37	[illegible]
1934	4.73	5.02	45.43	34.24	13.18	9.83	6.31	6.25	13.92	16.49	15.19	9.99	204.41
1935	5.35	1.47	6.00	8.74	15.46	18.81	11.70	18.14	14.63	10.92	5.70	3.44	109.56
1936	5.66	30.15	12.20	10.76	20.46	20.15	14.86	4.89	3.00	4.75	4.74	3.42	130.77
1937	3.05	4.46	14.53	4.87	48.85	72.30	9.92	5.12	4.69	9.77	9.41	4.63	151.74
1938	6.18	3.13	7.58	6.22	40.08	[illegible]	16.97	13.44	10.27	10.79	7.30	10.45	[illegible]
1939	6.06	24.75	15.00	11.31	3.42	6.55	7.55	100.19	[illegible]	90.23	12.40	8.40	[illegible]
1940	8.16	12.54	21.90	16.47	7.12	4.53	4.49	2.33	3.02	1.94	1.13	2.38	[illegible]
1941	1.63	4.17	4.74	8.65	8.43	14.77	13.24	9.19	6.44	7.34	6.74	7.89	[illegible]
1942	8.06	11.43	2.21	20.74	11.53	13.42	113.80	52.82	15.82	17.84	25.58	19.38	347.59
1943	36.33	30.77	30.07	7.56	8.59	10.14	7.23	3.56	8.20	16.71	7.44	15.42	170.70
1944	17.88	16.49	6.30	5.20	7.07	78.07	26.44	9.35	5.01	3.08	1.56	.22	[illegible]
1945	1.79	0.00	2.75	6.39	6.21	6.82	5.01	3.37	2.21	1.36	.27	.51	41.50
1946	3.70	4.83	6.15	6.61	16.10	20.11	15.17	8.74	7.23	6.71	5.90	5.85	[illegible]
1947	5.03	11.69	12.10	9.91	8.33	7.53	5.46	5.27	2.93	1.53	.57	.15	71.15
1948	1.42	4.75	3.80	4.38	9.13	8.48	36.97	23.45	11.59	7.87	4.71	7.20	123.42
1949	0.41	14.00	45.84	28.33	14.66	14.85	10.33	6.36	4.75	4.03	3.20	1.41	161.64
1950	1.60	0.00	4.20	4.70	2.12	3.07	3.43	2.67	3.47	2.09	8.84	17.31	48.27
1951	14.50	5.87	4.65	3.86	3.68	1.41	1.44	3.25	2.00	5.05	3.24	1.97	50.91
1952	1.54	6.81	6.42	3.30	3.80	4.13	3.39	1.98	1.20	1.35	1.11	2.41	44.59
1953	4.16	11.06	13.31	9.27	14.64	12.84	9.65	11.79	10.76	7.35	4.41	3.03	119.71
1954	113.24	48.42	7.62	9.26	6.52	72.36	40.73	16.40	8.22	4.89	2.56	2.41	337.27
1955	4.83	16.43	15.70	8.62	56.51	35.13	13.01	7.05	4.64	3.19	2.49	7.90	172.09
1956	5.78	16.64	244.73	103.58	33.54	19.55	19.76	13.86	7.44	7.84	7.72	101.13	580.76
1957	120.43	45.42	6.50	64.57	49.82	29.74	12.41	9.60	7.75	8.86	5.05	4.09	374.87
1958	5.32	6.40	6.26	12.18	7.63	16.4	.14	3.01	2.24	1.66	5.98	6.27	60.60
1959	8.30	3.90	6.21	4.46	9.74	14.78	17.11	13.70	8.71	5.16	3.30	3.47	[illegible]
1960	3.55	21.16	173.40	60.40	23.86	17.23	41.98	35.07	14.75	16.49	9.76	4.75	443.00
1961	9.80	12.17	1.71	6.07	2.01	5.88	6.44	4.32	3.60	1.77	2.56	1.19	65.19
1962	3.65	10.02	11.27	13.56	10.46	27.78	20.81	12.05	12.35	136.33	56.76	9.50	393.17
1963	7.14	6.75	1.02	10.65	10.74	6.73	7.43	5.49	4.34	4.51	[illegible]	2.33	[illegible]
1964	3.18	8.36	4.60	2.97	1.57	0.00	1.11	.93	4.54	5.56	7.35	7.76	45.00
1965	13.33	14.20	6.17	13.37	18.88	7.84	4.16	2.11	3.58	2.95	2.95	3.32	94.27
1966	3.17	2.56	5.74	11.30	35.35	30.81	67.89	30.10	8.03	6.49	3.05	3.04	[illegible]
1967	4.89	12.34	7.78	3.55	4.01	6.84	4.54	2.08	1.81	.86	4.44	5.83	[illegible]
1968	8.54	5.64	14.36	10.07	4.94	65.28	37.35	17.83	13.43	7.78	3.35	4.42	[illegible]
1969	11.50	11.12	6.13	1.88	.86	1.57	3.34	5.24	5.71	3.70	2.87	5.45	57.65
1970	16.15	20.36	33.71	13.92	10.84	9.33	33.71	78.87	40.46	19.92	14.77	10.66	[illegible]
1971	13.39	10.05	1.54	17.04	149.20	68.43	10.80	11.63	10.83	8.00	5.08	3.80	[illegible]
% TOTAL	6.56	6.72	11.47	7.23	11.64	18.22	11.63	7.71	8.33	9.23	7.61	4.11	100.00

MEAN LOG= 2.085026 STD. DEV.= [illegible] MEAN ANNUAL RUNOFF= 174.40 MILLION CUBIC METRES

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[11] 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 ($m^3 x 10^6$)

POR= 3.0 SI= 0.88 ST= 350.MM FT= 25.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %

XMIN= 5000.MM/MONTH XMAX= 6000.MM/MONTH PIA 1.5 MM/DAY CLAG=.00 MONTHS TL= .25 MONTHS NIT= 4/MONTH

P.EVAP.	104.0	140.0	185	180.0	135.0	130.0	95.0	82.0	65.0	56.0	74.0	90.0	MM - MM.5 [illegible]
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	3.73	23.55	11.45	19.33	6.44	7.84	4.20	6.46	4.41	5.15	53.13	4.44	141.27
1922	17.39	36.09	15.15	33.37	23.89	9.57	2.14	0.00	0.00	0.00	0.00	0.00	138.97
1923	0.00	0.00	6.47	0.00	1.71	8.37	8.24	4.63	3.40	1.46	.24	0.00	45.95
1924	6.45	32.40	46.29	46.43	47.32	1216.31	428.67	45.71	35.39	25.46	11.34	15.33	1960.85
1925	23.91	18.30	3.05	3.22	0.43	15.76	8.67	4.47	12.42	6.39	1.07	5.05	109.10
1926	59.30	33.58	11.45	8.93	11.28	29.49	17.71	14.27	5.51	12.30	6.26	6.39	166.70
1927	16.20	6.55	7.19	17.25	31.00	12.14	5.74	4.31	2.59	3.49	.38	0.00	102.72
1928	7.64	0.00	0.06	4.74	0.06	66.26	42.42	14.77	17.55	13.54	5.30	14.64	192.13
1929	13.74	20.82	4.07	33.07	24.73	14.04	14.06	3.70	4.79	2.83	3.13	4.47	157.55
1930	3.02	5.05	4.32	5.85	0.00	0.00	0.00	0.00	0.00	0.00	0.05	9.90	22.17
1931	1.90	2.30	1.63	0.00	294.36	431.88	54.13	55.34	44.56	16.56	5.03	1.30	541.15
1932	1.35	4.72	11.10	7.84	10.83	1.75	0.00	0.00	0.00	0.00	0.07	0.00	37.79
1933	0.00	13.94	24.61	28.22	34.01	30.09	26.30	27.09	19.06	19.07	19.48	9.38	254.97
1934	5.45	11.19	151.63	64.36	17.95	10.95	4.74	7.08	19.91	17.34	15.79	4.73	334.19
1935	3.90	2.03	5.89	12.71	21.79	34.10	17.49	27.57	21.65	15.23	3.47	3.42	171.72
1936	9.23	30.04	13.21	30.69	35.48	24.75	15.00	2.38	2.84	4.68	1.54	1.87	171.99
1937	3.18	5.20	56.36	58.07	221.44	84.14	28.83	15.17	18.74	23.58	16.47	5.03	556.24
1938	13.53	1.53	19.28	64.65	224.36	107.43	27.83	22.59	14.84	18.38	10.05	19.60	483.55
1939	15.63	73.01	35.83	22.34	7.87	13.27	13.04	145.30	104.60	40.84	18.29	13.15	508.21
1940	6.02	31.84	45.31	41.42	8.57	6.08	4.70	4.59	4.78	3.35	0.47	2.41	159.54
1941	.87	10.47	3.30	33.21	18.27	32.00	23.43	14.35	15.69	10.42	9.41	13.42	174.38
1942	12.85	23.72	37.65	40.69	22.13	26.71	216.70	88.51	37.49	33.96	46.19	36.75	711.42
1943	33.09	41.76	34.03	8.11	24.72	20.21	14.46	2.35	14.23	16.71	7.79	26.33	306.74
1944	20.38	24.03	7.73	8.10	33.04	160.72	26.75	33.83	5.93	1.96	0.00	0.00	355.75
1945	0.00	0.00	2.33	20.41	16.13	13.16	7.32	3.40	0.00	0.60	0.00	4.30	67.61
1946	9.15	10.53	33.23	13.45	30.35	35.33	24.37	15.44	13.03	9.93	6.70	6.83	197.54
1947	5.84	22.14	25.65	21.10	17.34	17.20	16.57	7.85	2.65	0.00	0.00	0.50	142.50
1948	3.01	8.79	3.50	12.66	30.09	20.91	28.69	34.88	20.09	9.76	2.07	2.13	211.67
1949	16.40	27.70	102.07	54.34	23.87	28.48	15.43	9.25	5.84	3.80	2.27	0.00	297.76
1950	0.00	0.00	26.32	6.73	0.00	3.19	3.67	.35	.85	0.00	15.50	21.36	77.78
1951	17.33	2.43	8.19	4.20	4.73	1.87	1.49	5.39	3.87	10.47	3.28	8.39	72.87
1952	.89	8.88	10.85	14.33	16.29	8.87	3.27	0.00	0.00	0.00	0.00	1.47	65.41
1953	4.74	33.21	18.49	15.69	26.56	38.48	16.84	21.43	15.80	9.30	3.53	15.35	181.47
1954	181.44	56.41	13.03	22.76	18.57	114.37	64.51	74.31	11.60	4.47	0.40	.24	547.67
1955	14.30	20.12	38.55	5.85	155.42	76.88	17.84	8.64	4.35	1.83	.19	5.38	349.53
1956	11.15	36.35	262.45	152.52	41.10	28.86	33.80	19.73	4.78	14.04	51.39	200.47	830.51
1957	249.34	33.05	18.00	33.44	162.58	51.82	25.34	19.71	9.38	6.16	0.49	1.72	632.14
1958	6.55	5.07	37.51	28.04	21.82	5.06	1.41	8.44	2.36	.39	7.31	0.12	126.97
1959	23.40	2.78	22.78	18.42	22.58	28.08	34.25	31.30	8.89	6.50	1.44	9.48	177.73
1960	6.63	47.45	298.37	124.76	38.41	23.46	36.81	30.35	24.38	13.15	3.27	9.80	672.60
1961	13.24	18.77	13.79	10.27	5.27	14.66	18.04	6.13	3.13	.43	3.47	0.50	108.17
1962	8.83	26.70	31.54	29.31	17.57	33.34	36.46	16.59	21.12	198.03	89.58	17.18	500.77
1963	5.93	13.27	6.05	23.68	15.83	6.05	14.34	5.72	4.94	5.30	.14	0.00	94.85
1964	15.20	14.58	14.69	1.86	3.04	0.00	0.00	6.00	5.71	7.87	11.83	10.41	87.73
1965	23.05	36.02	16.64	21.50	16.57	11.84	4.28	2.98	2.04	.50	1.50	1.43	141.81
1966	3.05	9.91	12.13	25.38	134.67	78.86	82.76	38.57	12.41	9.30	1.73	0.00	405.86
1967	10.29	23.82	54.75	5.42	5.40	35.07	6.40	0.00	0.00	0.05	7.83	3.38	93.55
1968	8.75	8.18	25.68	17.37	4.51	180.13	58.46	30.53	17.88	19.30	1.00	5.76	390.81
1969	21.87	17.71	6.61	0.00	0.08	.33	1.84	8.53	5.53	2.79	3.79	13.01	80.77
1970	19.40	35.63	15.23	25.19	16.83	13.71	21.67	132.83	66.12	33.22	28.13	13.37	425.27
1971	19.19	10.15	36.43	35.37	241.61	98.14	15.15	21.66	16.45	11.32	4.48	0.00	495.07
% TOTAL	4.52	4.87	12.23	9.35	14.14	19.04	11.04	6.88	4.44	4.20	2.64	2.49	100.00

MEAN(LOG)= 2.307385 STD. DEV.= .381505 MEAN ANNUAL RUNOFF= 305.08 MILLION CUBIC METERS

Table 2.19 : Synthesized runoff from catchment No. 2 for 1970 conditions ($m^3 x 10^6$)

POR= 3.0 SK= 0.MM ST= 250.MM FT= 25.0 MM/MONTH GW= 0.0 MM/MONTH AI= 0.0 %

ZMIN= 5000.MM/MONTH ZMAX= 6000.MM/MONTH PI= 1.8 MM/DAY CLAG=0.00 MONTHS TL= .25 MONTHS NIT= 4/MONTH

P.EVAP.	104.0	140.0	165.0	160.0	136.0	130.0	88.0	82.0	65.0	56.0	74.0	90.0	MM - MM .5 [illegible]
YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	1.81	37.81	42.47	8.28	0.00	.46	0.00	0.00	0.00	0.00	3.39	0.00	91.53
1922	4.43	16.37	0.00	25.73	2.11	0.00	0.00	0.00	0.02	0.00	0.00	0.00	49.05
1923	0.00	0.00	0.00	0.00	0.00	3.83	1.55	45.38	24.25	0.00	3.80	10.07	89.89
1924	4.75	14.54	24.84	14.34	29.01	422.11	148.76	40.41	14.30	10.04	0.00	4.94	735.94
1925	8.82	4.21	0.00	0.00	.56	8.65	2.60	0.00	3.67	6.13	0.00	3.21	39.10
1926	4.78	3.02	3.15	3.16	0.00	8.17	.10	4.50	1.33	6.49	0.00	0.00	35.70
1927	4.33	0.00	0.00	3.35	2.41	0.00	.86	6.12	2.60	1.12	3.22	0.00	23.26
1928	0.00	0.00	0.00	5.59	0.00	60.46	10.54	4.77	8.96	3.70	6.43	7.76	126.26
1929	4.48	0.00	0.00	8.57	0.00	10.37	3.83	0.08	4.05	3.26	1.40	2.86	36.91
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	83.24	40.13	95.88	57.50	15.08	2.50	0.00	0.00	294.47
1932	0.00	0.00	.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.13
1933	0.00	0.00	0.00	4.75	8.64	5.36	4.04	3.63	7.58	5.30	5.20	0.00	49.26
1934	0.00	0.00	5.20	0.00	0.00	0.05	0.08	5.22	17.62	9.85	11.80	.35	57.57
1935	0.00	0.00	0.00	1.50	10.58	9.52	1.05	10.78	7.62	8.79	0.00	.36	50.22
1936	1.83	16.36	0.00	7.78	44.65	20.80	10.80	0.06	1.07	3.81	3.31	0.00	110.67
1937	0.00	.88	32.90	16.83	24.71	0.00	0.00	0.00	4.13	7.43	4.70	0.00	93.67
1938	1.28	0.00	3.30	0.00	59.41	44.79	4.71	10.53	9.75	10.12	1.74	.36	157.97
1939	.23	13.57	0.50	0.00	0.00	5.60	3.81	36.92	72.08	38.87	10.68	1.56	175.40
1940	.64	12.36	3.28	0.00	0.00	0.00	0.00	0.00	0.00	8.98	0.00	9.30	36.18
1941	0.00	2.22	0.00	5.07	0.00	12.50	6.21	6.39	9.69	10.50	4.35	7.95	64.61
1942	.17	3.63	9.66	0.00	1.23	10.72	72.44	25.00	3.17	8.60	15.82	3.65	153.86
1943	10.38	6.49	2.50	0.00	2.52	.18	0.00	9.00	6.01	8.19	1.48	10.36	51.43
1944	7.30	12.13	0.00	0.00	3.34	29.83	12.63	8.15	1.45	0.00	0.00	0.00	75.97
1945	0.00	0.00	0.00	0.00	0.00	4.15	.13	0.00	0.00	0.00	0.00	0.00	4.29
1946	0.00	0.00	0.00	0.00	13.86	14.59	8.55	5.38	6.83	5.70	0.00	4.01	69.03
1947	0.00	3.43	6.06	0.00	7.59	7.59	5.33	0.00	0.00	0.00	0.00	0.00	27.03
1948	0.00	1.34	0.00	0.00	4.87	.48	58.68	19.02	5.86	1.22	0.00	0.00	91.37
1949	4.90	0.00	40.42	14.24	11.08	11.43	5.36	2.63	.78	3.02	0.00	.41	95.77
1950	0.00	0.00	1.06	0.00	0.00	0.00	3.97	0.00	.43	.93	7.90	7.42	20.37
1951	8.60	0.00	0.00	0.00	0.00	0.00	0.00	5.11	.73	8.64	0.00	0.00	28.30
1952	0.00	0.00	0.00	3.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.38	4.97
1953	6.03	13.92	.67	4.06	46.79	18.40	10.70	12.67	13.98	7.40	1.48	9.34	139.48
1954	77.44	18.98	0.00	4.60	0.00	24.76	18.29	6.82	.88	0.00	.11	.76	152.44
1955	6.06	6.38	0.00	0.00	38.51	57.30	14.85	.82	4.64	0.00	.25	1.66	131.74
1956	7.64	11.00	208.83	78.72	11.63	10.49	15.07	4.65	7.22	5.76	1.26	25.12	394.91
1957	40.88	11.74	0.40	42.40	21.26	9.05	4.82	0.00	1.32	1.38	0.00	3.12	137.85
1958	3.35	0.00	0.00	5.83	0.00	0.05	0.00	1.36	0.00	0.06	3.13	5.53	19.35
1959	2.40	0.00	0.06	0.00	4.98	3.92	11.44	15.40	3.36	3.48	0.00	0.00	44.61
1960	0.00	46.49	132.63	40.22	9.02	3.00	10.67	4.16	9.50	6.38	.40	.53	263.80
1961	2.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	2.48
1962	0.00	0.00	0.00	0.00	0.00	1.34	3.00	0.00	7.38	142.60	48.26	0.00	202.47
1963	.76	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	1.84	0.00	0.00	2.30
1964	4.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.42	0.00	3.48	2.18	12.44
1965	8.82	0.00	0.00	4.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	13.42
1966	0.00	0.00	0.00	0.00	0.00	1.53	37.72	12.63	0.00	4.81	0.00	0.00	56.74
1967	0.00	0.00	0.00	0.00	1.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.46
1968	0.00	0.00	0.00	0.00	0.00	6.04	4.35	6.01	1.66	.13	0.00	.31	22.98
1969	4.76	0.00	0.00	0.00	0.00	0.00	0.00	2.84	0.00	0.00	0.00	0.00	7.60
1970	4.21	0.00	0.00	0.00	0.00	3.96	6.07	110.80	38.43	11.37	2.41	1.82	179.17
1971	4.87	0.00	0.00	1.75	43.83	13.89	.83	6.31	2.23	3.76	0.00	0.00	74.40
% TOTAL	5.36	5.73	11.18	6.12	10.16	18.48	13.62	10.00	6.55	3.36	3.15	2.77	100.00

MEAN(LOG)= 1.541199 STD. DEV.= .464717 MEAN ANNUAL RUNOFF= 94.27 MILLION CUBIC METRES

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.

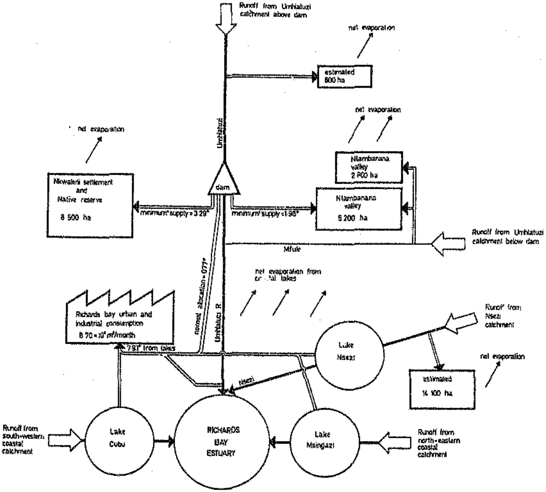
** It is proposed to supply this area from dam storage only when direct pumping from the Mfule proves inadequate.

*** 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 x 10^6 m^3/month) while those for the Ntambonana valley have been set at 65 00 m^3/d (1,98 x $10^6 m^3$/ month).

From table 2.20 it may be noted that to satisfy a highly reliable continuous demand of 7,93 x 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 x 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 ($m^3 x 10^6$)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	0.00	18.83	31.46	10.84	0.00	0.00	0.00	0.00	0.00	0.00	5.74	[illegible]	[illegible]
1922	9.52	16.29	3.40	17.46	13.37	.47	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]
1923	0.00	0.00	0.00	0.00	0.00	2.00	7.45	7.25	1.12	.38	0.00	4.21	[illegible]
1924	3.07	16.10	35.00	26.61	34.46	1072.71	430.42	42.72	18.46	22.82	3.15	14.53	[illegible]
1925	21.42	14.81	0.00	0.00	0.00	8.14	.09	0.00	4.06	2.64	0.00	.14	[illegible]
1926	7.96	3.83	.49	0.00	0.00	15.74	2.48	[illegible]	0.00	7.49	0.00	0.00	[illegible]
1927	4.46	6.09	0.00	3.62	5.76	0.00	0.00	3.17	.52	0.00	0.00	0.00	[illegible]
1928	0.00	0.00	0.00	4.38	0.00	82.36	21.04	0.81	10.48	7.81	5.64	4.27	[illegible]
1929	8.60	2.07	0.00	18.10	4.44	1.72	0.00	0.00	.57	0.00	[illegible]	2.44	[illegible]
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	182.46	95.00	64.40	74.65	36.13	9.73	0.00	[illegible]	[illegible]
1932	0.00	0.00	0.00	0.00	.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.64
1933	0.00	1.16	4.01	16.53	16.09	23.46	24.79	10.63	19.53	15.01	16.37	[illegible]	[illegible]
1934	0.00	0.00	180.11	43.03	17.01	5.16	0.00	4.80	19.44	19.27	16.76	1.17	[illegible]
1935	0.00	0.00	0.00	3.17	18.68	17.19	4.42	21.57	14.64	12.61	0.00	0.10	[illegible]
1936	1.74	26.76	1.21	18.18	43.78	20.44	0.59	0.00	0.00	2.50	0.00	0.10	[illegible]
1937	0.00	0.00	44.08	63.48	178.14	54.81	35.04	4.02	15.47	20.10	4.70	0.00	[illegible]
1938	4.51	0.00	5.65	.21	183.63	93.11	22.28	21.32	4.33	14.47	3.43	16.31	[illegible]
1939	7.40	66.32	25.66	12.74	0.00	6.65	5.51	175.13	134.14	77.30	13.06	2.45	[illegible]
1940	0.00	17.61	130.14	40.00	0.00	0.03	0.00	0.00	0.00	0.00	0.05	0.00	[illegible]
1941	0.00	1.88	0.00	9.56	0.00	14.77	0.84	7.90	7.78	9.14	6.07	6.74	[illegible]
1942	.89	7.07	[illegible]	40.65	13.43	24.86	201.74	88.62	22.23	33.41	67.98	32.27	[illegible]
1943	84.02	64.12	25.67	0.00	11.67	12.64	2.45	0.00	0.30	13.73	1.96	24.75	[illegible]
1944	23.73	24.81	0.00	0.00	4.47	140.06	83.13	10.63	0.00	0.00	0.10	0.10	[illegible]
1945	0.00	0.00	0.00	3.21	0.00	3.23	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]
1946	0.00	0.00	0.00	0.00	16.50	18.84	12.76	4.57	6.07	9.04	[illegible]	1.41	71.65
1947	0.00	0.06	4.53	3.16	4.95	6.34	16.30	0.00	0.00	0.00	0.00	0.30	[illegible]
1948	0.00	0.00	0.00	0.00	7.08	1.27	36.97	17.84	17.88	1.14	0.00	0.00	[illegible]
1949	0.41	13.88	65.63	47.25	21.73	26.89	0.58	1.82	0.00	0.00	[illegible]	0.30	[illegible]
1950	0.00	0.00	0.00	[illegible]	0.00	0.00	0.00	0.00	0.00	0.00	4.91	13.45	[illegible]
1951	14.10	0.00	0.00	0.00	0.00	0.00	0.00	1.73	0.00	4.03	0.00	0.00	[illegible]
1952	0.00	0.00	0.00	3.23	.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]
1953	2.38	11.06	7.70	2.17	14.84	0.28	7.81	17.70	8.44	4.66	0.00	[illegible]	[illegible]
1954	113.34	45.71	0.00	0.26	.43	70.28	61.71	78.68	3.73	0.00	0.00	[illegible]	[illegible]
1955	[illegible]	16.67	23.77	0.00	141.16	73.74	10.63	6.48	2.17	.08	0.00	1.15	[illegible]
1956	4.20	28.46	365.70	133.18	38.73	26.37	32.43	13.97	1.09	11.61	4.30	[illegible]	[illegible]
1957	140.06	76.33	7.83	43.61	124.66	38.43	36.23	4.69	4.71	1.30	0.00	3.44	[illegible]
1958	2.00	0.00	2.81	14.03	36.43	0.00	0.00	0.00	0.00	0.00	2.78	2.54	[illegible]
1959	7.20	0.00	6.13	3.78	40.76	34.70	31.26	19.41	7.84	3.73	0.00	0.00	[illegible]
1960	0.00	81.14	286.65	110.84	38.74	19.74	83.06	25.01	21.00	8.14	3.17	2.04	[illegible]
1961	0.00	12.70	2.21	.61	7.00	1.24	2.71	6.00	0.00	0.00	0.00	0.00	[illegible]
1962	0.00	6.72	3.81	14.67	6.81	31.33	52.80	5.08	21.34	190.14	74.35	.00	[illegible]
1963	[illegible]	1.73	0.00	6.21	7.06	0.00	3.29	0.00	0.00	.36	0.00	0.00	[illegible]
1964	[illegible]	2.04	[illegible]	0.00	0.00	0.00	0.00	0.00	2.73	.14	6.45	[illegible]	[illegible]
1965	[illegible]	11.70	0.00	14.27	30.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]
1966	0.00	0.00	0.06	8.08	87.46	76.21	85.41	32.37	2.58	6.97	0.00	0.00	[illegible]
1967	.03	6.48	6.09	0.00	0.00	4.10	0.00	0.00	0.00	0.00	.35	0.00	[illegible]
1968	.16	0.00	8.01	0.00	0.00	84.10	54.30	30.20	12.22	3.64	0.00	0.00	[illegible]
1969	14.03	7.83	0.00	0.00	0.00	0.00	0.00	3.08	0.00	0.00	0.00	0.00	[illegible]
1970	16.15	15.80	6.04	8.32	8.72	10.34	19.75	127.63	60.25	11.63	14.08	[illegible]	[illegible]
1971	21.12	2.81	9.13	42.30	263.94	87.58	8.57	21.07	12.26	4.13	0.00	0.00	[illegible]
% TOTAL	5.88	5.47	12.27	7.47	13.04	20.41	12.50	7.58	4.40	[illegible]	2.37	[illegible]	100.00

MEAN LOG = 1.488300 STD. DEV. = .261130 MEAN ANNUAL RUNOFF = 210.58 MILLION CUBIC METERS

Table 2.22 : Synthesized runoff from catchment No. 2 for 1990 conditions ($m^3 x 10^6$)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	0.00	31.83	42.47	1.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]
1922	3.26	16.66	0.04	25.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]
1923	0.00	0.00	0.00	0.00	0.00	3.29	.44	44.05	21.06	5.16	0.00	[illegible]	[illegible]
1924	.60	14.54	24.04	13.28	17.81	422.11	148.40	40.61	12.71	7.55	0.00	3.65	[illegible]
1925	5.80	.07	0.00	0.00	0.00	3.75	0.00	0.00	0.00	.43	0.00	0.00	[illegible]
1926	0.00	0.00	0.00	0.00	0.00	2.07	0.00	.46	0.00	.80	0.00	[illegible]	[illegible]
1927	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.18	0.00	0.00	0.00	0.00	2.18
1928	0.00	0.00	0.00	0.00	0.00	40.40	30.62	1.08	6.60	2.85	[illegible]	[illegible]	[illegible]
1929	.27	0.00	0.00	3.77	0.00	5.25	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]
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	[illegible]	[illegible]	[illegible]	57.60	14.22	0.00	0.00	[illegible]	[illegible]
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	2.01	0.33	[illegible]	.01	0.00	7.58	8.32	8.49	0.00	[illegible]
1934	0.00	0.00	4.43	0.00	0.00	0.05	0.00	1.08	17.62	8.73	0.41	0.10	[illegible]
1935	0.00	0.00	0.00	0.00	8.71	7.41	0.00	[illegible]	8.40	5.00	0.00	[illegible]	[illegible]
1936	0.00	15.42	0.00	3.09	[illegible]	20.27	10.60	0.00	0.00	0.00	0.00	0.00	[illegible]
1937	0.00	0.00	34.44	11.98	32.30	0.00	0.00	0.00	.63	7.43	3.77	[illegible]	[illegible]
1938	0.00	0.00	0.00	3.00	55.08	44.70	4.43	10.53	8.37	8.22	0.00	9.16	[illegible]
1939	0.00	13.67	0.00	0.00	0.00	5.60	2.64	36.02	72.08	28.46	7.76	0.00	[illegible]
1940	0.00	[illegible]	.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	[illegible]
1941	0.00	0.00	0.00	0.00	0.00	7.76	.68	1.08	5.60	6.19	1.19	[illegible]	[illegible]
1942	0.00	0.06	7.22	0.00	0.00	10.72	73.44	23.44	[illegible]	8.18	13.97	1.30	[illegible]
1943	7.36	3.34	0.00	0.00	0.00	0.00	0.00	0.00	3.58	7.27	0.00	10.74	[illegible]
1944	6.10	12.13	0.00	0.00	0.00	30.05	8.01	8.30	0.00	0.00	0.00	0.00	[illegible]
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	11.16	14.44	7.65	4.42	6.60	8.70	2.98	3.11	[illegible]
1947	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]	0.00	0.00	0.00	0.00	0.00	[illegible]
1948	0.00	0.00	0.00	0.00	0.00	0.00	66.01	12.84	.83	0.00	0.00	0.00	[illegible]
1949	.26	0.00	[illegible]	10.66	7.58	8.00	.63	0.00	0.00	0.00	0.00	0.00	[illegible]
1950	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.17	3.19	[illegible]
1951	[illegible]	0.00	0.00	0.00	0.00	0.00	0.00	.26	0.00	1.53	0.00	0.00	7.14
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	1.01	6.73	0.00	0.00	46.50	15.47	10.70	11.57	10.68	3.43	0.00	6.11	[illegible]
1954	77.44	[illegible]	0.00	.18	0.00	22.52	16.61	1.44	0.00	0.00	0.00	0.00	[illegible]
1955	[illegible]	[illegible]	0.00	0.00	36.01	97.30	12.06	0.00	4.17	0.00	0.00	.94	[illegible]
1956	7.04	11.00	206.83	79.39	11.11	10.10	18.07	3.70	0.00	2.72	0.00	[illegible]	[illegible]
1957	[illegible]	6.14	0.00	43.40	[illegible]	0.00	3.63	0.00	0.00	0.00	0.00	0.00	[illegible]
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	[illegible]	0.00	0.00	0.00	.60	0.00	[illegible]	10.80	0.00	0.00	0.00	0.00	[illegible]
1960	0.00	[illegible]	[illegible]	37.61	0.74	[illegible]	10.67	[illegible]	[illegible]	[illegible]	0.00	0.00	[illegible]
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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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	.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	[illegible]
1965	[illegible]	0.00	0.00	.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]
1966	0.00	0.00	0.00	0.00	0.00	0.00	37.72	10.68	[illegible]	.88	0.00	0.00	[illegible]
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	[illegible]
1968	0.00	0.00	0.00	0.00	0.00	8.04	[illegible]	[illegible]	0.00	[illegible]	0.00	0.10	[illegible]
1969	[illegible]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]	0.00	[illegible]	[illegible]
1970	[illegible]	0.00	0.00	0.00	0.00	3.22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1971	4.20	0.00	0.00	1.24	[illegible]	[illegible]	0.00	6.31	1.23	0.00	0.00	0.00	[illegible]
% TOTAL	[illegible]	5.66	[illegible]	[illegible]	10.76	[illegible]	11.77	[illegible]	[illegible]	[illegible]	[illegible]	3.11	100.00

MEAN LOG = [illegible] STD. DEV. = [illegible] MEAN ANNUAL RUNOFF = [illegible] MILLION CUBIC METERS

Table 2.23 : Synthesized runoff from catchment No. 3 for 1990 conditions ($m^3 x 10^6$)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	0.00	0.00	3.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.43
1922	3.00	5.00	5.00	11.83	1.95	0.90	0.00	0.00	0.00	0.00	0.00	0.00	27.99
1923	0.00	0.00	0.00	0.00	0.00	3.71	6.65	0.00	0.00	0.00	0.00	0.00	10.36
1924	0.00	8.95	6.88	0.00	23.05	38.84	48.25	33.56	14.22	0.00	0.00	0.10	234.96
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
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	1.29	0.00	0.00	10.75	6.81	7.96	1.77	[illegible]
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	4.77	10.83	33.89	24.04	3.99	0.00	0.00	0.00	77.52
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	2.50	9.23	.60	0.00	11.43
1934	0.00	0.00	0.00	2.44	0.00	0.00	0.00	0.00	17.41	5.50	0.00	0.00	25.41
1935	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.44	0.00	0.00	0.00	0.00	1.44
1936	2.00	0.00	0.00	0.00	2.47	15.82	6.14	0.00	0.00	0.00	0.00	0.00	26.43
1937	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.16	2.01	0.00	5.17
1938	0.00	0.00	0.00	0.00	0.00	3.24	0.00	10.18	4.10	0.00	0.00	4.97	22.49
1939	0.00	2.53	0.00	0.00	0.00	.60	.10	16.56	23.61	0.81	0.00	0.30	54.51
1940	0.00	4.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.34
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	17.45	25.63	8.07	0.00	0.00	5.01	0.00	56.16
1943	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.85	0.00	14.05	14.63
1944	4.26	.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.75
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	6.60	9.16	.75	3.02	9.78	2.24	0.00	31.55
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	6.11	15.78	4.18	0.00	0.00	0.00	26.07
1954	24.06	5.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	29.96
1955	0.00	0.00	0.00	0.00	13.70	33.32	14.10	3.04	5.38	0.00	4.71	7.57	81.90
1956	6.27	3.33	47.33	19.40	3.37	5.96	23.50	9.87	0.00	0.00	0.00	14.47	133.50
1957	18.00	3.46	0.00	28.55	15.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	65.68
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	1.09	.64	0.00	0.00	0.00	0.00	1.73
1960	[illegible]	6.77	36.35	13.22	0.00	0.00	25.96	0.47	18.05	16.00	2.06	0.10	[illegible]
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	24.30	38.17	13.99	0.10	76.46
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	1.47	1.04	2.51
1965	16.17	6.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.65
1966	0.00	0.00	0.00	0.00	0.00	0.00	38.26	18.27	0.00	0.00	0.00	0.00	56.53
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	16.66	19.72	7.42	0.00	0.00	0.00	0.00	43.80
1969	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00
1970	0.00	3.57	0.00	0.00	0.00	0.00	[illegible]	64.65	30.60	12.00	2.09	0.00	[illegible]
1971	0.00	0.00	0.00	.04	28.46	14.45	[illegible]	16.73	6.31	0.00	0.00	0.00	[illegible]
% TOTAL	4.78	3.38	2.81	5.01	6.36	15.43	18.36	16.42	11.32	7.30	2.49	[illegible]	100.00

MEANLOG1= -.347820 STD. DEV.= 2.187719 MEAN ANNUAL RUNOFF= 29.20 MILLION CUBIC METRES

Table 2.24 : Synthesized runoff from catchment No. 4 for 1990 conditions ($m^3 x 10^6$)

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1921	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1922	0.00	0.00	0.00	.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.09
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	0.00	0.00	0.00	6.19	50.44	22.17	12.97	.21	0.00	0.00	0.00	91.98
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
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	0.00	0.00	5.47	.47	0.00	0.00	5.94
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	3.72	0.00	15.18	0.03	0.00	0.00	0.00	0.00	18.93
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	2.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.40
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	4.05	0.00	0.00	0.00	0.00	0.00	0.00	4.05
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	2.16	0.00	0.00	0.00	0.00	2.16
1939	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.38	13.45	.51	0.00	0.00	17.34
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	1.80	[illegible]	0.00	0.00	0.00	0.00	0.00	10.42
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	.88	0.00	0.00	0.00	0.00	.88
1954	2.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.04
1955	0.00	0.00	0.00	0.00	.73	11.91	.27	0.00	0.00	0.00	0.00	0.00	12.91
1956	.08	0.00	17.67	7.27	0.00	0.00	6.74	0.00	0.00	0.00	0.00	2.33	[illegible]
1957	4.00	0.00	0.00	11.40	1.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.29
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	1.66	0.00	0.00	0.00	0.00	0.00	1.66
1960	0.00	2.54	7.39	0.00	0.00	0.00	1.17	0.00	3.35	3.41	0.00	0.00	17.86
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	16.69	3.06	0.00	19.75
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	10.33	.77	0.00	0.00	0.00	0.00	11.10
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	1.76	0.00	0.00	0.00	0.00	0.00	1.76
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	35.20	10.34	0.00	0.00	0.00	45.54
1971	0.00	0.00	0.00	0.00	13.25	2.38	0.00	1.41	0.00	0.00	0.00	0.00	17.04
% TOTAL	2.31	.73	4.17	6.10	7.43	21.77	18.65	19.43	9.46	5.55	.51	.47	100.00

MEANLOG1=-1.410354 STD. DEV.= 1.967008 MEAN ANNUAL RUNOFF= 6.90 MILLION CUBIC METRES 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 295×10^6 m^3. From table 2.15, it is evident that the MAR of the catchment commanded by the dam is 168×10^6 m^3. The draft that should be sustained by the reservoir at a high degree of assurance is 6,04* $\times 10^6$ 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. 40×10^6 m^3. Thus for the purposes of simulation it was assumed that whenever the storage dropped below 40×10^6m^3, the monthly irrigation supplies to the Nkwaleni Settlement and the Ntombonana Valley were restricted to 3,29 and 1,98 $\times 10^6$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 $\times 10^6$m^{3}per month is broken down as follows:

Richards Bay and Eshowe urban and industrial demand	0,77 $\times 10^6$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 $\times 10^6$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 km^2) 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 km^2 in area.

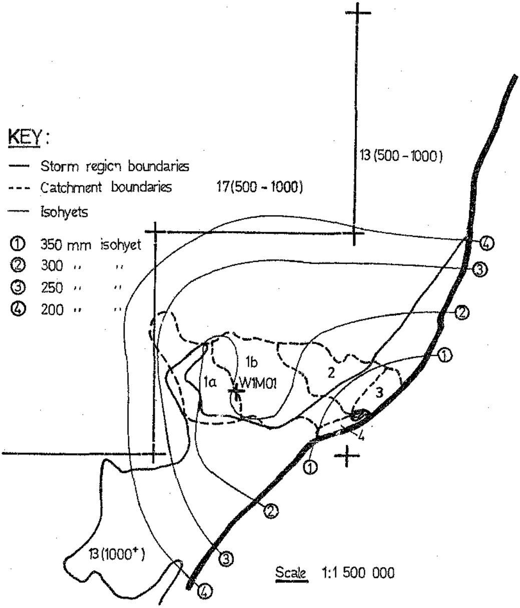


FIG. 2.7 :
Catchment boundaries with superimposed isohyets of the maximum observed storm for storm region No. 13 of HRU Report No. 1/72

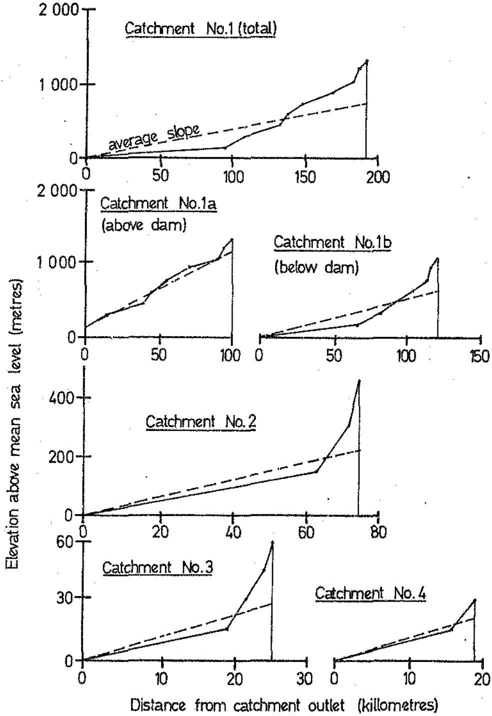


FIGURE 2.8: Longitudinal sections along the main water courses of each catchment

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

sub-catchment No.	description	area km²	L km	Lc km	S	catchment index	lag,T 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	0.0029	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 No.	mm	storm region 13(1000+) catchment area enclosed	total area enclosed	storm region 13(500-1000) 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+) 13(500-1000)	120 -	90 75	75 55	70 45
10	13(1000+) 13(500-1000)	155 -	120 100	100 75	95 65
20	13(1000+) 13(500-1000)	190 -	150 125	135 95	130 85
50	13(1000+) 13(500-1000)	235 -	195 150	175 115	170 100
100	13(1000+) 13(500-1000)	265 -	225 165	205 130	200 120
probable maximum	13(1000+) 13(500-1000)	390 -	320 270	270 220	260 210

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 mm	storm loss mm
		1	1a	1b	2	3	4	total		
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 years	storm duration hours	2	4	8	12	18	24
	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	96	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 Richards Bay. The flood hydrographs thus obtained appear 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 for all 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:

$$Q = 1{,}65\ L\sqrt{gh}^{\,3/2} \quad \ldots\ldots\ldots\ldots (2.9)$$

where L = spillway length (m)
g = 9,81 m^2/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	8939
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:

$$O_2 = C_oI_2 + C_1I_1 + C_2O_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.10)$$

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_o, C_1 and C_2 are constants defined as follows:

$$C_o = \frac{-(Kx - 0{,}5\Delta t)}{(K - Kx + 0{,}5\Delta t)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.11)$$

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

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

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 km^2

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 (?) 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[13], 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

$$\frac{\partial Q}{\partial x} + B\frac{\delta z}{\partial t} = \frac{q}{\partial x} \qquad (3.1)$$

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)

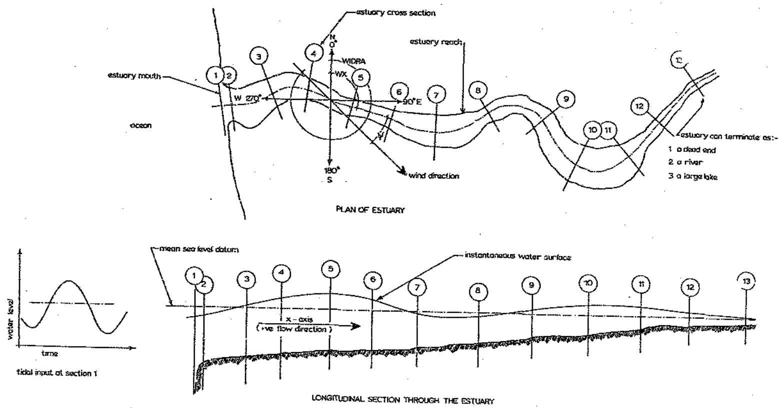


FIGURE 3.1 Typical one-dimensional estuary

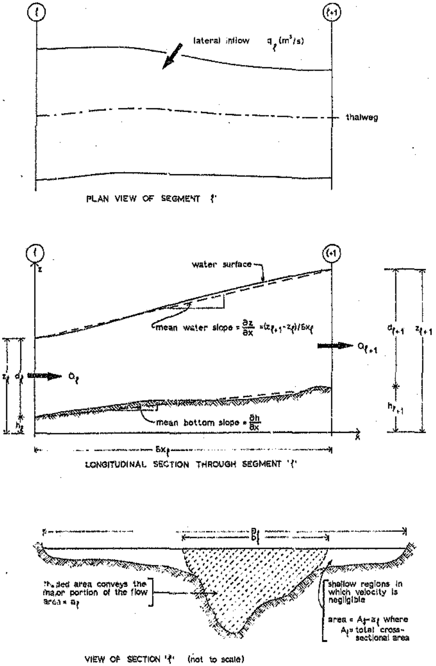


FIGURE 3.2 Views of a typical estuary reach bounded by sections ℓ and $\ell+1$

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

(b) Momentum equation

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

$$-\frac{\alpha Q}{ga^3}\frac{\partial a}{\partial x} + \frac{H}{2\gamma}\frac{\partial \gamma}{\partial x} + \frac{\beta q Q}{ga^2\delta x} - \frac{W}{\gamma H} + \frac{k_3 Q|Q|}{2ga^2\delta x} = 0 \quad \ldots\ldots\ldots\ldots(3.2)$$

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

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

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)
$\alpha, \alpha_{\ell+1}$ = 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.

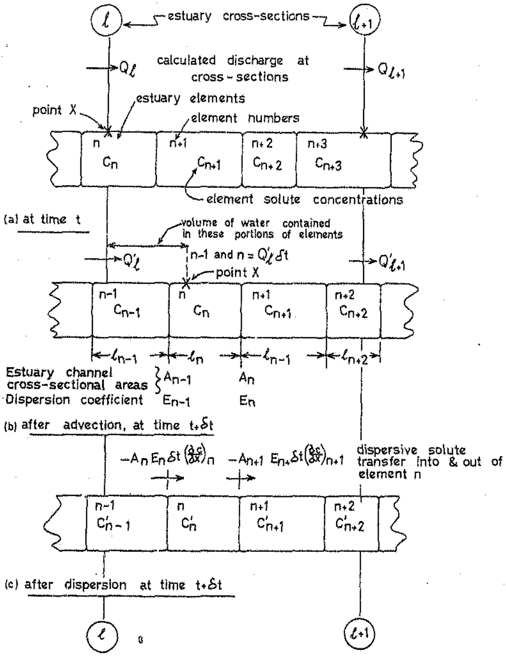


FIGURE 3.3 Schematic representation of one-dimensional advection & dispersion process in an estuary channel.

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)

$$\text{and} \quad T_{n-1} = \frac{A_{n-1} \cdot E_{n-1} \cdot \delta t}{(\ell_n + \ell_{n-1})} \quad \ldots \ldots \ldots \ldots (3.5)$$

$$T_n = \frac{A_n \cdot E_n \cdot \delta t}{(\ell_n + \ell_{n+1})} \quad \ldots \ldots \ldots \ldots (3.6)$$

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)

$\ell_{n-1}, \ell_n, \ell_{n+1}$ = 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

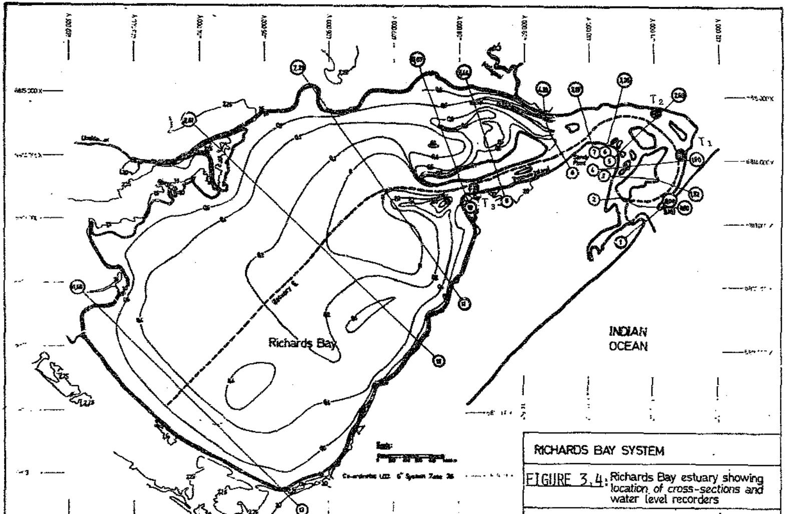
The location of the Richards Bay estuary system is shown in figure 2.1. A plan of the estuary is given in figure 3.4. The survey datum for all the hydrographic data presented in this chapter is LWOST(HRD) as defined in Appendix E.

(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 SYSTEM

FIGURE 3.4: Richards Bay estuary showing location of cross-sections and water level recorders

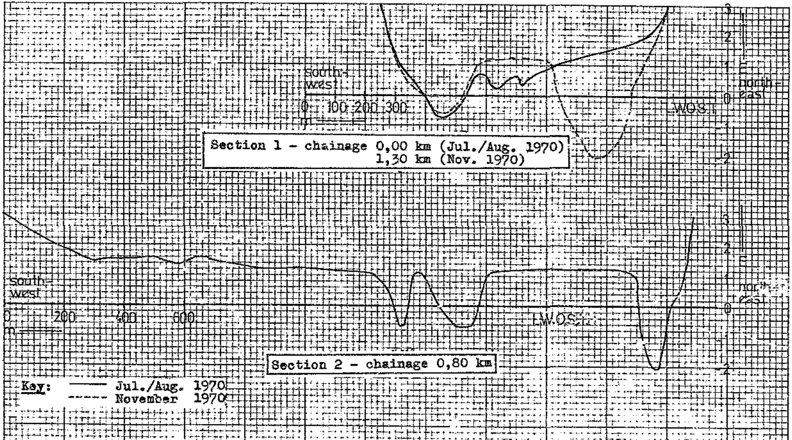


FIGURE 3.5 - Richards Bay estuary cross-sections (original system)

horizontal scale 1:10 000
vertical " 1: 100
" exag. 100

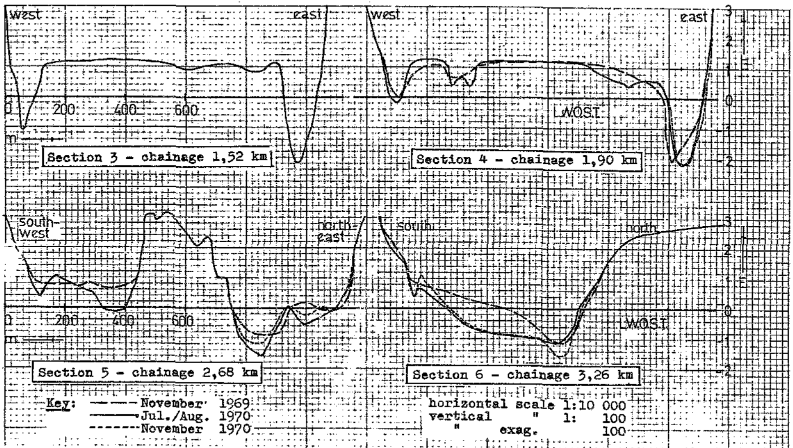


FIGURE 3,6 - Richards Bay estuary cross-sections (original system)

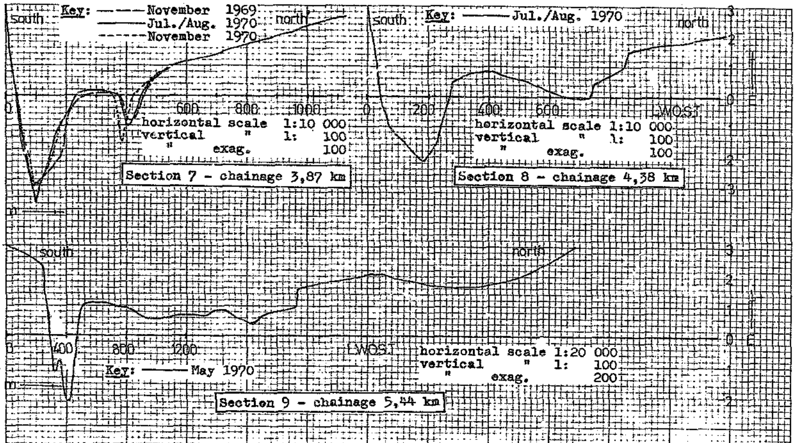


FIGURE 3.7 - Richards Bay estuary cross-sections
(original system)

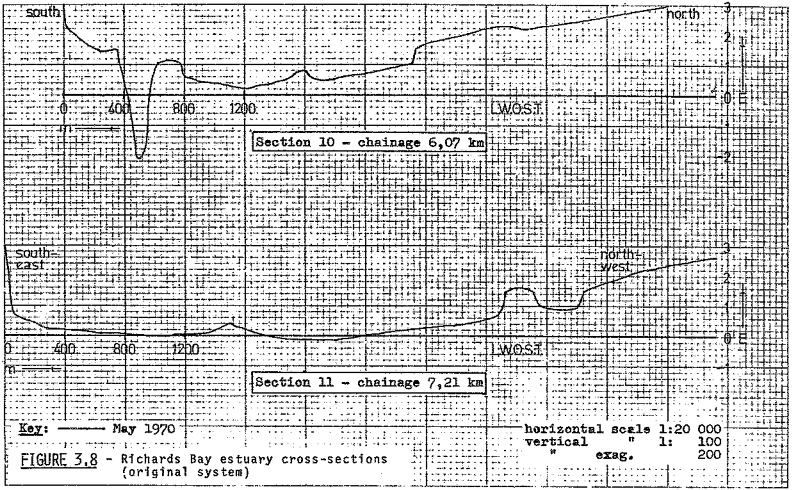


FIGURE 3.8 - Richards Bay estuary cross-sections (original system)

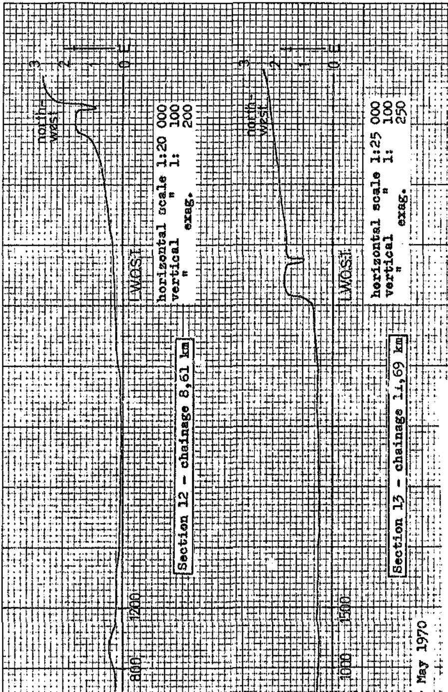


FIGURE 3.9 - Richards Bay estuary cross-sections (original system)

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:mouth	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	99,9	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	99,6	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 <u>Model calibration for the period 7 to 17 October 1969</u>

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).

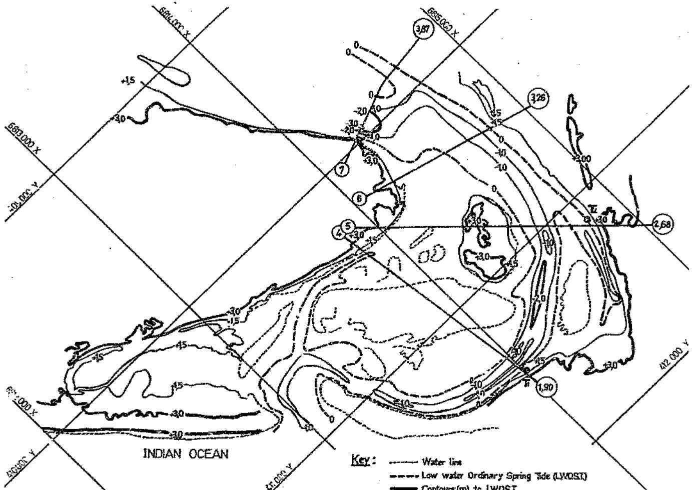
Estuary mouth geometry used for this simulation was obtained from the depth survey carried out by the CSIR[19] during November 1969 and is shown in figure 3.10.

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 <u>Model calibration for the period 5 to 8 October 1970</u>

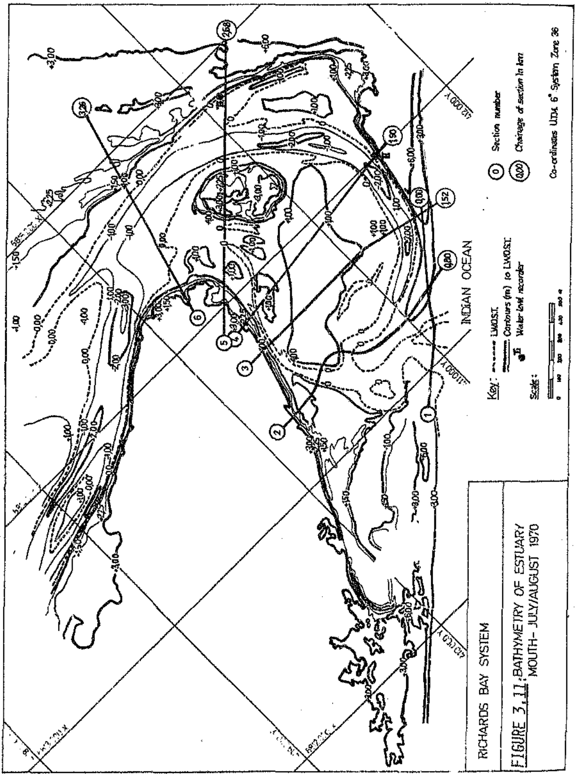
The data recorded during this period were used to calibrate the model between the estuary mouth (section 1) and the upstream end of the bay (section 13). Sea level data at Richards Bay were not available for this period. Durban sea level data were used for the downstream boundary condition. Water levels 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.



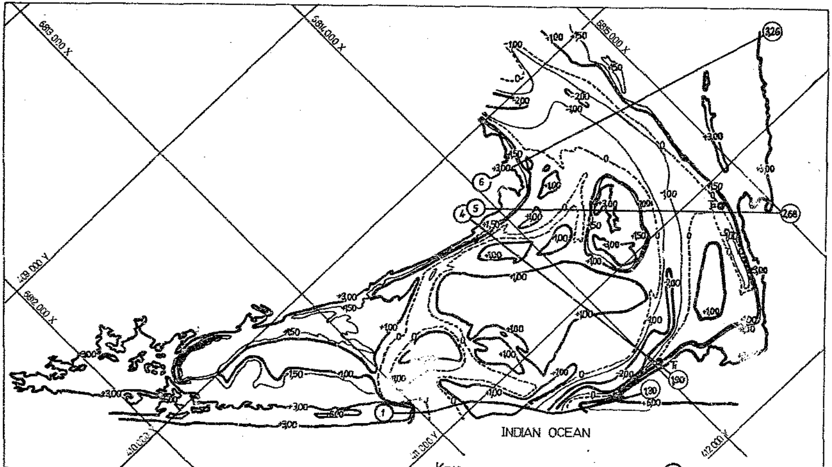
RICHARDS BAY SYSTEM

FIGURE 3.10: Bathymetry of estuary mouth – November 1969



RICHARDS BAY SYSTEM

FIGURE 3.11. BATHYMETRY OF ESTUARY MOUTH- JULY/AUGUST 1970



RICHARDS BAY SYSTEM

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[19].

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

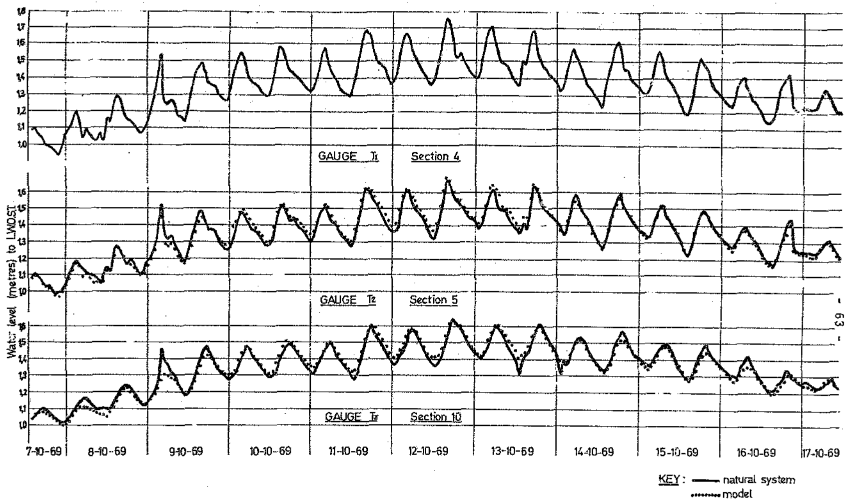


FIGURE 3.13 - Richards Bay estuary-
comparison of measured and
modelled water levels for the
October 1969 calibration run

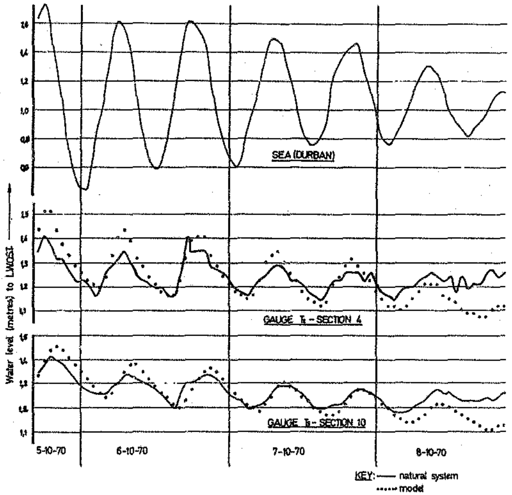


FIGURE 3.14: RICHARDS BAY ESTUARY - Comparison of measured and modelled water levels for early October 1970 calibration run

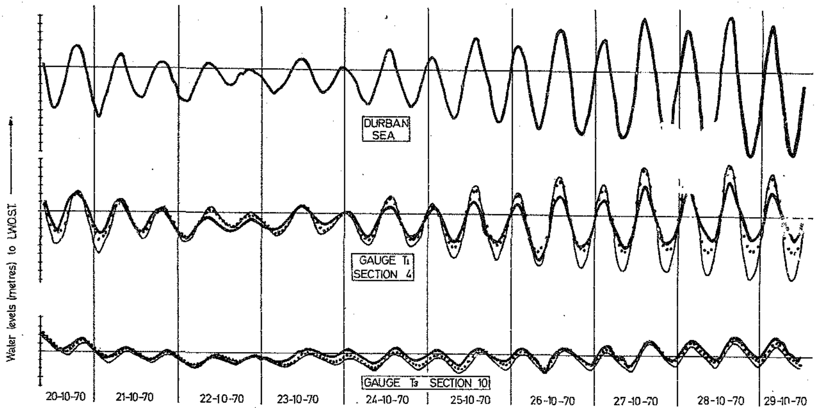


FIGURE 3.15: Richards Bay estuary – comparison of measured and modelled water levels for late October 1970 calibration runs

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	1,091	-	-	-
		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	59,2
	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

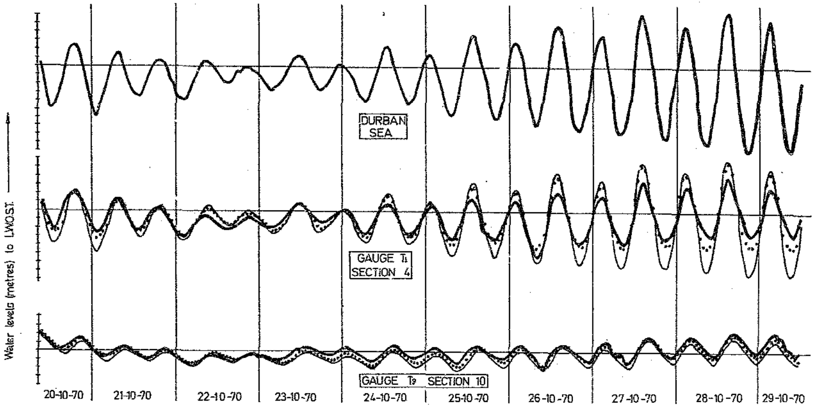


FIGURE 3.15: Richards Bay estuary - comparison of measured and modelled water levels for late October 1970 calibration runs

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 $m^{\frac{1}{2}}/s$	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 3.16. 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.

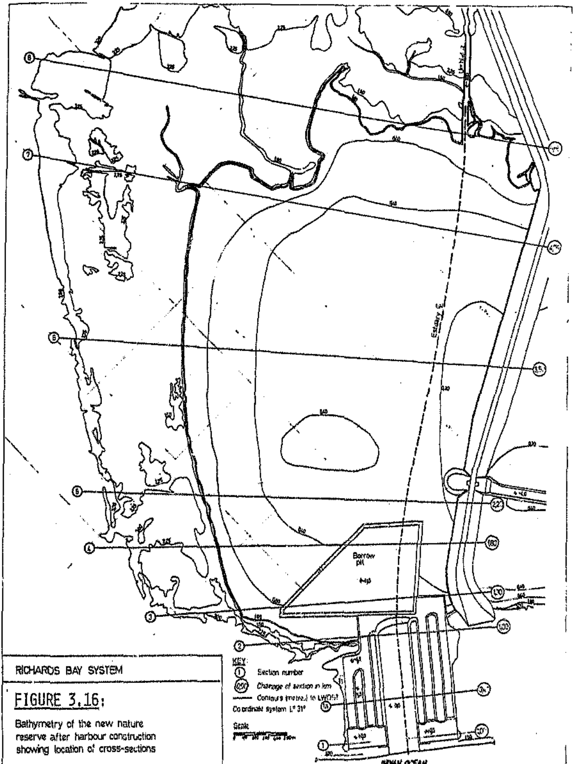
The following estuary mouth conditions were used:

(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.



RICHARDS BAY SYSTEM

FIGURE 3.16:

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

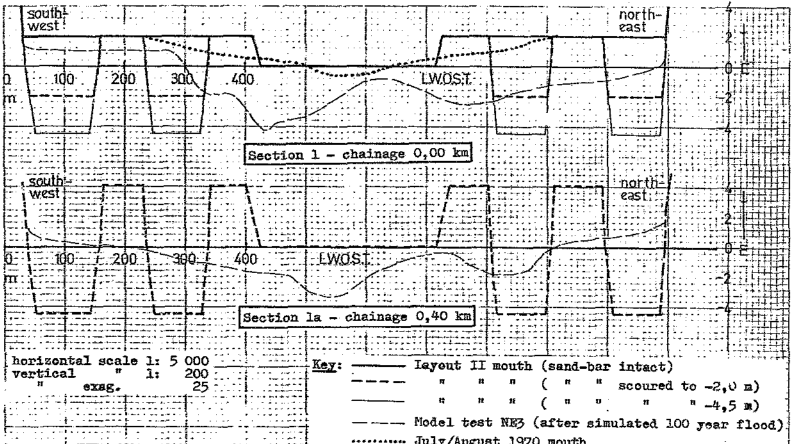


FIGURE 3.17 - Richards Bay estuary cross-sections (proposed new nature reserve)

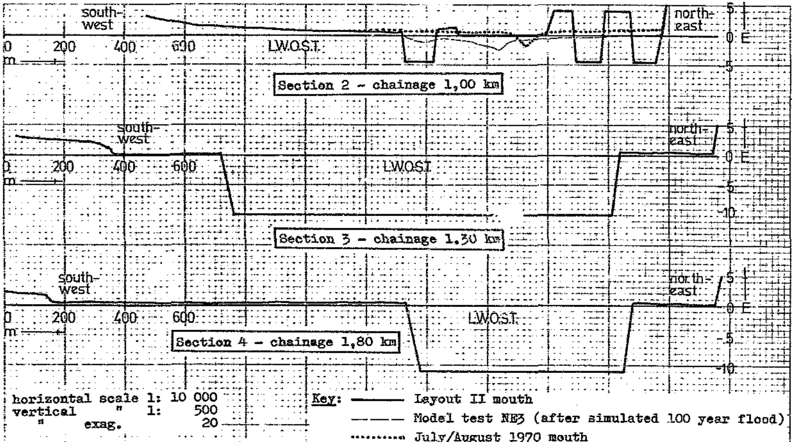
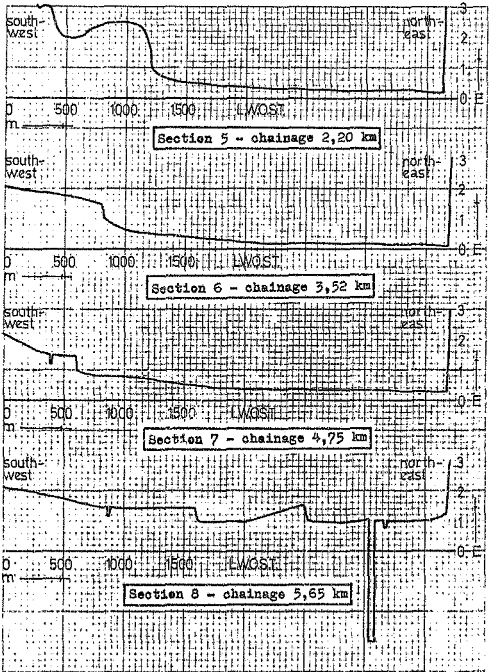


FIGURE 3.18 - Richards Bay estuary cross-sections (proposed new nature reserve)



Key: ——— based on May 1970 depth survey

horizontal scale 1: 25 000
vertical " 1: 100
" exag. 250

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 dischrge 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 proagation and advection in the natural system with that of the proposed new nature reserve

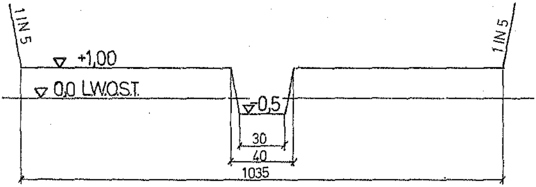
Table 3.5 gives the mean and extreme bay levels and the tidal prisms for each of the simulations. Figures 3.21 to 3.23 show the maximum and minimum water levels and the maximum tidal advection occurring at each estuary cross-section. From table 3.5 and figure 3.23 it is seen that in all of the runs simulating 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

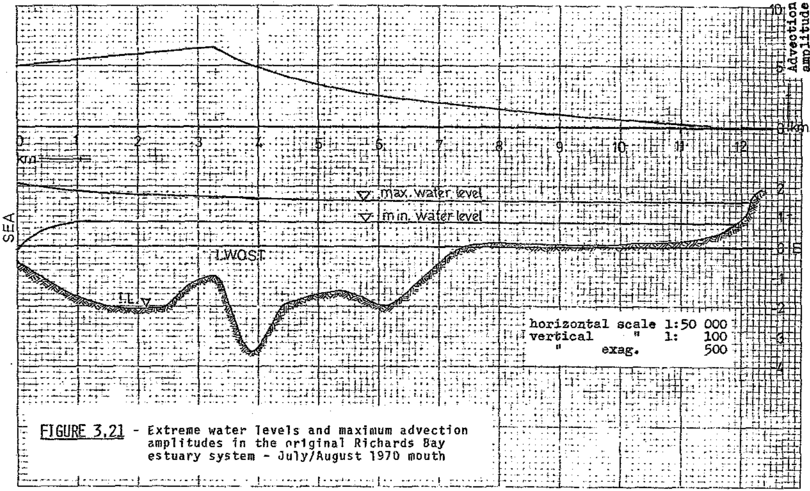


FIGURE 3,21 - Extreme water levels and maximum advection amplitudes in the original Richards Bay estuary system - July/August 1970 mouth

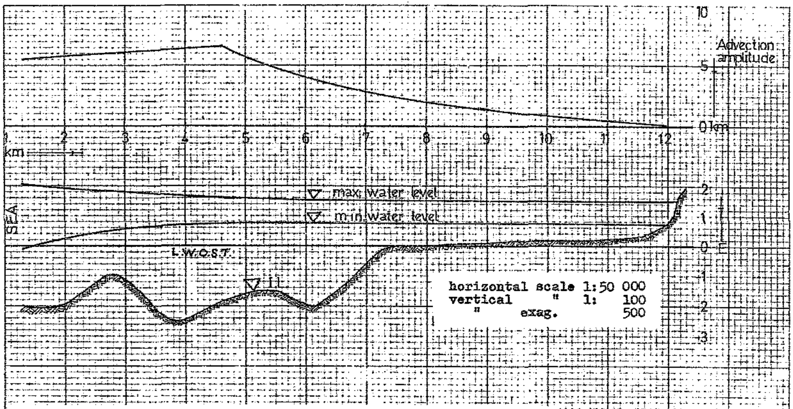


FIGURE 3.22 - Extreme water levels and maximum advection amplitudes in the original Richards Bay estuary system - November 1970 mouth (after flood)

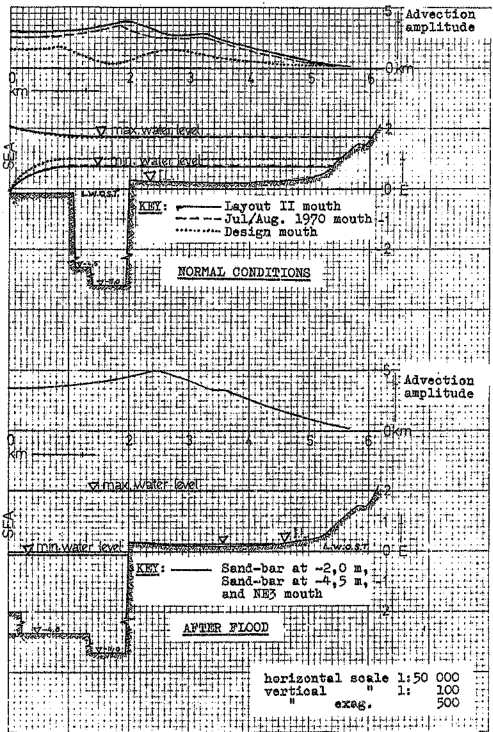


FIGURE 3.23 - Extreme water levels and maximum advection amplitudes in the proposed new nature reserve estuary system

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	0,39*	1,68	22,6
		0,82	1,90	0,93	1,83	0,26*	1,57	19,3
	model test NE3	1,06	1,90	1,13	2,05	0,40*	1,65	22,5
		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
	Me3 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.

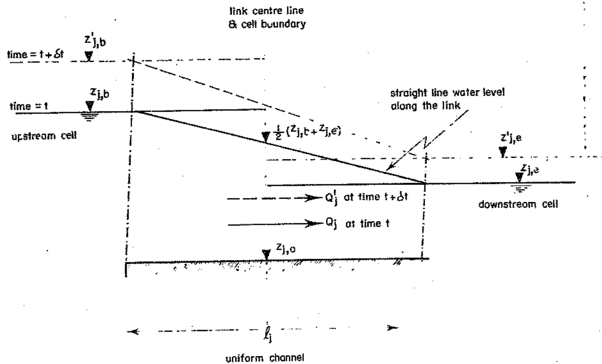


FIGURE 4.1 LONGITUDINAL SECTION THROUGH A TYPICAL FLOW LINK (channel)

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:

$$I = \Delta S + 0 \quad \ldots\ldots(4.1)$$

where, during time increment Δt, I = inflow

0 = 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^1 = 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 HDYP05 is described in detail in reference 22.

4.1.2 HDYP06

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.

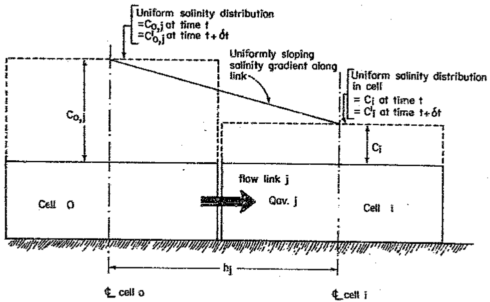


FIGURE 4.2 LONGITUDINAL SECTION THROUGH A GENERAL FLOW LINK, j

(a) Advection

The advective currents in the flow links are averages obtained from the program HDYP05. 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:-

$$\text{Advection} = LAI = 0{,}0864\ r_{i,j}\ \tfrac{1}{2}(C'_{o,j} + C_{o,j})Qav_j\delta t$$
$$-0{,}0864\ s_{i,j}\ \tfrac{1}{2}(C'_i + C_i)Qav_j\delta t \quad \ldots\ldots\ldots\ldots(4.3)$$

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:-

$$\text{Advection} = EAI = 0{,}0864\ r_k C_s QEav_k\delta t - s_k\ \tfrac{1}{2}(C'_i + C_i)QEav_k\delta t \quad \ldots\ldots\ldots(4.4)$$

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:-

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

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' = average salinity of cell i at time t and $t+\delta t$ (ppt)

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

Dispersion into cell via estuary k :-

$$\text{Dispersion} = \text{EDI} = \frac{Dg_k}{2h_k}(2.C_s - C_i' - C_i)\delta t \quad \text{.................}(4.6)$$

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:-

$$\Delta s = Vs_i'C_i' - Vs_iC_i \quad \text{.............................}(4.7)$$

where Vs_i, Vs_i' = cell i volumes at time t and $t+\delta t$ ($m^3 x 10^6$)

The cell salt conservation equation is:-

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

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

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

$$s_kQEav_k)\} - \frac{\delta t}{2}\sum_{j=1}^{j=n_i}C_{o,j}'(\frac{Dg_j}{h_j} - 0{,}0864\ r_{i,j}Qav_j) =$$

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

$$0{,}0864\ s_kQEav_k)\} + C_s\{\delta t\sum_{k=1}^{k=m_i}\frac{Dg_k}{h_k} + 0{,}0864\ r_kQEav_k\}$$

$$+ \frac{\delta t}{2}\sum_{j=1}^{j=n_i}C_{o,j}(\frac{Dg_j}{h_j} + 0{,}0064\ r_{i,j}Qav_j) \quad \text{....................}(4.9)$$

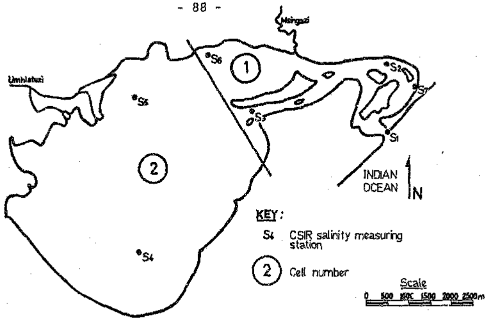


FIGURE 4.3 Richards bay – plan of the bay showing locations of cells and salinity measuring stations

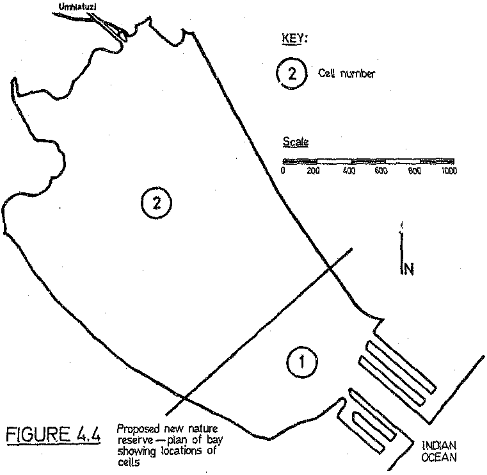


FIGURE 4.4 Proposed new nature reserve – plan of bay showing locations of cells

(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 caibration of the model. Table 4.6 demonstrates the correlation achieved between model and natural system behaviour. The final value of D adopted was 13 km²/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	35	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 km^2	level m	area km^2
-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	15,012
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 m^3/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 1970 catchment		proposed nature reserve			
				1970 catchment		1990 catchment	
		cell 1	cell 2	cell 1	cell 2	cell 1	cell 2
mean annual							
net evaporation	$m^3 x10^6$	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	$m^3 x10^6$	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.

6. ACKNOWLEDGEMENTS

The author is grateful to Professor D.C. Midgley, Mr. I.P.G. Hutchison and Dr. W.V.Pitman for their guidance throughout this study.

The co-operation of officials of the Department of Water Affairs, the Weather Bureau of the Department of Transport, the South African Railways and Harbours, the CSIR and the Building Services Department of the Natal Provincial Administration is gratefully acknowledged.

7. REFERENCES

(1) Heydorn, A.E.F. *The Interdependence of Marine and Esturine Ecosystems in South Africa.* South African Journal of Science, Volume 69 No.1, January 1973.

(2) Jones, R.[illegible] *[illegible]ards Bay - Largest Construction Project in South Af[illegible]a.* International Construction, Vol. 13, July 1971.

(3) *Richards Bay Harbour Development : New Estuary Layout.* Report No. C/SEA/74/11/2, National Research Institute for Oceanology, CSIR, Stellenbosch, July 1974.

(4) *New Estuary for the Richards Bay Lagoon. A Preliminary Investigation.* National Mechanical Engineering Research Institute, CSIR, Report No. ME 1143/1,2, Stellenbosch, July 1972.

(5) Weater Bureau, Pretoria. Unpublished monthly rainfall data.

(6) *Monthly rainfall and evaporation records of evaporation stations up to September 1967.* Hydrographic Survey Publication No. 9, Department of Water Affairs, Government Printer, Pretoria 1968.

(7) H[illegible], I.P.G. and Pitman, W.V. *Climatology and Hydrology of the St. Lucia Lake System.* Hydrological Research Unit, Report No. 1/73, University of the Witwatersrand, Johannesburg 1973.

(8) Pitman, W.V. *A mathematical model for generating monthly river flows from meteorological data in South Africa.* ph.D. thesis, Hydrological Research Unit, Report No. 2/73, University of the Witwatersrand, Johannesburg, 1973.

(9) *Monthly flow records of gauging stations up to September 1960.* Hydrographic Survey Publication No. 8, Vol. II, Department of Water Affairs, Government Printer, Pretoria, 1961.

(10) Midgley, D.C and Pitman, W.V. *Surface Water Resouces of South Africa.* Hydrological Research Unit, Report No. 2/69, University of the Witwatersrand, Johannesburg, 1969.

(11) *Mhlatuzi - Government water scheme, Goedertrouw dam.* White paper No. W.P. Q - '73, Department of Water Affairs, Government Printer, Pretoria, 1973.

(12) Midgley, D.C. and Pitman, W.V. *Design Flood Determination in*

South Africa. Report No. 1/72, Hydrological Research Unit, University of the Witwatersrand, August 1969.

(13) Pitman, W.V. *Flood Hydrograph Synthesization Program (unit-graph method)*. HRU Program Manual Series, Report No. M3/1973, Hydrological Research Unit, University of the Witwatersrand, August 1973.

(14) Rouse, H. *Engineering Hydraulics*. Wiley, 1949, Page 528.

(15) Report on agricultural and pastoral production, Agricultural Census, South African Department of Statistics, Pretoria.

(16) *Datum levels for hydrographic survey work*. Hydraulics Research Unit, CSIR Report No. ME 1182/6, Stellenbosch, November 1973.

(17) Director of Hydrography, South African Navy, Youngsfield, Kenwyn. Personal communication.

(18) Hutchison, I.P.G. *Mathematical modelling of one-dimensional tidal propagation and dispersion in estuaries*. Hydrological Research Unit, Report No. 4/74, University of the Witwatersrand, Johannesburg, 1974.

(19) *Richards Bay Harbour Development Studies : Progress Report, June, 1970 to May, 1971*. CSIR Report No. ME 1120, Stellenbosch, South Africa, February, 1972.

(20) Hutchison, I.P.G. *St. Lucia Lake - mathematical modelling and evaluation of ameliative measures*. Hydrological Research Unit, Report No. 1/76, University of the Witwatersrand, Johannesburg, 1976.

(21) Zwamborn, J.A. Head of the Coastal Engineering and Hydraulics Division, CSIR, personal communication.

(22) Hutchison, I.P.G. *Mathematical models for simulating monthly water levels and salinities in shallow lakes*. Hydrological Research Unit, Report No. 6/75, University of the Witwatersrand, Johannesburg, 1975.

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

Table A.1

AVERAGE RAINFALL ON CATCHMENT COMMANDED BY GAUGE W1H02 -UMHLATUZI RIVER

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD
303/122	1901 TO 1971
303/445	1900 TO 1955
303/485	1966 TO 1971
303/833	1915 TO 1966
303/835	1961 TO 1971
337/163	1926 TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	NO. OF GAUGES	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL TOTAL
1921-22	3	72	210	433	84	83	88	36	44	38	13	74	18	881
1922-23	3	149	146	74	208	83	44	28	4	1	10	9	14	740
1923-24	3	86	104	136	83	102	86	40	20	9	0	27	72	710
1924-25	3	64	221	141	187	136	481	73	46	5	63	6	81	1676
1925-26	3	167	86	82	73	64	168	44	54	45	3	17	78	776
1926-27	3	154	118	62	93	131	144	3	27	1	44	25	41	833
1927-28	3	183	48	127	131	110	70	36	61	0	11	24	28	713
1928-29	4	73	44	71	99	68	301	34	7	48	24	14	83	773
1929-30	4	104	136	48	204	80	96	83	13	5	63	58	49	808
1930-31	4	81	106	376	120	48	89	34	4	6	23	3	10	807
1931-32	4	65	86	76	78	373	142	88	121	14	3	7	35	1090
1932-33	4	83	84	145	84	104	34	24	1	3	30	11	30	675
1933-34	4	40	166	241	311	80	130	86	86	33	33	44	13	1234
1934-35	4	83	132	277	47	20	76	48	18	80	8	30	18	807
1935-36	4	46	76	56	147	186	177	25	118	7	2	9	43	840
1936-37	4	84	106	67	132	156	42	33	1	16	16	12	40	802
1937-38	4	48	83	380	177	248	75	114	6	55	87	16	26	1282
1938-39	4	109	63	203	83	270	133	38	48	8	61	25	78	1093
1939-40	4	32	202	184	132	48	104	41	232	63	1	10	58	1406
1940-41	4	90	143	283	76	52	84	63	84	38	18	10	34	908
1941-42	4	66	81	79	148	106	133	48	27	40	4	41	68	848
1942-43	4	93	150	226	161	109	109	228	86	28	98	128	16	1347
1943-44	4	166	144	107	66	181	100	30	3	157	13	1	147	1000
1944-45	4	74	85	66	187	195	247	31	40	3	1	1	13	784
1945-46	4	67	26	132	244	54	74	38	12	3	3	4	20	687
1946-47	4	114	136	105	136	161	159	41	15	88	7	14	46	838
1947-48	4	72	104	164	116	103	119	63	16	3	1	16	37	870
1948-49	4	88	116	96	128	164	153	133	33	30	4	7	48	938
1949-50	4	126	148	104	119	82	128	30	19	16	16	[illegible]	8	849
1950-51	4	54	55	173	98	76	65	36	12	11	7	[illegible]	43	731
1951-52	4	112	19	145	160	87	71	48	43	12	5	[illegible]	18	717
1952-53	4	74	115	127	109	141	93	38	8	13	[illegible]	[illegible]	27	750
1953-54	4	66	140	117	17	131	66	87	68	16	[illegible]	[illegible]	107	910
1954-55	4	226	141	84	187	103	185	49	34	11	1	4	36	1030
1955-56	4	133	143	161	21	211	33	12	25	11	8	17	60	1034
1956-57	2	103	164	243	115	134	66	114	15	6	79	32	261	1344
1957-58	2	109	134	107	180	191	47	121	1	7	0	7	33	1033
1958-59	2	66	80	166	166	177	28	48	46	0	8	34	32	852
1959-60	2	59	84	248	62	128	135	38	30	0	31	8	89	948
1960-61	3	67	184	270	145	99	47	114	38	48	0	6	73	1100
1961-62	4	67	124	132	84	89	106	47	63	8	4	84	9	758
1962-63	4	133	140	130	148	63	188	70	3	73	179	4	7	1136
1963-64	3	33	139	43	115	86	20	88	30	13	16	8	67	751
1964-65	3	103	106	190	65	74	59	46	37	34	33	61	43	781
1965-66	3	113	126	115	215	153	77	47	36	9	2	29	44	966
1966-67	4	63	163	145	176	226	136	93	31	8	23	5	18	1008
1967-68	4	116	156	80	33	86	130	21	1	8	3	66	46	844
1968-69	4	70	154	161	76	70	224	58	83	13	7	6	43	967
1969-70	4	164	96	101	66	70	69	45	57	16	3	48	84	798
1970-71	4	161	128	76	199	88	74	84	172	1	12	33	48	1088
1971-72	4	97	48	161	117	251	67	20	88	18	12	14	98	1026
MEANS MM		86	132	156	136	134	118	58	33	20	20	24	47	920
% ANNUAL MEAN		10	13	18	14	14	13	6	4	2	3	3	6	100

Table A.2

AVERAGE RAINFALL ON CATCHMENT COMMANDED BY GAUGE W1H01 -UMHLATUZI RIVER

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD
303/122	1856 TO 1971
303/405	1900 TO 1955
303/486	1866 TO 1971
303/833	1916 TO 1955
303/835	1961 TO 1971
304/280	1925 TO 1970
304/487	1934 TO 1952
337/163	1926 TO 1971
337/628	1937 TO 1951

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	NO. OF GAUGES	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL TOTAL
1921-22	4	77	190	126	45	13	82	31	35	38	18	76	18	811
1922-23	4	121	145	66	113	40	46	35	4	2	42	8	13	683
1923-24	4	38	86	137	48	20	84	40	15	4	0	21	71	648
1924-25	5	47	318	186	184	116	723	70	61	8	84	4	82	1487
1925-26	5	57	93	73	16	56	180	13	11	60	3	8	73	708
1926-27	5	118	104	72	59	301	173	3	41	6	61	21	43	916
1927-28	5	68	62	104	140	112	58	44	37	3	21	22	24	695
1928-29	6	68	38	57	232	47	228	83	4	87	24	20	76	910
1929-30	6	98	117	52	338	66	72	75	12	10	8	36	58	835
1930-31	6	64	17	106	87	48	81	31	3	8	16	2	25	531
1931-32	6	72	50	86	60	374	176	135	113	11	1	19	30	1060
1932-33	6	62	88	130	88	104	48	31	0	8	23	15	36	661
1933-34	6	48	168	146	176	84	112	73	58	28	33	43	13	1086
1934-35	6	47	124	276	38	97	77	37	24	36	11	79	12	910
1935-36	6	42	90	87	173	163	103	54	116	1	10	3	38	772
1936-37	6	42	163	41	142	171	44	42	1	31	31	18	37	868
1937-38	7	63	80	238	137	246	56	114	8	14	84	19	14	1000
1938-39	7	180	47	76	16	282	118	26	42	15	49	19	61	1056
1939-40	7	44	265	85	110	35	106	88	363	26	0	16	86	1023
1940-41	7	41	165	212	70	47	76	69	32	10	11	11	50	796
1941-42	7	40	122	14	174	54	146	30	33	47	0	40	43	873
1942-43	[illegible]	38	187	211	53	88	134	226	41	17	83	214	18	1352
1943-44	[illegible]	[illegible]	142	100	28	164	18	38	8	100	10	5	188	1030
1944-45	[illegible]	84	100	60	154	107	283	18	28	5	3	7	10	759
1945-46	[illegible]	62	24	126	100	67	72	30	13	4	3	0	18	531
1946-47	[illegible]	103	110	182	215	188	94	42	14	42	11	26	48	868
1947-48	7	85	174	126	13	86	86	68	1	3	8	7	24	748
1948-49	7	70	165	86	133	123	85	154	17	28	2	5	40	856
1949-50	7	130	134	187	110	67	121	33	24	10	10	24	14	863
1950-51	7	48	38	129	18	34	84	43	13	11	2	138	93	609
1951-52	7	86	22	128	65	70	90	33	42	11	53	6	13	611
1952-53	7	89	133	111	117	114	80	50	16	11	6	35	30	603
1953-54	6	60	345	206	80	138	84	40	82	16	5	15	88	882
1954-55	6	238	108	60	143	90	316	64	54	8	0	3	30	883
1955-56	6	137	148	138	18	248	48	0	31	80	9	17	40	830
1956-57	4	80	154	284	166	247	45	106	10	0	66	28	364	1348
1957-58	4	180	31	82	176	311	27	136	8	13	1	3	38	843
1958-59	4	74	104	181	162	106	59	36	68	0	0	60	35	900
1959-60	4	45	83	316	80	130	126	80	17	1	12	11	40	897
1960-61	4	78	200	366	142	193	80	130	37	25	1	0	71	1080
1961-62	8	53	112	98	81	70	158	40	12	0	3	46	6	702
1962-63	8	103	145	126	141	64	177	66	2	58	185	9	8	1470
1963-64	6	71	173	36	204	65	43	77	14	17	15	4	28	688
1964-65	6	134	85	127	32	60	38	48	37	52	23	48	48	698
1965-66	5	307	115	80	182	361	33	28	30	16	2	22	35	786
1966-67	6	32	303	136	188	330	130	100	11	3	20	8	13	968
1967-68	6	164	163	93	69	73	136	56	7	5	4	41	41	778
1968-69	6	43	85	198	70	88	225	84	58	11	7	0	87	801
1969-70	6	140	60	64	47	88	78	42	46	16	3	37	85	704
1970-71	6	181	110	72	186	76	69	94	151	18	48	21	43	1002
1971-72	6	84	48	182	184	220	73	68	82	16	5	16	18	873
MEANS MM		86	143	129	118	115	106	56	34	21	18	34	46	868
% ANNUAL MEAN		10	13	14	13	13	12	6	4	2	2	3	5	100

Table A.3

AVERAGE RAINFALL ON CATCHMENT DOWNSTREAM OF GAUGE W1H01 -UMHLATUZI RIVER

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD
303/445	1890 TO 1955
303/486	1866 TO 1971
303/835	1915 TO 1955
304/833	1951 TO 1971
304/282	1921 TO 1970
304/487	1934 TO 1952
304/734	1914 TO 1971
304/736	1918 TO 1971
337/628	1937 TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	NO. OF GAUGES	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL TOTAL
1921-22	4	82	326	161	48	61	88	36	42	37	15	76	17	857
1922-23	3	116	144	82	202	57	55	36	16	4	20	9	19	751
1923-24	4	34	40	128	80	48	96	94	21	30	0	27	89	674
1924-25	5	48	150	163	542	136	166	72	94	7	43	6	15	1760
1925-26	5	65	68	70	46	88	157	23	16	80	6	10	48	715
1926-27	5	202	102	92	82	134	170	2	47	3	44	36	[illegible]	938
1927-28	5	181	80	82	134	110	87	58	37	8	28	37	77	736
1928-29	5	80	38	28	158	37	287	43	31	45	35	24	74	968
1929-30	5	75	80	73	246	42	45	42	32	15	39	24	34	780
1930-31	5	81	78	84	80	44	80	42	5	8	22	14	41	580
1931-32	5	78	70	85	84	348	86	140	113	11	1	14	22	1068
1932-33	5	44	80	153	48	101	36	20	4	8	16	31	32	581
1933-34	5	46	161	112	121	310	88	64	61	46	27	41	66	947
1934-35	5	48	106	264	38	79	39	37	41	10	3	11	18	773
1935-36	5	47	38	84	144	166	89	29	128	11	3	4	25	804
1936-37	5	76	266	28	146	186	81	40	3	36	23	30	60	977
1937-38	5	46	181	291	102	186	80	61	13	16	6	11	27	1003
1938-39	5	95	41	157	76	175	171	39	25	37	81	21	11	1001
1939-40	5	45	308	75	158	13	136	64	244	108	1	38	62	1061
1940-41	5	37	178	168	75	48	76	89	30	11	12	33	92	866
1941-42	5	36	133	97	133	63	186	36	15	15	44	44	94	986
1942-43	6	62	132	161	227	88	132	131	16	115	17	11	18	1312
1943-44	6	172	224	186	87	141	81	31	10	158	17	11	147	1428
1944-45	6	64	120	83	81	111	244	34	38	6	2	14	8	742
1945-46	6	64	31	124	264	38	81	37	20	4	1	6	21	614
1946-47	6	81	88	166	301	184	100	48	31	45	24	24	88	802
1947-48	6	40	184	202	17	40	82	70	4	5	1	11	34	696
1948-49	6	62	111	48	121	504	84	161	13	14	8	10	41	984
1949-50	6	135	132	236	174	97	118	36	37	24	19	28	18	817
1950-51	6	44	38	147	57	48	87	47	24	18	8	132	62	714
1951-52	6	57	14	164	46	68	54	32	53	11	46	9	14	568
1952-53	6	44	120	94	118	92	86	32	30	7	11	33	82	748
1953-54	5	78	159	112	36	146	60	84	88	31	5	31	114	940
1954-55	5	243	48	63	190	76	148	77	32	8	1	68	42	1011
1955-56	5	121	144	104	21	272	104	34	33	17	4	24	68	927
1956-57	3	78	178	308	118	147	80	103	13	9	46	88	288	1464
1957-58	3	172	74	92	260	154	16	117	14	33	18	8	62	963
1958-59	3	46	80	136	120	45	63	33	72	8	1	36	47	707
1959-60	3	62	84	154	43	186	118	46	37	8	22	31	46	737
1960-61	4	62	224	264	126	141	70	176	16	60	11	7	13	1267
1961-62	4	67	111	78	84	47	118	49	32	0	4	44	10	644
1962-63	4	64	148	104	138	69	361	64	0	24	313	8	18	1116
1963-64	4	70	94	46	115	63	66	78	17	28	29	14	37	718
1964-65	4	138	78	84	48	70	38	49	40	[illegible]	33	46	81	710
1965-66	4	126	64	78	162	84	26	40	21	43	8	33	42	740
1966-67	6	48	84	118	149	185	132	148	10	4	30	14	16	937
1967-68	6	84	137	65	63	80	107	13	8	6	7	87	64	734
1968-69	6	65	84	103	66	48	272	66	71	14	4	8	67	838
1969-70	4	136	64	73	14	84	72	41	71	18	4	24	76	690
1970-71	4	157	133	73	142	17	88	84	184	24	64	30	65	1104
1971-72	4	[illegible]	61	134	144	166	66	38	104	16	19	20	31	1007
MEANS MM		43	104	134	112	135	116	48	42	24	24	36	80	874
% ANNUAL MEAN		8	12	13	13	13	13	7	4	3	3	3	4	100

Table A.4

AVERAGE RAINFALL ON UMHLATUZI RIVER CATCHMENT (EXCLUDING [illegible] CATCHMENT)

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD
303/122	1856 TO 1971
303/445	1890 TO 1955
303/486	1861 TO 1971
303/833	1915 TO 1966
303/835	1961 TO 1971
304/282	1921 TO 1970
304/487	1934 TO 1952
304/734	1913 TO 1971
337/163	1926 TO 1971
337/628	1937 TO 1951

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	NO. OF GAUGES	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL TOTAL
1921-22	4	66	313	145	54	71	86	33	41	39	16	75	16	860
1922-23	3	118	147	65	189	68	81	35	6	3	13	8	11	687
1923-24	4	37	46	127	48	88	101	84	26	17	1	24	81	680
1924-25	5	51	308	158	168	125	733	71	75	7	61	6	86	1941
1925-26	5	69	70	74	46	87	167	24	12	67	4	8	73	701
1926-27	6	116	108	76	67	100	173	3	49	5	53	24	43	881
1927-28	6	103	80	104	140	119	41	60	32	7	14	33	26	739
1928-29	6	65	34	51	137	45	242	48	5	66	38	33	76	837
1929-30	7	87	113	48	228	64	70	60	13	17	13	35	60	814
1930-31	7	81	36	104	90	48	83	48	4	7	13	3	27	544
1931-32	7	71	66	87	42	372	113	144	116	13	2	13	28	1081
1932-33	7	51	87	126	54	97	44	20	0	3	21	16	38	580
1933-34	7	44	156	163	172	87	106	71	57	28	35	44	44	1001
1934-35	7	48	118	268	38	78	73	30	41	14	12	44	12	826
1935-36	7	43	46	85	174	160	105	31	129	14	3	17	30	814
1936-37	7	43	166	31	145	172	82	41	3	22	31	20	30	848
1937-38	7	61	214	324	121	227	137	63	10	16	8	14	29	1198
1938-39	7	97	48	174	76	197	171	30	30	31	31	7	38	1003
1939-40	8	42	311	80	111	39	135	68	210	96	1	24	54	1066
1940-41	8	40	163	201	81	61	78	77	30	10	11	11	37	791
1941-42	8	39	126	118	131	67	136	38	20	15	4	41	43	795
1942-43	8	73	134	216	121	88	136	203	38	38	51	117	17	1273
1943-44	8	181	128	104	47	143	103	40	10	116	15	9	168	1067
1944-45	8	61	108	58	164	120	262	18	38	6	2	35	9	718
1945-46	8	83	38	124	134	46	83	37	17	6	1	8	38	626
1946-47	8	163	104	186	132	172	174	44	35	47	18	30	49	813
1947-48	8	88	139	128	57	86	96	70	8	4	1	0	37	764
1948-49	8	74	163	77	130	124	78	148	17	33	4	8	43	804
1949-50	8	130	131	301	104	81	129	27	34	30	21	37	18	836
1950-51	8	49	35	189	86	38	67	47	18	16	7	131	86	727
1951-52	8	67	61	127	63	78	62	36	53	12	60	6	12	638
1952-53	8	84	134	105	118	110	56	28	16	11	3	38	47	708
1953-54	7	68	130	106	62	167	60	53	67	18	6	18	104	951
1954-55	7	233	183	81	106	86	114	71	34	8	1	11	31	1017
1955-56	7	130	180	141	36	200	87	13	33	15	3	33	63	946
1956-57	5	127	181	318	155	142	80	160	14	3	47	35	278	1422
1957-58	5	149	80	71	133	104	37	118	10	43	9	4	47	888
1958-59	5	76	87	148	161	44	19	32	71	0	5	46	40	787
1959-60	8	80	63	194	86	146	121	31	38	3	17	18	81	888
1960-61	6	60	237	384	136	141	48	140	38	42	8	9	74	1302
1961-62	6	63	118	83	64	38	116	41	62	4	3	47	12	732
1962-63	6	88	146	118	144	69	370	48	3	42	204	4	8	1120
1963-64	6	78	[illegible]	43	118	65	46	83	16	18	33	31	31	724
1964-65	6	137	68	111	81	94	22	40	33	60	33	64	40	746
1965-66	6	124	116	80	100	[illegible]	31	43	34	20	4	33	34	734
1966-67	7	86	100	128	170	215	123	140	44	4	35	9	57	979
1967-68	7	185	140	81	70	44	130	14	6	9	7	80	43	763
1968-69	7	49	16	101	44	84	231	85	64	14	5	2	63	719
1969-70	7	144	70	86	26	80	78	43	42	19	3	24	82	722
1970-71	7	184	118	71	181	77	83	94	184	18	88	20	18	1041
1971-72	8	54	88	148	142	248	77	26	87	37	12	18	68	1011
MEANS MM		87	116	124	114	117	112	40	66	38	24	26	44	908
% ANNUAL MEAN		10	13	14	13	13	13	7	4	3	3	3	5	100

Table A.5

AVERAGE RAINFALL ON [illegible] RIVER CATCHMENT

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD
304/487	1924 TO 1952
304/730	1915 TO 1971
304/821	1916 TO 1971
305/ 37	1926 TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	NO. OF GAUGES	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL TOTAL
1921-22	2	119	266	143	57	66	99	39	44	30	20	68	20	1012
1922-23	2	141	143	46	243	31	51	22	16	3	30	7	31	751
1923-24	2	25	49	125	36	103	125	36	215	53	31	37	127	892
1924-25	3	55	183	177	122	182	215	63	143	12	72	7	21	1252
1925-26	3	104	55	76	56	108	185	37	17	56	61	11	72	893
1926-27	4	81	65	127	111	76	160	26	76	23	61	10	46	845
1927-28	4	50	45	76	137	157	56	64	66	21	17	58	26	808
1928-29	4	41	31	56	226	34	282	93	27	85	27	70	83	1005
1929-30	4	70	76	37	244	54	171	35	21	57	30	44	66	905
1930-31	4	35	81	75	33	67	66	42	14	20	35	0	36	508
1931-32	4	57	76	95	86	316	114	261	119	36	2	11	17	1235
1932-33	4	64	99	117	103	55	38	19	11	3	18	28	35	613
1933-34	4	55	101	113	154	126	94	64	47	31	80	52	24	963
1934-35	4	54	56	130	55	74	76	45	100	139	15	96	15	957
1935-36	4	30	36	42	142	201	103	18	156	26	46	11	40	983
1936-37	4	76	203	15	157	213	106	68	2	32	48	66	34	1074
1937-38	4	34	114	266	111	145	17	41	35	71	82	47	13	1001
1938-39	4	76	27	151	54	260	155	34	118	40	50	20	176	1182
1939-40	4	31	156	46	60	20	198	86	164	166	30	63	43	1123
1940-41	4	53	209	56	53	47	81	27	13	34	16	14	43	672
1941-42	4	25	132	61	171	35	217	46	62	65	50	45	77	880
1942-43	4	46	210	184	63	52	106	210	30	24	115	82	74	1186
1943-44	4	133	118	26	27	132	46	30	14	134	42	19	155	991
1944-45	4	61	140	42	92	124	234	29	95	30	3	24	9	864
1945-46	4	51	27	112	111	49	131	61	35	16	0	15	23	621
1946-47	4	73	46	106	83	226	125	65	50	66	59	38	74	1003
1947-48	4	43	110	103	55	110	92	43	6	20	2	16	44	734
1948-49	4	40	116	48	103	137	81	247	12	49	15	15	45	917
1949-50	4	110	76	264	165	146	126	62	41	25	33	26	60	1060
1950-51	4	46	25	146	51	38	57	40	29	14	27	135	62	690
1951-52	4	11	3	195	81	67	60	65	166	13	53	3	19	652
1952-53	4	32	114	107	133	64	74	17	28	5	27	20	05	713
1953-54	4	102	176	76	40	232	43	100	116	67	20	24	140	1239
1954-55	4	232	32	16	144	74	215	33	42	15	3	47	60	1025
1955-56	4	167	123	74	46	153	132	32	32	56	4	47	64	1040
1956-57	4	115	145	[illegible]	126	117	117	136	26	17	59	36	196	1500
1957-58	4	124	66	73	239	115	22	132	13	35	33	15	79	1015
1958-59	4	47	15	[illegible]	12	52	15	12	41	3	6	34	75	643
1959-60	4	102	63	117	[illegible]	172	36	147	60	10	43	20	53	901
1960-61	4	42	[illegible]	352	[illegible]	177	[illegible]	[illegible]	22	81	30	22	43	1161
1961-62	4	41	11	46	77	[illegible]	66	60	35	1	12	40	24	584
1962-63	4	71	93	46	46	[illegible]	332	24	2	145	309	3	3	1001
1963-64	4	[illegible]	24	[illegible]	143	[illegible]	[illegible]	71	16	17	46	23	26	616
1964-65	4	123	75	56	27	40	21	32	34	72	15	69	60	624
1965-66	4	134	56	33	176	45	34	46	26	21	[illegible]	54	40	676
1966-67	4	43	26	35	73	83	116	219	16	5	53	26	16	725
1967-68	3	[illegible]	75	17	14	126	35	48	4	35	11	51	34	595
1968-69	4	65	95	17	17	22	207	[illegible]	24	21	15	6	68	704
1969-70	4	145	55	55	95	52	54	34	41	52	5	7	51	572
1970-71	4	116	75	86	144	97	122	64	105	6	71	13	47	1102
1971-72	4	14	41	77	153	223	80	49	56	29	30	14	16	967
MEANS MM		77	97	114	96	113	121	72	55	41	36	34	51	929
% ANNUAL MEAN		8	11	12	11	12	13	8	6	4	4	4	6	100

Table A.6

AVERAGE RAINFALL ON NORTH-EASTERN COASTAL CATCHMENT

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD
304/661	1915 TO 1954
304/681	1954 TO 1970
304/736	1915 TO 1971
305/167	1921 TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	NO. OF GAUGES	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL TOTAL
1921-22	3	168	361	276	85	67	144	58	66	44	20	101	30	1494
1922-23	3	107	228	74	335	43	76	33	25	6	49	12	8	1003
1923-24	3	52	84	161	43	225	278	145	46	35	41	55	172	1337
1924-25	3	103	223	176	146	354	594	147	330	41	74	15	109	[illegible]
1925-26	3	146	126	73	45	41	155	43	14	34	35	13	40	800
1926-27	3	38	56	44	66	41	73	33	39	38	30	11	14	485
1927-28	3	34	60	151	172	167	124	106	236	37	42	27	41	1198
1928-29	3	43	36	71	14	44	461	88	124	252	98	143	84	1586
1929-30	3	60	65	90	136	65	130	66	63	198	98	63	112	1144
1930-31	3	31	136	75	72	147	174	145	25	137	109	51	26	1129
1931-32	3	75	180	97	116	432	220	401	180	64	26	26	25	1914
1932-33	3	70	132	128	56	136	120	47	16	16	72	46	24	906
1933-34	3	75	126	105	264	215	65	123	122	135	107	58	30	1450
1934-35	3	62	85	248	226	71	91	70	183	205	32	176	28	1505
1935-36	3	36	63	213	163	198	164	44	206	86	62	34	87	1325
1936-37	3	113	213	23	249	256	274	90	3	34	39	27	58	1380
1937-38	3	79	167	287	110	193	82	63	65	130	116	108	38	1460
1938-39	3	67	36	136	127	260	208	74	263	94	93	39	142	1540
1939-40	3	43	235	31	144	183	330	135	235	316	40	101	59	1773
1940-41	3	75	288	116	58	59	126	34	44	84	30	31	62	996
1941-42	3	37	132	71	243	46	236	99	77	47	11	61	111	1271
1942-43	3	45	120	281	60	115	366	184	28	33	187	125	35	1677
1943-44	3	148	83	26	72	163	153	43	56	260	110	24	215	1427
1944-45	3	89	206	65	60	185	216	80	23	22	26	42	15	1061
1945-46	3	52	27	88	166	33	246	128	47	38	1	45	39	920
1946-47	3	63	34	164	160	351	214	168	62	143	123	40	48	1569
1947-48	3	92	116	105	160	165	145	129	8	97	22	66	98	1252
1948-49	3	64	106	61	119	150	65	273	33	30	44	33	100	1108
1949-50	3	72	168	200	122	164	104	111	76	43	10	61	37	1111
1950-51	3	56	32	153	104	67	173	54	67	34	67	175	05	1084
1951-52	3	152	14	160	35	28	03	110	162	51	118	11	20	1022
1952-53	3	31	155	145	105	138	180	44	41	41	73	43	63	1013
1953-54	3	140	272	119	146	214	121	167	183	77	37	53	142	1661
1954-55	3	264	57	57	156	98	278	123	86	25	5	113	80	1344
1955-56	2	142	164	86	11	434	389	35	120	106	37	134	130	1493
1956-57	3	163	157	517	262	213	186	294	67	49	161	78	258	2310
1957-58	3	225	77	172	461	144	34	178	8	69	109	58	140	1685
1958-59	3	122	84	167	168	40	51	28	120	7	33	76	88	853
1959-60	3	153	106	122	64	217	146	256	91	35	56	46	60	1304
1960-61	3	63	411	297	117	224	41	282	46	230	139	70	104	2105
1961-62	3	127	130	72	141	47	223	154	66	15	72	52	25	1184
1962-63	3	137	153	84	154	64	134	118	12	204	170	5	1	1604
1963-64	3	109	97	132	165	71	76	257	18	19	55	24	60	1100
1964-65	3	162	137	136	50	52	56	06	115	340	37	152	110	1252
1965-66	3	205	74	47	255	157	38	73	78	52	14	111	98	1231
1966-67	3	61	59	42	237	138	180	455	53	10	66	45	46	1379
1967-68	3	106	111	41	234	291	162	30	24	56	20	85	79	1176
1968-69	3	112	117	75	22	40	509	120	116	49	42	0	123	1325
1969-70	3	147	91	98	149	301	111	85	150	41	27	35	35	[illegible]
1970-71	3	271	161	37	166	679	231	182	678	27	120	27	115	2229
1971-72	2	175	70	164	262	423	143	150	155	91	54	23	4	1763
MEANS MM		116	125	139	142	156	164	132	101	80	65	62	74	1390
% ANNUAL MEAN		8	9	10	10	11	14	10	7	6	5	4	5	100

Table A.7

AVERAGE RAINFALL OF SOUTH-WESTERN COASTAL CATCHMENT

DETAILS OF RAINFALL STATIONS USED

STATION	PERIOD OF RECORD
305/ 43	1931 TO 1971
305/167	1921 TO 1971
305/305	1930 TO 1971

AVERAGE MONTHLY CATCHMENT RAINFALL IN MM

YEAR	NO. OF GAUGES	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL TOTAL
1921-22	1	142	305	114	60	116	136	52	76	44	21	96	31	1415
1922-23	1	201	200	77	287	78	99	57	26	11	54	15	12	1161
1923-24	1	42	86	155	58	285	270	143	67	31	53	65	144	1457
1924-25	1	88	220	185	162	304	506	153	102	35	101	16	111	[illegible]
1925-26	1	148	132	92	61	59	219	72	25	44	31	24	66	975
1926-27	1	80	66	90	136	76	140	30	52	35	62	25	39	[illegible]
1927-28	1	65	57	142	167	119	105	37	174	40	37	46	42	1125
1928-29	1	47	37	67	126	53	425	86	61	167	75	136	78	1372
1929-30	1	80	74	67	167	61	96	72	57	160	87	66	104	1116
1930-31	2	34	139	62	42	141	136	139	26	103	180	36	55	1034
1931-32	3	92	130	92	114	308	190	331	151	64	10	25	34	1561
1932-33	3	64	123	165	121	117	130	46	15	22	76	52	34	1019
1933-34	3	66	112	116	205	142	91	123	116	137	124	42	29	1346
1934-35	3	66	92	276	66	74	82	70	165	276	25	128	31	1394
1935-36	3	78	71	267	126	215	147	44	175	47	54	26	15	[illegible]
1936-37	3	120	202	25	173	126	260	44	[illegible]	[illegible]	41	46	39	1214
1937-38	3	57	181	236	123	167	197	60	65	135	152	93	16	1424
1938-39	3	77	32	153	132	240	167	73	190	61	74	40	154	1474
1939-40	3	76	203	57	136	20	300	112	200	194	34	101	47	1484
1940-41	3	81	234	103	73	75	91	28	22	73	32	20	62	913
1941-42	3	36	131	75	172	46	258	43	96	42	42	67	117	1106
1942-43	3	36	113	278	61	57	375	230	28	30	140	136	41	1564
1943-44	3	140	70	63	26	85	128	43	35	256	144	69	219	1252
1944-45	3	87	132	57	25	181	240	32	31	24	36	47	21	1055
1945-46	3	57	30	37	126	90	274	156	74	21	4	43	45	975
1946-47	3	69	43	129	153	215	181	154	[illegible]	126	110	57	70	1541
1947-48	3	56	121	122	150	260	145	108	31	[illegible]	31	28	30	1097
1948-49	3	76	25	74	111	112	82	246	21	25	40	41	33	1005
1949-50	3	132	93	226	120	151	125	43	60	57	19	53	34	1205
1950-51	3	56	31	113	102	54	132	55	61	36	86	149	106	1021
1951-52	4	116	7	105	36	73	54	114	134	41	46	36	20	[illegible]
1952-53	4	34	121	[illegible]	[illegible]	155	166	44	45	20	53	26	106	974
1953-54	4	116	212	76	164	[illegible]	134	176	173	71	25	98	162	[illegible]
1954-55	4	273	73	41	115	61	[illegible]	[illegible]	104	36	4	131	113	1421
1955-56	4	131	147	65	7	422	327	[illegible]	100	114	43	170	149	[illegible]
1956-57	4	164	176	446	147	142	161	308	65	34	161	67	232	[illegible]
1957-58	4	168	72	300	356	153	51	[illegible]	11	74	65	35	151	[illegible]
1958-59	3	46	47	[illegible]	55	67	55	34	[illegible]	05	43	112	32	561
1959-60	3	147	107	142	65	234	116	151	101	45	19	36	31	1244
1960-61	3	81	122	[illegible]	[illegible]	174	122	426	[illegible]	211	113	56	107	[illegible]
1961-62	3	120	146	82	172	61	207	135	47	24	45	75	41	1250
1962-63	3	121	145	62	155	58	230	144	5	342	260	36	5	[illegible]
1963-64	3	126	54	116	151	75	300	[illegible]	4	25	43	4	31	[illegible]
1964-65	3	148	128	126	91	79	60	[illegible]	111	207	52	165	149	1366
1965-66	3	224	70	57	172	150	21	132	74	57	34	126	56	1227
1966-67	3	61	77	81	125	113	402	157	47	25	49	72	41	1406
1967-68	3	83	95	36	192	211	186	30	26	71	12	41	69	1116
1968-69	3	54	135	17	32	43	[illegible]	174	117	42	14	1	[illegible]	[illegible]
1969-70	4	121	77	23	114	74	91	64	137	[illegible]	[illegible]	23	[illegible]	[illegible]
1970-71	3	249	101	56	54	132	417	127	[illegible]	[illegible]	200	[illegible]	[illegible]	2040
1971-72	3	121	62	137	216	276	122	171	153	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MEANS MM		103	120	126	124	143	150	121	57	60	67	74	75	[illegible]
% ANNUAL MEAN		8	9	10	10	11	14	9	7	5	5	6	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.

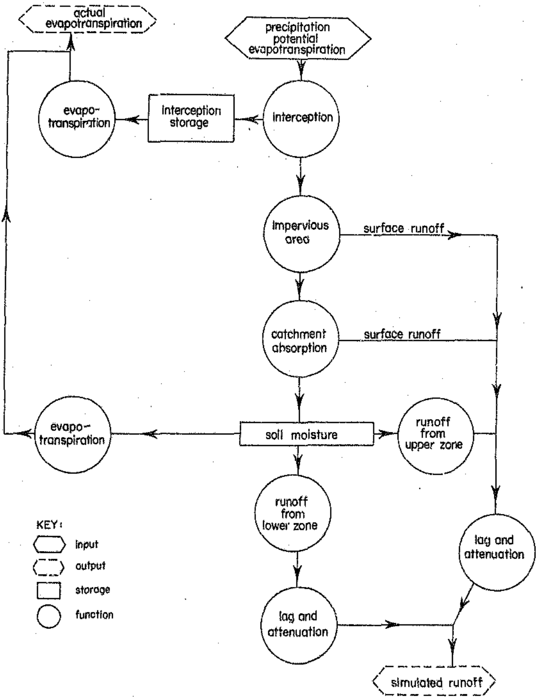


FIGURE B.1 CATCHMENT MODEL FLOWCHART

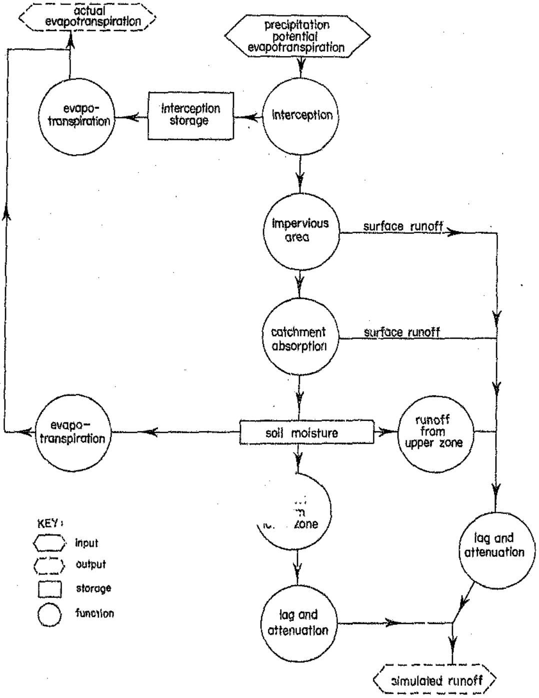


FIGURE B.1 CATCHMENT MODEL FLOWCHART

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	7 098	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.

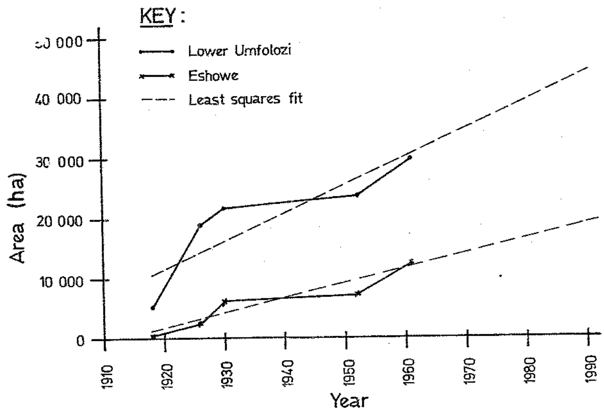


FIGURE C1.: Areas of land under sugar in the Eshowe and Lower Umfolozi magisterial dis·ˈicts

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	n.a.	n.a.	600
	Lower Umfolozi	-			-
	total	40			600
above W1M09	Eshowe	n.a.	2 300	n.a.	n.a.
	Lower Umfolozi		5 300		
	total		7 600		
Umhlatuzi	Eshowe	n.a.	n.a.	2 800	4 000
	Lower Umfolozi			9 500	12 000
	total			12 300	16 000
Nsezi	Eshowe	n.a.	n.a.	-	-
	Lower Umfolozi			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

TABLE D.1 : FLOOD HYDROGRAPHS FOR 5 YEAR R.I. STORM

TIME HOURS	CATCHMENT NUMBER 1 VIRGIN	1 INC. DAM	2	3	4
0	0	0	0	0	0
2	0	0	0	1	0
4	1	2	9	33	47
6	5	7	65	83	75
8	40	20	181	124	91
10	81	68	268	154	90
12	127	118	330	173	103
14	181	144	362	172	68
16	230	177	356	126	51
18	263	206	285	75	29
20	283	228	290	68	17
22	262	237	143	44	9
24	216	189	107	30	4
26	172	168	81	20	2
28	134	148	63	13	1
30	103	121	45	8	1
32	67	114	34	6	0
34	53	89	26	5	0
36	61	47	17	3	0
38	54	77	11	2	0
40	47	58	7	2	0
42	41	60	4	1	0
44	36	54	3	1	0
46	32	47	2	1	0
48	29	41	1	1	0
50	23	35	1	1	0
52	20	33	0	0	0
54	17	25	0	0	0
56	14	21	0	0	0
58	11	17	0	0	0
60	9	14	0	0	0
62	7	11	0	0	0
64	5	9	0	0	0
66	4	8	0	0	0
68	2	5	0	0	0
70	1	3	0	0	0
72	0	2	0	0	0

TABLE D.2 : FLOOD HYDROGRAPHS FOR 10 YEAR R.I. STORM

TIME HOURS	CATCHMENT NUMBER 1 VIRGIN	1 INC. DAM	2	3	4
0	0	0	0	0	0
2	0	0	0	2	16
4	4	4	24	57	76
6	12	12	221	136	118
8	33	33	286	200	141
10	156	100	367	243	152
12	215	157	468	269	158
14	315	252	510	277	124
16	400	314	511	223	75
18	452	360	407	131	42
20	458	466	284	93	23
22	454	383	203	62	13
24	376	242	150	41	7
26	300	203	115	27	3
28	234	214	77	18	2
30	156	178	66	12	1
32	151	165	48	8	0
34	127	148	34	6	0
36	100	144	24	4	0
38	88	129	16	3	0
40	83	115	10	2	0
42	73	100	6	2	0
44	63	88	4	1	0
46	57	77	2	1	0
48	47	67	1	1	0
50	41	57	1	1	0
52	35	48	0	1	0
54	30	41	0	0	0
56	23	34	0	0	0
58	20	28	0	0	0
60	17	23	0	0	0
62	13	18	0	0	0
64	10	14	0	0	0
66	7	10	0	0	0
68	4	7	0	0	0
70	2	5	0	0	0
72	1	3	0	0	0

TABLE D.3 : FLOOD HYDROGRAPHS FOR 20 YEAR R.I. STORM

TIME HOURS	CATCHMENT NUMBER 1 VIRGIN	1 INC. DAM	2	3	4
0	0	0	0	0	0
2	1	1	1	2	31
4	7	[illegible]	21	72	95
6	28	20	182	171	144
8	59	53	413	247	171
10	130	166	624	205	164
12	361	313	661	226	101
14	530	436	715	336	142
16	672	536	728	243	89
18	771	637	567	163	45
20	831	758	383	103	27
22	743	678	279	72	15
24	632	583	207	47	5
26	505	519	154	31	4
28	384	446	120	20	2
30	313	380	50	13	1
32	254	321	46	9	0
34	214	274	47	6	0
36	193	227	33	5	0
38	160	208	21	3	0
40	139	181	13	3	0
42	122	160	6	2	0
44	107	141	4	1	0
46	83	124	3	1	0
48	66	106	2	1	0
50	68	91	1	1	0
52	59	78	0	1	0
54	50	65	0	0	0
56	43	54	0	0	0
58	34	45	0	0	0
60	28	37	0	0	0
62	22	28	0	0	0
64	16	22	0	0	0
66	12	16	0	0	0
68	9	11	0	0	0
70	4	7	0	0	0
72	2	5	0	0	0

TABLE D.4 : FLOOD HYDROGRAPHS FOR 50 YEAR R.I. STORM

TIME HOURS	CATCHMENT NUMBER 1 VIRGIN	1 INC. DAM	2	3	4
0	0	0	0	0	0
2	4	1	1	2	27
4	9	1	28	97	121
6	27	57	252	222	182
8	75	72	734	316	215
10	241	222	725	377	231
12	465	421	845	414	238
14	721	840	816	422	201
16	905	834	829	301	118
18	1025	869	715	190	60
20	1102	864	424	130	33
22	1024	830	351	65	17
24	846	854	260	56	5
26	678	761	107	30	4
28	625	586	153	22	2
30	420	506	143	16	1
32	342	425	62	10	1
34	257	362	56	7	0
36	246	312	40	5	0
38	216	272	26	4	0
40	157	232	16	3	0
42	164	210	9	2	0
44	146	185	5	2	0
46	125	167	3	1	0
48	108	136	2	1	0
50	93	120	1	1	0
52	80	102	1	1	0
54	66	86	0	0	0
56	57	71	0	0	0
58	46	58	0	0	0
60	38	46	0	0	0
62	30	34	0	0	0
64	22	29	0	0	0
66	16	21	0	0	0
68	10	15	0	0	0
70	6	10	0	0	0
72	3	2	0	0	0

TABLE D.5 : FLOOD HYDROGRAPHS FOR 100 YEAR R.I. STORM

TIME HOURS	CATCHMENT NUMBER 1 VIRGIN	1 INC. DAM	2	3	4
0	0	0	0	0	0
2	3	2	2	4	33
4	12	12	36	118	144
6	35	35	362	265	214
8	56	52	646	273	251
10	369	245	871	443	260
12	622	541	1010	484	277
14	812	749	1097	483	234
16	1157	851	1141	348	126
18	1327	1128	857	226	68
20	1413	1261	657	147	37
22	1313	1158	376	96	18
24	1089	1041	308	63	10
26	868	803	233	47	5
28	678	585	173	25	2
30	638	644	124	16	1
32	438	536	88	11	1
34	366	457	69	8	0
36	316	384	47	5	0
38	275	343	28	4	0
40	245	301	18	3	0
42	210	264	11	2	0
44	184	233	6	2	0
46	162	208	3	1	0
48	138	178	2	1	0
50	120	152	1	1	0
52	103	128	1	1	0
54	87	107	0	0	0
56	73	82	0	0	0
58	60	73	0	0	0
60	48	60	0	0	0
62	38	47	0	0	0
64	28	36	0	0	0
66	20	26	0	0	0
68	13	18	0	0	0
70	8	12	0	0	0
72	4	7	0	0	0

TABLE D.6 : FLOOD HYDROGRAPHS FOR PROBABLE MAXIMUM FLOOD

TIME HOURS	CATCHMENT NUMBER 1 VIRGIN	1 INC. DAM	2	3	4
0	0	0	0	0	0
2	15	15	14	18	118
4	77	76	141	492	468
6	221	215	1332	806	662
8	410	572	2707	1301	756
10	1864	1767	3520	1274	805
12	3836	3504	4016	1472	829
14	5770	5024	4331	1475	682
16	7220	6424	4256	576	346
18	8195	7674	3265	405	182
20	6838	6447	3180	374	49
22	6301	7120	1844	234	47
24	6084	6510	1146	144	33
26	5658	5742	868	86	5
28	4267	4454	555	51	5
30	3412	3831	468	31	3
32	2773	3129	351	20	1
34	2228	2628	243	13	1
36	1858	2250	159	8	0
38	1741	1556	57	6	0
40	1520	1717	56	6	0
42	1322	1409	36	3	0
44	1165	1317	14	3	0
46	1021	1150	8	2	0
48	878	925	4	1	0
50	781	845	3	1	0
52	651	720	3	1	0
54	552	606	1	1	0
56	464	572	0	1	0
58	380	416	1	0	0
60	313	336	0	0	0
62	245	263	0	0	0
64	184	156	0	0	0
66	131	141	0	0	0
68	85	86	0	0	0
70	53	69	0	0	0
72	30	35	0	0	0

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