CONFIDENTIAL

FRESHWATER REQUIREMENTS OF THE ORANGE RIVER ESTUARY

Submitted to

DEPARTMENT OF WATER AFFAIRS

SEDIMENT DYNAMICS DIVISION AND
MARINE BIOLOGY DIVISION
NATIONAL RESEARCH INSTITUTE FOR OCEANOLOGY
COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH

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Stellenbosch, South Africa
September 1985

W. Laubscher.

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SCOPE

Several major dams have been constructed in the catchment of the Orange-Vaal River system in the last two decades and two further projects, the Orange-Fish Scheme and the Lesotho Highlands Water Project, are planned. In view of the resulting changes in the hydrology of the lower Orange River, freshwater releases required to keep the estuary in a viable condition are recommended while the effects of these freshwater releases on the morphology of the estuary and adjacent coastline and on the ecology of the estuary are examined.

The engineering and ecological sections of the report were written by Dr J Nicholson and Mr P Morant respectively. The report was edited for technical content by Dr D Swart.

Anderson.

F P ANDERSON
CHIEF DIRECTOR

Stellenbosch
September 1985

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1. INTRODUCTION

It is planned that water be transferred out of the Orange River catchment area by the Orange-Fish Scheme and also that further transfers may be associated with the Lesotho Highlands Water Project. The catchment of the Orange River and its main tributaries is given in Figure 1 and two photographs of the estuary of the river are contained in Plate 1.

In a letter, B73/2/6 dated 7 March 1984, and a second undated letter, the then Department of Environment Affairs (DEA) requested that this Institute undertake a study of the effects of reduced freshwater flows on the estuary of the Orange River. The various aspects of the study were to be as follows:

(a) a determination of the minimum freshwater flow needed to maintain the estuary in a viable condition;
(b) the morphological effects of reduced freshwater flow on the estuary;
(c) the morphological effects of reduced freshwater flow on the adjacent coastline;
(d) the ecological effects of reduced freshwater flow on the estuary.

It is assumed in this study that freshwater flows will be released from the P.K. le Roux Dam (see Figure 1).

Chapters 2 to 7 of this report cover the engineering aspects of the study. Background information such as the hydrology of the river, the wave climate and sediment transport rates in the vicinity of the estuary mouth and the stability of the latter are contained in Chapters 2 to 5 respectively. The minimum freshwater requirements are then discussed in Chapter 6 and the effects of the reduced flow on the adjacent coastline are given in Chapter 7. The ecological aspects of the study are covered in Chapter 8 and, finally, the conclusions are summarized in Chapter 9.

2. HYDROLOGY

2.1 General

The hydrology of the lower Orange River was examined with the aid of monthly flow rates for the hydrological years 1935/36 to 1968/69 and 1971/72 to 1982/83 (a hydrological year runs from October to September) and details of peak monthly events for the period October 1974 to July 1983. These data were recorded at gauging station D8M03A, which is located 275 km upstream of the Orange River mouth at Vioolsdrif (see Figure 1) and were supplied by the Department of Water Affairs (DWA). In addition, details of floods recorded at Alexander Bay between 1957 and 1967 were obtained from Consolidated Diamond Mines of South West Africa, Limited (CDM). Evaporation data recorded at gauging station D8E03 (see Figure 1) for the hydrological years 1952/53 to 1979/80 were also supplied by the DWA and further information on the average evaporation rates for the Orange River between the P.K. le Roux Dam and the sea was extracted from Pitman *et al*. (1981). Information on the mean annual runoff at the P.K. le Roux Dam was also extracted from Pitman *et al*. (1981).

The catchment of the Orange River, including that of the Vaal River, has a total area of 830 000 km^2 (Rogers, 1977). It covers the NW, N and Central Cape, the Orange Free State, the SW Transvaal, S South West Africa and S Botswana and is shown in Figure 1. However, only the area lying within the borders of South Africa is considered in this report, the remainder of the catchment being neglected because it is extremely arid (Rogers, 1977). The South African part of the catchment covers 555 000 km^2. Several major dams which affect the hydrology of the system have been constructed on the upper reaches of the Orange River and on the Vaal River. Their locations are also shown in Figure 1 and further details are listed in Table I.

A description of the runoff and evaporation rates in the lower Orange River is contained in the succeeding sections of this chapter.

2.2 Runoff

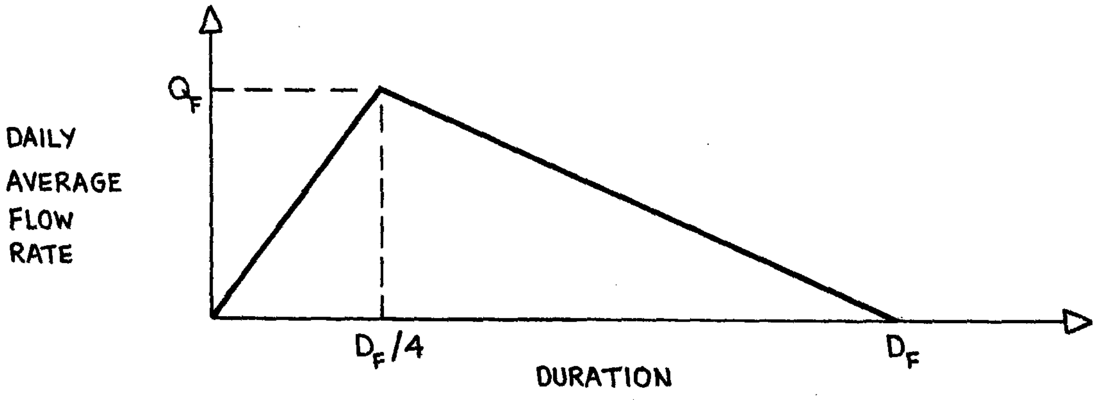
Runoff has a major influence on the morphology of the river mouth. However, the runoff of the lower Orange River has been modified considerably during the last two decades by the construction of several major dams, details of which are given in Table I. Two sets of runoff data were therefore considered. The first set (DWA, pers. comm.) was collected during the hydrological years 1935/36 to 1968/69 and relates to the period before construction of all the major dams except the Vaal Dam. Although the latter was constructed as early as 1937/38, it is located so far upstream of the Orange River mouth that its effects on the runoff at the latter can be taken to be relatively small. The second data set (DWA, pers. comm.) was collected during the hydrological years 1971/72 to 1982/83 and relates to the period after construction of all the major dams except the P.K. le Roux Dam. The latter was completed in 1977/78 and hence this year, to be strictly accurate, should mark the start of the post-dam period. However, so few data were available for the period after 1977/78 that the earlier year, namely 1971/72, was used instead.

The available runoff data were analysed to yield the following information:

i) peak monthly flood discharges;
ii) mean annual runoff.

Peak monthly flood discharges

The peak monthly floods were found to have a hydrograph of the following form:



It thus follows that the total runoff associated with a typical peak monthly flood is

$$\Omega_F = 24 \cdot 3600 \cdot Q_F \cdot D_F/2 \ (m^3) \qquad \ldots (2.1)$$

where

Q_F = monthly maximum, daily average flow rate (m^3/s);
D_F = duration of the peak, monthly flood (days).

A survey of the available data for the pre-dam period 1935/36 to 1968/69 and the post-dam period 1971/72 to 1982/83 (DWA, pers. comm.) yielded the mean value for the parameter 'Q_F', which is defined as the maximum flow rate averaged over a period of one day and occurring during a given calendar month. The resulting values for 'Q_F' and their standard deviations are listed in Tables IIa and IIb and the 'Q_F' values alone are plotted in Figure 2. As can be seen, 'Q_F' ranged from a minimum of 95 m^3/s in June to a maximum of 1 299 m^3/s in February between 1935/36 and 1968/69; the corresponding minimum and maximum values for 1971/72 to 1982/83 were 163 m^3/s in September and 713 m^3/s also in February. In addition, the duration of a typical peak monthly flood, 'D_F', was estimated to be 13 days during both the pre-dam and the post-dam periods (DWA, pers. comm.; CDM, pers. comm.). The resulting peak monthly flood discharges derived with the aid of Equation 2.1 have also been included in Tables IIa and IIb.

A comparison of peak flow rates measured at Alexander Bay near the river mouth and at Prieska (Midgley and Kelly, 1963) shows that these two quantities are of similar magnitude. As Prieska is situated approximately 1 100 km upstream of the river mouth (see Figure 1), it can be concluded that most floods in the lower Orange River are caused by heavy precipitation in the higher parts of the catchment upstream of the major dams. This conclusion is confirmed by Pitman *et al*. (1981) who state that 95 per cent of the Orange River runoff (excluding that of the Vaal River) originates upstream of the Hendrik Verwoerd Dam.

Mean annual runoff

The mean annual runoff recorded at Vioolsdrif during the pre-dam and the post-dam periods is as shown in the table below. Also included is the mean annual runoff for the P.K. le Roux Dam because the latter is assumed to be the release point for the freshwater flows. The relevant information for the P.K. le Roux Dam is based on simulated data for the period 1921/22 to 1976/77 (Pitman *et al*., 1981).

Location	Duration	Mean annual runoff (10^6 m^3)	Standard deviation (10^6 m^3)
Vioolsdrif	1935/36 - 1968/69	8 336	5 300
Vioolsdrif	1971/72 - 1982/83	5 766	4 664
P.K. le Roux Dam	1921/22 - 1976/77	6 933	-

2.3 Evaporation

The rate of evaporation, in conjunction with the water extraction rights of riparian owners downstream of the P.K. le Roux Dam, determines the minimum discharge that must be released from the dam. The available evaporation data for the reach of the Orange River below the P.K. le Roux Dam (Pitman *et al.*, 1981) were therefore analysed to determine the mean annual and monthly evaporation rates and an estimate was made of the water area from which evaporation takes place.

The average monthly net evaporation rates for the hydrological years 1952/53 to 1979/80 are listed in Table III and plotted in Figure 3 (net evaporation is total evaporation less rainfall). These quantities were based on monthly data recorded at the mouth of the Orange River but adjusted in proportion to the ratio between the average annual net evaporation between the P.K. le Roux Dam and the sea and the corresponding quantity at the river mouth. Table III and Figure 3 show that the net evaporation rate varies from a minimum value of 100 mm/month in July to a maximum value of 289 mm/month in January. The annual net evaporation rate is 2 270 mm.

The area from which evaporation takes place consists of the surface areas of the estuary and of the 1 400 km reach of river between the P.K. le Roux Dam and the estuary. Aerial photographs indicate that the estuary has an area of approximately $2 \cdot 10^6$ m^2 and, assuming a river width of between 50 m and 100 m, the surface area of the river is approximately $100 \cdot 10^6$ m^2. The surface area of the estuary, therefore, can be neglected leaving a total evaporation area of $100 \cdot 10^6$ m^2.

The volumetric evaporation rate commensurate with the above linear evaporation rate of 2 270 mm/year and surface area of $100 \cdot 10^6$ m^2 is approximately $200 \cdot 10^6$ m^3/year.

3. WAVE DATA

3.1 General

The frequencies of occurrence of wave heights, periods and directions at the breaker line were required for the computation of the longshore transport rate at the mouth of the Orange River. This breaker line wave climate was derived from the deep-sea wave climate by means of a refraction study.

The available deep-sea wave data, the refraction study and the resulting breaker line wave data are discussed below.

3.2 Deep-Sea Wave Data

The only available deep-sea wave height, period and direction data for the sea area opposite the Orange Estuary were collected by Voluntary Observing Ships (VOS). The VOS data (Swart and Serdyn, unpublished work), which are divided into sets of information valid for one degree 'squares' of latitude and longitude, consist of series of tables showing monthly wave height versus period occurrences for 30° direction sectors. Three such data sets were used in this study, the associated 'squares' being numbered 57, 58 and 60 as shown in Figure 1. Besides the set valid for the 'square' directly opposite the Orange Estuary (no. 60) two more southerly sets (nos. 57 and 58) were included because of the sparseness of the data and the fact that the dominant wave direction in the area is from the southern quadrant.

The number of available readings was 3 911, a breakdown of which is given below:

directions undefined = 97
directions defined = 3 814

and of the latter,

heights and/or periods undefined = 276
heights and periods defined = 3 538

It thus followed that 3 538 observations were suitable for use in the longshore transport computations. Of these, 696 observations had directions between 315° and 165° and were treated as 'calms' because the waves were travelling away from the coast; the orientation of the coastline is approximately 330°-150° (see Figure 1). The VOS deep-sea wave occurrence tables in the form of periods, 'T_{VOS}', versus deep-sea wave directions and corresponding, representative wave heights, 'H_{VOS}', are set out in Appendix A. The representative wave heights were taken to be the root mean square significant values because the longshore transport rate is a function of the square of the wave height.

The wave heights and periods actually used in the longshore transport computations were the so-called 'instrument' values, namely the deep-sea significant wave height, 'H_{OS}', and the period corresponding to the peak of the energy spectrum, 'T_p'. The best available relationships between these two variables and their VOS counterparts for the Orange River coastal area are as follows:

$$H_{OS} = 1{,}5 + 0{,}5 \cdot H_{VOS}$$

$$T_p = 6{,}0(T_{VOS})^{0{,}4}.$$

However, the VOS wave-occurrence tables given in Appendix A combine all waves with 'T_{VOS}' values less than or equal to 5,0 s, the latter being equivalent to a 'T_p' value of 11,4 s. As 27 per cent of all suitable data fell into this category, they could not be neglected and therefore it was necessary that a representative value be derived for 'T_p'. This derivation, which is described in Appendix B, yielded a representative 'T_p' value of 9,5 s. The resulting annual and monthly occurrences of peak energy wave period as a function of deep-sea direction and the corresponding representative, deep-sea, significant wave height are given in Table IV. As with the VOS data, the representative deep-sea significant wave heights were taken to be the root mean square significant values.

3.3 Refraction Study

The conversion of deep-sea wave data to breaker line data was achieved by means of a refraction study. A refraction study determines the paths taken by adjacent sections of a wave front as the wave advances towards the shoreline and thus results in a series of lines which are orthogonal to the wave front. At points where the orthogonals converge, the wave height increases and vice versa, this change in wave height being expressed in terms of a refraction coefficient. A given refraction analysis is valid for one particular wave period and one particular deep-sea wave direction only.

All wave orthogonals were terminated at the breaker line. Various criteria can be used to establish the break point of a wave, the one used in this case being (US Army, 1975)

$$H_B/d_B = 0{,}78$$

where 'H' is the wave height, 'd' is the water depth and subscript 'B' denotes breaking.

A set of 30 refraction analyses was carried out for the 6 wave periods and 5 deep-sea wave directions listed in Table IV. The analyses were based on the bathymetry shown in Figure 4 and were carried out using the finite difference method developed by Perlin and Dean (1983).

3.4 Breaker Line Wave Data

The breaker line wave data yielded by the refraction study consisted of the breaker height to deep-sea wave height ratio, the wave group velocity, the wave celerity and the wave direction. These parameters were then combined to give the longshore energy flux factors, the significance of which is explained in Appendix C. The computations were carried out for 20 coastal sections situated north and south of the Orange River Mouth. However, only the results pertaining to the 7 central sections shown in Figure 5 were used in an attempt to eliminate boundary effects. The average flux factor for these 7 sections for each deep-sea wave condition is listed in Table V.

4. SEDIMENT TRANSPORT

4.1 General

Waves approaching a coastline obliquely produce a flux of momentum in a direction parallel to the coastline. This, in turn, generates a longshore current which transports sediment that has been stirred up by the wave and current action. Because the wave direction is a variable, this longshore transport may take place in an upcoast or a downcoast direction. The sum of these two quantities, the gross longshore transport rate, is of primary importance in determining the stability of an estuary mouth. Also of importance, in the case of the Orange Estuary, is the transport of fluvial sediment, that is, the material carried by the river itself. Both the coastal and the fluvial sediment transport rates are assumed to refer to sand only ($60\ \mu m <$ diameter $< 2\ 000\ \mu m$).

This chapter consists of a derivation of the longshore and fluvial sediment transport rates occurring in the vicinity of the Orange River Mouth. Because the estuary mouth stability analysis was carried out for each month of a typical year, the two transport rates were also computed for periods of a month.

4.2 Longshore Sediment Transport

The longshore sediment transport rates were computed using the following relationship, details of which are given in Appendix C:

$$S_X = 2{,}06 \cdot 10^{-3} \rho \cdot g \cdot H_{OS}^2 \cdot f_I \cdot K(D) \cdot F_F$$

where

S_X = longshore transport rate (m^3/year);
ρ = water density (kg/m^3);
g = gravitational acceleration (m/s^2);
H_{OS} = deep-sea significant wave height (m);
f_I = fractional occurrence for a given wave condition (-);
K(D) = grain size parameter
= $91 \cdot 10^4 \log(0{,}00146/D_{50})(m/(s \cdot year))$;
D_{50} = median grain size (m);
F_F = longshore energy flux factor (m^3/s).

The above formula was applied to each wave condition in turn and the results summed to give the total longshore transport rate. The wave variables (H_{OS};f_I) are contained in Table IV and the longshore energy flux factors (F_F) are contained in Table V. The median grain size of the beach sediment (D_{50}) was taken to be 550 µm. This value was based on samples collected immediately to the north of the river mouth (CSIR, 1979; Rogers, 1977), which had an average median diameter of 570 µm, and samples collected immediately to the south of the river mouth (Martin, pers. comm.; Rogers, 1977), which had an average median diameter of 530 µm.

Table VI/1 contains the computed, potential longshore transport rates. The net annual rate was found to be approximately $4{,}6 \cdot 10^6$ m^3 which deviates markedly from a value of $1{,}4 \cdot 10^6$ m^3/year found for the section of coastline immediately to the north of the Orange River Mouth (CSIR, 1979). The latter transport rate had been derived using a ray refraction method and its accuracy had been confirmed by field measurements. A comparison of the two sets of calculations indicated that the finite difference refraction method of Perlin and Dean used in this study (see Section 3.3) was unable to handle waves with a very oblique angle of approach to the coastline. Nevertheless, it was assumed that the Perlin and Dean method yielded the correct monthly longshore transport distribution and the values listed in Table VI/1 were therefore modified by scaling them down in the ratio of 1,4 to 4,6. This exercise resulted in the corrected values for the longshore transport rates given in Table VI/2.

Aerial photographs of the coastline in the vicinity of the Orange River Mouth indicate that a plentiful supply of sand is available for transport and it was concluded, therefore, that the actual and the potential transport rates are identical. Referring to Table VI/2, the gross longshore transport rate was found to range from a minimum of $1{,}7 \cdot 10^6$ m^3/year in May to a maximum of $2{,}3 \cdot 10^6$ m^3/year in August.

4.3 Fluvial Sediment Transport

Information on the fluvial sediment transport was obtained from two sources, namely direct measurement by Rooseboom and Maas (1974) and sediment yield maps prepared by Rooseboom (1978) and presented by Pitman et al. (1981) and Middleton et al. (1981). Direct measurement of the sediment load was carried out at several points on the Orange River, Upington being the monitoring station closest to the coast. It was assumed, therefore, that data measured at this point, which is situated 700 km upstream of the river mouth (see Figure 1), are also valid for the estuary. Support for this assumption is provided by a close similarity between the river discharges at Prieska and at the estuary (Midgley and Kelly, 1963), despite Prieska being located further upstream than Upington (see Figure 1). With regard to the sediment yield maps, these comprise zones of equal sediment yield within a catchment, the yield being expressed in t/km^2/year.

The sediment loads measured at Upington indicate that this quantity decreased progessively during the pre-dam period. As Figure 5 shows, the sediment load fell from $90 \cdot 10^6$ t/year in 1935 to just over $40 \cdot 10^6$ t/year in 1967. Reasons put forward for this trend (Rooseboom and Maas, 1974) are the exhaustion of supplies of topsoil and the construction of dams. Based on the above figures, a mean value of $65 \cdot 10^6$ t/year was adopted for the pre-dam sediment load.

The post-dam sediment load was based on the sediment yield maps, it being assumed that the Bloemhof Dam on the Vaal River and the P.K. le Roux Dam on the Orange River (see Figure 1) act as sediment traps. Using this approach, it was concluded that the post-dam fluvial sediment load was of the order $35 \cdot 10^6$ t/year.

The grain size distribution of the sediment load at Upington has been examined by Rogers (1977) whose results are presented in the form of a histogram in Figure 6. This figure indicates that the sand fraction (median diameter greater than 50 µm) constitutes 18 per cent of the total sediment load.

Based on the above quantities, estimates for the sand fraction of the sediment load are as follows:

Pre-dam period (before 1969/70): $0{,}18 \cdot 65 \cdot 10^6 = 12 \cdot 10^6$ t/year;
Post-dam period (after 1970/71): $0{,}18 \cdot 35 \cdot 10^6 = 6 \cdot 10^6$ t/year.

Hence, assuming a void ratio (volume/total volume) of 40 per cent and a particle density of 2 700 kg/m^3, these quantities become:

Pre-dam period (before 1969/70): $8 \cdot 10^6$ m^3/year;
Post-dam period (after 1970/71): $4 \cdot 10^6$ m^3/year.

The monthly fluvial sediment loads were derived by assuming that this parameter is a function of the monthly maximum daily average flow rate. The relevant relationship was taken to have the form

$S_F \propto Q_F$

where 'S_F' is the monthly fluvial sediment transport rate and 'Q_F' is the monthly maximum daily average flow rate. This linear relationship was based on data obtained by Rooseboom and Maas (1974) which are given in Figure 7 and indicate that the fluvial sediment load is directly proportional to the runoff. The monthly maximum daily average flow rates are given in Tables IIa and IIb and, using these quantities as weighting factors, the resulting monthly fluvial sediment transport rates in the lower Orange River for both the pre-dam and the post-dam periods are as contained in Tables VIIa and VIIb. This variable ranged in value from $1{,}2 \cdot 10^6$ m^3/year in August to $16{,}1 \cdot 10^6$ m^3/year in February during the pre-dam period, the corresponding values for the post-dam period being, respectively, $1{,}9 \cdot 10^6$ m^3/year in September and $8{,}3 \cdot 10^6$ m^3/year in February.

5. STABILITY OF THE ESTUARY MOUTH

The stability of an estuary mouth is determined by the balance between factors which tend to flush the mouth out and factors which tend to block it. There are two flushing factors, namely, tidal flow and fluvial flow, and two blocking factors, namely, longshore sediment transport and fluvial sediment transport. It is, moreover, the peak values of these factors which have most influence on the estuary mouth stability.

Bruun and Gerritsen (1960) were the first to propose that the stability of an estuary mouth be expressed in terms of the ratio between the flushing factors and the blocking factors. Fluvial flow and fluvial sediment transport were neglected with the result that the total flushing factor, 'Ω_{TOT}', comprised the spring tidal prism in m^3, 'Ω_T', and the total blocking factor, 'S_{TOT}', comprised the gross longshore transport rate in m^3/year, 'S_{XG}'. In the case of the Orange Estuary, however, the fluvial flow and the fluvial sediment transport cannot be neglected and hence it was necessary to include these two factors in the stability analysis. Fluvial sediment transport is a straightforward, measurable quantity but some variable had to be chosen which is equivalent to a tidal prism yet represents the fluvial flow. In the event, it was decided to use the volume of water associated with a peak, monthly event, that is the peak, monthly flood discharge. This resulted in the total flushing factor, 'Ω_{TOT}', comprising the actual spring tidal prism, 'Ω_T', and the peak, monthly flood discharge ('fluvial spring tidal prism'), 'Ω_F', and the total blocking factor, 'S_{TOT}', comprising the gross longshore transport rate, 'S_{XG}', and the fluvial sediment transport rate, 'S_F'.

The peak monthly flood discharges ('fluvial spring tidal prisms'), the gross longshore transport rates and the fluvial sediment transport rates are contained in Tables II, VI/2 and VII respectively. However, to obtain the monthly values for the actual spring tidal prism, 'Ω_T', it was necessary to determine the mean monthly cross-sectional areas of the estuary mouth, 'A', and then to compute the values for the tidal prism using an empirical relationship between these two variables. The relevant computations are described in Appendix D and yielded the values listed in Table VIII. The contents of this table were assumed to be valid for both the pre-dam and the post-dam periods.

The resulting 'Ω_{TOT}/S_{TOT}' values are set out in Tables IXa and IXb which show that, during a typical year, the extreme values for this ratio were as follows:

Period	Ω_{TOT}/S_{TOT}			
	Min. (year)	Occurrence	Max. (year)	Occurrence
Pre-dam (before 1969/70)	16	Aug.	41	Feb., Mar.
Post-dam (after 1970/71)	23	Sep.	40	Feb.

It is evident from the above table, therefore, that the estuary mouth stability was virtually unchanged during the post-dam period compared with that existing during the pre-dam period. This state of affairs was brought about by the reduction in the freshwater flows (see Tables IIa and IIb), which tended to decrease the estuary mouth stability, being counterbalanced by the reduction in the fluvial sediment load (see Tables IXa and IXb), which tended to increase the estuary mouth stability. Although not reflected in the above 'Ω_{TOT}/S_{TOT}' ratios, other factors had an influence on the estuary mouth stability. These were a flattening of the hydrographs of the post-dam 'flood' releases (CSIR, 1978) and a probably more frequent artificial breaching of the estuary mouth spit.

6. MINIMUM FRESHWATER REQUIREMENTS

6.1 General

The pre-dam and the post-dam flow regimes in the lower Orange River consisted of low flows during the winter months and high flows during the summer months. In the case of the pre-dam regime, secondary peak flows also took place in November. These patterns are reflected in the monthly maximum, daily average flow rates contained in Figure 2 and also in the estuary mouth stability indices, 'Ω_{TOT}/S_{TOT}', contained in Table IX.

Two sets of minimum freshwater flow requirements are proposed, one being based on the pre-dam river flow regime and the other on the post-dam river flow regime. In each case, the freshwater flow requirements are such that the original pattern of river discharges is reinstated. This pattern, however, is not reproduced in detail but is represented by a simulated flood released in the summer and a minimum, perennial flow maintained during the remainder of the year. From an engineering standpoint, the flood release serves the following purposes:

i) to keep the estuary mouth open for most of the year;
ii) to scour out sediment that has accumulated in the estuary.

In addition, the minimum perennial flow is required for the following reasons:

iii) to counteract the evaporation and seepage losses in the lower Orange River;
iv) to maintain an aesthetically pleasing, continuous flow in the river course.

The simulated flood and the minimum perennial flow are described in more detail in the following sections of this chapter.

6.2 Simulated Flood

The simulated flood should be of such a magnitude and duration that the estuary mouth stability index, 'Ω_{TOT}/S_{TOT}', attains its maximum monthly pre-dam or post-dam value. The former, according to Table IXa, was 41 and occurred in February and March and the latter, according to Table IXb, was 40 and occurred in February. If it is accepted that the actual spring tidal prism and the fluvial sediment transport rates are as given in Tables IXa and IXb, then the required duration of the freshwater release for various discharge rates is given by one or other of the following relationships:

Based on pre-dam conditions : $D_F = 8{,}1 \cdot 10^3/Q_f$
Based on post-dam conditions: $D_F = 4{,}6 \cdot 10^3/Q_F$

The above relationships are plotted in Figure 8 which shows clearly how large flow rates are associated with short flow durations and vice versa. The volume of water required by a 'flood' is $700 \cdot 10^6$ m^3, if based on the pre-dam conditions, and $397 \cdot 10^6$ m^3, if based on the post-dam conditions. These two quantities represent 10,1 per cent and 5,7 per cent respectively of the mean annual runoff at the P.K. le Roux Dam.

It should be noted that the simulated flood may not be large enough to keep the estuary mouth open throughout the year. This state of affairs, however, is known to have existed on several occasions in the past, even before construction of the major dams (CSIR, 1978; Rogers, 1977). In the event of the estuary mouth being closed immediately prior to the release of a 'flood', it is recommended that inundation of the wetlands be allowed prior to any artificial breaching of the coastal barrier. If breaching is necessary, it should take place at, or to the north of, the position shown in Plate 1, that is close to the northern river bank.

As was mentioned in Section 2.2, the runoff into the Orange River downstream of the P.K. le Roux Dam (excluding that of the Vaal River) is only 5 per cent of the total. Floods from this source, therefore, are erratic and any that do occur should be considered as a bonus and not used as a substitute for freshwater releases from the P.K. le Roux Dam.

6.3 Minimum, Perennial Flow

The minimum, perennial flow must be large enough to counteract losses due to evaporation and seepage. According to Table III, the net evaporation rate is lowest between April and September, when it has a mean value of 127 mm/month, and is highest between October and March, when it has a mean value of 252 mm/month. Using the evaporation area of $100 \cdot 10^6$ m^2 derived in Section 2.3 and including a 20 per cent allowance for seepage losses, the resulting minimum perennial flows are as follows:

Period of the year	Flow rate (m^3/s)	Flow rate (10^6 m^3/month)	Percentage of mean annual inflow into P.K. le Roux Dam
April - September	6	15,8	1,4
October - March	12	31,6	2,7

It should be noted that these minimum perennial flows, which allow for the effects of evaporation and seepage, are included automatically in existing releases made to satisfy the extraction rights of downstream riparian owners.

7. EFFECT OF REDUCED FRESHWATER FLOW ON THE ADJACENT COASTLINE

The effect of the reduced freshwater flow on the coastline adjacent to the Orange River Mouth cannot be determined with any degree of certainty. However, the basic trends in the coastal morphology both before and after construction of the major dams are known and an estimate can be made of the coastal morphology associated with the reduced freshwater flow.

Prior to construction of the major dams in 1969, the Orange River discharges were characterized by large summer flows, low flows for the remainder of the year (see Figure 2) and massive floods which occurred every few years (see Figure 9). The latter constituted the dominant feature, as far as coastal morphology was concerned, because large volumes of sediment were deposited in the nearshore zone opposite the estuary mouth where a delta formed. This caused the prevailing waves from the south, south-southwest and southwest (see Table IV/1) to be diffracted around the northern end of the delta which, in turn, produced a local reversal of the longshore transport direction. A reduction in the width of the estuary mouth, therefore, took place following the growth of a spit on the northern side of the estuary mouth, thereby pushing the mouth towards the southern bank of the river. Ultimately, the channel connecting the estuary to the open sea became so long and tortuous that the reduced tidal prism was no longer sufficient to keep the mouth open. Although this cycle of morphological changes describes the basic, underlying trends, variations occurred whenever the magnitude of, or the interval between, large floods was abnormal. Similar, although less well defined, trends existed after construction of the major dams in 1970.

The proposed freshwater releases, however, include only moderate 'floods' at yearly intervals. It is unlikely, therefore, that there will be enough fluvial sediment transport to form a delta of any significant size and consequently there will not be a local reversal of the net longshore transport direction. Hence, the estuary mouth will tend to be closed by the northbound longshore drift and the mouth should remain close to the northern river bank. As the channel connecting the estuary to the sea will be comparatively short and straight (see Plate 1), the estuary mouth will be more likely to remain open during periods of low flows than was the case previously, especially prior to 1969.

8. EFFECT OF REDUCED FRESHWATER FLOW ON THE ESTUARINE BIOTA

8.1 Background

In the case of the Orange River, the solution to the question of how much freshwater should be released to maintain the estuary or river in a viable condition is fraught with difficulties. The present estuary reflects the effects of human manipulation of both the catchment and the estuary itself.

In the late 19th and early 20th centuries the sediment load of the Orange River greatly increased. This was a consequence of widespread poor farming methods which led to a massive loss of topsoil (Rooseboom and Harmse, 1979). However, since 1935 the sediment load has declined and now appears to have stabilized (see Figure 5).

The estuary has also been modified directly. The spit at the mouth is breached regularly to counter the southwards migration of the mouth or to reconnect the river to the sea when the spit has closed the mouth completely. Embankments have been built to provide vehicular access to the mouth on the south bank which have led to the large-scale destruction of saltmarsh vegetation (Plate 2). Wetlands along the river have been infilled to provide agricultural land, for example, at Alexander Bay.

The estuary of the Orange River has been little studied (Day, 1981). Such studies as have been undertaken to date have been reconnaissances. The most important of these are the biological survey in 1956 by the University of Cape Town (Brown, 1959); the physico-chemical survey in 1979 by the NRIO (Eagle and Bartlett, 1984) and the sedimentological study by the Geological Survey (Rogers, 1979).

Against this background, therefore, a decision has to be made as to whether the objective is to maintain the status quo or to allow the estuary to adapt to a new state which is ecologically viable.

8.2 Maintenance of the Status Quo

The status of the Orange Estuary is problematical: does it function as a true estuary with an appreciable tidal input of seawater or is it a river mouth discharging freshwater directly into the sea? During the NRIO survey in January 1979, the river flow was so strong that it almost prevented the penetration of saltwater through the mouth. All salinity values were lower than the minimum which can be measured by the salinometer (that is, < 2,5 $^{o}/oo$). Consequently Eagle and Bartlett (1984) suggested that the system should be classified as a river mouth rather than an estuary. However, as the river flow drops with the onset of the dry season in the catchment, seawater penetration increases. Simultaneously, the sand spit at the mouth extends and narrows the mouth until the river may be cut off from the sea by a sand bar. Complete closure can occur during severe droughts (Day, 1981).

In the absence of data spanning the entire year on the salinity regime of the Orange River mouth, the species composition of the wetland vegetation can be used to obtain a general picture of the long-term salinity regime. The Orange River mouth is on the desert coast of Namaqualand where the average annual rainfall does not exceed 50 mm (Schulze, 1965). The wetland vegetation at the river mouth, therefore, depends almost entirely upon the river as its source of fresh water, that is, the effect of rainfall is negligible.

At present, healthy stands of the reed Phragmites australis occur within 500 metres of the sand bar on the south bank (Figure 10). This is indicative of the predominantly fresh water regime although Phragmites is tolerant of saline conditions lasting several months. However, it does appear to require a period of at least 2-3 months each year when the water is almost completely fresh in order to grow and reproduce. Upstream of the lower islands, that is, about 3 km from the mouth, the species composition of the wetland vegetation reflects a predominantly fresh or very low (< 3 $^{o}/oo$) salinity regime.

The main area of saltmarsh, dominated by 'Inkbos', Sarcocornia pillansiae, lies on the south bank of the estuary. A large area of this saltmarsh has been destroyed by the road embankment which has cut it off from the river.

To date it would appear that, despite major impoundments on the Orange River, sufficient freshwater reaches the mouth to maintain the vegetation. The effect of the impoundments has been to reduce peak flow rates and raise the dry season flow. The latter has probably been beneficial to the freshwater wetland vegetation at the river mouth.

The main immediate effect of attenuating river (freshwater) flow into the estuary would be the greater penetration by sea water thus increasing the salinity of the lower reaches. With time the vegetation would respond to this change in the salinity regime. It can be expected that there would be a replacement of the freshwater wetland plants by more salt-tolerant species, that is, Sarcocornia pillansiae would spread upstream and Phragmites would retreat. The scale of this change will depend upon the degree to which the freshwater input is reduced.

8.3 Adaptation to a New, Ecologically Viable, State

If it is not possible to maintain the status quo, that is, if insufficient fresh water is available, an alternative, acceptable condition must be sought. In this regard, the recent geomorphological history of the Orange River mouth may give an indication of its configuration prior to the European settlement of South Africa's hinterland. Relevant in this context is the state of the estuary prior to the massive erosion of topsoil which has occurred since the last century (see Section 8.1).

The mudbanks and islands in the Orange River immediately upstream from the mouth may have formed, or have been enlarged, by the input of these sediments. These banks and islands act as a "choke" which confines the river to a relatively narrow channel thereby allowing it to flow, almost unaffected by tidal input, directly into the sea. If this fluvial flow is significantly reduced, increased tidal penetration will result thus changing the predominantly river mouth conditions to estuarine conditions for longer periods. Because the dams on the Orange River act as silt traps the amount of silt reaching the mouth will be reduced. The existing sediments in the lower reaches will become de-watered and more compact so that the basin inside the mouth will subside. This, in turn, could marginally increase the tidal prism and, as a consequence, enhance the estuarine character of the river mouth (I. van Heerden, 1985).

This situation, namely the development of a more estuarine character, will in all probability not be detrimental in ecological terms. However, this change may not be desirable for a number of reasons. A prime consideration is the fact that the Orange River mouth is an "oasis" on the desert coast. The nearest perennial rivers are the Olifants 380 km to the south and the Kunene 1 400 km to the north. Certain species, birds in particular, may depend quite extensively upon the Orange River mouth as an oasis. An example is the White Pelican, _Pelecanus onocrotalus_, which occurs in flocks of up to 400 in number in the immediate vicinity of the Orange River mouth. This is a Red Data Book species which is considered to be rare (Brooke, 1984). It prefers warm freshwaters, especially large river deltas and wetlands (Cramp and Simmons, 1977). It is likely, therefore, that should the system become very saline these birds will be forced to seek other habitats further upstream or elsewhere.

The main objection to allowing the Orange River mouth to seek a new equilibrium consequent upon reduced freshwater inflow is that the _status quo_ has been inadequately studied. It would be most unwise to initiate changes without having a reliable baseline against which the changes could be monitored and their effects assessed.

8.4 Release Policy

Any release programme should attempt to simulate the normal annual river flow profile that existed prior to the construction of major dams on the Orange River. An analysis of the flow data obtained from the Vioolsdrif Gauging Station during the hydrological years 1941/42 to 1967/68, that is, prior to the constructions of the dams, and the years 1971/72 to 1982/83, that is, post-dam construction shows that peak flows occur in February to April and the lowest flows in the period July to October. The mean monthly runoff for the four dry months July-October is approximately $200 \cdot 10^6$ m^3. It is apparent that under this minimum (dry season) flow regime the predominantly freshwater nature of the Orange River mouth has been maintained. Any policy under which markedly lower volumes are released is very likely to have a profound ecological impact on the biota of the Orange River mouth, although as stated in Section 8.3, this change may not be detrimental in broad ecological terms. However, it is necessary to determine whether freshwater-dependent species will be able to accommodate to this new regime by local movement, that is, upstream, or whether they will be forced to seek alternative habitats elsewhere.

Two flood release policies are proposed in this report (see Section 6.2). These proposals are:

Based on	Volume (10^6 m^3)	% of mean annual runoff at P.K. le Roux Dam
Pre-dam	700	10,1
Post-dam	397	5,7

The proposed perennial flow (see Section 6.3) is common to both flood releases namely:

Period	Flow rate (10^6 m^3/month)	% of mean annual inflow to P.K. le Roux Dam
April - September	15,8	1,4
October - March	31,6	2,7

The two flood proposals are based on conditions prevailing prior to and after the construction of the major dams. The pre-dam flood plus perennial flow constitutes a total of 14,2 per cent of the annual runoff at the P.K. le Roux Dam whereas the post-dam flood plus perennial flow is equivalent to 9,8 per cent of the annual flow. It is of interest that the second of these figures approximates to estimates that 9 per cent of the total exploitable water resources of South Africa or 11 per cent of the probable total water requirement of all sectors in the year 2000 is necessary for environmental management (Roberts, 1983). In selecting the flood release policy to be adopted, a conservative approach is necessary, that is, the option that is closer to the *status quo* should be selected. Thus, in this instance, the pre-dam option should be adopted. The impact of the considerably reduced perennial flow (approximately 10 per cent of the present mean value) on the biota of the Orange Estuary cannot be predicted with any certainty.

8.5 Discussion

It is accepted that greater volumes of water will have to be abstracted from the Orange River than at present, that is, the perennial flow will be much reduced from the present level. Research is required to determine whether, provided an annual flood equivalent to a pre-dam flood is released, this greatly attenuated perennial flow will cause significant changes in the biota of the estuary. For example, as outlined in Section 8.2, it is expected that the vegetation of the estuary will respond to the expected changed salinity regime resulting from reduced freshwater inflows. Seawater will penetrate further upstream than at present and thus freshwater plant species such as *Phragmites* will retreat and salt-tolerant species, for example, *Sarcocornia* will replace them. Similarly other components of the biota will also respond to the changed freshwater inflow and salinity regimes. These probable changes, brought about by reduced perennial flow, may not be undesirable but in view of the paucity of knowledge concerning the Orange Estuary the need for further research can only be reiterated.

Experience with rivers and estuaries in southern Africa has shown that the annual flood is crucial to the ecological viability of estuaries and the flood plains in the lower riverine reaches. The flood provides a period when salinities are low, permitting active growth and reproduction of the wetland vegetation, and also allows access to the flood plains and marginal wetlands by various organisms, for example fish, for breeding and feeding. The rôle of the annual floods in the ecology of the Orange Estuary requires further investigation to determine which plants and animals are flood-dependent in order to complete their life cycles. Such a study should determine the magnitude and duration of the annual floods necessary for the biological processes in the estuary. The resultant information could then be used to refine the release policy.

9. CONCLUSIONS

The conclusions reached during the course of this study are as follows:

i) **If the estuary is to be maintained for the conditions described below, then the following minimum freshwater flows would appear to be required:**

a) April to September: 6 m^3/s } already included in
b) October to March : 12 m^3/s } existing releases;
c) one 'flood' release of $700 \cdot 10^6$ m^3 in February or March, if based on pre-dam conditions, or $397 \cdot 10^6$ m^3 in February, if based on post-dam conditions;
d) the freshwater requirement of the 'flood' release, expressed in terms of the mean annual runoff at the P.K. le Roux Dam, is 10,1 per cent if based on pre-dam conditions and 5,7 per cent if based on post-dam conditions.

ii) **Morphological effects of reduced freshwater flows on the estuary and adjacent coastline:**

a) no delta of any significant size will form in the nearshore zone opposite the estuary mouth;
b) the estuary mouth is more likely to remain open during periods of low flow.

iii) **Ecological effects of reduced freshwater flows on the estuary:**

The above-mentioned freshwater flow during April to September, which appears necessary for maintaining the physical condition of the estuary as described, is approximately 10 per cent of the present dry season flow. If this minimum flow regime is adopted, considerable changes in the estuary's ecology can be expected although this will not necessarily be detrimental. The main effect of reduced freshwater flow will be to change the estuary from being a predominantly fresh river mouth system to one more truly estuarine in character. The scale of this change cannot be predicted at present. Similarly, it is not possible to predict beforehand the conditions that might arise if a policy is adopted which involves the release of less water than that which is apparently necessary to maintain the post-dam conditions in the estuary. An annual flood is almost certainly necessary to maintain the ecological viabiity of the estuary. Under conditions of reduced flow, it is highly probable that this annual flood will be even more vital for the biota of the estuary.

Recommendations

Although essential, freshwater input is but one component influencing this complex system. The present configuration of the estuary is the product of extensive but unco-ordinated human activity both in the catchment and at the mouth. Bearing this in mind, there is an obvious need for an overall estuarine management plan which allows for human influence in all its various forms. Before embarking upon any course of action which may bring about irreversible change, the estuary should be the subject of a detailed study spanning at least one year during which seasonal physical processes and biotic responses should be recorded. The Cape Department of Nature and Environmental Conservation is the authority responsible for the control and management of this estuary and, as a matter of urgency, should be requested to undertake the proposed study. The data thus acquired are necessary to assess more accurately the effects of reduced freshwater flow and could also be used to obtain a more reliable estimate of the possible changes to the estuary should a policy be adopted which results in the release of less water than that required to maintain the post-dam condition.

Finally, it should be accepted that the proposed release policy can, and should, be modified in time in the light of experience and research findings. It may be necessary, for example, to increase the perennial flow if the proposed release regime leads to severe environmental degradation in the estuary and lower reaches of the river.

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TABLE I: MAJOR DAMS

Dam	Capacity (10^6 m^3)	Completion date	Catchment (km^2)
Vaal	2 330	1937/38	38 518
Bloemhof	1 273	1969/70	103 636
H.F. Verwoerd	5 952	1970/71	70 642
P.K. le Roux	3 226	1977/78	89 560

TABLE II: MONTHLY MAXIMUM, DAILY AVERAGE FLOW RATES AND PEAK MONTHLY FLOOD DISCHARGES

(a) 1935/36 - 1968/69

Month	Monthly maximum, daily average flow rate Q_F (m^3/s)	Standard deviation (m^3/s)	Peak monthly flood discharge Ω_F (10^6 m^3)
October	481	967	270
November	864	1 091	485
December	829	998	466
January	819	778	460
February	1 299	1 312	730
March	1 216	928	683
April	899	676	505
May	562	612	316
June	316	329	177
July	162	235	91
August	95	129	53
September	202	412	113

(b) 1971/72 - 1982/83

Month	Monthly maximum, daily average flow rate Q_F (m^3/s)	Standard deviation (m^3/s)	Peak monthly flood discharge Ω_F (10^6 m^3)
October	200	114	112
November	253	211	142
December	326	278	183
January	396	474	222
February	713	717	400
March	503	547	282
April	498	531	280
May	353	379	198
June	248	152	139
July	206	89	116
August	248	237	139
September	163	107	92

TABLE III: AVERAGE MONTHLY NET EVAPORATION RATES

Month	Average net evaporation rate (mm/month)
October	219
November	261
December	281
January	289
February	245
March	217
April	156
May	118
June	103
July	100
August	121
September	162
Total	2 270 (mm/year)

TABLE IV/1: DEEP-SEA WAVE OCCURRENCES

Source: VOS data (Swart and Serdyn, unpublished work) converted to 'instrument' values.

Year

No. of obs.: 3 538

Sector / Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,100	0,052	0,016	0,005	0,005	0,092	0,270
12,7	0,129	0,098	0,025	0,004	0,002	0,056	0,314
14,1	0,095	0,083	0,018	0,004	0,001	0,034	0,235
15,4	0,038	0,048	0,014	0,002	0,002	0,008	0,112
16,5	0,015	0,028	0,009	0,001	0,001	0,006	0,060
17,5	0,004	0,003	0,001	0	0	0,001	0,009
Total	0,381	0,312	0,083	0,016	0,011	0,197	1,000

TABLE IV/1: DEEP-SEA WAVE OCCURRENCES (continued)

January No. of obs.: 368

Sector Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0106	0,0032	0,0007	0,0002	0	0,0052	0,0199
12,7	0,0125	0,0108	0,0018	0	0	0,0035	0,0286
14,1	0,0078	0,0078	0,0012	0,0002	0,0002	0,0007	0,0179
15,4	0,0052	0,0048	0,0002	0	0	0,0002	0,0104
16,5	0,0012	0,0048	0,0005	0	0	0,0007	0,0072
17,5	0,0002	0,0007	0	0	0	0	0,0009
Total	0,0375	0,0321	0,0044	0,0004	0,0002	0,0103	0,0849

February No. of obs.: 316

Sector Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0081	0,0059	0,0007	0	0,0002	0,0034	0,0183
12,7	0,0158	0,0122	0,0024	0	0,0002	0,0038	0,0344
14,1	0,0078	0,0061	0,0007	0	0	0,0022	0,0168
15,4	0,0024	0,0028	0	0	0	0,0002	0,0054
16,5	0,0017	0,0005	0	0	0	0,0002	0,0024
17,5	0	0	0	0	0	0	0
Total	0,0358	0,0275	0,0038	0	0,0004	0,0098	0,0773

March No. of obs.: 371

Sector Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0130	0,0060	0,0021	0,0002	0	0,0071	0,0284
12,7	0,0137	0,0092	0,0021	0	0	0,0057	0,0307
14,1	0,0076	0,0057	0	0	0	0,0018	0,0151
15,4	0,0027	0,0034	0,0009	0	0	0	0,0071
16,5	0,0005	0,0025	0	0	0	0,0002	0,0032
17,5	0	0	0	0	0,0002	0,0002	0,0004
Total	0,0375	0,0268	0,0051	0,0002	0,0002	0,0150	0,0849

TABLE IV/1: DEEP-SEA WAVE OCCURRENCES (continued)

April

No. of obs.: 223

Sector / Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0085	0,0033	0	0	0,0011	0,0077	0,0206
12,7	0,0121	0,0074	0,0018	0,0007	0,0004	0,0052	0,0276
14,1	0,0114	0,0055	0,0007	0	0	0,0040	0,0216
15,4	0,0029	0,0052	0,0004	0	0	0,0011	0,0096
16,5	0,0004	0,0004	0,0004	0	0	0,0011	0,0023
17,5	0,0004	0	0	0	0	0	0,0004
Total	0,0357	0,0218	0,0033	0,0007	0,0015	0,0191	0,0821

May

No. of obs.: 234

Sector / Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0087	0,0058	0,0011	0,0006	0,0011	0,0105	0,0278
12,7	0,0105	0,0044	0,0015	0,0004	0	0,0083	0,0251
14,1	0,0076	0,0073	0,0006	0,0006	0	0,0033	0,0194
15,4	0,0033	0,0029	0,0011	0	0	0,0004	0,0077
16,5	0,0015	0,0022	0,0004	0,0004	0	0	0,0045
17,5	0,0004	0	0	0	0	0	0,0004
Total	0,0320	0,0226	0,0047	0,0020	0,0011	0,0225	0,0849

June

No. of obs.: 229

Sector / Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0061	0,0029	0,0014	0,0004	0	0,0104	0,0212
12,7	0,0043	0,0054	0,0039	0,0018	0	0,0050	0,0204
14,1	0,0043	0,0050	0,0039	0,0018	0,0004	0,0029	0,0183
15,4	0,0014	0,0039	0,0032	0,0007	0	0,0004	0,0096
16,5	0,0018	0,0061	0,0025	0,0004	0	0,0004	0,0112
17,5	0,0007	0,0007	0	0	0	0	0,0014
Total	0,0186	0,0240	0,0149	0,0051	0,0004	0,0191	0,0821

TABLE IV/1: DEEP-SEA WAVE OCCURRENCES (continued)

July

No. of obs.: 334

Sector Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0056	0,0023	0,0008	0	0,0005	0,0084	0,0176
12,7	0,0092	0,0064	0,0023	0,0002	0	0,0051	0,0232
14,1	0,0084	0,0079	0,0038	0,0002	0	0,0038	0,0241
15,4	0,0033	0,0043	0,0023	0,0002	0,0018	0,0010	0,0029
16,5	0,0013	0,0018	0,0010	0,0002	0	0,0003	0,0046
17,5	0,0005	0,0013	0,0002	0	0	0,0005	0,0025
Total	0,0283	0,0240	0,0104	0,0008	0,0023	0,0191	0,0849

August

No. of obs.: 309

Sector Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0047	0,0038	0,0022	0,0014	0,0011	0,0099	0,0231
12,7	0,0063	0,0071	0,0019	0,0006	0,0008	0,0027	0,0194
14,1	0,0069	0,0097	0,0022	0,0003	0	0,0022	0,0213
15,4	0,0016	0,0063	0,0016	0,0006	0	0,0011	0,0112
16,5	0,0016	0,0030	0,0027	0	0	0,0014	0,0087
17,5	0,0006	0,0003	0,0003	0	0	0	0,0012
Total	0,0217	0,0302	0,0109	0,0029	0,0019	0,0173	0,0849

September

No. of obs.: 283

Sector Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0075	0,0029	0,0011	0,0006	0	0,0075	0,0196
12,7	0,0102	0,0078	0,0029	0	0,0003	0,0041	0,0253
14,1	0,0084	0,0029	0,0014	0,0006	0,0006	0,0044	0,0183
15,4	0,0029	0,0064	0,0023	0,0003	0	0,0003	0,0122
16,5	0,0017	0,0023	0,0009	0,0003	0,0003	0,0006	0,0061
17,5	0,0003	0	0	0	0	0,0003	0,0006
Total	0,0310	0,0223	0,0086	0,0018	0,0012	0,0172	0,0821

TABLE IV/1: DEEP-SEA WAVE OCCURRENCES (continued)

October

No. of obs.: 324

Sector / Period T_p (s)	Fractional occurrence, F_I						Total
	180°	210°	240°	270°	300°	Calm	
9,5	0,0081	0,0045	0,0023	0,0013	0,0003	0,0075	0,0240
12,7	0,0081	0,0102	0,0016	0	0,0003	0,0037	0,0239
14,1	0,0076	0,0096	0,0018	0,0003	0	0,0031	0,0224
15,4	0,0042	0,0042	0,0016	0,0003	0	0,0005	0,0108
16,5	0,0013	0,0011	0,0003	0	0	0,0003	0,0030
17,5	0,0005	0	0,0003	0	0	0	0,0008
Total	0,0298	0,0296	0,0079	0,0019	0,0003	0,0151	0,0849

November

No. of obs.: 286

Sector / Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0057	0,0054	0,0017	0,0003	0,0006	0,0095	0,0232
12,7	0,0123	0,0069	0,0003	0	0	0,0066	0,0261
14,1	0,0086	0,0080	0,0003	0	0	0,0032	0,0201
15,4	0,0032	0,0020	0,0009	0	0,0003	0,0017	0,0081
16,5	0,0011	0,0023	0,0009	0	0	0	0,0043
17,5	0,0003	0	0	0	0	0	0,0003
Total	0,0312	0,0246	0,0041	0,0003	0,0009	0,0210	0,0821

December

No. of obs.: 261

Sector / Period T_p (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
9,5	0,0124	0,0059	0,0010	0	0,0006	0,0075	0,0274
12,7	0,0124	0,0062	0,0029	0,0006	0	0,0039	0,0260
14,1	0,0091	0,0059	0,0013	0,0003	0	0,0036	0,0202
15,4	0,0042	0,0020	0,0003	0	0	0,0013	0,0078
16,5	0,0010	0,0010	0,0003	0	0	0,0006	0,0029
17,5	0	0,0003	0,0003	0	0	0	0,0006
Total	0,0391	0,0213	0,0061	0,0009	0,0006	0,0169	0,0849

TABLE IV/2: DEEP-SEA WAVE HEIGHTS

Source: VOS data (Swart and Serdyn, unpublished work) converted to 'instrument' values.

Year　　　　　　　　No. of obs.: 3 538

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,4	2,3	2,3	2,2	2,0
12,7	2,7	2,6	2,5	2,1	2,2
14,1	2,9	3,0	2,8	2,3	2,2
15,4	3,0	3,1	2,8	2,9	2,3
16,5	3,3	2,9	3,4	2,8	2,5
17,5	3,3	3,7	3,9	-	3,3

TABLE IV/2: DEEP-SEA WAVE HEIGHTS (continued)

January No. of obs.: 368

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,5	2,5	2,5	2,3	-
12,7	2,8	2,5	2,5	-	-
14,1	2,8	2,9	2,9	2,0	2,0
15,4	2,7	3,1	3,8	-	-
16,5	3,3	3,2	3,5	-	-
17,5	2,8	3,4	-	-	-

February No. of obs.: 316

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,5	2,3	2,2	-	1,8
12,7	2,7	2,5	2,7	-	2,3
14,1	2,7	2,7	2,5	-	-
15,4	3,2	2,9	-	-	-
16,5	3,3	2,9	-	-	-
17,5	-	-	-	-	-

March No. of obs.: 371

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,4	2,1	2,0	2,0	-
12,7	2,7	2,4	2,3	-	-
14,1	3,0	2,5	-	-	-
15,4	2,9	2,9	2,4	-	-
16,5	2,8	3,6	-	-	-
17,5	-	-	-	-	3,3

TABLE IV/2: DEEP-SEA WAVE HEIGHTS (continued)

April No. of obs.: 223

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,1	2,4	-	-	2,0
12,7	2,6	2,3	2,5	2,6	2,0
14,1	2,8	2,5	2,6	-	-
15,4	2,9	2,9	2,5	-	-
16,5	3,0	2,8	3,0	-	-
17,5	3,0	-	-	-	-

May No. of obs.: 234

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,2	2,3	2,7	2,3	2,2
12,7	2,8	2,5	2,5	2,3	-
14,1	2,7	2,7	2,6	2,2	-
15,4	2,4	3,2	2,8	-	-
16,5	2,5	2,8	3,0	3,5	-
17,5	3,0	-	-	-	-

June No. of obs.: 229

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,2	2,1	2,4	1,8	-
12,7	2,7	2,5	2,6	2,1	-
14,1	2,7	2,8	2,8	2,3	2,2
15,4	2,7	3,1	2,8	2,8	-
16,5	3,0	3,0	3,4	2,5	-
17,5	4,0	3,3	-	-	-

TABLE IV/2: DEEP-SEA WAVE HEIGHTS (continued)

July — No. of obs.: 334

Sector Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,2	2,3	2,4	-	1,9
12,7	2,7	2,6	2,4	2,0	-
14,1	2,8	3,0	2,7	2,5	-
15,4	3,0	2,9	2,5	1,8	2,2
16,5	3,2	3,6	3,6	2,5	-
17,5	3,3	3,6	3,3	-	-

August — No. of obs.: 309

Sector Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,3	2,5	2,4	2,1	2,1
12,7	2,8	2,8	2,6	2,1	2,1
14,1	2,8	3,5	3,3	2,5	-
15,4	3,4	3,9	2,5	3,3	-
16,5	4,1	3,3	3,6	-	-
17,5	3,0	5,5	5,5	-	-

September — No. of obs.: 283

Sector Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,2	2,0	2,4	1,9	-
12,7	2,7	2,7	2,8	-	2,3
14,1	3,0	2,6	3,1	2,2	2,3
15,4	3,4	2,8	2,9	2,5	-
16,5	3,1	3,0	3,0	2,5	2,5
17,5	6,5	-	-	-	-

TABLE IV/2: DEEP-SEA WAVE HEIGHTS (continued)

October — No. of obs.: 324

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,5	2,4	2,2	1,9	1,8
12,7	2,7	2,6	2,3	-	2,0
14,1	2,7	3,0	2,5	2,3	-
15,4	3,1	2,7	2,9	2,8	-
16,5	3,6	3,4	3,0	-	-
17,5	3,7	-	2,8	-	-

November — No. of obs.: 286

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,4	2,3	2,3	3,5	2,4
12,7	2,7	2,8	2,3	-	-
14,1	3,1	3,2	2,8	-	-
15,4	3,4	2,4	2,4	-	2,5
16,5	3,5	3,1	3,5	-	-
17,5	2,8	-	-	-	-

December — No. of obs.: 261

Sector / Period T_p (s)	Wave height, H_{OS} (m)				
	180°	210°	240°	270°	300°
9,5	2,4	2,4	1,9	-	2,3
12,7	2,7	2,6	2,3	1,9	-
14,1	2,7	2,6	3,0	2,8	-
15,4	3,1	2,7	4,0	-	-
16,5	3,2	2,9	2,5	-	-
17,5	-	3,3	3,0	-	-

TABLE V: BREAKER LINE WAVE DATA

Deep-sea wave direction θ_o ($^\circ$)	Peak energy wave period T_p (s)	Mean longshore energy flux factor F_F (m^3/s)
180	9,5	0,155
	12,7	0,226
	14,1	0,227
	15,4	0,251
	16,5	0,262
	17,5	0,239
210	9,5	0,041
	12,7	0,042
	14,1	0,036
	15,4	0,031
	16,5	0,029
	17,5	0,030
240	9,5	- 0,085
	12,7	- 0,160
	14,1	- 0,181
	15,4	- 0,244
	16,5	- 0,194
	17,5	- 0,238
270	9,5	- 0,205
	12,7	- 0,141
	14,1	- 0,242
	15,4	- 0,254
	16,5	- 0,253
	17,5	-
300	9,5	- 0,091
	12,7	- 0,065
	14,1	- 0,058
	15,4	- 0,052
	16,5	- 0,043
	17,5	- 0,041

TABLE VI/1: UNCORRECTED LONGSHORE TRANSPORT RATES

Month	Longshore transport rate, S_x (10^6 m^3/year)			
	Northbound	Southbound	Net	Gross
October	5,5	0,9	4,6	6,4
November	6,4	0,6	5,8	7,0
December	6,0	0,8	5,2	6,8
January	6,4	0,6	5,8	7,0
February	6,7	0,4	6,3	7,1
March	5,8	0,4	5,4	6,2
April	5,5	0,5	5,0	6,0
May	4,7	0,8	3,9	5,5
June	3,4	2,7	0,7	6,1
July	5,0	1,4	3,6	6,4
August	5,1	2,4	2,7	7,5
September	5,9	1,3	4,6	7,2
Year	5,6	1,0	4,6	6,6

TABLE VI/2: CORRECTED LONGSHORE TRANSPORT RATES

Month	Longshore transport rate, S_x (10^6 m^3/year)			
	Northbound	Southbound	Net	Gross
October	1,7	0,3	1,4 N	2,0
November	1,9	0,2	1,7 N	2,1
December	1,8	0,2	1,6 N	2,0
January	2,0	0,2	1,8 N	2,2
February	2,0	0,1	1,9 N	2,1
March	1,8	0,1	1,7 N	1,9
April	1,7	0,2	1,5 N	1,9
May	1,4	0,3	1,1 N	1,7
June	1,0	0,8	0,2 N	1,8
July	1,5	0,4	1,1 N	1,9
August	1,6	0,7	0,9 N	2,3
September	1,8	0,4	1,4 N	2,2
Year	1,7	0,3	1,4 N	2,0

TABLE VII: MONTHLY FLUVIAL SEDIMENT TRANSPORT RATES

(a) 1935/36 - 1968/69

Month	Fluvial sediment transport rate S_F (10^6 m^3/year)
October	6,0
November	10,7
December	10,3
January	10,2
February	16,1
March	15,1
April	11,1
May	7,0
June	3,9
July	2,0
August	1,2
September	2,5
Year	8,0

(b) 1971/72 - 1982/83

Month	Fluvial sediment transport rate S_F (10^6 m^3/year)
October	2,3
November	3,0
December	3,8
January	4,6
February	8,3
March	5,9
April	5,8
May	4,1
June	2,9
July	2,4
August	2,9
September	1,9
Year	4,0

TABLE VIII: MONTHLY SPRING TIDAL PRISMS

Month	Spring tidal prism Ω_T (10^6 m^3)
October	6
November	11
December	15
January	19
February	20
March	19
April	15
May	11
June	6
July	3
August	2
September	3

TABLE IX: ESTUARY MOUTH STABILITY

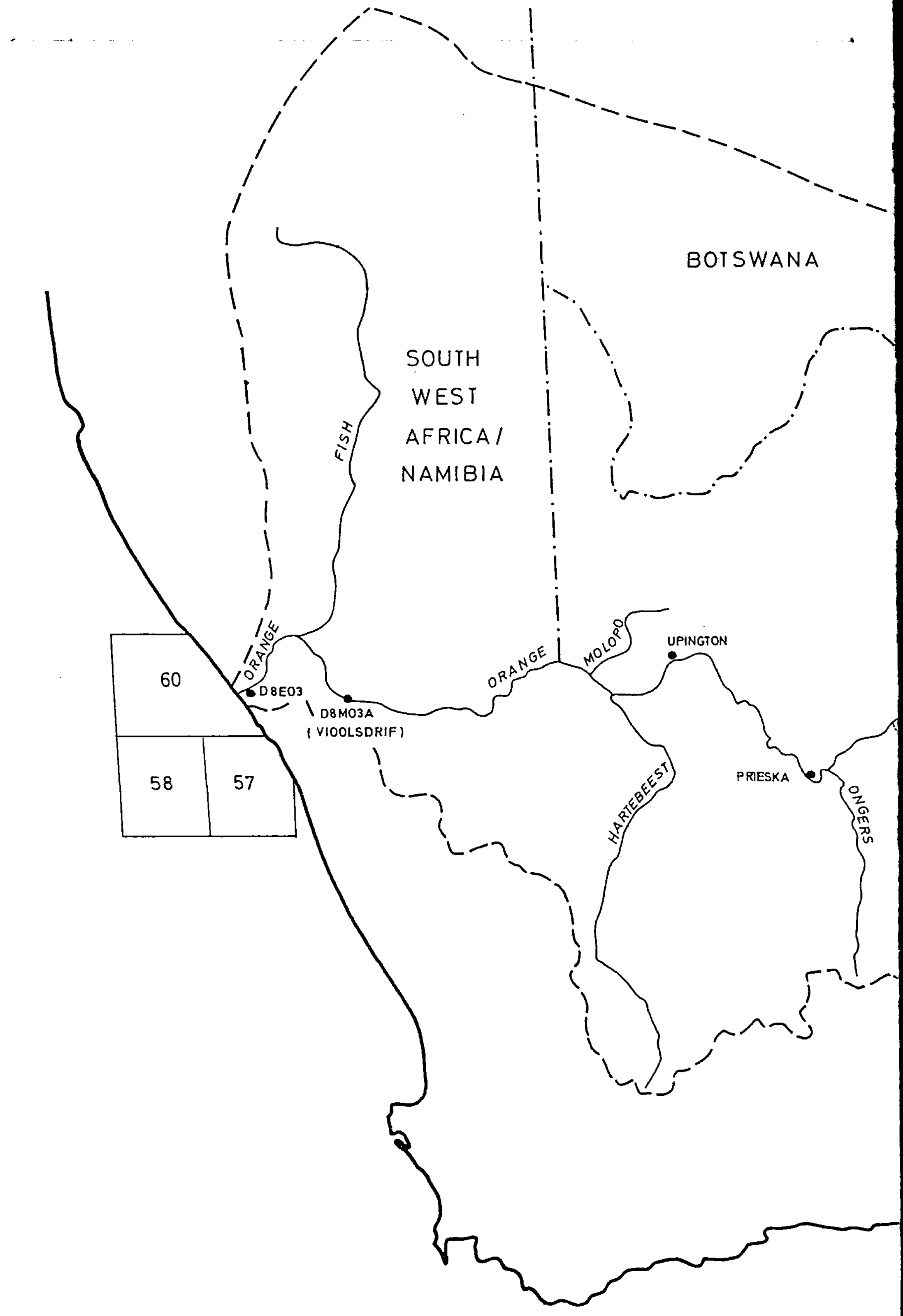
(a) 1935/36 - 1968/69

Month	Ω_{TOT}		S_{TOT}		Ω_{TOT}/S_{TOT}
	Actual spring tidal prism Ω_T (10^6 m^3)	Fluvial spring tidal prism Ω_F (10^6 m^3)	Gross longshore transport rate S_{XG} (10^6 m^3/year)	Fluvial transport rate S_F (10^6 m^3/year)	(year)
October	6	270	2,0	6,0	35
November	11	485	2,1	10,7	39
December	15	466	2,0	10,3	39
January	19	460	2,2	10,2	39
February	20	730	2,1	16,1	41
March	19	683	1,9	15,1	41
April	15	505	1,9	11,1	40
May	11	316	1,7	7,0	38
June	6	177	1,8	3,9	32
July	3	91	1,9	2,0	24
August	2	53	2,3	1,2	16
September	3	113	2,2	2,5	25
Source	Table VIII	Table IIa	Table VI/2	Table VIIa	-

TABLE IX: ESTUARY MOUTH STABILITY (continued)

(b) 1971/72 - 1982/83

Month	Ω_{TOT}		S_{TOT}		Ω_{TOT}/S_{TOT} (year)
	Actual spring tidal prism Ω_T (10^6 m^3)	Fluvial spring tidal prism Ω_F (10^6 m^3)	Gross longshore transport rate S_{XG} (10^6 m^3/year)	Fluvial transport rate S_F (10^6 m^3/year)	
October	6	112	2,0	2,3	27
November	11	142	2,1	3,0	30
December	15	183	2,0	3,8	34
January	19	222	2,2	4,6	35
February	20	400	2,1	8,3	40
March	19	282	1,9	5,9	39
April	15	280	1,9	5,8	38
May	11	198	1,7	4,1	36
June	6	139	1,8	2,9	31
July	3	116	1,9	2,4	28
August	2	139	2,3	2,9	27
September	3	92	2,2	1,9	23
Source	Table VIII	Table IIb	Table VI/2	Table VIIb	-



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CATCHMENT OF THE ORANGE RIVER SYSTEM

FIGURE
1

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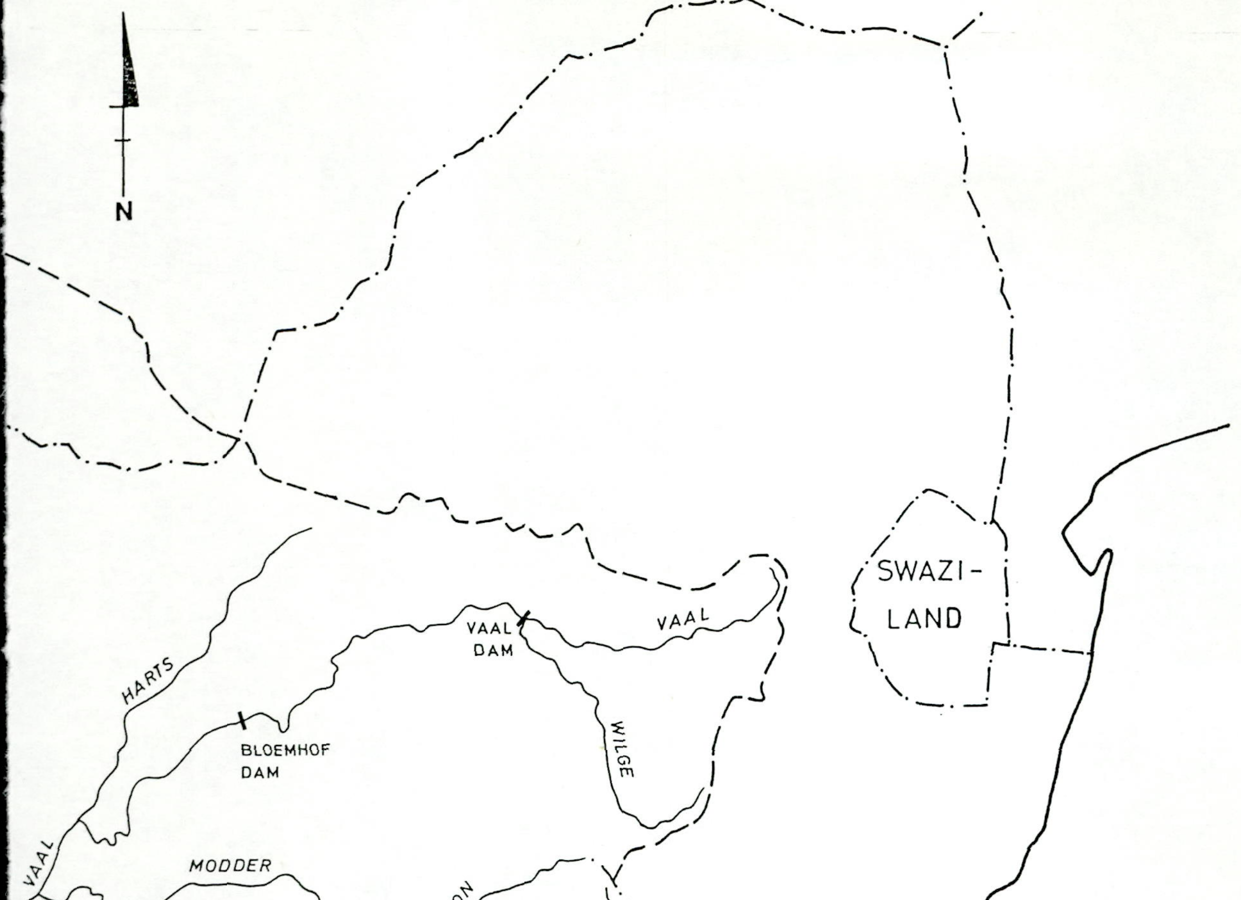
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RIET
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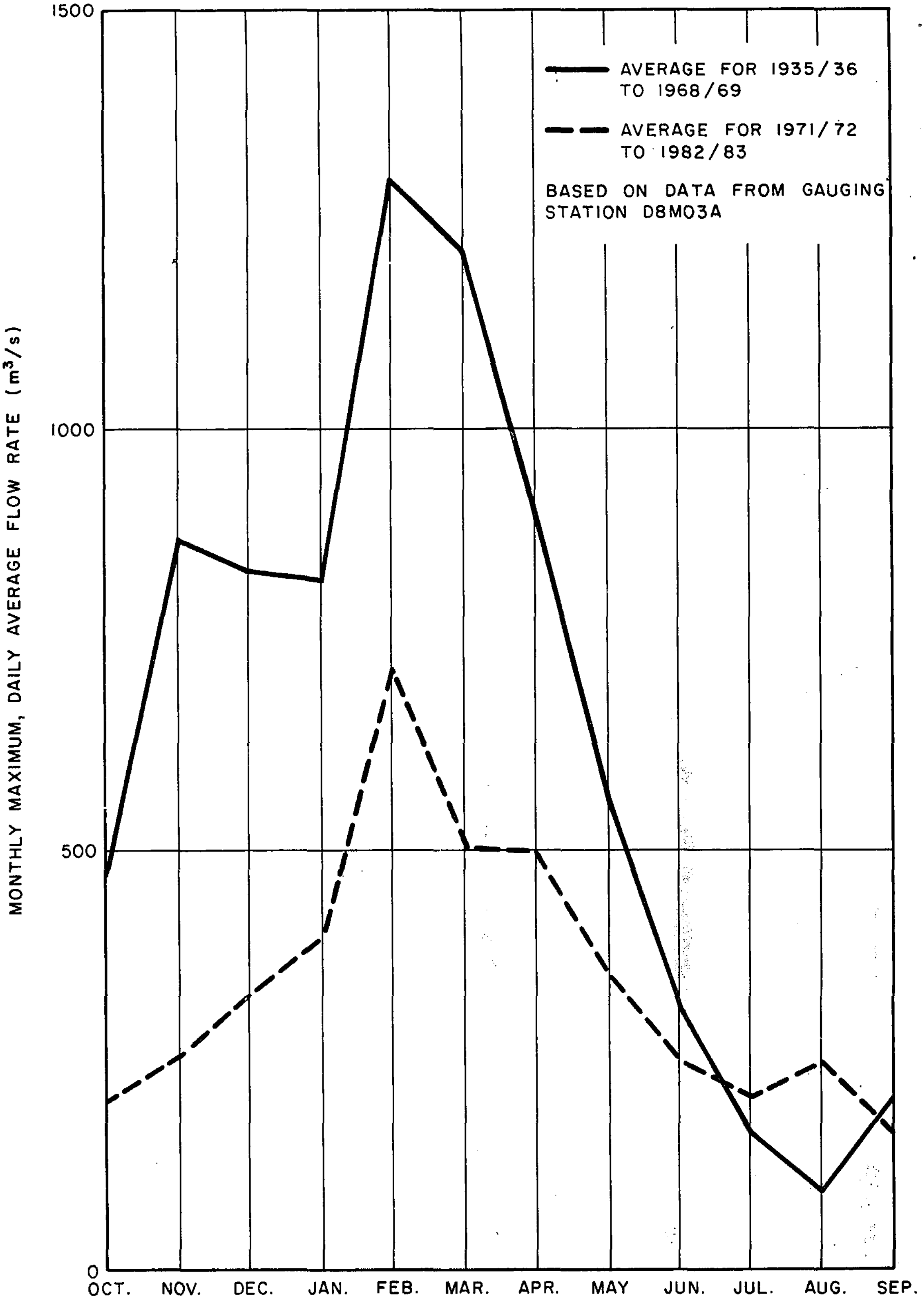

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AVERAGE MONTHLY NET EVAPORATION RATES

FIGURE
3

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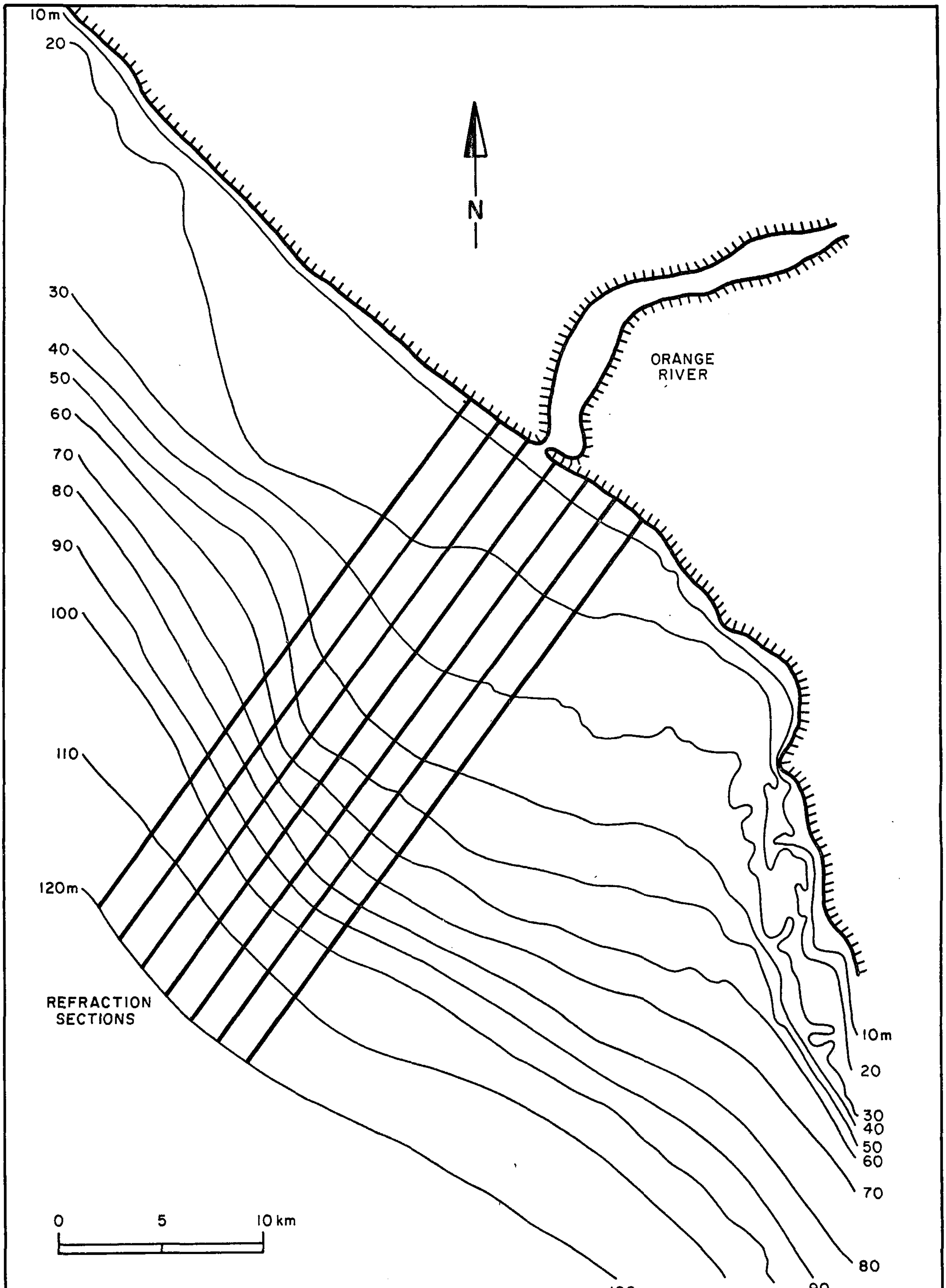

SOURCE: ROGERS (1977)

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ORANGE RIVER MOUTH BATHYMETRY

FIGURE 4

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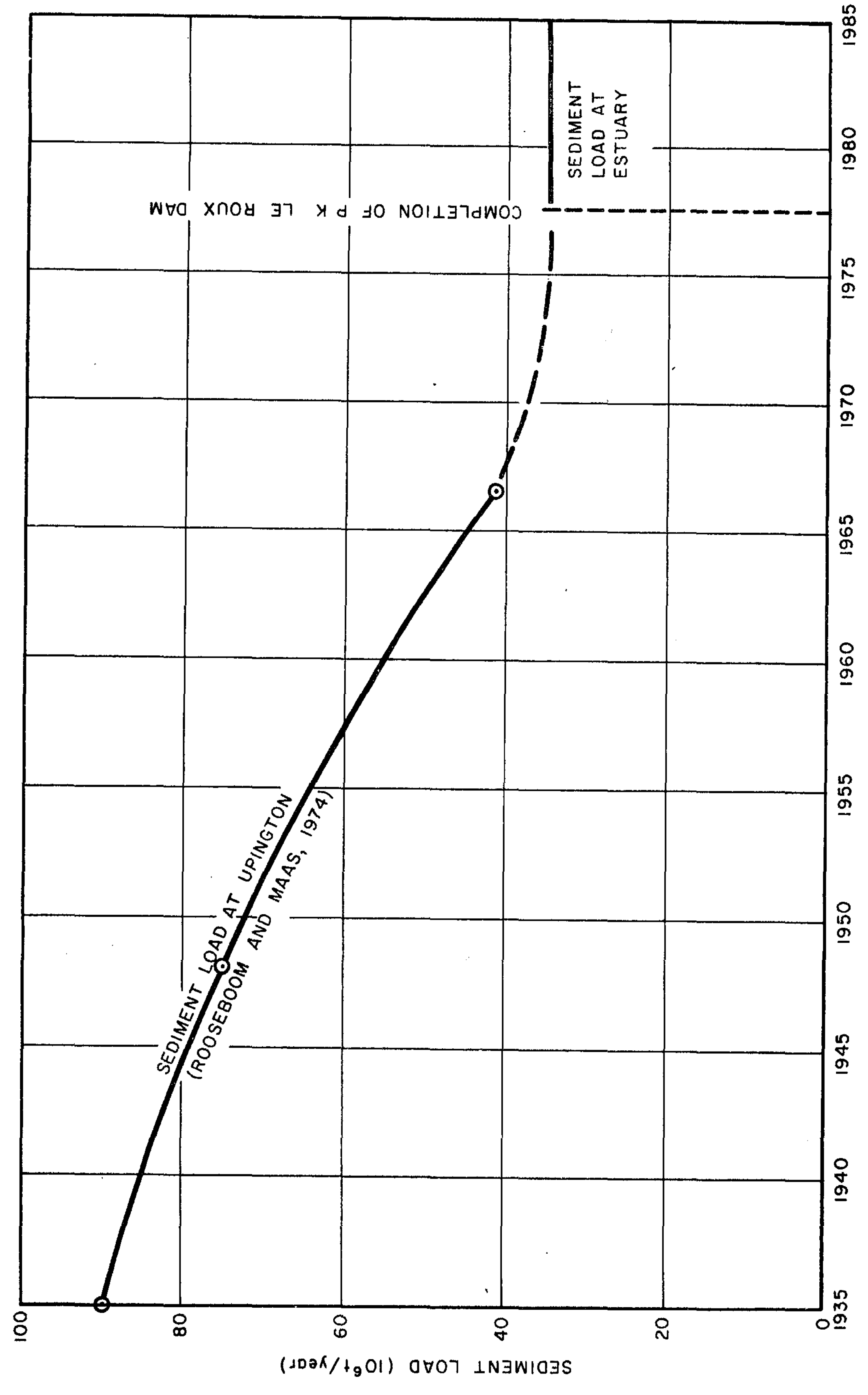

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LOWER ORANGE RIVER FLUVIAL SEDIMENT LOAD

FIGURE
5

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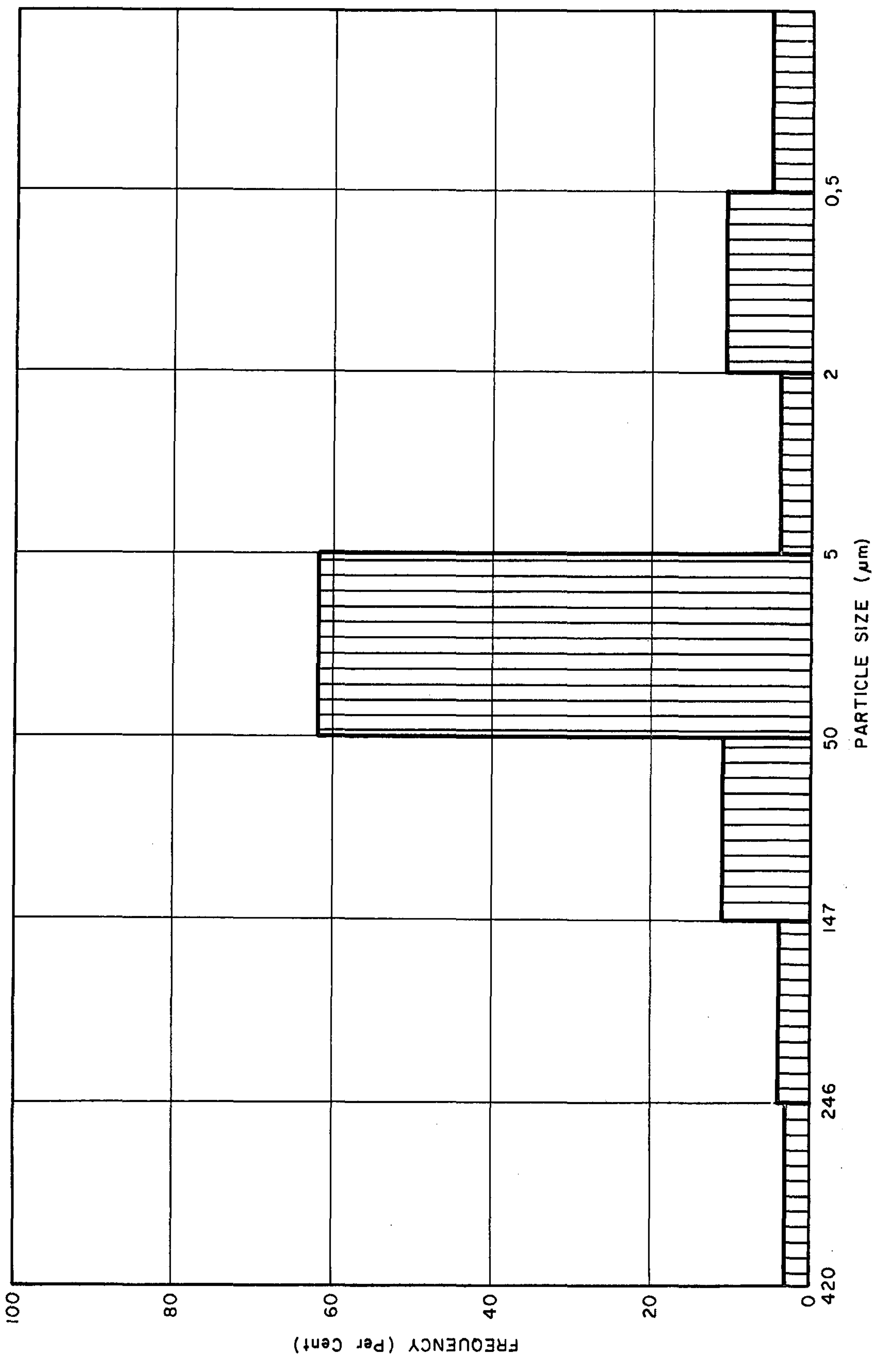

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SIZE DISTRIBUTION OF THE FLUVIAL SEDIMENT LOAD AT UPINGTON: AFTER ROGERS (1977)

FIGURE 6

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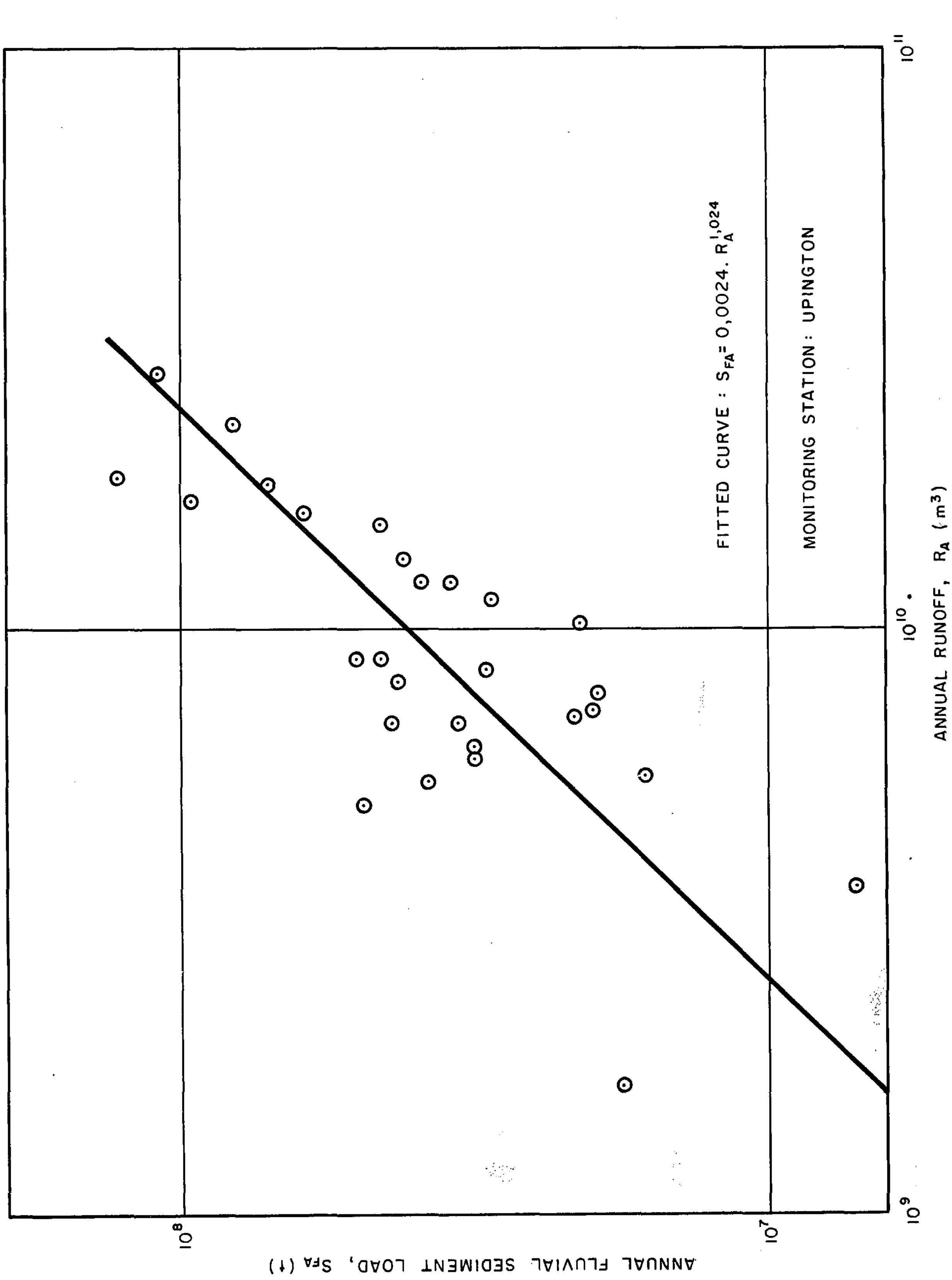

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FLUVIAL SEDIMENT LOAD VERSUS ANNUAL RUNOFF

FIGURE 7

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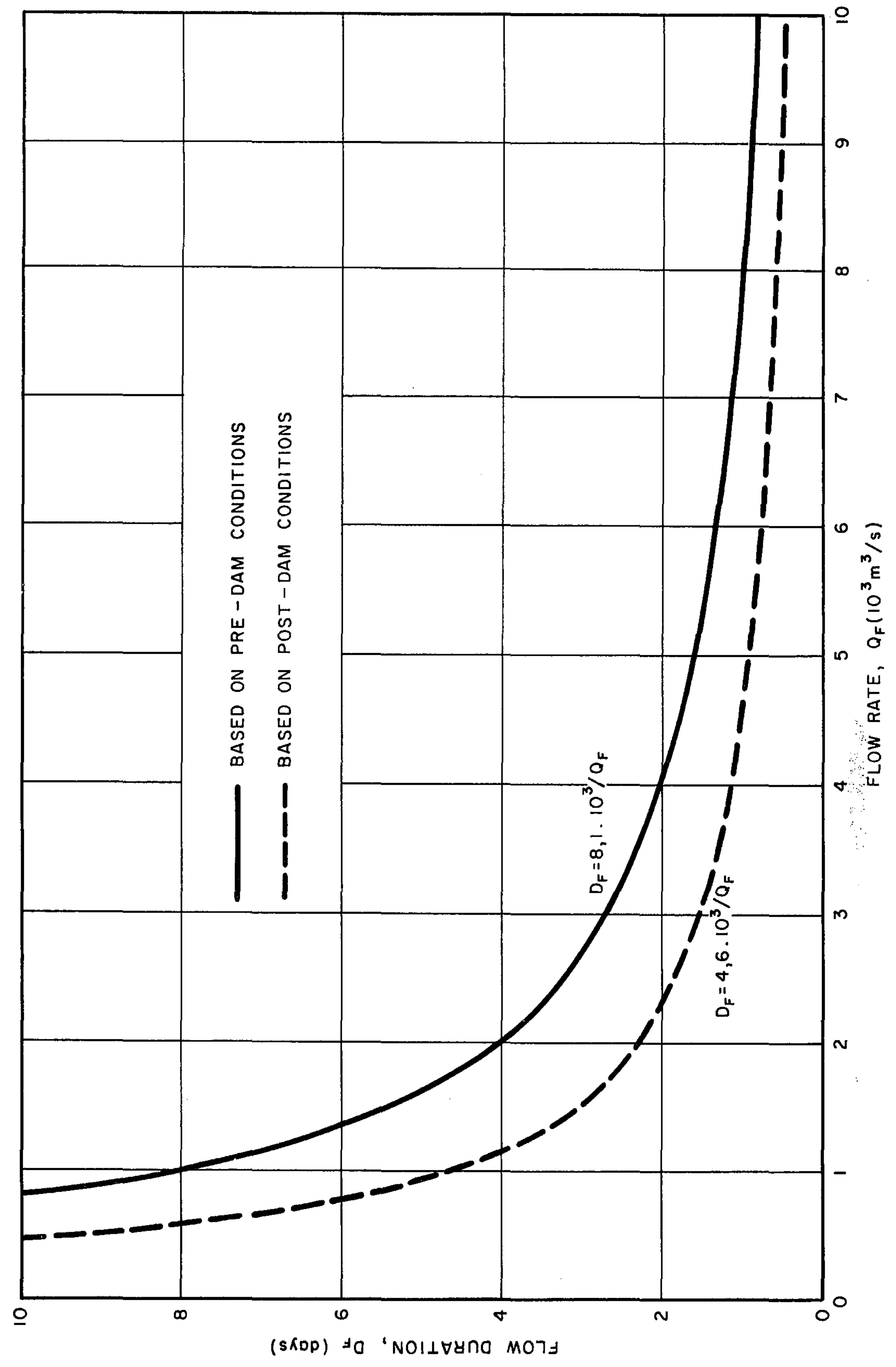

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SIMULATED FLOOD DURATION VERSUS FLOW RATE

FIGURE
8

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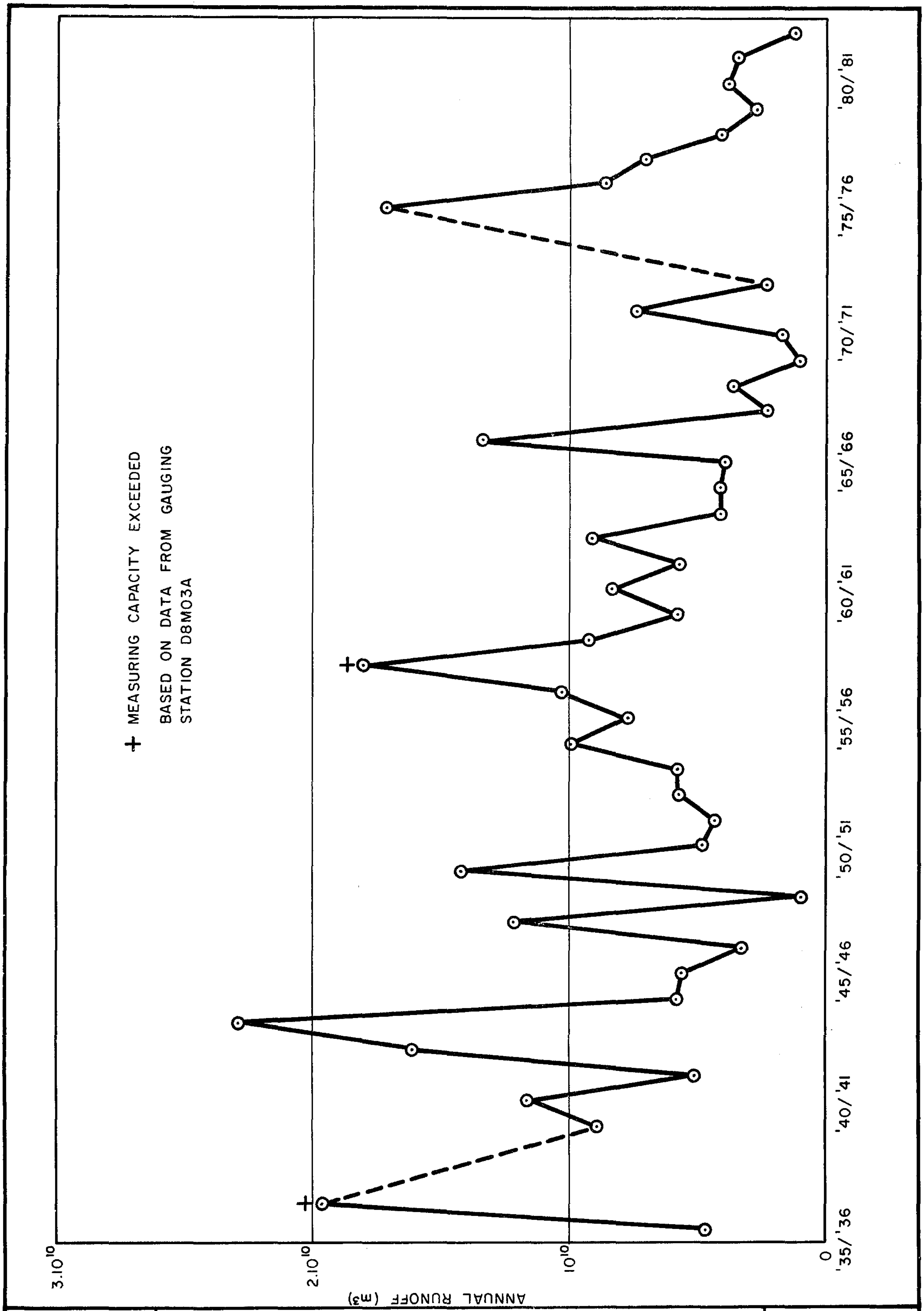

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VARIATION IN THE ANNUAL RUNOFF

FIGURE
9

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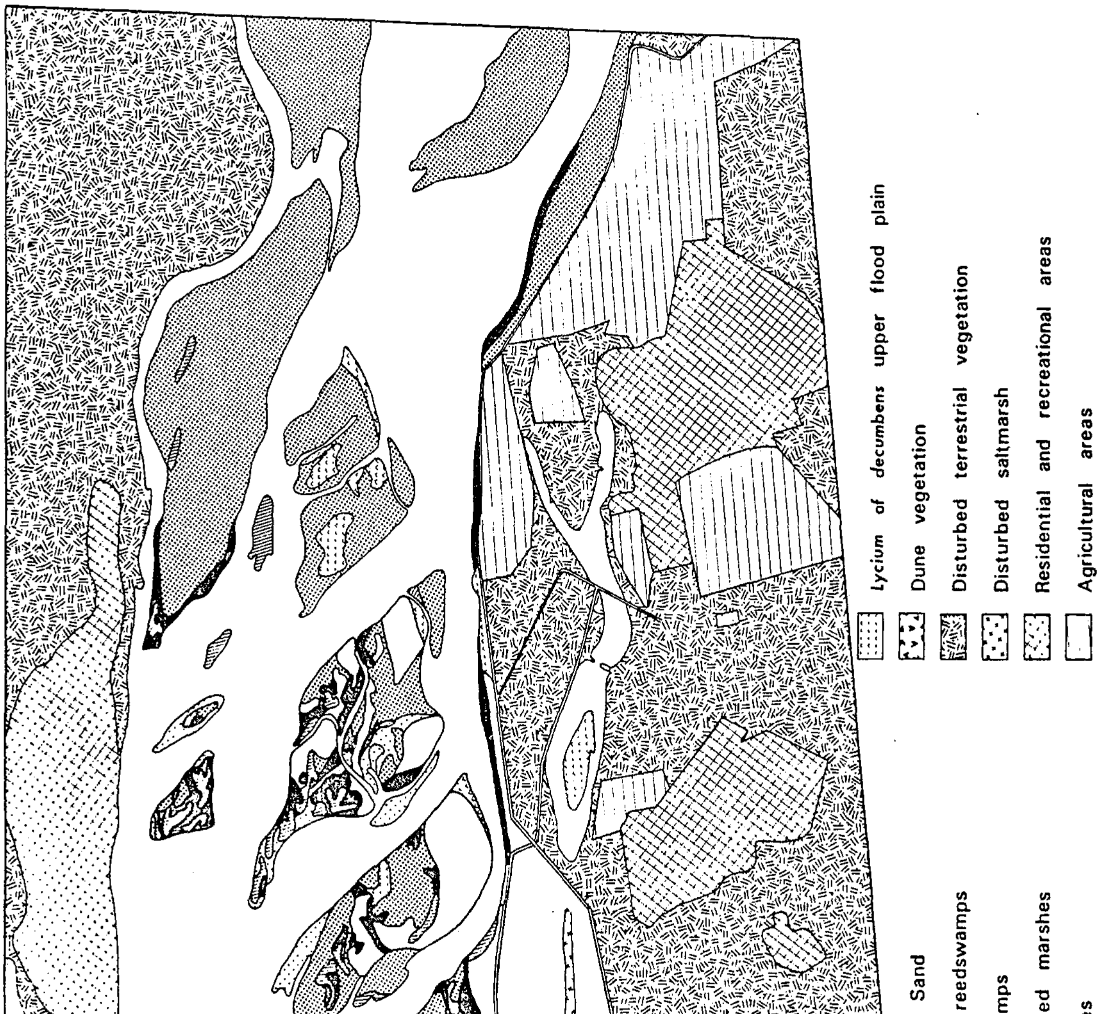

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DISTRIBUTION OF VEGETATION TYPES
AROUND THE ORANGE RIVER MOUTH

FIGURE
10

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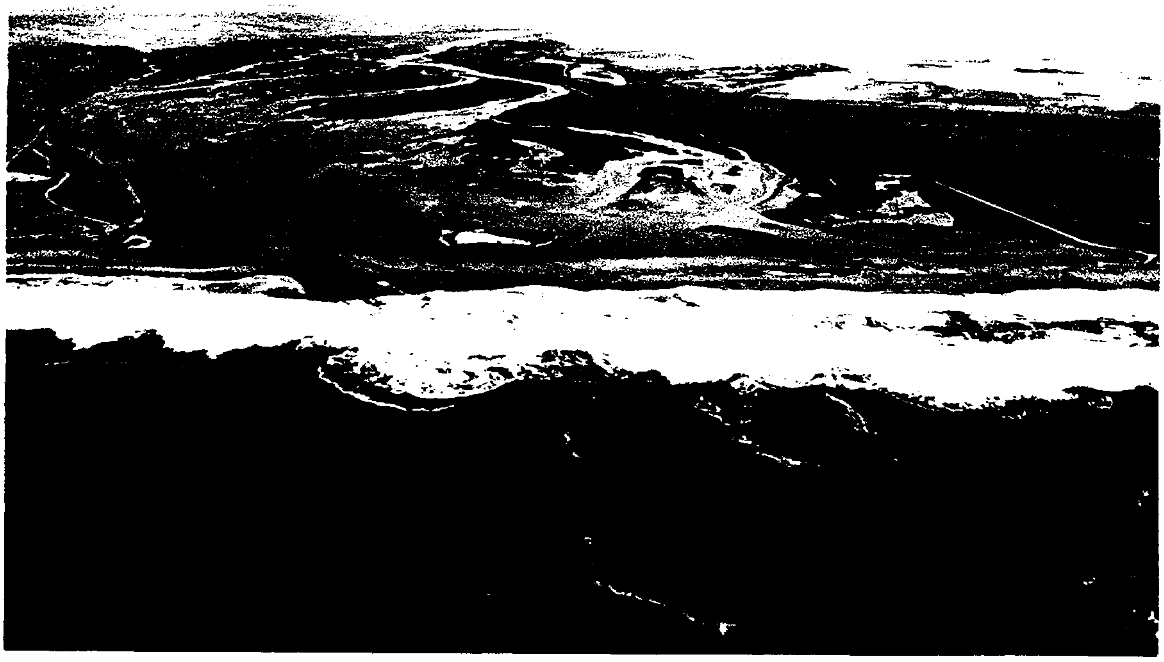

FEBRUARY 1984

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SALTMARSH DESTROYED BY ROAD EMBANKMENT ISOLATING IT FROM THE ESTUARY

PLATE
2

NATIONAL RESEARCH INSTITUTE FOR OCEANOLOGY

APPENDIX A

DEEP-SEA WAVE CLIMATE

CONTENTS

GENERAL

The deep-sea wave climate was recorded by Voluntary Observing Ships (VOS) (Swart and Serdyn, unpublished work). The results are contained in Tables A.I/1 and A.I/2 which show, respectively, wave occurrence and root mean square significant wave height as a function of period and direction; both the annual and the monthly values are given in each case.

REFERENCE

SWART, D.H. and SERDYN, J.deV. (unpublished work). Statistical analysis and visually observed wave data from Voluntary observing ships for Southern African coast. Vols. 57, 58 and 60. CSIR Report, Stellenbosch.

TABLE A.I/1: DEEP-SEA WAVE OCCURRENCES

Source: VOS data (Swart and Serdyn, unpublished work).

Year

No. of obs.: 3 538

Sector / Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
≤ 5,0	0,100	0,052	0,016	0,005	0,005	0,092	0,270
6,5	0,129	0,098	0,025	0,004	0,002	0,056	0,314
8,5	0,095	0,083	0,018	0,004	0,001	0,034	0,235
10,5	0,038	0,048	0,014	0,002	0,002	0,008	0,112
12,5	0,015	0,028	0,009	0,001	0,001	0,006	0,060
≥14,0	0,004	0,003	0,001	0	0	0,001	0,009
Total	0,381	0,312	0,083	0,016	0,011	0,197	1,000

TABLE A.I/1: DEEP-SEA WAVE OCCURRENCES (continued)

January

No. of obs.: 368

Sector / Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
< 5,0	0,0106	0,0032	0,0007	0,0002	0	0,0052	0,0199
6,5	0,0125	0,0108	0,0018	0	0	0,0035	0,0286
8,5	0,0078	0,0078	0,0012	0,0002	0,0002	0,0007	0,0179
10,5	0,0052	0,0048	0,0002	0	0	0,0002	0,0104
12,5	0,0012	0,0048	0,0005	0	0	0,0007	0,0072
≥14,0	0,0002	0,0007	0	0	0	0	0,0009
Total	0,0375	0,0321	0,0044	0,0004	0,0002	0,0103	0,0949

February

No. of obs.: 316

Sector / Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
< 5,0	0,0081	0,0059	0,0007	0	0,0002	0,0034	0,0183
6,5	0,0158	0,0122	0,0024	0	0,0002	0,0038	0,0344
8,5	0,0078	0,0061	0,0007	0	0	0,0022	0,0168
10,5	0,0024	0,0028	0	0	0	0,0002	0,0054
12,5	0,0017	0,0005	0	0	0	0,0002	0,0024
≥14,0	0	0	0	0	0	0	0
Total	0,0358	0,0275	0,0038	0	0,0004	0,0098	0,0773

March

No. of obs.: 371

Sector / Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
< 5,0	0,0130	0,0060	0,0021	0,0002	0	0,0071	0,0284
6,5	0,0137	0,0092	0,0021	0	0	0,0057	0,0307
8,5	0,0076	0,0057	0	0	0	0,0018	0,0151
10,5	0,0027	0,0034	0,0009	0	0	0	0,0071
12,5	0,0005	0,0025	0	0	0	0,0002	0,0032
≥14,0	0	0	0	0	0,0002	0,0002	0,0004
Total	0,0375	0,0268	0,0051	0,0002	0,0002	0,0150	0,0849

TABLE A.I/1: DEEP SEA WAVE OCCURRENCES (continued)

April

No. of obs.: 223

Sector / Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
< 5,0	0,0085	0,0033	0,0000	0,0000	0,0011	0,0077	0,0206
6,5	0,0121	0,0074	0,0018	0,0007	0,0004	0,0052	0,0276
8,5	0,0114	0,0055	0,0007	0,0000	0,0000	0,0040	0,0216
10,5	0,0029	0,0052	0,0004	0,0000	0,0000	0,0011	0,0096
12,5	0,0004	0,0004	0,0004	0,0000	0,0000	0,0011	0,0023
≥14,0	0,0004	0,0000	0,0000	0,0000	0,0000	0,0000	0,0004
Total	0,0357	0,0218	0,0033	0,0007	0,0015	0,0191	0,0821

May

No. of obs.: 234

Sector / Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
< 5,0	0,0087	0,0058	0,0011	0,0006	0,0011	0,0105	0,0278
6,5	0,0105	0,0044	0,0015	0,0004	0,0000	0,0083	0,0251
8,5	0,0076	0,0073	0,0006	0,0006	0,0000	0,0033	0,0194
10,5	0,0033	0,0029	0,0011	0,0000	0,0000	0,0004	0,0077
12,5	0,0015	0,0022	0,0004	0,0004	0,0000	0,0000	0,0045
≥14,0	0,0004	0,0000	0,0000	0,0000	0,0000	0,0000	0,0004
Total	0,0320	0,0226	0,0047	0,0020	0,0011	0,0225	0,0849

June

No. of obs.: 229

Sector / Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
< 5,0	0,0061	0,0029	0,0014	0,0004	0	0,0104	0,0212
6,5	0,0043	0,0054	0,0039	0,0018	0	0,0050	0,0204
8,5	0,0043	0,0050	0,0039	0,0018	0,0004	0,0029	0,0183
10,5	0,0014	0,0039	0,0032	0,0007	0	0,0004	0,0096
12,5	0,0018	0,0061	0,0025	0,0004	0	0,0004	0,0112
≥14,0	0,0007	0,0007	0	0	0	0	0,0014
Total	0,0186	0,0240	0,0149	0,0051	0,0004	0,0191	0,0821

TABLE A.I/1: DEEP-SEA WAVE OCCURRENCES (continued)

July

No. of obs.: 334

Sector / Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
≤ 5,0	0,0056	0,0023	0,0008	0	0,0005	0,0084	0,0176
6,5	0,0092	0,0064	0,0023	0,0002	0	0,0051	0,0232
8,5	0,0084	0,0079	0,0038	0,0002	0	0,0038	0,0241
10,5	0,0033	0,0043	0,0023	0,0002	0,0018	0,0010	0,0129
12,5	0,0013	0,0018	0,0010	0,0002	0	0,0003	0,0046
≥14,0	0,0005	0,0013	0,0002	0	0	0,0005	0,0025
Total	0,0283	0,0240	0,0104	0,0008	0,0023	0,0191	0,0849

August

No. of obs.: 309

Sector / Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
≤ 5,0	0,0047	0,0038	0,0022	0,0014	0,0011	0,0099	0,0231
6,5	0,0063	0,0071	0,0019	0,0006	0,0008	0,0027	0,0194
8,5	0,0069	0,0097	0,0022	0,0003	0	0,0022	0,0213
10,5	0,0016	0,0063	0,0016	0,0006	0	0,0011	0,0112
12,5	0,0016	0,0030	0,0027	0	0	0,0014	0,0087
≥14,0	0,0006	0,0003	0,0003	0	0	0	0,0012
Total	0,0217	0,0302	0,0109	0,0029	0,0019	0,0173	0,0849

September

No. of obs.: 283

Sector / Period T_{VOS}(s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
≤ 5,0	0,0075	0,0029	0,0011	0,0006	0	0,0075	0,0196
6,5	0,0102	0,0078	0,0029	0	0,0003	0,0041	0,0253
8,5	0,0084	0,0029	0,0014	0,0006	0,0006	0,0044	0,0183
10,5	0,0029	0,0064	0,0023	0,0003	0	0,0003	0,0122
12,5	0,0017	0,0023	0,0009	0,0003	0,0003	0,0006	0,0061
≥14,0	0,0003	0	0	0	0	0,0003	0,0006
Total	0,0310	0,0223	0,0086	0,0018	0,0012	0,0172	0,0821

TABLE A.I/1: DEEP-SEA WAVE OCCURRENCES (continued)

October

No. of obs.: 324

Sector Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
≤ 5,0	0,0081	0,0045	0,0023	0,0013	0,0003	0,0075	0,0240
6,5	0,0081	0,0102	0,0016	0	0,0003	0,0037	0,0239
8,5	0,0076	0,0096	0,0018	0,0003	0	0,0031	0,0224
10,5	0,0042	0,0042	0,0016	0,0003	0	0,0005	0,0108
12,5	0,0013	0,0011	0,0003	0	0	0,0003	0,0030
≥14,0	0,0005	0	0,0003	0	0	0	0,0008
Total	0,0298	0,0296	0,0079	0,0019	0,0006	0,0151	0,0849

November

No. of obs.: 286

Sector Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
≤ 5,0	0,0057	0,0054	0,0017	0,0003	0,0006	0,0095	0,0232
6,5	0,0123	0,0069	0,0003	0	0	0,0066	0,0261
8,5	0,0086	0,0080	0,0003	0	0	0,0032	0,0201
10,5	0,0032	0,0020	0,0009	0	0,0003	0,0017	0,0081
12,5	0,0011	0,0023	0,0009	0	0	0	0,0043
≥14,0	0,0003	0	0	0	0	0	0,0003
Total	0,0312	0,0246	0,0041	0,0003	0,0009	0,0210	0,0821

December

No. of obs.: 261

Sector Period T_{VOS} (s)	Fractional occurrence, F_I						
	180°	210°	240°	270°	300°	Calm	Total
≤ 5,0	0,0124	0,0059	0,0010	0	0,0006	0,0075	0,0274
6,5	0,0124	0,0062	0,0029	0,0006	0	0,0039	0,0260
8,5	0,0091	0,0059	0,0013	0,0003	0	0,0036	0,0202
10,5	0,0042	0,0020	0,0003	0	0	0,0013	0,0078
12,5	0,0010	0,0010	0,0003	0	0	0,0006	0,0029
≥14,0	0	0,0003	0,0003	0	0	0	0,0006
Total	0,0391	0,0213	0,0061	0,0009	0,0006	0,0169	0,0849

TABLE A.I/2: DEEP-SEA WAVE HEIGHTS

Source: VOS data (Swart and Serdyn, unpublished work).

Year No. of obs.: 3 538

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,7	1,6	1,6	1,4	1,0
6,5	2,4	2,1	2,0	1,2	1,3
8,5	2,7	2,9	2,6	1,6	1,4
10,5	3,0	3,2	2,6	2,7	1,5
12,5	3,6	2,8	3,8	2,6	2,0
≥14,0	3,5	4,4	4,8	-	3,5

TABLE A.I/2: DEEP-SEA WAVE HEIGHTS (continued)

January No. of obs.: 368

Sector / Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	2,0	2,0	1,9	1,5	–
6,5	2,5	2,0	1,9	–	–
8,5	2,6	2,8	2,7	1,0	1,0
10,5	2,4	3,1	4,5	–	–
12,5	3,6	3,3	4,0	–	–
≥14,0	2,5	3,8	–	–	–

February No. of obs.: 316

Sector / Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,9	1,6	1,4	–	0,5
6,5	2,4	1,9	2,3	–	1,5
8,5	2,4	2,3	2,0	–	–
10,5	3,4	2,8	–	–	–
12,5	3,5	2,8	–	–	–
≥14,0	–	–	–	–	–

March No. of obs.: 371

Sector / Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,8	1,1	1,0	1,0	–
6,5	2,4	1,7	1,6	–	–
8,5	2,9	2,0	–	–	–
10,5	2,8	2,8	1,8	–	–
12,5	2,5	4,2	–	–	–
≥14,0	–	–	–	–	3,5

TABLE A.I/2: DEEP-SEA WAVE HEIGHTS (continued)

April

No. of obs.: 223

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,2	1,8	-	-	0,9
6,5	2,1	1,5	1,9	2,2	1,0
8,5	2,5	2,0	2,1	-	-
10,5	2,7	2,8	2,0	-	-
12,5	3,0	2,5	3,0	-	-
≥14,0	3,0	-	-	-	-

May

No. of obs.: 234

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,3	1,6	2,3	1,5	1,4
6,5	2,5	1,9	2,0	1,5	-
8,5	2,4	2,4	2,2	1,3	-
10,5	1,8	3,4	2,6	-	-
12,5	2,0	2,5	3,0	4,0	-
≥14,0	3,0	-	-	-	-

June

No. of obs.: 229

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,3	1,1	1,8	0,5	-
6,5	2,4	2,0	2,2	1,2	-
8,5	2,4	2,6	2,6	1,6	1,5
10,5	2,4	3,2	2,5	2,5	-
12,5	3,0	3,0	3,8	2,0	-
≥14,0	5,0	3,5	-	-	-

TABLE A.I/2: DEEP-SEA WAVE HEIGHTS (continued)

July — No. of obs.: 334

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,3	1,5	1,7	-	0,7
6,5	2,4	2,1	1,7	1,0	-
8,5	2,6	3,0	2,4	2,0	-
10,5	3,0	2,7	2,0	0,5	1,4
12,5	3,3	4,1	4,1	2,0	-
≥14,0	3,6	4,1	3,5	-	-

August — No. of obs.: 309

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,5	2,0	1,8	1,1	1,1
6,5	2,6	2,5	2,2	1,1	1,2
8,5	2,6	4,0	3,6	2,0	-
10,5	3,7	4,8	1,9	3,7	-
12,5	5,2	3,5	4,1	-	-
≥14,0	3,0	8,0	8,0	-	-

September — No. of obs.: 283

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,3	1,0	1,8	0,8	-
6,5	2,3	2,3	2,5	-	1,5
8,5	2,9	2,2	3,2	1,5	1,6
10,5	3,8	2,6	2,8	2,0	-
12,5	3,1	3,0	2,9	2,0	2,0
≥14,0	10,0	-	-	-	-

TABLE A.I/2: DEEP-SEA WAVE HEIGHTS (continued)

October

No. of obs.: 324

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,9	1,8	1,3	0,7	0,5
6,5	2,3	2,1	1,6	-	1,0
8,5	2,3	3,0	2,0	1,5	-
10,5	3,2	2,3	2,7	2,5	-
12,5	4,2	3,8	3,0	-	-
≥14,0	4,3	-	2,5	-	-

November

No. of obs.: 286

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,8	1,6	1,6	4,0	1,8
6,5	2,4	2,5	1,5	-	-
8,5	3,1	3,3	2,5	-	-
10,5	3,7	1,8	1,7	-	2,0
12,5	4,0	3,2	4,0	-	-
≥14,0	2,5	-	-	-	-

December

No. of obs.: 261

Sector Period T_{VOS} (s)	Wave height, H_{VOS} (m)				
	180°	210°	240°	270°	300°
≤ 5,0	1,8	1,7	0,7	-	1,5
6,5	2,3	2,2	1,6	0,8	-
8,5	2,4	2,1	3,0	2,5	-
10,5	3,2	2,3	5,0	-	-
12,5	3,4	2,7	2,0	-	-
≥14,0	-	3,5	3,0	-	-

APPENDIX B

DERIVATION OF A MINIMUM WAVE PERIOD

CONTENTS

GENERAL

The tables of VOS wave data (Swart and Serdyn, unpublished work) combine all waves with a VOS period less than or equal to 5,0 s. As waves falling into this category form a significant part of the overall wave climate, it is necessary that a representative value be derived for this period. It is also more convenient to express this representative wave period in the form of a peak energy value, 'T_p', rather than a VOS value, 'T_{VOS}'. As the relationship between these two variables is given by

$$T_p = 6{,}0(T_{VOS})^{0{,}4},$$

it follows that the waves in question have a peak energy period $T_p < 11{,}4$.

The representative peak energy wave period for the shortest VOS waves was derived by computing the mean value weighted according to percentage occurrence from Oranjemund Waverider data held in the NRIO data bank. Details of the relevant wave occurrences are as follows:

T_p (s)	<5,22	5,22	5,51	5,82	6,17	6,56	7,01	7,53	8,13	8,83	9,66	10,67	Total
Percentage occurrence	0,2	0,1	0,2	0,3	0,3	0,6	1,0	1,9	2,9	4,0	7,4	15,8	34,7

Omitting peak energy wave periods less than 5,2 s, the resulting weighted mean peak energy wave period for waves with a VOS period less than or equal to 5,0 s ('T_p' less than or equal to 11,4 s) is

$$T_p = 9{,}5 \text{ s}.$$

REFERENCE

SWART, D.H. and SERDYN, J.deV. (unpublished work). Statistical analysis of visually observed wave data from voluntary observing ships for Southern African coast. Vols. 57, 58 and 60. CSIR Report, Stellenbosch.

APPENDIX C

LONGSHORE TRANSPORT FORMULA

CONTENTS

GENERAL

The longshore sediment transport rate is given by the Shore Protection Manual (SPM) formula (U.S. Army, 1975) as modified by Swart (1976). The SPM formula states that

$$S_X = 7{,}5 \cdot 10^3 \cdot P_X \cdot f_I \text{ (Imperial units)}$$

or

$$S_X = 1{,}29 \cdot 10^3 \cdot P_X \cdot f_I \text{ (metric units)}$$

where

S_X = longshore transport rate (m^3/yr);
P_X = longshore energy flux ($N \cdot m/m \cdot s$);
f_I = fractional occurrence of a give wave condition.

The modification carried out by Swart (1976) introduced the effect of grain size which caused the equation for the longshore transport rate to take the form

$$S_X = (1{,}29 \cdot 10^3/(62{,}5 \cdot 10^4))P_X \cdot f_I \cdot K(D)$$

$$= 2{,}06 \cdot 10^{-3} \cdot P_X \cdot f_I \cdot K(D) \text{ } (m^3/\text{year}) \qquad \text{... C.1)}$$

where

$K(D) = 91 \cdot 10^4 \log(0{,}00146/D_{50})$ $(m/(s \cdot \text{year}))$
D_{50} = median grain size (m)

and the factor $(62{,}5 \cdot 10^4)$ accounts for the SPM formula being valid for 300 μm sand. However, the longshore energy flux is given by (U.S. Army, 1975)

$$P_X = (\rho \cdot g/16) H_{BS}^2 \cdot n_B \cdot C_B \cdot \sin 2\theta_B \ (N \cdot m/m \cdot s) \qquad \ldots \ (C.2)$$

where

ρ = water density (kg/m^3);

g = gravitational acceleration (m/s^2);

H_{BS} = significant breaker height (m);

n_B = ratio between the wave group velocity and the wave celerity at the break point;

C_B = wave celerity at the break point (m/s);

θ_B = angle between the normal to the wave front and the local bed contour at the break point.

Combining Equations C.1 and C.2 then gives

$$S_X = 2{,}06 \cdot 10^{-3} \cdot \rho \cdot g((H_{BS}/H_{OS})^2 n_B \cdot C_B \cdot \sin 2\theta_B/16) H_{OS}^2 \cdot K(D) \cdot f_I (m^3/year)$$

where

H_{OS} = deep-sea significant wave height (m).

It is convenient, however, to represent all breaker line characteristics by a single parameter, the longshore energy flux factor, which has the form

$$F_F = (H_{BS}/H_{OS})^2 n_B \cdot C_B \cdot \sin 2\theta_B/16 \ (m^3/s).$$

It thus follows that

$$S_X = 2{,}06 \cdot 10^{-3} \cdot \rho \cdot g \cdot H_{OS}^2 \cdot f_I \cdot K(D) \cdot F_F \ (m^3/year).$$

REFERENCES

SWART, D.H. (1976). Predictive equations regarding coastal transports. Proc. Fifteenth Coastal Engrg. Conf., Hawaii.

U.S. ARMY, (1975). Shore protection manual. Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va.

APPENDIX D

MONTHLY SPRING TIDAL PRISM

CONTENTS

GENERAL

Typical monthly values for the spring tidal prism of the Orange River Estuary were not available and therefore had to be estimated. This was achieved by determining the mean monthly cross-sectional areas of the estuary mouth, 'A', and then computing the volumes of the tidal prism, 'Ω_T', using an empirical relationship between these two variables.

During a site visit in March 1985, it was estimated that the estuary mouth had a width of approximately 100 m. Hence, assuming a triangular cross section and a maximum depth of 2 m, the cross-sectional area had a value of about 100 m^2. Based on the work of Jarrett (1976), who plotted 'Ω_T' as a function of 'A' for American inlets as shown in Figure D.1, this 'A' value of 100 m^2 (1 100 ft^2) corresponds to an 'Ω_T' value of $1{,}7 \cdot 10^6$ m^3 ($6 \cdot 10^7$ ft^3). A check on the accuracy of these computations can be obtained from the estuarine spring tidal range, which was deduced from water levels measured during the site visit to be 0,95 m, and from the plan area of the estuary, which was estimated from aerial photographs to be approximately $1{,}5 \cdot 10^6$ m^2. When combined, these two quantities give a spring tidal prism of $1{,}4 \cdot 10^6$ m^3 which compares favourably with the $1{,}7 \cdot 10^6$ m^3 given by the Jarrett relationship. A value of $1{,}5 \cdot 10^6$ m^3, therefore, was adopted for 'Ω_T'. As the river flows were low during the site visit, this estimate for the spring tidal prism was considered to be equivalent to the minimum value of 'Ω_T' during a typical year. These conditions occurred in August during the low flow period.

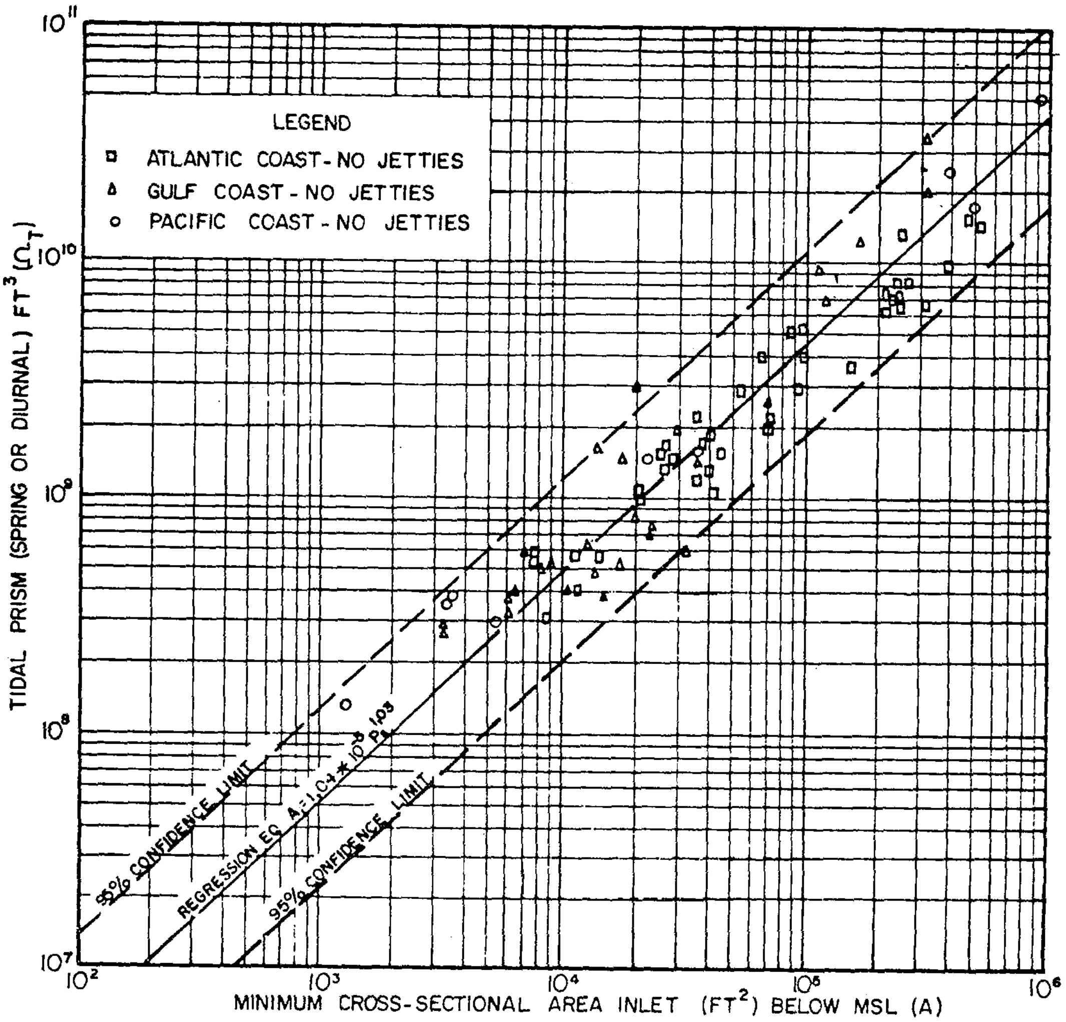
As regards the maximum value for 'Ω_T' during a typical year, aerial photographs indicate that the width of the estuary mouth was of the order of 500 m. Hence, assuming a triangular cross section once again and a maximum depth of 5 m, the estuary mouth cross-sectional area was estimated to have had a value of

1 250 m^2 (13 500 ft^2). According to Figure 9, the corresponding spring tidal prism is $1{,}8 \cdot 10^7$ m^3 ($6{,}5 \cdot 10^8$ ft^3). Based on these estimates, a maximum, monthly value of $2 \cdot 10^7$ m^3 was adopted for the spring tidal prism which occurred during the February floods.

The variation in the spring tidal prism from month to month throughout the year was obtained by assuming a sinusoidal variation between the minimum August value of $1{,}5 \cdot 10^6$ m^3 and the maximum February value of $2 \cdot 10^7$ m^3. The results are given in Table VIII of the main text.

REFERENCE

JARRETT, J.T. (1976). Tidal prism - inlet area relationships. US Army Corps of Engineers, Coastal Engineering Research Center and Waterways Experiment Station, GITI Report 3.



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SPRING TIDAL PRISM VERSUS MINIMUM INLET CROSS-SECTIONAL AREA BELOW MSL: AFTER JARRETT (1976)

FIGURE D.1

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