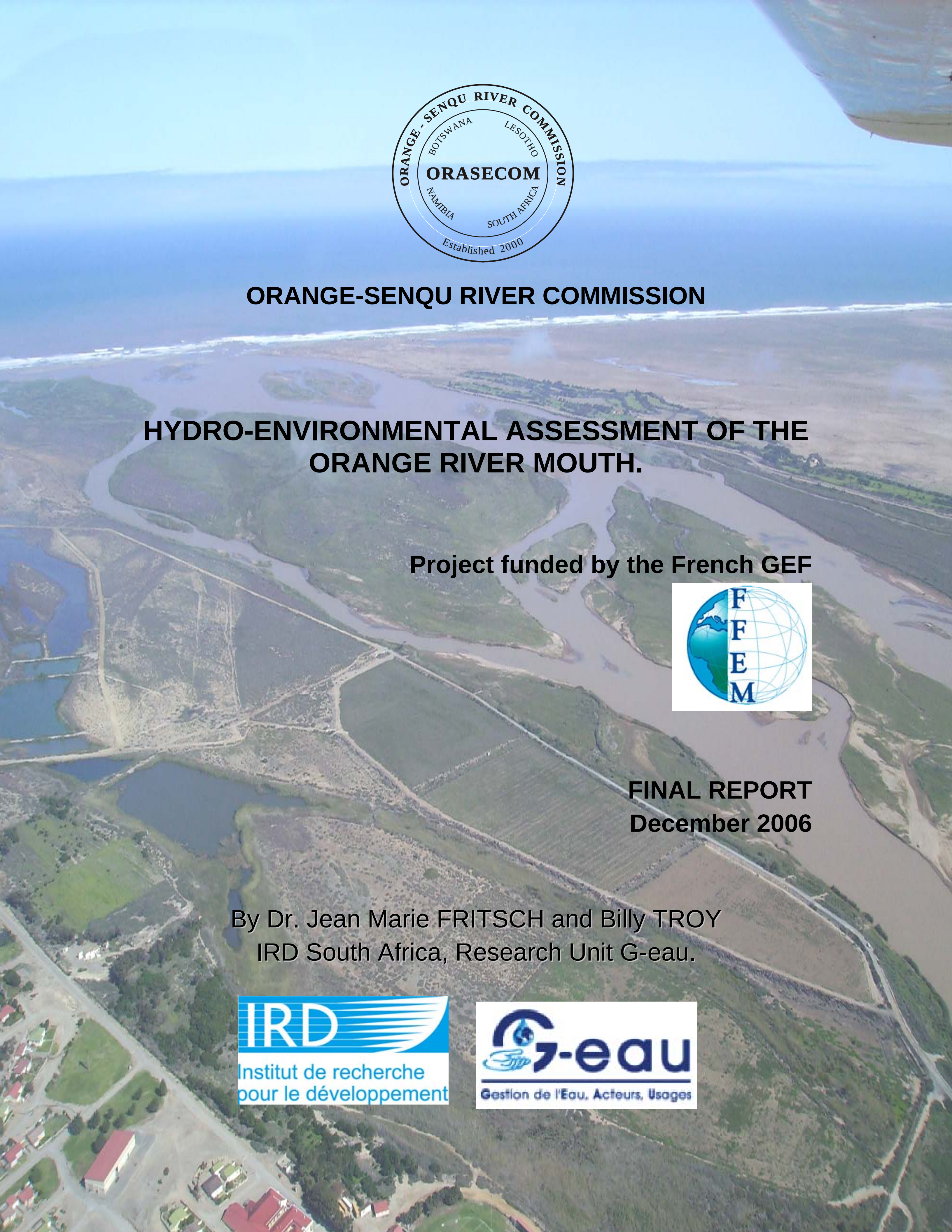

ORANGE-SENQU RIVER COMMISSION

HYDRO-ENVIRONMENTAL ASSESSMENT OF THE ORANGE RIVER MOUTH.

Project funded by the French GEF

FINAL REPORT
December 2006

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Executive Summary

The Orange River estuary shelters wetlands of international importance and is classified as a Ramsar site. The main driver of the ecological state of these wetlands is the flood from the Orange River. These wetlands, and especially a saltmarsh located on the south bank of the river, have been threatened during the last decades due to changes in the hydrological regime of the Orange River. This degradation has been reinforced by the construction of inappropriate (environmentally speaking) road works within the wetland. Currently, the soils and the groundwater salinity within the saltmarsh are too high and freshwater flooding would be required to allow the rehabilitation of this Ramsar site.

Despite the importance of hydrological processes in the functioning of the wetlands, the daily flow regime, crucial for flood assessment, is unknown. The water levels immediately upstream of the estuary are poorly known and for a short period of time only. There is no flow gauging station located near the inlet of the estuary.

Within that context, the present study first presents a simulation of daily flows and water levels entering the estuary, based on a Spatial Interpolation Approach. This allows an analysis of the evolution of the flow regime at the estuary before and after the major developments (especially dams) that have been taking place over the Orange River basin. The observed changes in the flow regime at the estuary from 1935 to 2005, under the limits of the modeling, are dramatic. Medium and high flows have been substantially reduced, with observed decreases of the magnitude of 50% for most of the range of the return periods. On the other hand, low flows increased and prevented the river to dry out as frequently as before.

Then a hydraulic study has been carried out at the level of the estuary, in order to assess the frequency of the potential flooding of the saltmarsh. This assessment then allowed to calculate a design flood at the estuary likely to support the rehabilitation of the saltmarsh and the Orange River Mouth Wetlands. It has been found that the corresponding hydrograph is equivalent to a mean daily flow of 1 270 $m^3.s^{-1}$ during 7 days.

The return period of such a flooding of the saltmarsh has been reduced from almost one year before 1960 to 3.3/3.8 years during the last 25 years (under the limits of the modeling). The actual flooding events are even more rare due to the construction of a causeway and dykes near and along the saltmarsh, which are obstacles to the circulation of water along the natural channels.

Nevertheless the provision of this design flood at the acceptable frequency of once per 3 years seems achievable (according to some environmentalists) with the present state of the flow regime of the Orange River.

However, further surveys and actions would have to be carried out, especially for rehabilitating the former flow routing channels in the saltmarsh. Moreover, the implementation of an effective rehabilitation program would require extensive coordination between the different levels of management at the local, sub-basin (Lower Orange) and basin levels.

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Terms and Abbreviations

AFD: *Agence Française de Développement*

CSIR: Council for Scientific and Industrial Research

DEAT: Department of Environmental Affairs and Tourism

DWA: Department of Water Affairs

DWAF: Department of Water Affairs and Forestry

FDC: Flow Duration Curve

1D-FDC: Daily Flow Duration Curve

1M-FDC: Monthly Flow Duration Curve

FGEF: French Global Environment Facility

GPS: Global Positioning System

IRD: French Research Institute for Development (*Institut de Recherche pour le Développement*)

IWR: Institute of Water Research (Rhodes University, Grahamstown, South Africa)

IWRM: Integrated Water Resources Management

MAP: Mean Annual Precipitation

MAR: Mean Annual Runoff

MASL: Meters Above Sea Level

Mm3: Millions of cubic meters

PIU: Project Implementing Unit

ORASECOM: Orange- Senqu River Commission

ORM: Orange River Mouth

ORMIMC: Orange River Mouth Interim Management Committee

ORMW: Orange River Mouth Wetlands

ORP: Orange River Project

SIA: Spatial Interpolation Approach

WRP: Water Resource Planning and conservation (Consulting engineers, Pretoria, South Africa).

1. Introduction

1.1. Background

The Orange River Mouth (ORM) is a site of major ecological interest in Southern Africa. Indeed it shelters a wetlands area supporting exceptional biodiversity, especially in terms of plants, birds and fishes, in a particularly arid region. On that basis, both the South African and the Namibian parts of the Orange River Mouth Wetlands (ORMW) were designated as Ramsar sites, i.e. wetlands of international importance, in 1991 and 1995 respectively (Le Maître et al., 2001).

Nevertheless, this site has been highly impacted by anthropogenic activities. In particular, the construction of the Gariep and Van der Kloof dams, situated 1 400 km upstream of the River Mouth, has deeply modified the flow regime at the estuary, implying major ecological evolutions. The human activities which are taking place on the banks of the estuary, especially mining, as well as the various abstractions of water along the lower part of the river, also impacted on the environmental equilibrium of the site (LORMS, 2005a).

As a consequence of these local and basin-wide impacts, a large area of saltmarsh located on the South African bank of the mouth has collapsed, implying a decrease in the biodiversity of the wetlands. It resulted in the South African part of the ORMW being placed on the Montreux Record in September 1995 (Le Maître et al., 2001, and Edward Netshithothole, DEAT South Africa, personal communication, 2006). The Montreux record is “a record of Ramsar sites where changes in ecological character have occurred, are occurring or are likely to occur” (Bornman et al., 2005). Within the framework of the Ramsar convention, it implies that the ecological quality of the wetlands has to be restored. A rehabilitation program of the saltmarsh is currently carried out within the framework of the Working for Wetlands programme.

It is thus now a major challenge in terms of IWRM on the Orange River basin to achieve a sustainable trade-off between environmental requirements at the estuary and human activities locally and all over the basin. This challenge is especially crucial as the estuary is the most downstream site for environmental demand.

One of the major drivers of the ecological state of the ORMW is the flow regime entering the mouth. In particular, the medium and high floods are crucial to allow flooding of the saltmarsh, presently too saline, even for the dominant saltmarsh vegetation (Bornman et al., 2005). However, there is no flow gauging station close to the river mouth that would allow appropriate knowledge and management of the flows. On the Orange River, the only flow data available are provided by the gauging station of Vioolsdrift (measuring daily flows), situated 280 km upstream of the estuary, and by a water level recorder near Alexander Bay, 10 km upstream of the mouth. On the Fish River, daily flow measurements are available at Ai-Ais, about 145 km upstream of the mouth.

Time series of simulated monthly flows at the estuary are available and were used for the ecological categorisation of the estuary for the Pre feasibility study entitled “Measures to improve the Management of the Lower Orange River” (LORMS, 2005a). Nevertheless, time series of daily flows at the inlet of the estuary would be necessary in order to substantially enhance the ecological knowledge of the functioning of the estuary and the sustainability of the ORMW. Indeed this type of data is crucial to:

- Analyse the role of floods of different frequencies (large or small) in shaping the habitats found in the estuary,
- Establish the correlation between the state of the mouth and the flow regime,
- Assess the influence of tides on the state of the mouth,
- Assess the evolution of water quality (regarding among others salinity, temperature or dissolved oxygen).

1.2. Objectives of the study

Within this context, the present research study proposes to achieve the following objectives:

1. **Characterization of the hydrological regime at the mouth at a daily time step**: simulation of daily flows and water levels at the estuary. As the information was rather poor, a spatial interpolation approach (SIA) was implemented. This method aims to simulate hydrological time series at an ungauged site using data available at relatively close gauged sites. The

previous case studies on that method have shown that it can perform as well as more complex models without being as much costly to apply (Smakhtin, 2004). It is thus of important methodological interest at the scale of the basin to inquire the effectiveness of such methods in the Orange River context, considering the potential transposition of this method to other sites in the basin. Simulated flows have then been correlated with observed water levels at the estuary, thus allowing to draft a rating curve between simulated flows and observed water levels at the Oppenheimer bridge. Then this curve is used to patch the observed time series of water levels.

2. **Assessment of the contribution of the Orange River to the potential flooding of the saltmarsh**: simulation of flooding events in the saltmarsh resulting from Orange River basin floods (Orange and Fish rivers). A simple hydraulic modeling was carried out to simulate water conveyance from the upstream boundary of the estuary (located at the Oppenheimer bridge) to the saltmarsh. The modeling reproduced a permanent and uniform flow via a fictive canal of constant slope to the saltmarsh (functioning as a reservoir), running on a daily time step. The main input data for the model were the simulated time series of daily water levels at the bridge. The validation of this model has been done with respect to available information on saltmarsh flooding, which are actually poor (a few aerial pictures and expert's knowledge). The study of the potential flooding events has allowed the identification of a flood hydrograph necessary to flood the saltmarsh.

3. **Recommendations for the implementation of a flow regime commensurable with the environmental demand at the Orange River estuary,** with particular relation with the current rehabilitation program of the saltmarsh.

This report will detail these different steps after having presented a description of the study area.

1.3. Assumptions and limitations

The hydrological data used as inputs in this study are of diverse qualities. One major source of uncertainty comes from the measured flows at Vioolsdrift on the Orange River. The gauging station being a large weir, the low flows are known with poor accuracy. This study has also used the simulated monthly flows at the estuary computed by WRP for previous studies. Consequently it bears the same uncertainties, due to the corresponding complex modeling, on the quality of the simulated hydrological data.

In terms of driving forces for the ecological state of the estuary, the present study only deals with river flows entering the estuary, which are reputed to be the main factor (LORMS, 2005a). Other phenomena, in particular back flooding due to the closure of the mouth, were not considered here. This back flooding phenomenon is indeed very poorly known and documented, both in terms of processes, frequency and importance for the ecosystem. Moreover the poor accuracy affecting low flows at Vioolsdrift prevents from any satisfactory knowledge of the flow conditions that might cause mouth closures.

This study will not consider the whole ORMW but will focus on the saltmarsh area located on the South bank of the estuary. This part of the wetlands is the most threatened and its ecological state can be considered as a good indicator of the general state of the whole ORMW.

2. Description of the study area

2.1. Situation of the estuary within the basin

The Orange River estuary constitutes the outlet of the Orange River basin in the Atlantic Ocean (coordinates: S 28º 38’ 50.4” - E 16º 29’ 04.3” in Latitude/longitude WGS 84 system) and is crossed by the border between South Africa and Namibia.

It is bordered by the towns of Alexander Bay (South Africa, south bank) and Oranjemund (Namibia, north bank), which are both diamonds mining sites managed by Alexkor in Alexander Bay and Namdeb in Namibia.

The estuary drains the whole Orange River basin (**Figure 1**), which covers around 1 000 000 km^2 and represents a mean annual runoff around 5 700 Mm^3 (period between 1976 and 1987 - source: DWAF South Africa). On its lower part, the Orange River receives the flows of the Fish River catchment on its right bank, the confluence being approximately 120 km upstream of the estuary (see flow regime below).

The altitude of the Orange River is below 100 m along the first 10 km upstream of the mouth and remains below 200 m until 300 km upstream of the estuary (**Figure 2**).

2.2. Climate

The precipitation is particularly low in the lower part of the Orange River basin. The Mean Annual Precipitation (MAP) on the lower parts of the Orange and the Fish rivers are below 100 mm (**Figure 3**).

The mean temperature in Alexander Bay is 17.3ºC, ranging from 9ºC in July to 24ºC in January (monthly means). The potential evaporation (A-Pan equivalent) is more than 2 800 $mm.a^{-1}$ in Vioolsdrift and downstream on the Orange River, with values higher than 2 600 $mm.a^{-1}$ in Alexander Bay (Schulze et al., 1997). On the Fish River, potential evaporation is higher than 2 950 $mm.a^{-1}$ (LORMS, 2005b). Consequently, in average terms, the contribution of rainfall to the runoff of the Orange River downstream of Vioolsdrift and of the Fish River downstream of Ai-Ais is negligible.

Figure 1: The Orange River Basin
(Source: DWAF South Africa)

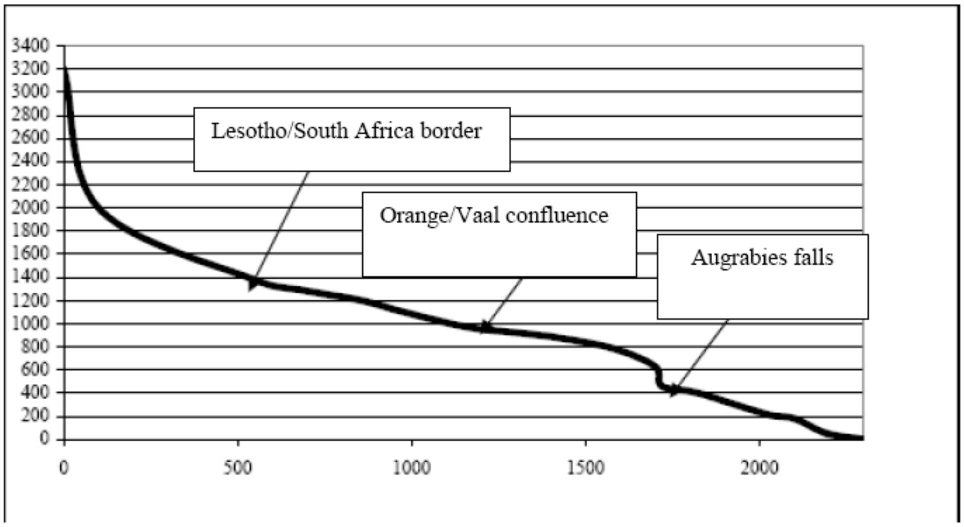

Figure 2: Longitudinal profile of the Orange River: altitude (in masl) versus distance from the source of the river (in meters)
(Source: Du Plessis et al., 1987 in Blanchon, 2003)

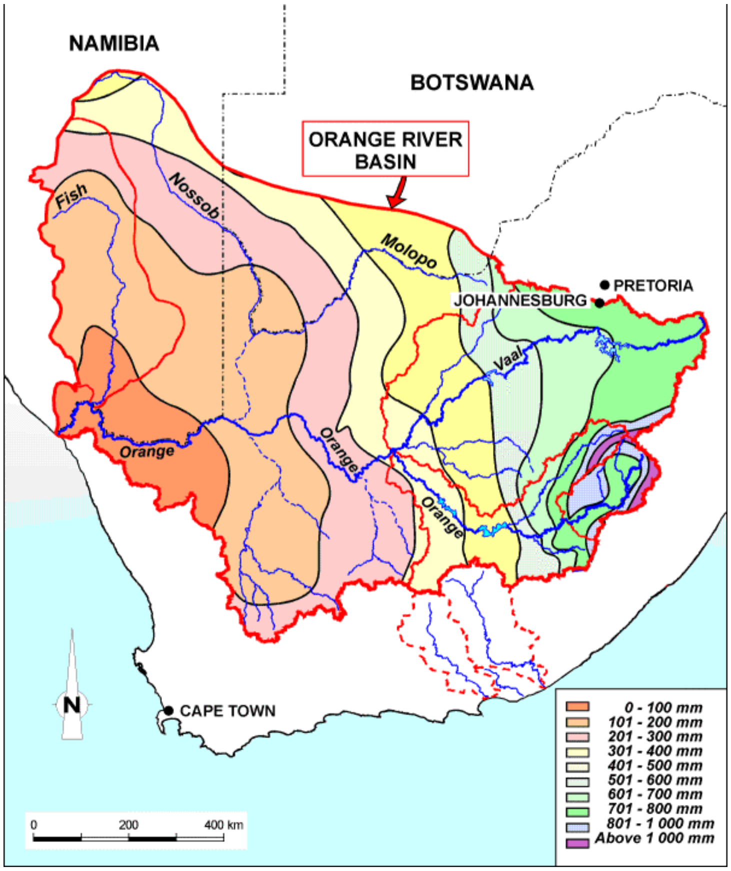

Figure 3: Mean annual precipitation on the Orange River Basin
(Source: DWAF South Africa)

2.3. Flow regime in the hydrographical network of the Orange River system in the region of the estuary

Note: the calculation of FDC was performed with the SPATSIM software from IWR.

2.3.1. Description of the network of hydrological stations

As previously mentioned, there is no flow gauging station at the estuary, but only a water level recorder at the Oppenheimer bridge (9. 5 km upstream of the ORM). The nearest gauging stations on the main streams of the hydrographical network are described below.

On the Orange River, the nearest flow gauging station is located at Vioolsdrift, about 280 km upstream of the estuary. The low flows measured at that site are known with poor quality and has to be considered with caution: indeed the gauging station is a long weir, and a slight variation in water level leads to major differences in flow values. It can be noted that a water level recorder is operated at Brandkaros, between the estuary and the Richtersveld National Park. As the focus of this study is on the estuary, the water level recorder at Oppenheimer bridge was preferred, especially for the purpose of hydraulic study of the estuary. Apart from the Fish River, no other major tributary joins the Orange River between Vioolsdrift and the mouth (**Figure 4**).

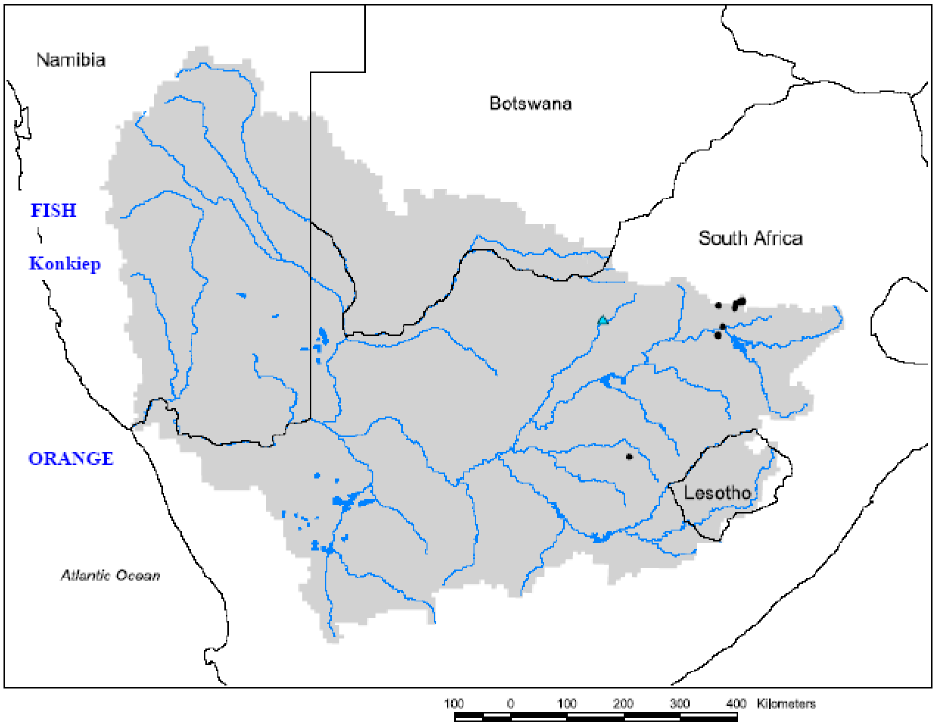

Figure 4: Hydrographical network of the Orange River basin
(Source: Earthtrends 2002, World Resources Institute)

On the Fish River, the nearest flow gauging station is located at Ai-Ais, about 65 km upstream of the Fish/Orange confluence, the confluence being about 120 km upstream of the Orange River Mouth (LORMS, 2005a). The rating quality of the station is considered as good.

Moreover, the Konkiep River is a significant tributary of the Fish River in terms of catchment surface, representing 33.4% of the Fish River catchment (LORMS, 2005b). The Konkiep River joins the Fish River downstream of Ai-Ais (about 40 km upstream of the Fish/Orange confluence) and consequently the contribution of the Konkiep is not monitored by the Ai-Ais station. On the Konkiep River, the nearest flow gauging station of interest for this study is located at Bethanien, about 190 km upstream of the Konkiep/Fish confluence. Nevertheless the flows recorded there are minor compared to the total flow entering the lower Orange system. Moreover, the quality of the record is reputed as quite poor (Guido Van Langenhove, DWA Namibia, personal communication, 2006), and the station is located very far from the estuary. The data have been integrated in the simulation (cf. Characterization of the hydrological regime at the estuary at a daily time step, Section 3), but due to the limitations mentioned above, it did not improve the quality of the results. Consequently it will not be considered in this report.

Considering the elements described below, the hydrological stations selected to characterize the flow regime at the estuary were Vioolsdrift on the Orange River and Ai-Ais on the Fish River, as well as the water level recorder at the Oppenheimer bridge (**Table 1, Figure 5**).

Station	Name	Data type	Source	Latitude	Longitude	Record length	MAR (Mm3.a^{-1})
D8H003	Orange River at Vioolsdrift	Mean daily flow	DWAF South Africa	S 28°45'39"	E 17°43'49"	From 17 October 1935	8376
0499M02	Fish River at Ai-Ais	Mean daily flow	DWA Namibia	S 27°55'	E 17°30'	From 12 October 1975	221
D8H012	Orange River at Alexander Bay-Ernst	Mean Water level	DWAF South Africa	S 28°33'58"	E 16°30'29"	From 26 October 1993 to 20 July 2005	N/A

Table 1: Hydrological stations used for the hydrological study of the Orange River estuary[1]
(Source: computed from DWAF South Africa and DWA Namibia)

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[1] Note: the MAR at Vioolsdrift is calculated for a period that dates back to the 1930's, when the basin was in a more natural state, implying higher flows than at present.

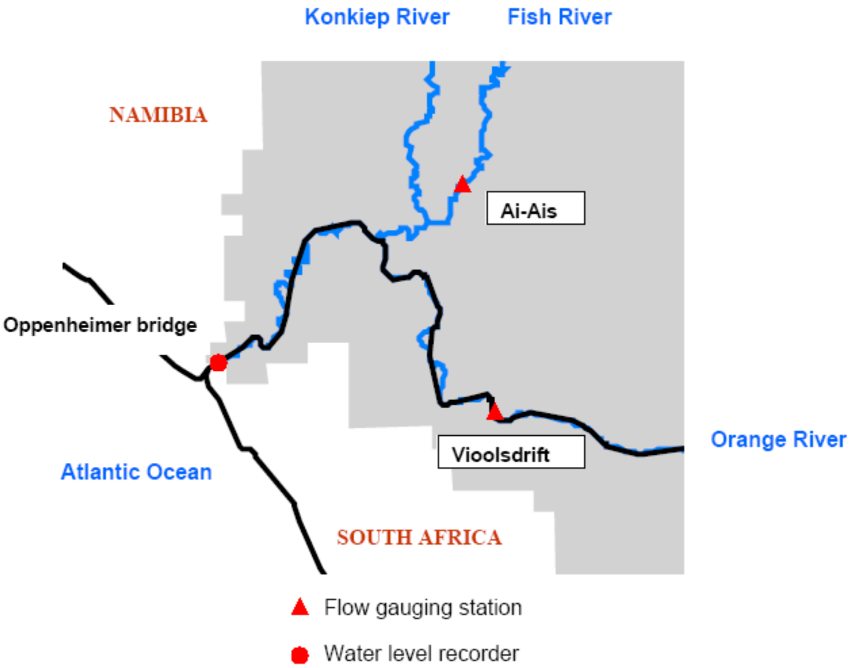


Figure 5: Location of the hydrological stations used for the hydrological study of the Orange River estuary

2.3.2. Description of the flow regime based on measured daily flows

This paragraph will provide a general picture of the flow regime in the region of the estuary on the sole basis of flow measurements provided by the gauging stations identified above. An extended assessment based on simulated flows will be presented in Section 3 "Characterization of the hydrological regime at the estuary at a daily time step".

The Orange River basin is now the most developed basin in Southern Africa, being highly regulated with at least 29 dams with a storage capacity higher than 12 Mm3 (Turton et al., 2004). The major evolution in the development of the water resources in the 20th century was the Orange River Project (ORP), with the construction of the Gariep and Van der Kloof dams (from 1966 to 1971 and from 1971 to 1977 respectively), for purposes of irrigation, drinking water supply and production of hydro-electricity. The aggregated storage capacity of these two dams is 8 800 Mm3, which represents 79 % of the natural MAR of the river (10 833 Mm3 - LORMS, 2005a). These dams and the increase of the demands in the basin since the 1960's implied significant changes in the hydrological regime of the river, especially at the estuary, which is impacted by the whole of the developments in the basin.

Consequently it appeared relevant to consider the periods prior and posterior to the impoundments of the ORP. Two periods were considered: 1935 to 1960 and

1980 to 2005. Time series of daily flows at Vioolsdrift are available for the two periods, while the flow records at Ai-Ais start in 1975 and do not cover the first period (**Table 1**).

The flow regime of the Orange River at Vioolsdrift and of the Fish River at Ai-Ais is described in **Table 2, Figure 6 and 7**.

Interannual mean monthly flows	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Mean
Vioolsdrift 1936-1960													
$m^3.s^{-1}$	331	461	441	452	824	745	498	386	173	87.3	57.4	121	381
Mm3	886	1190	1180	1210	2010	2000	1290	1030	449	234	154	314	996
Vioolsdrift 1981-2005													
$m^3.s^{-1}$	114	127	204	181	238	451	237	146	126	103	81	111	177
Mm3	306	329	546	484	580	1210	614	392	326	276	217	289	464
Ai-Ais 1980-2005													
$m^3.s^{-1}$	0.060	0.570	1.79	4.80	13.8	23.4	12.4	1.46	0.220	0.060	0.010	0.100	4.88
Mm3	0.161	1.48	4.79	12.9	33.6	62.6	32.1	3.91	0.570	0.161	0.027	0.259	12.7

Table 2: Interannual mean monthly flows of the Orange River at Vioolsdrift and of the Fish River at Ai-Ais

(Source: computed from DWAF South Africa and DWA Namibia)

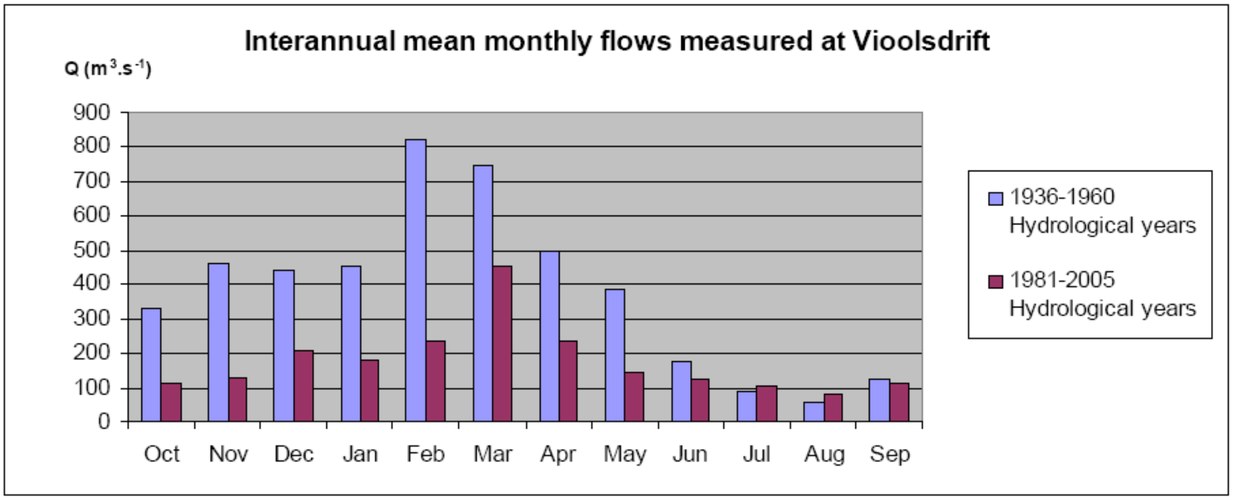


Figure 6: Interannual mean monthly flows measured at Vioolsdrift for periods 1936-1960 and 1981-2005

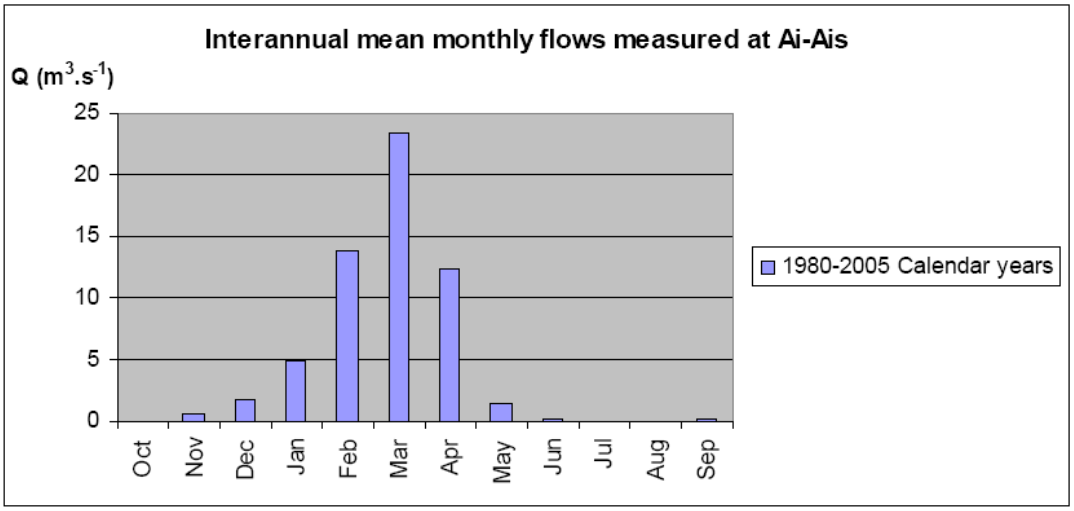


Figure 7: Interannual mean monthly flows measured at Ai-Ais - 1980-2005

Flow regime at Vioolsdrift

The flow regime has dramatically evolved between the two periods considered (1936-1960 and 1980-2005, **Table 2**):

- The mean monthly flow has been more than halved (from 381 $m^3.s^{-1}$ to 177 $m^3.s^{-1}$),
- The high flows (from October to May) have been drastically reduced. The maximum mean monthly flow thus decreased from 824 to 451 $m^3.s^{-1}$,
- The low flow period has extended, lasting now from June to November. Nevertheless the minimum mean monthly flow has increased (from 57.4 to 81.0 $m^3.s^{-1}$), as a result of the releases of the Van der Kloof dam during winter to produce hydroelectricity.

The flow regime now presents high flows from December to April and low flows from May to November, with a flatter seasonal distribution.

This evolution towards regulation of flows is also visible on the daily and monthly flow duration curves (FDC) (**Figure 8, 9 and Table 3**). In particular, the median daily flow (exceeded 50 % of the time) decreased from 134 $m^3.s^{-1}$ to 63.3 $m^3.s^{-1}$. It can also be noted from these curves that the probability to have the Orange River drying out completely at Vioolsdrift during one day was 5% before 1960 (**Figure 8**) while it only happened 0.1 % of the time during the last 25 years (**Figure 9**). On the other hand, in terms of high flows, the monthly flow exceeded

1 % of the time is far smaller in the recent period (1 120 $m^3.s^{-1}$ compared to 2 810 $m^3.s^{-1}$).

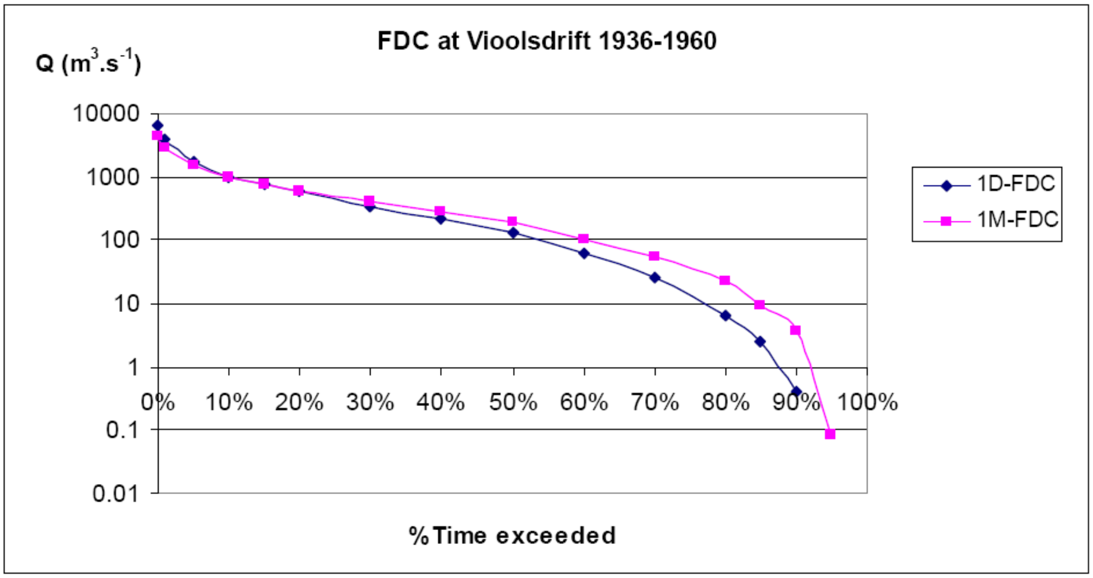


Figure 8: Daily and monthly FDC at Vioolsdrift for 1936-1960

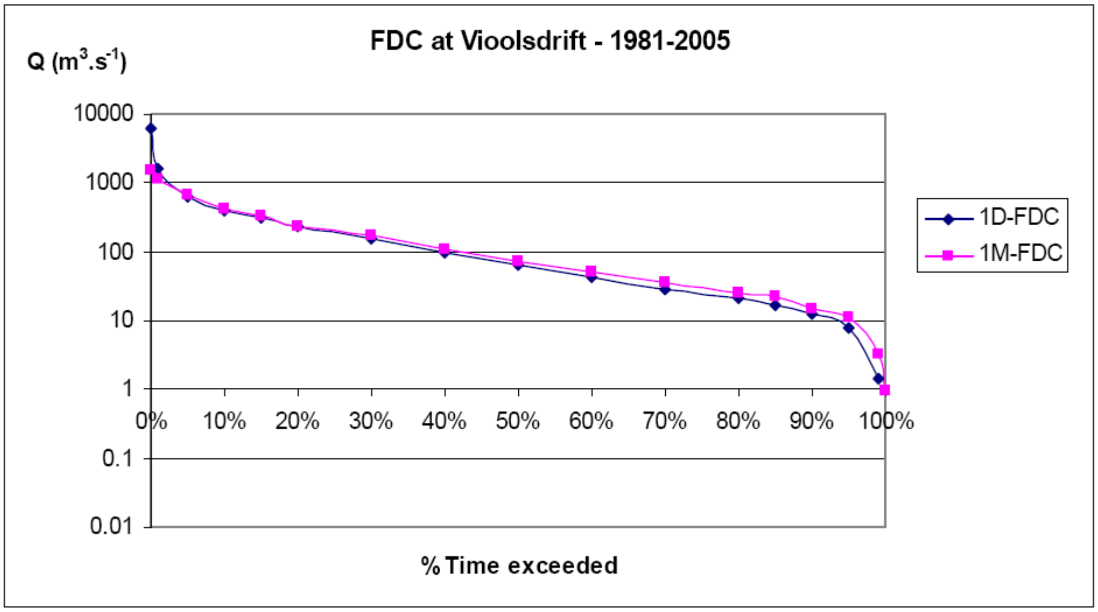
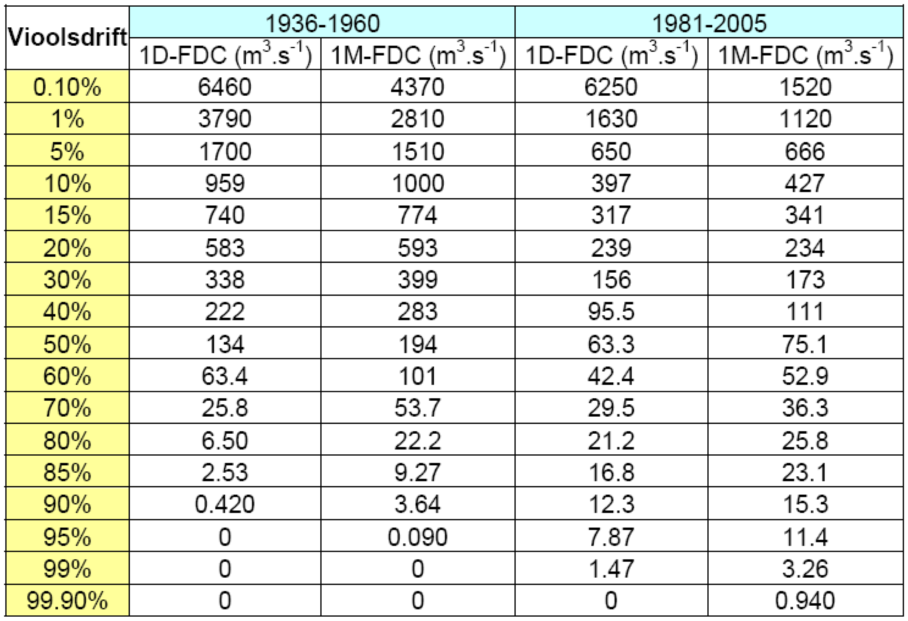


Figure 9: Daily and monthly FDC at Vioolsdrift for 1981-2005



Vioolsdrift	1936-1960		1981-2005	
	1D-FDC ($m^3.s^{-1}$)	1M-FDC ($m^3.s^{-1}$)	1D-FDC ($m^3.s^{-1}$)	1M-FDC ($m^3.s^{-1}$)
0.10%	6460	4370	6250	1520
1%	3790	2810	1630	1120
5%	1700	1510	650	666
10%	959	1000	397	427
15%	740	774	317	341
20%	583	593	239	234
30%	338	399	156	173
40%	222	283	95.5	111
50%	134	194	63.3	75.1
60%	63.4	101	42.4	52.9
70%	25.8	53.7	29.5	36.3
80%	6.50	22.2	21.2	25.8
85%	2.53	9.27	16.8	23.1
90%	0.420	3.64	12.3	15.3
95%	0	0.090	7.87	11.4
99%	0	0	1.47	3.26
99.90%	0	0	0	0.940

**Table 3: Daily and monthly FDC at Vioolsdrift
for 1936-1960 and 1981-2005**

Flow regime at Ai-Ais

The regime of the Fish River at Ai-Ais is considered from 1980 to 2005, while the station has been monitored since 1975. This period is posterior to the construction of the two major dams of Hardap (1963 - 294 Mm^3) and Naute (1970 - 84 Mm^3) on the Fish River basin.

Almost all the volumes recorded at Ai-Ais flow during the months of February, March and April, with a maximum mean monthly flow around 23.4 $m^3.s^{-1}$ in March (**Figure 7**). During the rest of the year, there is hardly any water in the river. FDC (**Figure 10, Table 4**) shows that in average the daily flow was zero for 70 % of the time during the period 1980-2005.

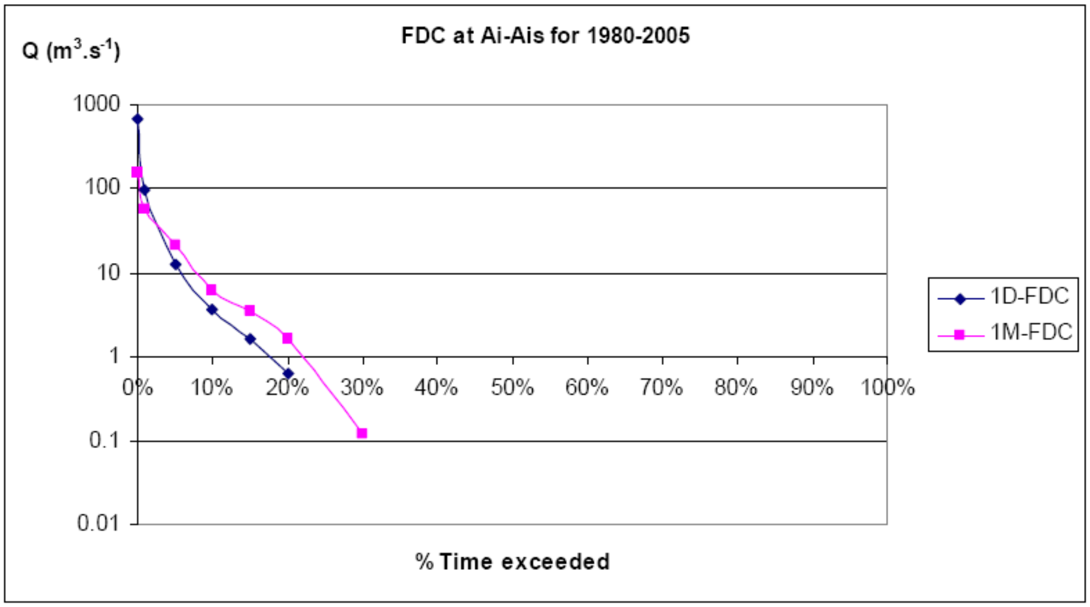


Figure 10: Daily and monthly FDC at Ai-Ais for 1980-2005

Ai-Ais	1980-2005	
	1D-FDC ($m^3.s^{-1}$)	1M-FDC ($m^3.s^{-1}$)
0.10%	669	153
1%	95.5	57.1
5%	12.5	21.7
10%	3.63	6.08
15%	1.60	3.44
20%	0.620	1.59
30%	0	0.120
40%	0	0
50%	0	0
60%	0	0
70%	0	0
80%	0	0
85%	0	0
90%	0	0
95%	0	0
99%	0	0
99.90%	0	0

Table 4: Daily and monthly FDC at Ais-Ais for 1980-2005

The contribution of the Fish River to the Lower Orange system is very small in average: the maximum mean monthly flow is 23.4 $m^3.s^{-1}$ at Ai-Ais while it reaches 451 $m^3.s^{-1}$ for the Orange River at Vioolsdrift. Nevertheless, the contribution of the

Fish River occurs on very small number of days; thus it can contribute periodically to relatively important daily peak flows downstream of the Fish/Orange confluence.

2.4. Description of the Orange River estuary and the Orange River mouth wetlands

2.4.1. The estuary

An estuary can be defined as “a partially closed coastal body of water, which is either permanently or temporarily open to the sea and within which there is a measurable variation of salinity due to the mixture sea water with fresh water derived from land drainage” (Day, 1981).

The Orange River estuary is identified as the stretch of the river located between the mouth and the Ernest Oppenheimer bridge, constructed in 1951 (ORMTFCA, 2000) and located around 9.5 km upstream (**Figure 11 and 12**). The estuary covers a surface of around 30 km^2 (Bornman et al., 2005). It comprises the river channel between sand banks, a tidal basin, the river mouth confined by a sandbar and a saltmarsh towards the south bank (**Figure 13**).

Seaman and Van As (1998) classified the Orange River estuary as a blend between a “normal partially mixed estuary” and a “closed or blind estuary”, according to the classification of Day (1981). Partially mixed estuaries present a vertical salinity gradient with various degrees of mixing between outward-flowing surface layer of fresh water and the inward-flowing layer of saline water. “Closed or blind” estuaries are temporally closed by a sandbar across the sea mouth. Nevertheless the Orange River estuary tends to close less and less: the low flows are now higher due to releases of the Van der Kloof dam in winter to produce hydroelectricity, which limits mouth closures. The last documented closure events occurred in spring 1993, December 1994 and December 1995 (LORMS, 2005a). Very few data are available on these events.

At the ORM, mean tidal range is 0.62 m during neap tides and reaches 2.24 m during spring tides (Bornman et al., 2005). The tidal influence decreases upstream and is very limited at the bridge (0.02 m).

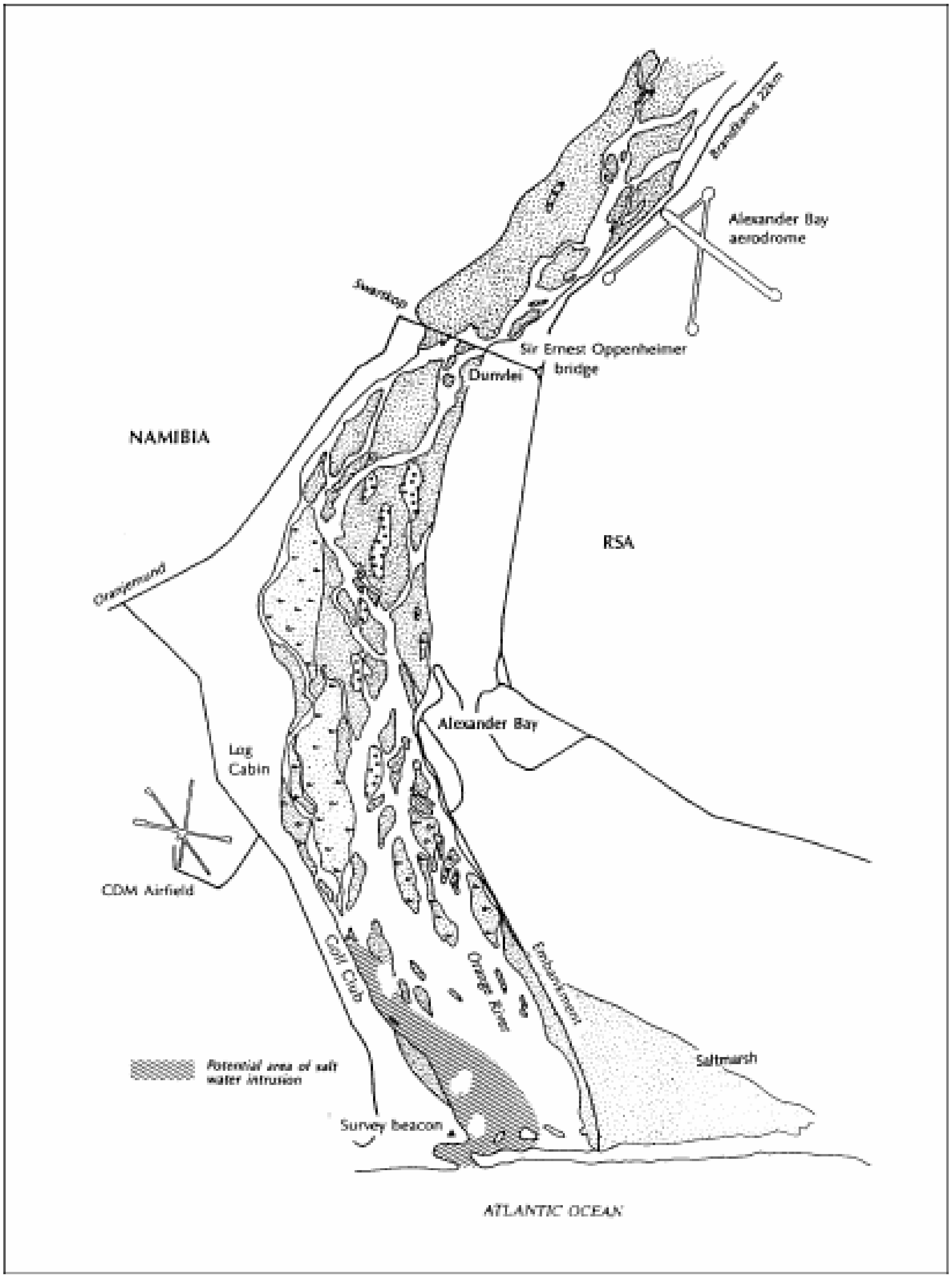


Figure 11: Map of the Orange River estuary
(Source: LORMS, 2005a)

Figure 12: Aerial view of the Orange River estuary, 2 June 2006
(Photo: Billy Troy)

Figure 13: Aerial view of the saltmarsh, south bank of the ORM, 2 June 2006
(Photo: Tom Bornman)

The estuary is located on hard rock formations, comprising greywacke, quartzite and lava. The corresponding geology is a complex of unconsolidated superficial deposits, conglomerate, limestone, sandstone, marl and high level gravel. Moreover phyllite, lava, quartzite, schist, tillite and hornfels occur in many places (ORMTFCA, 2000).

Detailed historical elements of the human occupation and activities in the estuary, from pre-history until nowadays, are provided in ORMTFCA (2000). In this study we will focus on the human activities that impacted the environmental state of the ORMW (cf. 2.4.2. below).

2.4.2. The Orange River Mouth wetlands: recent evolution and present state

A wetland can be characterised as an area where there is a surplus of water at or close to the surface of the earth, with a periodic saturation of soils by water (Ellery et al., 2005).

In this study, we will consider the ORMW classified as Ramsar sites, i.e. as wetlands of international importance. Indeed the South African and Namibian parts of the ORMW were classified as Ramsar sites in 1991 and 1995 respectively, with respect to the achievements of criteria 1, 2, 3 and 6 of the Ramsar classification (Le Maître et al., 2001). In particular, prior to 1990, the ORMW were supporting more than 1% of the world populations of several seabird species endemic to south-western Africa (which corresponds to criterion 6): the Cape Cormorant, the Hartlaub’s Gull and the Damara Tern (Le Maître et al., 2001). At times the bird population was higher than 20 000 individuals. It can be noted that the Ramsar classification does not imply any particular status of protected area, and presently the ORMW have no such kind of status. A project of classification of the Orange River estuary as a Provincial Natural Reserve by the Northern Cape Province of South Africa is currently under process.

The ORMW Ramsar site extends from the Oppenheimer bridge to the ORM, covering a surface of 2 298 ha (Bornman et al., 2005). The wetlands habitats are located on the river channel system, the river mouth, the tidal basin and the saltmarsh located on the south bank of the mouth. According to the classification of the wetlands in Southern Africa provided by Ellery et al. (2005), the saltmarsh can be considered as a floodplain wetland, mainly driven by Orange River floods, while the areas bordering the tidal basin are fringe wetlands, where the influence of tides is dominant (**Figure 14 and 15**). Flooding of the wetlands can occur during the floods of the river but also when mouth closures produce back flooding, during specific low flow periods. During such events, water cannot flow to the sea and the water level increases in the closed estuary, thus flooding the wetlands.

Analyses of aerial pictures from 1938 allow a description of a relatively pristine state of the saltmarsh (**Figure 16**). The state of the ORMW in 1938 will then be taken as a reference ecological state for the purpose of this study. The saltmarsh as a whole was flooded along several natural channels oriented from the river to southwestern part of the saltmarsh and almost parallel one to another. It can be noted that the vegetation cover on the northern part of the saltmarsh was more extended than at present, the southern part being already bare soils.

Figure 14: The saltmarsh during high flows, 28 February 2006
(Photo: Billy Troy)

Figure 15: Fringe wetlands bordering the ORM, August 2005
(Photo: Tom Bornman)

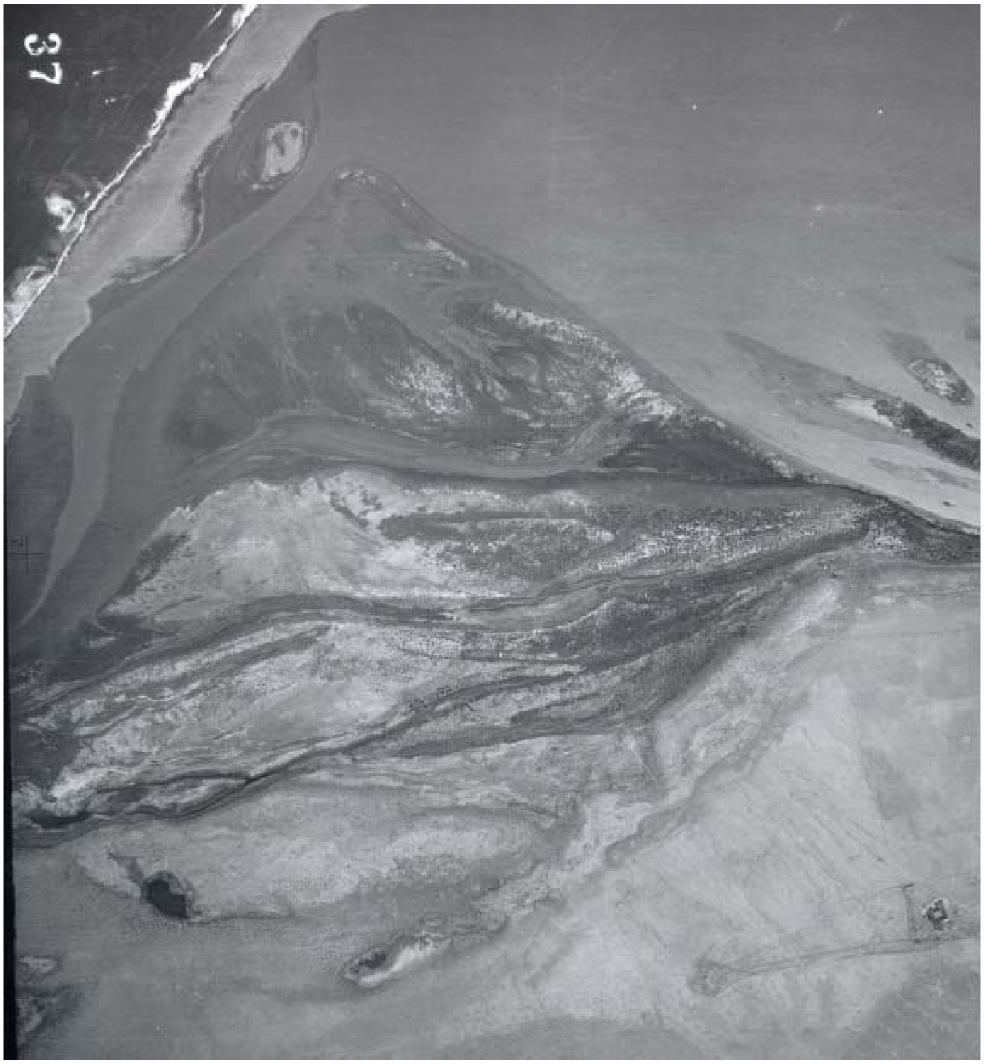


Figure 16: Aerial picture of the saltmarsh in 1938
(Source: Borman et al., 2005)

Then the ORWM was highly impacted by both upstream basin developments and by the local diamond mining, especially in Alexander Bay for the saltmarsh. Bornman et al. (2005) described a possible sequence of events that led to the degradation of the saltmarsh (**Figure 17**).

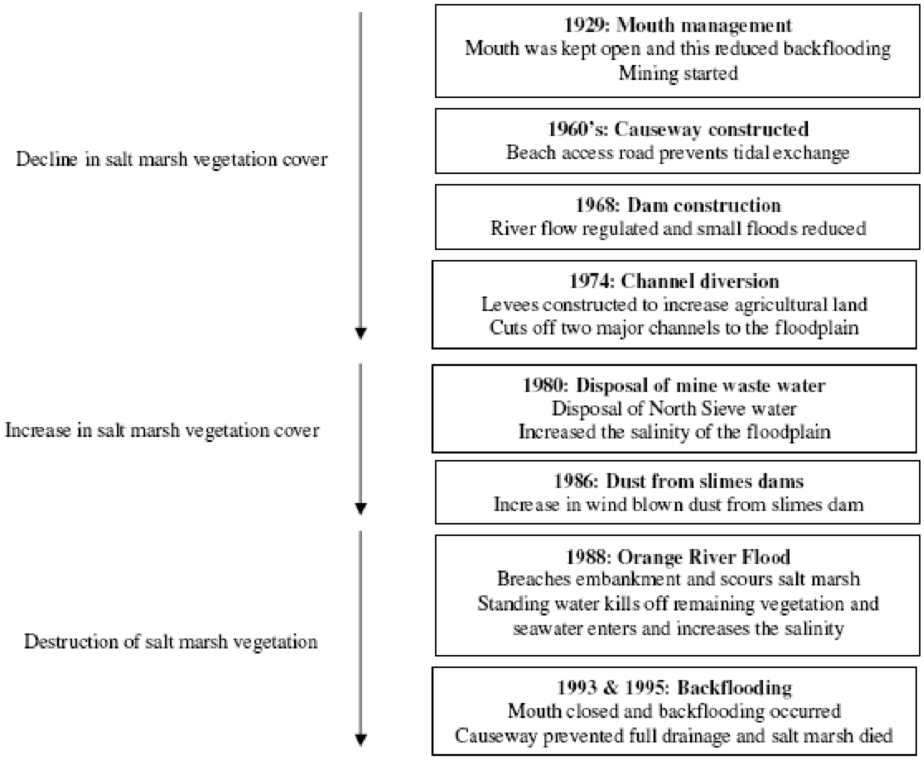


Figure 17: Possible sequence of events contributing to the loss of saltmarsh vegetation at the ORM
(Source: Bornman et al., 2005)

It appears that the main disturbing events for the ORMW have been:

- The change in the flow regime of the Orange River system as a consequence of the damming: mean flows reaching Vioolsdrift have been halved and the magnitude of extreme events, both floods and low flows, has been reduced. This provoked a decrease in the magnitude and frequency of flooding and back flooding events, which are crucial for the functioning of the wetlands,
- At the level of the estuary itself, the dyke constructed in the 1970's along the river channel, to allow agricultural production, as well as the causeway going through the saltmarsh towards the beach, were major obstacles to the periodical flooding of the wetlands (**Figure 18**). These constructions cut off the circulation of water along its natural channels during floods. Moreover, whenever the area got nevertheless flooded, for instance by local runoff, the causeway prevented water to get out the saltmarsh, thus preventing the dissolving and the flushing of salt. After evaporation, the salt eventually remains within the soils and prevent vegetation to develop. This phenomenon is strongly suspected to have led to the degradation of the saltmarsh after the 1988 floods.

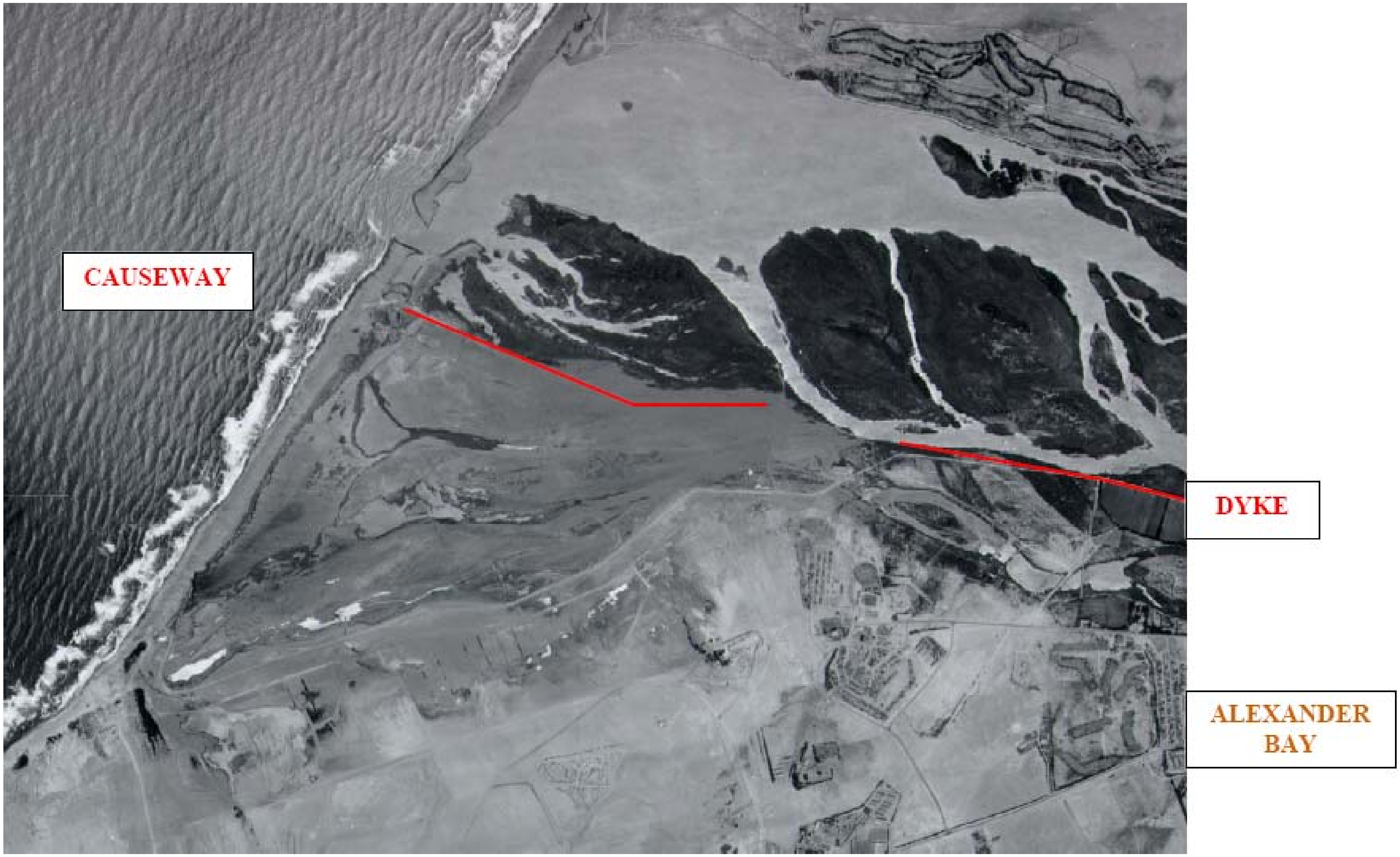


Figure 18: Aerial view of the saltmarsh in 1998, with location of the causeway and the dyke

During the 1990's, the ecological state of the saltmarsh collapsed, implying a decrease in the biodiversity of the wetlands. As far as birds are concerned, it is estimated that the bird population was around 9 000 in 2005, against more than 20 000 prior to 1990 (ORMIMC, 2006).

It resulted in the South African part of the ORMW being placed on the Montreux Record in September 1995. Then several initiatives have been launched to rehabilitate the saltmarsh:

- CSIR and Alexkor: in 1995 the causeway was breached on its most western part, very close to the tidal basin. This allowed water circulation in the lower reaches of the saltmarsh, triggering the development of a freshwater wetland. Part of the eastern part of the causeway was also removed.
- Working for wetlands: under this programme additional breaching of the causeway are currently carried out. In August 2006, there were three additional breaching on the western side of the causeway.

Despite the local beneficial impacts of these works, Bornman et al. (2005) identified that **the excessive salinity of groundwater is at present the limiting factor for development of biodiversity in the saltmarsh.** Indeed the dominant saltmarsh plant, S. Pillansii, is prevented from development due to electro-conductivity levels higher than 80 $mS.cm^{-1}$ in the saltmarsh groundwater (**Figure 19**).

Figure 19: The desertified saltmarsh, south of the causeway, 2 June 2006 (Photo: Jean Marie Fritsch)

2.5. Position of the study with respect to the stakes of the management of the ORM

From the elements described above, it can be concluded that:

- The ORMW are of international ecological importance. The main driver of their ecological state is the floods from the Orange River,
- The ORMW are now threatened due to changes in the hydrological regime of the Orange River, which is reinforced by the existence of inappropriate (environmentally speaking) road works within the wetland. At present the salinity of the soils and of the groundwater are too high ; more intense and more frequent flooding are required to allow the rehabilitation of this Ramsar site,
- Despite the importance of hydrological processes in the issues described above, the daily flow regime, crucial for flood assessment, is unknown. Indeed, as there is no flow gauging station at the inlet of the estuary, flows and water levels are respectively unknown and poorly known.

Within that context, the present study aims to achieve the following:

- Simulation of **daily** flows and water levels entering the estuary,
- Assessment of the regime of the potential flooding of the saltmarsh, using water levels immediately upstream of the estuary,
- Definition of a flow pattern likely to allow the rehabilitation of the saltmarsh and the ORMW.

These steps are presented in the following parts of this report. Because of the absence of adequate information and data, the influence of back flooding could not be addressed in the present study.

3. Characterization of the hydrological regime at the estuary at a daily time step

Note: the implementation of the Spatial Interpolation Approach and the calculation of FDC were performed with the SPATSIM software from IWR.

3.1. Presentation of the Spatial Interpolation Approach (SIA)

The SIA of observed flow records has been first developed by Hughes and Smakhtin (1996). It has been applied successfully in various contexts in South Africa, Sri-Lanka and Nepal, in particular to assess environmental flows at ungauged sites (Smakhtin, 2004, Smakhtin et al., 2004 and Smakhtin and Weragala, 2005).

An overview of the methodology applied in this study is given in Smakhtin (2004). This method transfers hydrological time series (for example times series of daily flows) from a gauged site or a group of gauged sites (called “source sites”) to an ungauged site (called “destination site”) where hydrological time series are needed. The key tool in this method is FDC, which links a value of flow to the frequency of occurrence of this flow. The main assumption in the SIA is that flows occurring simultaneously at two sites reasonably close one to another have the same frequencies of occurrence in their respective FDC. The SIA algorithm is described in **Figure 20**.

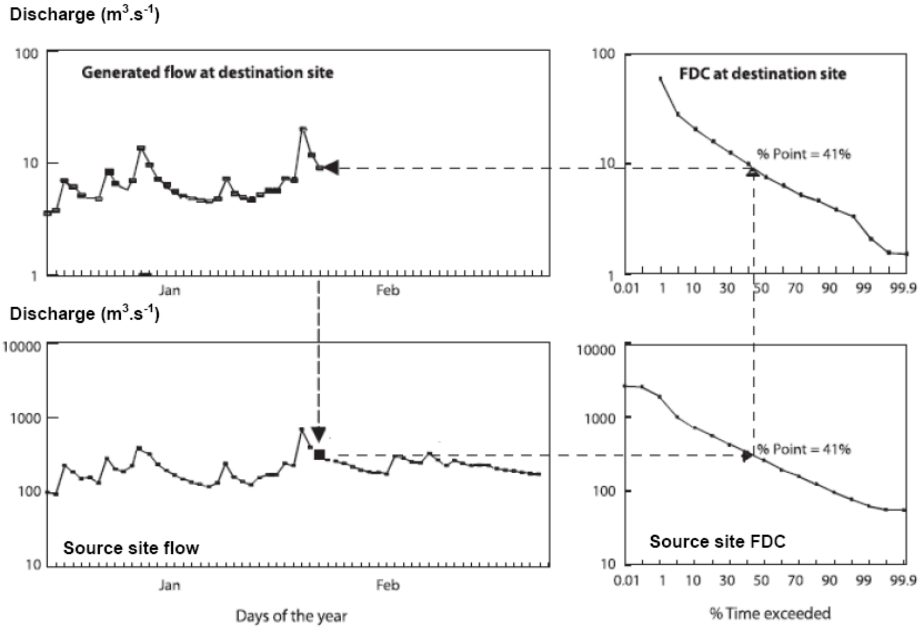


Figure 20: Illustration of the Spatial Interpolation Approach
(Source: modified from Smakhtin and Weragala, 2005)

Knowing the observed value of flow at a particular source site on day N, it is possible to get its frequency of occurrence via the FDC at this source site. This value of frequency is reported on the FDC at the destination site, and then the corresponding value of flow is taken as the flow at day N at destination site. The implementation of this method thus requires:

- Time series of daily flows at source site(s),
- Daily FDC at source(s) and destination site.

3.2. Simulation of time series of daily flows at the inlet of the estuary

In that study the destination site is Orange River at the Ernest Oppenheimer bridge. The source sites have to be chosen in the vicinity of the destination site, on the same catchment preferably, or in adjacent catchments. The assumption of the method is that source and destination sites will then have similar hydrological responses. Hereafter, Vioolsdrift (Orange river) and Ai-Ais (Fish river) have been selected as source sites.

This study focuses on two periods: 1935 to 1960, corresponding to a more natural state of the basin, and 1980-2005, corresponding to the present state. For 1935-1960, data are only available at Vioolsdrift, which will be the sole source site for this period. For 1980-2005, data are available at Vioolsdrift and Ai-Ais. When several source sites exist, the method recommends calculating the flows at destination site with each source site separately, and then calculating a weighted average. However, as the flows coming from Vioolsdrift and Ai-Ais add together in the stretch of the river downstream of the confluence, it has been preferred to create a synthetic source site (called “sum”), whose flows at day N are the sum of the flows at Vioolsdrift and Ai-Ais at day N. This method eventually gave significantly better results than the original one. Time series of daily flows and daily FDC were thus calculated at each of the source sites identified for the two considered periods.

On the other hand, daily FDC are needed at the estuary. As previously mentioned, no observed flow data are available there. However, simulated monthly flows at the estuary are available for natural and present state of the basin (LORMS, 2005a). The natural runoff of each sub-catchment of the Orange River basin was simulated and then computed to produce naturalised monthly flows at the estuary for the period 1920-1987 (called “natural state”). Then the present state was worked out by adding to the naturalised flows the effects of the development of the basin in 2003 (Manie Mare, WRP, personal communication, 2006). Thus time series of simulated monthly flows were produced for the period 1920-1987, as if the development level for all this period would have been the same as in 2003. These two time series, natural and present state, are used to compute monthly FDC at the estuary for natural and present state (**Figure 21**). The natural state FDC will be used for the 1935-1960 period and the present state one for the 1980-2005 period.

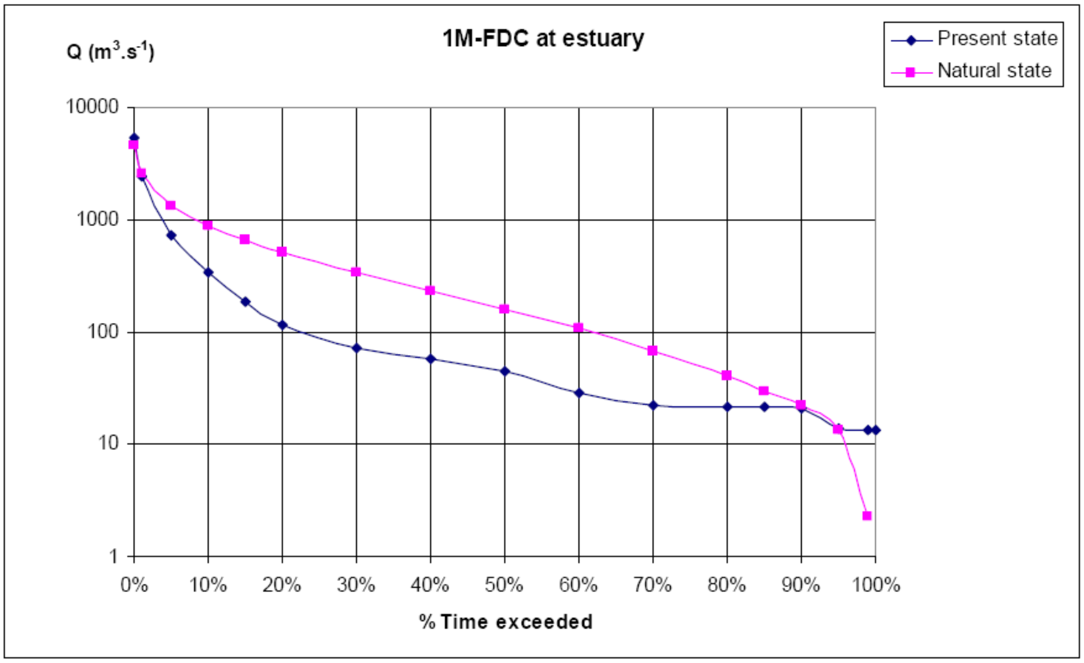


Figure 21: Monthly FDC at the estuary
(computed from LORMS, 2005a)

Then daily FDC have been calculated from monthly FDC using a method of explicit ratio curve (Smakhtin, 2000). At the source site, daily FDC and monthly FDC have been computed to work out a “ratio curve”: for each given frequency of occurrence, the ratio between the corresponding daily and monthly flows has been calculated. For the period 1935-1960, the source site was Vioolsdrift while for 1980-2005 the synthetic source site “sum” has been used. Then, the ratio curve at the source site is multiplied by the monthly FDC at the estuary to obtain the daily FDC at the estuary, for each of the two periods (**Table 5** and **Figure 22**).

% time exceeded	0.10%	1%	5%	10%	15%	20%	30%	40%	50%	60%	70%	80%	85%	90%	95%	99%	99.90%
Q (m^3.s^{-1}) 1935-1960	6790	3450	1500	824	637	501	285	184	110	68.3	32.3	11.7	8.1	2.57	0.00	0.00	0.00
Q (m^3.s^{-1}) 1980-2005	6470	2910	710	329	187	121	66.4	48.2	39.5	23.6	18.6	17.6	15.4	14.4	9.95	6.11	0.00

Table 5: Daily FDC at the estuary

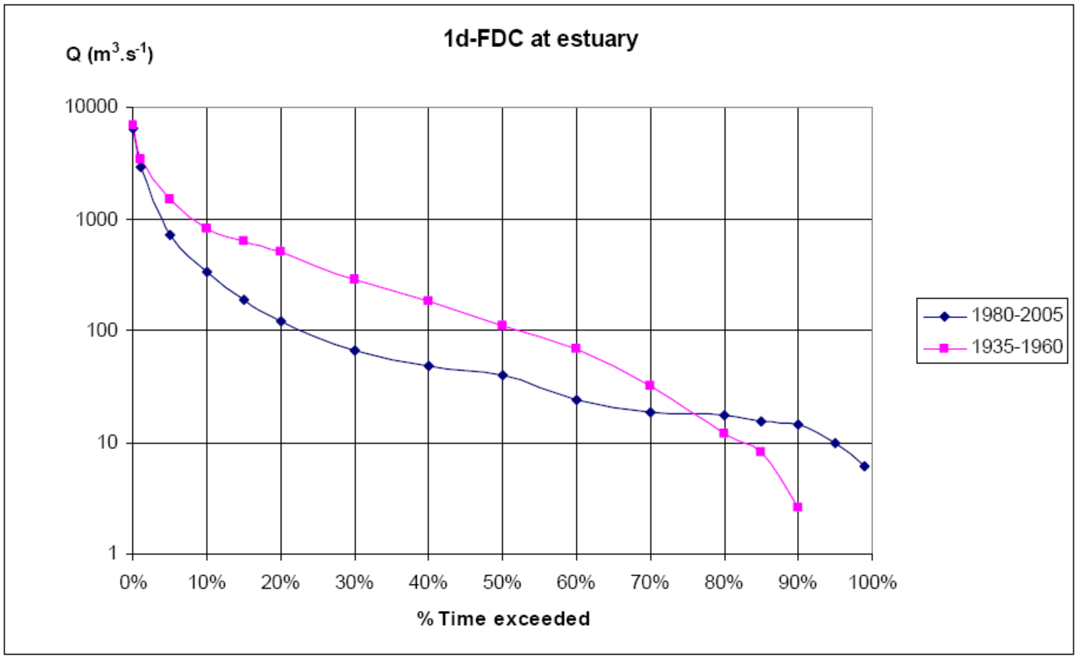


Figure 22: Daily FDC at the estuary

Then the SIA can be implemented to simulate daily flows at the estuary for 1935-1960 and 1980-2005 (**Figure 23**). The proposed SIA method does not consider any delay corresponding to the transfer of water from source to destination sites. In this study, a time lag of one day was included in the time series obtained at the estuary to take into account the time of transfer from Vioolsdrift and Ai-Ais. This resulted in an improved correlation with observed water levels at the bridge.

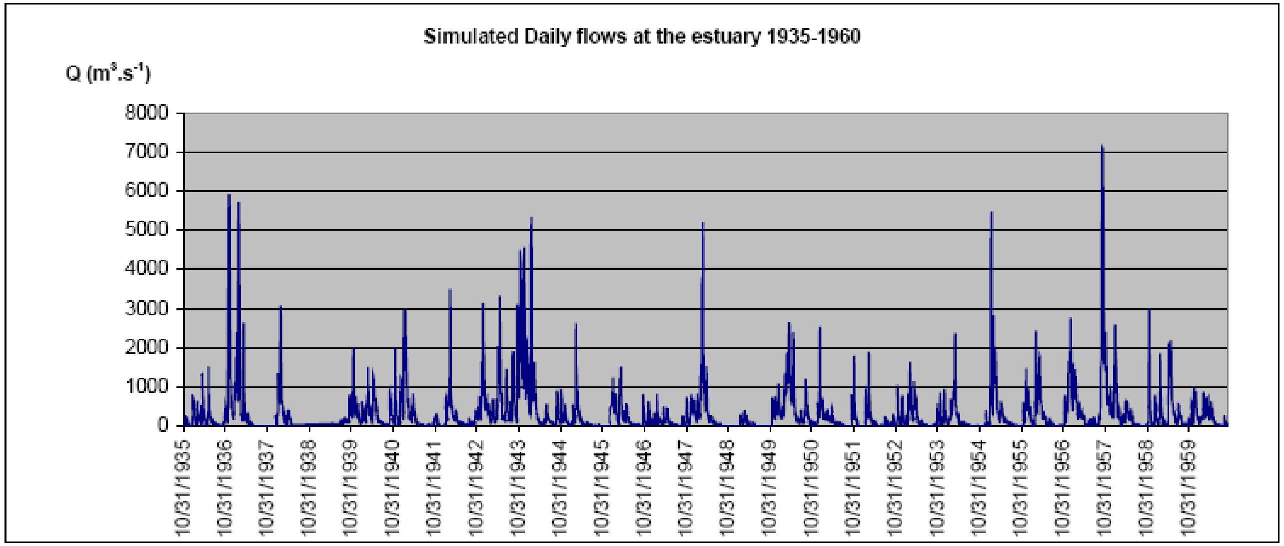
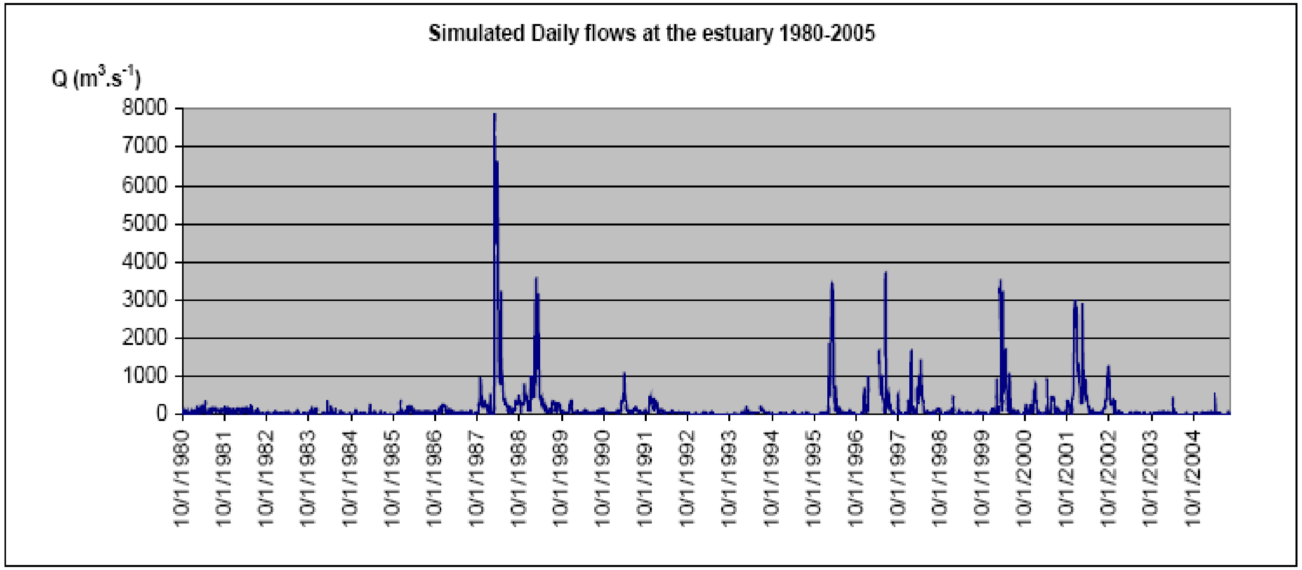


Figure 23: Simulated daily flows at the estuary for 1935-1960 (top) and 1980-2005 (bottom)



No daily flow could be simulated when either Vioolsdrift or Ai-Ais data was missing. **Table 6** details the missing periods in the time series of simulated daily flows.

Hydrological year	Missing data in simulation of daily flows	Hydrological year	Missing data in simulation of daily flows
1936	20-28 November	1986	6-13 October
1938	1 June- 30 September	1987	5-12 July
1939	1 October- 14 May	1989	30 July - 6 August
	1 June- 31 July	1990	22 February- 13 March
1941	1 June - 14 July		27 May - 3 June
1981	26 April- 5 May	1991	23-24 April
	23-30 August	1994	5-19 June
1982	10-17 January	1995	30 May- 4 June
	22-29 August	1996	2-19 October
1983	17-24 July	1997	16 January - 10 April
1984	13-20 November	1999	31 January - 7 February
	11 December- 2 February	2000	21-23 February
	27 May - 3 June		3-4 March
	22-29 July	2001	19-24 April
1985	23 June	2004	24-25 February
	11-18 August	2005	22 April

Table 6: Missing data in time series of simulated daily flows at the estuary

Almost all the hydrological years are correctly represented in the simulation. Major gaps are nevertheless noticed in 1939, 1984 and 1997.

3.3. Validation of the simulation with observed water levels

Time series of observed daily water levels at Oppenheimer bridge were used to assess the accuracy of the simulated daily flows entering the estuary. Water levels were observed from 26 October 1993 to 20 July 2005 (cf. **Table 1**). **Figure 24** presents water levels versus simulated daily flows for this period.

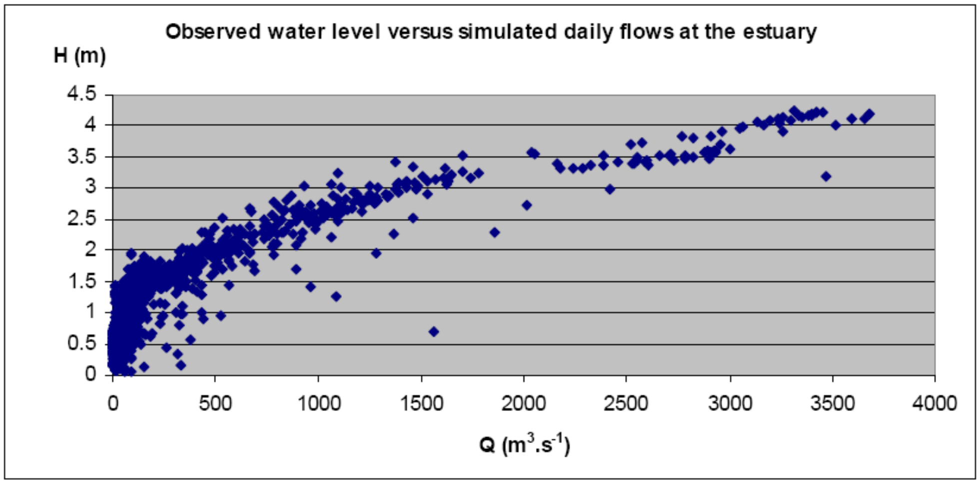


Figure 24: Observed water levels versus simulated daily flows at the estuary

The correlation appears quite satisfactory, except for low values of water levels and flows. This is due to poor accuracy on low flows measurements at Vioolsdrift, and this uncertainty has been transferred to the results of the simulation. Consequently we would not consider flows lower than 200 $m^3.s^{-1}$ and water levels lower than 1.5 m for correlation (**Figure 25**). Under these conditions, it appears that a relationship can be proposed between water levels and flows, with a quite high correlation coefficient of 0.929:

$$H = -2*10^{-7}*Q^2 + 0.0014*Q + 1.3161 \qquad (1)$$

Where H is in meters and Q in $m^3.s^{-1}$, H>1.5 m and Q>200 $m^3.s^{-1}$

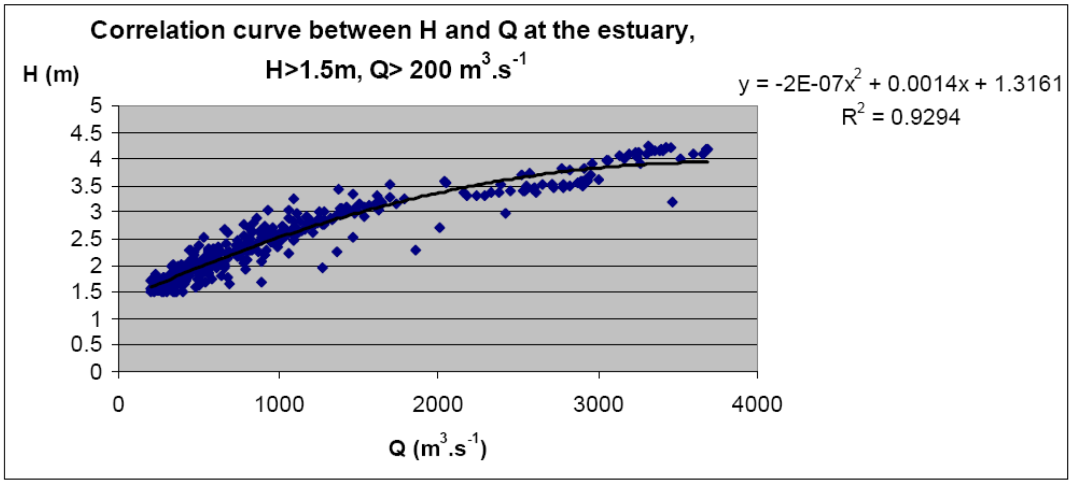


Figure 25: Correlation between observed water levels and simulated daily flows at the estuary, low values excluded

It can thus be asserted that the quality of the simulation of daily flows at the estuary is quite satisfactory for medium and high flows. Low flows are poorly known and will be considered with caution. The time series previously described can thus be used and analyzed quite confidently.

3.4. Analysis of the daily flow regime at the inlet of the estuary

Simulated daily FDC at the estuary (cf. **Figure 22** and **Table 5**) allow a comparison between the two periods 1935-1960 and 1980-2005:

- The frequency of occurrence of the Orange river drying out at the estuary for one day was 5% in the 1935-1960 period and is 0.1% for 1980-2005,
- Medium flows have been substantially reduced: from 32.3 to 18.6 $m^3.s^{-1}$ for flows exceeded 70% of time and from 501 to 121 $m^3.s^{-1}$ for flows exceeded 20% of time,
- High flows exceeded 10 % of the time have been reduced from 824 to 329 $m^3.s^{-1}$, i.e. have been more than halved.

The impacts of this evolution of the hydrological regime on the ORMW will be assessed in the next chapter.

3.5. Simulation of water levels at the Oppenheimer bridge

The relationship calculated between H and Q (equation (1)) allows to extend the time series of water levels at the bridge to periods 1935-1960 and 1980-2005. When water level is missing, and when the simulated daily flow exists and is higher than 200 $m^3.s^{-1}$, water level can be calculated to patch the time series. When simulated daily flow is lower than 200 $m^3.s^{-1}$, water level is assumed to be lower than 1.5m (cf. **Figure 25**). Time series of simulated daily flows and patched daily water levels are presented in **Figure 26**.

Table 7 details the missing periods in the time series of patched water levels.

Hydrological year	Missing data in patched water level
1936	20-28 November
1938	1 June- 30 September
1939	1 October- 14 May 1 June- 31 July
1941	1 June - 14 July
1981	26 April- 5 May 23-30 August
1982	10-17 January 22-29 August
1983	17-24 July
1984	13-20 November 11 December- 2 February 27 May - 3 June 22-29 July
1985	23 June 11-18 August
1986	6-13 October
1987	5-12 July
1989	30 July - 6 August
1990	22 February- 13 March 27 May - 3 June
1991	23-24 April
2000	21-23 February
2001	19-24 April
2005	22 April

Table 7: Missing data in patched water levels at the estuary

The few major gaps in the patched time series are in 1939 and 1984. The other hydrological years are correctly represented in the simulation.

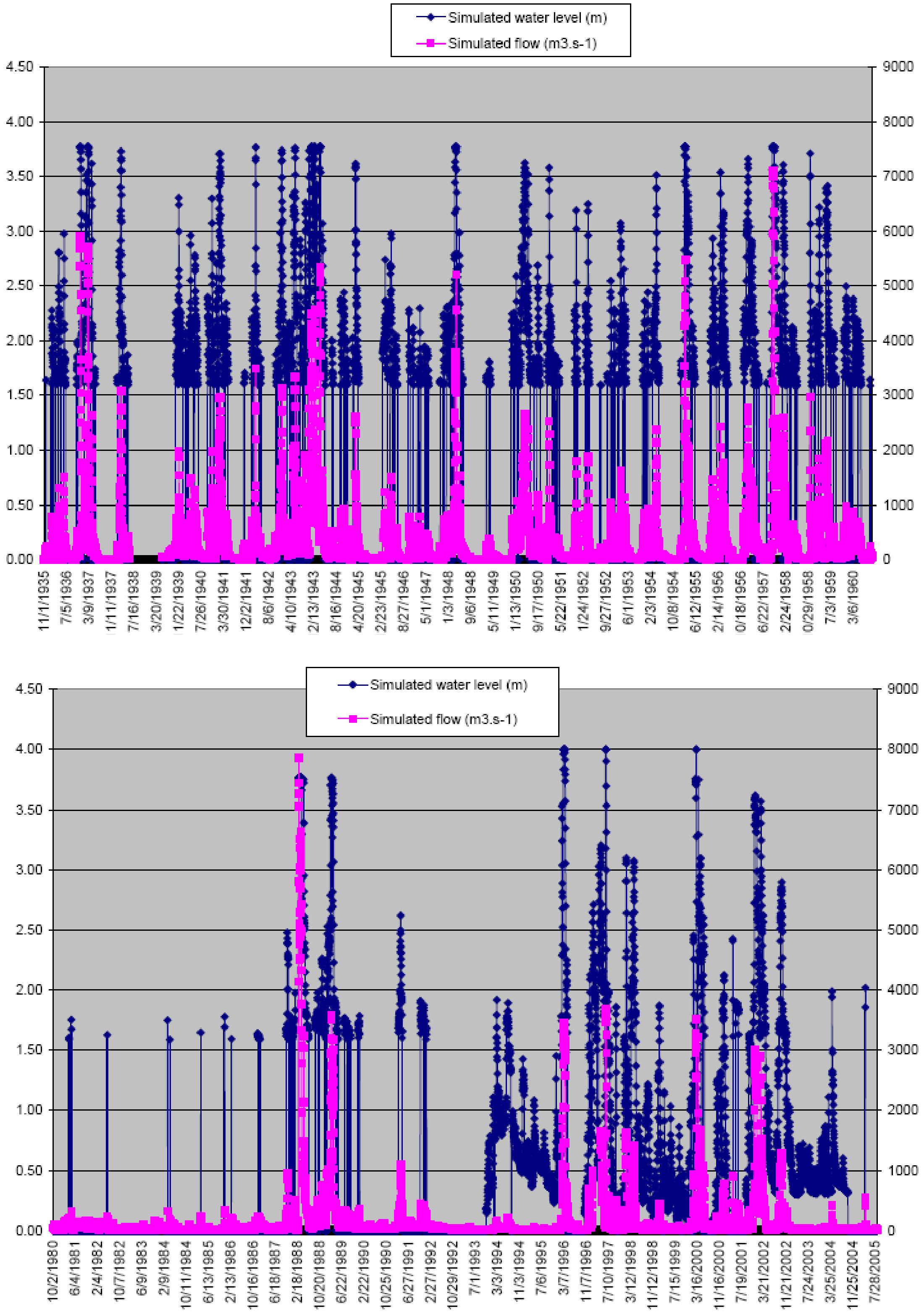


Figure 26: Simulated daily water levels and daily flows at the estuary
Top: Period 1935-1960 - Bottom: Period 1980-2005

4. Assessment of the potential flooding of the Orange River Mouth Wetlands

4.1. Presentation of the hydraulic modelling approach

Note: all distances and altitudes have been measured with differential GPS (Trimble GPS Rover).

Given the poor informative context of the area, it was not possible to carry out a hydraulic modelling of the whole of the estuary. Nevertheless, a simplified approach was developed to assess the potential flooding by gravity of the saltmarsh, which is the most endangered part of the ORMW. The main assumption is that the saltmarsh can be flooded when the water level at the bridge goes over a certain threshold. The flows, routing naturally through channels within the estuary, would then flood the saltmarsh.

This channelling is modelled as a fictitious canal, which would convey water from the bridge to the saltmarsh. Input of water in the canal is provided by the simulated time series of water levels at the bridge. Water will flow in the canal if the water level at the bridge is higher than 2.5 m. As no data is available in terms of water levels in the saltmarsh, this value is an estimation by the authors, according to a preliminary topographical survey of the area done by GPS. The other characteristics of this fictitious canal are:

- A slope calculated with the difference of altitude between the water level at the bridge and at the saltmarsh, divided by the distance between the bridge and the saltmarsh. Altitudes are expressed relatively to the altitude of the bottom of the river at the bridge, which corresponds to the zero of the water level recorder.
- A fixed width of 10 meters, which corresponds to the estimated part of the section of the river at the bridge which contributes to the flooding of the saltmarsh,
- A roughness coefficient, corresponding to the roughness of the channels conveying the water to the saltmarsh. It has been observed that these channels are very rough, the banks and the main channel of the river being covered by vegetation like grass, macrophytes or

shrubs. Consequently this coefficient was estimated at 20 $m^{1/3}.s^{-1}$ for the canal (corresponding to the Manning- Strickler formula).

The calculation has been done on a daily time step. The water level in the canal is calculated each day (determined by the water level at the bridge) and is assumed to be uniform along the canal. If the water level at the bridge is lower than 2.5 m, there is no flow in the canal and no water will reach the saltmarsh. If it is higher than 2.5 m, a flow enters the canal and its discharge is calculated with the Manning-Strickler formula, corresponding to the assumption of a uniform and permanent flow in the canal:

$$Q = K*S*R^{2/3} * i^{1/2} \tag{2}$$

Where:

- K: roughness coefficient
- S: flow cross-section
- R: hydraulic mean depth
- i: slope of the canal

The height of the water in the canal is taken equal to the difference between the water level at the bridge and the threshold value of 2.5 m.

The saltmarsh is modeled as a reservoir, whose surface is 273,96 ha (calculated with differential GPS). When water flows into the canal, the discharge calculated as above allows to calculate the volume of water reaching the saltmarsh at a daily time step. This volume is then spread on the surface of the wetlands and a daily evaporation rate is applied, computed from monthly values taken from Schulze et al. (1997). It can be noted that in reality, and contrary to the assumption of the modeling, the saltmarsh may not be flooded as a whole: different areas could be flooded successively. This modeling approach thus maximizes the effects of evaporation. Then the water level in the saltmarsh is calculated (**Figure 27**). The maximum water level within the saltmarsh has been limited to 20 cm; above this level it is assumed that water spills out towards the estuary and the main course of the Orange River. Moreover, infiltration has been neglected: at the considered time step, infiltration is very reduced, especially during floods where the water table level is quite high.

The algorithm is then applied every day, with each day a new water level at the bridge, a new water level in the canal and a slope taking into account the elevation of water in the saltmarsh.

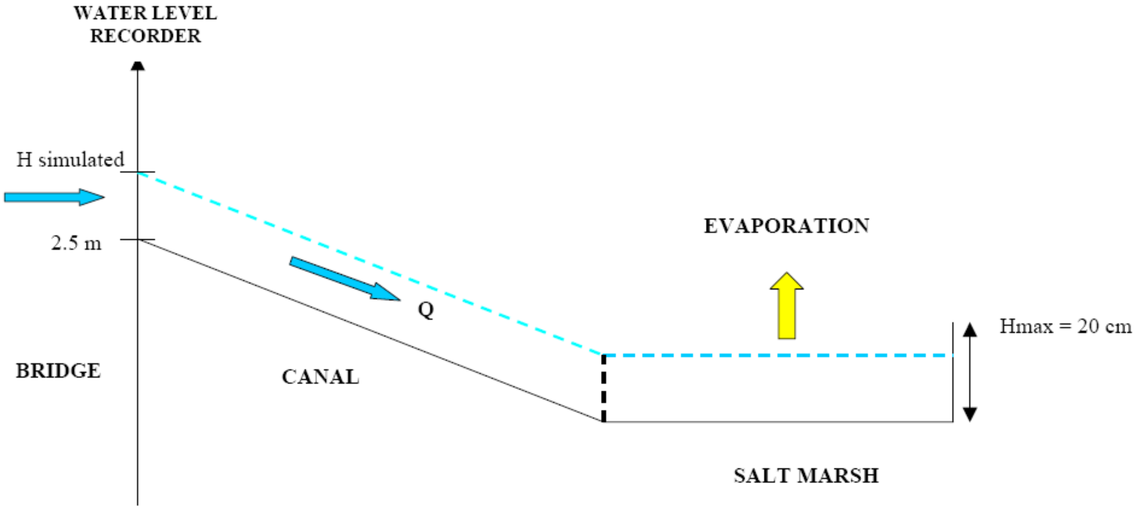


Figure 27: Hydraulic modelling of the water transfer from the bridge to the saltmarsh

This modeling of the saltmarsh flooding is quite rough and is based on values estimated from field observations. **The results have to be considered as orders of magnitude.** This modeling thus allows to assess the flooding of the saltmarsh as if the proposed canal existed and was channeling water from the river to the saltmarsh. This configuration is fictitious but **the results can be considered as a potential for the flooding of the saltmarsh.**

It can be noted that this approach models the saltmarsh without the influence of the causeway, which has completely separated the saltmarsh from the main channels of the river from the 1960's to 1995 (when the first breaches were carried out). It thus allows to isolate the effects of the change in the flow regime of the basin on the flooding of the saltmarsh between 1935-1960 and 1980-2005, independently of the causeway that is a local transformation. The interest is then to assess whether, under the present hydrological regime, the saltmarsh could be flooded at a satisfactory frequency if the causeway was removed.

4.2. Assessment of the potential flooding of the saltmarsh

This modeling allows to calculate a time series of potential water levels in the saltmarsh **(Figure 28).**

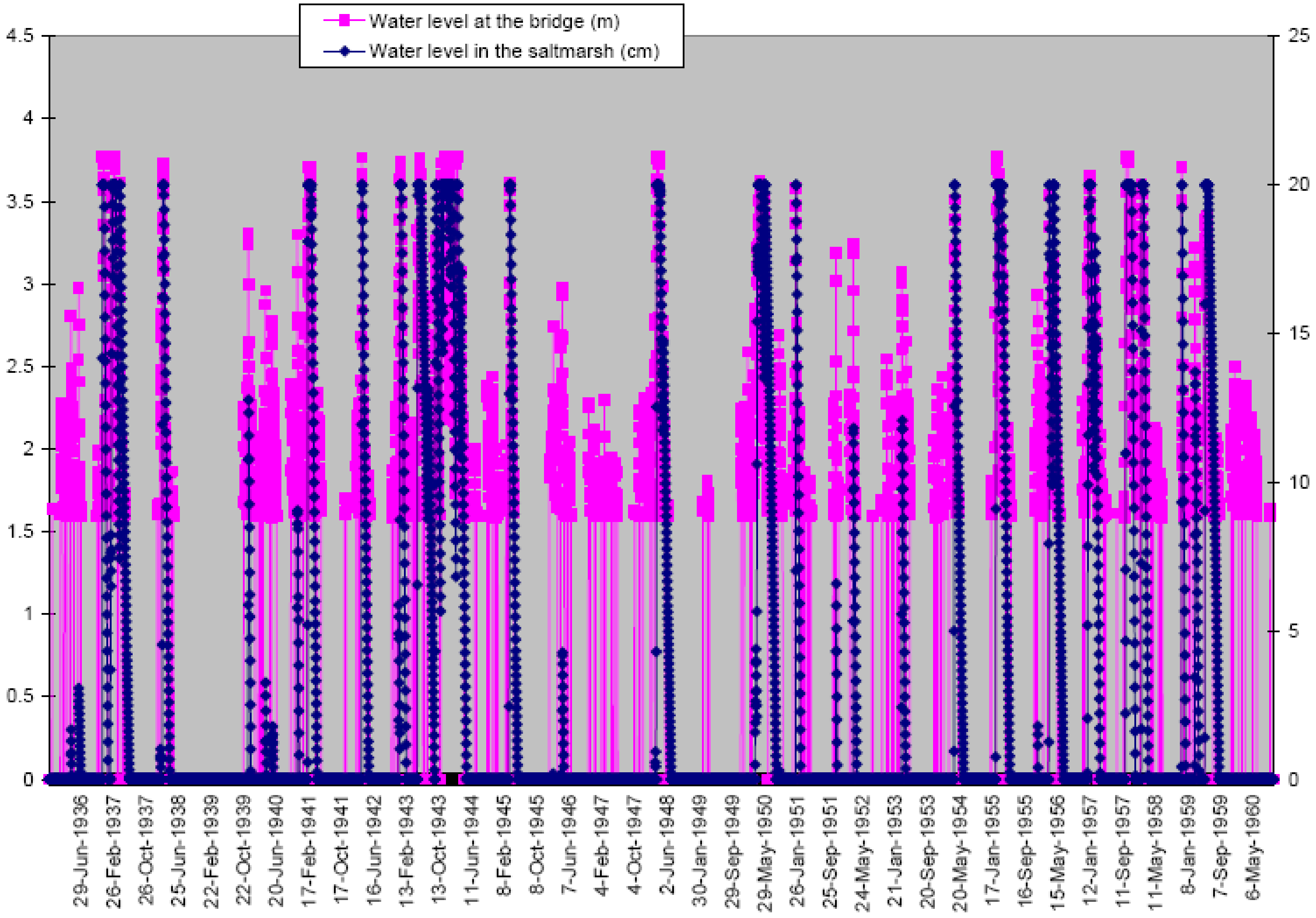
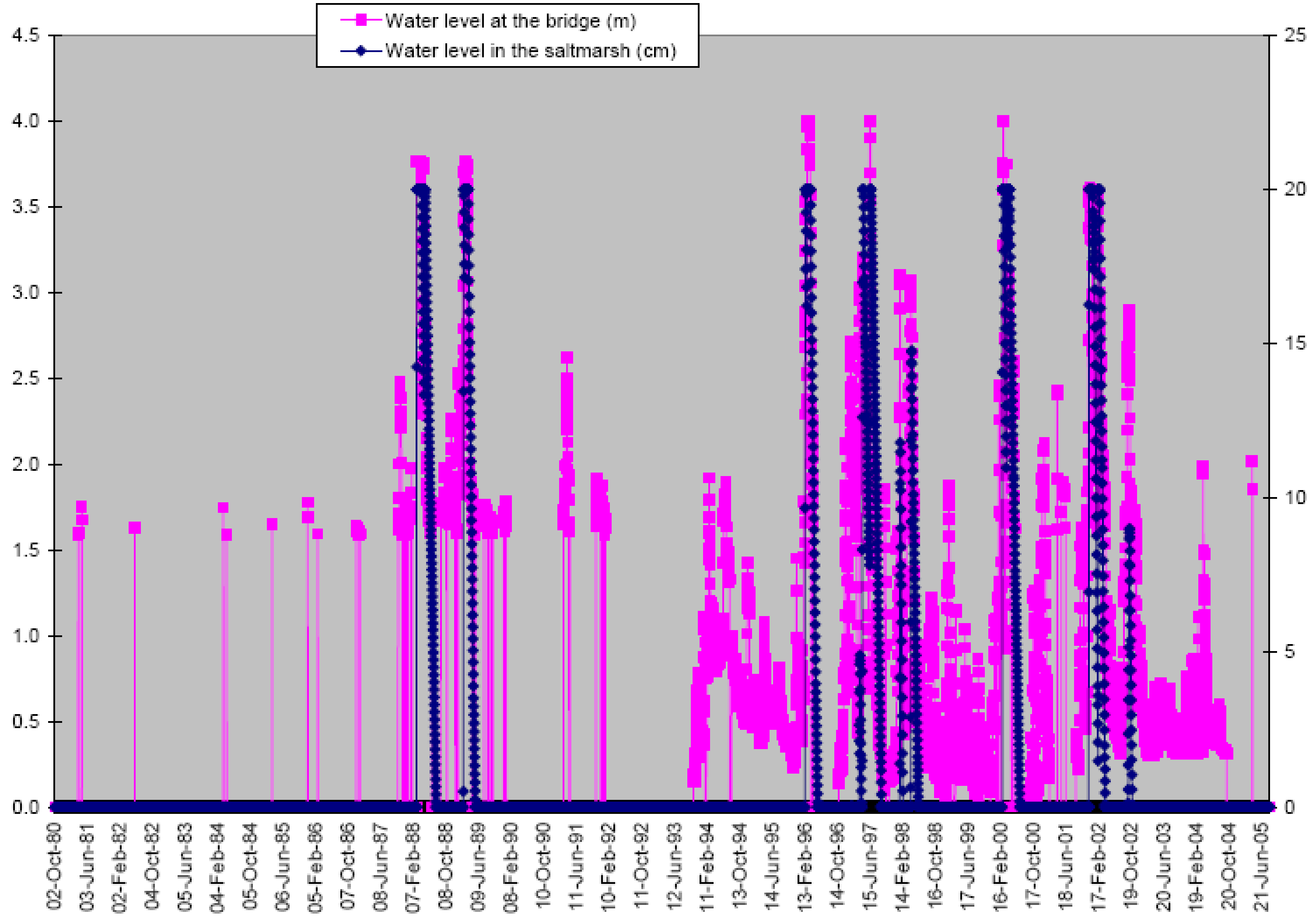


Figure 28: Times series of daily water levels at the bridge and in the saltmarsh
Top: Period 1935-1960 - Bottom: Period 1980-2005



Water level at the bridge (m)
Water level in the saltmarsh (cm)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
25
20
15
10
5
0
02-Oct-80
03-Jun-81
02-Feb-82
04-Oct-82
05-Jun-83
04-Feb-84
05-Oct-84
06-Jun-85
05-Feb-86
07-Oct-86
08-Jun-87
07-Feb-88
08-Oct-88
09-Jun-89
08-Feb-90
10-Oct-90
11-Jun-91
10-Feb-92
11-Oct-92
12-Jun-93
11-Feb-94
13-Oct-94
14-Jun-95
13-Feb-96
14-Oct-96
15-Jun-97
14-Feb-98
16-Oct-98
17-Jun-99
16-Feb-00
17-Oct-00
18-Jun-01
17-Feb-02
19-Oct-02
20-Jun-03
19-Feb-04
20-Oct-04
21-Jun-05

From these time series, only the potential flooding events leading to water levels in the saltmarsh of at least 5 cm were considered, as it is assumed that only such events would trigger a significant flushing of the marsh. **Figure 29** presents the number of such events that would have potentially occurred for each year of the considered time series.

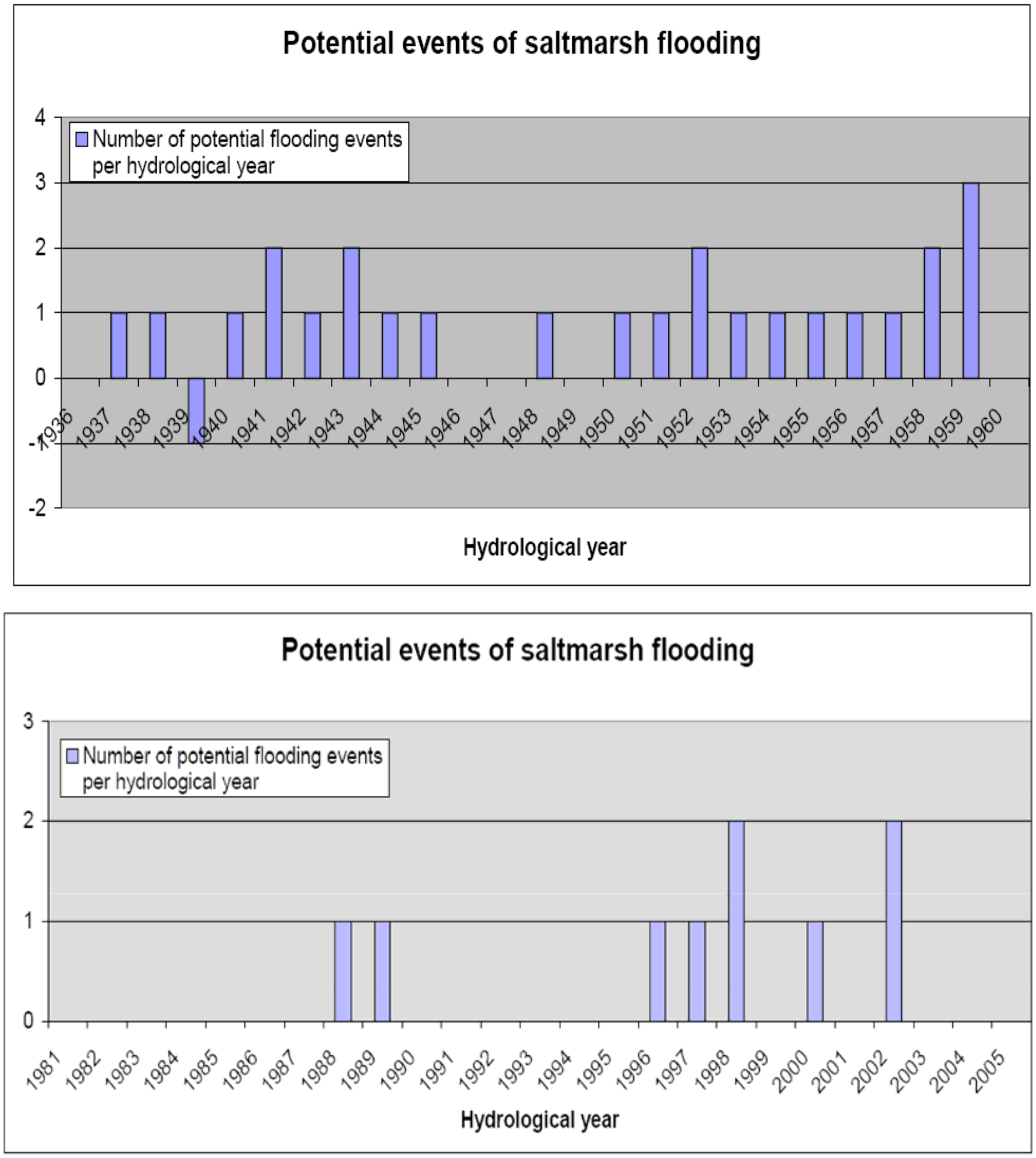


Figure 29: Time series of potential events of significant saltmarsh flooding[2]. Top: Period 1935-1960 - Bottom: Period 1980-2005

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[2] Note: in 1939 there were not enough data (gaps in Vioolsdrift time series of measured flows) to assess the potential flooding. This gap is represented by a value of – 1 on the figure

During the 1935-1960 period, the estuary received flows potentially able to flood the saltmarsh during 19 years out of 24 (one year, 1939, could not be studied because of lack of data). On the contrary, during the 1980-2005 period, flood events could potentially occur only during 7 years out of 25. This represents less than the half of the events under the previous more natural conditions (it can be noted that the decrease would be higher, knowing that the flows from the Fish River could not be integrated in the 1935-1960 period).

4.3. Definition of a flood hydrograph allowing support of the ORMW ecosystem

The different significant potential flooding events have been assessed in terms of water level variations at the bridge. This allowed to define an average typical flood hydrograph at the bridge, under which the saltmarsh would be potentially flooded. This hydrograph has the following pattern:

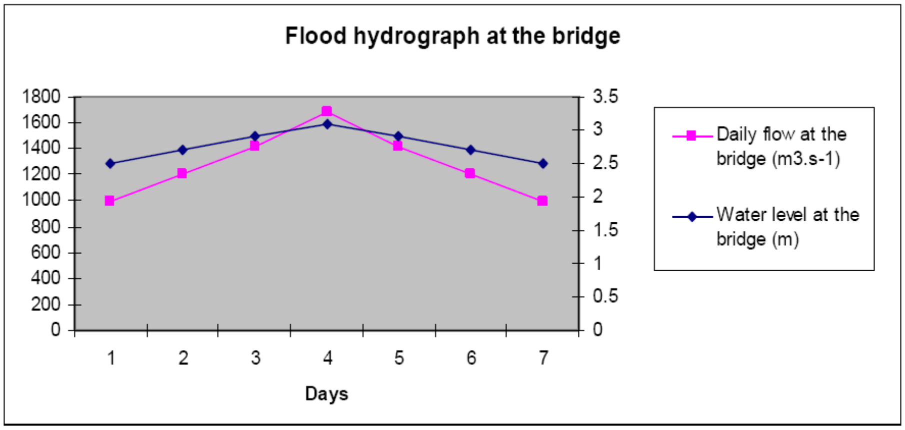

Figure 30: Flood hydrograph at the bridge corresponding to a potential flooding event of the saltmarsh

This hydrograph lasts for 7 days, starts and ends at a flow level of 990 $m^3.s^{-1}$, with a maximum flow of 1 680 $m^3.s^{-1}$**.** This hydrograph corresponds to a **mean daily flow of 1 270 $m^3.s^{-1}$ during 7 days**.

In order to assess what this hydrograph represents relatively to the flow regime at the estuary, a time series of daily flows calculated over a 7-day average was generated. In other words, in this time series, the value of flow at day N is the mean of daily flows over the 7-day period centered on day N. The corresponding flows are named Vd. The objective is then to compare the time series of Vd with the target value of 1 270 $m^3.s^{-1}$.

The annual maximum values of the flows Vd were selected for each year of the time series. The empiric frequency of occurrence and the corresponding return periods of these annual maximum values were calculated using the Gringorten formula (Lang, 2000):

$$\mathrm{Prob}(Q<Q_i) = (i-0.44)/(N+0.12) \qquad (3)$$

Where $Q_1<Q_2<\ldots<Q_N$ are the classified annual maximum flows of a time series of N years.

Table 8 presents the annual maximum values Vd with their respective return period T, for periods 1935-1960 and 1980-2005.

Year	Vd annual max (m3.s-1)	T (years)
1958	7050	43.1
1937	5900	15.5
1944	4960	9.4
1955	4890	6.8
1948	3960	5.3
1943	2710	4.3
1941	2520	3.7
1938	2460	3.2
1950	2440	2.8
1957	2360	2.5
1942	2130	2.3
1945	2070	2.1
1959	1950	1.9
1954	1870	1.8
1956	1700	1.7
1951	1690	1.6
1953	1452	1.5
1940	1350	1.4
1952	1290	1.3
1946	1120	1.2
1936	983	1.2
1960	792	1.1
1947	560	1.1
1949	282	1.0

Year	Vd annual max (m3.s-1)	T (years)
1988	6930	44.9
1997	3470	16.1
1996	3400	9.8
2000	3120	7.1
1989	3100	5.5
2002	2930	4.5
1998	1410	3.8
2003	1190	3.3
1991	919	2.9
2001	724	2.6
1992	372	2.4
1999	356	2.2
1990	278	2.0
1987	230	1.9
1981	193	1.7
2005	176	1.6
1994	176	1.5
1986	173	1.4
1982	160	1.4
1984	149	1.3
2004	148	1.2
1985	88.3	1.2
1983	72.4	1.1
1995	49.6	1.1
1993	41.6	1.0

Table 8: Annual maximum values of averaged flows (7 day period) and empiric return periods.

As previously mentioned, the target flow necessary to potentially flood the saltmarsh is Vd= 1 270 $m^3.s^{-1}$. According to table 8, the maximum Vd exceeds this value between once every 3.3 years and once every 3.8 years with the 1980-2005 flow pattern. It is more frequent than once every 1.3 year for the period 1935-1960.

It can thus be asserted that:

- Under more natural conditions, the saltmarsh might have been flooded, or at least received significant amount of water, almost every year,
- From 1980 to 1988, the saltmarsh did not receive any significant flood. Together with the causeway preventing water to circulate, this led to the degradation of the saltmarsh,
- Nowadays, the frequency of the potential flooding of the saltmarsh is once every 3.3/3.8 years. This dramatic decrease is the basis of the degradation between the present and the former state of the ORMW. Under the present level of development of the basin, the former hydrological conditions are unlikely to prevail again,
- Nevertheless, it is assumed that a frequency of flooding of once every 3 years might support a partial rehabilitation of the saltmarsh, provided that water could circulate freely within the saltmarsh (Bornman, personal communication, 2006). This is slightly higher than the present calculated potential frequency of the flooding and therefore these conditions might be possible to achieve.

These conclusions must be considered within the limits of the hydraulic modeling presented here. In particular, no calibration of the model was possible due to the absence of water level records in the saltmarsh.

It thus seems possible to set up and maintain a flow regime commensurable with a satisfactory ecological equilibrium for ORMW. A discussion of this possibility is provided in the next chapter.

5. Discussion and recommendations on the conditions of the rehabilitation of the Orange River Mouth Wetlands

A hydrological characterization of the flow regime at the estuary has been developed in the previous chapters. The evolution from 1935 to now, under the limits of the modeling, is dramatic. The saltmarsh has been thus significantly impacted, in particular because flooding by the river is a fundamental component of its ecological functioning. The potential flooding has been reduced from almost once every year before 1960 to once every 3.3/3.8 years these last 25 years (under the limits of the modeling). The actual flooding in the recent period has even been more rare due to the causeway and the dykes built within and along the saltmarsh, which have constituted obstacles to the circulation of water along the natural channels.

Consequently, it appears unrealistic to aim at resetting pristine conditions in terms of saltmarsh flooding: indeed the Orange River basin is at present too developed to allow such speculation. However, it can be assumed that a flooding once every 3 years could support a partial rehabilitation of the saltmarsh, provided water can circulate properly within it (Bornman, personal communication, 2006). Even if it has dramatically decreased, the frequency of potential flooding is slightly lower than this recommended frequency. Complementary surveys and actions could certainly allow to ensure the effectiveness of such flooding.

On the other hand, complementary sources of fresh water for the saltmarsh could be considered.

- **Back flooding** certainly used to play a role in watering and flushing the saltmarsh. However, this phenomenon is very poorly known and documented, both in terms of frequency of occurrence and of relative importance for the ecosystem. Artificial temporary closures of the mouth (which would require substantial civil works) might enhance the frequency and the effects of back flooding. Nevertheless, unless proper knowledge is built on that phenomenon, which would imply a specific monitoring program, the positive impacts of a back flooding-oriented management in terms of rehabilitation of the ORMW appear uncertain.
- **Releases of fresh water from Alexkor** can also be considered. At present freshwater is released along the southern boundary of the

saltmarsh, with a flow of approximately 5 l.s^{-1}. This contributed to locally support a small area of wetland (Bornman, 2005). However, even if developed, the impact of such releases would remain very local. Indeed the released volumes would be regular and provided at very low discharges, while the wetland ecosystem is shaped by extreme events. At best, the releases would support reconstitution of small areas of wetland in the saltmarsh. But it is likely that this fragmentation of the wetlands in several little blocks would not efficiently support local vegetal and animal populations, which need larger and continuous habitats to properly develop.

- **Artificial pumping of freshwater from the river to the saltmarsh** could also provide additional inflow to the saltmarsh. The pumping could be done by a windmill to avoid electro- mechanical equipments. The windmill could be located at the upper north east of the saltmarsh, at the connection with the river. It would supply a reservoir from which the water would be brought to the marsh by gravity through a pipe system. However, it is estimated that such a system would provide around 100 m^3 per day, which represents a water height of only 0.04 mm over the whole surface of the salt marsh, which would be easily taken by evaporation. Moreover this system could lead to the fragmentation of the wetland area, which is not advisable. Finally such equipments would repeatedly be damaged by the Orange River floods.

It then appears that the rehabilitation of the ORMW at the scale of the whole ecosystem shall be mainly based on ensuring proper flooding by the Orange River. This could be achieved through the regular provision of appropriate flood patterns at the estuary. Moreover, it has to be ensured that the high flows reaching the estuary would actually and effectively produce the flooding of the saltmarsh. This would imply specific management practices and civil works at the local level of the estuary.

Considering these elements, the following actions are suggested:

1. **Enhancement of the hydrological and environmental information system for the estuary**

   - Setting up of a flow gauging station directly upstream of the estuary. Moreover water level recording at the bridge should be maintained.
   - Definition and implementation of a protocol of direct observations of the state of the estuary, which could include observation of the state of the mouth and of the saltmarsh, description of the shape of the meanders along the estuary and close to the saltmarsh, aerial pictures (taken regularly for example from the planes of the mining companies).

2. **Refinement of the design hydrograph for the flooding of the saltmarsh: hydraulic study of the estuary**

   - Comprehensive assessment of the topography of the estuary, along cross sections perpendicular to the river. Ten sections shall be necessary, with at least 3 in the saltmarsh. Longitudinal profiles between the bridge and the different sections would also be needed. Precision of altitude measurements should be of the magnitude of 10 centimeters or less, as the topography of the main channel is very flat.
   - Setting up of water level recorders in the estuary and the salt marsh. At least three of them are needed. One should be placed at the north east of the saltmarsh, at the inlet of the river. Another one can be placed in the center south of the saltmarsh, where the water is required. Another can be placed in the main channel of the river, between the bridge and the saltmarsh, on the left bank of the river along the dyke.
   - Refinement of the design flood hydrograph

3. Feasibility study on the provision of the design hydrograph at recommended frequency

- The conditions of the provision of the design flood at the recommended frequency should be inquired. This would particularly imply analyses regarding the operation rules of the Gariep and Van der Kloof dams, the projected regulation dam on the lower Orange, as well as evolution of the demands in the basin in the mid and long term. It could be appropriate to connect this study to the projected real-time modeling for the Lower Orange system (based on hydrodynamic modeling).

4. Rehabilitation of the former natural channels in the saltmarsh

- The breaching of the causeway shall be continued, to allow freshwater to reach, flush and drain the saltmarsh. New breaching are currently carried out on the western side of the causeway, but the eastern side has also to be considered as it is the main inlet of flow from the river.
- Local channeling of the water to the salt marsh should be facilitated, particularly in the north east part of the saltmarsh. The very flat topography in this area and the vegetated main channel significantly slow down the circulation of water from the river to the saltmarsh. It is thus suggested that this area could be managed in terms of clearing the artificial obstacles, like parts of the causeway, and delimiting preferred channels of flows corresponding to the former natural channels. This would imply partial removal of the vegetation, excavation and reinforcement of these channels, for example with gabions. This possibility shall be preferred to construction of artificial canals to maintain the wetlands in the most natural state as possible.

  Possible implementation: these actions could be carried out within the framework of the on-going rehabilitation program of Working for wetlands, in collaboration with the Orange River Mouth Interim Management Committee.

Some of the actions proposed here are also parts of the recommendations formulated in the LORMS study on the estuary (LORMS, 2005a). **In particular, the requirements in terms of specific data collection and improvement of the monitoring system appear crucial to support any efficient rehabilitation program.**

It is important to note that these recommended actions concern different levels of management: local (estuary), sub-basin (Lower Orange) and basin management. The definition and the implementation of a comprehensive rehabilitation program would thus rely on coordination of these different scales of action.

6. Conclusion

The ORMW are of international environmental interest. The site is now dramatically endangered due to changes in the flow regime of the river and to local human activities. However initiatives of rehabilitation are limited by insufficient hydrological knowledge on the nearby hydrographical network.

The present study first provided a characterization of the flow regime at the estuary at a daily time step. The SIA method implemented there allowed to simulate time series of daily flows and water levels entering the estuary at the Oppenheimer bridge, with satisfactory correlation with observed values. This method thus constitutes a reliable tool to provide a first set of hydrological information at ungauged sites, without being as time and money consuming as more complex methods. Implementation in other sites of interest in the basin could then be considered.

Next, an assessment of the potential flooding of the saltmarsh was carried out. Due to the poor information environment, the corresponding modeling had to be kept at relatively rough level. Nevertheless orders of magnitude of the frequency of flooding of the saltmarsh could be calculated, as well as a design hydrograph for the flooding of the saltmarsh. It appeared that the return period of this hydrograph has dramatically increased compared to the period prior to the construction of the major impoundments on the Orange River. The perspective of coming back to the former conditions thus seems unrealistic.

However, it seems feasible to allow the flooding of the saltmarsh at a frequency that would support partial rehabilitation, namely once every 3 years. This objective could be achieved provided complementary surveys, data collection, studies and actions are implemented. In particular, a feasibility study for artificial flood enhancement at the basin and lower Orange level should be achieved, while local actions would take place over the estuary area. Among others, the restoration of the natural channels in the saltmarsh appears indispensable.

The implementation of these complementary studies could be integrated within the existing programs currently in place on the basin. As far as ORASECOM is concerned, the results of this study and the proposed developments could interact directly with several actions to be managed by the FGEF PIU, in particular regarding environmental management program and common information systems.

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List of appendices

Note: Due to the large number and size of the appendices, they are presented in a separate numerical format to avoid over sizing of the present report.

Appendix A: Time series and FDC at Vioolsdrift and Ai-Ais

1935-1960:

- Time series of daily flows at the SPATSIM format for Vioolsdrift,
- 1M and 1D-FDC for Vioolsdrift.

1980-2005:

- Time series of daily flows at the SPATSIM format for Vioolsdrift, Ai-Ais and the synthetic station “Sum”,
- 1M and 1D-FDC for “Sum”.

Appendix B: Time series of monthly flows and monthly FDC at the estuary

Simulated monthly flows at the estuary for natural and present state:

- Time series (taken from LORMS, 2005a),
- 1M-FDC.

Appendix C: Simulated time series of daily flows and daily FDC at the estuary

Simulated daily flows at the estuary for 1935- 1960 and 1980- 2005:

- 1D-FDC,
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Appendix D: Time series of patched daily water levels at the estuary

Appendix E: Hydraulic modelling of the flooding of the salt marsh

- Excel spreadsheet with calculation of time series of water levels in the saltmarsh,
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Appendix F: Averaged daily flows at the estuary on a 7 day period

- Time series,
- Annual maximum values and empiric frequencies of occurrence.

Appendix G: Pictures

- Historical aerial pictures,
- Directory of pictures taken on field trips: March, June and August 2006.

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