7 Development of catchment scenarios

7.1 Introduction

An important motivation for development of the hydrological and hydraulic models was to predict the effect of catchment development scenarios (which could affect streamflow) on floodplain inundation. The Olifantspruit Dam, proposed by the Nylstroom Town Council in the late 1980s to supplement the town's water supply (but was never built), is one such potential catchment development, which formed the catalyst for this study and a previous study conducted by the DWAF (Nel *et al*, 1989). Scenarios have been developed before this study with similar intentions; a scenario was developed using the DWAF model with the proposed Olifantspruit Dam on an annual time step. Another study was conducted by Steffen Robertson and Kirsten consulting engineers (1992), which included the Nyl River catchment, and present day and undeveloped catchment scenarios were developed on a monthly time-step. These previous studies (described in detail in Chapter 1) failed to address the catchment development issues due to various reasons including the coarse time resolution. The relevance of scenario studies in the Nyl River catchment is underlined by the potential for further development in afforestation, irrigation, urban expansion and dams (as described in Chapter 1). The development of five catchment scenarios is described in this chapter, using historical rainfall records as inputs, and their application to determine effects on flows and inundated areas is presented and discussed in Chapter 8.

7.2 Virgin catchment scenario

This scenario was created by removing all developments from the Nylsvlei floodplain catchments in the hydrological model, representing these catchments in their natural state before any developments began. The virgin scenario was created by Alan Bailey from Stewart Scott International using DAYFLOW, and was supplied as a daily flow series from 1 October 1973 to 1 May 2001 at the floodplain margin.

7.3 Historical catchment scenario

The historical scenario took into account growth in catchment developments during the period 1973 to 2001 in the hydrological model, such as changes in urban areas, irrigated areas, impoundments, abstractions (such as from the Donkerpoort Dam) and afforested areas. The daily flow data series for the historical scenario was modelled by Alan Bailey from Stewart Scott International using DAYFLOW, at each flow gauge in the Nyl River catchment, and was supplied for the period 1 October 1973 to 1 May 2001. These flow series were routed to the floodplain margin at the N1 using the following equations (Pitman and Bailey, 2003; Bailey, 2003):

$$\text{Nyl River at Middelfontein} = (\text{A6H018} + \text{A6H011} + \text{A6H006}) \times 1.358 + (\text{A6H019} + \text{A6H012}) \times (6.49 + \text{A1} \times 0.012) / 6.49 \qquad (7.1)$$

where:

- A1 = Catchment downstream of Groot/Klein Nyl confluence and gauges A6H019 and A6H012, to Point 1 (N1).
- A1 = 106.3 km^2

The catchment areas were obtained using a planimeter (Bailey, 2003).

7.4 Olifantspruit Dam with constant 30 l/s environmental flow release catchment scenario

This scenario was created using the historical scenario flow series for each gauge and including the Olifantspruit Dam as it was proposed by Theron Prinsloo Grimsehl & Pullen Ing. (1993) (TPGP, 1993). The site of the proposed Olifantspruit Dam was to be at the DWAF gauge A6H012 (Figures 1.3 and 6.2), therefore the modelled daily historical flow series at A6H012 were used as inflows to a spreadsheet mass balance model of the dam with the following characteristics:

- A reservoir capacity (S_{cap}) of 5.2 x $10^6 m^3$ (TPGP, 1993)
- A draft (D) of 2.1 x $10^6 m^3$/annum for the supply of water to Nylstroom (Modimolle) (TPGP, 1993)
- A constant environmental base flow release (B) of 30 l/s (TPGP, 1993)
- A reservoir area-storage relationship (C) of 0.5 km^2 = 1.0 x 10^6 m^3 (C = 0.5 x $10^{-6} km^2/m^3$), derived for the Olifantspruit Dam from data for other dams in the Olifantspruit Dam catchment (Bailey, 2003). This information could not be found in any of the reports for the dam.
- Daily evaporation losses from the reservoir surface (E) using daily Symons pan evaporation data (monthly averages) derived from monthly S pan data for nearby farm dams in the DAYFLOW hydrology model (DAYFLOW *.RES files) and Symons pan factors for lake surfaces given by Midgley *et al* (1994).

The reservoir capacity was approximately 83% of the MAR at A6H012 (6.26 x $10^6 m^3$). The draft was approximately 33.5% of the MAR at A6H012 (6.26 x $10^6 m^3$), 5.6% of the MAR at the downstream boundary of the Nylsvley Reserve (37.5 x $10^6 m^3$) and 4.9% of the MAR at the downstream boundary of the study area (42.9 x $10^6 m^3$). All the quoted MARs were derived using DAYFLOW for 1950 to 2000 (Bailey, 2003).

The reservoir mass balance spreadsheet model of the Olifantspruit Dam was set up and run on a daily time-step from 1 October 1973 to 1 May 2001, based on mass balance equation 7.2:

$$I - O - B - D - E - \Delta S = 0 \tag{7.2}$$

where:

- I is the inflow
- O is the outflow in the form of spill
- B is the environmental base flow release
- D is the draft

- E is the loss to evaporation from the reservoir surface
- ΔS is the change in reservoir storage ($\Delta S = S_t - S_{t-1}$)

Rainfall addition to the reservoir surface was ignored.

Equations 7.3 to 7.8 describe the spreadsheet model in more detail. Reservoir storage for the present day was calculated using equation 7.3, and was defined as full (S_{cap}) on the first day of the model run. E_t^{loss} is evaporation losses expressed as a flow rate. Omitting the outflow term (O), an unknown, from equation 7.3 enabled its calculation using equations 7.6 and 7.7.

$$S_t = S_{t-1} + I_t - E_t^{loss} - D - B_t \tag{7.3}$$

Evaporation losses were determined using equation 7.4. E_t is the daily evaporation depth lost from the reservoir surface and A_t is the reservoir surface area.

$$E_t^{loss} = E_t A_t \tag{7.4}$$

The reservoir surface area was determined using equation 7.5. C is the area/storage relationship of the reservoir. Present day surface area was calculated using the previous day storage to avoid a circular argument, as storage depends on evaporation, but evaporation also depends on storage. This gives an acceptable approximation, as storage (therefore surface area) only changes significantly during periods of high inflow (when evaporation is underestimated) or when the dam is nearly empty (when evaporation is overestimated). These periods do not last for longer than a few days and make up a very small part of total time series. For example, evaporation losses are overestimated by no more than 1% for storages larger than $10^6 m^3$ (less than one fifth of the reservoir capacity) with typical dry season inflows.

$$A_t = CS_{t-1} \quad (7.5)$$

Outflow due to spill was determined using equations 7.6 and 7.7. S_{cap} is the storage capacity of the reservoir.

$$O_t = 0 \qquad S_t \le S_{cap} \quad (7.6)$$

$$O_t = S_t - S_{cap} \qquad S_t > S_{cap} \quad (7.7)$$

As the base flow release was accounted for in equation 7.3, adding it to the outflow due to spill would yield the total outflow from the dam, as in equation 7.8 (E_t^{loss}). The total outflow time series was then defined as flows at the DWAF gauge A6H012, and routed together with historical flows for the other catchments to the floodplain margin using equation 7.1.

$$O_t^{total} = O_t + B_t \quad (7.8)$$

The Olifantspruit Dam ran dry on several occasions during the model period. Reasons for this include a reduction in MAR of the Olifantspruit catchment from 7.2 x $10^6 m^3$ used for design of the dam by Theron Prinsloo Grimsehl & Pullen Ing. (1993), to a modelled 6.26 x $10^6 m^3$ using DAYFLOW (1950-2000) (observed MAR was 6.59 x $10^6 m^3$ for 1966 to 2000) at stream gauge A6H012 (Bailey, 2003), and the constant base flow release of 30 l/s irrespective of inflow. Theron Prinsloo Grimsehl & Pullen Ing. (1993) suggested that the 30 l/s base flow release could be regarded as a maximum release, base flow releases could be set to equal inflows when inflows were less than 30 l/s. They also mentioned that additional capacity would possibly be required for releases, and that this additional capacity would be as a first guess 200 000 m^3.

7.5 Olifantspruit Dam with IFR flow release catchment scenario

7.5.1 Introduction

A Desktop Instream Flow Requirement (IFR) study was conducted by the DWAF in 2003 on the Olifantspruit, for Ecological Management Classes (EMC) C and D (moderate to largely modified) (Havenga, pers. comm.). The Desktop IFR time series consists of varying monthly flow releases for the hydrological years 1920/1921 to 1989/1990. The period 1 October 1973 to 30 September 1990 was modelled as a scenario, as only for this period were both historical scenario data and IFR flow releases available. The Desktop IFR releases were included in the Olifantspruit Dam mass balance model and routed to the floodplain, as described below.

7.5.2 Background

The South African National Water Act legislates that the requirements for basic human needs and the environment (referred to as the ecological reserve) are met before potential users are licensed to abstract water (Hughes and Hannart, 2003). Many rivers cannot be maintained in their pristine state due to water abstractions and modified flow regimes (such as dams) necessary for socio-economic development. The instream flow requirement stems from this reality; thus, a certain flow regime is determined as the minimum for the river to be maintained at a pre-determined ecological state. This pre-determined condition is referred to as the Ecological Management Class (EMC) and is related to the extent to which the required conditions differ from natural or pristine conditions. There are four classes (A to D) where A refers to a condition that is largely natural, while D assumes a largely modified condition with a significant loss of natural habitat, biota and basic ecosystem functioning (Hughes and Münster, 2000). The Act recognises that resource use should be sustainable and therefore all rivers should retain some basic ecological functioning, of at least a D category (Hughes and Hannart, 2003). There are four methods of conducting an IFR assessment, each with its own cost and level of accuracy (therefore level of confidence):

- The most expensive and accurate method (termed the Comprehensive Reserve) consists of a group of specialists in invertebrates, fish, riparian vegetation, geomorphology, hydraulics, hydrology and any other relevant disciplines who observe the state of a river to define 'building blocks' that describe the monthly distribution characteristics of the modified flow regime.
- The Intermediate Determination, a stripped down version of the Comprehensive Reserve, which takes about 2 months to complete
- The Rapid Determination, an enhancement of the Desktop estimate using limited input from ecological and hydraulic specialists to improve site specific application of generic estimates
- The Desktop Estimate, which is based on generic, regionalised values, used within the National Water Balance Model and taking no more than a few hours to complete

The essential components of flow (the "blocks") are seen as the low or base flows, the small increases in flows referred to as freshes, and the larger high flow events that may be required for channel maintenance purposes. South African flow regimes are highly variable and consequently a set of 'building blocks' have been defined that are considered to apply during 'normal years' (referred to as the maintenance requirements) and a set of building blocks that can be considered to apply during 'dry years' (referred to as the drought requirements). Natural climatic cues should determine the timing and frequency of occurrence of these. The final set of building blocks from a Comprehensive Reserve determination consists of the following for each month of the year:

- Maintenance low flows (in m^3/s)
- Maintenance high flow events defined as peak flows (in m^3/s) and durations in days
- Drought low flows (in m^3/s)
- Drought high flow events defined as peak flows (in m^3/s) and durations in days

Desktop reserve studies are almost completely based upon the hydrological characteristics of rivers (using historical streamflow data) and the biotic component is only included through a series of “fairly objective” parameters (Hughes and Münster, 2000). The method (in the form of a software package) is based on extrapolations from previous detailed IFR studies and some inputs of expert judgement, and was developed due to the relatively good availability of hydrological data (at the time from Midgley *et al* (1994)) while quantitative information on the biotic components were generally not available.

The Desktop software takes a historical data set of monthly flows and outputs the total annual water volume required for maintenance low flow, drought low flow, maintenance high flow and total instream flow requirement in tabular form. These recommended annual totals are then distributed through the year (using a distribution for the relevant geographical area, in this case ‘Lowveld’ (Table 7.1) to give a table of recommended flow volumes for each month. The model also includes a set of rule curves (for different geographical areas), which are used together with the above IFR flows and historical inflows to find a unique IFR flow volume for every month of the time series.

The time series of monthly IFR flow volumes output by the Desktop Model does not specify how the maintenance high flows (included in these flows) should be distributed through the month (peak duration and peak height). This is due to the Desktop Model being based on data at a monthly resolution, and peaks and durations (in days) of high flows would be inappropriate (Hughes and Münster, 2000).

A model (referred to as the IFR model) was developed by Hughes *et al* (1997) to simulate time series of reservoir releases for IFRs and later improved to include operating rules for a daily reservoir simulation (Hughes and Ziervogel, 1998), using a Desktop model IFR. These models can be run in near real time and linked to a flow gauge near the site (either upstream of the dam or in a catchment nearby) by deriving flow duration curves for each gauge from their historical flow data records and linking them by selecting the same points on the percentage exceedence curves. (For example, if the Olifantspruit Dam was built, the DWAF gauge A6H019 in the adjacent catchment to the Olifantspruit could be used for this purpose.) The low flow status is calculated from the last 30 days of flow duration curve percentage point equivalents and the value of the flow status is compared on a daily basis with the low flow operating rules to determine the required rate of release (Hughes and Ziervogel, 1998). The model identifies the high flow status from the duration curve percentage point equivalents for 10 days ahead in the time series, determines when a high flow release should be made and estimates the rate of release by comparing the operating rules with the value of the high flow status. The IFR flows are calculated in the model using an IFR rule curve that depends on the ecological management class, the month of the year and the geographical area. These IFR flows vary from the drought low flow to a flow that can be larger than the maintenance total flow (depending on the rule curve used). One of the principles of the building block methodology is that the specified maintenance flows are not considered the maximum that would be expected (Hughes & Münster, 2000). Hughes *et al* (1997) state that there is no intention to engineer a flood in a certain month unless sufficient rainfall has occurred at that time to indicate it would happen naturally.

7.5.3 The duration of the IFR high flow release and its effect on inundation of the Nylsvlei floodplain

An investigation into the sensitivity of floodplain inundation to different IFR high flow release durations was conducted by holding the high flow volumes constant and varying their durations. The results were evaluated in terms of inundation of the wild rice on the floodplain (described in detail in Chapter 8), which needs to be inundated for at least 25 days in January or February and longer in other months. Inundation was therefore evaluated in terms of the maximum area inundated for a continuous 25 days for each reach (explained in Chapter 8) in each period investigated. The results of this investigation were applied to this scenario.

IFR flow releases from the Olifantspruit Dam were simulated for Ecological Management Class C using the Olifantspruit Dam mass balance model during 1980/1981 and 1986/1987, when the dam never overflowed (therefore necessitating the IFR high flow release) but had relatively large inflows (up to 5.54 m^3/s). The timing of the start of the IFR high flow releases was determined by the peaks in the historical flow hydrograph at A6H012 modelled using DAYFLOW, representing inflows to the Olifantspruit Dam (Figure 7.1 and Figure 7.2). Maintenance high flow release durations from the dam of 1, 2, 5, 8, 9, 10, 15, 20, 25 and 30 days and maintenance low flows (distributed evenly over each month) were modelled for the months of October to April, when the flood peaks occurred (Table 7.1). Overlapping of some of the longer peak release durations occurred in the 1980/1981 scenario but no overlapping occurred in the 1986/1987 scenario. The IFR maintenance high flows were added to the IFR maintenance low flows and routed to the floodplain margin together with modelled historical flows for the same period from other catchments of the Nyl River and tributaries further downstream, and run through the hydraulic models for the three reaches. Rainfall additions on the inundated floodplain surface were included.

Table 7.1: Monthly IFR flow volumes for the Olifantspruit, for Ecological Management Class C, distribution: Lowveld (Volumes in million m^3)

	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
Maintenance low flow	0.023	0.037	0.046	0.059	0.062	0.056	0.045
Maintenance high flow	0.001	0.050	0.090	0.045	0.212	0.084	0.031

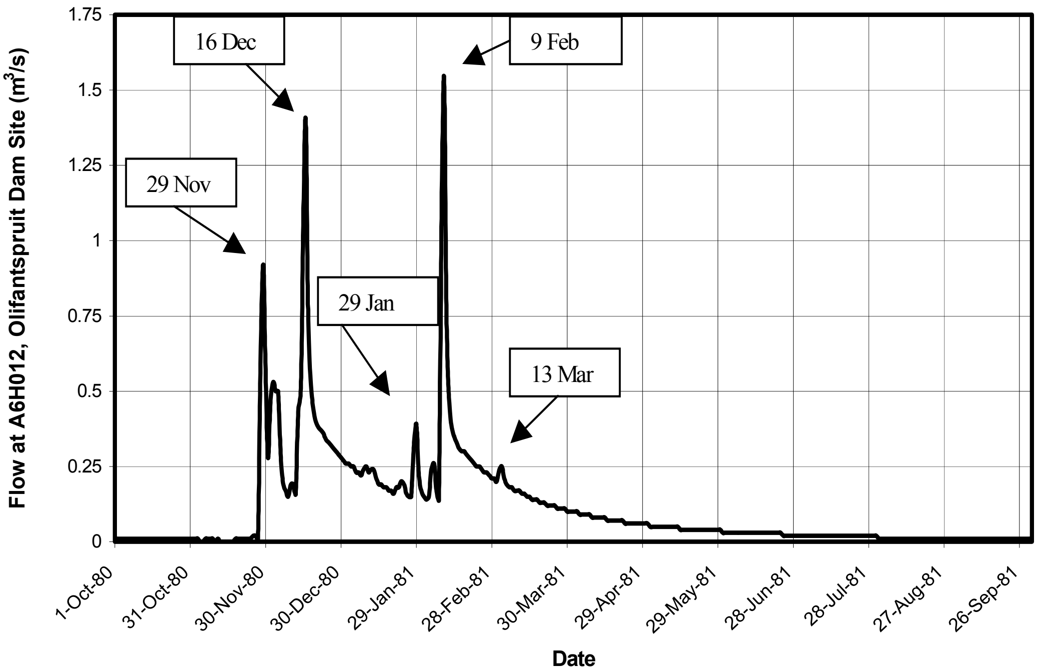

Figure 7.1: Flood peaks in the Olifantspruit from the modelled historical time series used to time the IFR high flow releases in 1980/1981

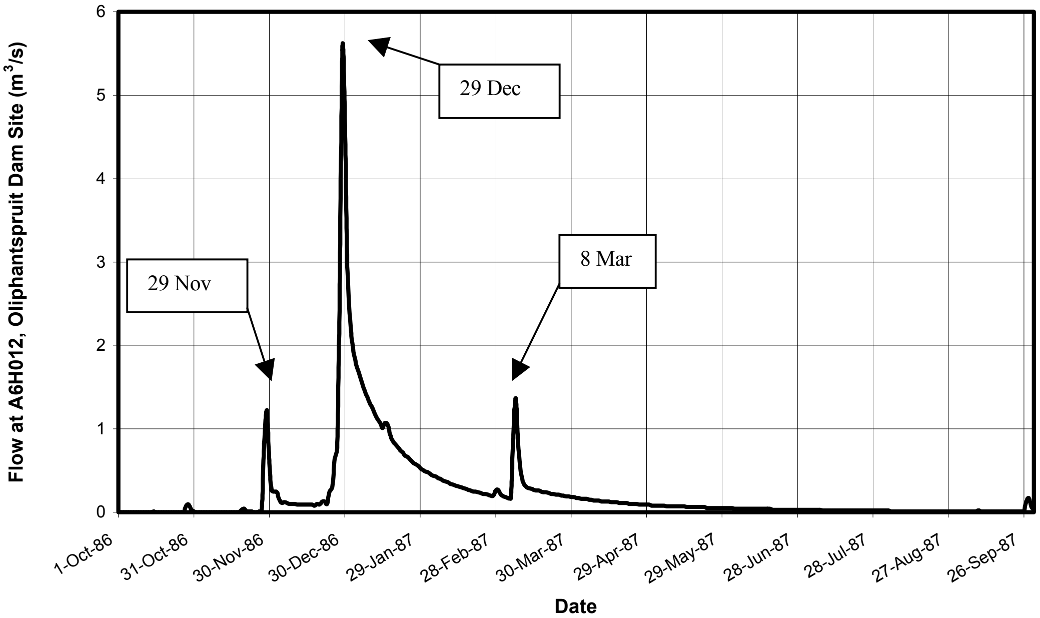

Figure 7.2: Flood peaks in the Olifantspruit from the modelled historical time series used to time the IFR high flow releases in 1986/1987

An investigation was also conducted for the month of February only, consisting of a base flow of 1.5 m^3/s (chosen as this flow caused the channel to run full, or for the floodplain to be partially inundated so that the entire IFR release caused inundation of the floodplain) and the February maintenance high flow volume of 0.212 x 10^6 m^3 (Table 7.1). This maintenance high flow was then released with durations of 1, 2, 5, 10, 15, 17, 18, 20, 22, 23, 25 and 30 days. Rainfall additions to the inundated floodplain surface and inflows from other catchments of the Nyl River and tributaries were ignored.

7.5.4 Results

The maximum areas continuously inundated for 25 days for each period investigated versus the IFR maintenance high flow release durations are shown in Figures 7.3 to 7.5 for each reach. Also shown in Figures 7.3 and 7.4 are the maximum areas continuously inundated for 25 days for the historical scenario (if there was no dam in the system) and for the Olifantspruit Dam with no IFR releases for the same periods (1980/1981 and 1986/1987). The Olifantspruit Dam did not overflow during the 1980/1981 and 1986/1987 hydrological years and consequently there was no flow contribution from the Olifantspruit for the scenario of the Olifantspruit Dam without IFR releases. As there were no releases in the historical scenario (due to there being no dam) and the Olifantspruit Dam with no IFR releases, and hence no release durations, the maximum areas inundated for 25 continuous days for these two scenarios appear as straight lines.

The optimum IFR high flow release period from the Olifantspruit Dam to achieve the maximum 25 continuous days of floodplain inundation for 1980/1981 (Figure 7.3) decreased from 25 days in the Middelfontein reach to 5 days in the Nylsvley Reserve reach to 2 days in the Vogelfontein – Mosdene reach. Similarly, the optimum IFR high flow release period to achieve the maximum 25 continuous days of floodplain inundation for the base flow of 1.5 m^3/s in February (Figure 7.5) scenario decreased from 25 days in the Middelfontein reach to 17 days in the Nylsvley Reserve reach to 15 days in the Vogelfontein – Mosdene reach. This trend of decreasing IFR release durations from the Olifantspruit Dam required to achieve optimum inundation for 25 continuous days in reaches further downstream is due mainly to increasing attenuation and storage effects with distance downstream.

The 1986/1987 scenario (Figure 7.4) showed the opposite trend with increasing IFR high flow release durations from the Olifantspruit Dam required to achieve the maximum 25 days of continuous inundation in each reach downstream, with the optimum release periods being 9 days for the Middelfontein reach, 10 days for the Nylsvley Reserve reach and 15 days for the Vogelfontein – Mosdene reach. Reasons for the difference between this and the other two periods investigated include effects of downstream tributary inflows during the same period combining with the longer duration maintenance high flow releases. For example the Eersbewoondspruit (Blindefontein) had a very long duration flood peak during the December/January flood lasting over a month (of at least 0.1 m^3/s), peaking twice at 0.19 m^3/s on 2 January 1987 and 0.16 m^3/s on 13 January 1987. The Middelfonteinspruit also contributed two short duration floods, peaking at 0.74 m^3/s on 31 December 1986 and 0.12 m^3/s on 11 January 1987. The other tributaries of the Nyl River contributed peaks of 4.8m^3/s on 29 December 1986 and 4.0 m^3/s on 16 January 1987. The IFR releases including base flows varied from 1.06 m^3/s for the one day duration release to 0.05 m^3/s for the 30 day duration release.

The Middelfontein reach in 1980/1981 and the Nylsvley Reserve reach in all three scenarios had two peaks in the maximum areas inundated for 25 days with different IFR high flow release durations due to flood peaks from other tributaries in the catchment combining with the IFR releases.

The addition of the IFR flows had the most significant impact on maximum areas inundated for a continuous 25 days in 1980/1981 (Figure 7.3). In the Nylsvley Reserve reach in 1980/1981, the IFR high flow released over 5 days combined with the low flow mitigated the impact of the Olifantspruit Dam significantly.

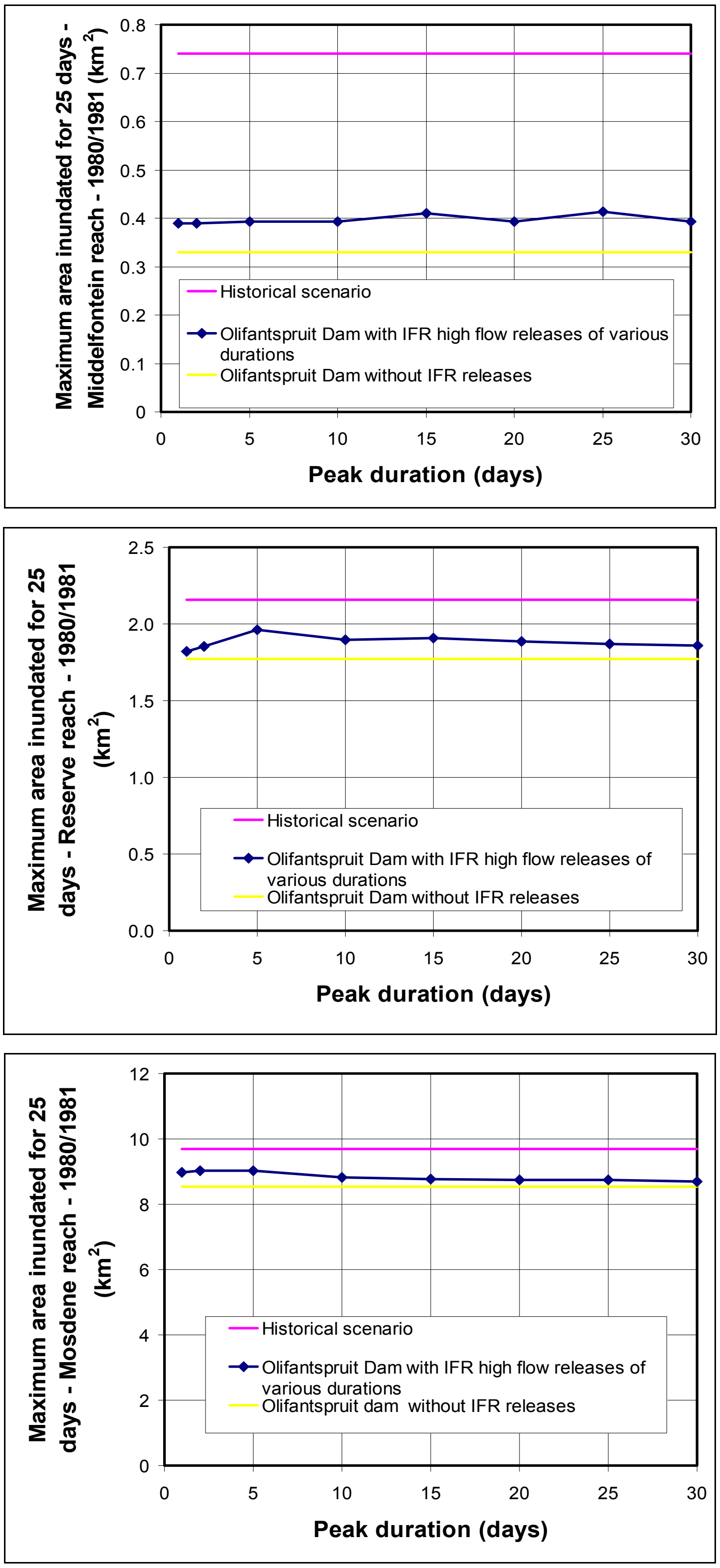

Figure 7.3: Comparison of maximum inundated areas of 25 continuous days duration with various maintenance high flow release durations from the Olifantspruit Dam for 1980/1981

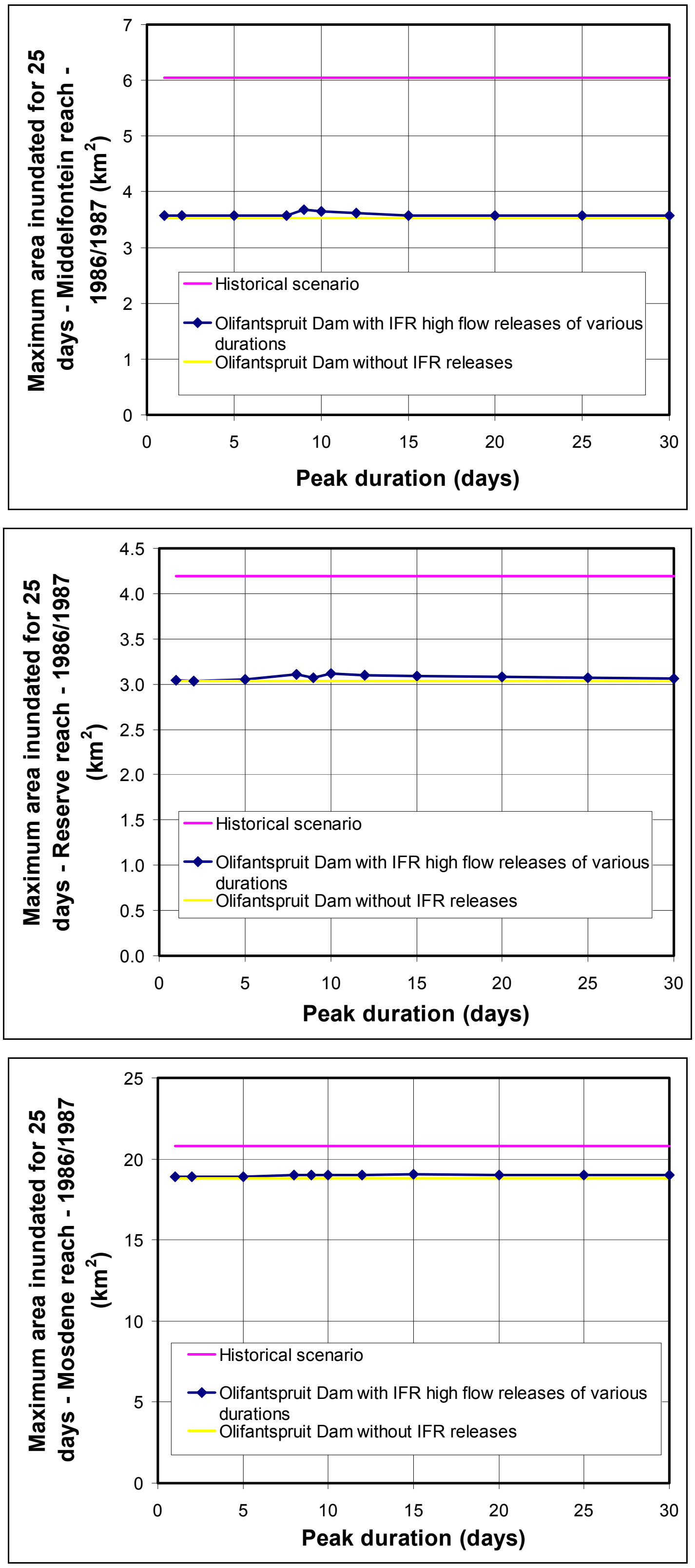

Figure 7.4: Comparison of maximum inundated areas of 25 continuous days duration with various maintenance high flow release durations from the Olifantspruit Dam for 1986/1987

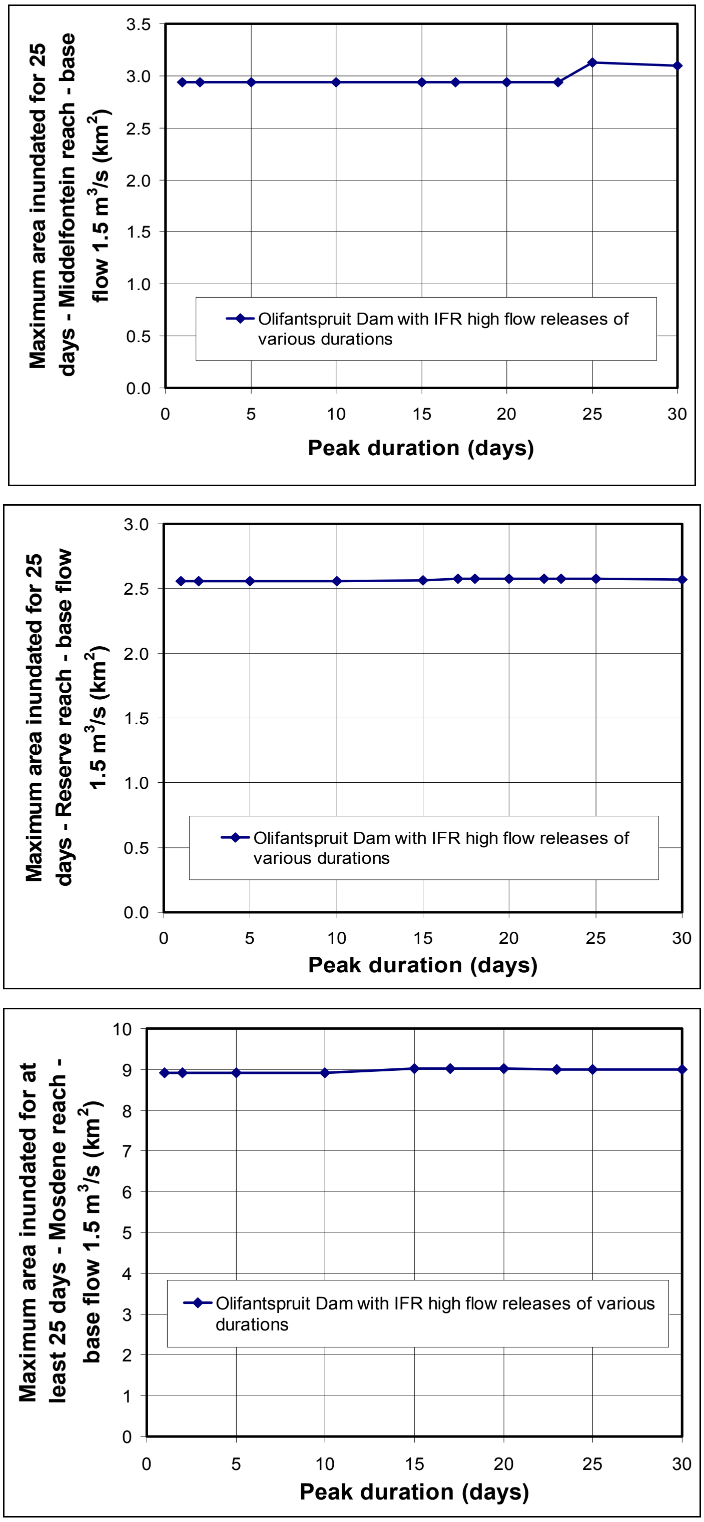

Figure 7.5: Comparison of maximum inundated areas of 25 continuous days duration with various maintenance high flow release durations from the Olifantspruit Dam for February with a base flow release of 1.5 m^3/s

No obvious trend in IFR high flow release duration was evident to obtain optimum inundation areas for 25 continuous days on the Nylsvlei floodplain from the three periods investigated. However, in dry years of extremely low flow the relative effects of the IFR releases may be significant. This investigation has shown that it is possible to relate IFR high flow release durations to inundation areas in wetlands and floodplains downstream, and may prove useful in other wetlands.

7.5.5 Maintenance high flow IFR release period for the scenario

The difference between the maximum area inundated at the optimum duration and the area inundated with a 30-day high flow release duration was not very significant in any of the cases, nor was there an obvious optimum release duration for any of the reaches or the whole study area for 1980/1981, 1986/1987 and the hypothetical month of February. The difference between the optimum IFR high flow release duration inundation areas and the 30 day IFR high flow release duration inundation areas varied between 1% and 5% in the Middelfontein reach, less than 1% and 5% in the Nylsvley Reserve reach and less than 1% and 4% in the Mosdene reach. These small differences are due to the IFR releases generally being small compared to the flow contributions of other catchments. The maintenance high flow releases were averaged over each month due to time constraints, and included in the Olifantspruit Dam reservoir mass balance model as the base flow release term (B) (equations 7.3 to 7.8). A better method would be to use the IFR model (Hughes *et al*, 1997; Hughes and Ziervogel, 1998) to model daily releases from the dam using the Desktop study monthly flow series, as the relative effect of the IFR releases would be increased in years of extremely low river flows. Outflows from spill and the base flow release were routed together with historical flows from other catchments to the floodplain using equation 7.1.

7.6 No flow from the Olifantspruit scenario

This scenario was created by removing the Olifantspruit from the historical scenario to investigate the sensitivity of the floodplain to extreme reductions in flow from this tributary. Modelled historical flows (from DAYFLOW) for all the gauges except A6H012 (at the Olifantspruit Dam site) were routed to the floodplain margin (equation 7.1). The Olifantspruit accounts for approximately 17% of the MAR to the downstream boundary of the Nylsvley Reserve (37.5 x $10^6 m^3$) and 15% of the MAR to the downstream boundary of the study area (42.9 x $10^6 m^3$). These quoted MARs were derived using DAYFLOW for 1950 to 2000 (Bailey, 2003).

7.7 Summary

Five catchment scenarios were created to run through the hydraulic model: a virgin catchment scenario, a historical catchment scenario, two scenarios with the Olifantspruit Dam in different forms within the historical catchment scenario and a scenario with no flow contribution from the Olifantspruit within the historical catchment scenario. All the scenarios were based on modelled hydrology from DAYFLOW. The two Olifantspruit Dam scenarios made use of a reservoir mass balance model to calculate outflows. Outflows were governed by the results of a Desktop instream flow requirement study for one scenario and optimum release durations of maintenance high flows were investigated to provide maximum benefit to the growth of wild rice on the floodplain. In the next chapter, flows from these scenarios are run through the hydraulic model and their impact on floodplain inundation is analysed.