A study of the development of water resources in the Olifants catchment, South Africa: Application of the WEAP model.

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Abstract

Increasing water scarcity makes the management of water resources an even more complex task. Water resource models are needed to understand complex systems and optimise water use.

In this study, the rainfall-runoff component of the Water Evaluation And Planning system (WEAP) was applied to simulate natural water resources in the Olifants catchment, South Africa. The model was set up without taking into account effects of development and it was calibrated against naturalised flow data available for the hydrological years 1920 to 1989 in South Africa (Midgley et al., 1994). A good agreement was observed between simulated and naturalised flow, and the Nash-Sutcliffe efficiency criterion obtained for the catchment was 0.93.

Following this, the model was reconfigured to simulate the impact of development interventions on water resources. Impact of change in land use was assessed by estimating crop coefficients for the current land use in the catchment. Water demand was estimated for four different sectors: rural, urban, irrigation and mining. Flow simulated was compared to measured flow from five gauging stations in the catchment.

Results of the different simulations provide insight into:

- availability of water resources in the catchment,
- water demand development for the period HY1920-HY1989,
- impact of hydrological structures on water resources in the catchment.

The results of the study demonstrate the potential of using WEAP for water resource management and assessment of future resource development in the catchment.

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Chapter 1

Introduction and Objectives

South Africa is a water-scarce country. Several regions face water deficits. Even though water quantities are judged to be sufficient to meet the nation's needs, former management has put in jeopardy water resources and therefore the social and economic development of the concerned regions.

Before 1994, and the end of the Apartheid regime, the 1956 Water Act gave access to water to those who owned the land above or alongside it. As white people predominantly owned the land, large inequities in water allocation occurred. Since the advent of the democratic regime, a new policy in water management has been developed to give access to water to everyone. However competition for water is rising with water demand, and assessment of water resources and water uses is a critical step to overcome.

The Olifants River Basin is one of the 19 water management areas that make up South Africa. Located in the northeast of the country, this basin contains important economic activities for the country such as power generation, mining, agriculture and tourism (in particular in the Kruger National Park, which attracts over one million visitors a year). As a consequence, water deficits can have negative impacts for human beings, ecosystems and economic activities.

The aim of this study was to develop a better understanding of the hydrology of the Olifants catchment and of the uses of its water. The Water Evaluation And Planning (WEAP) model, which was developed by the Stockholm Environment Institute (SEI), was used to simulate the hydrological processes and the water demand that occur in the catchment.

1. Water Management Context

Redressing the results of past racial discrimination, meeting the basic human needs and promoting equitable access to water have been set as the main purposes of the South African National Water Act (DWAF, 1997). Sustainability and Equity have been identified as the guiding principles to achieve these goals (DWAF, 2004).

The National Water Act has highlighted the need for integrated water resources management, i.e. considering the natural, social, economic and political environments in which water occurs. Within this approach, involving people in the decision process is a necessary condition. Moreover, managing the water resources at the national scale is not practicable. Therefore 19 Water Management Areas (WMA) were set up in 1999 to facilitate effective management of water resources. The next step is the establishment of Catchment Management Agencies that should give a better understanding of the water resources situation and develop catchment management strategies.

2. International Water Management Institute

The Olifants River Catchment constitutes the Olifants Water Management Area. This catchment is a benchmark basin for the International Water Management Institute (IWMI). Hence much of the research performed by IWMI in South Africa is focused on this basin (e.g. Levite et al., 2003, McCartney et al., 2004a). Projects are carried out either at the whole catchment scale or at smaller scales in order to build up a comprehensive assessment of the hydrology, environment, water uses, and socio-economic impacts of water in the catchment. Evaluation of present resources and forecasting of future resources are critical steps in understanding the catchment behaviour and evolution.

3. Value and limitations of hydrological models

Hydrological models have become a basic tool in hydrology. Their development, which was closely linked to increasing power of computer processing, started in the 1960s. They are now indispensable tools for planning, design and management of hydrologically related infrastructure. They can also improve system understanding which is required for decision making and policy analysis.

Nevertheless, the number of hydrological models now available has increased to such an extent that it has become a relatively hard task to choose one from amongst them all when a simulation is to be done. Selection of an appropriate model for a particular need is made easier thanks to several model classifications that have emerged in the past (Schulze, 1998). Hydrological models are usually distinguished on the basis of their:

- Function: prescriptive models are used to make predictions of catchment behaviour and are used in engineering and regulation studies. Descriptive models are more specifically concerned with testing of conceptual theory and mainly applied in scientific research.

- Structure: three groups of models exist depending on their structure. Deterministic models are physically-based and describe cause and effect relationships with mathematical equations. Stochastic models use statistical properties of existing records and probability laws to solve hydrological problems. Conceptual models average inputs/outputs of an area to get rid of time and space heterogeneities that constitute a hydrological system.

- Level of spatial disaggregation: lumped models represent processes in a spatially averaged way whereas distributed models represent them in a spatially disaggregated way.

Criteria for the selection of a model are mainly linked to the nature of the problem to be evaluated and to the resources available (data, computing facilities). The naive perception that model complexity is positively correlated with confidence in the results has faded in the recent years and the whole concept itself of physically-based hydrological modelling has been brought into question (Grayson et al., 1992): it must be kept in mind that equations underlying these models describe processes occurring in structurally stationary 'model' catchments which are spatially homogenous at the model grid-scale (Beven, 1989). Consequently, accuracy of the model depends on the degree of heterogeneity that is lumped in it, and improving descriptions without introducing parameter identifiability problems, this is a question that is still not resolved (Beven, 2000).

Conceptual models avoid parameter identifiability problems by estimating averaged parameters *via* calibration procedures. However inadequate model complexity usually results in difficulties of parameter estimation and model stability. Perrin et al. (2000) studied the relationship between the number of optimised parameters and model performance. They came to the conclusion that simple systems can reach a level of performance almost as high as more complex models, the latter being often subject to over-parameterisation. Their recommendation is to restrict the number of free parameters to between three and five in the case of lumped models.

4. Objectives of the study

In the current study, the Water Evaluation And Planning (WEAP) model, a lumped model, was used to simulate the hydrology of the Olifants catchment. The aims of the study were:

- to evaluate the rainfall-runoff component of WEAP and to test its ability to compute natural flow data, i.e. flow that would occur if no development had taken place in the catchment.
- to assess the impact of development on water resources by simulating water uses in the catchment.
- to provide information about WEAP's ability to be used as a water management analysis and planning tool in the Olifants and in other catchments.

Chapter 2

Description of the catchment

1. Overview

The Olifants River is a major tributary of the Limpopo River. It flows through three different provinces in the North-East of the country (Gauteng, Mpumalanga and Limpopo) before reaching Mozambique. The Letaba river (catchment area of 3,264 km^2) joins the Olifants river just before it flows into Mozambique. However the Letaba catchment is not included in the Olifants Water Management Area. The current study focused only on the area covered by the WMA. Throughout the remainder of this thesis, the Olifants catchment refers to the region of the Olifants WMA.

The total area of the catchment is 54,475 km^2 and the population living in this area is estimated to be approximately 3.4 million (about 7% of the national population). About two thirds of the population live in rural areas, and 60% of the population is gathered in the middle Olifants sub-area. The major urban centres are Witbank and Middelburg where over 80% of the population reside in an urban environment (DWAF, 2003b).

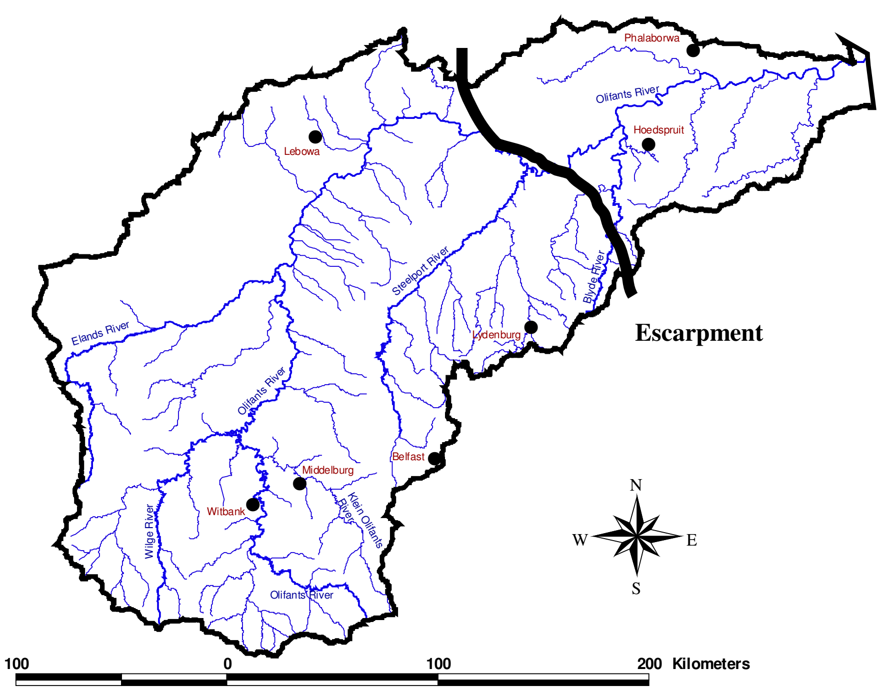


Figure 1 - Map of the Olifants catchment showing main tributaries, urban centres and the escarpment

Main tributaries of the Olifants River are the Wilge and Klein Olifants in the upper Olifants, the Elands in the middle Olifants, and the Steelport and Blyde in the lower Olifants (figure 1).

2. Catchment subdivision

For purposes of water resource management, South Africa is formally divided into hundreds of small catchments (known as quaternary catchments) that have similar runoff volumes. This partition is the result of a national water resource assessment that was undertaken in 1990 and that is known as the Surface Water Resources of South Africa 1990 (WR90) study (Midgley et al., 1994, see section 2.6). From that time quaternary catchments have been the principal water management unit in South Africa. The Olifants catchment comprises 114 quaternary catchments that can be grouped in 13 tertiary and 7 secondary catchments (table 1 and figure 2).

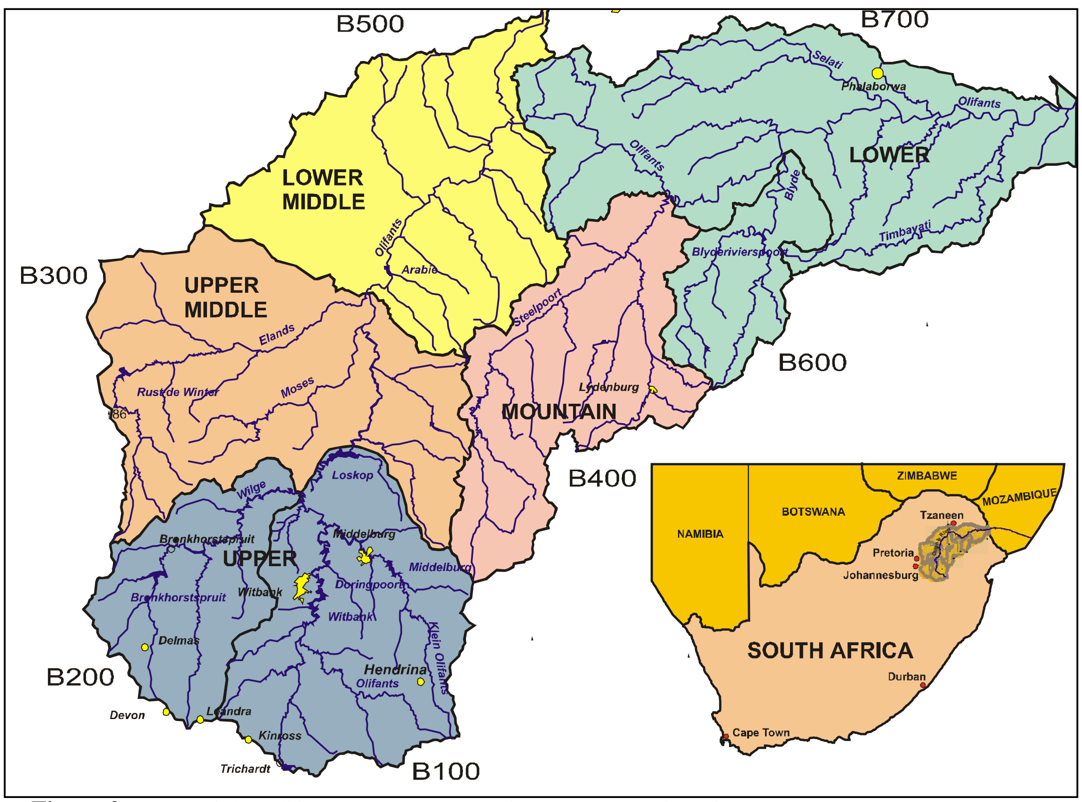


Figure 2 – Map of the Olifants catchment showing the boundaries of the 7 secondary catchments.

Table 1 – Secondary, tertiary and quaternary catchments in the Olifants Water Management Area.

Water Management Region	*Secondary Catchment Identifier*	*Tertiary Catchment Identifier*	*Quaternary Catchments Identifier*	*Description of Tertiary Catchment*
Upper Olifants River	B1	1	A to L	Olifants upstream of Loskop dam
		2	A to E	Klein Olifants
	B2	0	A to J	Wilge River
Upper Middle Olifants River	B3	1	A to J	Elands River
		2	A to J	Olifants from Loskop dam to confluence with Elands
Mountain region	B4	1	A to K	Steelport River
		2	A to H	Spekboom River to confluence with Steelport
Lower Middle	B5	1	A to H	Olifants from confluence with Elands to gauging station B5H002
		2	A to J	Olifants and tributaries from confluence with Elands to gauging station B5H002
Lower Olifants	B6	0	A to J	Blyde River
	B7	1	A to J	Olifants and tributaries from gauging station B5H002 to confluence with Blyde
		2	A to K	Olifants to confluence with Selati River
		3	A to H	Olifants from confluence with Selati River to the Mozambique border

3. Economic activity

Just over 5% of the gross domestic product (GDP) of South Africa originates from the Olifants Catchment (DWAF, 2003a). Main economic activities in terms of gross geographic product were in 1997: mining (22,1%), manufacturing (18,2%), and power generation (15,9%).

Mining activities in the Olifants catchment are dominated by coal mining (in the upper Olifants area), but also include gold, platinum, copper, phosphate and diamond mining.

The importance of coal-fired power stations is mainly attributable to the vast and easy supply of coal. The cheap supply of electricity and coal also drove the development of the manufacturing activities in the vicinity of Witbank and in other areas.

4. Geology and land use

The geology mainly consists of hard rock formations. Granite is the most dominant rock type, but dolerite intrusions in the form of dykes and sills are common. A large dolomitic intrusion known as 'the escarpment' extends along the Blyde River, curving westward along the northern extremity of the water management area (see figure 1). The western part of the escarpment is generally referred to as the Highveld (altitude>1,200m) and the eastern part is known as the Lowveld (altitude<800m).

Agriculture is a major land use sector in the WMA with dryland covering about 8,160 km^2 and irrigation land some 800 km^2. This cultivated land is divided into two agricultural sectors representative of South African agriculture: the commercial sector comprises large farms, which are mainly owned by white farmers. The semi-commercial/subsistence sector comprises small farms located mainly in former homelands (i.e. areas occupied by black people prior to 1994). Commercial farming represents about 80% of the cultivated area of the catchment and nearly the totality of the irrigated area.

Large parts of the WMA are being used for game and stock farming. There are a few forestry plantations covering about 400 km^2. Remaining indigenous forests cover only about 140 km^2. The Lower Olifants River catchment contains a section of the Kruger National Park. Several "Habitat and Wildlife Management Areas" also exist through the WMA.

Alien vegetation is also a major concern in the WMA. As a result of commercial afforestation and poor past forestry management practice, about 2,000 km^2 in the WMA are infested by alien plants such as pines, eucalyptus and acacias (table 2). The effect of alien vegetation on flow is still unclear, but DWAF estimated that water requirement for alien vegetation is about 122 Mm^3 per year (DWAF, 2003a), i.e. evapotranspiration is 122 Mm^3 higher than it would be with indigenous vegetation.

Table 2– Infestation by alien vegetation in the Olifants catchment.

Province	Area (km^2)
Gauteng	20.6
Mpumalanga	694.3
Limpopo	1273.4
Total WMA	1988.3

5. Climatic features

Rainfall

Rainfall is seasonal and mainly occurs during the summer months (October to April): high temperatures produce low pressures and moisture is brought to the catchment through the inflow of maritime air masses from the Indian Ocean. The dry season occurs during winter when a continental high pressure system is present. Mean Annual Precipitation (MAP) in the Olifants catchment is 630 mm per annum (Schulze et al, 1997) but there is a great spatial variability. On average MAP is higher in the south-western part of the catchment and decreases towards the eastern part (table 3 and figure 3). The region of the escarpment (i.e. secondary catchment B6) experiences much higher precipitation due to orographic rainfall (McCartney et al., 2004a). MAP can exceed 1,000 mm in some places.

Table 3 – Mean altitude and mean annual rainfall for each of the secondary catchments.

Secondary catchment	*Mean altitude (meters above sea level)*	*Mean annual precipitation (mm)*
B1	1,588	689
B2	1,501	670
B3	1,174	617
B4	1,430	681
B5	1,097	551
B6	1,207	823
B7	603	586
Total Catchment	1,149	630

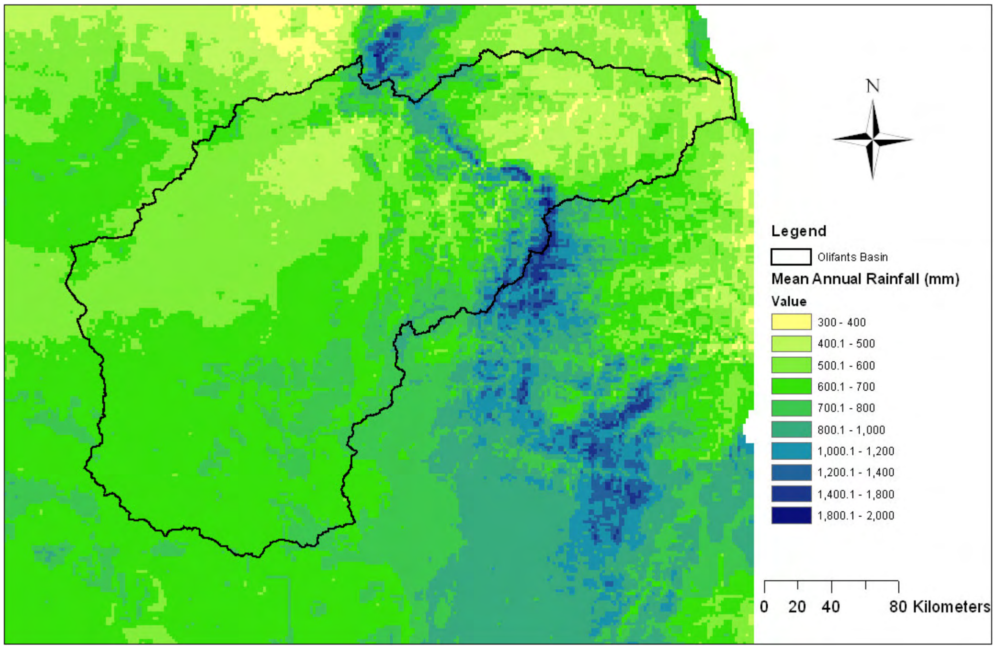


Figure 3 – Mean annual precipitation (mm) across the Olifants catchment.

Figure 4 presents the mean monthly precipitation at three different rainfall stations in the catchment: one on the Highveld, one on the Lowveld, and one on the escarpment. They all present the same pattern with high precipitation in summer months and very low precipitation in winter months: seasonality of precipitation is a common feature experienced all over the catchment.

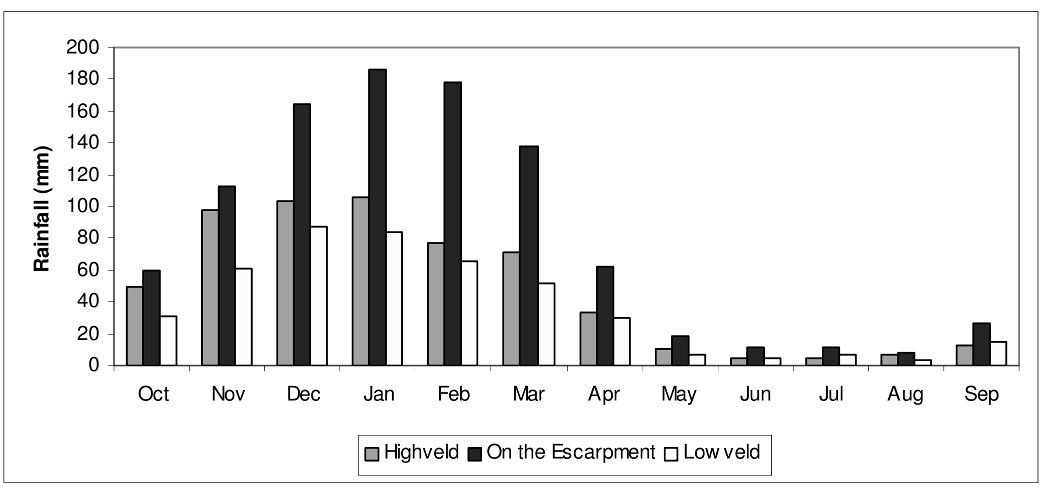


Figure 4 – Mean monthly precipitation at three rain stations in the Olifants catchment.

Evaporation

Evaporation is by far the largest water consumer in the catchment. In South Africa, the approach usually adopted to estimate evaporation is direct measurement of evaporation from the surface of a standard US Weather Bureau Class A pan.

The mean annual open water evaporation (as measured by A-pan) ranges from 1,600 mm to 2,600 mm over the whole Olifants catchment (Schulze et al., 1997). Evaporation is higher in the north and west of the catchment and decreases towards the southeast (figure 5). It is at its lowest in the region of the escarpment (1,600 mm). The lowest evaporation generally occurs in June and the highest between October and January (table 4).

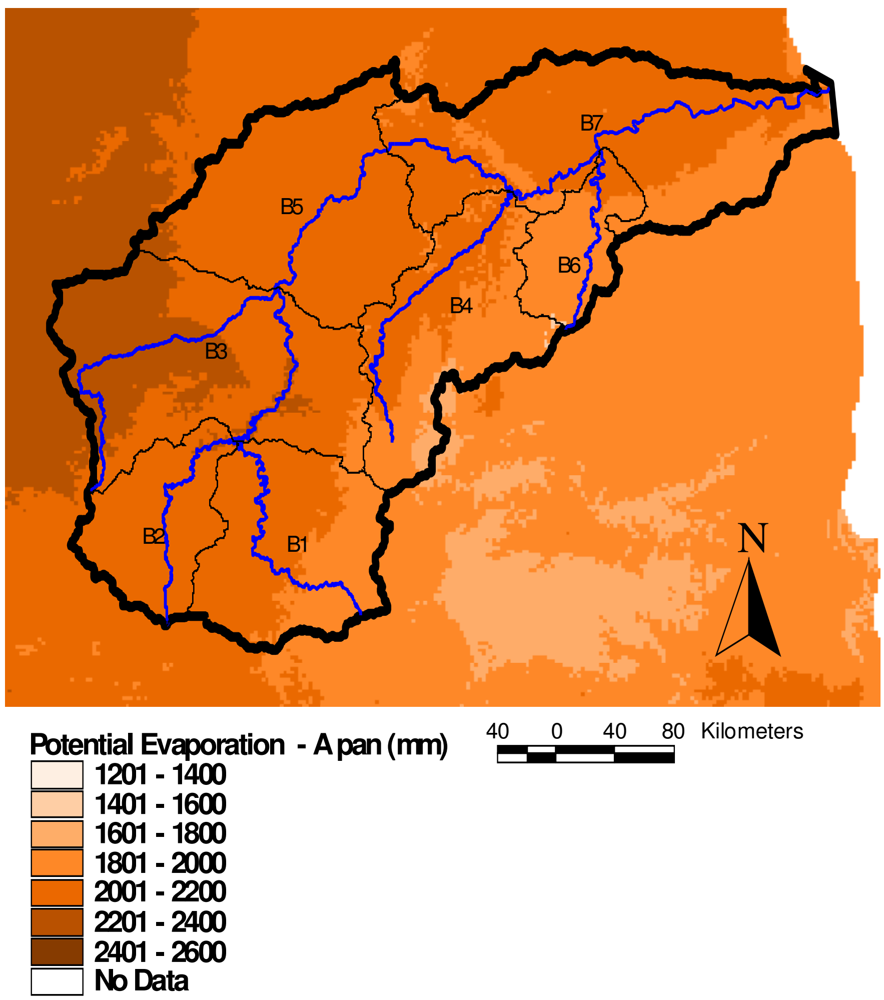


Figure 5 – Mean annual A-pan potential evaporation for the Olifants catchment. (Source: derived from data in Schulze et al., 1997).

Table 4 – Mean monthly and annual A-pan equivalent potential evaporation (mm) for each of the secondary catchments in the Olifants Water Management Area.

Secondary Catchment	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual mean
B1	210.8	205.6	215.1	204.8	170.5	173.0	141.0	125.0	102.8	115.0	156.1	188.5	2,013.7
B2	226.6	220.8	228.4	217.5	179.8	180.2	145.5	129.4	106.1	118.1	160.8	198.5	2,117.0
B3	230.8	226.1	233.3	228.6	189.7	187.3	149.0	133.2	110.2	122.0	163.6	200.1	2,179.4
B4	199.9	195.0	199.9	197.4	162.9	169.1	143.6	130.6	107.4	117.5	152.8	180.8	1,962.2
B5	221.2	220.7	221.6	222.5	181.4	181.9	148.7	133.0	110.8	121.2	159.2	193.4	2,121.0
B6	194.1	192.3	195.9	194.4	165.0	167.8	144.3	130.4	107.5	117.1	149.7	174.9	1,939.5
B7	201.3	209.4	214.6	217.3	183.1	178.6	143.2	125.7	105.8	117.5	150.0	179.2	2,031.2
WMA	213.7	212.6	218.1	215.2	178.7	178.6	145.4	129.6	107.5	118.8	156.5	188.8	2,068.9

Source: computed from data in Schulze et al., 1997.

The Penman-Monteith equation (FAO, 1992) provides an estimate of potential evapotranspiration from a well-watered vegetation surface and is recommended to estimate irrigation water requirements. Figure 6 compares the mean monthly rainfall in the Olifants catchment with the Penman-Monteith potential evapotranspiration.

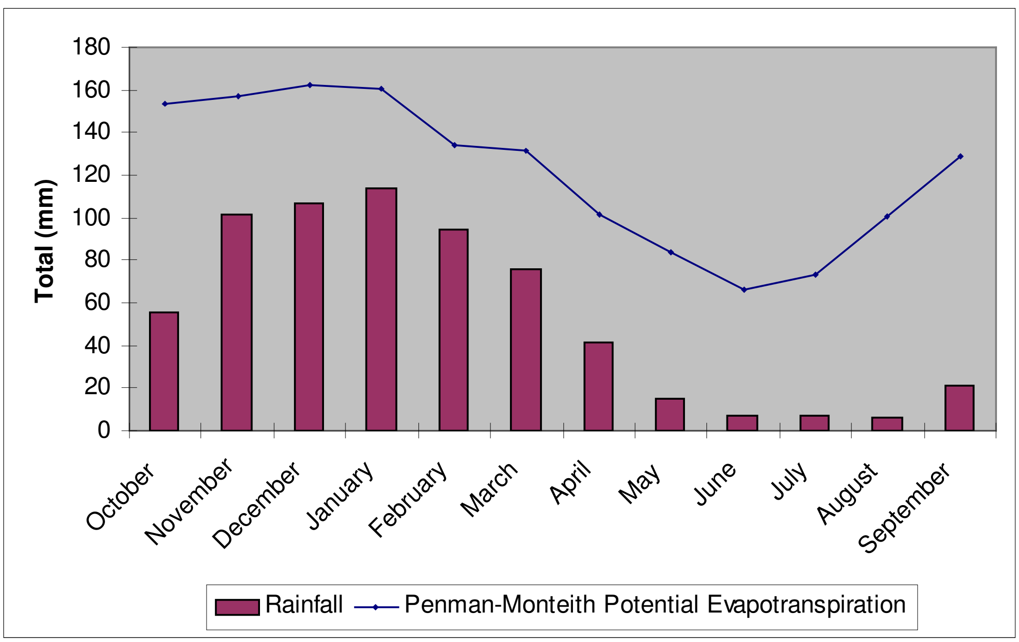


Figure 6 – Mean monthly rainfall and mean monthly potential evapotranspiration in the Olifants catchment.

This figure shows that mean monthly rainfall never exceeds mean monthly potential evaporation and that rainfall conditions are therefore disadvantageous to crops growth. It also reveals the need for irrigation to reduce risks of water shortages.

6. Flow in the catchment

<u>Measured flow</u>

Flow data in the Olifants basin are available from 72 different flow gauging stations that are (or were) operated by DWAF (figure 7). Records processed by DWAF often cover different periods of time, but common features can be extracted from these records:

- Flow generally increases with distance downstream
- Flow records show high seasonal variability
- There is a high inter-annual variability at all points on the river

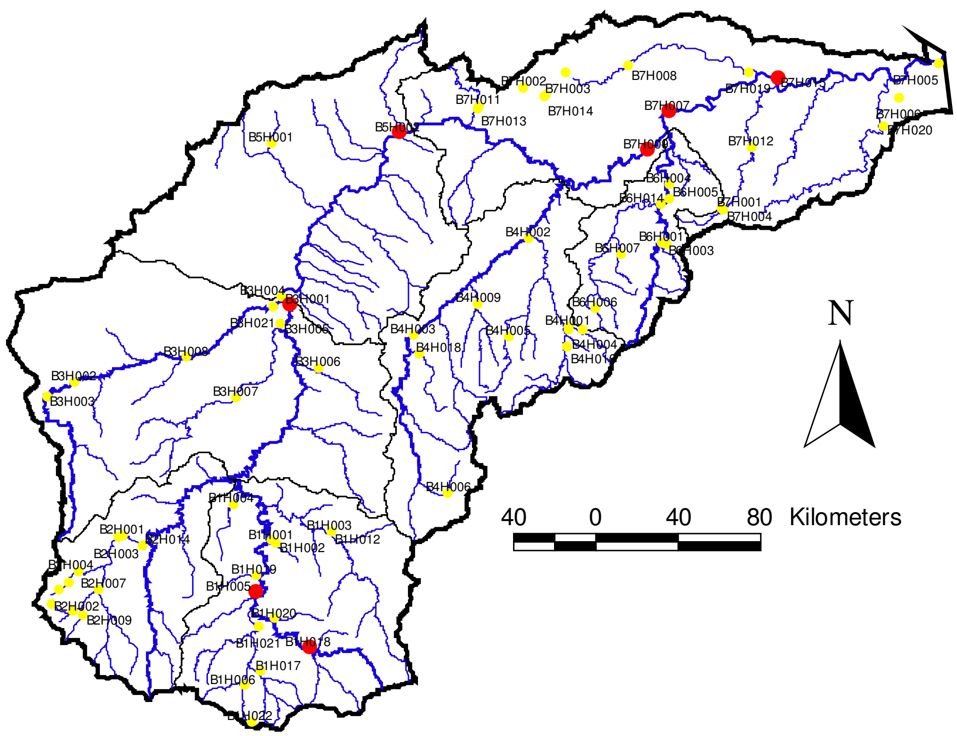


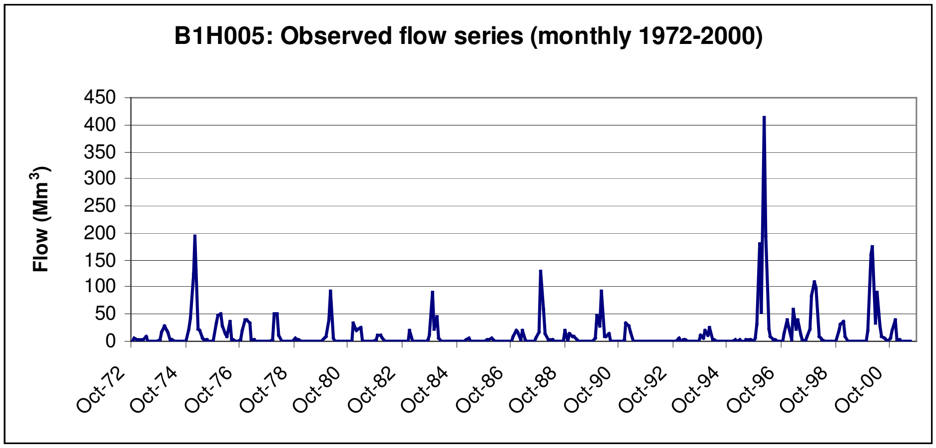
Figure 7 – Location of flow gauging stations in the Olifants catchment.

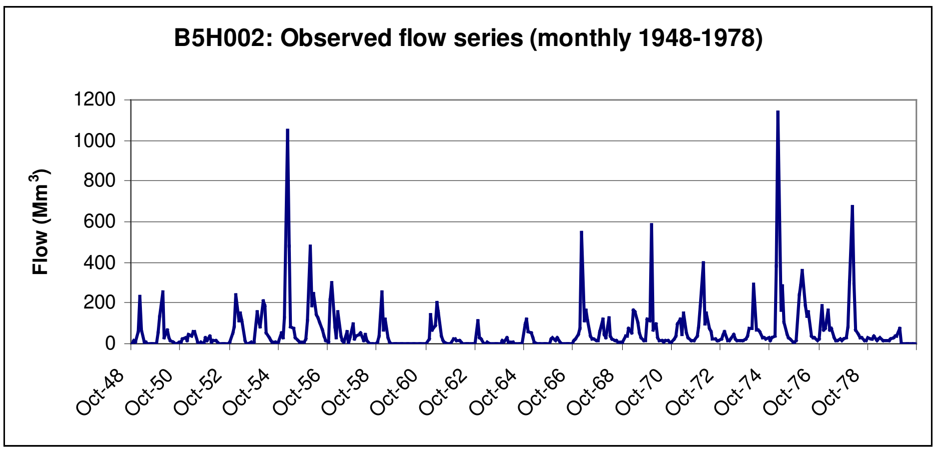
To illustrate these characteristics flow time-series have been plotted for three gauging stations (B1H005, B5H002 and B7H009) located on the Olifants main stem (figure 8). Catchment areas for these three stations are respectively 3,256 km^2, 31,416 km^2 and 42,472 km^2.

Baseflow Index (BFI) indicates the proportion of river's runoff that is derived from stored sources (Houghton-Carr, 1999). Mean BFI was calculated from mean daily flow time-series for the three gauging stations over the period of available records using HYDATA (Institute of Hydrology, 1999). It was decided that years with less than 100 days of data would not be included in the calculation, so one year had to be erased from the calculation for B5H002 and five years for B7H009. Results are presented in table 5. As a consequence of dam operations, baseflow index increases with distance downstream.

Table 5 – Mean baseflow index at three gauging stations on the Olifants River

Gauging station	*Number of years used for calculation*	*Mean BFI*
B1H005	28	0.1512
B5H002	29	0.4138
B7H009	32	0.5025





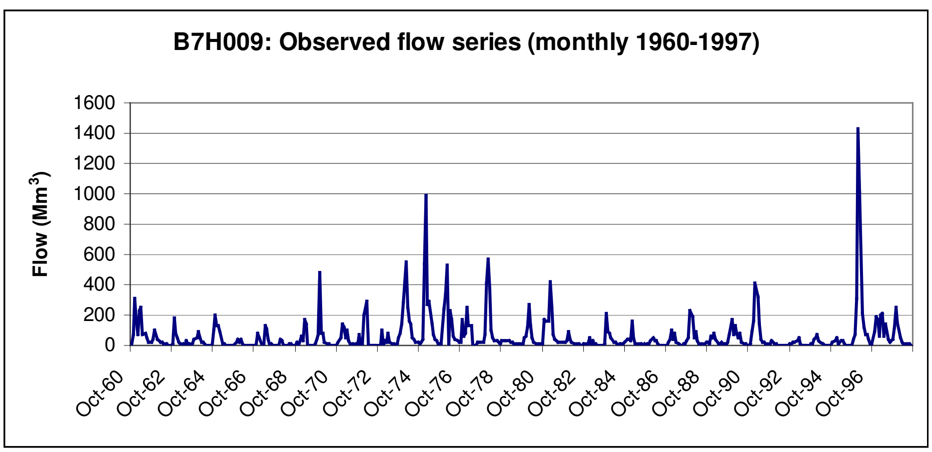


Figure 8 – Flow measured at three gauging stations on the Olifants River

Naturalised flow

In 1990 the Water Research Commission (WRC) undertook the project "Surface Water Resources of South Africa 1990" also known as WR90 study. The aim of the study was "*to provide a basis for a preliminary planning of water resources development*" and to "*make available valuable data and information for water resources planning and development*" (Midgley et al., 1994). This project that took five years to be achieved constitutes the major water resources assessment in South Africa.

Using data available from several gauging stations in the Olifants basin, the WR90 study simulated naturalised flow series for the period HY1920-HY1989 (HY: Hydrological Year, starting in October of the current year and finishing in September of the following year). Naturalised flow stands for a flow that would have occurred if no development had taken place in the catchment. Primary input of the deterministic model (WRSM90, Pitman & Kakebeeke, 1991) used in the WR90 study were rainfall time-series used to generate flow sequences. Water losses due to evaporation, land cover and water use were modelled and the simulated flow was calibrated against measured flow from gauging stations. Naturalised flow sequences were produced by running the model again with all land-use components set to 'virgin' conditions and with no water demand in the catchment. Naturalised flow data are available for each quaternary catchment on a monthly basis for the 70-years period.

Table 6 presents the mean monthly naturalised flow in each secondary catchment of the Olifants Water Management Area.

Table 6 – Mean monthly naturalised flow (Mm^3) for each secondary catchment.

Secondary catchment	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Annual total*
B1	10.4	35.46	34.55	44.67	46.89	31.69	18.60	11.97	7.66	5.91	4.84	4.50	257.12
B2	8.53	17.46	16.47	27.20	28.27	21.41	14.35	10.69	7.58	5.87	4.83	4.27	166.93
B3	8.68	36.03	34.69	47.57	41.44	29.38	19.04	10.66	6.81	5.56	4.63	4.15	248.64
B4	13.03	52.55	61.63	78.94	66.98	44.75	28.82	16.79	10.47	8.28	7.02	7.07	396.33
B5	2.52	18.44	23.50	33.22	25.67	13.15	3.78	0.53	0.06	0.04	0.03	0.26	121.21
B6	13.65	23.04	38.16	59.60	86.01	78.37	46.27	27.51	20.70	16.64	14.13	12.54	436.61
B7	6.62	14.35	34.11	71.55	113.78	86.76	35.91	15.32	11.27	9.03	7.59	6.53	412.82
Total Catchment	63.39	197.34	243.11	362.76	409.03	305.51	166.79	93.47	64.56	51.32	43.07	39.31	2,039.67

Source: Naturalised flow data from the WR90 study

7. Water resources

Most of the surface runoff originates from the higher rainfall southern and mountainous parts of the water management area. The mean annual surface runoff in the catchment is approximately 2,042 million m^3. This is augmented by a net import of water into the catchment of 230 million m^3 which is used to supply power stations and major industries in the South. The developed yield (defined by DWAF as the volume of water that can be abstracted with a '1 in 50 years' risk of failure) from surface water in 1995 was 630 million m^3 (DWAF, 2003b). This is about 49% of the potential yield from surface water which is estimated as 1,288 million m^3/a (table 7).

Table 7 – Surface water resources in each secondary catchment of the Olifants WMA (in Mm^3/a)

Secondary catchment	*Naturalised Mean Annual Runoff*	*Developed yield in 1995*	*Potential yield*
B1	257.1	157.0	163.2
B2	166.9	54.6	93.5
B3	248.6	204.2	152.3
B4	396.3	55.9	229.6
B5	121.2	35.0	69.2
B6	435.2	29.4	338.5
B7	416.1	93.9	242.1
Total Olifants WMA	2,041.6	630.0	1,288.4

Source: data taken from DWAF, 2003a.

Large quantities of groundwater are abstracted for rural water supplies throughout the catchment. The greatest use of groundwater occurs in the Middle Olifants sub-area where most of the rural population in the water management area reside, and where large quantities of groundwater are also abstracted for irrigation. The groundwater potential yield is estimated at 287.4 million m^3/a and the actual developed yield is 100.6 million m^3/a. Exploitable groundwater is nearly fully developed in the Steelport River catchment and overdeveloped in the Blyde River catchment (DWAF, 2003b).
Taking into account the relationship between groundwater and surface water, the total developed yield is 730.5 million m^3/a. The total potential exploitable yield is estimated at 1,576 million m^3/a.

8. Water users and trend of the demand

The main user of water in the basin is agriculture (45 %, DWAF, 2003b): irrigation mostly takes place in large commercial farms where high-value crops (e.g. citrus) are grown. Water requirements per user group in 1995 are summarised in table 8.

An assessment of water availability in the catchment indicates a current annual shortfall of 196 Mm^3. It is estimated that this will increase to 243 Mm^3 by 2025 (DWAF, 2003b). It means that currently water is not being supplied to users at the level of assurance DWAF would like and in dry periods, curtailments are necessary. It is not very clear to what extent these curtailments impact the regional development. As an example, the Limpopo Province Economic Development Strategy denounced the lack of regular water supply as one of the major constraints restraining development in the province (Cambridge Resources International, 2003). However making up the water deficit is one of the current tasks DWAF is working on.

Table 8 – Estimated water requirements per user group in 1995 (taken from DWAF, 2003b)

User	**Estimated water requirement (10^6 m^3/a)**
Ecological reserve[(1)]	480.3
Agriculture[(2)]	599.64
Bulk use[(3)]	257.78
Domestic use[(4)]	123.83
Alien vegetation	122.1
Afforestation	54.2
Water transfers[(5)]	5.0
Total	1,642.85

(1) At outlet of WMA..

(2) Includes requirements for irrigation, dryland sugar cane, livestock and game.

(3) Includes thermal power stations, major industries and mines.

(4) Includes urban and rural domestic requirements and commercial, institutional and municipal requirements.

(5) Only transfers out of the WMA are included.

In South Africa it is of prime importance to maintain a minimum level of water quality and quantity in the rivers in order to maintain a healthy biophysical environment (DWAF, 1997). This requirement, referred to as the 'Ecological Reserve', is as important in the South African legislation as meeting the basic human needs and must be met before any other users can abstract water. Determination of flow requirements, based on the Building Block Methodology (King & Louw, 1998), has only been achieved in a few rivers in the country. However, recent development of low-confidence desktop models can provide a rapid assessment of instream flow requirements (Hughes & Hannart, 2003).

Chapter 3

Water Evaluation And Planning system (WEAP)

1. Model description

The Water Evaluation And Planning (WEAP) model was developed by the Stockholm Environment Institute (SEI, 2005). The system operates on the basic principle of water balance accounting and is applicable to both municipal and agricultural systems. Depending on the objectives of the user, WEAP can either be used as a database, as a forecasting tool or as a policy analysis tool.

The system is represented in terms of supply sources (e.g. rivers, groundwater, reservoirs), of water transfers (withdrawal, transmission) and of water demand and requirements.

2. Previous IWMI study

WEAP can be utilised either as a rainfall-runoff model or as a water allocation model. In a previous study, WEAP was used as a water allocation model to simulate water demand in the catchment. This study did not use the rainfall-runoff component of WEAP: input to the model was the naturalised flow time-series from HY1920 to HY1989 (see section 2.6). Historical variations in demands were estimated for all the water-use sectors, and simulated flows were compared to observed flows from several gauging stations in the catchment (McCartney et al., 2004b). This study demonstrated that WEAP functions well as a water allocation model and can therefore provide a baseline against which the potential impacts of water resource development can be assessed.

3. Approach adopted in the study

In the current study, the primary objective was to test WEAP's ability to simulate the rainfall-runoff process of the Olifants catchment. Initially all components of the model but the rainfall-runoff component were disabled. Hydrological processes occurring in the catchment were modelled and streamflow, simulated on a monthly time-step, was compared to the naturalised flow series available from the WR90 study. This was done because in this catchment, measured flow records from gauging stations are affected by human water abstractions and do not represent the flow originally from the rainfall-runoff process. The model was calibrated over the HY1920-HY1989 period using two different assessment criteria (see chapter 5).

Once the model was simulating the naturalised flow series satisfactorily, water demand sites were added and WEAP was run in its water allocation mode using the rainfall-runoff parameters determined from the first phase. This was done to assess WEAP's ability to simulate water resources and water uses in the catchment. Simulated streamflow was compared to measured flow from 5 different gauging stations located on the Olifants main stem (see chapter 8).
The latest version of the WEAP model (update 2005) was used: this version includes new modules that enable a more accurate simulation of runoff and infiltration to groundwater, as described in the following sections.

4. Model operating rules

For the ease of the simulations and the calibration, the Olifants catchment was divided into eight subcatchments (figure 9) referred in the following as the WEAP subcatchments (WB1 to WB8). There are several reasons for this subdivision:

- First because rainfall data, which are the primary input of the model, are only available for 27 different rainfall zones in the Olifants catchment (see section 4.1). Consequently subcatchments of the model had to encompass these rainfall zones.
- Secondly because limited computer power made it impractical for WEAP to simulate more than a dozen of catchments separately.
- Thirdly because most of the data required to run the model in its water allocation mode were available at this catchment level from McCartney et al (2004b).
- Eventually because most of these subcatchments have a gauging station at their outlet (figure 9), which were used for comparison with simulated flow in chapter 8.

Groups of quaternary catchments encompassed by each WEAP subcatchment are shown in figure 10.

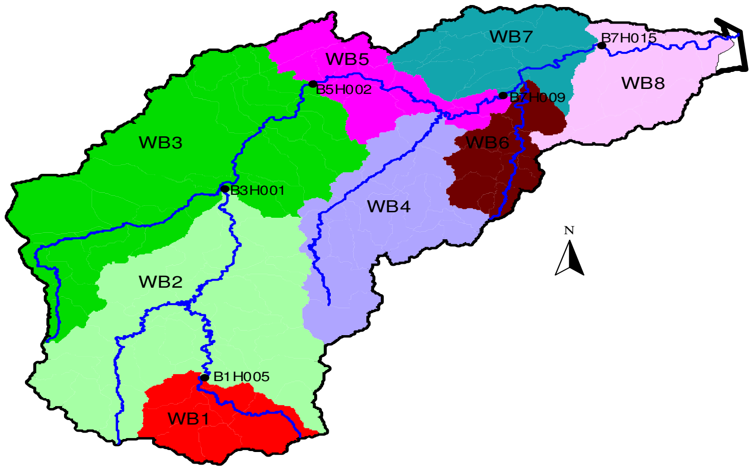
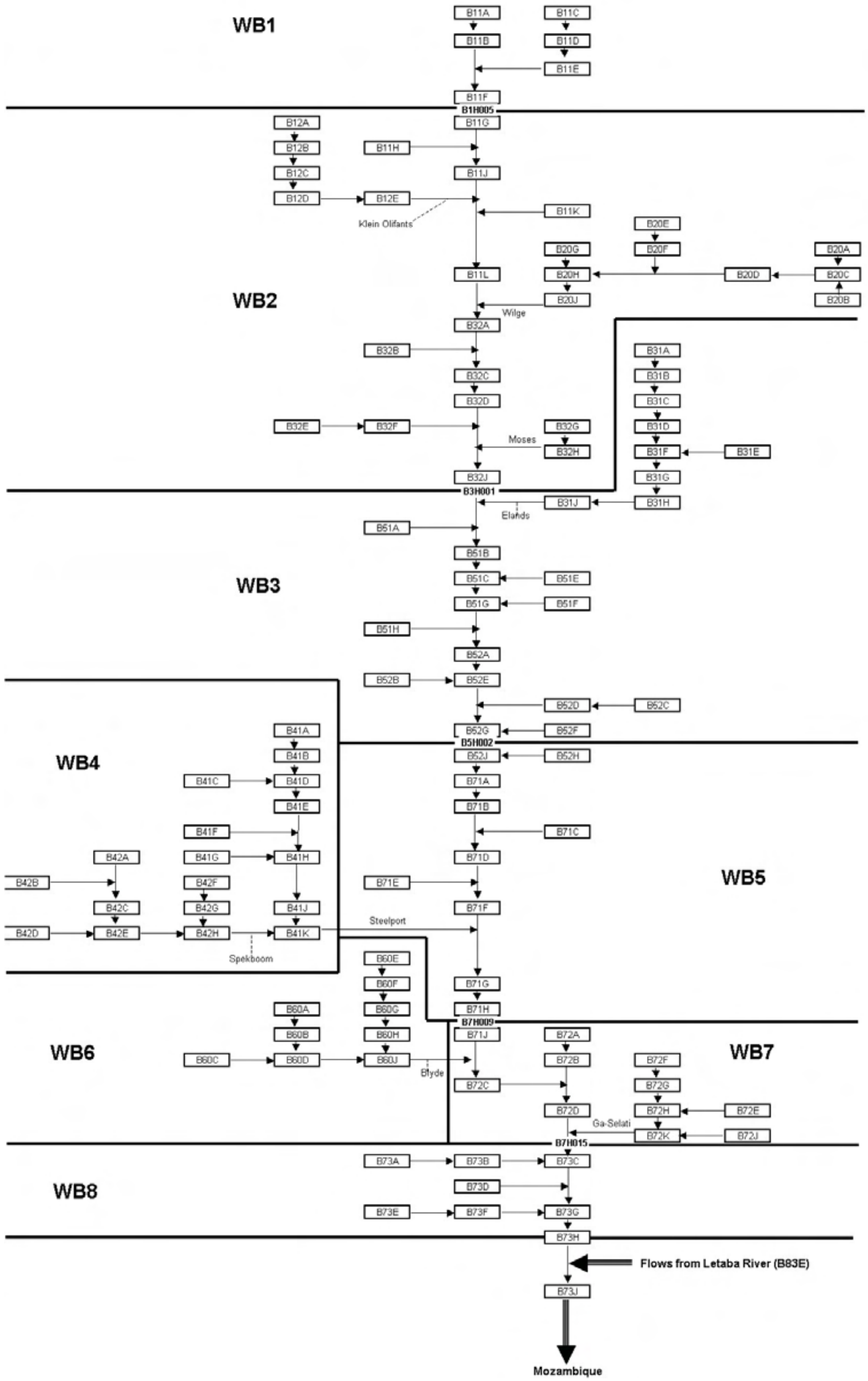


Figure 9 – Map showing configuration of the WEAP model to simulate flow within eight subcatchments (WB1 to WB8) and the five gauging stations (B1H005 etc) which were used for the model validation.

The model as it is used in this study operates at the 'WEAP subcatchment' scale and on a monthly time-step. The period of study was from HY1920 to HY1989, the period for which naturalised flow data are available.



▭ = a quaternary catchment.

Figure 10 - Schematic of the quaternary catchments comprising each of the eight WEAP subcatchments.

The model can be represented as follows:

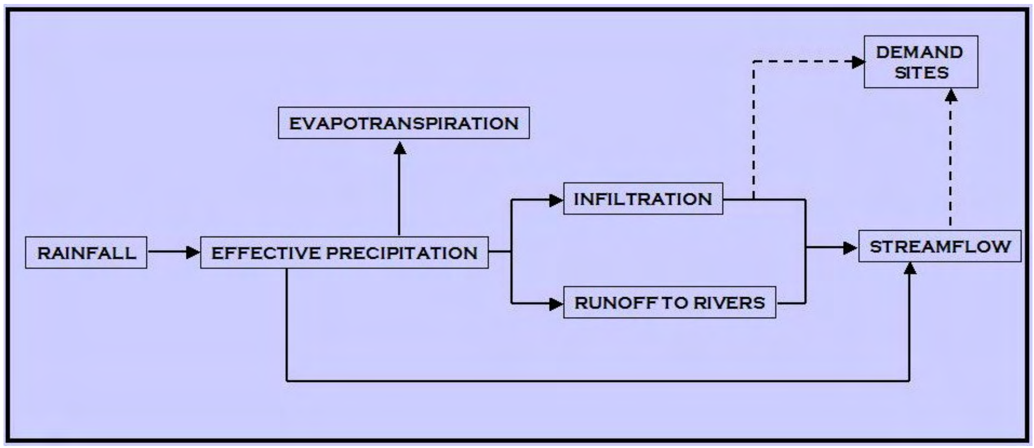


Figure 11 – Schematic of WEAP rainfall-runoff component

Effective precipitation is the percentage of rainfall available for evapotranspiration. If not equal to 100%, the remainder is available for runoff.

Evapotranspiration is determined using the following equation:

$$ET = Min(ETpotential, Precip)$$

with:

$$ETpotential = ETref * Kc * Area$$

Precip: effective precipitation

ETref: reference evapotranspiration

Kc: crop coefficient

Area: area over which evapotranspiration is calculated.

The amount of rainfall that is not evapotranspired is available for infiltration and runoff. Independently of the rainfall intensity, the amount of rainfall going to runoff (or groundwater) is specified as a percentage (fixed for the whole simulation) of the amount of water still available after evapotranspiration has occurred.

Runoff corresponds to the rapid response of the catchment and is therefore directly turned into river streamflow whereas infiltrated water (slow response) goes to aquifers and is released to rivers after a certain amount of time that depends on the characteristics of the aquifer.

The variables required to characterise the aquifer are:

- Storage capacity (Mm^3): maximum theoretically accessible capacity of the aquifer.
- Initial storage (Mm^3): water stored at the beginning of the first month of the simulation
- Hydraulic conductivity (m/day): ability of the aquifer to transmit water through its pores.
- Specific yield: porosity of the aquifer, represented as a fractional volume of the aquifer.
- Groundwater recharge (Mm^3/month): inflows to the groundwater source that are not explicitly modelled in WEAP.
- Wetted depth (m): depth of the river
- Horizontal distance (m): a representative distance for the groundwater –river geometry, taken as the length from the farthest edge of the aquifer to the river.
- Reach length (m): horizontal length of the interface between the reach and linked groundwater.
- Storage capacity below river level (Mm^3): groundwater storage volume at which the top of groundwater is level with the river.

Groundwater is represented in WEAP as a wedge that is symmetrical about the surface water body. Recharge and extraction from one side of the wedge will therefore represent half the total rate.

Total groundwater storage is estimated using the assumption that the groundwater table is in equilibrium with the river (WEAP, 2005).

Equilibrium storage for one side of the wedge, *GSe*, is given as:

$$GSe = (h_d)\ (l_w)\ (A_d)\ (S_y)$$

where h_d represents the distance that extends in a direction horizontally and at a right angle to the stream, l_w is the wetted length of the aquifer in contact with the stream, S_y is the specific yield of the aquifer, and A_d is the aquifer depth at equilibrium.

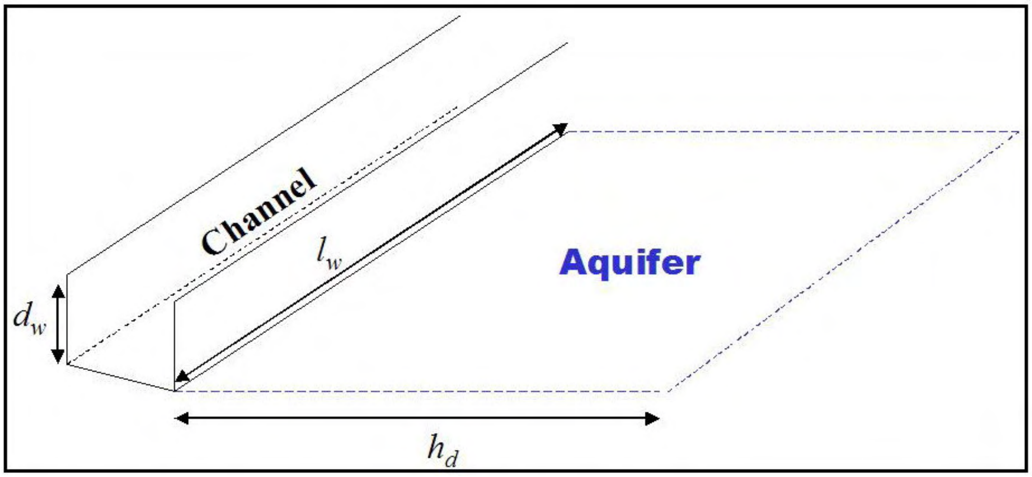


Figure 12 - Schematic showing conceptual model of groundwater

The vertical height of the aquifer above or below the equilibrium position is given as a function of the groundwater storage *GS*:

$$y_d = \frac{GS - GS_e}{(h_d)(l_w)(S_y)}$$

The more the water table rises relative to the stream channel, the greater the seepage going to the stream. The more the water table falls relative to the stream channel, the greater the loss of water from the stream channel to the aquifer. Total seepage from both sides of the river is defined by,

$$S = 2\left(K_s \frac{y_d}{h_d} \right)(l_w)(d_w)$$

where *Ks* is an estimate of the saturated hydraulic conductivity of the aquifer and d_w is an estimate of the wetted depth of the stream, which is time invariant. The wetted depth, together with the wetted length, approximate the area through which the seepage takes place. The saturated hydraulic conductivity controls the rate at which water moves toward or away from this seepage area.

In each subcatchment, catchment runoff and groundwater seepage are linked to one and only one of the reaches in the subcatchment. In the simulation, catchment runoff and groundwater seepage were designated as headflow to the major river of each subcatchment (table 9). This implies that two major rivers cannot be simulated in the same subcatchment within WEAP. Moreover water demand sites or hydrological structures located on minor tributaries cannot be simulated.

Table 9 – Subcatchments and the corresponding major rivers used in WEAP.

Subcatchment	***River***
WB1	Olifants River
WB2	Wilge River
WB3	Elands River
WB4	Steelport River
WB5	Olifants River
WB6	Blyde River
WB7	Olifants River
WB8	Olifants River

Chapter 4

Data

In this chapter, data required to run the rainfall-runoff component of WEAP are presented. Most of the data were extracted from the WR90 study (see section 2.6), as described in the following paragraphs.

1. Rainfall Data

The primary input of the system is the data collection for rainfall between HY1920 and HY1989 in each of the eight WEAP sub-catchments. Using data from the South African Weather Bureau rainfall stations having record lengths longer than 15 years, the WR90 study derived rainfall time-series for the whole Olifants catchment from HY1920 to HY1989. For the ease of the WR90 study, the Olifants catchment was divided into 27 rainfall zones, each zone corresponding to groups of quaternary catchments having similar rainfall characteristics. Records from 280 rainfall stations were used to estimate precipitation in each zone.

The WEAP subcatchments have been designed so that they correspond to groups of rainfall zones as represented in figure 13. For each subcatchment, monthly rainfall time-series were derived by calculating an area-weighted rainfall average from the corresponding rainfall zones.

2. Reference potential evaporation

Vegetation play a significant role in the plant and soil water evaporation processes. In the Olifants basin where agriculture and forestry are the main uses of the land, evaporation is by far the largest water consumer of the catchment.

Reference potential evaporation *ETref* has different definitions. In the current study, the monthly A-pan equivalent is taken as the reference potential evaporation as in South Africa, crop coefficients have been mostly tested against the standard United States Weather Bureau Class A evaporation pan.

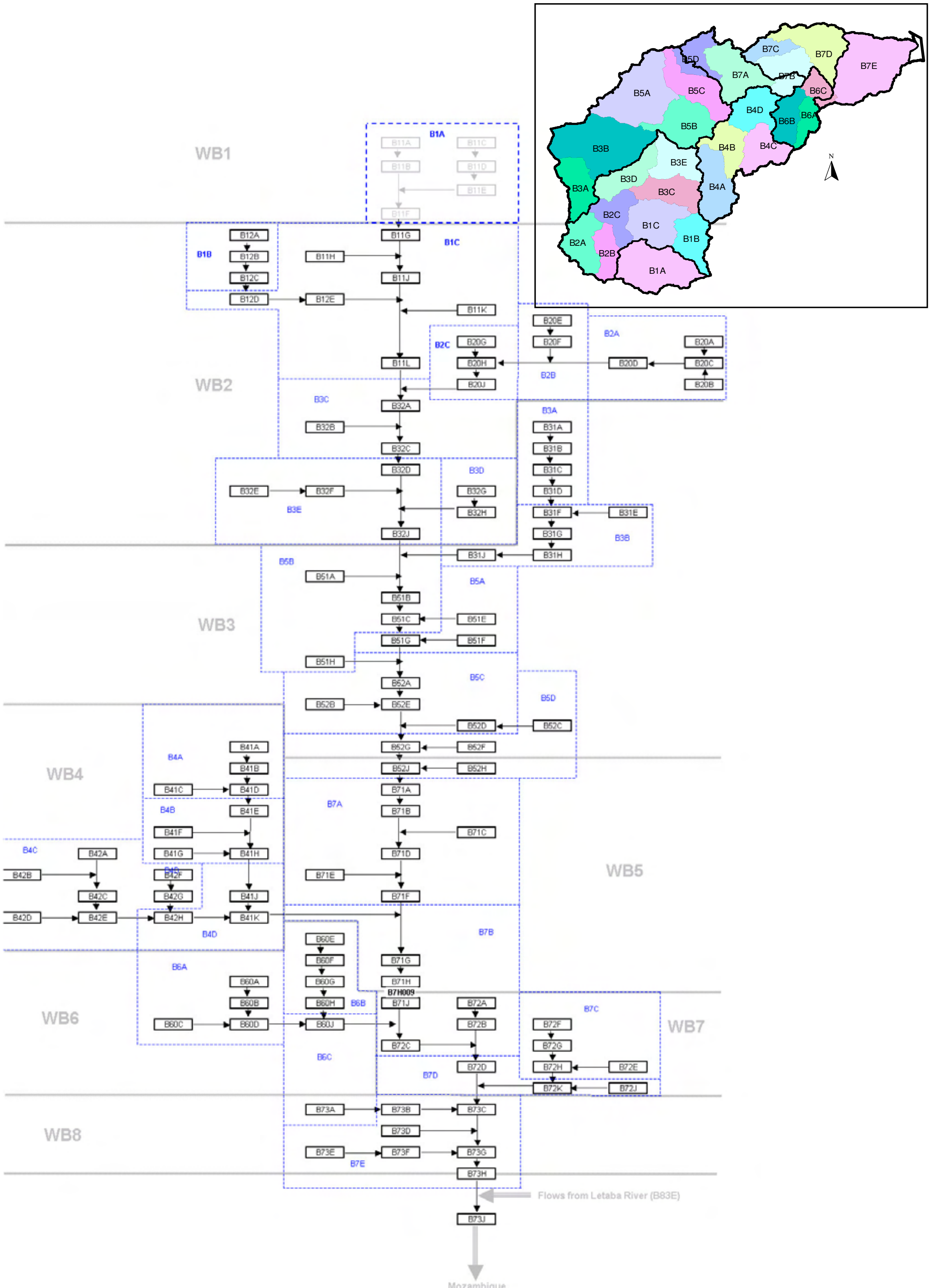


Figure 13 - WR90 rainfall zones in the Olifants catchment and their relationship to the quaternary catchments and the eight WEAP subcatchments

Reference evaporation for each WEAP subcatchment (table 10) were computed from data from the South African Atlas of Agrohydrology and Climatology (Schulze et al., 1997).

Table 10 - Monthly A-Pan potential evaporation in each of the WEAP subcatchments

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
WB1	205.6	170.7	172.7	140.6	122.0	101.0	113.2	154.7	188.7	211.0	206.5	216.0
WB2	214.4	178.2	179.2	145.2	130.1	106.8	118.8	160.2	194.4	220.4	214.9	223.4
WB3	228.8	187.9	186.0	149.1	133.1	110.7	121.9	161.7	198.1	228.5	226.3	229.7
WB4	197.4	162.9	169.1	143.6	130.6	107.4	117.4	152.8	180.8	199.9	195.0	199.9
WB5	210.6	173.3	175.4	146.2	131.8	109.8	120.0	155.6	185.4	209.7	210.7	209.5
WB6	194.3	164.9	167.8	144.3	130.4	107.5	117.1	149.7	174.8	194.1	192.2	195.8
WB7	221.7	187.3	181.2	144.1	125.8	106.2	118.1	151.2	182.3	204.7	214.0	218.9
WB8	217.5	184.8	178.2	141.0	122.3	103.3	115.5	145.9	173.2	193.8	205.1	214.1

3. Crop coefficients

Crop coefficients *Kc* are required to estimate potential evaporation from a given land use type. It can be expressed as:

$$Kc = ETmax/ETref$$

which is the ratio of the maximum evaporation from the plant at a given stage of growth (*ETmax*) to the reference potential evaporation (*ETref*).

As the model does not take into account the effects of development, the land use was assumed to be 'virgin', i.e. as it was before development occurred. According to similarities in land use, WEAP subcatchments could be merged into 3 groups of similar virgin land type:

WB1, WB2, WB3, WB4 and WB5: *northern tall grassveld.*

WB6: *woodland*

WB7 and WB8: *lowveld*

Monthly values of crop coefficients were extracted from the ACRU database (Schulze, 1995), which comprises crop coefficients for numerous land-use types in South Africa.

Table 11 presents crop coefficients associated with the virgin land types used for the model.

Table 11 – Crop coefficients associated with virgin land-use types used for WEAP simulation

Land use	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Type1	0.55	0.6	0.6	0.6	0.6	0.58	0.55	0.4	0.3	0.3	0.45	0.55
Type2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.75
Type3	0.65	0.7	0.7	0.7	0.7	0.7	0.6	0.5	0.45	0.4	0.45	0.58

Type1: Northern tall grassveld
Type2: Woodland
Type3: Lowveld

4. Groundwater

Knowledge about aquifers characteristics is relatively poor in the Olifants WMA. In particular most of the data available are provided for secondary catchments. As they do not match with WEAP subcatchments, it was not possible to infer parameter values from these data. The following assumptions had to be made to design aquifers in WEAP subcatchments:

- for each subcatchment storage capacity of the aquifer was supposed to be unlimited. This was assumed partly because in WEAP, infiltration of water to a full aquifer is lost from the system. Consequently, no overflow of groundwater was possible. However it was verified that groundwater storage was not reaching unrealistic values.
- Initial storage was assumed to be null as no data were available about the storage in 1920. This is supposed to influence at most the first five years of simulation and to have a weak impact on the overall results.
- The 8 aquifers of the model (one for each subcatchment) were designed on the same pattern: a symmetrical wedge with a wetted depth of 3 meters and 800 meters wide on both sides of the river.
- Specific yield of each aquifer was fixed at 0.2 (average value estimated from Todd, 1980).
- Storage at river level was supposed to be equal to 0. It means that in the simulation, no water could be transferred from the river to the aquifer. This

represents the general impression from the literature that in the Olifants catchment, the predominant groundwater movement is from the ground to the rivers (Aston, 2000).

- Interface between groundwater and surface water was set at 500 meters.

Hydraulic conductivity was used as a free parameter and was not fixed in the model.

5. Naturalised flow

Naturalised flow time-series were used for calibration of the model in each subcatchment. The WR90 study produced naturalised flow data at the quaternary catchment level. Monthly time-series of cumulative flow within each WEAP subcatchment were estimated by summing naturalised flows for the appropriate quaternary catchments (table 12).

Table 12 – Area and mean annual naturalised flow in each WEAP subcatchment.

Subcatchment	*Area (km²)*	*Annual naturalised flow (Mm³)*
WB1	3,211	111.6
WB2	13,344	477.8
WB3	14,918	176.6
WB4	7,136	396.3
WB5	3,918	228.6
WB6	2,842	435.3
WB7	4,542	138.2
WB8	4,397	75.3

Chapter 5

Model calibration and sensitivity analysis

Calibration procedures in hydrological modelling usually aim to fit simulated data to observed flow data from gauging stations. Traditional approach is to calibrate a model against measured values for a specific period, say ΔT1, and to test its predictive ability over another period ΔT2 (Klemes, 1986). In the Olifants catchment, measured flow is significantly affected by human abstractions and development effects (changes in land use). So it was decided to calibrate the rainfall-runoff component of the model using the 70 years naturalised flow series derived in the WR90 study (see section 2.6). As naturalised flow data have been produced using another hydrological model (WRSM90), it did not seem to be relevant to test the predictive ability of the model against these data. It was rather decided to calibrate the model against the 70 years naturalised flow time-series. Validation of the model was tested against measured flow time-series in its water allocation mode (see chapter 8).

1. Criteria and Objective functions

In order to assess the performance of the model, a validation of the simulated values needs to be done. An obvious validation is first made by comparing graphically the simulated values with the naturalised values. However this enables only an assessment of the overall adequacy of the model to the observation (here the naturalised flow).

There are a large number of objective functions that can be used to estimate the goodness-of-fit of the simulation. Choosing one of these functions for calibration or validation is not easy, as the function chosen depends on the application of the model. With regard to a rainfall-runoff model, one may want to have a good simulation of the baseflow or of the peak values. This will determine the objective function that the modeller uses.

A brief summary of often-used rainfall-runoff validation functions is presented in the following:

- Least squares objective function:

$$LS=\frac{\sum_{i=1}^{N}(Qobs_i-Qsim_i)^2}{N}$$

This is one of the most widely used functions in model calibration. Minimisation of the function tends to lower the residual error between simulated and observed values.

- Least squares of logarithms objective function:

$$LSL = \frac{\sum_{i=1}^{N} \left(\log Qobs_i - \log Qsim_i \right)^2}{N}$$

This function evaluates the sum of the squares of the residuals of the logarithms of the flows and therefore prevents the optimisation becoming biased towards the largest flows.

- Efficiency criterion:

The least squares and least squares of logarithms objective functions are not normalised functions. The function values depend on the flow volumes and it is therefore not possible to compare function values between different catchments. Another approach is to use an efficiency criterion such as the Nash-Sutcliffe (1970) efficiency criterion:

$$EFF = 1 - \frac{\sum_{i=1}^{N} \left(Qobs_i - Qsim_i \right)^2}{\sum_{i=1}^{N} \left(Qobs_i - Qbar \right)^2}$$

where *Qbar* is the observed mean monthly flow over the whole period.

An efficiency criterion of 1 means that observed and simulated values are in perfect agreement whereas a negative criterion means that the simulation gives worse results than replacing simulated values with the observed mean monthly flow.

2. Calibration approach

Table 13 is a list of the different parameters used in the model. Although the model is a quite simple view of the real hydrological process, it still relies on a large set of parameters. Therefore it was decided to reduce the number of parameters that were used in the calibration routine, and estimated values derived from literature were used for most of the parameters.

Table 13 – Parameters used for WEAP simulation

	Parameter	Value
Catchment	Area (km²)	Data
	Crop coefficients	Data +multiplier
	Effective precipitation	*Unfixed parameter*
	Precipitation (mm)	Data
	Reference evapotranspiration (mm)	Data
Runoff and Infiltration	*Runoff/Infiltration ratio*	*Unfixed parameter*
Groundwater	Storage capacity (Mm^3)	Unlimited
	Initial storage (Mm^3)	0
	Hydraulic conductivity (m/day)	*Unfixed parameter*
	Specific yield	0.2
	Horizontal distance (m)	800
	Wetted depth (m)	3
	Storage at river level (Mm^3)	0

Three parameters were kept unfixed for the calibration approach (table 11), one for each step of the hydrological process modelled in WEAP (evaporation, runoff/infiltration, groundwater behaviour). They were chosen because they are the parameters that are the most likely to be dependent on the catchment characteristics and for which no common value could be inferred from the data.

Most of the fixed parameters are estimates of aquifer characteristics. Although they are likely to be different in-between subcatchments, it was decided to keep them fixed to improve the robustness of the simulation (see section 1.3). Another reason was that errors that were likely to be done on these parameter estimates could be counter balanced by values of hydraulic conductivity (see section 3.4), which were unfixed.

Period of calibration was from HY1920 to HY1989, period for which naturalised and precipitation time-series are available at the quaternary catchment scale.

As there is no optimisation routine included in the WEAP model, a manual optimisation had to be achieved by a trial and error routine (Görgens, 1983). This method, which is particularly time-consuming, has the advantage of giving the user a good idea of the model structure and of the model sensitivity to the different parameters.

Two different calibration procedures were used. They aimed to optimise the Efficiency Criterion and the least squares of logarithms objective function by determining the best set of the unfixed parameters.

The optimisation process was undertaken by changing manually the parameters by fixed amounts (table 14).

Table 14 – Unfixed parameter initial values and steps used for calibration of WEAP

Parameter	Initial value	Step
Effective precipitation	100 %	± 0.5 %
Runoff/Infiltration ratio	50/50	± 5/5
Hydraulic conductivity	1	± 0.1

From the initial set of parameters, one parameter was changed at a time until the routine could not optimise the assessment criterion anymore.

3. A Priori approach

The model was first run with the set of parameters presented in tables 13 and 14. It came out from this simulation that runoff calculated by the model was in some catchments twice as high as runoff from naturalised flow. In particular it seemed that not enough water was lost from the system in WEAP. It meant that either evaporation from the model was too low or there were losses in the naturalised flow model that WEAP did not take into account. However it was assumed that evaporation from the *A priori* approach was too low, especially because WEAP only simulates evaporation from plants and not evaporation from soil, and because it is likely to have an error in the virgin crop coefficients estimation. It was therefore decided to apply a multiplying factor to each set of crop coefficients in order to obtain the right quantity of water. A common factor was determined for each virgin land use type by running the model and comparing mean simulated runoff with mean naturalised runoff. Results are presented in table 15. Simulated time-series before and after adjustment in WB7 and WB8 are presented in figure 14.

Table 15 – Multiplying factors corresponding to each land-use type used for calibration of WEAP

Land use type	Multiplying factor
Type 1: Northern tall grassveld	1.3
Type 2: Woodland	1
Type 3: Lowveld	1.3

This method appeared to be efficient in all subcatchments but WB8, in which simulated runoff was still much higher than naturalised runoff. It was not very clear why there was such a difference in runoff between WB7 and WB8, which have similar areas (4542 km^2 and 4397 km^2 respectively), which experience similar precipitation (MAP=626mm and 614mm respectively), and which seem to have similar characteristics in terms of land use and reference evapotranspiration. Naturalised mean annual runoff is 138.2 Mm^3 in WB7 and 75.3 Mm^3 in WB8. It means that either water is lost from WB8 by a way that is not modelled in WEAP (for example groundwater transfer to another catchment) or estimation of naturalised flow in this subcatchment is wrong. However the aim of the study was to simulate naturalised flow data and so water losses had to be added to WB8. This was done by setting a groundwater storage in WB8. The reason for that is that in WEAP, all net water inflow to a full aquifer is lost from the system. Setting a storage capacity of 70 Mm^3 for WB8 made it possible to simulate the losses occurring in this catchment (figure 14).

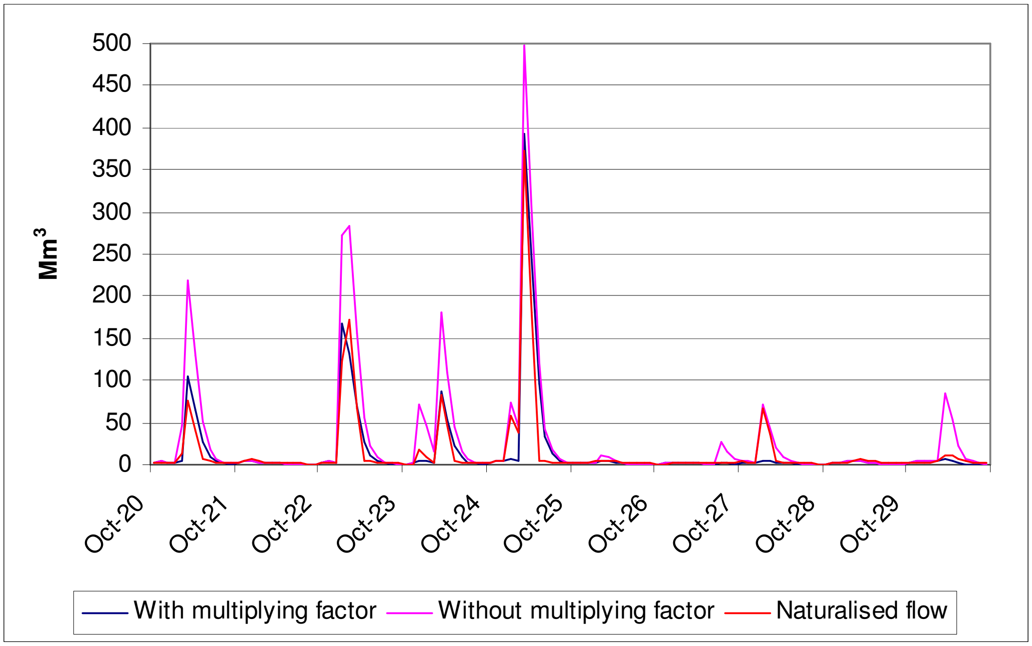


Figure 14a – Change in simulated flow in WB7 after applying the multiplying factor

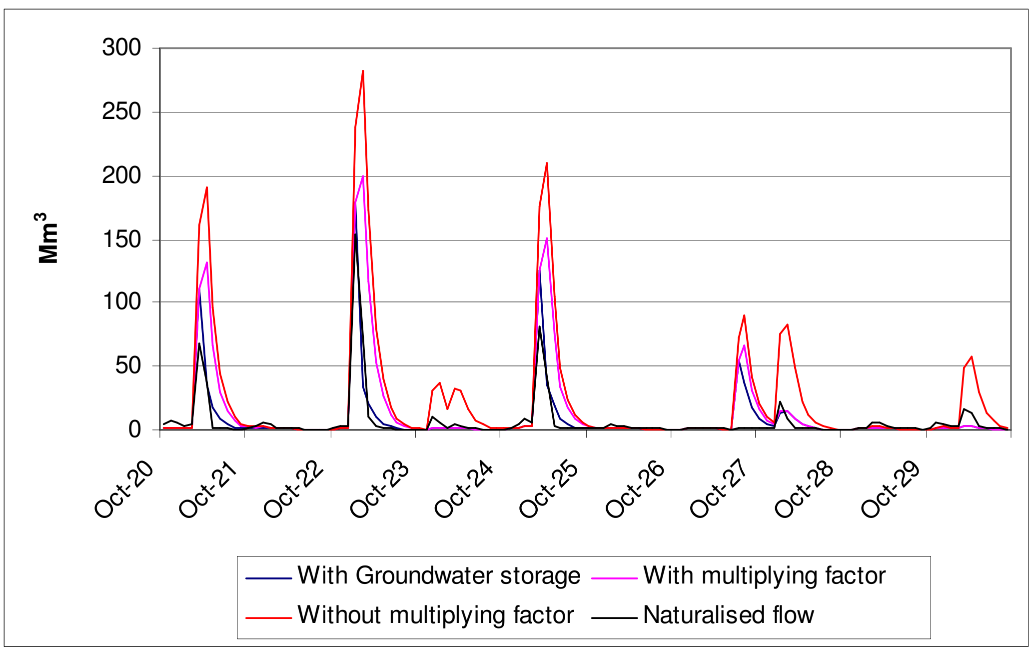


Figure 14b – Change in simulated flow in WB8 after applying the multiplying factor and groundwater storage

4. Calibration of the model

Agreement between simulated and naturalised values was assessed using two criteria: the least squares of logarithms objective function and the Nash-Sutcliffe efficiency criterion.

Optimisation of these two criteria led to different sets of parameters. However the best set of parameters was taken as the one that gave the 'best' model fit, using the two criteria. Table 16 presents the set of parameters that optimised the simulation for each subcatchment, the assessment criteria associated with each set of parameters, and compares the simulated and naturalised mean annual flow.

Table 16 – Results of calibration in each WEAP subcatchment

Catchment	Eff Precip	Run/infil	Hconduc	EFF	LSL	Avge/yr	Avge/nat
WB1	98	70/30	1.3	0.87	0.1	115.4	1.03
WB2	96.3	65/35	1	0.85	0.07	461.2	0.97
WB3	98	65/35	1.5	0.59	0.22	202.5	1.15
WB4	95	60/40	1.2	0.9	0.07	363.3	0.92
WB5	98	45/55	1.2	0.88	0.21	224.5	0.98
WB6	91	40/60	0.8	0.86	0.04	435.5	1.00
WB7	99	50/50	1.2	0.82	0.16	152.3	1.10
WB8	99.5	30/70	1	0.8	0.16	78.6	1.04
Olifants				0.93	0.046	2033	1.00

Eff Precip: Effective precipitation
Run/Infil: Runoff/Infiltration ratio
Hconduc: Hydraulic conductivity (m/day)
EFF: Nash-Sutcliffe efficiency criterion
LSL: Least squares of logarithms objective function
Avge/yr: simulated mean annual flow (Mm^3/year)
Avge/nat: ratio of simulated and naturalised mean annual flow

The lowest efficiency criterion is 0.59 for WB3 catchment and the highest is 0.9 for WB4 catchment. Overall criterion for the Olifants catchment is 0.93, which means that errors of the model are counterbalanced within different catchments to give a better overall simulation.

The least squares of logarithms objective function indicates large differences between the catchments. Comparing the values between catchments is not possible because the function depends on the volumes of flow. However overall value of the function for the Olifants catchment is less than many other (0.046), which means that the counterbalancing effect also occurs for the values of the least squares of logarithms objective function.

5. Parameters

In this section, the values of the different sets of parameters found in the model are reviewed.

Effective precipitation: the range goes from 91 to 99.5%. Lowest values are found for mountainous regions (WB6) and highest values are found in flat regions (WB8). Effective precipitation (i.e. precipitation available for evapotranspiration) usually depends on the intensity and duration of a rainfall event. Therefore it was not possible to compare parameter values with values inferred from the literature. However it is assumed that the steeper the area the lower the effective precipitation, which corresponds to the values found in the model.

Runoff/Infiltration ratio: the ratio ranges from 70/30 (WB1) to 30/70 (WB8). Groundwater recharge in the Olifants catchment is approximately 5% of mean annual rainfall (DWAF, 1991). This implies much lower values for runoff fraction. Ratio between 10/90 and 5/95 would be more likely to be found. However as the model is run on a monthly-time step, a large part of the runoff fraction simulated in WEAP could correspond to the rapid response of the aquifers.

Hydraulic conductivity: Values of hydraulic conductivity are about 1 meter/day for all subcatchments, which is relatively moderate. It corresponds to typical values for fractured rocks (Todd, 1980). Lowest hydraulic conductivity is found in WB6 where the dolomitic intrusion lies and for which hydraulic conductivity is supposed to be much lower (0.001 m/day, estimated from Todd, 1980).

6. Sensitivity analysis

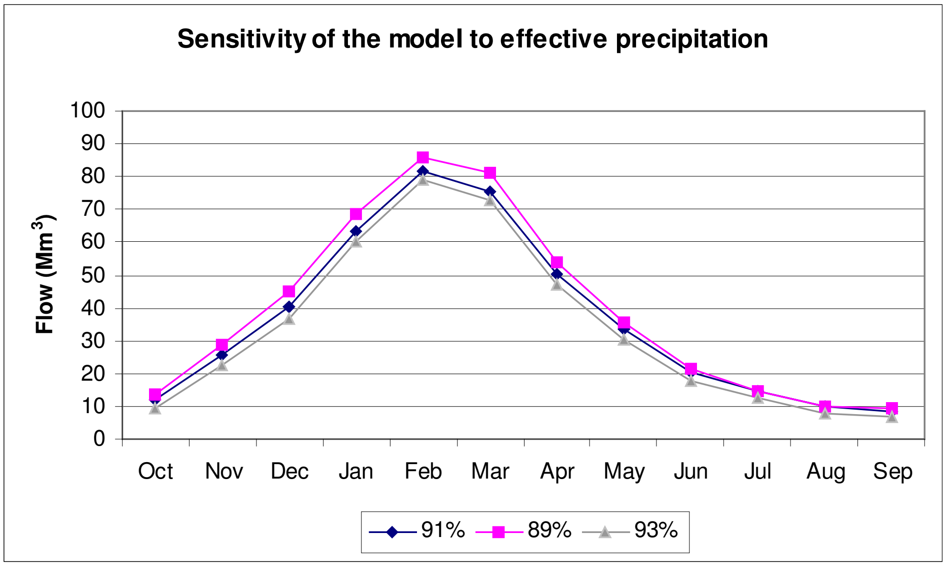
In order to assess the sensitivity of the model to the different parameters used for calibration, a sensitivity analysis was undertaken. Sensitivity of the model to parameters was assessed by estimating effects of changes in parameters on the Least squares objective function in the WB6 subcatchment. This function was chosen because it varies the same way as the Efficiency criterion but it is much more sensitive and it was easier to assess changes in the efficiency of the model. Mean monthly flow was also plotted and compared to the mean monthly flow corresponding to the best set of parameters.

Table 17 and figure15 present the results of the sensitivity analysis.

Table 17 – Variations of the Least Squares Objective function and of the mean annual simulated flow due to changes in the parameter values in WB6 subcatchment.

Parameter	Value		Least squares	Mean annual flow (Mm^3)
Effective precipitation	91		**334.7**	**435.5**
	89		342.7	467.9
	93		345.5	403.6
Runoff/infiltration ratio	40/60			
	35/65		343.5	435.5
	45/55		374.7	435.5
Hydraulic conductivity (m/day)	0.8			
	0.6		428.8	435.4
	1		305.8	435.5
Crop coefficients				
	+10%		347.6	385.8
	-10%		448.7	498.1

The sensitivity analysis shows that only effective precipitation and crop coefficients have an impact on the mean annual flow. Compared to the other parameters, Effective precipitation has a relatively low impact on the quality of the simulation (lowest variation of the Least squares objective function). In contrast hydraulic conductivity and crop coefficients variations seem to have the greatest impact on the model efficiency. Figure 15 (mean monthly flow variations) shows that hydraulic conductivity and runoff/infiltration ratio changes vary the balance in the quantity of water between summer and winter months, whereas effective precipitation and crop coefficients affect the mean monthly flow curve without impacting the relative flow in each month.



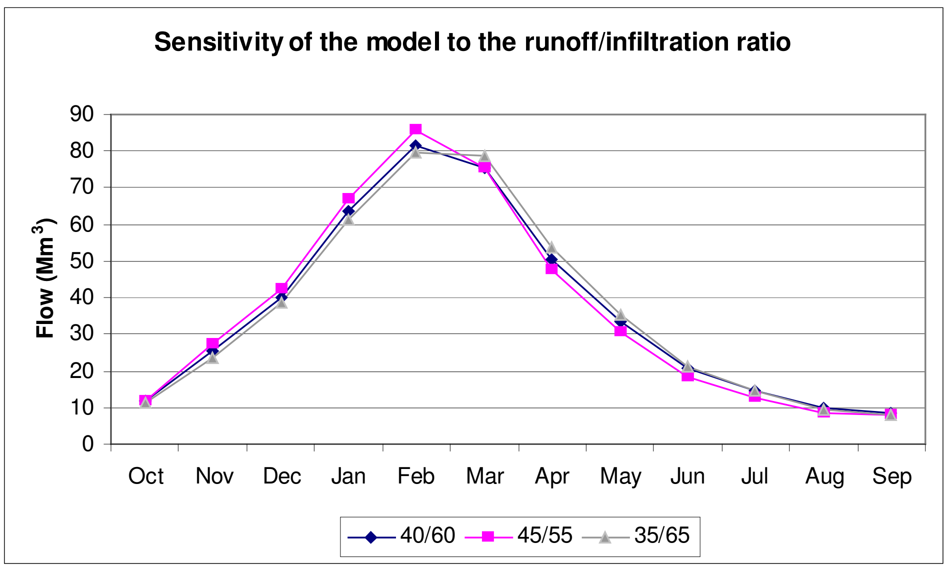
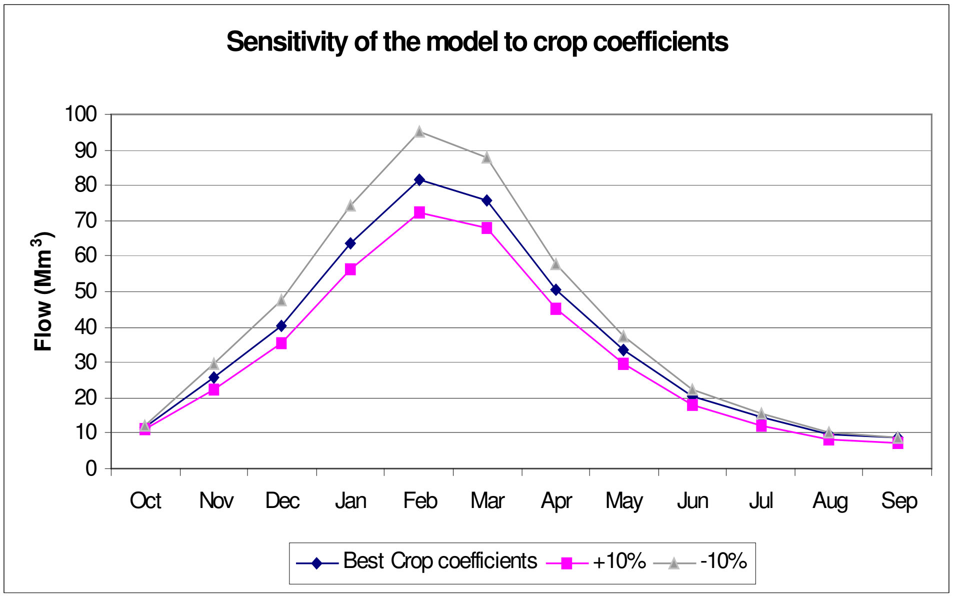


Figure 15 – Change in simulated mean monthly flow due to a) effective precipitation variation, b) runoff/infiltration ratio variation



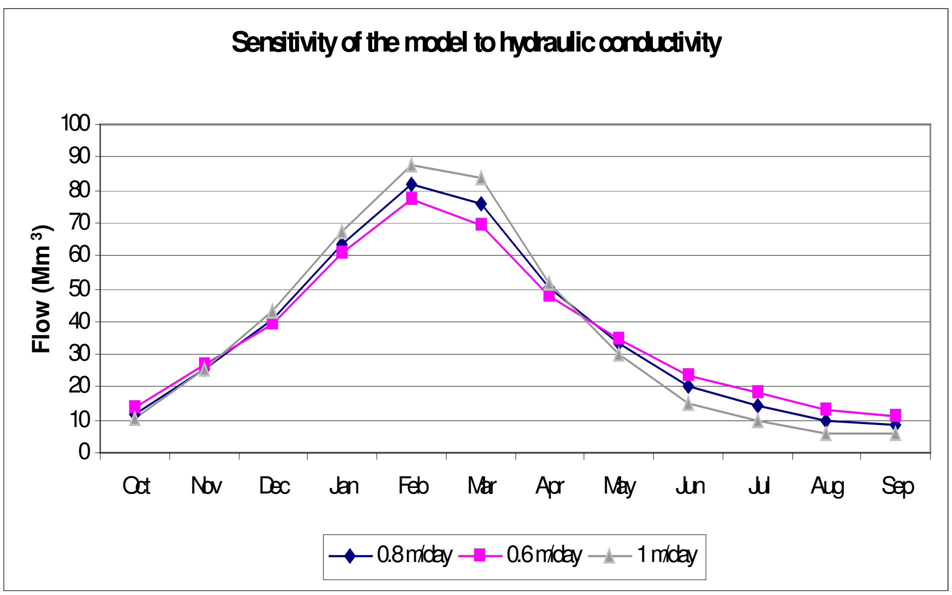


Figure 15 (continued) – Change in simulated mean monthly flow due to a) crop coefficients variation, b) hydraulic conductivity variation

Chapter 6

Simulation of flow in virgin conditions

This section presents the results of the simulation realised in WEAP with all the components disabled but the rainfall-runoff component.

1. Simulation of monthly flow

Figure 17 (a to r) is a comparison of naturalised and simulated flows at the outlet of each subcatchment for the period HY1980-HY1989 (arbitrarily chosen). Comparison of mean monthly naturalised and simulated flow for the entire period of simulation (HY1920-HY1989) is also presented in figure 14. It seems to be a good agreement in each subcatchment between naturalised and simulated flow. As for the efficiency criterion, it is in WB3 that simulated mean monthly flow seems to agree the least with naturalised data. In this catchment the model is systematically underestimating values of peak flows and overestimating low flows, but this could not be resolved during the optimisation routine. The fact that WB3 encompasses a large endhoeric region (i.e. an area with zero runoff) could be an explanation for the difficulty of calibration.

However important conclusions about the efficiency of the model are that:

- there is a good agreement in time concordance of peak flows
- return to low flow after a peak flow follow the same pattern in simulated and naturalised-plots which means that groundwater modelling gives an acceptable view of the slow response of the catchment.
- The model is generally either overestimating in summer and underestimating in winter or the contrary: error on the mean monthly flow seems to be seasonal.

Contribution of each subcatchment to the simulated runoff in the catchment is presented in figure 16.

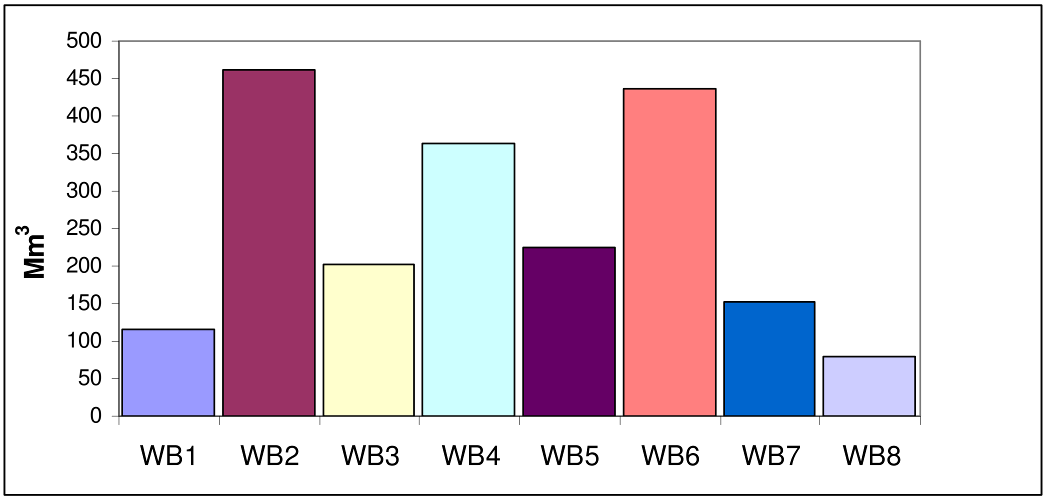


Figure 16 – Contribution of each subcatchment to simulated mean annual runoff.

Main contributions to mean annual runoff are from WB2 and WB6 catchments (respectively 461 and 436 Mm^3 per year). However calculation of runoff per unit area in each subcatchment (table 18) shows that WB6 is by far the most 'productive' in terms of runoff. On the contrary, WB3 and WB8 are the least 'productive' catchments, in particular because mean annual rainfall is at its lowest in these two catchments (see figure 3).

Table 18 – Mean annual runoff per unit area simulated in WEAP

Subcatchment	*Mean annual runoff (thousands of m^3 per km²)*
WB1	35.94
WB2	34.56
WB3	13.57
WB4	50.91
WB5	57.30
WB6	153.24
WB7	33.53
WB8	17.88

Mean annual runoff only represents about 6% of mean annual rainfall, which is a very low rainfall/runoff ratio even for a semi-arid area. The ratio ranges from 2.5% in WB3 to 17.8% in WB6. Evaporation therefore plays a determinant role in the water budget.

This simulation shows that the rainfall-runoff component of WEAP enables, given the monthly rainfall time-series, to assess the water resources of each subcatchment with good confidence.

The approach adopted by the WR90 study (see section 2.6) was to use flow records from gauging stations to derive naturalised flow-time series. In the current study, the only inputs required to run the model are the rainfall time-series, which makes of it a much more powerful tool to assess water resources in each subcatchment.

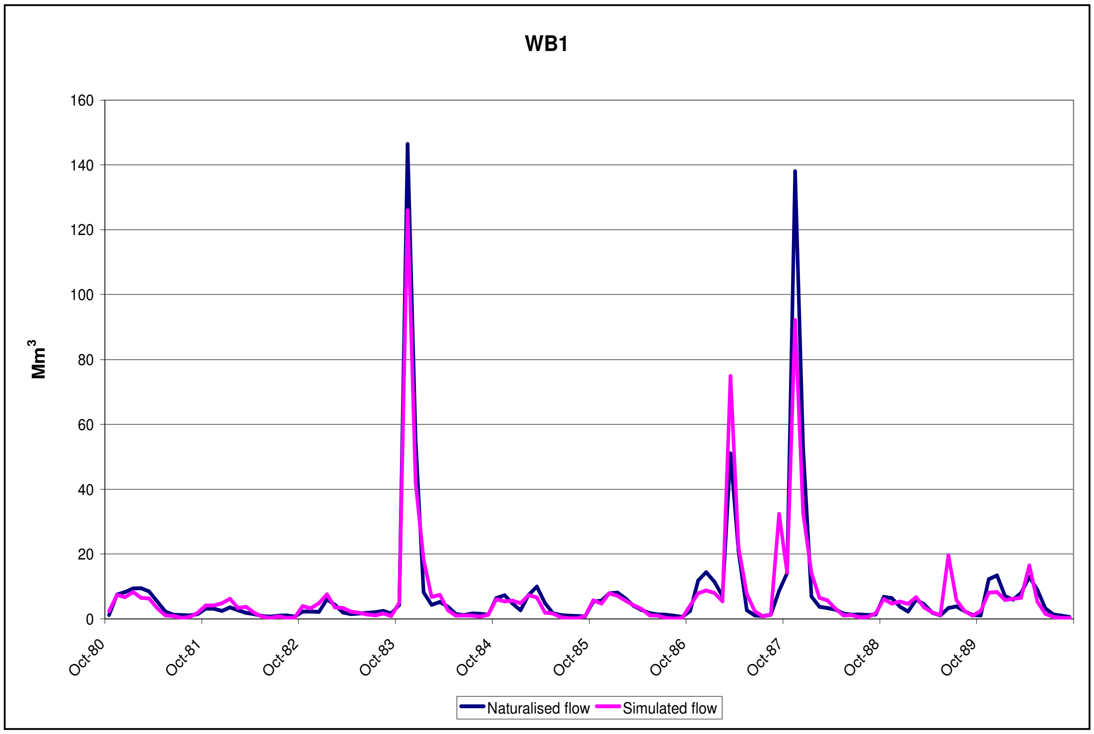


Figure 17-a)

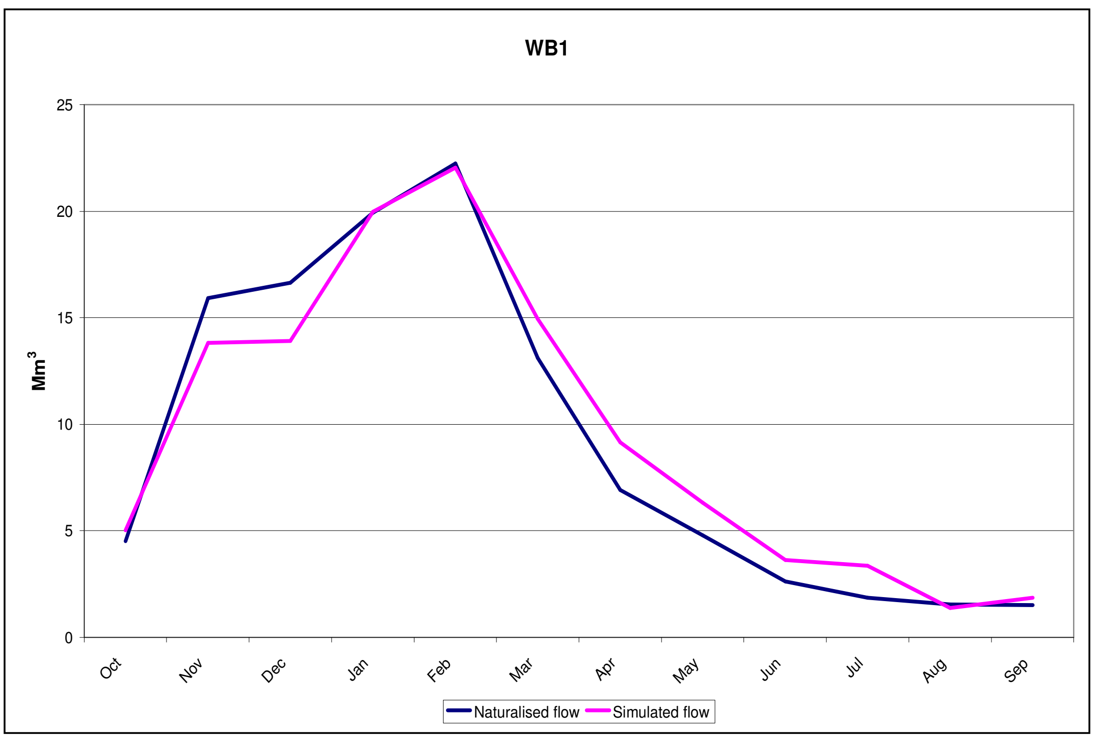


Figure 17-b)

Figure 17 – Comparison of simulated and naturalised a) monthly flow (HY1980-HY1989), b) mean monthly flow (HY 1920-HY1989) in WB1 subcatchment.

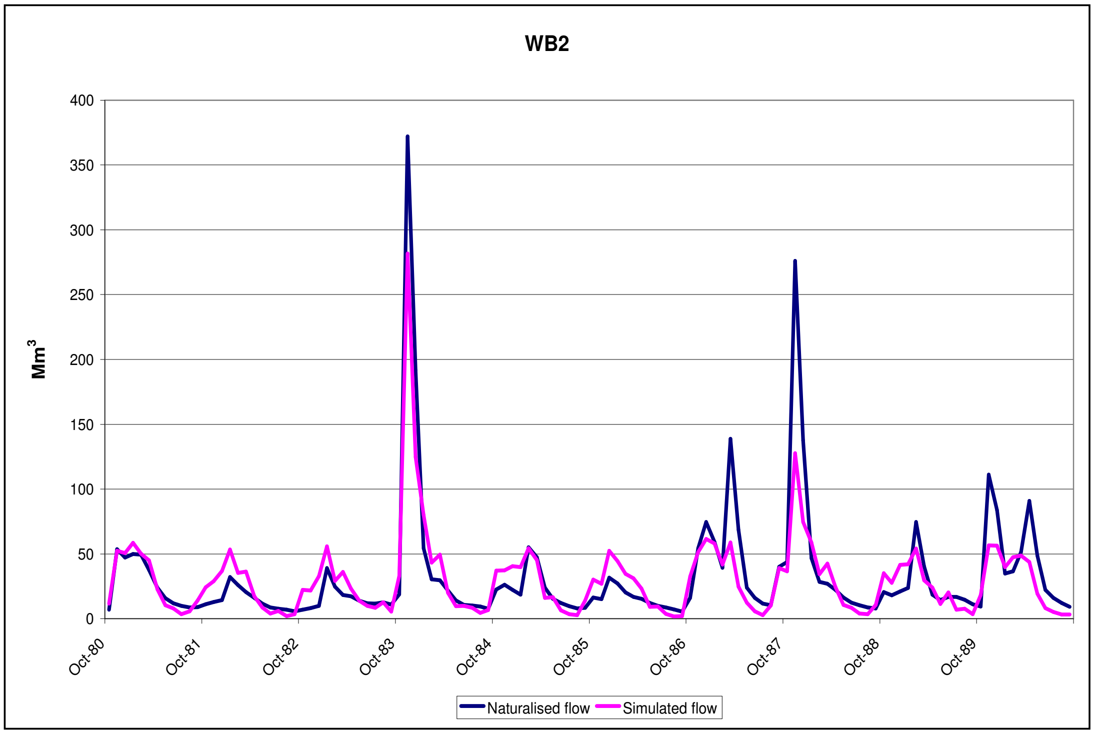


Figure 17-c)

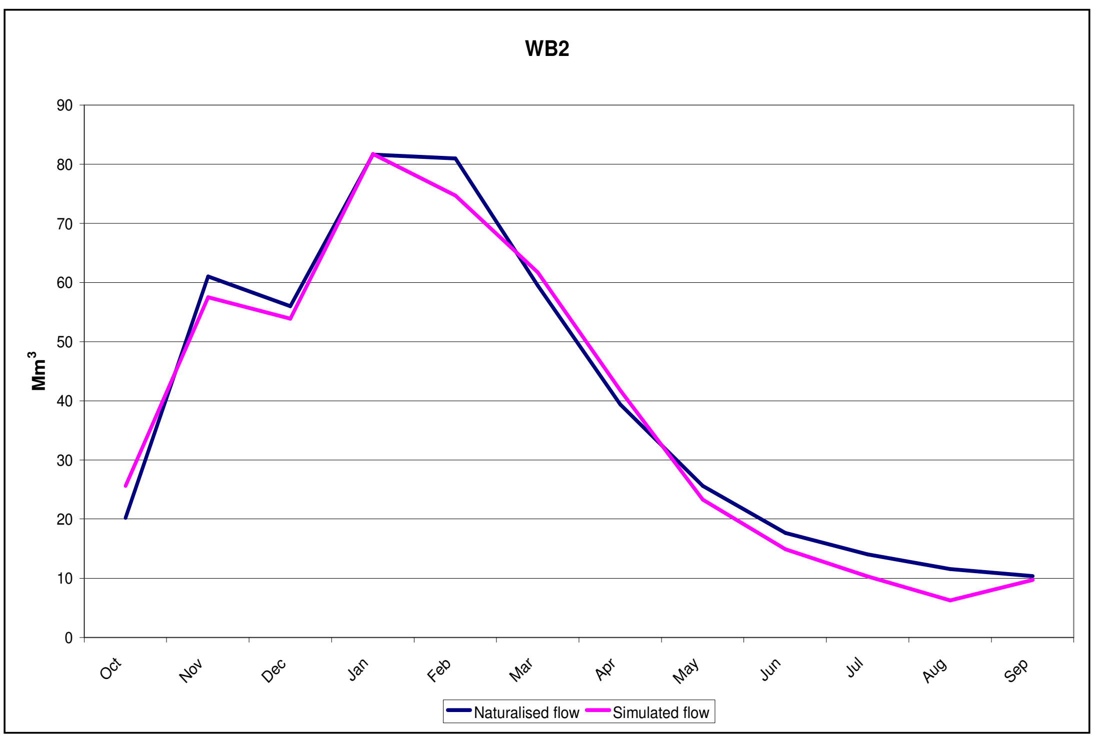


Figure 17-d)

Figure 17 – Comparison of simulated and naturalised c) monthly flow (HY1980-HY1989), d) mean monthly flow (HY 1920-HY1989) in WB2 subcatchment.

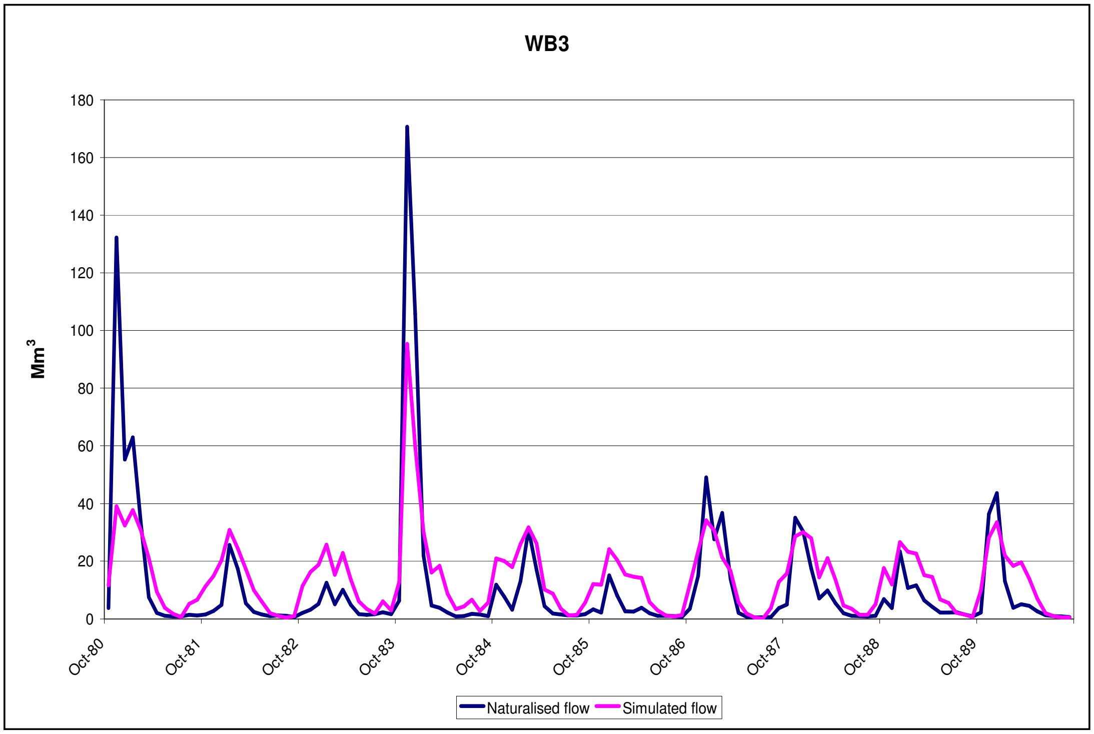


Figure 17-e)

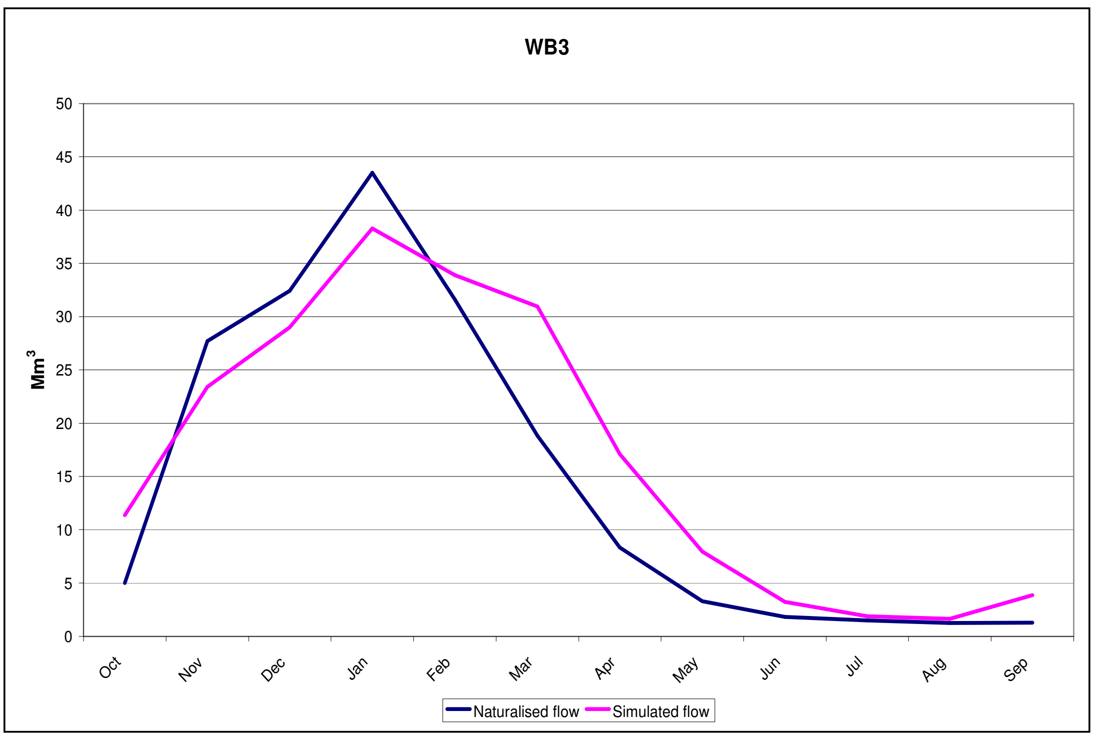


Figure 17-f)

Figure 17 – Comparison of simulated and naturalised e) monthly flow (HY1980-HY1989), f) mean monthly flow (HY 1920-HY1989) in WB3 subcatchment.

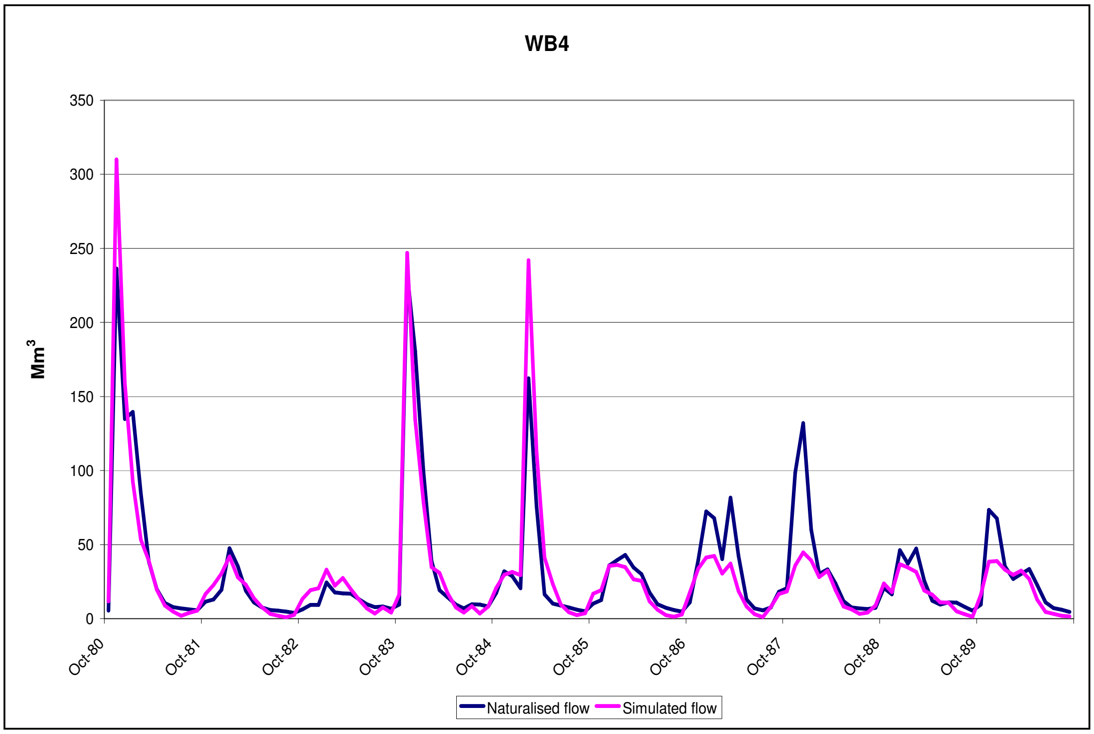


Figure 17-g)

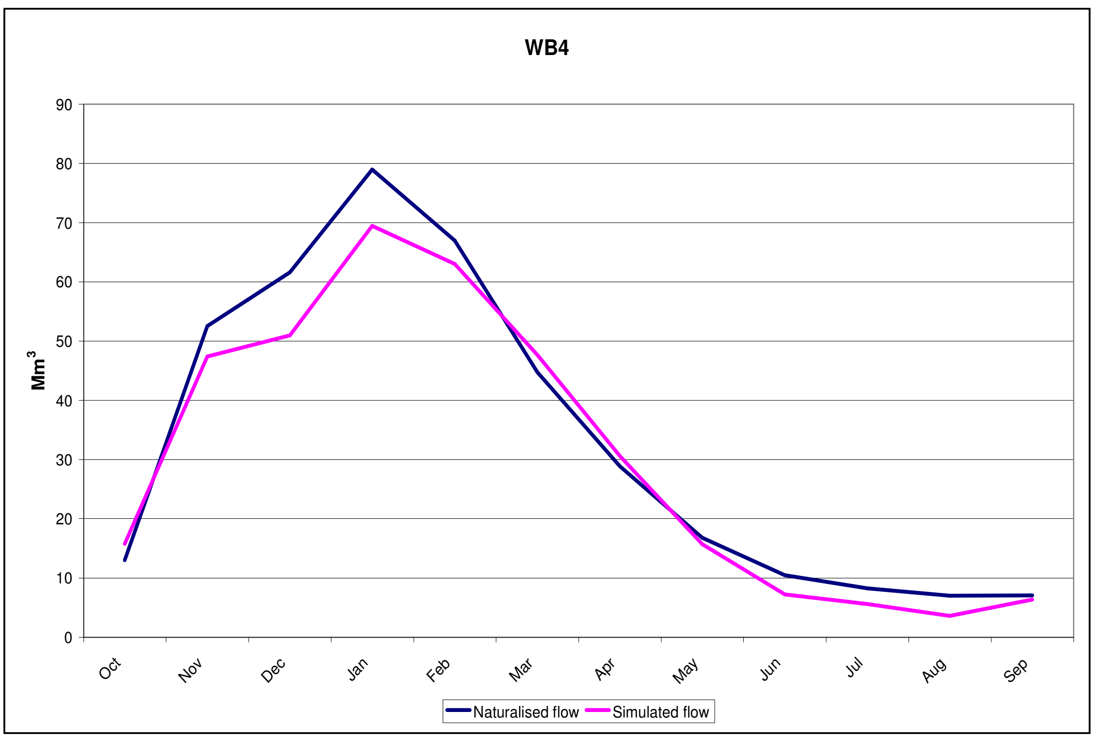


Figure 17-h)

Figure 17 – Comparison of simulated and naturalised g) monthly flow (HY1980-HY1989), h) mean monthly flow (HY 1920-HY1989) in WB4 subcatchment.

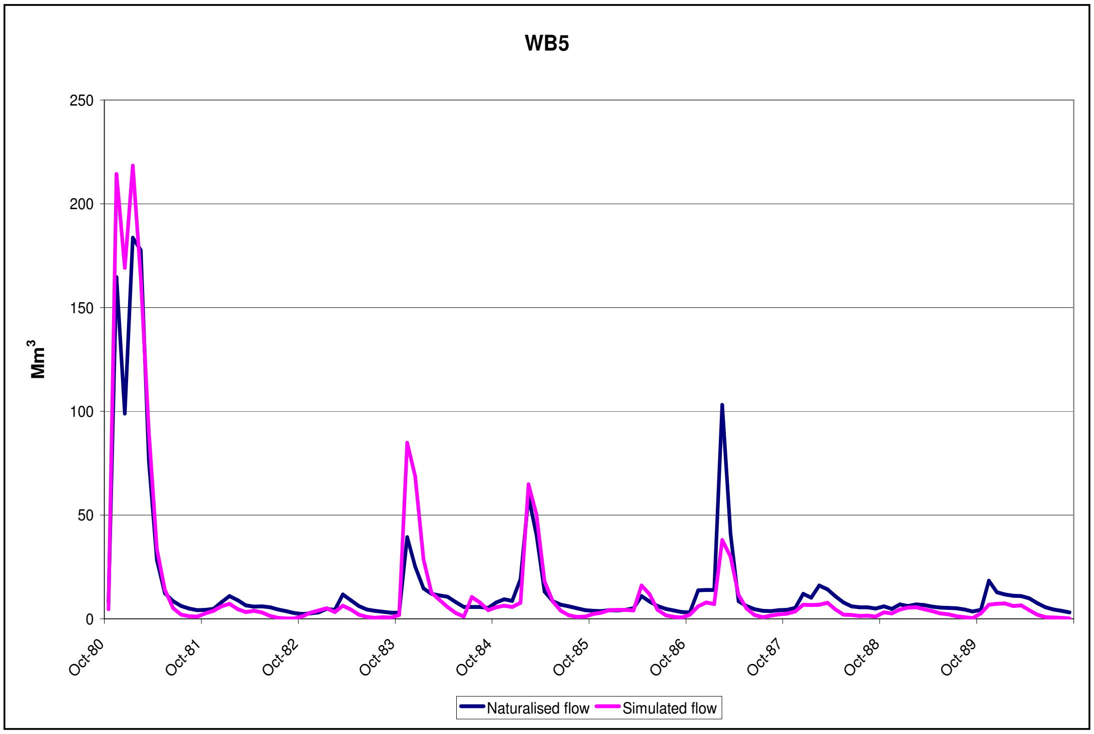


Figure 17-i)

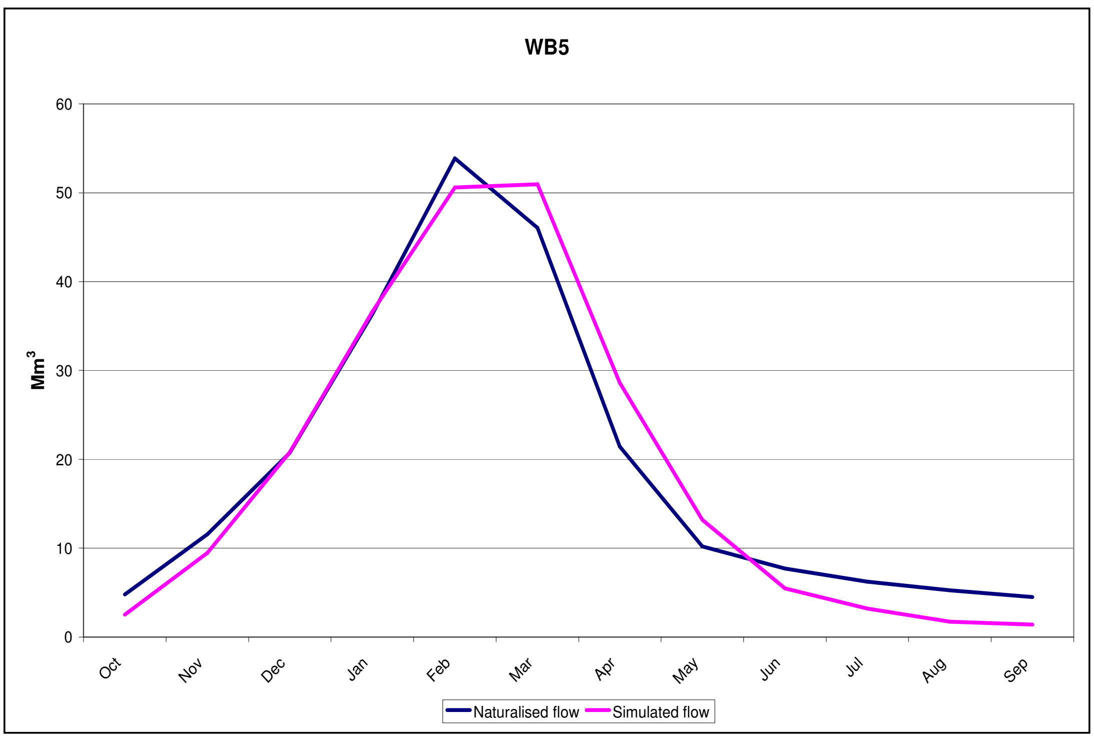


Figure 17-j)

Figure 17 – Comparison of simulated and naturalised i) monthly flow (HY1980-HY1989), j) mean monthly flow (HY 1920-HY1989) in WB5 subcatchment.

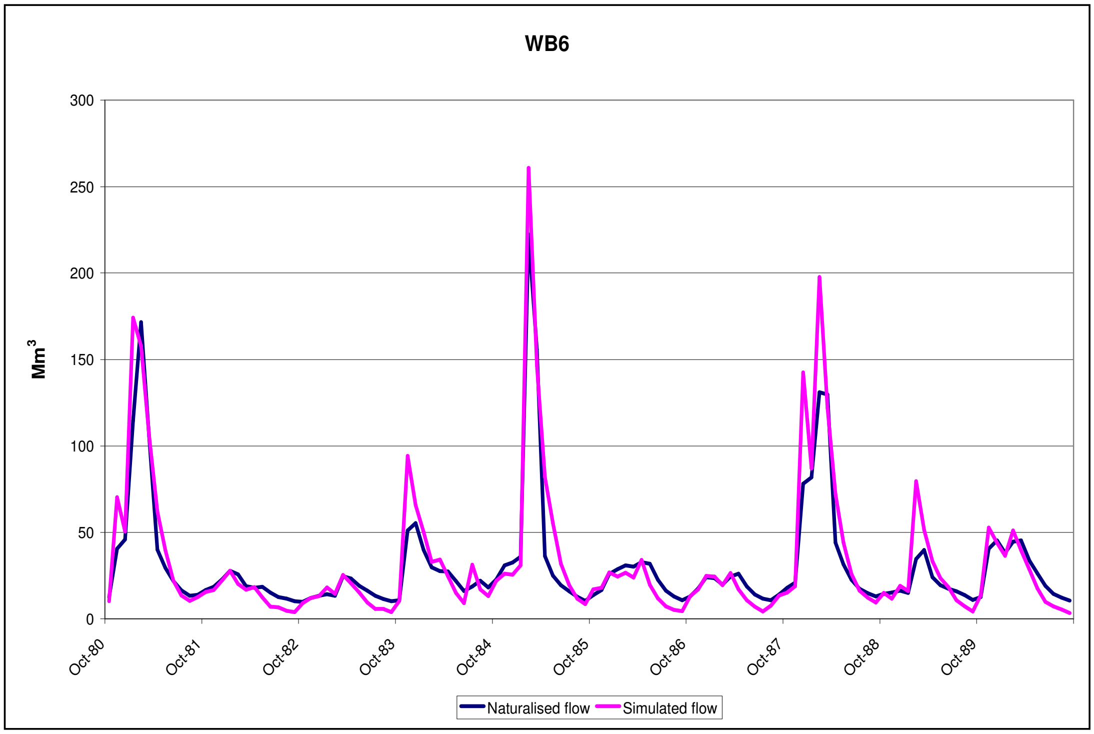


Figure 17-k)

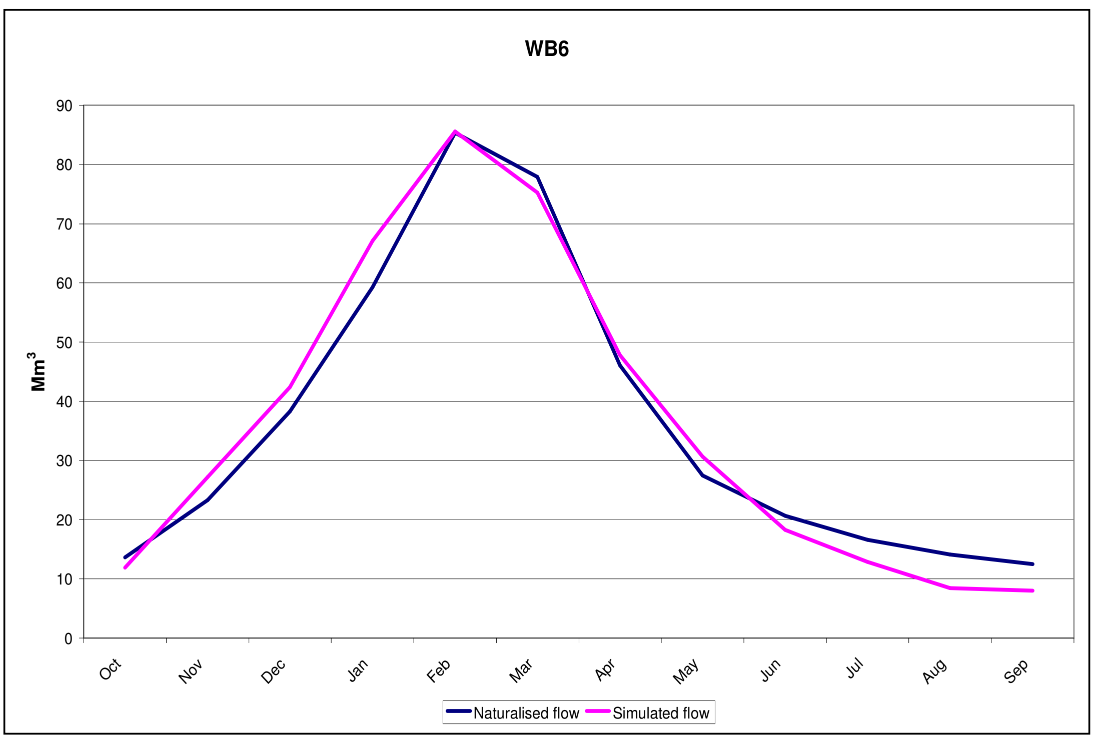


Figure 17-l)

Figure 17 – Comparison of simulated and naturalised k) monthly flow (HY1980-HY1989), l) mean monthly flow (HY 1920-HY1989) in WB6 subcatchment.

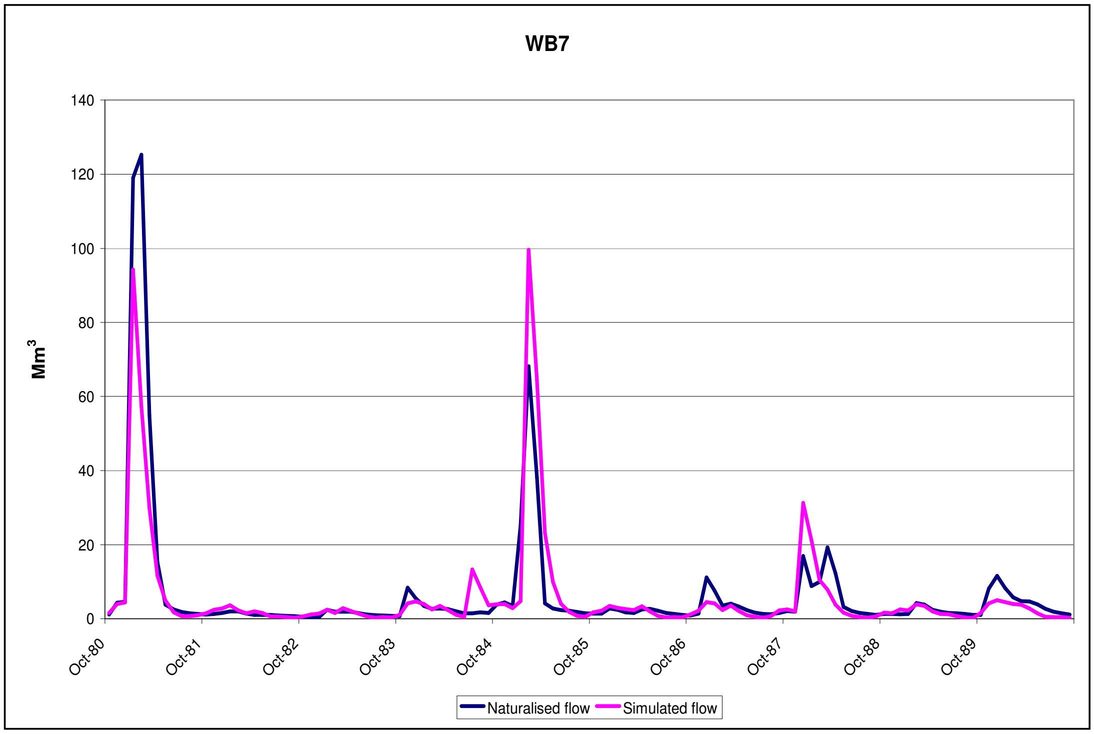


Figure 17-m)

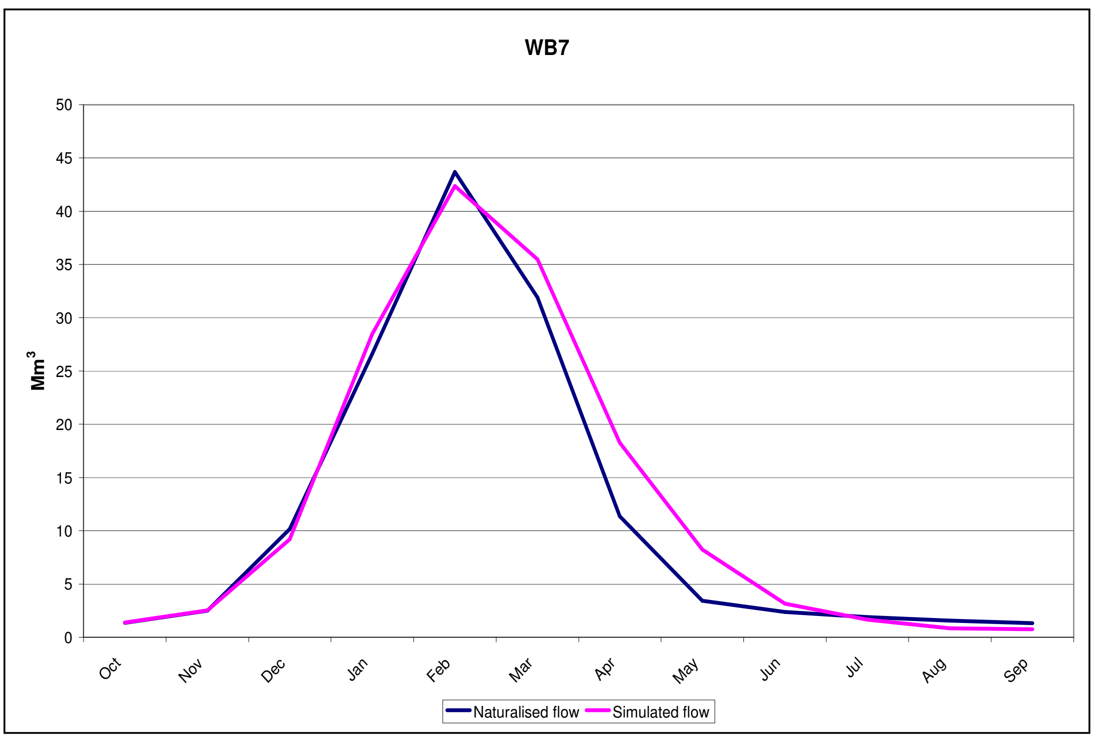


Figure 17-n)

Figure 17 – Comparison of simulated and naturalised m) monthly flow (HY1980-HY1989), n) mean monthly flow (HY 1920-HY1989) in WB7 subcatchment.

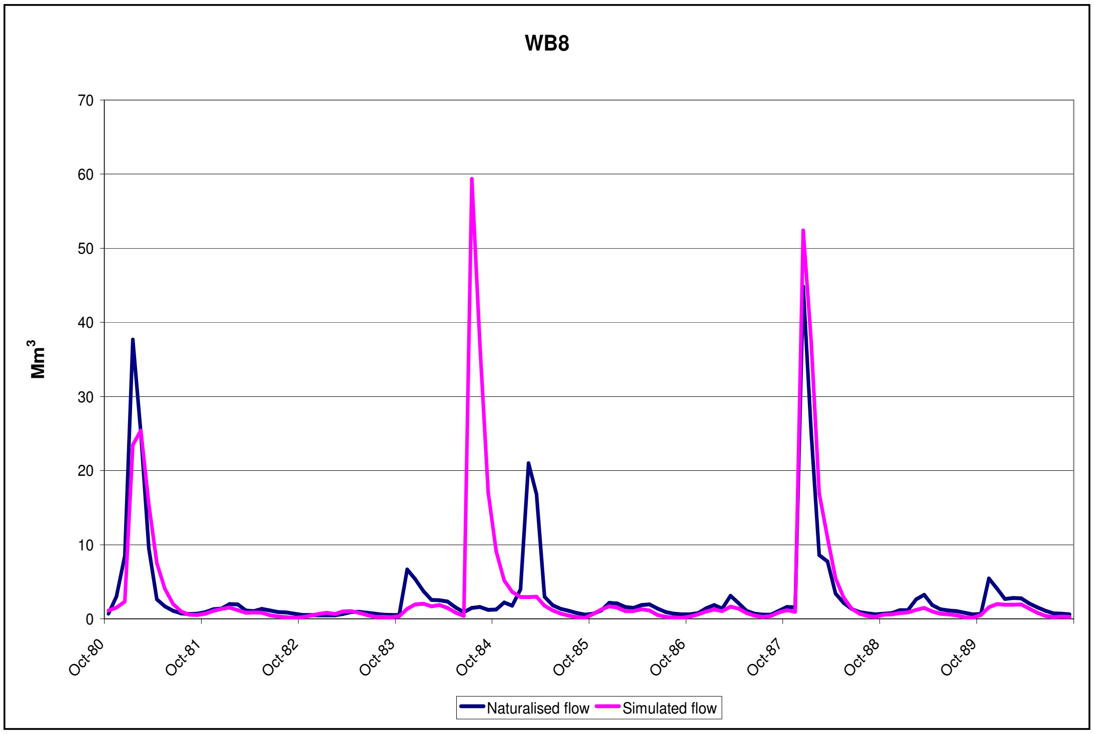


Figure 17-o)

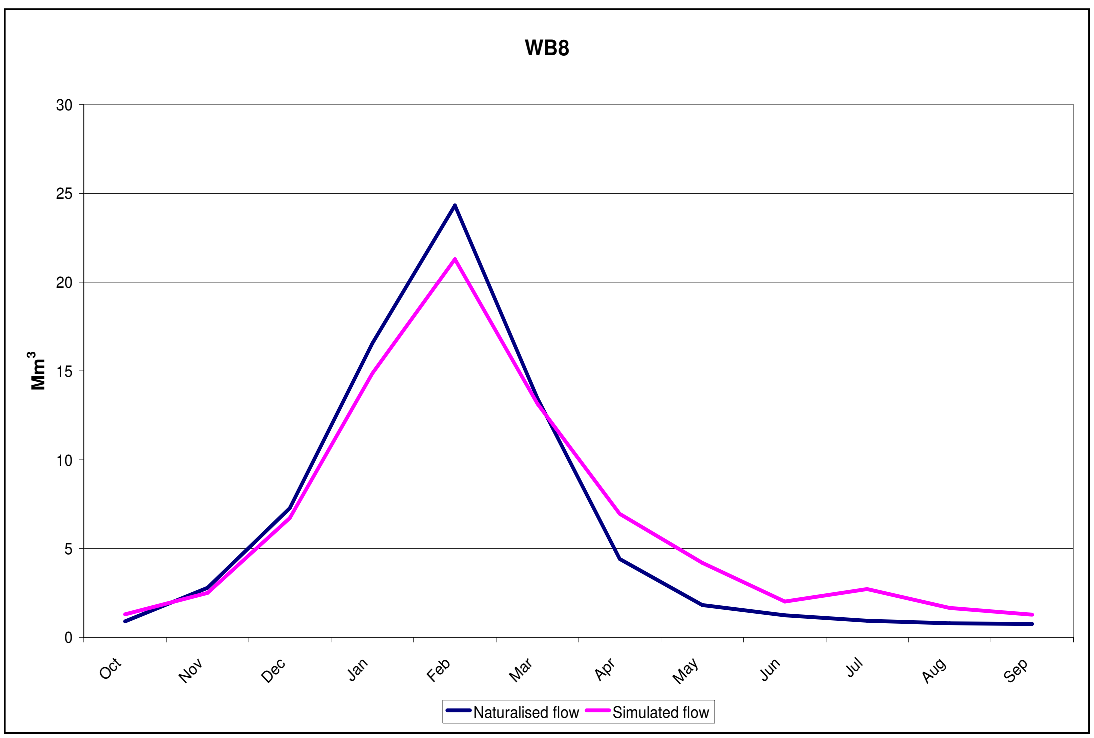


Figure 17-p)

Figure 17 – Comparison of simulated and naturalised o) monthly flow (HY1980-HY1989), p) mean monthly flow (HY 1920-HY1989) in WB8 subcatchment.

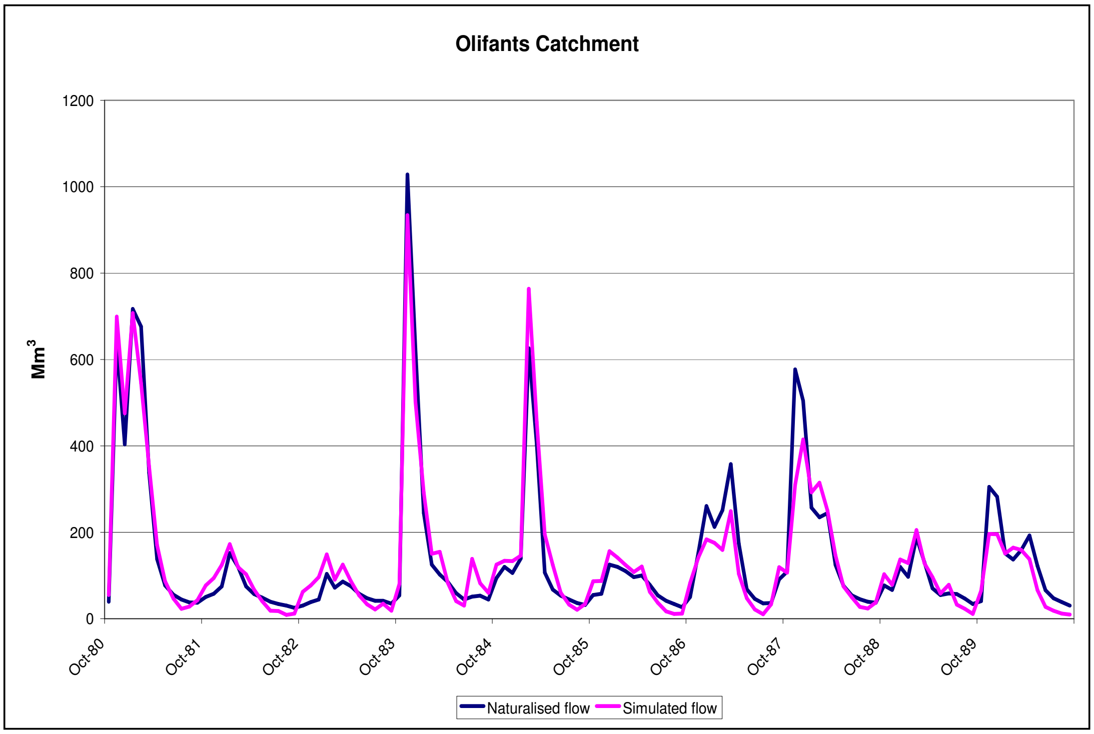


Figure 17-q)

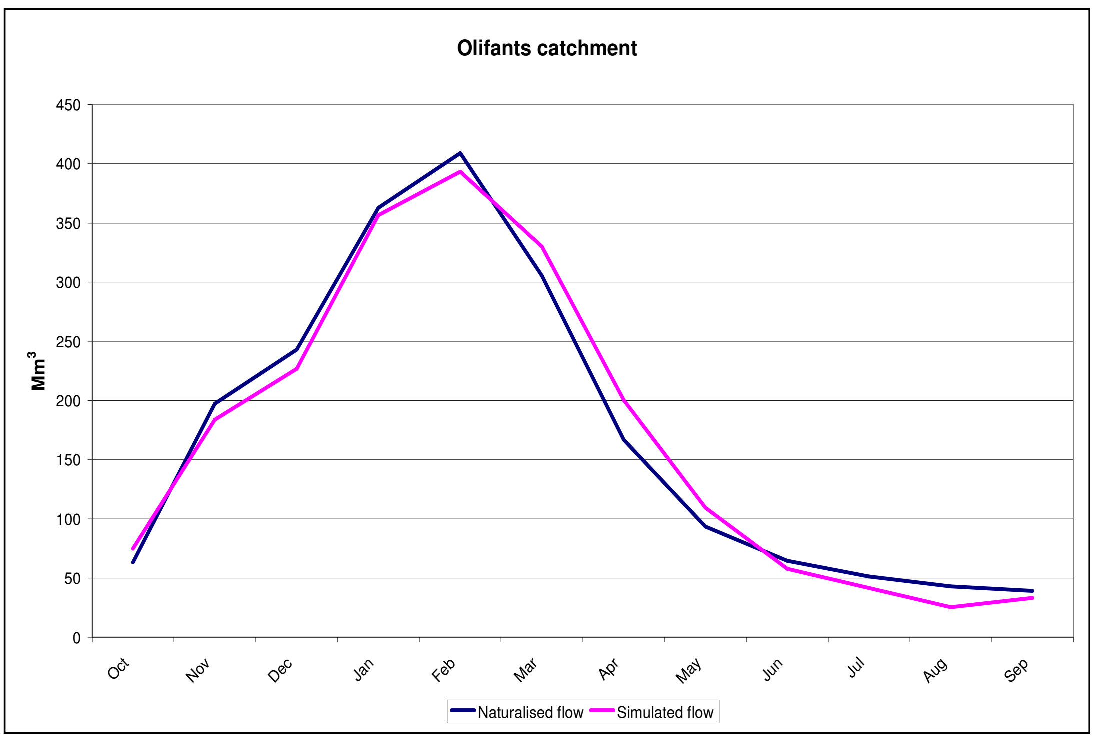


Figure 17-r)

Figure 17 – Comparison of simulated and naturalised q) monthly flow (HY1980-HY1989), r) mean monthly flow (HY 1920-HY1989) in the Olifants catchment.

Chapter 7

Simulation of current land use

Once the rainfall-runoff component of WEAP was calibrated and the model parameters determined for each WEAP catchment, the model was run in its water allocation mode, including effects of development due to land-use change and water demand. Validation of the simulation was achieved by comparing simulated flow with monthly time-series from 5 gauging stations with different flow record periods (see section 8.10) and located on the Olifants main stem.

First the model was run considering only land-use changes. This was done in order to assess the impact of the current land use on the catchment runoff. Changes in land use mainly impact the catchment response, on a monthly time-scale, because of the change in evapotranspiration they induce. In the Olifants catchment, afforestation and development of tree plantations (like eucalyptus and pine which demand much more water than indigenous vegetation) are supposed to have reduced runoff by 175 Mm^3 per year (DWAF, 2003b).

1. Computation of WEAP catchments crop coefficients

Changes in land use are modelled in WEAP by changing the crop coefficients values. Land use data are available for each quaternary catchment in the Olifants basin. This is the result of a national high-resolution satellite imagery project known as the South African National Land Cover Project (CSIR 2003), and which provides detailed maps of land use within each catchment. Land use data (available for quaternary catchments) were used to compute land-use classification of each WEAP subcatchment (Appendix A).

In each subcatchment, land-use types accounting for more than 5% of the total area were then considered for the computation of area weighted crop coefficients. This gave 9 land use classes. Crop coefficients associated to each land use class were extracted from the ACRU database (Schulze et al, 1995) as presented in table 19.

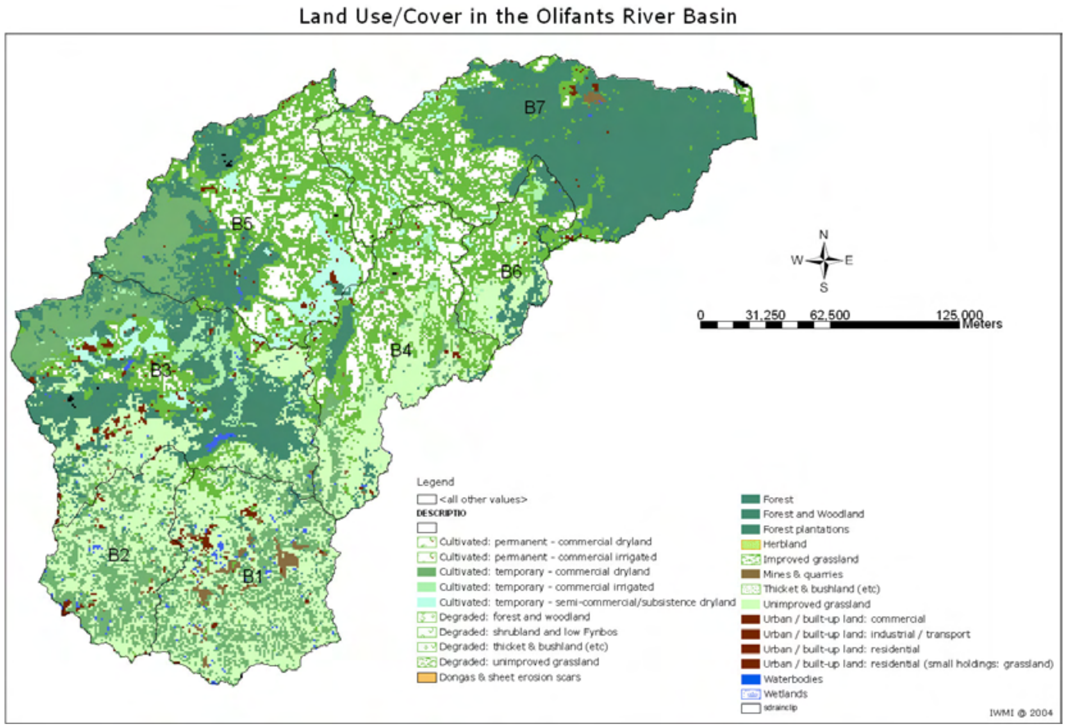


Figure 18 – Map of land use in the Olifants catchment

Table 19 – Land-use types used for simulation of current land-use impact on the catchment runoff

Land use type	Name in ACRU	Total area in the whole Olifants catchment (km²)
Cultivated: temporary - commercial dryland	Maize	8,146
Cultivated: temporary - commercial irrigated	Maize	1,035.1
Cultivated: temporary - semi-commercial/subsistence dryland	Subsistence crops	2,264.5
Degraded: forest and woodland	Woodland - Indigenous/Tree-bush savannah	3,917
Degraded: thicket & bushland (etc)	Bush/Veld general	729.8
Forest and Woodland	Woodland - Indigenous/Tree-bush savannah	14,011
Forest plantations	Eucalyptus mature	823.55
Thicket & bushland (etc)	Bush/Veld general	8,958
Unimproved grassland	Veld in good conditions	12,132

Area-weighted crop coefficients were determined using the following equation:

$$Kc = \frac{\sum_{i=1}^{N} Kc_i \times A_i}{A}$$

with Kc_i the crop coefficient associated to land use type i, A_i the area occupied by land use i in the subcatchment and A the area of the whole subcatchment.

The same multiplying factors determined in the calibration of the rainfall-runoff component of the model (see section 5.3) were then applied to each set of crop coefficients.

Table 20 presents the crop coefficients corresponding to the current land use in each subcatchment (after the multiplying factor has been applied).

Table 20 – Monthly variations of crop coefficients used in each WEAP subcatchment for simulation of current land-use impact on the catchment runoff

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
WB1	0.57	0.76	1.05	1.15	1.07	1.07	0.74	0.52	0.28	0.28	0.28	0.35
WB2	0.69	0.83	1.02	1.09	1.04	1.03	0.81	0.60	0.42	0.40	0.40	0.49
WB3	0.76	0.87	1.03	1.09	1.04	0.99	0.84	0.72	0.63	0.62	0.62	0.68
WB4	0.81	0.92	0.95	0.98	0.98	0.96	0.86	0.68	0.53	0.45	0.45	0.61
WB5	0.83	0.98	1.01	1.03	1.02	0.99	0.88	0.74	0.62	0.49	0.49	0.69
WB6	0.65	0.75	0.80	0.83	0.82	0.81	0.70	0.57	0.46	0.40	0.40	0.52
WB7	0.96	1.01	1.02	1.03	1.03	1.00	0.97	0.84	0.81	0.77	0.77	0.87
WB8	1.03	1.04	1.04	1.04	1.04	1.04	1.04	0.91	0.90	0.90	0.90	0.97

2. *Assessment of current land-use impact on catchment runoff*

Once again the model was run on a monthly time-step over the 70 years period HY1920-HY1989.

Results of the model gave a mean annual runoff of 1,681 Mm^3, compared to a mean annual runoff of 2,033 Mm^3 in the virgin conditions. Reduction in runoff simulated by the model (352 Mm^3) is about twice the reduction in runoff estimated by DWAF due to afforestation and alien vegetation.

Change in runoff for each WEAP subcatchment is given in table 21.

Table 21 – Difference in simulated mean annual flow (Mm^3) in each WEAP subcatchment depending on the land-use type used for simulation.

Catchment	Virgin land use	Current land use
WB1	115.4	97.9
WB2	461.2	368.3
WB3	202.5	196.8
WB4	363.3	275.1
WB5	224.5	134.7
WB6	435.5	442.4
WB7	152.3	114.4
WB8	78.6	51.8
Olifants	2033	1681.4

Reductions in runoff were observed in all subcatchments but WB6. This catchment was supposed to be heavily forested under virgin conditions, and reduction of forested areas under current land-use conditions caused the runoff to increase. In all other subcatchments flow was reduced by approximately 20% compared to virgin land-use conditions.

Chapter 8

Water allocation model

Water demand data used in the study were derived from a database established by DWAF and known as the Water Situation Assessment Model (WSAM). This database provides data of water demand and uses throughout South Africa at the quaternary catchment scale for the year 1995 (Schultz and Watson, 2002). Data taken from WSAM were used as a baseline to estimate water use within the Olifants WMA for the period of study.

Water use in the Olifants catchment has already been modelled in a previous IWMI study (McCartney et al., 2004b). In that study water demand was divided into five water-use sectors: irrigation, urban, rural, mining and commercial forestry. As water use from commercial forestry was already taken into account through the land use changes, this was disabled in the current study. For the other sectors, changes in water demand over time were taken from that study. However, very little quantitative information is available on changes in demand over time and for most sectors these were simply estimated.

1. Urban water demand

The urban water requirement encompasses industrial, commercial, institutional and municipal water requirement and losses. Within WEAP the total consumptive water requirement (i.e. that which is consumed and does not contribute to sewage/effluent) was used. There was assumed to be no monthly variation. Change in demand over time was assumed to be linear, with a more rapid rise after 1950 to reflect perceived population increase (Table 22).

Table 22 - Estimated change over time in annual net urban demand (Mm^3) for WEAP simulation

Subcatchment	1920	1950	1989	1995
WB1	0.05	0.20	0.81	0.90
WB2	2.00	5.00	17.14	19.01
WB3	0.50	1.00	4.20	4.69
WB4	0.05	0.20	0.80	0.89
WB5	0.00	0.00	0.02	0.02
WB6	0.00	0.00	0.02	0.03
WB7	0.10	0.50	2.00	2.23
WB8	0.00	0.00	0.00	0.00
Total	2.70	6.90	24.99	27.77

2. *Rural water demand*

The rural water requirement encompasses all domestic water requirements outside of urban areas. It includes stockwatering and subsistence irrigation on small rural garden plots. Irrigation on large plots and formal irrigation schemes are included in the irrigation demand (section 8.4). Within WSAM the domestic and stockwater requirements are based on per capita consumption rates. Return flows are believed to be negligible, so the total requirement is the same as the net demand. Again there was assumed to be no monthly variation and change in demand over time was assumed to be linear, with a slightly more rapid rise after 1950 to reflect perceived population increase (table 23).

Table 23 - Estimated change over time in annual net rural demand (Mm^3) for WEAP simulation

Subcatchment	1920	1950	1989	1995
WB1	0.40	0.60	0.89	0.93
WB2	2.00	7.00	18.06	19.76
WB3	5.00	12.00	29.69	32.41
WB4	0.75	3.00	6.54	7.08
WB5	0.75	2.50	6.39	6.99
WB6	0.30	0.40	0.66	0.70
WB7	0.50	2.00	5.17	5.66
WB8	0.01	0.01	0.02	0.02
Total	9.71	27.51	67.42	73.55

3. *Mining*

Mining represented 22.1 % of the economic activity of the management area in terms of GGP in 1997. Average growth in the sector between 1988 and 1997 was 4.2 % (DWAF, 2003b).

Mines use a significant amount of water in the processing of ores and constitute the next largest water user after irrigation. The total consumptive water requirement was entered within WEAP. As no data were available on change of demand over time, water use was assumed to be negligible before 1950 and to rise linearly after 1950 (Table 24).

Table 24 - Estimated change over time in annual consumption of water in mines for WEAP simulation

Subcatchment	*1950*	*1989*	*1995*
WB1	0.00	5.63	6.49
WB2	0.00	8.76	10.11
WB3	0.00	1.59	1.83
WB4	0.00	11.74	13.54
WB5	0.00	7.81	9.01
WB6	0.00	0.22	0.37
WB7	0.00	30.60	35.31
WB8	0.00	0.00	0.00
Total	0.00	73.40	76.70

4. Irrigation

Irrigation is the largest consumer of water within the Olifants catchment. Between 1950 and 1995 the irrigated area increased from approximately 34,000 ha to approximately 110,000 ha (Table 25). McCartney et al. (2004b) estimated the average annual water demand and return flows for each WEAP subcatchment using the 1995 data available for each quaternary catchment in WSAM. Within WEAP the annual demand was expressed as a volume per hectare irrigated, while return flows were expressed as a percentage of the demand (Table 25). Differences between subcatchments in relation to per hectare demand and return flows are believed to reflect differences in rainfall and the crops irrigated.

From 1955, the change in irrigated area over time for each of the delineated secondary catchments within the Olifants catchment was derived from DWAF reports (McCartney et al., 2004b). Using the geographically most contiguous secondary catchment, these data were used to estimate the temporal patterns of change for each of the WEAP subcatchments (table 25 and figure 19). No quantitative data were available for the years before the 1950s. However, it is known that formal irrigation schemes largely commenced between the mid-1920s and the early 1930s (Turton and Meissner, 2003). For the WEAP simulation, the assumption was made that irrigated area in 1920 was negligible and a linear rise occurred, in all subcatchments, until 1955 (i.e., the first date when actual data are available). The percentage of return flow was assumed to be the same in all years (Table 25).

Table 25 - The effective annual demand of each irrigated hectare and the estimated change over time in irrigated area in each of the WEAP subcatchments

Subcatchment	Annual demand (m^3/ha)	Area Irrigated (ha)					Return flow (% of demand)
		1920	1955	1968	1988	1995	
WB1	3,567	0	306	451	2,332	2,413	6.4
WB2	4,513	0	12,081	35,742	45,186	47,315	9.5
WB3	5,835	0	14,524	17,604	12,166	29,892	10.0
WB4	5,690	0	4,203	7,654	12,118	13,104	8.6
WB5	6,577	0	1,702	2,062	1,425	3,502	7.6
WB6	3,770	0	3,875	9,400	11,297	8,291	8.1
WB7	5,039	0	1,819	3,295	5,842	5,730	7.3
WB8	-	0	0	0	0	0	-
Total		0	38,510	76,208	90,366	110,247	

Source: estimated from data in DWAF, 1991 and the WSAM database.

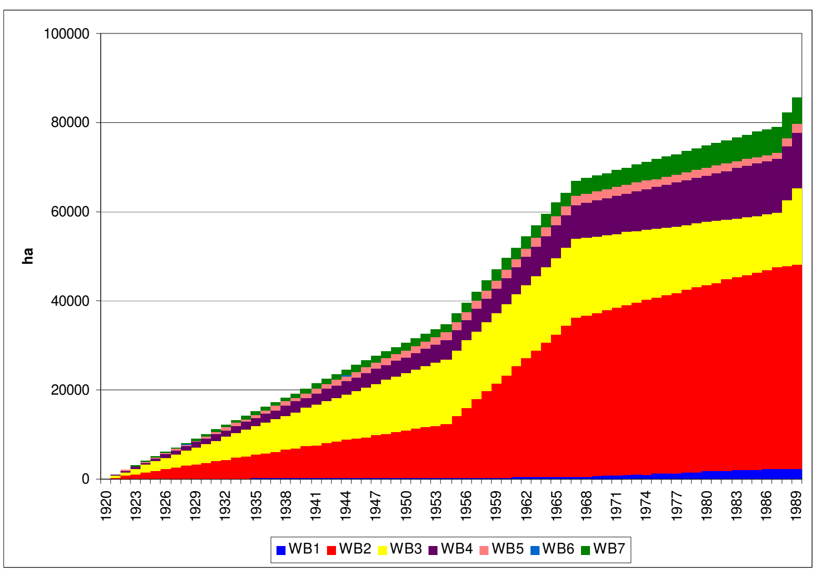


Figure 19 - Estimated change in irrigated area between 1920 and 1990 (derived from data in DWAF, 1991 and the WSAM database).

Assuming that differences in rainfall are the predominant cause for inter-catchment variation in the quantities of water used per hectare of irrigation, McCartney et al. (2004b) derived a linear relationship, by regression, between the mean annual precipitation and the mean annual per hectare irrigation demand in each of the subcatchments (Figure 20). This relationship was used to compute annual irrigation demand per hectare from the time series of annual rainfall derived for each of the subcatchments. The equation constant was altered for each subcatchment to ensure that the mean of the annual demand per hectare, calculated over the 70 year time series, remained that presented in table 25. The sets of linear relationships derived for each subcatchment are presented in table 26 and have been plotted in figure 21. The different curves can be perceived as allowing for differences in crops and irrigation practices in each of the subcatchments.

Table 26 - Equations to compute annual irrigation demand (m^3ha^{-1}) from area averaged annual rainfall (mm) for each of the WEAP subcatchments.

Subcatchment	Multiplier	Constant
WB1	-7.66	8892.4
WB2	-7.66	9631.0
WB3	-7.66	10217.3
WB4	-7.66	10860.4
WB5	-7.66	11593.4
WB6	-7.66	10375.6
WB7	-7.66	9832.6

Source: McCartney et al., 2004b.

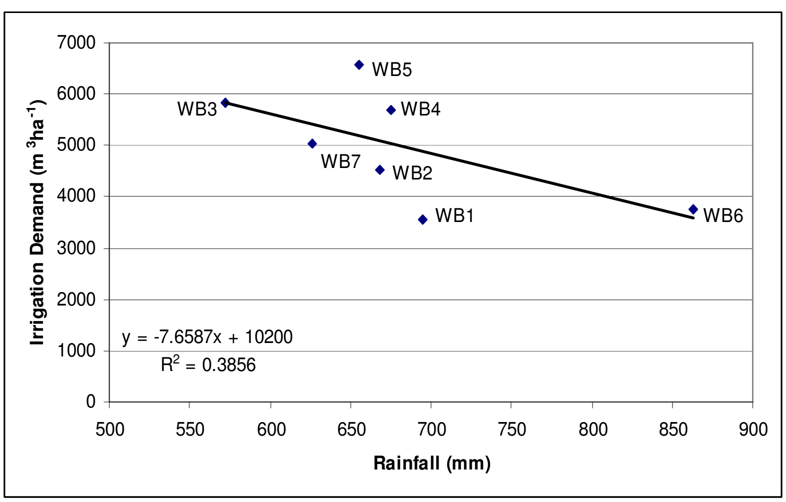


Figure 20 - Relationship between mean annual rainfall and per hectare irrigation demand in the WEAP subcatchments. (Source: McCartney et al., 2004b).

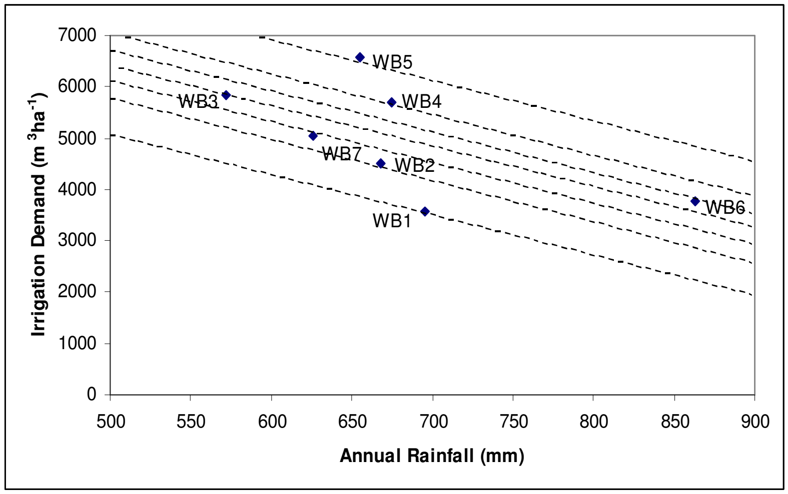


Figure 21 - Curves derived to compute annual irrigation demand (m^3ha^{-1}) from area averaged annual rainfall (mm) for each of the WEAP subcatchments. (Source: McCartney et al., 2004b).

McCartney et al. (2004b) simulated the within-year variation in irrigation demand by altering the percentage of total demand in each month of the year. Demand was reduced during the wet season (November to April) to reflect higher rainfall. The same pattern was used in all years and for all the WEAP subcatchments (Figure 22). The return flows, expressed as a percentage of demand (Table 25), were also kept constant in all years and all months.

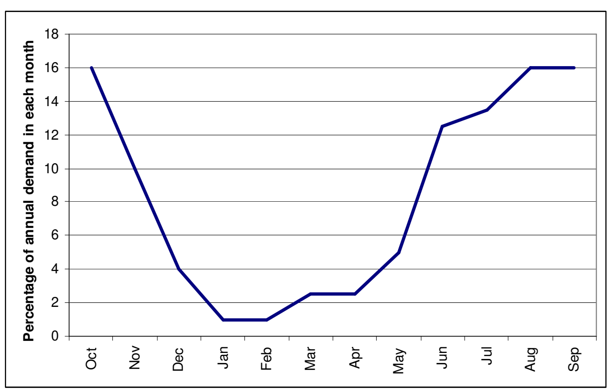


Figure 22 - Monthly variation in irrigation demand (Source: McCartney et al., 2004b).

5. Inter-basin transfers

Water is transferred both into and out of the Olifants basin. The water transferred into the basin is used mainly as cooling water for power generation and is therefore released into the atmosphere as evaporation. This water transfer does not affect the water balance of the catchment and was not simulated within WEAP for this reason. Water transfers out of the catchment began in the early 1990s (towards Limpopo and Crocodile West Management Areas) and were disabled in this simulation.

6. Reservoirs

There are 37 major dams (i.e. storage capacity greater than 2 Mm^3) and approximately 300 minor dams (i.e. storage capacity between 0.1 and 2 Mm^3) in the Olifants WMA. It is estimated that there are also between 3,000 and 4,000 small dams (i.e. storage capacity less than 0.1 Mm^3) in the catchment, most of which have been constructed for irrigation and livestock watering. The actual cumulative storage of dams is approximately 1,480 Mm^3 (73% of the naturalised mean annual runoff).
In the previous study, McCartney et al. (2004b) only included reservoirs larger than 25 Mm^3 within the model. The same approach was used in the current study. Nine reservoirs were identified, with a cumulative capacity of over 1,000 Mm^3 (i.e. 68% of the total storage within the catchment).

Table 27 - Reservoirs explicitly included in the WEAP modeling.

Dam	River	Located in WEAP subcachment	Current Height (m)	Current storage at FSL$^+$ (Mm^3)	Built	Raised
Loskop	Olifants	WB2	53	374.3	1939	1977
Rhenosterkop	Elands	WB3	35	205.8	1984	-
Flag Bosheilo	Olifants	WB3	36	105.0	1987	-
Witbank	Olifants	WB2	42	104.0	1949	1958, 1976
Bronkhorspruit	Bronkhorst	WB2	32	57.9	1948	-
Blyderiverspoort	Blyde River	WB6	71	54.1	1975	-
Rust de Winter	Elands	WB3	31	27.2	1934	-
TOTAL				1004.7		

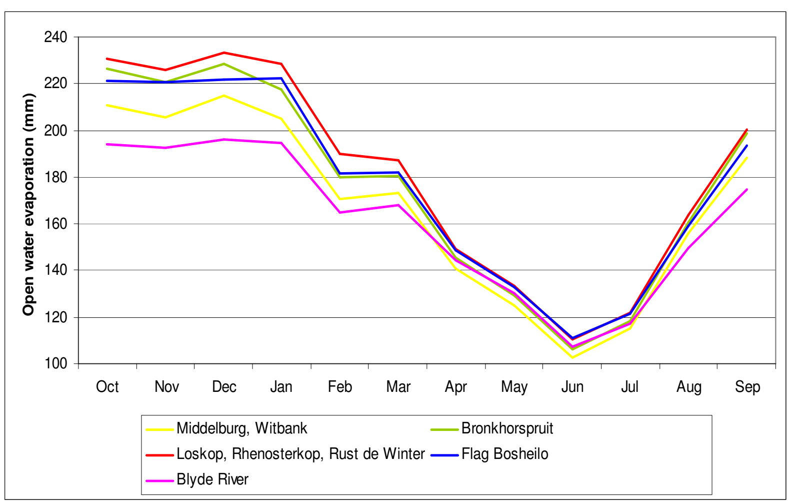
Source: data supplied by DWAF
$^+$ FSL = full supply level

The Kennedys Vale dam, which is not operated by DWAF, was removed from the simulation because no additional information was available for it. The Middelburg dam, which is not located on the main reach of the WB2 subcatchment, could not be simulated (see section 3.4) and was thus also removed from the simulation. For all other dams (table 27), storage-volume curves required for configuration of the model were obtained from DWAF (Appendix B).

Net evaporation from reservoirs was specified in WEAP by computing the difference between monthly potential evaporation and precipitation. Time series of rainfall were derived from the "rainfall zone" in which each of the reservoirs was located. As no monthly evaporation data were available, potential evaporation was estimated using monthly values of A-pan potential evaporation specific to the subcatchment in which each reservoir was located.

No operating rules could be obtained from DWAF for the dams and consequently, no rules were incorporated within WEAP. Only for the Blyderivierspoort dam, which is used for flood control, McCartney et al. (2004b) assumed a simple rule that drew the reservoir down prior to wet season. The same rule was applied in the current simulation.

Figure 23 - Estimates of mean monthly open water evaporation for each of the reservoirs simulated in WEAP. (Source: McCartney et al., 2004b).



7. Groundwater abstraction

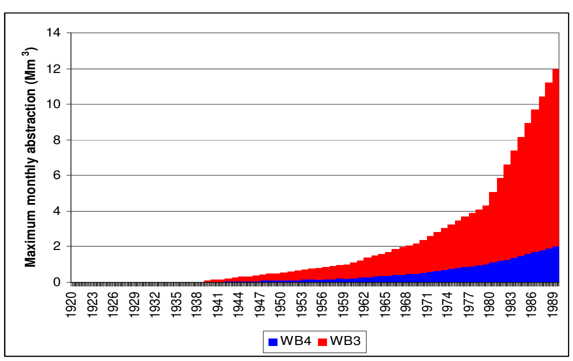
Data computed from the WSAM database indicate that groundwater abstraction mostly occurs in WB3 and WB4 subcatchments (table 28). It is believed that abstractions mainly supply irrigation in WB3 and mines in WB4. Groundwater abstractions were only simulated in these 2 subcatchments and were assumed to be negligible in the other WEAP subcatchments. As no information was available on how groundwater use had changed over time, McCartney et al. assumed that it had commenced in 1930 for irrigation in WB3 and in 1940 for mines in WB4. Maximum monthly withdrawals were estimated to have gradually increased over time in both subcatchments (figure 24).

Table 28 – Estimated groundwater utilisation in 1995 in each of the WEAP subcatchments

Subcatchment	*Potential utilisable groundwater resource (Mm3)*	*Currently utilised (Mm3)*
WB1	15.9	0.14
WB2	75.3	6.04
WB3	66.9	41.41
WB4	25.8	12.20
WB5	15.4	6.38
WB6	15.5	2.55
WB7	22.3	6.38
WB8	12.8	0.25
Total	249.8	75.4

Source: derived from WSAM database

Figure 24 – Estimated change in maximum monthly groundwater abstraction rates in WB3 and WB4.



(Source: McCartney et al., 2004b).

8. Instream flow requirements

Two environmental flow requirements were specified in WEAP. The first one is a minimum flow of 0.57 m^3s^{-1} which was required at the inlet of the Kruger National Park. This historical flow requirement was assumed to have commenced in 1940 (no precise data were available).

Another environmental flow requirement was introduced into the model immediately upstream of gauging station B5H002. This was assumed to represent the fact that in reality, demand allocation upstream of B5H002 is not completely optimised (McCartney et al., 2004b). For this reason, it was included in the simulation.

There is no international agreement with Mozambique specifying transboundary flow requirements for the Olifants River. However, this could be simulated in WEAP if an agreement was negociated.

9. Priorities

In WEAP all demand sites are assigned a priority between 1 and 99, with 1 the highest priority and 99 the lowest. Demand priorities determine the order that WEAP will follow when allocating the water, restricting water allocation to low-priority sites when water demand can not be met.

McCartney et al. calibrated their model by modifying the priority for each demand site in order to represent the true priorities between the different water-use sectors as well as the probable realities of upstream-downstream allocation. The resultant set of priorities was used in the current study (table 29). Priorities were considered to have remained constant over the period of simulation.

Meeting the Ecological Reserve was given priority 1 (i.e. the highest) and dams were given priority 51 (the lowest in the current simulation). This means that in model simulations, priority was given to meeting demands in preference to filling reservoirs. Priorities were progressively lowered with increasing distance downstream, except for WB4 and WB6 that are separate isolated subcatchments.

Table 29 – Priorities attributed to demand sites and dams in each WEAP subcatchment

Subcatchment	*Rural*	*Urban*	*Mining*	*Irrigation*	*Dams*	*Ecological Reserve*
WB1	2	10	20	30	-	-
WB2	3	11	21	31	51	-
WB3	4	12	22	32	51	1
WB4	2	3	4	5	51	-
WB5	6	14	24	34	-	-
WB6	2	3	4	5	51	-
WB7	7	15	25	35	-	-
WB8	8	-	-	-	-	1

10. Simulation of flow

Flow simulated in WEAP was compared to measured flow from 5 gauging stations on the Olifants main stem. Figure 25 presents for each of the gauging stations:

- the mean monthly measured flow.
- the mean monthly flow simulated in WEAP.
- the mean monthly flow simulated taking only the land use changes into account.
- the mean monthly naturalised flow.

This enables to say which of the land use changes or of the water demand mainly impact the runoff of the catchment. It also shows whether errors in data estimation come from current land use crop coefficients or from estimation of water demand.

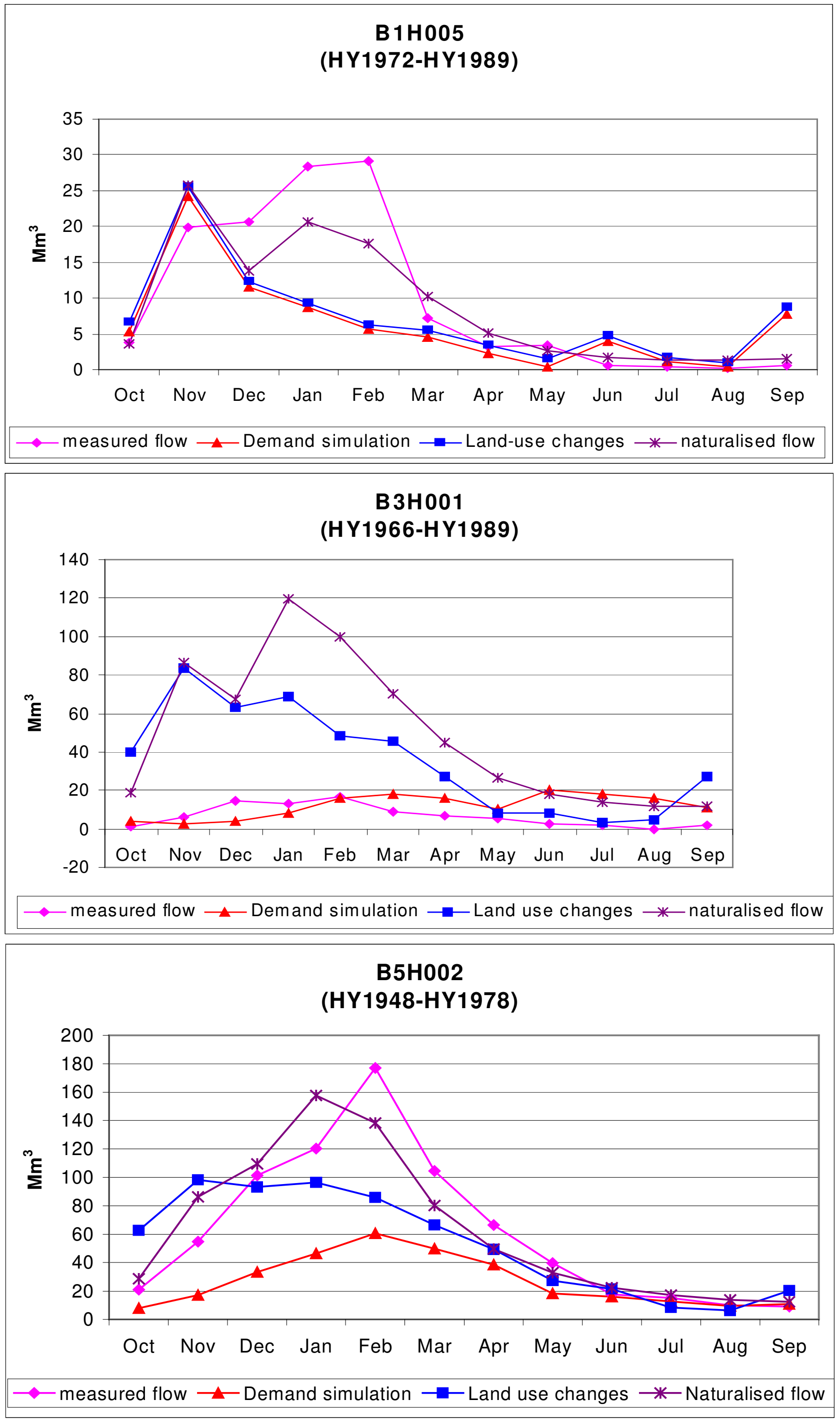
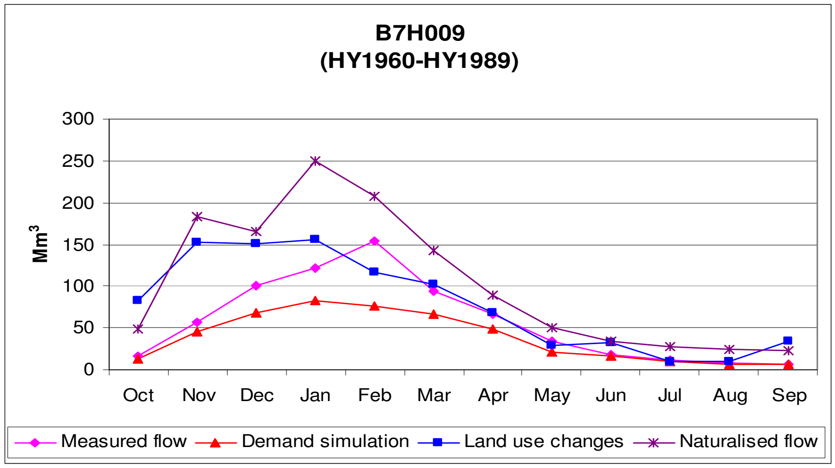


Figure 25 – Comparison of mean monthly: measured flow, simulated flow, simulated flow taking only land use changes into account, and naturalised flow, at five gauging stations: B1H005, B3H001, B5H002, B7H009, B7H015.



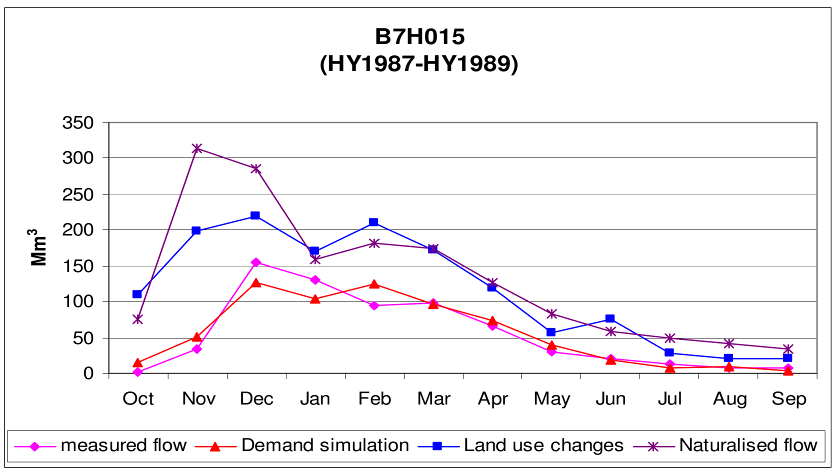


Figure 25 (continued)– Comparison of mean monthly: measured flow, simulated flow, simulated flow taking only land use changes into account, and naturalised flow, at five gauging stations: B1H005, B3H001, B5H002, B7H009, B7H015.

Results for B1H005 (located at the outlet of WB1 subcatchment) show a poor agreement between simulated and measured mean monthly flow. However one would expect to have a naturalised monthly flow higher than the measured flow which is not the case. Mean naturalised flow is lower than measured flow for the months of October, December, January and June. This suggests that there is error in the calculation of the wet season naturalised flow series (i.e. that derived from the WR90 study), and results from this location should be discarded.

Results also show that demand in WB1 is very low and that mainly land use changes could explain differences between naturalised and measured flow.

Results at the other gauging stations show a better agreement. However the model tended to underestimate the flow most of the time. There are only three years of record that match the simulation period for B7H015, but this is the station that shows the best agreement between mean monthly simulated and measured flow. As this station is located furthest downstream, two different explanations could be formulated. First, as the water demand were estimated from data available for 1995, the earlier the period of simulation, the lower the reliability of these data. That would explain why all simulations but for B7H015 show a poor agreement. Mean monthly simulated flow at the four other gauging stations was plotted for the three last years of simulation (the period for which records at B7H015 are available), but no real improvement was observed.

Second, it could be that the simulation is quite good for the Blyde River (in WB6), which joins the Olifants between B7H009 and B7H015. As the Blyde contributes to a large part of the runoff in the catchment (21%), this would favour results at B7H015.

11. Water demand and consumption

In this section, water demand and consumption simulated with the model for the different water-use sectors are presented.

Table 30 presents the relative impact of land use changes and water abstraction on the reduction of flow at the 5 gauging stations. Except for WB1, in which water demand is relatively low compared to other subcatchments, land-use changes account for about one third of the reduction in runoff attributable to human development.

Table 30– Relative impact of land use changes and water abstraction on the reduction of flow at the 5 gauging stations.

Gauging station	*Land use impact*	*Water demand impact*
B1H005	63.6 %	26.4 %
B3H001	35.9 %	64.1 %
B5H002	26.5 %	73.5 %
B7H009	38.5 %	61.5 %
B7H015	19.9 %	80.1 %

Simulated annual consumption within each WEAP subcatchment is presented in figure 26. Main water demand is in WB2 (on average 37 % of the water consumption). This is mainly because of the high water demand for irrigation: 82 % of water consumed is for the irrigation sector in this subcatchment. On the contrary, water demand is very low in WB1 and WB8, in which industrial and urban centres are underrepresented. Results show an almost steady increase in consumption over the 70 years simulation period. This increase occurs in the four demand sectors (figure 27), but is mainly driven by irrigation demand, which represents on average 78% of the water consumption in the whole catchment. The high inter-annual variability of the demand is attributable to change in irrigation demand arising from variation in rainfall.

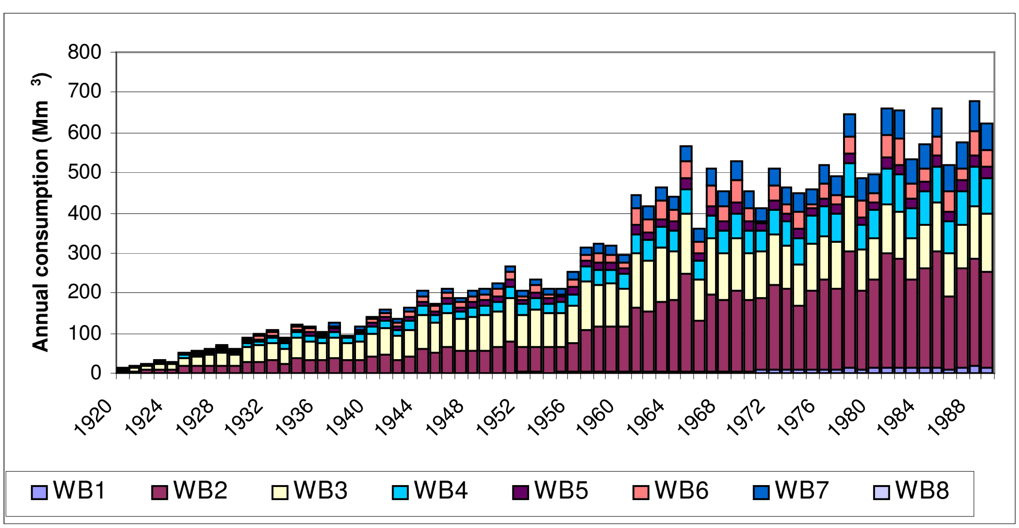


Figure 26 – Variation in simulated annual consumption within each of the WEAP subcatchments.

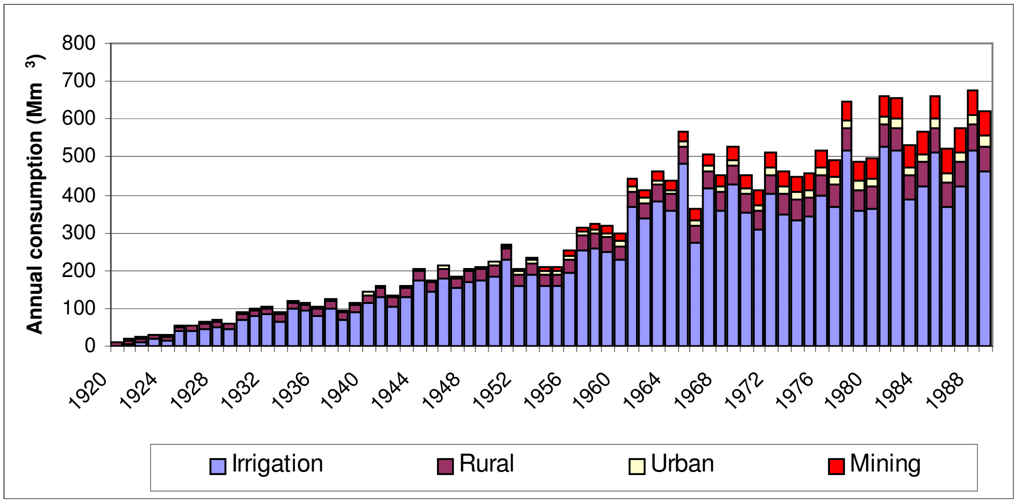


Figure 27 – Variation in simulated annual consumption within each water demand sector.

Mean annual consumption for each sector over the last ten years of simulation is presented in table 31. Irrigated areas, that account for about 2% of the total area of the catchment, are by far the largest water consumers. This outlines the large discrepancy in water use between commercial and subsistence agricultural sectors.

Table 31 – Mean annual water consumption simulated in each demand sector (HY1980-HY1989)

Demand sector	*Mean annual water consumption (Mm^3)*	*Percentage of total*
Irrigation	449.5	75.3 %
Urban	23.4	3.9 %
Rural	63.8	10.7 %
Mining	60.3	10.1 %

Figure 28 presents the unmet demand in the irrigation sector. In WEAP, the irrigation demand was given the lowest priority. This means that in periods of water scarcity, irrigation demand is curtailed in order to ensure that water requirements of the other sectors are met.

In the first years of simulation, unmet demand only occurred in WB2 and WB3. In these two subcatchments, the building of Loskop dam in 1939 has enabled irrigation demand to be met in all years but in periods of very severe droughts (e.g. 1965, 1979).

The results show that from the 1940s, most of the unmet demand occurs in the Steelport River catchment (i.e. the WB4 subcatchment). This is the only subcatchment with no major dam at present. Building of the De Hoop dam, which will have a storage capacity of 347 Mm^3 and should be completed by 2009 (section 9.4), should help solve this problem.

During the severe drought of 1965, all the catchments were affected by water curtailments.

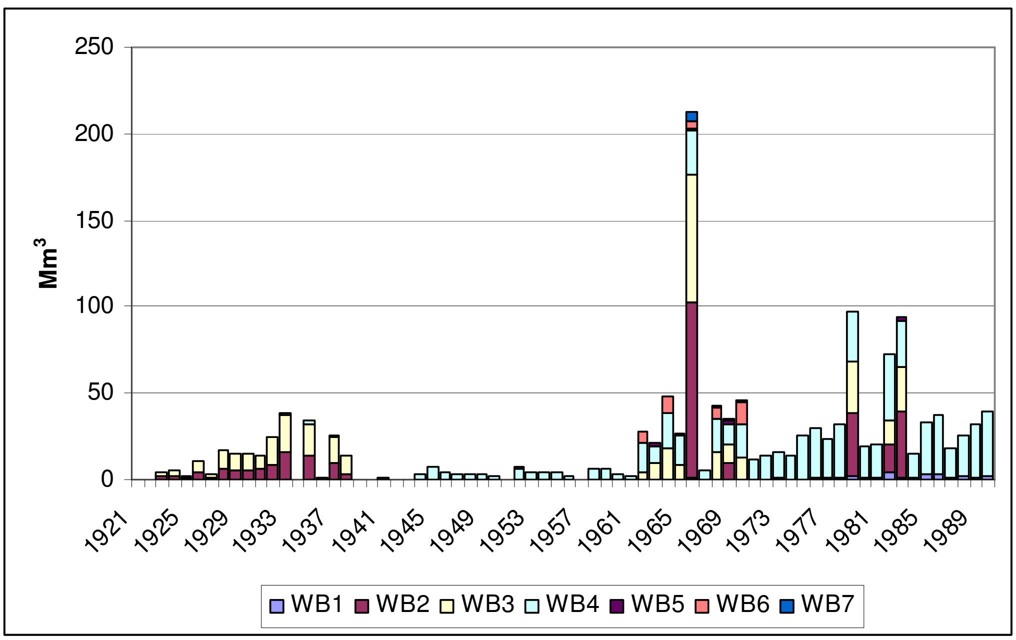


Figure 28 – Unmet irrigation demand in each of the WEAP subcatchments.

Simulation achieved using WEAP in its water allocation mode shows that it can provide useful information about development of water demand and consumption in the catchment, as well as the impacts of development such as hydrological structures. More information about other outputs that are provided by WEAP can be found in McCartney et al (2004b).

Chapter 9

Discussion and concluding remarks

1. Approach, assumptions and improvements

Modelling the hydrological processes and response of a 54,000 km² catchment is a complex task and the results of such a simulation have to be treated with caution. Errors are likely to be introduced from the structure of the model itself as well as from the sets of data that were used to run it. Some of the main assumptions of the study are reviewed here.

Instead of trying to model each hydrological component (e.g. evapotranspiration, runoff, infiltration) with accuracy, it was decided to use a system that relied on simplified equations and to run it at a much larger scale than it is usually done: the average subcatchment area in the study was approximately 7,000 km². There were two main reasons for adopting this approach: Firstly, because the aim of the study was to assess water resources in the whole catchment, it was not practical to set the model up using a finer spatial resolution. Secondly, most of the data required for the aquifer design are not available and it was easier to estimate them at a larger scale.

Nevertheless the use of a simple system has numerous drawbacks. Firstly, the simplified equations are likely to introduce errors arising from the model structure itself (Beven, 1989). The catchment response to a rainfall event is dependent on several factors (e.g. intensity and duration) which the model does not take into account. Instead the model averages the different possible responses of the catchment to give a relationship between rainfall and response that is only volume-dependent (i.e. the response to a rainfall event only depends on its volume). Secondly, catchment averaged parameters (e.g. crop coefficients, hydraulic conductivity) will not represent the spatial heterogeneities that occur in reality.

Several assumptions also had to be made in the data estimation because of the lack of consistent data for the catchment. Even though this is a difficulty that has to be overcome in most of the hydrological studies, the catchment area was so large that determination of the data by a field study was not possible. Results of the simulation show that the main bias resides in the estimation of water demands. Therefore it seems that the quality of the simulation could be improved by:

- Obtaining better values of crop coefficients. As evapotranspiration is the largest water consumer in the catchment, estimation of evapotranspiration is of primary importance in assessing water resources. In the Olifants, land-use types from the National Land Cover Project (CSIR, 2003) do not match with land uses from the ACRU database (Schulze, 1995). It was therefore difficult to estimate “average” crop coefficients for the subcatchments with great confidence.

- Improving accuracy in the temporal patterns of water demand. In this study most of the demand was supposed to have varied linearly during the period of simulation. Use of census data to estimate changes in rural and urban demand, and use of mining production figures to estimate changes in mining demand, would enable better estimates of temporal patterns in demand to be derived.
- Applying dam operating rules which are representative of current dam operations in terms of minimum releases, flood control and constraints during periods of low flow.

2. Water Evaluation And Planning system

WEAP was chosen because it operates in a simple manner. The purpose was not to describe accurately the hydrological process of the Olifants catchment, but to be able to simulate the water resources of the catchment with limited data and using a small number of parameters.

Results of the simulation of flow with virgin land-use conditions show WEAP’s reasonable ability to produce natural flow time-series from rainfall data. Although less confidence can be placed in these results than the time-series derived from the WR90 study because they are generated in a less accurate and more simplified way, they show that WEAP is a powerful tool for rapid assessment of natural water resources in the catchment. Chapter 8 also revealed that WEAP can simulate human water abstractions with some accuracy and could therefore be used as a planning tool or as a policy analysis tool. As outlined in the previous paragraph, more consistent data sets for water demand sectors would enable more confidence to be placed in the output of the model simulations.

However there are also some drawbacks in the application of the model: calibration of the rainfall-runoff component of WEAP was undertaken manually as no

optimisation routine is included in WEAP. One major drawback of such a method is that it is time-consuming because the model has to be configured for each run of the model. A major improvement for the user would be to include an optimisation module in WEAP that would give as output the set of parameters that optimise one of the efficiency criteria described in section 5.1. It is assumed that programming this module would be relatively easy for the model developer. Although automatic calibration procedures can lead to errors in parameter estimation due to the choice of either the optimisation algorithm or the objective function or the calibration data (Gan et al., 1997), it would represent a significant gain of time for the user.
In addition, the structure of the model enables the inclusion of only one aquifer and one catchment runoff/river interaction in each subcatchment. As a consequence, more accurate simulation requires a finer space scale for catchment design.

3. Output of the study

The last version of WEAP, released in May 2005, incorporates a new rainfall-runoff module. So far, previous applications of WEAP in the Olifants catchment made use of naturalised flow time-series as primary input of the system (Levite et al., 2003, McCartney et al., 2004b) because simulation of rainfall-runoff process in WEAP was not possible. Consequently, results were likely to be biased because of errors that occur in the naturalised flow time-series from the WR90 study. In future, following the demonstration that WEAP can simulate with good accuracy the rainfall-runoff process of the Olifants catchment, applications of WEAP might be achieved with rainfall time-series as the primary input. Moreover, inclusion of a rainfall-runoff module in WEAP may allow scenarios of change in climate to be explored.

The WEAP system was developed for the purpose of water resource management. Although the current study only provides assessment of the water resource between HY1920 and HY1989, it also demonstrates the potential of using WEAP for water resource management in the Olifants insofar as it can analyse:

- Effects of hydrological structures on the river flows.
- Effects of the change in water demand over time.
- Effects of upstream/downstream allocation rules.

- Effects of the setting up of the Ecological Reserve.

The main limitation of the model in its actual configuration is that WEAP subcatchments do not match the five water management regions set up by DWAF. The current configuration was chosen because it enabled direct testing of the model results against observed flow series. However, as a consequence, recommendations that can be formulated from simulations in WEAP are currently not necessarily directly applicable to the DWAF management regions. It is believed that reconfiguring the model in order to match DWAF subcatchments and water management regions is a necessary step if WEAP is intended to be used as a management tool.

Update WR90

The period of simulation used in this study was from HY1920 to HY1989, the period for which naturalised flow and rainfall time-series are available from the WR90 study. Detailed information on water demand was not available for this period and water demand had to be assumed from data taken from the WSAM database which correspond to water demand in 1995. However an update of the WR90 study is intended to be released by DWAF in 2005. This should enable the model to be run for an extended period. In particular, comparison of simulated and measured flow for HY1995 should allow more accurate assessment of the origin of the errors in the model.

4. Future opportunities

The current study constituted a test of WEAP's ability to assess water resources in a catchment. However it raises opportunities for further research using WEAP.

In South Africa and in the Olifants WMA, the new national water policy requires tools to assess impact of future development on water resources. For instance the current research could be a starting point for assessing the impact of the De Hoop dam, a new dam on the Steelport River with a storage capacity of 347 Mm^3 that is to be completed in 2009. More generally, the impact of new management practices in terms of water allocation could be assessed using WEAP.

Moreover, this study did not find any limitations for WEAP to be used in other parts of the world. As for most hydrological models, the main limitation in application of WEAP is the lack of consistent data to run the model.

5. Concluding remarks

The work conducted for this thesis tested WEAP's ability to simulate the rainfall-runoff process in the Olifants catchment and assessed the impact of development on water resources. The study revealed that WEAP was able to simulate well the naturalised flow time-series from the WR90 study. This constituted a good test of its ability to model the rainfall-runoff response of the catchment. Results from the water allocation simulation also showed that WEAP is a useful tool for assessment of water resource development in a catchment.

There are very few studies that deal with water resource assessment and impact of development at the scale undertaken in the current study. However this seems to be a critical step as water management (especially with the establishment of Water Management Agencies) will have to be achieved at this scale. In that perspective, WEAP could be a useful planning and management tool, and not only in the Olifants catchment or in South Africa, but also in other areas.

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Appendix A: Land use classification for each WEAP subcatchment

Land use type	WB1		WB2		WB3		WB4	
	Area (km²)	%of total	Area (km²)	%of total	Area (km²)	%of total	Area (km²)	%of total
Cultivated: permanent - commercial dryland	0.0	0.0%	0.0	0.0%	27.6	0.2%	0.0	0.0%
Cultivated: permanent - commercial irrigated	0.0	0.0%	18.6	0.1%	30.7	0.2%	0.7	0.0%
Cultivated: temporary - commercial dryland	1295.9	40.2%	3293.7	24.6%	2908.3	19.4%	605.3	8.5%
Cultivated: temporary - commercial irrigated	7.2	0.2%	369.7	2.8%	256.0	1.7%	151.9	2.1%
Cultivated: temporary - semi-commercial/subsistence dryland	0.0	0.0%	133.4	1.0%	1383.6	9.2%	255.9	3.6%
Degraded: forest and woodland	0.0	0.0%	149.4	1.1%	2962.5	19.8%	2.6	0.0%
Degraded: shrubland and low Fynbos	0.0	0.0%	0.2	0.0%	0.0	0.0%	0.0	0.0%
Degraded: thicket & bushland (etc)	0.0	0.0%	15.0	0.1%	99.9	0.7%	28.0	0.4%
Degraded: unimproved grassland	0.0	0.0%	10.0	0.1%	90.4	0.6%	57.8	0.8%
Dongas & sheet erosion scars	0.0	0.0%	0.0	0.0%	16.5	0.1%	12.1	0.2%
Forest	0.0	0.0%	0.0	0.0%	3.8	0.0%	0.0	0.0%
Forest and Woodland	0.0	0.0%	2100.0	15.7%	4535.6	30.3%	294.6	4.1%
Forest plantations	17.9	0.6%	297.3	2.2%	25.4	0.2%	152.0	2.1%
Herbland	0.0	0.0%	0.1	0.0%	0.0	0.0%	0.0	0.0%
Improved grassland	7.8	0.2%	13.5	0.1%	0.9	0.0%	0.0	0.0%
Mines & quarries	133.6	4.1%	243.2	1.8%	12.3	0.1%	40.4	0.6%
Thicket & bushland (etc)	3.7	0.1%	442.4	3.3%	1278.8	8.5%	2952.6	41.3%
Unimproved grassland	1708.2	53.1%	5862.6	43.8%	789.6	5.3%	2515.6	35.2%
Urban / built-up land: commercial	0.0	0.0%	2.7	0.0%	0.0	0.0%	0.3	0.0%
Urban / built-up land: industrial / transport	2.9	0.1%	32.0	0.2%	4.2	0.0%	0.5	0.0%
Urban / built-up land: residential	18.8	0.6%	244.8	1.8%	513.6	3.4%	72.7	1.0%
Urban / built-up land: residential (small holdings: grassland)	0.0	0.0%	37.3	0.3%	4.9	0.0%	0.0	0.0%
Waterbodies	18.2	0.6%	90.6	0.7%	20.9	0.1%	12.6	0.2%
Wetlands	5.8	0.2%	25.5	0.2%	0.0	0.0%	0.4	0.0%
Total	**3220**		**13382**		**14965**		**7156**	

Land use type	WB5		WB6		WB7		WB8	
	Area (km²)	%of total	Area (km²)	%of total	Area (km²)	%of total	Area (km²)	%of total
Cultivated: permanent - commercial dryland	1.1	0.0%	4.8	0.2%	0.0	0.0%	0.0	0.0%
Cultivated: permanent - commercial irrigated	4.5	0.1%	10.6	0.4%	152.3	3.4%	27.9	0.6%
Cultivated: temporary - commercial dryland	0.0	0.0%	34.6	1.2%	8.0	0.2%	0.0	0.0%
Cultivated: temporary - commercial irrigated	20.1	0.5%	224.7	7.9%	1.2	0.0%	4.4	0.1%
Cultivated: temporary - semi-commercial/subsistence dryland	257.1	6.6%	34.2	1.2%	178.0	3.9%	22.2	0.5%
Degraded: forest and woodland	395.9	10.1%	21.9	0.8%	354.6	7.8%	30.1	0.7%
Degraded: shrubland and low Fynbos	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Degraded: thicket & bushland (etc)	262.7	6.7%	3.9	0.1%	296.8	6.5%	23.6	0.5%
Degraded: unimproved grassland	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Dongas & sheet erosion scars	14.5	0.4%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Forest	32.1	0.8%	40.8	1.4%	54.1	1.2%	25.6	0.6%
Forest and Woodland	44.3	1.1%	280.5	9.9%	2690.5	59.2%	4065.8	92.6%
Forest plantations	45.0	1.1%	268.0	9.4%	0.4	0.0%	17.5	0.4%
Herbland	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Improved grassland	0.0	0.0%	0.0	0.0%	0.0	0.0%	1.6	0.0%
Mines & quarries	0.5	0.0%	0.0	0.0%	48.1	1.1%	0.6	0.0%
Thicket & bushland (etc)	2377.9	60.6%	1135.8	39.9%	633.9	14.0%	132.8	3.0%
Unimproved grassland	415.4	10.6%	771.4	27.1%	68.6	1.5%	0.6	0.0%
Urban / built-up land: commercial	0.0	0.0%	0.0	0.0%	0.9	0.0%	0.2	0.0%
Urban / built-up land: industrial / transport	0.0	0.0%	0.0	0.0%	2.5	0.1%	1.9	0.0%
Urban / built-up land: residential	50.6	1.3%	9.6	0.3%	45.6	1.0%	34.0	0.8%
Urban / built-up land: residential (small holdings: grassland)	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Waterbodies	0.6	0.0%	5.6	0.2%	6.3	0.1%	2.7	0.1%
Wetlands	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Total	**3922**		**2847**		**4542**		**4391**	

Appendix B: Elevation-Storage curves for reservoirs simulated in WEAP