RESEARCH
REPORT

118

Evaluation of Historic, Current and Future Water Demand in the Olifants River Catchment, South Africa

Matthew P. McCartney and Roberto Arranz

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International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

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The authors: Matthew P. McCartney is a senior researcher specializing in hydrology and water resources based at the subregional office for Nile Basin and East Africa of the International Water Management Institute (IWMI) in Addis Ababa, Ethiopia. At the time this research was conducted, Roberto Arranz was an MSc student in the Department of Civil Engineering at the Colorado State University, USA.

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Cover photographs:
Top left: The Olifants River, close to the Kruger National Park (photo credit: Matthew P. McCartney)
Top right: Sprinkler irrigation, close to Groblersdal (photo credit: Dominique Rollin)
Bottom left: Collecting water from a dry riverbed, Sekororo (photo credit: Matthew P. McCartney)
Bottom right: Ploughing, near GaMampa (photo credit: Dominique Rollin)

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Contents

Acronyms and Abbreviations

CMA	Catchment Management Authority
DWAF	Department of Water Affairs and Forestry
GGP	Gross Geographic Product
HD	High Demand
LD	Low Demand
lpcpd	liters per capita per day
MD	Medium Demand
RESIS	Revitalization of Small-scale Irrigation Systems
SEI	Stockholm Environment Institute
WCDM	Water Conservation and Demand Management
WEAP	Water Evaluation and Planning
WMA	Water Management Area
WSAM	Water Situation Assessment Model

Summary

Water resources development has played a significant role in the expansion of agriculture and industry in the Olifants River Catchment. However, currently, water resources are severely stressed and water requirements continue to grow. Water deficit is one of the major constraints hampering development in the catchment; both the mining and agricultural sectors are producing below optimal levels because of their reliance on insufficient supplies. Furthermore, the colonial and apartheid regimes have left a legacy of inequity. There is inadequate water supply to many households and now there is a considerable effort to improve the basic supply in lots of places. Against this background, the Water Evaluation and Planning (WEAP) model was applied to evaluate: i) an 'historic' (1920–1989) scenario of water resources development; ii) a 'baseline' (1995) scenario of current water demand; and iii) a set of three plausible 'future' (2025) scenarios. For each scenario, the WEAP model was used to simulate water use in five different sectors (rural, urban, mining, commercial forestry and irrigation) over a 70-year period of varying rainfall and flow. For the 'baseline' and 'future' scenarios, levels of assured supply were estimated for each sector and, based on water productivity data, the economic cost of failing to provide water was predicted. Current shortfalls are estimated to cost between US$6 and US$50 million per year, depending on rainfall and hence river flows. If increases in demand are not checked this cost will increase significantly. Under a high demand scenario, the economic benefits increase greatly but, even with infrastructure development and improvements in water conservation, the financial cost of water supply failures rises to US$10.5 million in most years and, in exceptionally dry years, up to US$312 million. The study illustrates the value of scenarios to provide insight for resource planning and to evaluate different options for meeting future water demand.

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> "Those who cannot remember the past are condemned to repeat it."
> George Santayana (1863 – 1952)

Introduction

Optimizing water use for the benefit of people must take into account a wide range of often competing requirements, including domestic needs, industry and agriculture as well as the requirements of communities dependent on natural resources and the needs of aquatic ecosystems. Good management of water resources should be based on an insight into the evolution of past water use, as well as an understanding of current demand and an awareness of possible future trends (Molle 2003).

Water allocation models estimate the quantity of water available to different users within a river basin at different times. Over the last 30 to 40 years major advances have been made in their development and they are increasingly used to assist in the planning and management of complex water resource systems (Jamieson 1996). These models are of use because they help support the analysis of allocation problems involving complicated hydrological, environmental and socioeconomic constraints and conflicting management objectives (McCartney 2007). They allow policymakers and managers to gain insight into the potential consequences of policy changes, changes to physical infrastructure and changes in processes that affect runoff (e.g., those due to land-use modifications). They can also help set the expectations of different water users with respect to the reliability and security of supply, which can help secure investment in water dependent enterprises (Etchells and Malano 2005). In some instances models have been integrated within an economic framework, thereby enabling an assessment of the potential economic consequences of different options used for the management of water resources (e.g., Rosegrant et al. 2000).

In this study, the Water Evaluation and Planning (WEAP) model was used to investigate scenarios of water demand in the Olifants River Catchment in South Africa. Scenarios are commonly used to investigate complex systems that are inherently unpredictable or insufficiently understood to enable precise predictions. In this instance, although there is reasonable, but not total, knowledge of current (i.e., 1995) water demand, there is considerable uncertainty about future water needs. Furthermore, just as future demand is uncertain, the lack of monitoring and consequent paucity of data, make it impossible to discern historic water demand exactly. Consequently, this study comprised three components:

(i) development of a scenario of 'historic' water demand in the catchment from 1920 to 1989;

(ii) development of a 'baseline' scenario, based on estimates of water demand in 1995; and

(iii) development of three scenarios of 'future' water demand, based on plausible projections of water use in 2025.

Each scenario provides a coherent, internally consistent and plausible description of water demand within the catchment. The 'historic' scenario, which was based on observed and deduced changes in human water demand over time, allows an assessment of water resources development in the context of varying demand and provides insight into how the current situation was attained (i.e., how we got to where we are). The 'baseline' scenario, which was based on demand estimates for 1995, but for which there remains uncertainty because of lack of data, provides a reference (i.e., where we are currently) against which future change may be assessed.

Since the future is very unpredictable, three alternative 'future' scenarios were developed. These three scenarios reflect alternative paths for water resources development in the catchment (i.e., where we are going). Each scenario illustrates the possible effect of different water demand trajectories. These scenarios are not the only possibilities for future water resources development in the catchment and, currently, it is not possible to attach probabilities to them. Nevertheless, they are of value because they provide a basis for discussion and, by evaluating different options for meeting possible future water demand, a framework for strategic planning. To this end, the implications of constructing new infrastructure and implementing improved water conservation and demand management measures were determined for each scenario.

This report describes how each of the scenarios was developed and the assumptions which underpin them. Application of the WEAP model enabled quantitative assessments of each scenario. Since year-to-year variation is important for water management and needs to be considered, 70-years of monthly time step flow and rainfall data were used to mimic natural hydrological variation. The demands of the scenarios were superimposed on these time series. For the baseline and future demand scenarios, levels of assurance for supply under the different conditions simulated were calculated. By combining water productivity data with simulated estimates of unmet demand, the approximate economic cost of failing to supply water was estimated in each scenario. Although economic efficiency alone should not guide decisions about water resources development[1], these data nevertheless provide a useful starting point for comparison of alternatives.

The following section of this report describes the natural characteristics and economic and water resources development in the catchment. The Reserve, an important component of the National Water Act (1998) with significant implications for water resources development, is described and a brief overview of water allocation in South Africa is presented. The following chapter describes the WEAP model and its configuration to the Olifants River Catchment. The subsequent chapters describe the historic, baseline and future scenarios. In each case, the scenarios are described, the results are presented and the economic implications are assessed. The final section comprises concluding remarks.

The Olifants Catchment

Natural Characteristics

The Olifants River is a major tributary of the Limpopo River. The river rises at Trichardt, to the east of Johannesburg, in the province of Gauteng, and flows northeast, through the provinces of Mpumalanga and Limpopo, into Mozambique (Figure 1). The Letaba River (catchment area of 3,264 square kilometers (km^2)) joins the Olifants River just before it flows into

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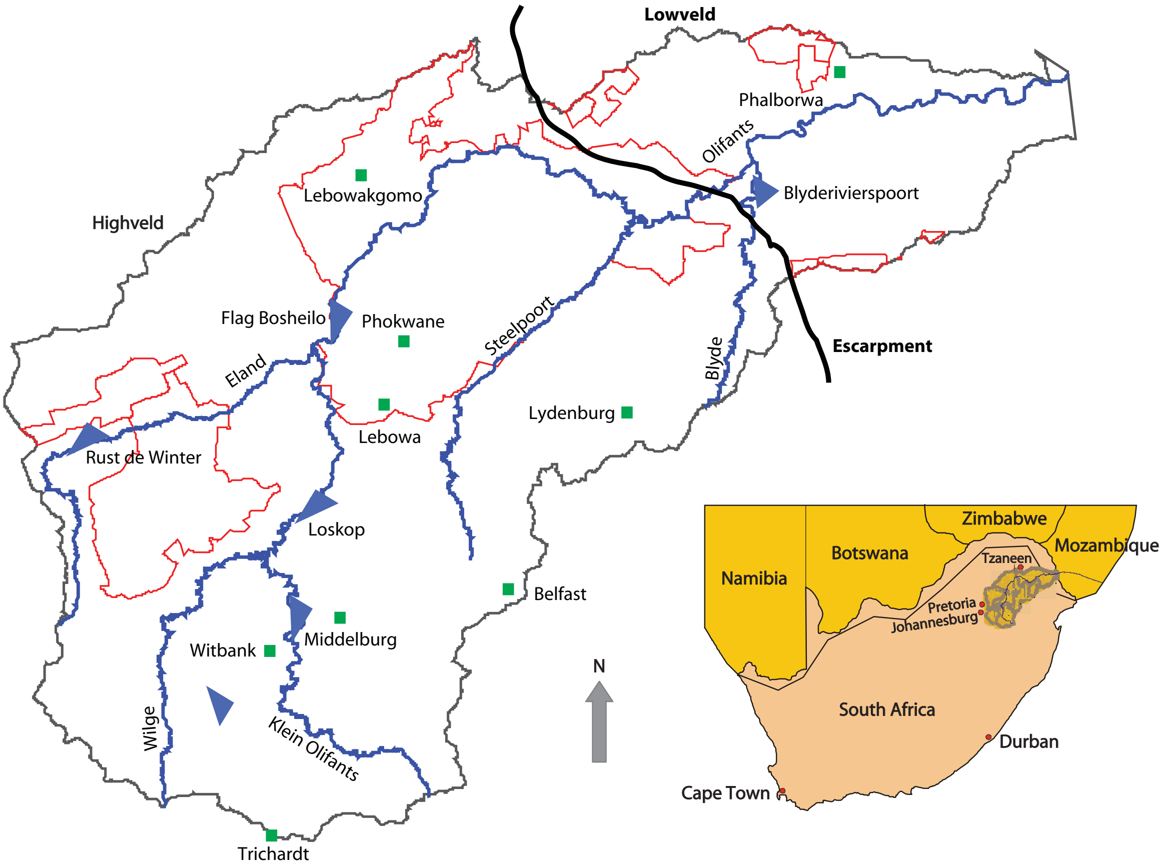
[1] Other factors that need to be considered include issues of equity, requirements for social development and the possible environmental and health impacts.

Mozambique. However, the Letaba Catchment is not included in the Olifants Water Management Area (WMA)[2]. For this reason and because most previous studies have not included the Letaba River, the current study focused on the area (54, 475 km^2) of the Olifants WMA, hereafter simply referred to as the 'Olifants Catchment'.

The geology of the catchment is complex. Granite is the most dominant rock type, but dolerite intrusions, in the form of dikes and sills, are common (DWAF 1991). An escarpment running approximately north-south separates the highveld (i.e., land above 1,200 meters (m)) from the lowveld (i.e., land below 800 m) (Figure 1). The climate of the catchment is largely controlled by the movement of air-masses associated with the Inter-Tropical Convergence Zone. For this reason, rainfall is seasonal and largely occurs during the summer months, October to April. The mean annual rainfall is in the range of 500 to 800 millimeters (mm) over most of the catchment, but exceeds 1,000 mm in the mountains and in places along the escarpment (Figure 2). However, the temporal pattern of rainfall is irregular with coefficients of variation greater than 0.25 across most of the catchment (McCartney et al. 2004). Evaporation varies across the catchment but is highest in the north and west. The mean annual potential evapotranspiration (estimated by the Penman-Monteith method) for the catchment is 1,450 mm. Runoff from the catchment reflects the temporal and spatial distribution of the rainfall with the greatest volumes in the south and along the escarpment

FIGURE 1.
Map of the Olifants River Catchment, showing the major rivers, dams and urban centers. The former homelands are demarcated in red.



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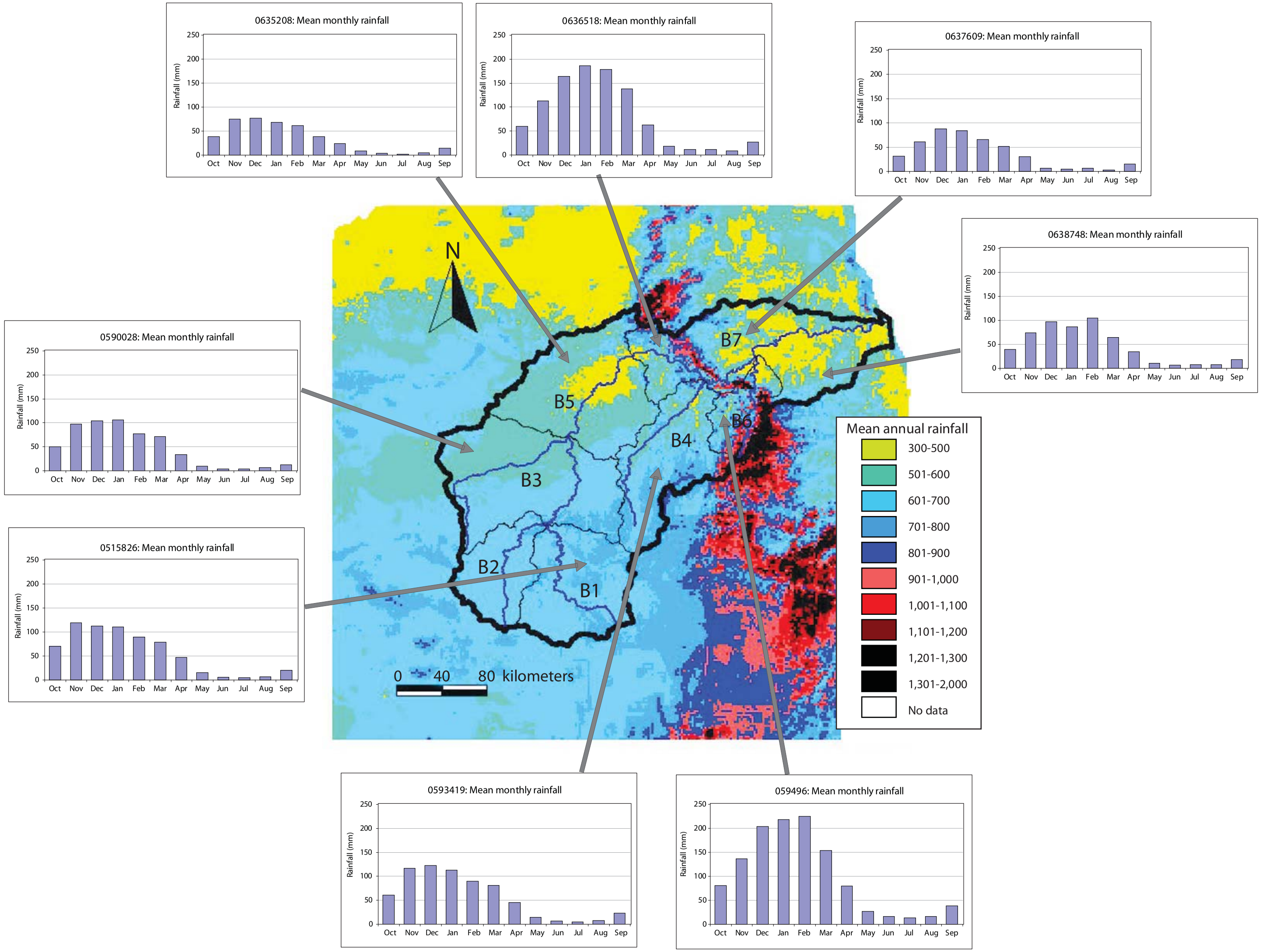
[2] In compliance with the National Water Act (1998) and the National Water Resources Strategy, future water resource management in South Africa will be focused on 19 WMAs, of which the Olifants will be one.

FIGURE 2.

Mean annual rainfall in mm (*Source:* developed from data in Schulze et al. 1997). Graphs show mean monthly rainfall in mm at selected rain gauges (*Source:* data provided by the DWAF).

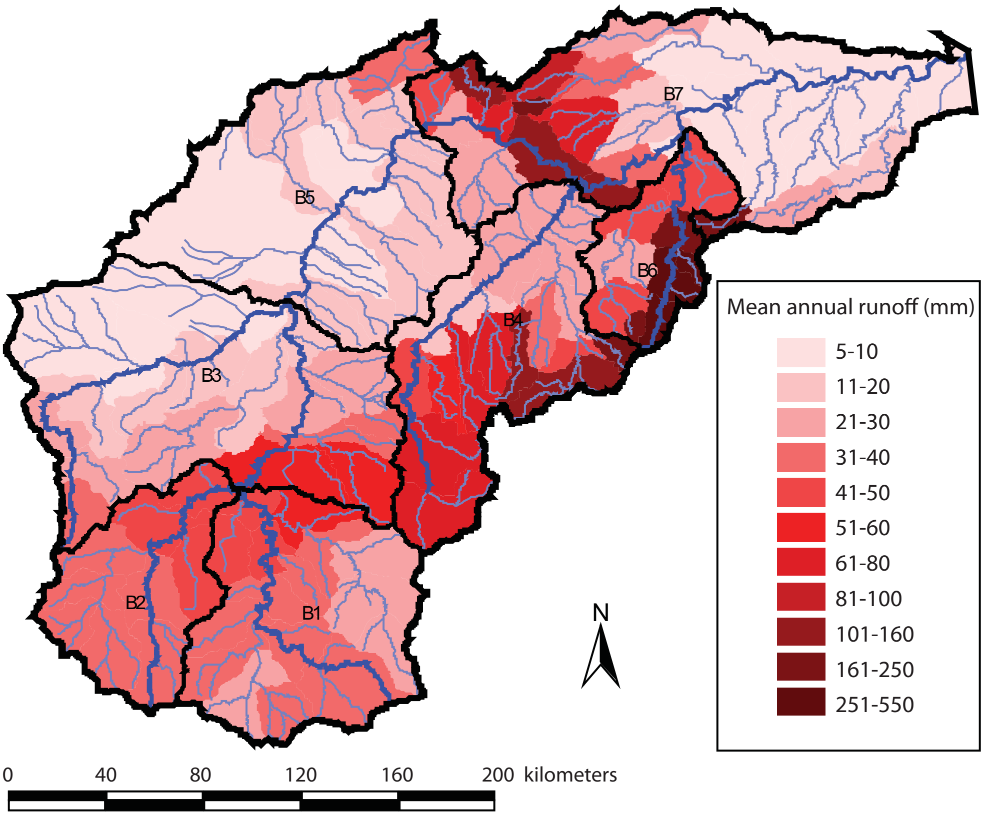


(Figure 3). The average annual runoff from the catchment is 37.5 mm (i.e., 6% of the average annual rainfall)[3], which equates to 2,040 million cubic meters (Mm^3). However, there is considerable inter-annual variation and consecutive years where flow is below the mean annual discharge are a common occurrence (McCartney et al. 2004).

Economic and Water Resources Development

The population of the Olifants River Catchment is estimated to be approximately 3.2 million, of which approximately two-thirds live in rural areas (Magagula et al. 2006). The major urban centers are Witbank and Middelburg (Figure 1). It is estimated that activities within the catchment, many of which are highly dependent on water, generate between 5 and 6 percent of the gross domestic product (GDP) of South Africa. Economic ventures are diverse and include mining, power generation, metallurgic industries, irrigation, dryland and subsistence agriculture, and ecotourism. However, there are wide variations in economic development throughout the catchment and large inequities in domestic and productive water use between areas that were formerly "homelands" under the apartheid regime and the rest of the catchment (Magagula et al. 2006; Cullis and van Koppen 2007; van Koppen n.d.). Currently, as throughout the rest of South Africa, the Department of Water Affairs and Forestry (DWAF) is making a concerted effort to improve domestic water supplies in many areas (DWAF 2003a).

FIGURE 3.
Mean annual runoff across the Olifants Catchment.



Source: Derived from WR90 data.

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[3] Flow that would occur in the catchment if there were no human interventions (i.e., virgin land cover and no water resource development).

The main economic activity is concentrated in the mining and industrial centers of Witbank and Middelburg in the south, and near Phalaborwa in the east. The total area of rainfed cultivation is estimated to be 945,948 hectares (ha) (CSIR 2003). This compares with an estimated irrigated area of approximately 110,240 ha (McCartney et al. 2004). Extensive irrigation occurs in the vicinity of the Loskop Dam, along the lower reaches of the Olifants River, in the vicinity of its confluence with the Blyde River, as well as in the Steelpoort Valley and the Upper Ga-Selati catchment. Much of the central and northwestern areas (former homelands in the apartheid era) are largely undeveloped, but have high rural populations, many of whom are highly dependent on the income from migrant workers. Commercial forestry occurs in some of the higher rainfall areas, particularly in the Upper Blyde Catchment. Just before the border with Mozambique, the Olifants River is one of the principal rivers flowing through, and hence maintaining the ecology of, the Kruger National Park, which receives more than one million visitors a year.

Water resources development has played a prominent role in the economic development of the catchment. Over the last century there has been substantial state investment in water resource infrastructure. There are 37 major dams (i.e., reservoir capacity greater than 2 Mm^3) and approximately 300 minor dams (i.e., reservoir capacity 0.1 to 2 Mm^3). In addition, it is estimated that there are between 3,000 and 4,000 small dams (i.e., reservoir capacity less than 0.1 Mm^3), most of which were constructed for livestock watering and irrigation. Currently, the cumulative storage of dams in the catchment is estimated to be approximately 1,480 Mm^3 (i.e., 73% of the mean annual runoff) (McCartney et al. 2004). Groundwater resources in the catchment are used for partial fulfilment of agricultural and mining requirements. The greatest utilization is in the northwest of the catchment where high yields, in the order of 30-20 liters per second $(ls)^{-1}$, are obtained from dolomite. Here the groundwater is used extensively for irrigation and domestic supply. The mines are increasingly utilizing groundwater, but, currently, the extent of utilization is not very clear. For the whole of the Olifants Catchment, the annual utilizable quantity of groundwater is estimated to be approximately 250 Mm^3, of which between 75 and 100 Mm^3 are currently abstracted (McCartney et al. 2004).

Within the catchment, water requirements are growing rapidly with the development of mines and increasing power generation, and domestic demand. An assessment of water requirements and availability in the catchment indicates that deficits occur in most years (DWAF 2003b). The deficits occur, in part, because it is a requirement of the National Water Act (1998) that contemporary water resource planning makes provision for a Reserve to ensure both basic human needs and to protect aquatic ecosystems (see section, *The Reserve*). The water 'deficit' means that the Reserve is currently not being fully met. Furthermore, water is not being supplied to users at the level of assurance that the DWAF would like and curtailments are necessary. The Limpopo Province Economic Development Strategy reveals that the lack of regular water supply is one of the major constraints hampering development in the region and both the mining and agriculture sector are producing at below optimal levels because of reliance on insufficient supplies (Cambridge Resources International 2003). There is a widely recognized need to manage water resources in the catchment more effectively to ensure the sustainability of agriculture and secure the livelihoods of people.

The Reserve

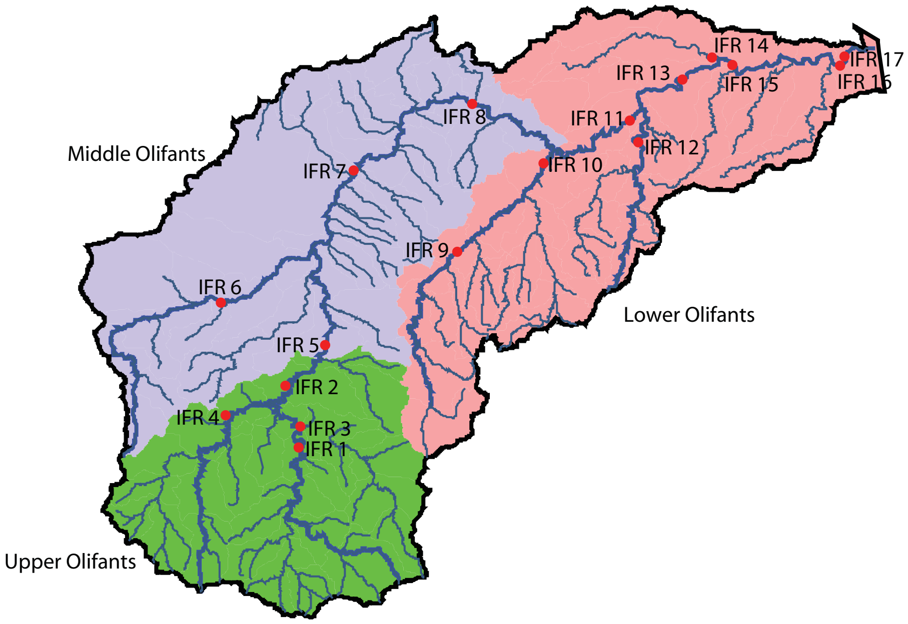
Key principles of the National Water Act (1998) are sustainability and equity. The Act asserts that, in conjunction with using water resources to promote social and economic development, it is essential to protect the environment to ensure that the water needs of present and future generations can be met. This is partly achieved by leaving enough water (i.e., a reserve) in a river to maintain its ecological functioning. To this end, the Reserve is the only water right specified in the National Water Act. As such, it has priority over all other uses of water and must strictly be met before water resources can be allocated to other uses. The Reserve comprises two parts:

- the basic human needs reserve (i.e., water for drinking and other domestic uses); and
- the ecological reserve (i.e., water to protect aquatic ecosystems).

A comprehensive study has been undertaken to determine the Reserve for the Olifants Catchment (Louw and Palmer 2001; Palmer 2001a, 2001b, 2001c). The study focused primarily on estimating flow quantities, although there was also limited consideration of water quality issues. An assessment of the extent to which local rural communities are dependent on a healthy river ecosystem was also conducted (Joubert 2001)[4]. The latter was used to assist in identifying the desired ecological condition of the river at key locations.

The study divided the catchment into three zones: the Upper, Middle and Lower Olifants. Flow requirements were determined through detailed studies conducted at 17 sites, located both on the main river and tributaries (Figure 4). The sites were carefully selected for their representativeness of instream and riparian habitat. For each site, requirements of the Reserve were determined with cognizance of both the need to maintain the Olifants as a "working river" for industry, mining and agriculture as well as the need to protect valuable ecosystems, particularly in the lower reaches of the catchment (Louw and Palmer 2001). At each site, a 70-year time series (1920-1989) of environmental flow requirements (monthly time step) was developed using the Building Block Methodology, which replicates key components of the natural flow variability (King et al. 2000).

FIGURE 4.
Location of points in the Olifants River Catchment where environmental flows (instream flow requirements) have been determined.



Source: derived from Louw and Palmer 2001.

Note: IFR = Instream flow requirements.

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[4] This was based on group discussions, interviews and the distribution of questionnaires among various user groups. The duration and magnitude of reliance on the river was ranked to provide an overall indication of the significance of the river on the daily lives of the local community.

The environmental flow requirements vary from year to year, depending on rainfall, but overall the flows recommended for the long-term ecological maintenance of the Olifants River constitute between 15.7 and 33.5 percent of the mean annual flow. At IFR 16, located within the Kruger National Park, the total requirement of the Reserve is estimated to be 394 Mm^3 (i.e., about 20% of the natural mean annual runoff from the catchment). However, analyses show that dry season environmental flow requirements represent a significantly greater proportion (i.e., exceptionally up to 78%) of the natural river flow.

Water Reallocation

At present, water allocation in South Africa is the responsibility of the DWAF. However, it is envisaged that in future this will revert to Catchment Management Authorities (CMAs). Source Directed Controls have been established as a framework to regulate water use and minimize the negative impacts of human water use on water sources (DWAF 2007). Key amongst these measures are authorizations and entitlements to utilize water resources in an equitable and sustainable manner. Under the National Water Act an entitlement is granted for a particular water use for a specified time, with attached conditions. Entitlements may or may not require licenses but, with the exception of the Reserve (see section, *The Reserve*) and small volumes abstracted for household use (regarded as low impact), all entitlements must be formally authorized. In future, water allocation plans that set out the amounts and conditions for use will be established for all WMAs (DWAF 2007).

To address past imbalances in allocations that occurred during the apartheid era, a process of allocation reform and water reallocation is being undertaken (DWAF 2005b). A key mechanism for this process is compulsory licensing of all existing and potential water uses. This procedure, which has been initiated in the Olifants Catchment through a survey of existing lawful use, aims to determine where reallocation is necessary to achieve a fairer distribution of resources compared to what has occurred in the past. The reallocation of water is intimately linked to the land reform process, which is also being undertaken in the country to redress the inequities that occurred during the apartheid era (Hall 2004). In some places there has been reallocation of land and water from commercial farmers to smallholders and many believe that this form of redistribution should increase in the future. However, currently, it is envisaged that overall future water entitlements for irrigation will, for the most part, remain the same as those of the present landowner (DWAF 2007). It is anticipated that mechanisms for water trading, similar to those created in Australia (Turral et al. 2005), will be established in the future to facilitate temporary and permanent reallocation, not only within the agricultural sector but also between sectors.

Application of the WEAP Model

In order to be useful, water allocation models must accurately represent the significant features of water resource systems within catchments. Ideally they should simulate: i) availability of water, including variability and storage behavior; ii) water demand (i.e., the behavior of water users); and iii) the water allocation framework, including entitlements, processes and rules (Etchells and Malano 2005). This section describes how the WEAP model was configured for the Olifants River Catchment and its application to the different scenarios.

Model Description

Developed by the Stockholm Environment Institute (SEI), the WEAP model was designed to be used to evaluate planning and management issues associated with water resources development. It can be applied to both municipal and agricultural systems and can address a wide range of issues including: sectoral demand analyses, water conservation, water rights and allocation priorities, streamflow simulation, reservoir operation, ecosystem requirements and cost-benefit analyses (SEI 2001). The WEAP model has two primary functions (Yates et al. 2005):

- simulation of natural hydrological processes (e.g., evapotranspiration, runoff and infiltration) to enable assessment of the availability of water within a catchment; and
- simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (i.e., consumptive and non-consumptive water demands) to enable evaluation of the impact of human water use.

To allow simulation of water utilization, the elements that comprise the water demand-supply system and their spatial relationship are characterized for the catchment under consideration. The system is represented in terms of its various water sources (e.g., surface water, groundwater and water reuse elements), withdrawal, transmission, reservoirs, wastewater treatment facilities, and water demands (i.e., user-defined sectors, but typically comprising industry, mines, irrigation and domestic supply, etc.). A graphical interface facilitates visualization of the physical features of the system and their layout within the catchment.

The WEAP model essentially performs a mass balance of flow sequentially down a river system, making allowance for abstractions and inflows. To simulate the system, the river is divided into reaches. The reach boundaries are determined by points in the river where there is a change in flow as a consequence of the confluence with a tributary, or an abstraction or return flow, or where there is a dam or a flow gauging structure. Typically, the WEAP model is applied by configuring the system to simulate a recent 'baseline' year, for which the water availability and demands can be confidently determined. The model is then used to simulate alternative scenarios to assess the impact of different development and management options. The model optimizes water use in the catchment using an iterative Linear Programming Algorithm, the objective of which is to maximize the water delivered to demand sites according to a set of user-defined priorities. All demand sites are assigned a priority between 1 and 99, where 1 is the highest priority and 99 is the lowest. When water is limited, the algorithm is formulated to progressively restrict water allocation to those demand sites that have been given the lowest priority. More details of the model are available in Yates et al. (2005) and SEI (2001).

Configuration of the WEAP Model to the Olifants River Catchment

In South Africa the primary water management unit is the 'quaternary catchment' and the DWAF has made a considerable effort to collate information on water resources for all these catchments. Within the Olifants Catchment there are 114 quaternary catchments. In this study, the analyses conducted using the WEAP model were underpinned by data for these catchments. However, although theoretically possible, limited computer power made it impractical for the WEAP model to simulate each quaternary catchment separately[5]. Consequently, the WEAP model was configured to replicate eight sub-catchments (Table 1). This configuration was adopted for two reasons. First, because it meant

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[5] It took approximately one hour to complete a 70-year WEAP model run for the eight sub-catchments delineated in the study.

TABLE 1.
The sub-catchments used for the WEAP model simulation.

Sub-catchment	Area (km²)	Quaternary catchments	Flow gauging station
WB1	3,211	B11A to B11F	B1H005
WB2	13,344	B11G to B11L; B12A to B12E; B20A to B20J; B32A to B32J	B3H001
WB3	14,918	B31A to B31J; B51A to B52G	B5H002
WB4	7,136	B41A to B41K; B42A to B42H	-
WB5	3,918	B52H to B52J; B71A to B71H	B7H009
WB6	2,842	B60A to B60J	-
WB7	4,542	B71J; B72A to B72K	B7H015
WB8	4,397	B73A to B73H	-

that the most important tributaries (i.e., the Steelpoort and Blyde) were simulated individually. Second, because it facilitated model calibration, since five of the sub-catchments have flow gauging stations located at their outlets (see section, *Model Calibration*). Figure 5 is a schematic representation of the system as it was configured, showing the quaternary catchments incorporated in each of the sub-catchments in the WEAP model (WB1 to WB8). For the eight sub-catchments in the WEAP model estimates were made of water resources. Water abstraction and net demand[6] were estimated for five different sectors: rural, urban, mining, commercial forestry and irrigation.

Water Resources

In this study, data on water resources were obtained from a variety of sources, but primarily from the DWAF. Naturalized river flow and rainfall data were taken from the WR90 study, which was a national five-year project undertaken in South Africa to provide baseline hydrological data for water resources planning and development (Midgeley et al. 1994). This study provided a 70-year time series for quaternary catchments for the period 1920 to 1989. For the current study, these data were combined (using areal weighted averages for rainfall and by summing for the flow) to provide time series estimates (on a monthly time step) for rainfall and naturalized flow for each sub-catchment in the WEAP model (Table 2).

Given the large number of dams (see section, *Economic and Water Resources Development*), it was not possible to simulate all the reservoirs located in the Olifants Catchment individually. However, in the current study, reservoirs with a capacity greater than 25 Mm^3 were explicitly incorporated in the model. Details of the nine reservoirs which exceeded this capacity were obtained from the DWAF Dam Safety Register (Table 3). These nine reservoirs have a total capacity of nearly 1,005 Mm^3 (i.e., 68% of the estimated total reservoir storage in the catchment). The DWAF has not formalized rule curves for the dams in the Olifants Catchment yet. Currently, each dam is operated independently, based, to a large extent, on expert judgment. As a result, no operating rules were available for the dams. Consequently, with the exception of the Blyderivierspoort Dam, no operating rules were incorporated within the WEAP model. This meant that the reservoirs were not drawn down to attenuate wet season floods and no restrictions were applied on abstractions as the reservoirs emptied. Because the Blyderivierspoort Dam, which is located on the highest flowing tributary, is used for flood

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[6] In this report the term net demand is used synonymously with consumption (i.e., the volume of water abstracted and not returned to the hydrological system of the catchment).

FIGURE 5.
Schematic of the quaternary catchments comprising each of the eight sub-catchments in the WEAP model (WB1 to WB8). Inset map shows configuration of the WEAP model and the five gauging stations (B1H005, etc.) which were used for the model validation.

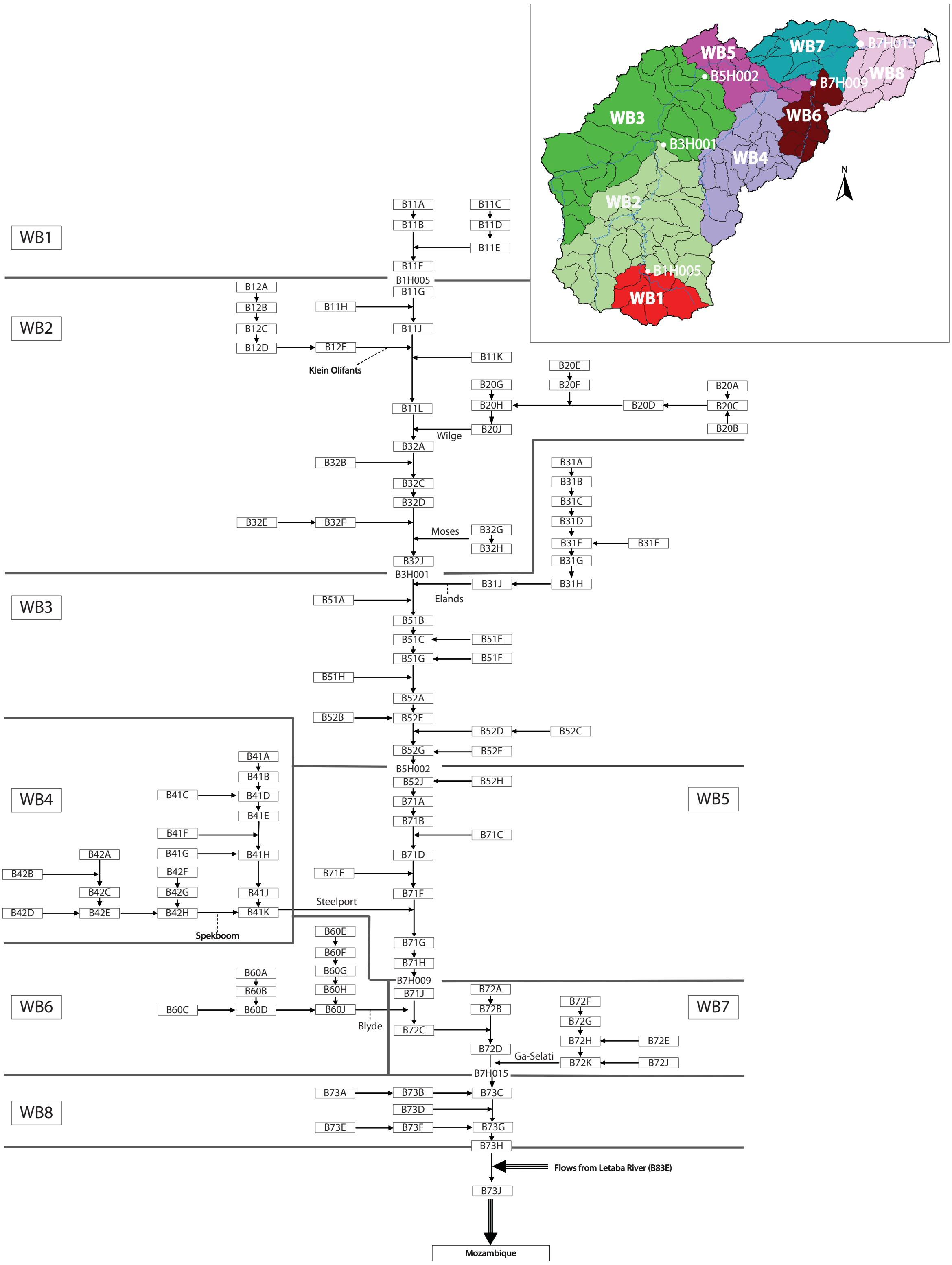


TABLE 2.
Summary of mean annual precipitation and mean annual naturalized flow (1920 to 1989) derived for each of the sub-catchments in the WEAP model.

Sub-catchment	Area (km^2)	Annual Precipitation (mm)[1]			Annual Naturalized Flow (Mm^3)[2]		
		Average	Maximum	Minimum	Average	Maximum	Minimum
WB1	3,211	695	920	407	111.6	495.7	17.9
WB2	13,344	668	876	378	477.8	1,558.9	89.7
WB3	14,918	572	800	360	176.6	685.4	27.8
WB4	7,136	675	972	443	396.3	1,509.6	138.5
WB5	3,918	655	1,184	376	228.6	1,283.9	56.4
WB6	2,842	863	1,577	577	435.3	1,785.2	180.9
WB7	4,542	626	1,219	328	138.2	971.8	14.8
WB8	4,397	616	1,139	322	75.3	724.8	7.8

Notes:

[1] Derived as area-weighted average from WR90 rainfall zones (*Source:* Midgeley et al. 1994).

[2] Derived as accumulated WR90 naturalized flow from quaternary catchments (*Source:* Midgeley et al. 1994).

control, a simple rule that did draw the reservoir down prior to the wet season was applied to this dam. However, this was an assumed curve, which was not verified by the DWAF. For each dam, stage-volume and stage-area curves were obtained from the DWAF. Net evaporation from the reservoirs (i.e., the difference between monthly evaporation and precipitation) was computed from rainfall and estimates of potential open water evaporation data derived from Schulze et al. (1997).

It is estimated that there are close to 10,000 operating boreholes in the Olifants Catchment. A DWAF database includes an estimate of the proportion of groundwater that is utilizable in each quaternary catchment. The proportion that is utilizable is defined as a function of ease of extraction and water quality constraints (McCartney et al. 2004). An estimate of the total sustainable groundwater yield for each sub-catchment in the WEAP model was determined by summing the estimated utilizable groundwater resource from the quaternary catchments located in each sub-catchment (Table 4). In relation to the sub-catchments in the WEAP model, groundwater abstraction is highest in WB3 and WB4. In the former it is believed that it primarily supplements irrigation, whilst in the latter it is primarily used to

TABLE 3.
Reservoirs explicitly included in the WEAP modeling.

Dam	DWAF number	Longitude °E	Latitude °S	River	Located in WEAP sub-catchment	Current height (m)	Current storage at FSL[1] (Mm^3)	Built	Raised
Loskop	B3R002	29.36	25.42	Olifants	WB2	53	374.3	1939	1977
Rhenosterkop	B3R005	28.92	25.10	Elands	WB3	35	205.8	1984	-
Flag Bosheilo	B5R002	29.43	24.80	Olifants	WB3	36	105.0	1987	2006
Witbank	B1R001	29.32	25.89	Olifants	WB2	42	104.0	1949	1958,1976
Bronkhorstspruit	B2R001	28.73	25.89	Bronkhorstspruit	WB2	32	57.9	1948	-
Blyderivierspoort	B6R003	30.80	24.54	Blyde River	WB6	71	54.1	1975	-
Middelburg	B1R002	29.55	25.77	Klein Olifants	WB2	36	48.4	1979	
Kennedy's Vale		30.10	24.84	Dwars	WB4	43	28.0	1988	-
Rust de Winter	B3R001	28.53	25.23	Elands	WB3	31	27.2	1934	-
TOTAL							1,004.7		

Source: The DWAF (Dams Safety Register).

[1] FSL = full supply level.

TABLE 4.
Estimated groundwater utilization in 1995 in each of the sub-catchments in the WEAP model.

Sub-catchment	Number of operational boreholes	Potential utilizable groundwater resource (Mm^3)	Currently utilized groundwater resources (Mm^3)
WB1	14	15.9	0.14
WB2	375	75.3	6.04
WB3	6,055	66.9	41.41
WB4	757	25.8	12.20
WB5	1,689	15.4	6.38
WB6	196	15.5	2.55
WB7	688	22.3	6.38
WB8	17	12.8	0.25
Total	9,791	249.9	75.35

Source: derived from the WSAM database

contribute to water requirements for mining. The model was only configured to simulate groundwater use in these two sub-catchments, WB3 and WB4.

Water Demand

The DWAF has established a comprehensive database of water demand and use throughout South Africa. This database, known as the Water Situation Assessment Model (WSAM), provides data for all quaternary catchments for the year 1995 (Schultz and Watson 2002). In the current study, this database was used to estimate the demands within each sub-catchment for the ‘baseline’ scenario and provided the basis for modifying demands for both the ‘historic’ and ‘future’ scenarios. It had been hoped to use an updated version of the database for the year 2000, but this was unavailable at the time the modeling was conducted.

Five water-use sectors were simulated in the WEAP model. These were irrigation, mining, rural, urban and commercial forestry. Within the Olifants Catchment, there is also a large demand from the power sector for cooling water. This is estimated to be 188.8 Mm^3 per year. However, this demand is largely met through inter-basin transfers from the Vaal, Inkomati and Usutu catchments (McCartney et al. 2004). Most of the water is transferred directly to reservoirs located at the power stations and leaves the catchment as evaporation. Consequently, it is believed to have a negligible impact on the net water resources of the catchment and so was not simulated within the WEAP model.

Data on water demand in 1995 for each of the sectors were obtained from the WSAM database. The data for each sub-catchment in the WEAP model were derived by summing the relevant data from the quaternary catchments located within that sub-catchment. The WSAM database contains information that enables calculation of both gross and net demand for each sector. In the current study, with the exception of irrigation, all demands were entered into the WEAP model as net demand. For irrigation, the demands were entered as gross demand, but with an estimate of the return flow. Table 5 describes and presents the net demand for each sector incorporated within the WEAP model simulation.

Inter- and intra-annual differences in irrigation demand were computed based on variations in rainfall. For each sub-catchment an equation was developed to estimate the irrigation demand as a function of rainfall. Similarly, for commercial forestry, intra-annual variation was simulated by altering the percentage of annual demand, in each month, to reflect variations in soil moisture. Further details are provided in McCartney et al. (2005).

TABLE 5.
Estimated average annual net water demand for different sectors in the Olifants River Catchment in 1995.

Sector	Description	Annual net water demand (Mm^3)
Irrigation	Irrigation is the largest consumer of water within the Olifants Catchment. The total irrigated area, excluding smallholder irrigation, which in the WSAM database is incorporated in the 'rural' water use (see below), is estimated to be approximately 110,000 ha. In this study, the average annual water demand and return flows were estimated for each sub-catchment in the WEAP model by summing the data available, for 1995, for each quaternary catchment in the WSAM database. Within the WEAP model the annual demand was expressed as a volume per hectare irrigated, while return flows were expressed as a percentage of the demand. Average annual demand in the sub-catchments varied from 3,567 to 6,577 m^3 per hectare and return flows varied from 6.4 to 10%. These differences between sub-catchments reflect differences in rainfall and the crops irrigated.	511
Mining	Mining activities are dominated by coal mining, particularly in the highveld, but also include copper, gold, tin, platinum, phosphate and diamonds in the lowveld (DWAF 2003c). The mines use water for the processing of ores. The number of active mines in the catchment was estimated to be 93 (South African Council of Geoscience cited in DWAF 2003b). Net water demand was determined for each quaternary catchment from the WSAM database but this does not specify the type of mines. WSAM data were summed to provide the estimates for each sub-catchment in the WEAP model. No allowance was made for mine dewatering activities or changes to water quality in returning effluents.	77
Rural	Rural water demand encompasses all domestic water requirements outside of urban areas. It includes stockwatering and subsistence irrigation on small rural garden plots. Domestic and stockwater requirements are based on per capita consumption rates derived from the WSAM database. Domestic use varies from 32 to 113 lpcpd with an average of 84 lpcpd for the whole of the Olifants. Livestock consumption was estimated to be 42 lpcpd. Return flows are believed to be negligible, so the total requirement is the same as the net demand. It was assumed that there was no intra-annual variation.	74
Urban	The urban water demand encompasses industrial, commercial, institutional and municipal water requirements. Within the WSAM database the domestic water demand is determined based on per capita consumption related to a household classification system. Thus, demand varies from 320 lpcpd for big houses to 10 lpcpd for shantytown houses supplied by communal taps. Within the WEAP model the total consumptive water requirement (i.e., that which is consumed and does not contribute to sewage/effluent) was used. No allowance was made for changes to water quality in returning effluents.	28
Commercial forestry	Afforestation impacts the hydrology of the catchment by increasing evapotranspiration (and so reducing runoff) relative to indigenous vegetation. It is this flow reduction characteristic that was simulated as a demand within the WEAP model. Annual demand was estimated from the WSAM database based on volume per hectare of forest in each quaternary catchment.	54

Water Allocation

As described above (section *Model Description)*, water allocation is simulated in the WEAP model using priorities to curtail certain water uses during periods of scarcity. In the past, demands have been considerably affected by entitlements and these were incorporated into the historic scenario implicitly. It is also likely that future demands will be increasingly influenced by water entitlements. However, since the water demands within each sector were lumped for each sub-catchment, it was not possible to simulate specific authorizations and license conditions in the current study.

The priority for the demand sites were set on the basis of not only the true priorities within the catchment (i.e., between different sectors), but also the probable realities of upstream-downstream allocation. Hence, priorities were progressively lowered with increasing distance downstream (Table 6). The exceptions were sub-catchments WB4 and WB6. Since these are separate sub-catchments (i.e., located off the main-stem of the river) the demands within these catchments were assumed to be separate and not directly affected by upstream use. In all the sub-catchments, forestry was given priority one, because, as discussed in Table 5, it is a flow reduction activity rather than a true demand. All dams were given priority 51 (i.e., lower than all the demand sites), which meant that, at any given time, keeping the reservoirs full was of less importance than meeting demands. This is unlikely to be the case in reality, since limits would have been placed on demands during periods of water shortage. However, since the dam operating rules were not available from the DWAF none were included.

Model Calibration

The complexity of water allocation models and the fact that they are required to simulate human behavior (i.e., to reflect changes in demand) in addition to physical processes means that model calibration and validation is extremely difficult and has often been neglected in the past (Etchells and Malano 2005). In this study an attempt was made to calibrate the WEAP model using observed flow data obtained from the five gauging stations located on the main stem of the Olifants River (Figure 5). These flows integrate the impact of climate, changes in demand, water resource development and land-use within a catchment. Calibration involved changes to model parameters to better simulate the historic scenario. These included changing assumptions about the pattern of historic demand, altering demand priorities, modifying the operating rules of the Blyderivierspoort Dam and including environmental flow requirements, to improve the fit between simulated and observed flows.

TABLE 6.
Priorities for different water demand sites within the WEAP model.

Sub-catchment	Rural	Urban	Mining	Irrigation	Forestry	Dams
WB1	2	3	4	5	1	-
WB2	6	7	8	9	1	51
WB3	10	11	12	13	1	51
WB4	2	3	4	5	1	51
WB5	14	15	16	17	1	-
WB6	2	3	4	5	1	51
WB7	18	19	20	21	1	-
WB8	22	-	-	-	1	-

As there is no automatic routine for calibration within the WEAP model, changes were implemented and tested manually, by trial and error; a time consuming task. Calibration was based primarily on visual comparison of the simulated and observed time series and mean monthly flows. Since the data records for the gauging stations cover different periods of time, the stations used for different time periods varied. The oldest record extends back to October 1948, hence there was no calibration of the model before this date.

For the calibration, just two environmental flow locations were included. One in the Kruger National Park and one immediately upstream of gauging station B5H002. The first reflected a true environmental flow, since attempts were made to maintain a baseflow of 0.57 m^3s^{-1} through the Park from the 1940s onwards. The second was introduced simply to improve the low flow simulation at gauge B5H002. As such it does not represent a genuine environmental flow requirement, but rather the reality that demand allocation upstream of B5H002 was not completely optimized. Both environmental flow sites were given priority one.

Figure 6 is a comparison of the simulated and observed flow at each of the five gauging stations. Both the monthly time series and the mean monthly flows are presented for the period that each gauging station was operating.

There is very good agreement between the observed and simulated hydrographs at two of the gauging stations, B5H002 and B7H009 (Figures 6e to 6h). Certainly in relation to the mean monthly flows, the WEAP model performed well. For these two stations the percentage error in the simulated mean annual flow is less than 3 percent (Table 7). At B1H005, based on the 17 years of complete data, the percentage error in the simulated mean annual flow is just over 20 percent (Table 7). At this station the simulation of the dry season recession is good, but there is a tendency for the wet season flows to be too high (Figure 6b). Given that there are no large reservoirs upstream of this location, the model fit could only be improved by better simulation of wet season demands, but no additional information was available to enable this.

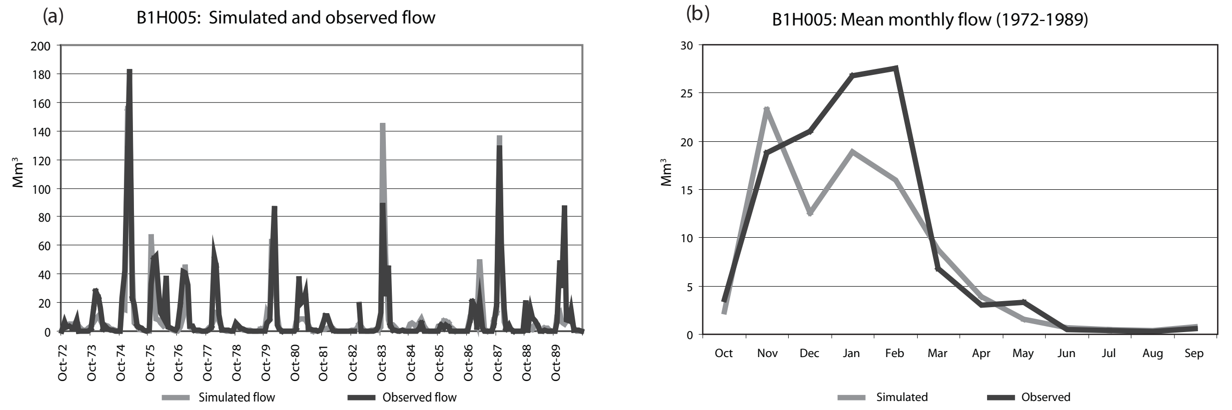
The simulation at B3H001 and B7H015 is poor. At both stations the WEAP model significantly overestimates the flow, particularly in the wet season. At B3H001, there may be a problem with the observed flows. Although the record extended from 1966 to 1989, only 13 years of complete data were available and the record indicates that missing data are often associated with high flow periods (Figure 6c). Even when available, the measured flows in the wet season appear very low (given the size of the catchment). It is possible that there is some bypassing at this gauging station. Further attempts to improve the model fit at this location were believed to be unwarranted without further analysis and quality control of the observed flow series, which was beyond the scope of the current study. At B7H015, observed data are only available for two complete years, hence evaluation of model performance at this station is less meaningful than at the others. However, in one year, 1988, the model performed reasonably well (Figure 6i). More observed data are required

TABLE 7.
Comparison of observed and simulated mean annual flow at the gauging stations.

Gauging station	Catchment area (km^2)	Period of record	Number of years of complete data	Observed (Mm^3)	Simulated (Mm^3)	Error (%)
B1H005	3,256	1972-2000	17	99.3	124.5	+20.3
B3H001	16,533	1966-2000	13	103.5	187.8	+81.4
B5H002	31,416	1948-1979	29	761.8	783.8	+2.9
B7H009	42,472	1960-1997	23	710.2	699.3	-1.5
B7H015	49,826	1987-2000	2	538.9	914.0	+69.6

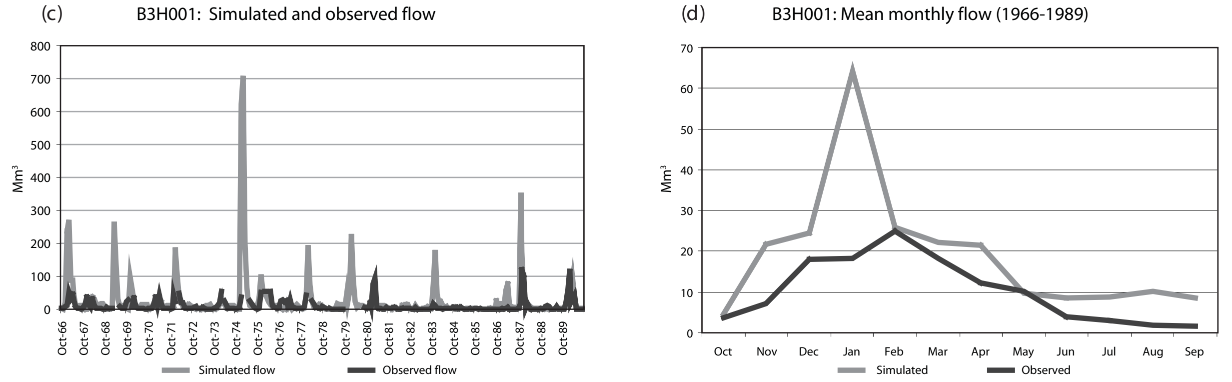
FIGURE 6.

Simulated and observed flow series and mean monthly flows for: (a) and (b) B1H005 (Oct 1972-Sep 1990); (c) and (d) B3H001 (Oct 1966-Sep 1990); (e) and (f) B5H002 (Oct 1948-Sep 1979); (g) and (h) B7H009 (Oct 1960-Sep 1990); (i) and (j) B7H015 (Oct 1987-Sep 1990).



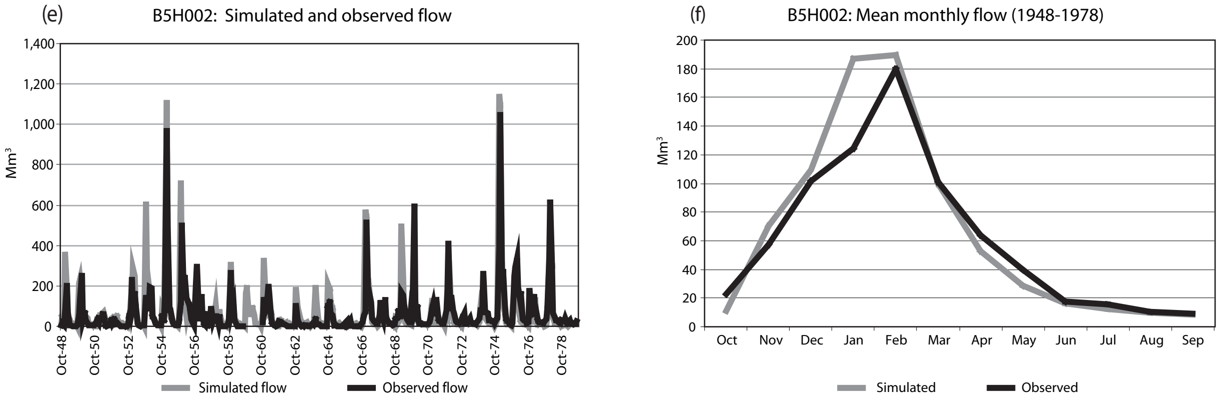
(a) B1H005: Simulated and observed flow

(b) B1H005: Mean monthly flow (1972-1989)



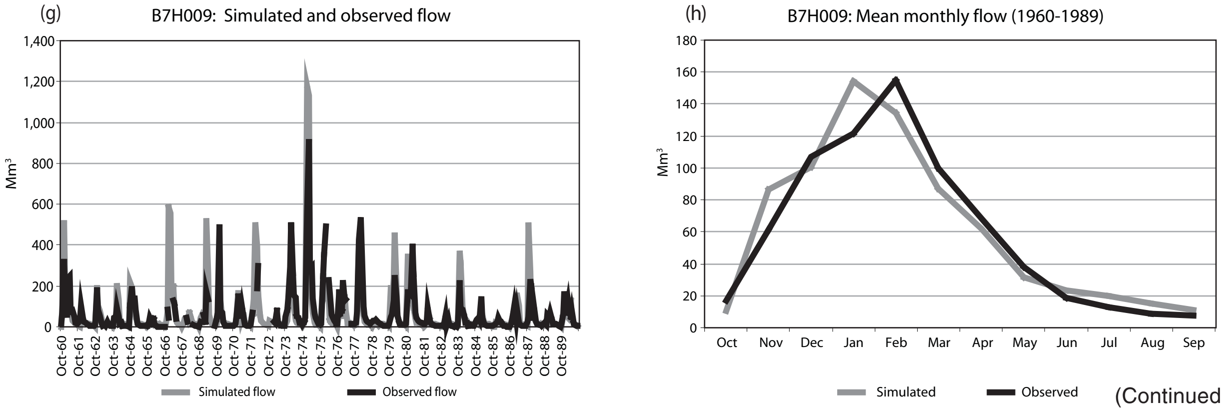
(c) B3H001: Simulated and observed flow

(d) B3H001: Mean monthly flow (1966-1989)



(e) B5H002: Simulated and observed flow

(f) B5H002: Mean monthly flow (1948-1978)

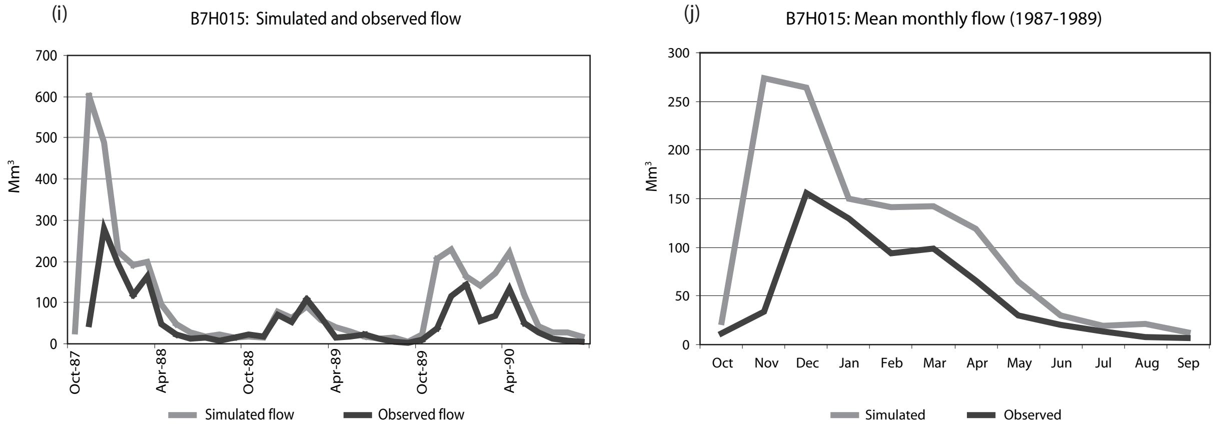


(g) B7H009: Simulated and observed flow

(h) B7H009: Mean monthly flow (1960-1989)

(Continued)

FIGURE 6. (Continued)



to make a fully objective assessment of the model performance at this location.

Although impossible to quantify, there remains considerable uncertainty in the model output. This uncertainty arises from both uncertainties associated with the structure of the model and a lack of understanding (and data) of the complex processes being simulated. Many assumptions had to be made in all the scenarios simulated. The model could be improved but, overall, the results of the calibration were sufficiently encouraging to suggest that model outputs are at least indicative of the likely impacts of changes predicted in the scenarios. Nevertheless, the uncertainty (and the fact that it cannot be quantified) should be kept in mind when interpreting results of the model and findings of the study.

Historic Scenario

Description

An attempt was made to simulate historic water demand in the catchment for the period 1920 to 1989. This period was chosen because the WR90 naturalized flow and rainfall data series are available for input to the model (see section, *Water Resources*) and also because it represents the period of greatest water resource development in the catchment (van Koppen n.d.).

This ‘historic’ water demand scenario was based on estimates of changes in demand within each sector over time and, as such, represents a ‘transient’ scenario[7] (Table 8). Changes in the irrigation demand were interpolated based on recorded estimates of irrigated area from 1955, 1968, 1988 and 1995. No allowance was made for changes in irrigation practices or crops grown over time (i.e., the demand per hectare and the proportion of return flows in each sub-catchment

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[7] In this study, a transient scenario is one in which demands change over the duration of the scenario. In comparison, an equilibrium scenario is one in which demands are fixed at a specific level throughout the duration of the scenario.

TABLE 8.
Estimates of average annual net water demand in different sectors (1920 to 1989).

Sector	Estimated net demand (Mm^3)			
	1920	1950	1968	1989
Irrigation[1]	0	180.8	340.2	394.3
Mining	0	0	33.8	73.4
Rural	9.7	27.5	45.9	67.4
Urban	2.7	6.9	15.3	25.0
Commercial forestry	3.9	11.2	2.4	48.5
Total	16.3	226.4	437.6	608.6

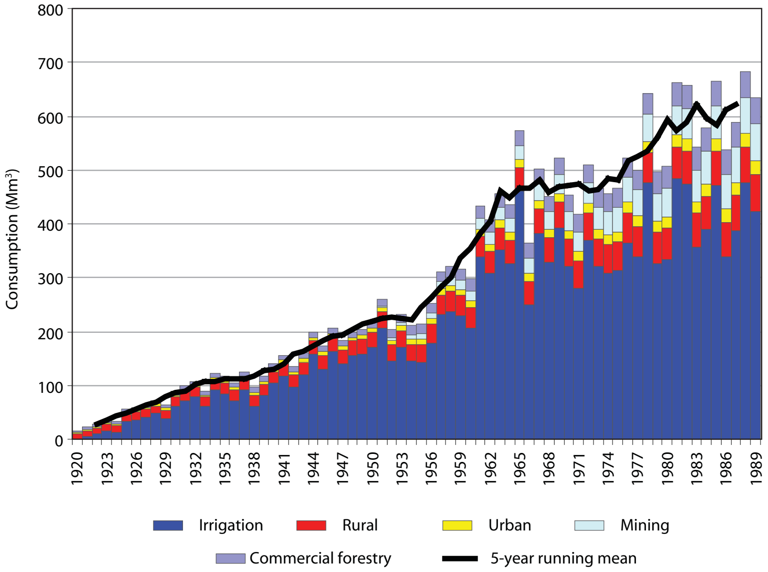
Note: [1] Mean demand – varied depending on rainfall.

in the WEAP model were assumed constant). In the rural and urban sectors, changes in demand were based primarily on population growth. For the mining and commercial forestry sectors, very little data were available on temporal variation and thus changes were based primarily on perceptions of change over time (McCartney et al. 2005). The timing of dam construction and, for some dams (e.g., the Loskop and Witbank dams), the dates when they were raised were obtained from the DWAF Dam Safety Register (Table 3).

Results

Figure 7 presents a time series of simulated annual consumption within each sector for the period 1920 to 1989. Without more information on changing demands over time there is no way to validate this graph. A recent evaluation of the water development trajectory within the catchment (van Koppen n.d.), would suggest that, because mining and irrigation commenced earlier than assumed in the current study (i.e., at the end of the nineteenth century),

FIGURE 7.
Variation in simulated annual net water demand within each sector (1920 to 1989).



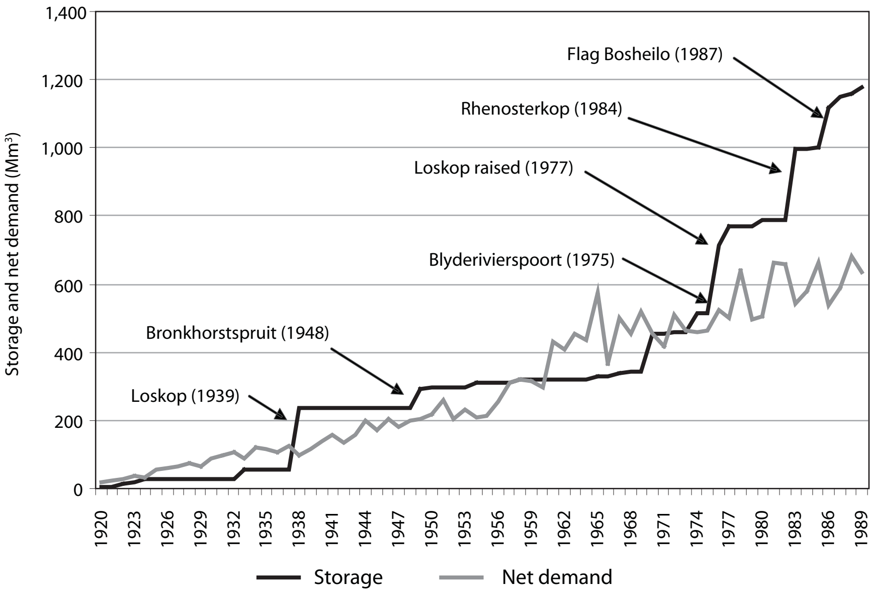
demands in the early part of the simulation (i.e., specifically the 1920s and possibly the 1930s) are most likely to be underestimated. However, for the most part it is believed to be a plausible representation of the changing net water demand in the catchment over time.

The graph highlights: i) the general upward trend, driven primarily by increasing demand for irrigation, and ii) the considerable inter-annual variability in demand, arising from changes in irrigation demand, reflecting variability in rainfall. The five-year running mean shows two periods of more rapid rise in consumption. The first extended from approximately the mid-1950s to the mid-1960s and the second extended from approximately the mid-1970s to the mid-1980s. The first, in particular, was driven by a rapid increase in irrigated area. However, net demand was exacerbated by drought. Within the 70-year period of simulation, the most severe drought occurred over the five years from 1961 to 1965 (McCartney et al. 2004). The lack of rain significantly increased irrigation demand and hence consumption in this period. In fact, this scenario indicates that the levels of irrigation consumption attained in 1965 (461 Mm^3) were not exceeded again until 1978 (476 Mm^3), another drought year. In the second period, increasing consumption was driven less by the rate of increase in irrigated area, which slowed considerably from the early 1970s (perhaps a consequence of lack of investment caused by economic recession) but was largely a consequence of droughts. Severe droughts in 1978, 1981-1982 and 1984-1986, drove up irrigation demand in this period.

Figure 8 compares the evolution of reservoir storage and the simulated net demand over time. It is based on the DWAF Dam Safety Register and shows the storage in all the major (but not all the minor) reservoirs in the catchment. These had a total storage of just under 1,200 Mm^3 in 1989. Reservoir storage does not equate to yield, but nonetheless it is interesting that dam construction in the 1930s and 1970s occurred after net demand outstripped storage, potentially leaving the catchment vulnerable to droughts.

Analysis of evaporation from the reservoirs simulated in the WEAP model highlights another interesting result of the historic scenario. As would be expected, evaporation from reservoirs increased significantly as the amount of water stored increased over time. Extrapolating the results from the WEAP model to all reservoirs in

FIGURE 8.
Comparison of storage and annual net water demand in the Olifants Catchment (1920 to 1989)



the catchment, it is estimated that by 1989 evaporation from the reservoirs equated to between 200 and 225 Mm^3. This means that currently, after irrigation, reservoir evaporation is by far the largest anthropogenic 'use' of water in the catchment.

Baseline Scenario

Description

The baseline scenario was developed using demands in 1995 derived from the WSAM database (Table 5). As with the historic scenario, the simulation was conducted using the 70 years of naturalized flow and rainfall data derived from the WR90 study. However, in this case both the demands and storage (i.e., dams) were fixed at the 1995 level for the entire period. As such, the scenario represents an 'equilibrium' type scenario. Table 9 summarizes the key data underpinning the scenario. From the WSAM database, the average annual net demand for the whole catchment was estimated to be 744 Mm^3. Tables 10 and 11 present the average annual net demand for each sector and each sub-catchment in the WEAP model, respectively. However, inter and intra-annual fluctuations in irrigation demand, arising from variations in rainfall, meant that the total annual net demand varied from 577 to 995 Mm^3.

From the WEAP model the unmet demand was determined for each sector for each month simulated. These data were summed to calculate the annual unmet demand for each of the 70 years of simulation. The frequency of occurrence of unmet demand is of more interest to planners than the mean annual unmet demand. Consequently, standard frequency analyses were applied to the 70-year series of unmet demand to determine the return periods for different magnitudes of shortfall. This involved fitting a statistical distribution to each series of annual unmet demand, ranked by the magnitude of shortfall. A number of different statistical distributions were tested and, though the one producing the best fit varied from one series to another, overall, a two-parameter log-normal equation proved the best for most series and hence was used in all cases. Figure 9 presents two examples of the statistical distributions fitted.

TABLE 9.
Baseline scenario: Statistics underpinning the simulation.

Population		Per capita demand (lpd^{-1})		Irrigation (ha)		Livestock	Number of active mines	Commercial forestry (ha)
Rural	Urban	Rural	Urban	Commercial	Smallholder[1]			
1,737,874	836,259	84	133	110,240	-	337,019	93	40,000

Note: [1] No area was included in the baseline scenario because in the WSAM database smallholder irrigation is incorporated in the rural per capita demand.

TABLE 10.
Baseline scenario: net water demand for each sector (Mm^3).

	Irrigation	Mining	Rural[1]	Urban[2]	Forestry	Total
Baseline	511	77	74	28	54	744

Notes: [1] includes domestic use, smallholder irrigation and livestock requirements.

[2] includes domestic use and industrial use.

FIGURE 9.
Examples of the statistical distribution fitted to unmet demand for the baseline scenario: (a) total unmet demand; and (b) unmet demand in the irrigation sector.

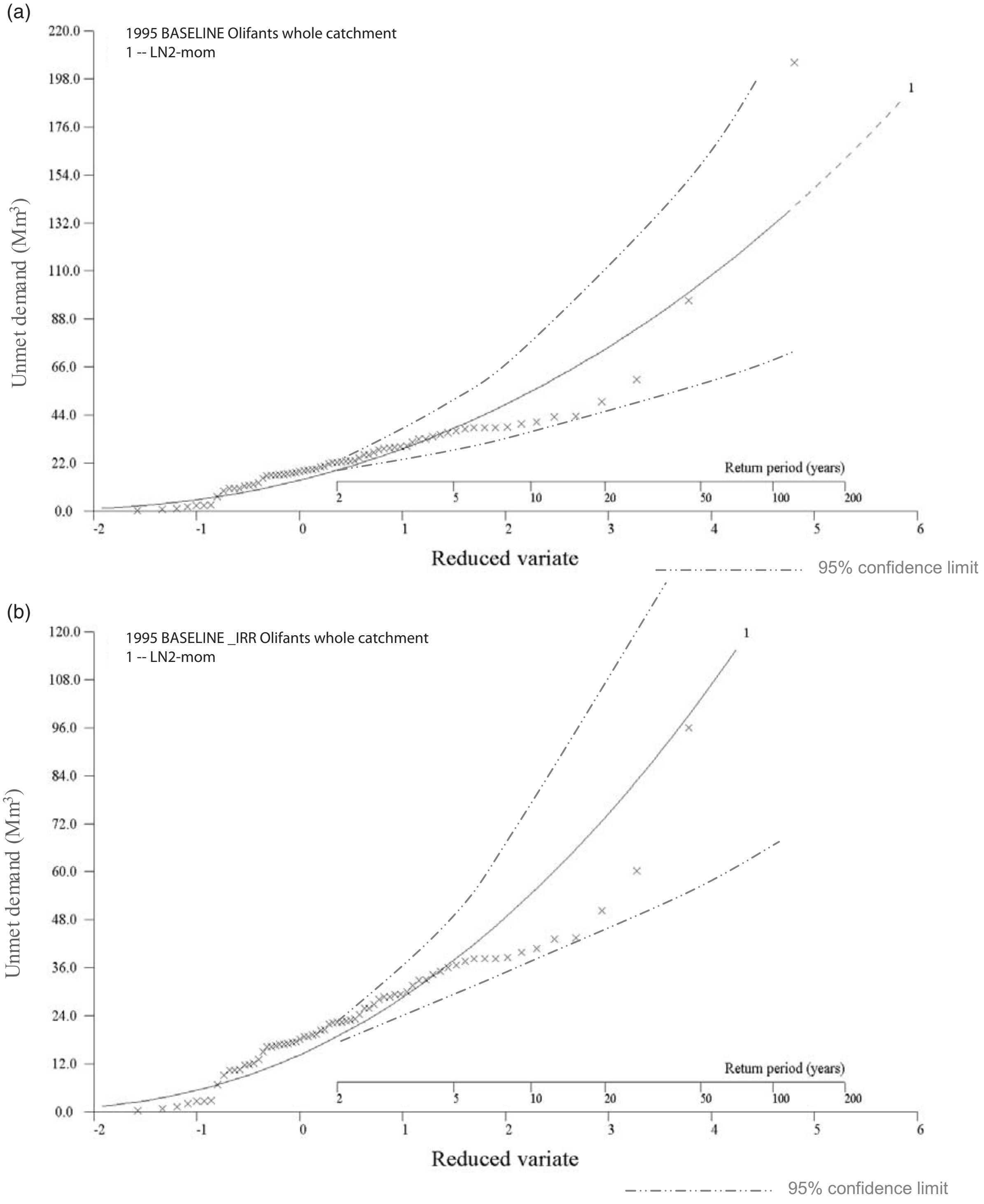


TABLE 11.
Baseline scenario: Net water demand for each sub-catchment in the WEAP model (Mm^3).

	WB1	WB2	WB3	WB4	WB5	WB6	WB7	WB8	Total
Baseline	16	247	201	95	39	73	73	0.02	744

Finally, the results were converted to assurance levels (i.e., volumes of water that can be guaranteed with different degrees of certainty). For each sector and each return period estimate, this was done by subtracting the shortfall from the demand (to give the volume that could be guaranteed) and converting the return period to a percentage level of assurance (e.g., return periods of two, five and 100 years are equivalent to assurance levels of 50, 80, and 99 percent, respectively). There is always some uncertainty associated with fitting statistical distributions. In this study this was particularly the case for those series in which failure to meet demand occurred in only a few years of the 70-year series. Consequently, the assurance levels are not precise, but in each case are indicative of the probability of satisfying demand in any year.

Water productivity figures, expressed as rand m^{-3}, have been estimated for the Olifants Catchment based on an estimate of the gross geographical product (GGP) of the catchment (Prasad et al. 2006). The total GGP of the catchment is estimated to be 24,400 million rand (i.e., US$3,253 million), which equates to 9,478 rand (i.e., US$1,264[8]) per capita. This compares to a per capita GGP of US$1,200 reported by Magagula and Sally (n.d.). Water productivity estimates have been derived for four sectors: agriculture, industry, mining, and water supply services (Table 12). These figures were determined by dividing each sector's contribution to GGP by the volume of water 'used' in that sector. For each sector, water is just one of many vital inputs and its relative importance may be small. For example, iron ore may make a much larger contribution than water to revenue generated by the steel industry. Furthermore, the analysis only accounts for 'blue' water use (i.e., water abstracted from rivers or groundwater). In particular, for the agricultural sector it ignores the contribution made by rainfall. Nevertheless, GGP contributions determined with respect to blue water use provide an indication of the relative productivity of water supplied by DWAF for each sector (Prasad et al. 2006).

The water productivity data were used to estimate the cost of failing to supply water (i.e., effectively foregone contributions to GGP arising from water shortages) to each of the sectors simulated in the WEAP model. Since the commercial forestry sector is rainfed it was not included in the analyses. For these analyses, all the rural demand was assumed to be for water supply. This almost certainly over-estimates the productivity of rural water use. An alternative would have been to use the agricultural sector value, but since rural water has multiple uses this would probably underestimate its true value. The urban demand was divided between water supply and industry based on direct (i.e., domestic demand) and indirect (i.e., industrial, commercial and institutional demands) demands as categorized in the WSAM database.

TABLE 12.
Water productivity data demarcated by sector.

Sector	Rand m^{-3}	US$ m^{-3}
Agriculture[1]	2.25	0.30
Industry	260.10	34.68
Mining	21.45	2.86
Water supply services	29.11	3.88

Source: Prasad et al. 2006

Note: [1] Takes no account of the contribution from rainwater, which, if included, would significantly reduce this figure.

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[8] Using an exchange rate of US$1 = 7.5 rand.

Results

Table 13 summarizes the results for the baseline scenario. The results indicate that in total 725, 706, and 639 Mm^3 can be provided with assurance levels of 50, 80, and 98 percent, respectively. The DWAF estimate the ‘yield’ of the catchment (i.e., the volume of water that can be guaranteed in 98% of years) to be 638 Mm^3 (Magagula et al. 2006). This corresponds very well with the estimate of 639 Mm^3, obtained from the WEAP modeling, and provides confidence that the simulation in the WEAP model is reasonable. Shortfalls are experienced every year, predominantly in the irrigation sector (mean annual shortfall to irrigation is approximately 26 Mm^3), but also with small shortfalls in the mining sector. In this scenario, rural and urban supplies are assured at the 99.5 percent level (i.e., failure to supply these sectors would occur less than once in 200 years).

The annual cost of unmet demand varies, depending on rainfall and hence river flows. The economic analysis, based on the water productivity figures, indicates that, currently, the costs of failure to deliver water to the irrigation and mining sectors in the Olifants River Catchment range from approximately US$6 to US$50 million per year (i.e., 0.2 to 1.5 percent of current GGP), depending on how dry it is (Table 14). The largest losses are in the agriculture sector, simply because water supply to irrigation is of a lower priority than provision to the mining sector. Since most irrigation is taking place in sub-catchments WB2, WB3 and WB4, the greatest economic losses occur in these sub-catchments.

Impact of implementing the Reserve

In the scenario discussed above, environmental flows were simulated exactly as in the historic scenario (i.e., simply at two locations, with fixed baseflows). To assess the implications of fully implementing the Reserve, environmental flow

TABLE 13.
Baseline scenario: Computed volumes of supply with different levels of assurance.

Assurance level (%)	Total	Irrigation	Mining	Rural	Urban
50	725	492	77	74	28
80	706	473	77	74	28
90	689	456	77	74	28
96	663	430	77	74	28
98	639	407	76	74	28
99	613	381	76	74	28
99.5	582	352	76	74	28

TABLE 14.
Baseline scenario: Cost (million US$) of failure to supply water (i.e., foregone GGP).

Return period (years)	Irrigation	Mining	Rural	Urban	Total
2	5.703	0.400	-	-	6.103
5	11.424	0.658	-	-	12.082
10	16.428	0.887	-	-	17.315
25	24.195	1.201	-	-	25.396
50	31.071	1.459	-	-	32.530
100	38.91	1.745	-	-	40.655
200	47.808	2.031	-	-	49.839

requirements, derived from the Reserve assessment (see section, *The Reserve*), were incorporated into the model. Of the 17 environmental flow time series, six, located close to the outlets of the sub-catchments in the WEAP model, were incorporated into the model (Table 15). Each was effectively included as a time series of additional demands with priority 1. The model was then rerun.

Table 16 summarizes the results of the model for the baseline scenario with the Reserve implemented. These results indicate that, as would be expected, full implementation of the Reserve reduces the volumes of water that can be provided to other sectors at any particular level of assurance (i.e., unmet demand to other sectors increase). As well as increasing unmet demand in the irrigation and mining sectors, under current conditions full implementation of the Reserve would also result in shortfalls in both urban and rural supply (Table 16). It is for this reason that the DWAF is not currently implementing the Reserve fully, despite the fact that it is the number one priority by law.

Table 17 shows that implementing the Reserve would increase the costs of failing to supply water to all sectors to be between approximately US$13 and US$78 million per year. This represents additional costs (i.e., above those already being incurred as a result of shortfalls) of between US$7 and US$29 million per year. These additional costs equate to just 0.2 to 0.9 percent of GGP, arguably a relatively small price to pay to safeguard the sustainability of the resource[9].

TABLE 15.
Selected environmental flow requirements incorporated in the sub-catchments in the WEAP model.

Sub-catchment in WEAP model	IFR cross section	% of naturalized streamflow	Long-term flow requirement (Mm^3)
WB2	IFR 5	24	120.2
WB3	IFR 8	19	155.1
WB4	IFR 10	18	69.9
WB5	IFR 11	13	174.1
WB6	IFR 12	34	128.5
WB8	IFR 16	20	393.6

Source: Derived from Palmer 2001a, 2001b, 2001c.

Note: IFR = Instream flow requirement.

TABLE 16.
Baseline scenario (with the Reserve implemented): Computed volumes of supply with different levels of assurance.

Assurance level (%)	Total	Irrigation	Mining	Rural	Urban
50	710	477	76.9	73.6	27.93
80	681	448	76.7	73.3	27.90
90	658	425	76.6	73.2	27.89
96	623	390	76.4	72.9	27.82
98	594	361	76.2	72.7	27.86
99	561	329	76.0	72.5	27.85
99.5	525	293	75.8	72.3	27.84

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[9] By comparison it is estimated that between 1989 and 2003, Thames Water in the UK spent the equivalent of US$244 million per year (using an exchange rate of US$2 to 1 UK sterling pound) on mitigating the environmental impacts of abstractions, effluent discharge and pollution (specifically nitrates, pesticides and other contaminants) in the Thames River. This compares to revenues from water supply and sewerage services of approximately US$3,059 million per year (Environment Agency 2005). Clearly this is not a direct comparison with the 'cost' of the Reserve, specified in terms of losses to GGP, but does indicate the costs associated with the environmental concerns of water resource development in a developed country.

TABLE 17.
Baseline scenario (with the Reserve implemented): Cost (million US$) of failure to supply water (i.e., foregone GGP).

Return period (years)	Irrigation	Mining	Rural	Urban	Total
2	10.2	0.4	1.6	1.0	13.2
5	18.8	0.9	2.6	1.5	23.8
10	25.8	1.3	3.3	1.6	32.0
25	36.2	1.8	4.2	1.9	44.1
50	45.0	2.3	5.0	2.1	54.4
100	54.7	2.9	5.8	2.2	65.6
200	65.5	3.6	6.6	2.3	78.0

Furthermore, this analysis of costs to other sectors makes no allowance for the benefits derived from full implementation of the Reserve, many of which are not valued by conventional markets (i.e., water-related environmental services, including water supply and maintenance of natural resources on which many poor rural communities depend).

Although, currently, there is no agreement between South Africa and Mozambique on flows across the border, analyses show that one advantage of implementing the Reserve is that baseflows are likely to exceed what may, according to the DWAF, be agreed as minimum cross border discharge in the future (i.e., 5 percent of the monthly naturalized streamflow) (Arranz and McCartney 2007).

Future Scenarios

Description

Each of the future scenarios was developed from a mixture of quantitative and qualitative information relating to possible future trends in population and the potential changes within each sector that might occur prior to 2025. As such, each scenario represents a coherent and consistent description of a possible state of the future water demand in the Olifants Catchment. Discussions that took place with DWAF officials (including Beyers Havenga, the Chief Engineer responsible for water resource development in the Olifants River Catchment) and at a workshop (in March 2006) attended by a number of water resource experts, were used to test the assumptions made and validate the plausibility of each of the three scenarios.

Some aspects were common to all three scenarios, including:

- Full implementation of the Reserve. Since it is a legal requirement, and of the highest priority for the DWAF, it was assumed that the Reserve will be fully implemented in 2025. Consequently, environmental flow requirements at six locations were simulated within the WEAP model with priority one (Table 15).
- No increase in commercial irrigation. The DWAF does not foresee any significant increase in commercial irrigation in the future. Where land is transferred from commercial to smallholder farmers, the total water allocation should stay the same (see section, *Water Reallocation*).

The one exception being that a small number of entitlements will be issued for new and revitalized smallholder irrigation schemes[10].

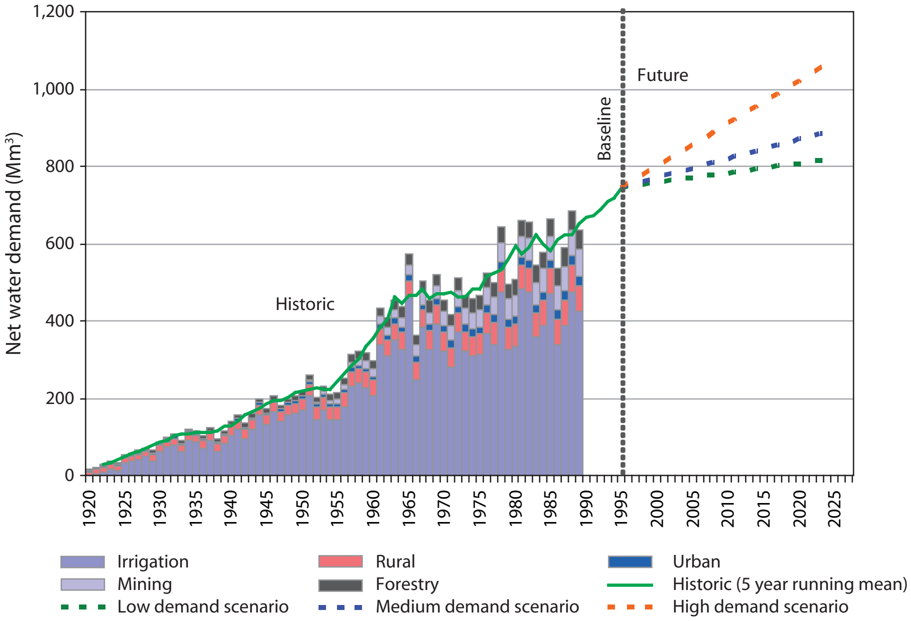
- No significant land-use change. The Olifants is regarded by the DWAF as a 'mature' catchment, with little scope for significant land-use change. Development of additional commercial forestry is currently prohibited. It is possible that new forestry practices currently being implemented (e.g., the clearance of buffer strips alongside river channels) will reduce the impact of forestry and improve flows slightly.

- No significant increase in livestock. The DWAF does not foresee significant changes in livestock numbers.

The key assumptions made in each of the scenarios are summarized in Table 18.

Table 19 summarizes the statistics used as the basis for water demand in each of the three future scenarios. Tables 20 and 21 present the average annual net demand for each sector and each sub-catchment in the WEAP model, respectively. Figure 10 shows the three future scenarios relative to the historic and baseline scenarios. As with the baseline scenario actual net demand varied from year to year, depending on rainfall and hence requirements for irrigation. Over the 70 years of simulation it varied from 652 to 1,070 Mm^3 for the low demand scenario, from 726 to 1,145 Mm^3 for the medium demand scenario and from 906 to 1,325 Mm^3 for the high demand scenario. Although unquantifiable, because uncertainties in the model are common to all the scenarios, their significance lies in

FIGURE 10.
Comparison of water demand in the Olifants River Catchment for the past, baseline and future scenarios.



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[10] The Revitalization of Small-scale Irrigation Systems (RESIS) program is currently being implemented across the Limpopo Region. The objective of this program is to reinstate failed smallholder irrigation schemes. The total area that will be revitalized is currently unclear and depends, to a large extent, on studies being conducted to assess the sustainability of individual schemes. The future scenarios assumed different areas of irrigation rehabilitated from this program.

the relative differences between them. Figure 11 presents the estimated GGP of each scenario. These were estimated by adding additional economic benefits, derived from each sector, to the baseline GGP, assuming that water demands in each scenario were fully met. Further details of the scenario development, including comparisons with those used by the DWAF for planning, are given in Arranz and McCartney (2007).

TABLE 18.
Summary of the key assumptions made in each of the future scenarios.

Scenario	Key assumptions
Low demand	• A slowing of both rural and urban population growth, in comparison to that experienced from 1996 to 2001 (i.e., varying between sub-catchments, but with an average across the whole catchment of 1.35% per annum). • Per capita demand remains constant for both rural and urban users (i.e., averages across the catchment of 85 and 133 lpcpd, respectively). • A small increase in smallholder irrigation (1,839 ha) largely arising through the RESIS program. For consistency with the baseline scenario this was added to the rural demand. • Some mines close and some open. No net increase in coal mining, but an increase in platinum group metal mines particularly in WB3. Overall, the number of active mines in the catchment increases from 93 to 118. • New practices in commercial forestry are effective. The impact is equivalent to reducing the area of forestry from 40,000 to 38,000 ha.
Medium demand	• Both rural and urban populations grow at the same rate as the growth between 1996 and 2001 (i.e., varying between sub-catchments, but with an average across the whole catchment of 1.85% per annum). • Per capita demand remains constant for both rural and urban users (i.e., averages across the catchment of 85 and 133 lpcpd, respectively). • An increase in smallholder irrigation of 3,679 ha largely arising through the RESIS program. For consistency with the baseline scenario this was added to the rural demand. • An increase in both coal and platinum group metal extraction. The total number of active mines in the catchment increases from 93 to 168. • New practices in commercial forestry only have a limited effect on runoff, so that the area under commercial forestry effectively remains constant at 40,000 ha.
High demand	• Both rural and urban populations grow at a higher rate than the growth between 1996 and 2001. Urban populations increase significantly, particularly in towns located close to new mines. Rural populations also increase. It varies between sub-catchments but the average population increase across the whole catchment is 2.35% per annum. • Per capita demand increases, due to increases in both socioeconomic status and improvement in rural supply. In catchments where urban per capita demand is currently less than 200 lpcpd, this increases to 200 lpcpd. In rural areas net demand increases from 85 to 125 lpcpd. • An increase in smallholder irrigation of 7,357 ha largely arising through the RESIS program. For consistency with the baseline scenario this was added to the rural demand. • Much of the current geological exploration is successful resulting in significant increases in the number of both coal and platinum group metal mines. The number of active mines in the catchment increases from 93 to 225. • New practices in commercial forestry only have a limited effect on runoff, so that the area under commercial forestry effectively remains constant at 40,000 ha.

FIGURE 11.
Comparison of estimated GGP for the baseline and each of the future scenarios.

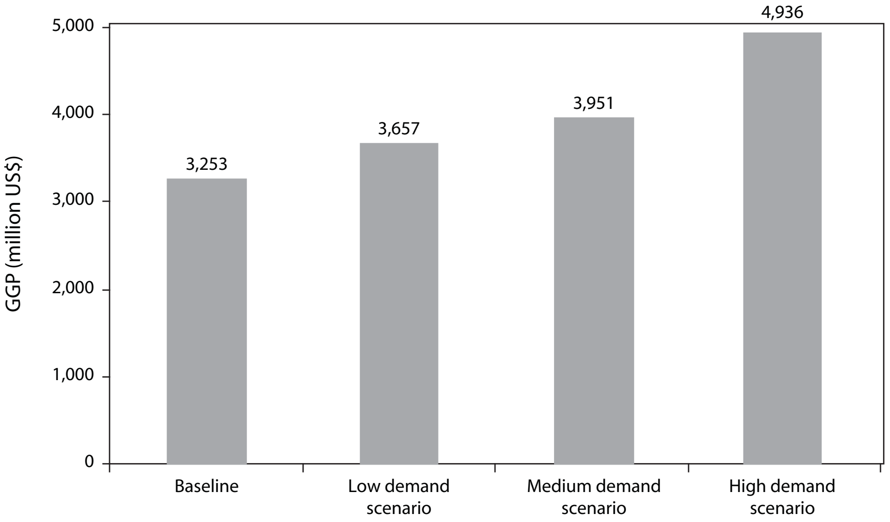


TABLE 19.
Future scenarios: Statistics underpinning the simulations.

	Population		Per capita		Irrigation (ha)		Livestock	Number of active mines[2]	Commercial forestry (ha)
	Rural	Urban	Rural	Urban	Commercial	Smallholder[1]			
Low demand	2,612,985	1,405,510	85	133	110,240	1,839	337,019	118	38,000
Medium demand	3,028,542	1,628,148	85	133	110,240	3,679	337,019	168	40,000
High demand	3,507,654	1,948,000	125	200	110,240	7,357	337,019	225	40,000

Notes: [1] Differences between scenarios are based primarily on the varying success of the RESIS (rehabilitation) project in the Olifants Catchment. For consistency with the baseline scenario, increased net water demand was added to the rural component.

[2] These scenarios assume the same 'average' water use in mining as the baseline scenario.

TABLE 20.
Future scenarios: Net water demand for each sector (Mm^3).

Scenario	Irrigation	Mining	Rural[1]	Urban	Forestry	Total
Low demand	511	97	118	40	52	818
Medium demand	511	139	144	45	54	893
High demand	511	186	246	76	54	1,073

Notes: [1] includes future smallholder irrigation demand arising from RESIS rehabilitation of irrigation schemes.

TABLE 21.
Future scenarios: Net water demand for each sub-catchment in the WEAP model (Mm^3).

	WB1	WB2	WB3	WB4	WB5	WB6	WB7	WB8	Total
Low demand	17	268	243	100	42	71	77	0.11	818
Medium demand	19	286	260	130	45	73	80	0.12	893
High demand	26	321	334	165	59	76	92	0.14	1,073

Results

Figure 12a provides a comparison of the total unmet demand (i.e., shortfall) for different return periods in each sector. Table 22 presents the estimates of water that can be supplied at different levels of assurance to each sector in each of the three scenarios. The results indicate that shortfalls occur every year, even in the low demand scenario. Irrigation suffers the most from shortfalls, as it is the sector that is given the lowest priority. Consequently, the greatest shortfalls are those in sub-catchments that have the greatest irrigation demand (i.e., WB2, WB3 and WB4). In the high demand scenario, shortfalls would occur in every sector virtually every year and no water can be guaranteed for irrigation at the 99 and 99.5 percent assurance levels. In the medium and the low demand scenarios, irrigation shortfalls occur every year. For these scenarios shortfalls also occur in the rural, urban and mining sectors above the 80 percent assurance level (i.e., demand in these sectors cannot be met at least one year in five).

Table 23 presents the estimated economic cost associated with the shortfalls in water supply in each sector. Figure 13a shows the estimated GGP at different assurance levels. The results indicate that, depending on the rainfall and hence flow in the river, annual costs are likely to vary between US$23 and US$404 million and between US$92 and US$1,334 million for the low demand and high demand scenarios, respectively. Thus, in exceptionally dry years (200-year return period), economic losses due to insufficient water supply are likely to be in the order of 11 percent of GGP (US$3,653) in the low demand scenario and 27 percent of GGP (US$ 4,936) in the high demand scenario. In all the scenarios, in more extreme years, urban losses are similar to, or exceed, losses in the irrigation sector.

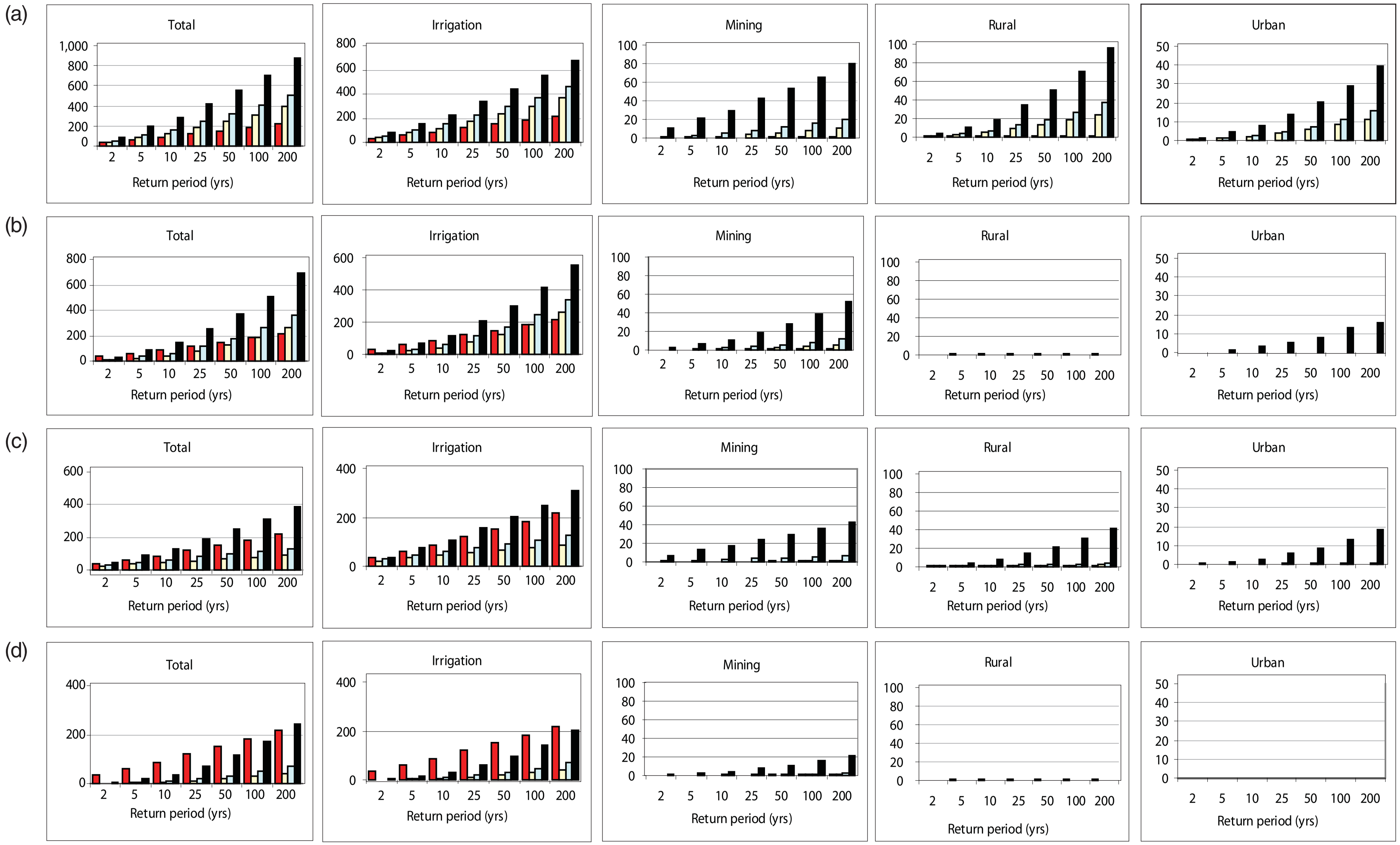
TABLE 22.
Comparison of future scenarios: Water that can be supplied at different levels of assurance (Mm^3).

Assurance level	Total			Irrigation			Mining			Rural			Urban		
(%)	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD
50	780	843	981	473	462	433	97	138	175	117	143	242	40	45	75
80	736	711	880	431	409	352	96	94	165	115	114	235	39	39	72
90	697	660	790	393	361	281	95	92	157	113	111	227	38	38	68
96	632	577	648	333	286	170	93	89	144	109	105	212	36	35	63
98	574	502	519	278	218	71	91	85	133	105	99	196	34	33	56
99	506	415	370	215	140	-	89	81	120	100	91	175	32	29	47
99.5	427	314	200	142	50	-	86	77	107	94	81	150	29	24	37

Notes: LD = Low demand scenario
MD = Medium demand scenario
HD = High demand scenario

FIGURE 12.

Comparison of unmet demand (Mm³) in each sector for the baseline (red), low demand (yellow), medium demand (blue) and high demand (black) scenarios: a) with no new infrastructure and no WCDM measures; b) with new infrastructure; c) with WCDM measures implemented; d) with both new infrastructure and WCDM measures implemented.



Note: Changing scale on the y-axis.

FIGURE 13.
Estimated GGP in the Olifants Catchment at different assurance levels, allowing for water shortages: a) with no additional infrastructure and no WCDM measures; b) with additional infrastructure; c) with WCDM measures implemented; and d) with additional infrastructure and WCDM measures implemented.

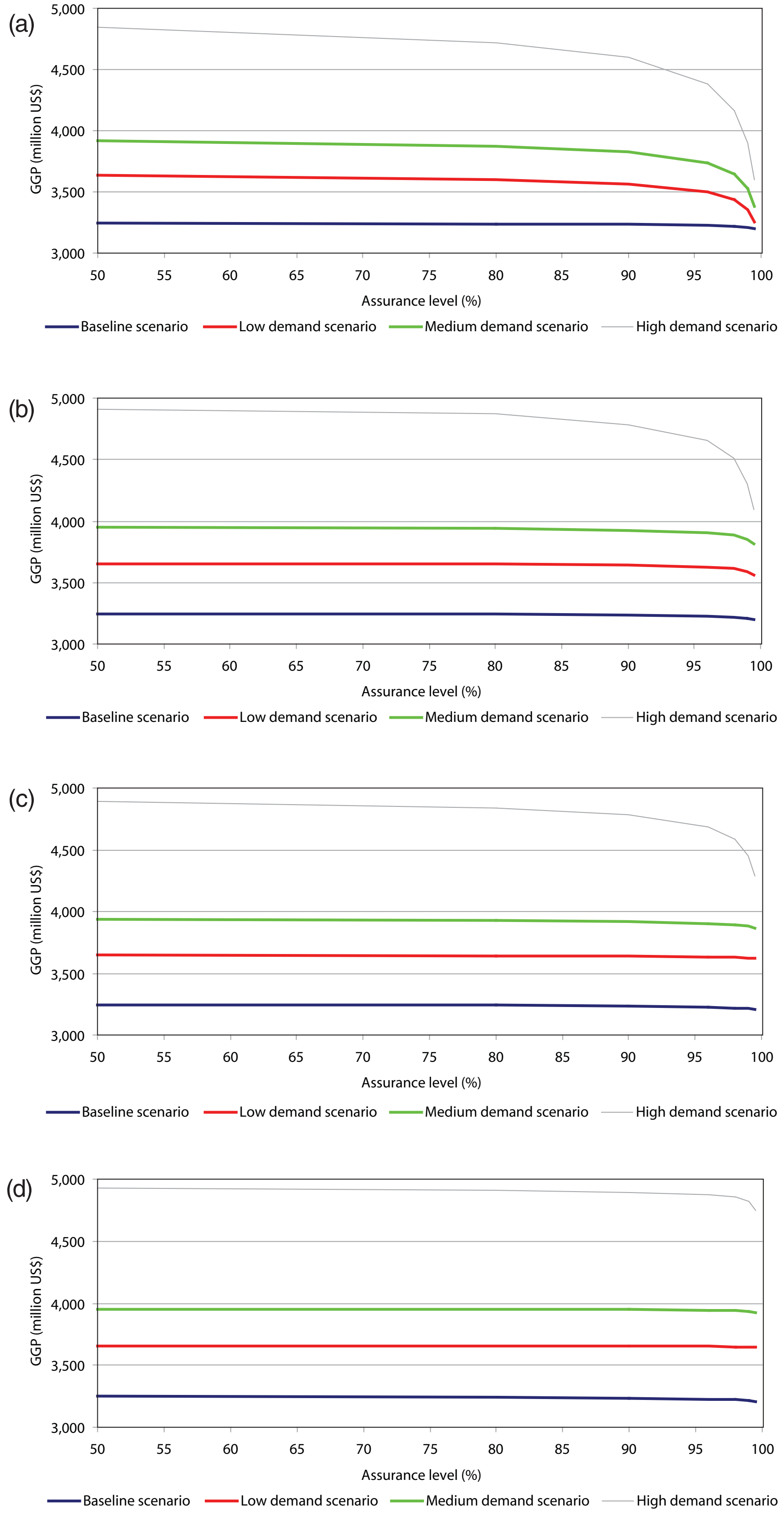


TABLE 23.
Comparison of scenarios: Costs (million US$) of failure to supply water (i.e., foregone contribution to GGP).

Return period	Total			Irrigation			Mining			Rural			Urban		
years	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD
2	22.9	29.8	91.6	11.4	14.8	23.5	1.0	3.6	31.4	4.7	5.7	14.7	5.7	5.9	22.0
5	57.0	75.2	214.0	24.0	30.7	47.7	3.1	8.8	60.0	12.6	16.3	42.3	17.3	19.4	64.1
10	92.6	123.7	338.6	35.4	44.9	68.9	5.6	14.3	84.1	21.0	28.3	73.6	30.6	36.2	112.0
25	156.9	212.8	558.6	53.5	67.5	102.2	10.3	23.8	120.6	36.3	50.9	132.7	56.7	70.5	203.1
50	221.5	304.2	776.7	68.9	87.8	131.9	15.4	33.1	152.2	51.7	74.4	194.3	84.6	108.8	298.3
100	302.7	421.1	1036.2	88.9	111.3	153.3	22.0	44.6	187.6	71.0	104.6	273.7	120.8	160.5	421.6
200	403.9	568.9	1333.9	110.8	138.3	153.3	30.5	58.6	227.2	94.9	142.9	374.6	167.7	229.1	578.8

Impact of infrastructure development and demand management

For each demand scenario an evaluation was made of the impact of both the likely future infrastructure development and water conservation and demand management measures that might be introduced in the catchment. For infrastructure development three changes were set up in the model:

- The DWAF has recently (i.e., 2006) completed modification of the Flag Bosheilo Dam (located in sub-catchment WB3). By raising the dam by 5 m, the reservoir storage has been increased from 105 to 193 Mm^3. Since this was completed after the 1995 baseline scenario, it was only incorporated in future scenarios.
- The DWAF is in the process of building a large dam on the Steelpoort River (i.e., sub-catchment WB4), called the de Hoop Dam, which should be completed in 2008. In terms of storage (347 Mm^3) it will be the second largest reservoir in the catchment, after the Loskop Dam (374 Mm^3). The primary purposes of the dam are: i) to provide water for the mines; ii) to provide bulk water supplies for municipalities; and iii) to enable maintenance of the downstream ecological reserve (DWAF 2005a).
- In addition to this dam the DWAF has conducted feasibility studies for a dam on the main stem of the Olifants River, called the Rooiport Dam (in sub-catchment WB5). In the analyses conducted it was assumed that building of this dam (300 Mm^3) would also have been completed by 2025.

The National Water Act (Act 36 of 1998) and the Water Services Act (Act 108 of 1997) have provided an enabling environment for the implementation of water conservation and demand management (WCDM) measures. The DWAF considers such measures to be an important approach to reconciling water demands and water resources in the Olifants Catchment. Potential savings for each sector are presented in Table 24. In the model runs, investigating WCDM, these savings were presumed to have been achieved by 2025.

Tables 25 and 26 present the results of the model runs with the new infrastructure, for each of the future scenarios. The new infrastructure reduces unmet demands and increases assured supplies. Compared to the baseline scenario the greatest proportional impact of the infrastructure is at the higher assurance levels. Shortfalls still occur in both the irrigation and mining sectors in the low and medium demand scenarios, but in both cases rural and urban supplies can be assured at the 99.5 percent level (Figure 12b). In the high demand scenario full irrigation demand cannot be met, even at the 50 percent assurance

TABLE 24.
Anticipated water savings due to water conservation and demand management (WCDM) measures.

Water sector	Description	Anticipated saving (%)
Irrigation	Even though efficient techniques like drip and sprinkler irrigation are widely used in the Olifants Catchment, significant water losses have been detected in the water distribution infrastructure (i.e., canals and ditches) (Havenga, pers. comm.). Considerable savings are anticipated.	25
Rural	In the rural sector significant water losses due to the deficiency in the water supply infrastructure and the existence of illegal connections have been found (Havenga, pers. comm.). Considerable savings are anticipated.	20
Urban	In the urban sector the losses and illegal connections are less important than in rural areas (Havenga, pers. comm.). Savings are anticipated, but these savings are not as great as in the rural sector.	15
Mining	The mining sector is quite efficient in water use. At most mines, the water used in most processes is recycled. Consequently, only relatively small improvements are anticipated in this sector.	5

TABLE 25.
Comparison of future scenarios with new infrastructure: Water that can be supplied at different levels of assurance (Mm^3).

Assurance level	Total			Irrigation			Mining			Rural			Urban		
(%)	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD
50	811	882	1,043	504	500	485	97	139	184	118	144	246	40	45	76
80	795	858	990	489	478	441	96	138	180	118	144	246	40	45	75
90	776	830	931	470	451	392	96	137	175	118	144	246	40	45	73
96	736	774	820	431	398	303	95	135	167	118	144	245	40	45	71
98	692	714	707	388	342	212	94	133	158	118	144	243	40	45	68
99	632	634	561	329	267	97	93	131	147	118	144	242	40	45	63
99.5	553	529	378	252	170	-	91	127	134	118	144	241	40	45	60

TABLE 26.
Comparison of future scenarios with new infrastructure: Costs (million US$) of failure to supply water (i.e., foregone contribution to GGP).

Return period	Total			Irrigation			Mining			Rural			Urban		
(years)	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD
2	2.6	4.2	27.7	2.0	3.2	7.7	0.6	1.0	6.4	0	0	13.6	0	0	0
5	8.3	13.1	65.6	6.6	9.9	21.1	1.7	3.1	17.9	0	0	11.9	0	0	14.7
10	15.4	23.7	148.9	12.4	18.0	35.7	3.0	5.8	30.7	0	0	38.5	0	0	44.0
25	29.5	44.8	279.2	24.1	33.8	62.5	5.5	11.0	54.6	0	0	88.8	0	0	73.3
50	45.1	67.4	426.7	37.0	50.7	89.7	8.1	16.7	79.1	0	0	140.7	0	0	117.3
100	66.0	97.5	632.1	54.5	73.2	124.1	11.5	24.3	110.5	0	0	206.9	0	0	190.6
200	93.6	136.5	842.0	77.8	102.4	167.1	15.8	34.1	150.0	0	0	290.3	0	0	234.6

level, and shortfalls in mining, rural and urban supplies occur at higher assurance levels (Figure 12b). As discussed previously, the costs of failing to supply water vary depending on rainfall and hence river flows (Figure 13b). The annual costs of failing to supply water are estimated to vary between US$2.6 to US$94 million (i.e., 0.07 to 2.6% of the potential GGP) for the low demand scenario and from US$28 to US$842 million (i.e., 0.6 to 17.1% of the potential GGP) for the high demand scenario.

Tables 27 and 28 present the results of the model runs with WCDM measures implemented, in each of the future scenarios. In comparison to the implementation of new infrastructure, the WCDM measures have less impact at low assurance levels, but, since they are the assumed proportion of the demand have a significantly greater impact at high assurance levels. Shortfalls occur in the irrigation sector in both the low and medium demand scenarios, but in both cases rural supplies are assured at the 99.5 percent level (Figure 12c). In the high demand scenario full irrigation demand cannot be met, even at the 50 percent assurance level and shortfalls in mining, rural and urban supplies occur at higher assurance levels. As discussed previously, the costs of failing to supply water vary depending on rainfall and hence river flows (Figure 13c). The annual costs of failing to supply water are estimated to vary between US$11 and US$39 million (i.e., 0.3 to 1.1% of the potential GGP) for the low demand scenario and from US$44 to US$645 million (i.e., 0.9 to 13.1% of the potential GGP) for the high demand scenario.

TABLE 27.
Comparison of future scenarios with WCDM measures implemented: Water that can be supplied at different levels of assurance (Mm^3).

Assurance level (%)	Total			Irrigation			Mining			Rural			Urban		
	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD
50	796	864	1,029	489	482	474	97	138	179	118	143	245	39	45	76
80	784	846	983	477	465	437	97	137	173	118	143	242	39	45	74
90	774	832	943	467	452	405	97	137	169	118	142	238	39	45	73
96	761	813	880	455	433	355	97	136	162	118	142	232	39	45	70
98	751	798	824	445	418	311	96	134	157	118	141	225	38	45	67
99	740	781	760	434	402	261	96	133	150	118	141	216	38	44	63
99.5	720	764	686	422	385	204	96	132	144	118	140	204	38	44	58

TABLE 28.
Comparison of future scenarios with WCDM measures implemented: Costs (million US$) of failure to supply water (i.e., foregone contribution to GGP).

Return period (years)	Total			Irrigation			Mining			Rural			Urban		
	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD
2	10.8	15.3	43.6	6.5	8.4	11.1	0.3	2.1	20.3	2.7	3.3	5.3	1.3	1.5	6.9
5	16.4	26.3	97.6	10.3	13.8	22.2	0.7	4.3	36.3	3.8	5.4	16.2	1.6	2.8	22.9
10	20.3	34.9	153.1	13.1	17.8	31.9	0.9	6.3	49.2	4.6	7.0	29.1	1.8	3.8	42.8
25	25.9	47.3	252.8	16.9	23.3	46.8	1.3	9.6	8.2	5.7	9.2	54.4	2.1	5.3	83.4
50	30.2	57.8	353.8	19.9	27.8	60.1	1.6	12.4	84.1	6.5	11.0	81.4	2.2	6.6	128.3
100	34.7	69.3	482.6	23.1	32.6	75.1	1.9	15.8	101.6	7.3	12.8	117.0	2.3	8.1	189.0
200	39.4	81.8	645.3	26.5	37.6	92.1	2.3	19.6	120.7	8.1	14.9	163.0	2.5	9.7	269.5

Tables 29 and 30 present the results of the model runs with both new infrastructure and WCDM measures implemented, in each of the future scenarios. As would be anticipated, the combination of new infrastructure and the implementation of WCDM measures result in better levels of supply than when only one or the other option is implemented. In this case, rural supplies are guaranteed (even at the 99.5% assurance level) even in the high demand scenario. However, shortfalls still occur in the urban sector in the high demand scenario and in irrigation and mining in all three scenarios, particularly during higher return period low flow events, but still occur every year for irrigation (Figure 12d). As discussed previously, the costs of failing to supply water vary depending on rainfall and hence river flows (Figure 13d). The annual costs of failing to supply water are estimated to vary between US$0.6 to US$14.7 million (i.e., 0.02 to 0.4% of the potential GGP) for the low demand scenario and from US$10.5 to US$312.2 million (i.e., 0.2 to 6.3% of the potential GGP) for the high demand scenario.

TABLE 29.
Comparison of future scenarios with new infrastructure and WCDM measures implemented: Water that can be supplied at different levels of assurance (Mm^3).

Assurance level	Total			Irrigation			Mining			Rural			Urban		
(%)	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD
50	817	892	1,067	510	510	506	97	139	185	118	144	246	40	45	76
80	815	888	1,054	508	506	494	97	139	183	118	144	246	40	45	74
90	812	883	1,036	505	502	480	97	138	480	118	144	246	40	45	73
96	806	873	1,000	499	492	450	97	138	450	118	144	246	40	45	72
98	799	861	959	492	480	416	96	138	416	118	144	246	40	45	71
99	789	844	903	483	463	369	96	137	369	118	144	246	40	45	68
99.5	776	821	827	470	440	307	96	137	306	118	144	246	40	45	63

TABLE 30.
Comparison of future scenarios with new infrastructure and WCDM measures implemented: Costs (million US$) of failure to supply water (i.e., foregone contribution to GGP).

Return period	Total			Irrigation			Mining			Rural			Urban		
(years)	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD	LD	MD	HD
2	0.6	1.0	10.5	0.3	0.4	1.4	0.3	0.6	2.6	-	-	-	-	-	6.5
5	1.5	2.7	35.0	0.9	1.4	4.8	0.6	1.3	7.3	-	-	-	-	-	22.9
10	2.6	4.7	64.5	1.8	2.8	9.2	0.9	1.9	12.5	-	-	-	-	-	42.8
25	4.8	8.8	101.8	3.6	5.8	18.3	1.3	3.0	22.0	-	-	-	-	-	61.5
50	7.2	13.2	143.7	5.6	9.4	28.5	1.6	3.9	31.8	-	-	-	-	-	83.4
100	10.4	19.3	204.0	8.5	14.3	42.5	1.9	5.0	44.2	-	-	-	-	-	117.3
200	14.7	27.4	312.2	12.4	21.2	61.3	2.3	6.2	59.9	-	-	-	-	-	191.0

Concluding Remarks

The demand for water in the Olifants River Catchment will change over the next twenty years. Future demand will depend, to a large extent, on population growth and changes that occur in different sectors as well as differing water use practices and government policies. Currently, it is impossible to forecast exactly how demand will change by 2025. To consider many of these different effects a scenario approach was used to investigate possible changes. These scenarios were used to investigate historic, current and future developments in water demand. Application of the WEAP model enabled quantitative assessments to be made. By linking model outputs with water productivity data it was possible to make preliminary estimates of the economic costs of each scenario. Although based on simple assumptions, these estimates are believed to be indicative of the economic costs and benefits of different water development strategies.

It is unlikely that in practice the future will closely follow any one scenario. However, by illustrating what could occur under each scenario, information has been obtained that is useful for resource planning. The scenarios offer a platform for discussion. Key findings of the study are:

(i) Past infrastructure development in the catchment has been driven, to a large extent, by the expansion of irrigation and mining. Though circumstantial, the evidence is that dams have been built following periods of drought, when demand outstripped supply.

(ii) It varies from year to year, but current mean annual demand is estimated to be approximately 744 Mm^3. Despite relatively low economic returns on the water used, irrigation is by far the largest user of water in the catchment. There is considerable inter-annual variability as a consequence of varying rainfall. With the exception of the revitalization of some smallholder schemes, the DWAF is currently prohibiting further development of irrigation. Future significant land-use changes in the catchment are unlikely. Evaporation from reservoirs is now the second largest anthropogenic ‘use’ of water in the catchment.

(iii) The cost of shortfalls in water supply varies depending on rainfall and hence river flows in the catchment; volumes of unmet demand and, consequently, costs of failing to supply water increase dramatically during periods of drought. Current shortfalls in supply, primarily to the irrigation and mining sectors, are estimated to be costing (i.e., in terms of foregone contributions to GGP) between US$6 and US$50 million per year.

(iv) To safeguard domestic rural and urban supplies, the DWAF is not currently fully implementing the Reserve. If it was fully implemented, under current conditions, the resultant increases in unmet demand in other sectors are estimated to cost an additional US$7 to US$29 million per year, again depending on rainfall. This represents between 0.2 and 0.9 percent of current GGP, arguably a small price to pay to safeguard the sustainability of the resource. Furthermore, this makes no allowance for the benefits (e.g., to poor rural communities) that implementation of the Reserve ensures.

(v) The future scenarios indicate an increased water demand as a consequence of increasing population, domestic demand and mining activities. By 2025 average annual demand was predicted to increase to 818 Mm^3 in the low demand scenario and up to 1073 Mm^3 in the high demand scenario. In the absence of water resource development measures, annual economic losses, arising from the failure to supply water, of between US$23 and US$404 million per year (i.e., 0.6 to 11.0% of the potential GGP) and between US$92 and

US$1,334 million per year (i.e., 1.9 to 27.0% of the potential GGP) are estimated for the low and high demand scenarios, respectively.

(vi) The construction of the dams proposed by the DWAF significantly increases water availability at all assurance levels, but has the greatest proportional impact at the highest assurance levels (i.e., during droughts). The dams alone would be sufficient to ensure rural and urban supplies at all assurance levels for both the low and medium demand scenarios. However, in these scenarios shortfalls still occur in both the irrigation and mining sectors in most years. In the high demand scenario, significant shortfalls occur in the irrigation and mining sectors in all the years and progressively at higher assurance levels in both the rural and urban sectors. Overall, the annual economic costs of supply failures are estimated to be in the range of US$2.6 to US$94 million (i.e., 0.07 to 2.6% of the potential GGP) for the low demand scenario and US$28 to US$842 million (i.e., 0.6 to 17.1% of the potential GGP) for the high demand scenario.

(vii) The introduction of WCDM measures has slightly less impact than dam construction at lower assurance levels, but significantly greater impact at higher assurance levels. Shortfalls still occur, even in the low demand scenario, particularly in the irrigation sector. In the medium and high demand scenarios, shortfalls occur in the mining, rural and urban sectors as well as in irrigation. Overall, the annual economic costs of supply failures are estimated to be in the range of US$11 to US$39 million (i.e., 0.3 to 1.1% of the potential GGP) for the low demand scenario and US$44 million to US$645 million (i.e., 0.9 to 13.1% of the potential GGP) for the high demand scenario.

(viii) A combination of new dam construction and the introduction of WCDM measures could improve the water resource situation in the low and medium demand scenarios to better levels than the current baseline. However, even with both sets of measures implemented, significant (and costly) shortfalls would still occur in the high demand scenario. Overall, the annual economic costs of supply failures are estimated to be in the range of US$0.6 to US$15 million (i.e., 0.02 to 0.4% of the potential GGP) for the low demand scenario and US$10.5 to US$312 million (i.e., 0.2 to 6.3% of the potential GGP) for the high demand scenario.

The scenarios developed in this study are simplistic. No allowance was made for reallocation of water between sectors. It is likely that in future, as demand, and hence scarcity, in the catchment increases, there will be increased pressure to utilize water in the most economically efficient manner. Reallocation of water towards higher value uses is seen by many as a logical step in demand management and one that maximizes the economic welfare to be derived from alternate uses (World Bank 1993; Dinar and Subramanian 1997). However, clearly, careful consideration of political, regulatory, environmental, organizational and social issues is also required. This is particularly important in South Africa where the issue of past inequities must be addressed. The reallocation of commercial irrigation licenses to smallholders, which may occur through the land reform process, requires careful consideration not only because of equity implications, but also due to the likely economic and water resource impacts. Methods of environmental economics are improving and should be applied to determine the value (not just possible costs) of full implementation of the Reserve. To deal with the high levels of uncertainty in future demand, the DWAF should develop a flexible, phased approach to water resources development in the catchment. This should be underpinned by efforts to constrain demand.

This study has demonstrated how relatively simple allocation models such as the WEAP model can be combined with simple economic analyses to provide at least indicative answers to important water resource questions. Further research is needed to improve the model and the scenarios developed. Work is required to: i) better assess model uncertainty and thereby improve the interpretation of model results; ii) evaluate the possible social and economic impacts of water reallocation between sectors; iii) evaluate possible policy and regulatory frameworks for improving water use efficiency and water reallocation; iv) assess the benefits (not only the costs) derived from implementation of the Reserve; v) assess the impacts of future development of groundwater resources and the implications on river flows; and vi) evaluate the possible impacts of climate change.

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Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127, Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2880000

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
http://www.iwmi.org

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