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SCHOOL OF ENVIRONMENTAL SCIENCES
DEPARTMENT OF HYDROLOGY AND WATER RESOURCES

An operating strategy for run-of-river abstractions for typical rural water supply schemes using Siloam Village as a case study

Rachel Makungo
Student no. 11512849

Supervisors: Prof J.O. Odiyo
Dr. B. Mwaka
Dr. J.G. Ndiritu

A research dissertation submitted to the Department of Hydrology and Water Resources in fulfillment of Master of Earth Sciences degree in Hydrology and Water Resources

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DECLARATION

I, Rachel Makungo, hereby declare that this research submitted to the Department of Hydrology and Water Resources at the University of Venda, for the Master of Earth Science degree in Hydrology and Water Resources, has not previously been submitted for a degree in this or any other university, and that it is my own work and all reference materials contained herein have been duly acknowledged.

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ABSTRACT

The study focuses on the development of an operating strategy for optimum scheduling of run-of-river abstractions in typical rural water supply schemes in accordance with the quantitative and qualitative requirements of the rural water demand sectors using Siloam Village as a case study. The operating strategy has been generalized to enable its use in any river system. Since Nzhelele River at Siloam Village is ungauged and no daily streamflow data was available in the nearby Mutshedzi River sub-quaternary catchment (SQC), within the same quaternary catchment A80A, a water balance model was used to compute the inflow into Mutshedzi Dam. The Mike 11 NAM and Australian Water Balance Model (AWBM) used in rainfall-runoff modelling of the Mutshedzi River SQC were calibrated and the results verified using the computed inflow hydrograph. Each of the model's performance was assessed based on the overall root mean square error, Nash Sutcliffe coefficient of efficiency, percentage bias, correlation coefficient and overall water balance error. The availability and suitability of Nzhelele River water for domestic use and the environment were assessed using the unregulated river water yields and water quality respectively. The results of the water resources assessment were used to derive operating rules for Nzhelele River at Siloam Village. The Mike 11 NAM model underestimated most of the peak flows while AWBM overestimated most of the small to medium peak flows and underestimated the major peak flows for both calibration and verification runs. Both models estimated the low flows reasonably well for the calibration and the verification runs, except in a few cases where they underestimated the low flows. The Mike 11 NAM and AWBM performances were good and comparable though the latter performed relatively better than the former. Both models were therefore used in the simulation of the streamflow hydrograph for Nzhelele River SQC at Siloam Village and the results compared. The model parameters were transferred based on the nearest neighbour regionalization technique. The simulated runoff was used to derive unregulated river water yields at different levels of assurance of supply (LAS) for Nzhelele River SQC at Siloam Village using 1 day flow duration curves. The results of the water resources assessment show that Nzhelele River water can meet the low flow and domestic water requirements for the survival, standard and high levels of supply services at a LAS of approximately 90% (1:10). The domestic water requirements cannot be supplied at the recommended LAS of 99.5% (1:200), 99% (1:100), 98% (1:50) and 95% (1:20). High levels of turbidity make Nzhelele River water unsuitable for domestic use unless treated at household level to reduce turbidity and microbiological risks to acceptable levels. The derived operating rules for Nzhelele River at Siloam Village are that the river water can be scheduled daily for LFR and domestic use at approximately 90% LAS, and other sources of water should be used to optimize the supply of domestic water requirements to or towards 99.5% LAS on daily scale. The development of an operating strategy integrating run-of-river abstractions, groundwater and rainwater to ensure that the domestic use, environmental flow requirements and possibly food security and irrigation are met at the required LAS has been recommended. The generic operating strategy for run-of-river abstractions has been derived by summarizing the procedure used in developing the operating rules for Nzhelele River at Siloam Village and can be applied to any river system to fully or partially supply the community with water.

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DEDICATION

This thesis is dedicated to my sons Rotondwa and Kharendwe James and my daughter Zwivhuya. Their patience, tolerance and the enduring loneliness can only be rewarded by God the Almighty. To my mother Thizwikoni Evelyn Makungo and father Nkhumeleni Elias Makungo who have kept on waiting.

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List of Abbreviations

ACRU	Agricultural Catchment Research Unit
ANN	Artificial Neural Networks
AWBM	Australian Water Balance Model
BBM	Building Block Methodology
BFI	Baseflow Index
CK1,2	Time constant for overland flow and interflow routing
CKBF	Baseflow time constant
CKIF	Time constant for interflow from the surface storage
CQOF	Overland flow runoff coefficient
DHI	Danish Hydraulic Institute
DLWAS	DWAF Limpopo Water Services
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
EWR	Environmental water requirements
FAO	Food and Agricultural Organization
FDCs	Flow Duration Curves
GRDM	Groundwater Resource Directed Measures
HFR	High-flow requirement
IHACRES	Identification of unit Hydrographs and component flows from Rainfall, Evapotranspiration and Streamflow
KBase	Baseflow recession constant
KSurf	Surface runoff recession constant
LAS	Level of assurance
LFR	Low-flow requirement
MAR	Mean Annual Runoff
MDGs	Millennium development goals
NAM	Nedbør-Afstrømnings-Model
NTU	Nephelometric Turbidity Units
NWQMS	National Water Quality Management Strategy
OWBE	Overall Water Balance Error
PDM	Probability Distributed Model

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PDSMM	Probability Distributed Soil Moisture Model
PGD	Palmer Development Group
RMSE	Root Mean Square Error
RRL	Rainfall Runoff Library
SAR	Sodium Adsorption Ratio
SAWS	South African Weather Services
SCE	Shuffled Complex Evolution
SCS	Soil Conservation Services
SPATSIM	Spatial and Time Series Information Modelling
TDS	Total Dissolved Solids
TG	Threshold value for Recharge
TIF	Threshold value for Interflow
TOF	Threshold value for Overland Flow
TWR	Total Water Requirements
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	United States Development Agency
VTI	Variable Time Interval
WHO	World Health Organization
WMAs	Water Management Areas
WRC	Water Research Commission
WR90	Water Resources of South Africa 1990
WWAP	World Water Assessment Programme

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CHAPTER 1: INTRODUCTION

1.1 Background

Rural water supply schemes are generally supplied by any one or combination of river water, groundwater and rain water. Developing operating strategy/rules for such schemes with multiple sources of supply can be done by developing separate components of the operating strategy for each source of supply. These strategies can then be combined to derive an operating strategy that integrates the use of water from all sources. Operating rules are statements on how to schedule water from a given resource at a given time (season) (Johnson, 1993).

The current study focuses on developing an operating strategy for one of the sources of supply, which is run-of-river water. This operating strategy for run-of-river abstractions was tested in a typical rural village (Siloam Village) located in the Limpopo Province within the Nzhelele River Catchment. Run-of-river abstractions occur when water is abstracted directly from the river without storage on the river.

1.2 Statement of the research problem

Water is scarce and limited in most parts of South Africa. Several South African rivers have limited water resources because of the unreliable and inadequate rainfall and the limited natural storage of water. The scarcity is exacerbated by uneven distribution, both geographically and seasonally within the country (DWAF, 2001) (Fig. 1.1).

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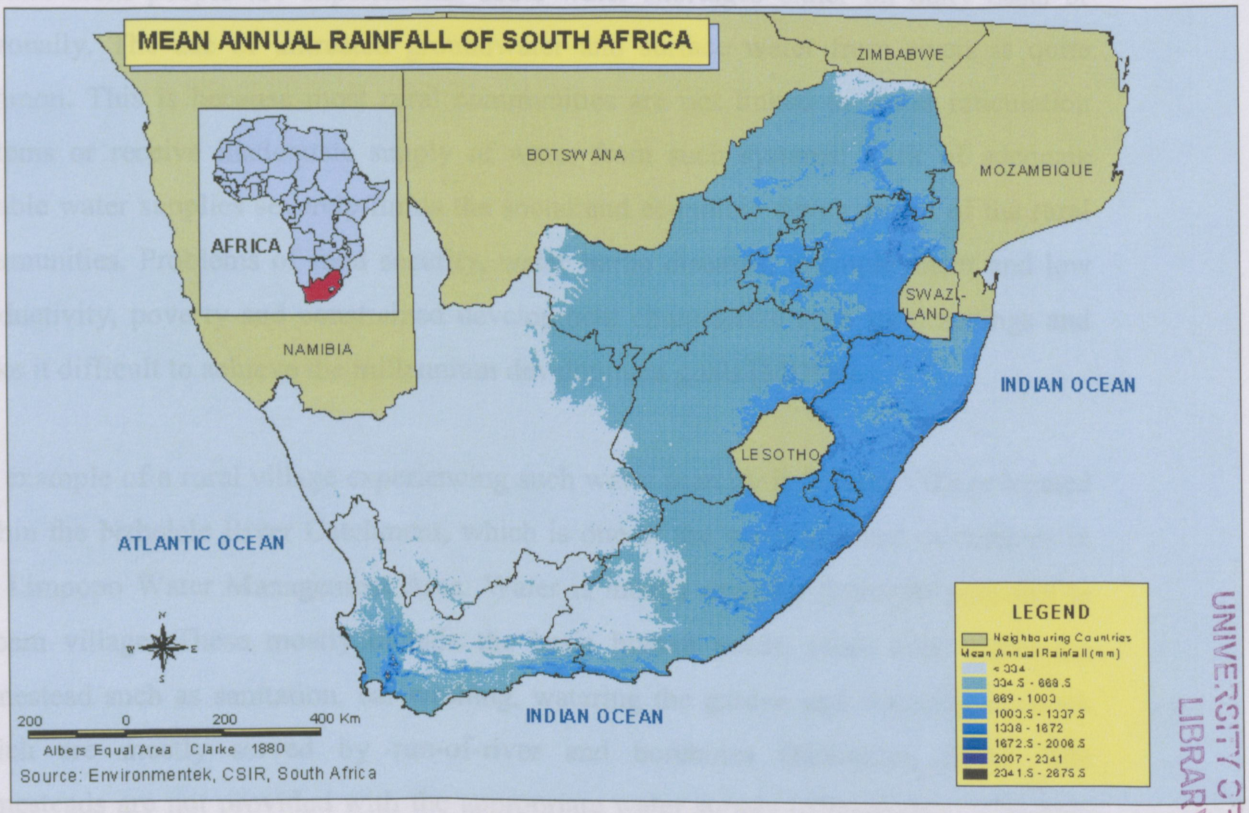


Figure 1.1: Mean annual rainfall distribution in South Africa (Source: State of Environment Report, 1999).

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Also due to uneven temporal distribution and high evaporation rates, streamflow in most of South African rivers is relatively low for most of the time, with sporadic high flows in summer (DWAF, 2004a). This is a characteristic that limits the proportion of streamflow that can be relied upon for use (DWAF, 2004a). This has been worsened by the increasing economic growth of South Africa with high domestic water requirements and the growth of other critical water demand sectors such as agriculture and mining among others. As a consequence, the requirements for water already far exceed the natural availability of water in several river basins (Basson and Rossouw, 2003).

Though the National Water Act No. 36 of 1998 of South Africa emphasizes equitable and sustainable use of water resources, this has not been achieved in most rural areas. During

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the last few years, it has become quite clear that in large parts of South Africa particularly in rural areas people are experiencing acute water shortages either on daily basis or seasonally. The use of untreated groundwater and surface water from rivers is quite common. This is because most rural communities are not linked to water reticulation systems or receive inadequate supply of water from such systems. Lack of adequate potable water supplies severely limits the social and economic development of the rural communities. Problems of food security, water borne diseases, unemployment and low productivity, poverty and constrained development characterize such rural settings and make it difficult to achieve the millennium development goals (MDGs).

An example of a rural village experiencing such water scarcity is Siloam Village located within the Nzhelele River Catchment, which is one of the water stressed catchments in the Limpopo Water Management Area. Water is mostly used for domestic purposes in Siloam village. These mostly include the basic human needs, other uses within the homestead such as sanitation, car washing, watering the garden and watering livestock which are mostly served by run-of-river and boreholes (Makungo, 2008). The homesteads are not provided with the appropriate water supply infrastructure. The only infrastructure provided by the government are some few communal stand pipes which are far from most homesteads. There are frequent shortages of water supply from the communal stand pipes. This makes community members to use water abstracted directly from the Nzhelele River and small seasonal rivers (Fig. 1.2).

Unregulated water abstractions are common in rural areas of South Africa. Lack of regulation of water use is not good for ecosystem sustenance and general sustainable use of water resources. For example communities tend to pollute water systems by washing clothes directly within the rivers or in their immediate neighbourhood (Fig. 1.2) because of lack of water in homesteads.

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Figure 1.2: Run-of-river abstraction (taken from Nzhelele River near Siloam Village on 24/03/2007).

In Siloam village, apart from the unreliable and inadequate standpipe water supply, some members of the community also receive some water supply from private boreholes, municipal community borehole and springs. Water from these sources is, however, salty and has unpalatable taste with high levels of fluorides (Mashai, 2007; Ramudzuli, 2009) above the recommended DWAF (1996a) standards for domestic use.

1.3 Justification of the study

The study is necessary in order to develop water resources operating strategy for run-of-river abstractions for rural villages of South Africa where the main uses of water are domestic and/or small scale subsistence farming. The only strategy that has been documented is that of Hughes (2006) which was developed to focus on the ecological reserve. The developed operating strategy will aid in reconciliation of water supply with domestic water demand and ensure that the available water resources are used optimally taking into account the environmental flow requirements.

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Abstracting water directly from the river without operating rules has the tendency of drawing down the water in the river below environmental water requirements. This is worsened by the fact that several South African rivers have low flows most of the times and high evaporation rates. This combined with pollution introduced through anthropogenic activities such as washing of clothes directly in the river, industrial waste discharges and informal settlements close to the river endanger the ecology of the river. This is a much more delicate situation since both the basic human needs of water and the ecological requirements should be considered as part of the total reserve. The development of an operating strategy for this situation is critical in order to serve the two water needs without harm to any other users particularly during drought periods. Figure 1.3 shows an example of dead fish due to anthropogenic pollution in the Olifants River in the Kruger National Park.



Figure 1.3: Dead fish on the banks of the Olifants River in the Kruger National Park due to anthropogenic pollution (Source: Water Wheel, 2009)

The fact that most parts of South Africa are water scarce also creates the need to develop an operating strategy for scheduling the scarce water resources especially in rural areas that experience acute water shortages. Such a strategy will aid in equitable allocation and

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sustainable use of the scarce water resources in order to satisfy the requirements of the National Water Act No. 36 of 1998. The Act considers water use for both basic human needs and the environment as a reserve that must be prioritized.

The strategy will help to solve the major problem of potable water shortages in rural setups of South Africa and thereby improve the quality of lives in rural villages. The improvement on ecosystem sustenance and survival of aquatic species in rural river environments will boost the economy by ensuring food security and improvement in tourism. Baseline information for future research in rural villages where such kind of study has never been done will also be provided.

1.4 Objectives of the study

1.4.1 The main objective

The main objective of the study is to develop a water supply operating strategy to optimize scheduling of run-of-river water abstractions for typical rural water supply systems, in accordance with the requirements of the National Water Act of South Africa.

1.4.2 The specific objectives

The specific objectives are:

- To determine the typical characteristics of rural water supply systems
- To develop an operating framework for run-of-river abstractions in typical rural water supply systems
- To develop run-of-river abstractions operating rules for a rural water supply scheme in Siloam Village case study area

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- To generalize the developed operating rules into a strategy for run-of-river abstractions in typical rural water supply systems

1.5 Hypotheses

Based on the discussions with DWAF officials, Systems Operation Directorate, it is hypothesized that:

- Present operating rules largely assume water supply from dams.
- Many rural villages are supplied from water supply systems without dams.
- An operating strategy for rural water supply systems without dams will improve the efficiency and reliability of rural water supplies.

1.6 Characteristics of the case study area

The proposed operating strategy for run-of-river abstractions, though being developed for use in typical rural areas, has been tested in Siloam Village. Siloam Village falls under quaternary catchment A80A of the Nzhelele River Catchment which is located in the northern region of Limpopo Province. The study area is found between 22°53'15.8" S and 22°54'5" S latitudes and 30°11'10.2" E and 30°11'23.5" E longitudes (Fig. 1.4).

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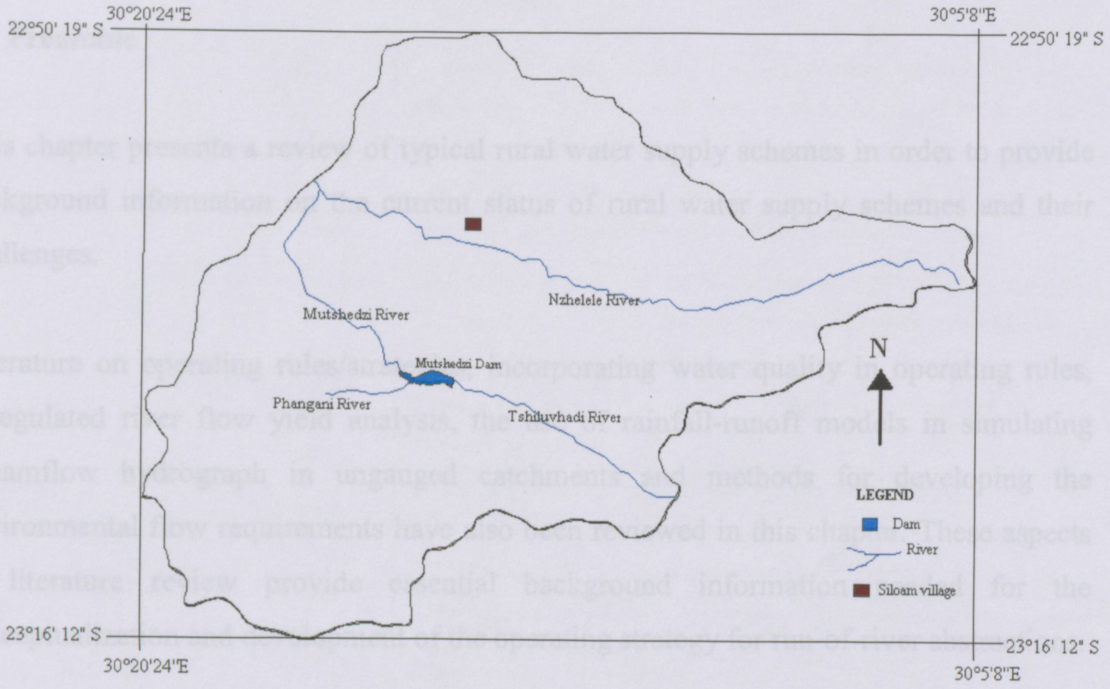


Figure 1.4: Location of Siloam Village in A80A quaternary catchment

The case study area is drained by the Nzhelele River. The flow pattern of Nzhelele River is highly variable because of its low and unpredictable rainfalls (average 350-400 mm) and the river is not perennial (Ashton et al., 2001). During dry years the river can remain without water for several months. Summer rainfalls cause dramatic increase in flows, though the tributary streams are mostly episodic and only contain water after rainfalls (Ashton et al., 2001). The mean annual evaporation varies from 1300-1400 mm. The case study area is dominated by human settlements and subsistence agriculture.

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CHAPTER 2: LITERATURE REVIEW

2.1 Preamble

This chapter presents a review of typical rural water supply schemes in order to provide background information on the current status of rural water supply schemes and their challenges.

Literature on operating rules/strategies, incorporating water quality in operating rules, unregulated river flow yield analysis, the use of rainfall-runoff models in simulating streamflow hydrograph in ungauged catchments and methods for developing the environmental flow requirements have also been reviewed in this chapter. These aspects of literature review provide essential background information needed for the conceptualization and development of the operating strategy for run-of-river abstractions.

2.2 Characteristics of typical rural water supply schemes

The characteristics of typical rural water supply schemes have been summarized in Table 2.1 and discussed under the ensuing sub-headings. These are the typical water supply schemes that dominate rural areas of South Africa and where most important water uses are domestic and/or small scale subsistence agriculture. This excludes the limited commercial farming found in rural areas of South Africa.

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Table 2.1: Typical characteristics of rural water supply schemes in South Africa

Parameter		Characteristics
Water uses		Domestic (including cooking, drinking, bathing, washing and sanitation) and small scale irrigation mostly aimed at ensuring household food security (and include water for watering vegetable gardens, irrigating fruit trees, livestock dipping and drinking, among others).
Water requirements	Basic human needs	15-35 *l*/c/d, mostly variable and depends on living standards.
	Small scale agriculture	2.5-2.88 *l*/m^2/d around Bushbuckridge area in the Sand and Sabie River Catchments (Ladki et al., (2004); Perez de Mendiguren and Mabelane (2001)); Unknown (or undocumented) in most WMAs
Water supply sources		Dams, rivers/streams, groundwater aquifers and in certain instances limited rainwater harvesting.
Adequacy of supply		Mostly inadequate or scarce particularly in semi-arid areas
Water abstraction points		Rainwater harvesting roofs, flowing springs, communal and private boreholes and communal standpipes, run-of-river abstraction weirs.
Water quality		Unknown as mostly there is no provision for monitoring and purification
Water supply infrastructure		Mostly poorly developed
Water abstraction patterns		Mostly unregulated
Operating rules		No or limited operating rules

2.2.1 Water supply sources and infrastructure

Rural areas of South Africa are typically supplied with water from water supply schemes without dams. The water supply schemes are generally without or have poorly developed water supply infrastructure. Water is normally abstracted directly from the river (Fig. 1.2), springs (Fig. 2.1), communal and private boreholes (Fig. 2.2) and abstractions weir with limited or no provision for water purification. This is despite the fact that some of the water resources may be polluted. For example, groundwater abstracted from a number of aquifers in South Africa have been found to be salty (see State of Environment Report, 1999; Mashai, 2007; Ramudzuli, 2009; among others). In rural water supply schemes where there are reservoirs (for example Soekodibeng Village in the Sand River

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Catchment) or abstractions from a weir (for example Siloam Village in Nzhelele River Catchment), water is normally reticulated to communal stand pipes. The main challenge in such systems is lack of maintenance of the water supply infrastructure, like repairs of broken taps (Ladki et al., 2004).

Some of the rural communities supplement their water supply with harvested rainwater particularly for domestic water supply. However, no quality considerations are taken into account. This makes the community vulnerable to health problems. The main limiting factors to rainwater harvesting are mostly low and irregular rainfalls and unplanned rainwater storage infrastructure (for example in the Nzhelele Regional Water Supply Scheme and various smaller villages in the Bushbuck Ridge region).



Figure 2.1: Water abstraction from a hot spring (taken from Siloam Village on 24/03/2007)

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Figure 2.2: Water abstraction from a borehole (taken from Siloam Village on 24/03/2007)

In a few rural areas, water is supplied from dams, but in insufficient amounts that lead to shortages, forcing communities to seek more water from rivers/streams, groundwater aquifers and in certain instances harvest rainwater. The most common problems with water supply from dams include the limited capacity of the water treatment works and inadequate water from dams or weirs due to hydrological conditions.

Thus, water scarcity is common in rural areas of South Africa, due to poor recharge of water sources from low rainfall in semi-arid areas; inadequate water sources, for example, low yielding fractured groundwater aquifers; inadequately developed water supply infrastructure; poor maintenance and operation of the water supply schemes, and lack of or limited capacity of water treatment plants.

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2.2.2 Water resources availability

The water resources potentially available for supply in rural areas include surface water, rainwater and groundwater.

(i) Surface water

The average rainfall in South Africa is 450 mm per year, but can vary significantly from less than 100 mm along the west coast to more than 1000 mm on the east coast and along the escarpment (WWAP, 2006). As a consequence of the uneven rainfall distribution and the topography, more than 60% of the river flow arises from only 20% of the area (WWAP, 2006). Only 9% of the country's precipitation finds its way as runoff into the rivers and streams (Davies and Day, 1998; DWAF, 1996d).

The total surface runoff from rainfall in South Africa is estimated to be about 53 500 million m^3/year, including that flowing out of Lesotho (South African Consulate General, 2007). However, the surface water produced internally has been estimated to be 43 km^3/year (FAO, 1995). The uneven variation of precipitation results in the variation of stream flow. This reduces the availability of run-of-river water, particularly during the dry season (winter). Another factor which may reduce run-of-river water availability for use is variation of water quality, which may be spatial or temporal. River water quality varies from high flow to low flow periods. During high flows, both water velocities and water volumes are high and may result in the dilution of the contaminants. This results in low levels of concentration of the contaminants. The opposite occurs during low flows. During low flows, both water velocities and water volumes are low and may result in high concentration of the contaminants. The water quality also varies along the river due to varying locations of the sources of pollution introduced into the river through runoff or leached into the river from adjacent groundwater aquifers.

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Surface water resources, in the context of rural water supply schemes, mostly include streamflow from small local catchments and adjacent large rivers (exploited through direct abstraction or some form of storage reservoir) (Hughes et al., 1995).

(ii) Groundwater

In the more semi-arid and arid rural parts of South Africa, people are dependent on the groundwater resources for domestic water supply. Increasing attention is being given by the Department of Water Affairs and other stakeholders to the development of groundwater resources in semi-arid areas with marginal water resources such as most parts of the Limpopo Province in South Africa. However, so far this has been able to account only for 13% of the national bulk water supply, though there is potential for further development. This is partly because the cost of developing groundwater resources is fairly high particularly in bedrock dominated areas. In such areas, water is mostly found in deep fractured aquifers where deep boreholes have to be drilled to bedrock formation. The bedrock formation also limits the groundwater recharge resulting in low groundwater yield potentials.

The groundwater harvest potential map of South Africa gave the first nationwide depiction of sustainable rates of groundwater potentially available for abstraction (Seymour and Seward, 1996). Groundwater harvesting potential is the maximum volume of water that may be abstracted per km^2 per annum without depleting the aquifers. The groundwater harvesting potential of South Africa varies from approximately 2500 to 100 000 m^3/km^2/annum (Seymour and Seward, 1996).

The per capita groundwater availability is 41 m^3/year in South Africa while the typical groundwater yields varies from 1-3 l/s in the Karoo sediments to 20-50 l/s in dolomite (karst) aquifers (Mutsayandima and Giordano, 2007). Thus, the amount of groundwater available in rural areas will depend on the aquifer type, its characteristics and the

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groundwater harvesting potential for a particular area. For example in the Nzhelele River Catchment which is dominated by intergranular and fractured aquifers the groundwater yield varies from as low as 0.5 l/s to 11.4 l/s (du Toit et al., 1998) while groundwater harvesting potential varies from 2500-4000 m^3/km^2/annum (Seymour and Seward, 1996). Though, this amount of water may be available for abstraction, it is also limited by the cost of drilling a borehole in this type of aquifer or by the local geology of the area.

During high recharge periods, groundwater levels are high and may result in the dilution of the contaminants. This results in low levels of concentration of the contaminants. The opposite occurs during low recharge periods; groundwater levels are low and may result in high concentration of the contaminants. As explained in (i) above, the variation of water quality limits the use of the water resource.

(iii) Rainwater

Rainwater harvesting involves the collection of water from the surface on which rain falls and subsequently storing this water for later use (Pacey, 1986). Rainwater can be collected from house roofs, or small areas of ground whose slope and surface area are suited to high rate of run-off into excavated tanks or onto cultivated terraces (Pacey, 1986).

Rainwater harvesting is an option which has been adopted in many parts of the world where conventional water supply systems have failed to meet the water demand (Srivanas, 2006). The feasibility of rainwater harvesting in a particular location is highly dependent upon rainfall intensity and the amount of rainfall. Other variables such as the catchment size and the type of the catchment surface usually can be adjusted according to the household needs (Srivanas, 2006).

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Studies that have been done in Siloam and Lwamondo Villages in Limpopo Province have shown that the two villages have good rainwater harvesting efficiencies for household water supply. Rainwater harvesting efficiency is the amount of rainwater that can be harvested from a unit rainfall depth per unit roof area. Siloam and Lwamondo Villages have rainwater harvesting efficiencies of 0.83 liters per m^2 of roof per mm of rainfall (Mashau, 2006) and 0.63 liters per m^2 of roof per mm of rainfall (Rasiuba, 2004) respectively. In Siloam village, analysis of the period in which the harvested rainwater could meet the demand showed that water demand of 28.67 *l*/c/d can be met throughout the year for a population of 2088 (Mashau, 2006). Rainwater was harvested from a roof area of 100 m^2 and a storage tank of 23.11 m^3. Similarly, in Lwamondo Village, analysis of the period in which the harvested rainwater could meet the demand showed that a water requirement of 50 *l*/c/d can be met in a period of 8 months for a population of 900 using a storage tank of 15 m^3 after collection from a roof area of 200 m^2 (Rasiuba, 2004). Thus, if a good storage system is provided and properly managed, rainwater can be used for household water supply throughout the dry season.

Rainwater in rural areas away from atmospheric and industrial pollution is fairly clean except for some dissolved gases that it may pick up while traveling through the atmosphere (Khalequzzaman, 2000). This makes rainwater a readily available water source which does not require costly water treatment.

2.2.3 Water uses and requirements

The main water uses in rural areas of South Africa include domestic and small scale agriculture. Domestic use is focused on meeting the basic human needs and includes water for cooking, drinking, bathing, washing and sanitation. Small scale agriculture or farming in rural areas of South Africa is mostly aimed at ensuring household food security and include water for watering vegetable gardens, irrigating fruit trees, livestock dipping and drinking, among others. Irrigation is only extended in limited cases to

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produce commercial crops for income earning.

The water requirements in typical rural areas are highly variable since they depend on the standard of living and the nature of use. For example, studies by Mokgope and Butterworth (2001), Perez de Mendiguren and Mabelane (2001) and Ladki et al. (2004) conducted in a number of villages around Bushbuckridge area in the Sand and Sabie River Catchments revealed that the amount of water used for basic needs (domestic) varies from 21-24.1 *l*/c/d while an average of 2.5-2.88 liters/m^2/day is used for irrigation. In another study by Lefebvre et al. (2005), the average water consumption was found to be 36 *l*/c/d in the former homelands of Lebowa and Kwa-Ndebele located in the Olifants River Basin. A study conducted in Siloam village located in the Nzhelele River Catchment by Makungo (2008) revealed that the amount of water required for basic needs (domestic) is 24.9 *l*/c/d.

Further studies by the PGD (1996), van Schalkwyk (1996) and Webster (1999) revealed that the water requirements are also dependent on the level of service (i.e. the location of the water source in relation to the communities' homesteads). PGD (1996) and Van Schalkwyk (1996) indicated that the water requirements of 15 *l*/c/d and 25 *l*/c/d are common in rural areas where homesteads are located at distances greater than 200 m from the communal standpipe while 30 *l*/c/d and 35 *l*/c/d are common in rural areas where homesteads are located at distances less than 200 m from the communal stand pipe. The water requirements for domestic use for Siloam Village case study area are 16, 25 and 35 *l*/c/d for survival, standard/basic and high levels of supply services respectively (DLWS, 2008) which fall within the above common requirements for rural areas.

It is important to note that the water requirements in most of the rural water use schemes are mostly unknown (or undocumented) or unreliable due to the absence of continuous water demand studies to estimate new demands associated with uncontrolled population growth in rural areas. The emerging new water demands in rural areas such as water use

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in small scale poultry farming, increased brick making as more developments occur and water requirement for sanitation, for example, promoted by the improved access to water use provided by the National Water Act No. 36 of 1998 have made it difficult to have reliable rural water demand estimates.

2.2.4 Water quality

The major water quality problems in South Africa include salinity, enrichments by plants nutrients (eutrophication), microbial contamination, sedimentation and silt migration and acidification (State of the Environment Report, 1999). For domestic use, typical pollutants of South Africa's water resources include effluent released by the growing industrial sectors, domestic and commercial sewage, acid mine drainage, faecal contamination linked to insufficient infrastructure and leaking sewers, domesticated animals grazing too close to water sources, agricultural runoff, and litter (State of Environment Report, 1999). Because many of these sources are spread out across the country, it is difficult to estimate the extent of the pollution problem.

The State of Environment Report (1999) indicated the general quality status of both surface and groundwater resources in South Africa. For surface water, phosphorus and nitrogen were chosen as indicators of domestic pollution while total dissolved solids (TDS) was chosen as indicator of the salt content. Nitrates concentrations were found to be generally low and therefore not posing major risk while TDS and phosphorus were found to be posing major water quality problems in general.

Holhs et al. (2002) did a study on the inorganic chemical water quality of surface water resources in South Africa. In the study, the main water quality problems throughout the country for domestic use were found to be related to the widespread high values of TDS and fluorides levels in certain locations such as the Lower Orange, Fish to Tsitsikamma, Gouritz, Breede and Berg WMAs. Magnesium (Mg), sulphate (SO_4), chloride (Cl),

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sodium (Na) and potassium (K) were also found to be high in various parts of the country. For agricultural use, the sodium adsorption ratio (SAR), electrical conductivity (EC), pH and chloride (Cl) were found to be high in various regions of the country. Little information is available on the extent of groundwater pollution in South Africa, particularly with regard to microbiological parameters (State of Environment Report, 1999). Generally, salinisation is recognized as a threat in South Africa, particularly in the eastern and southern Cape, the dry western section of the Northern Cape and the Limpopo Province (State of Environment Report, 1999).

Rainwater quality is often better than those of groundwater and surface water, as it does not come into contact with soil, dissolving salts and minerals in the process. It is not subject to pollutants found in rivers. However, in highly industrialised areas problems of acid rain are likely to contribute to pollution of rainwater which is likely to contain carbonic and sulphuric acids resulting from carbon dioxide and sulphur dioxide respectively.

Drinking water quality in rural areas is mostly very poor. A study by Mackintosh and Colvin (2003) shows that drinking water quality in rural areas of the Eastern Cape is below the recommended standards. It was suggested that this was as a result of pump breakdowns, deterioration of the storage and reticulation systems, and insufficient monitoring and management of the schemes. A study by Dalvie et al. (2003) indicated the contamination of surface and groundwater resources in rural areas of the Western Cape (the Hex River Valley, Grabouw and Piketberg) is by pesticides from agricultural practice. Another example of a rural area with potentially poor water quality is Siloam Village. In this village, there is no conventional water treatment plant and the community abstracts either raw water from rivers or untreated groundwater for use.

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2.3 Examples of typical rural water supply schemes in South Africa

Literature review reveals that 4 of the 19 Water Management Areas (WMAs) have schemes with easily accessible detailed or partially documented information that can be used to describe the typical characteristics of rural water supply schemes in South Africa given in Table 2.1. These WMAs include Olifants, Mzimvubu to Keiskamma, Nkomati and Limpopo (Table 2.2). The characteristics of different rural water supply schemes summarized in Table 2.2 confirm typical characteristics of such schemes as described in section 2.2.

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Table 2.2: Examples of typical rural water supply schemes in South Africa

Name	Location (WMA)	Water use/s	Water supply (l/c/d)	Source/s of supply	Adequacy of supply	Limiting factor (s)	Abstraction points	Water quality	Water abstraction patterns	Operating rules
Corona Rural Water Supply Scheme[1]	Mzimvubu	Domestic	13*	Corana Dam	Inadequate	Limited treatment plant capacity	Communal stand pipes	Indicators[6]: pH: 6.63-8.01 EC: 8.3- 19 mS/m TDS: 96.5-117 mg/L Treatment facility: Small treatment works	#	No rules
Nzhelele Regional Water Supply Scheme[2]	Limpopo	Domestic and small scale irrigation	22.1*	Abstraction weir on Nzhelele, Tshifhire and Tshedza Rivers and Mutshedzi Dam, boreholes	Inadequate	Poorly developed infrastructure, inadequate water sources, and water wastages (due to non-payment of water services)	Rainwater harvesting roofs, flowing springs, communal and private boreholes and communal standpipes.	Indicators[6]: pH: 6.33-8 EC: 5-9.91 mS/m TDS: 38-93 mg/L Treatment facility: chlorination of Nzhelele river water, treatment of dam water, treatment of water from Tshifhire and Tshedza Rivers and no purification of borehole water	Mostly unregulated	No rules

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Table 2.2 Continued

Name	Location (WMA)	Water use/s	Water supply (l/c/d)	Source/s of supply	Adequacy of supply	Limiting factor(s)	Abstraction points	Water quality	Water abstraction patterns	Operating rules
Labalelo Water Supply Scheme[4]	Olifants	Domestic, small scale irrigation and Mining	25 (domestic), 2.88 l/m^2/d (irrigation)	Olifants River, boreholes	Meets basic requirement but does not meet actual demand (65 l/c/d)	Poor maintenance and operation of the scheme	Communal stand pipes, borehole	No treatment	Unregulated	No rules
Schemes in the Bushbuckridge area[5]	Inkomati	Small scale irrigation and domestic	21-22 (domestic); 2.5 l/m^2/d (irrigation)	Rivers, wells on river bed, rainwater, spring, boreholes and dams	Inadequate	inadequate water sources, limited or no treatment	Communal stand pipes, boreholes, springs and wells	Inadequate or no treatment of river water, no treatment of groundwater, Inadequate or no treatment of dam water	Unregulated	No rules
Zweledinga Irrigation Scheme[1]	Mzimvubu	Small scale irrigation and domestic	12* (domestic); 1,50 million m^3/a (irrigation)	Bushmanskr -antz Dam	Inadequate	Inadequate water sources	#	Small treatment plant	#	No rules

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Table 2.2 Continued

Name	Location (WMA)	Water use/s	Water supply (l/c/d)	Source/s of supply	Adequacy of supply	Limiting factor/s	Abstraction points	Water quality	Water abstraction patterns	Operating rules
Nsikazi scheme[3]	Inkomati	Domestic	unknown	Sabie River	Inadequate	#	#	Indicators [6]: pH: 5.77-8.68 EC: 3.4-22.6 mS/m TDS: 21-159 mg/L Treatment: Disinfection	#	No rules
Mtangana[1]	Mzimvubu	Domestic	24*	Mtangana Dam, springs, borehole	Inadequate	Inadequate sources of supply, poor maintenance and operation of the scheme	#	#	#	No rules
Qumbu Town[1]	Mzimvubu	Domestic	20*	borehole	Inadequate	Inadequate sources of supply	No treatment facilities	#	#	No rules
Mt Ayliff Town[1]	Mzimvubu	Domestic	18*	Weir on stream	Inadequate	Inadequate sources of supply	#	#	#	No rules

[1]Blackhurst et.al. (2002); [2] van Vuuren et al. (2003); [3]Botha et al., (2003); [4]Ladki et al., (2004); [5]Mokgope and Butterworth, (2001); *1995 values obtained from Blackhurst et al., (2002); [6]Values obtained from DWAF RQS website; # Data not available; •Makungo (2008)

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As an example, in Mzimvubu to Keiskamma WMA, which has rural water supply schemes with detailed documented information, the water supplied to the domestic users in the schemes that are receiving water below the basic water requirement (25 *l*/c/d) ranges from as low as 12 *l*/c/d to a maximum of 24 *l*/c/d (Table 2.2). In most of the WMAs the water requirements and the water supplied for domestic and agricultural uses are not known.

2.4 Water quality indicators

The water quality indicators reviewed in this section cover the indicators that show the presence of the most important parameters that are set by the WRC et al. (1998) and Schutte (2001) to be of concern in the analysis of water quality required for domestic water supply. These include Total Dissolved Solids (TDS) and/or EC, pH and turbidity.

2.4.1 Total Dissolved Solids (TDS) and/or Electrical Conductivity (EC)

Total Dissolved Solids is a measure of the amount of various inorganic salts dissolved in water (DWAF, 1996a). The TDS show the presence of ions in water such as carbonate, bicarbonate, chloride, sulphate, nitrate, sodium, potassium, calcium and magnesium (DWAF, 1996a; NWQMS, 2000; WHO, 2006). Hence, TDS is an indicator of the above listed chemicals in water. The TDS is directly proportional to EC of water (WRC et al., 1998). Atekwana et al. (2004) expressed this relationship as:

$$TDS = k_e EC \qquad (2.1)$$

where TDS is expressed in milligrams per liter and EC is the electrical conductivity in microsiemens per centimeter at 25° C and k_e is the correlation factor. Thus, EC is a measure of TDS (Bate et al., 2004b; Schutte, 2001). For most natural waters EC is related to the TDS by a correlation factor ranging from 5.5 - 7.5 (DWAF, 1996a) giving the general correlation factor for most of the waters as 6.5 (DWAF, 1996a; Bate et al.,

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2004b; DWAF 1996b). In South Africa this correlation factor ranges from 3.74 to 9.27 (Bate et al., 2004a).

Because EC is much easier to measure than TDS, it is routinely used as an estimate of the TDS concentration (DWAF, 1996b). EC concentration greater than 150 mS/m (TDS concentration >1000 mg/*l*) indicates that the concentration of calcium, sodium, magnesium and total hardness, chloride and sulphate in water may have negative impacts on human health (DWAF, 1996a). High EC also lowers the pH of water resulting in the reduction of the concentrations of carbonate, bicarbonate and hydroxides (DWAF, 1996a).

2.4.2 pH

pH is a measure of the acidity or alkalinity of water and has a scale from 0 (extremely acidic) to 7 (neutral), through to 14 (extremely alkaline) (NWQMS, 2000). Metal ions (except manganese) are unlikely to dissolve readily at the pH range 6-9 unless complexing ions or agents are present (DWAF, 1996b). The metals that are most likely to have increased detrimental environmental effects as a result of lowered pH are silver, aluminium, cadmium, cobalt, iron, copper, mercury, manganese, nickel, lead and zinc (DWAF, 1996b). For example if the pH of water is less than 3.5, the dissolved iron concentration can be several hundred mg/*l* (DWAF, 1996c). Schutte (2001) also indicated that zinc, cadmium and copper are likely to be present in acidic waters. At pH values greater than 8, the NH_4^+ ions are converted to the highly toxic unionized ammonia (NH_3) (DWAF, 1996a).

Low pH of water reduces the concentrations of carbonate, bicarbonate and hydroxides (DWAF, 1996a), thereby increasing the concentration of toxic metals such as copper, zinc, lead, among others. Fluoride reacts readily with magnesium and aluminium at alkaline pH values to form complexes which are not easily absorbed by aquatic biota

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(DWAF 1996b). The form of phosphorus in natural surface waters and the equilibrium of the different forms is also influenced by pH (DWAF, 1996b).

2.4.3 Turbidity

The turbidity or 'muddiness' of water is caused by the presence of suspended particulate and colloidal matter consisting of suspended clay, silt, phytoplankton and detritus (NWQMS, 2000). Turbidity can have a significant effect on the microbiological quality of water. Microbial growth in water is most extensive on the surface of particulates and inside loose, naturally-occurring flocs (DWAF, 1996a). Turbidity concentrations greater than 1 NTU promote infectious disease transmission by micro-organisms (DWAF, 1996a).

2.5. Environmental water requirements (EWR)

Environmental water requirements are defined in a form of a suite of flow discharges of certain magnitude, timing, frequency, and duration (Smakhtin et al., 2004). King et al. (2008) defined environmental (or instream) flows as flows that are left in, or released into, a river system with the specific purpose of managing some aspect of its condition. Their purpose could be as general as maintenance of a 'healthy' riverine ecosystem, or as specific as enhancing the survival chances of a threatened fish species or targeting the river channel and its surface waters, groundwater, the estuary, linked wetlands or floodplains, the riparian zone, and/or any of the plant and animal species associated with any of these system components (King et al., 2008).

Existing methods for the estimation of EWR differ in input information requirements, types of ecosystems they are designed for, time needed for their application, and the level of confidence in the final estimates (Smakhtin et al., 2004). Pyrce (2004) grouped these methods into hydrological, hydraulic rate, habitat simulation and holistic methods. King et al. (2008) gives a thorough description of these methods including their strengths and

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weaknesses. Acreman and Dunbar (2004) indicated that none of these methods is better than the other and each may be suitable for different applications. For example, hydrology based methods have been adopted for environmental flow setting to determine simple operating rules for dams or off-take structures where few or local ecological data are available (Acreman and Dunbar, 2004). Hydrology based methods require relatively few resources, are appropriate for low controversy situation and also tend to be precautionary (Acreman and Dunbar, 2004).

Tharme (2003) suggested a number of hydrology-based indices and methods for the estimation of EWR. Hughes and Hannart (2003) focused on estimating the ecologically acceptable proportions of baseflow and quickflow, which could be allocated for freshwater ecosystem maintenance. Smakhtin et al. (2004) referred to these components as environmental low-flow requirement (LFR) and environmental high flow requirement (HFR).

Smakhtin et al. (2004) developed a hydrology based methodology for estimating the total environmental water requirements on a global scale. The total environmental water requirement developed consisted of ecologically relevant low flow and high flow components and is dependent upon the objective of environmental water management. The principles which were used when developing the method are similar to those which underpin the method for the preliminary estimation of the water quantity component of ecological reserve for rivers currently in use in South Africa (Smakhtin et al., 2004). Smakhtin et al. (2004) indicated that this method is described in detail by Hughes and Münster (2000) and Hughes and Hannart (2003). More details on this method can be found in Smakhtin et al. (2004).

The environmental water requirements are the sum of LFR and HFR. The LFR indicates the minimum water requirements for fish and other aquatic species throughout the year while the HFR is important for river channel maintenance, wetland flooding and riparian vegetation (Smakhtin et al., 2004). It is practically realistic to consider LFR component

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of the EWR only when developing operating rules for low flow rivers. This is because such rivers are dominated by low flows which are likely to meet the LFR at acceptable LAS. This will also ensure that water is equitably scheduled to other users such as domestic water use at relatively high LAS. LFR has also been widely used to set minimum flow requirements for rivers in South Africa (Tharme, 2003). Scheduling water to meet the LFR component of EWR maintains the river at a fair state which is considered acceptable from the management perspective (Smakhtin et al., 2004).

Hughes (2001) explained the detailed procedures for setting the ecological instream flow requirements. The basis of the approach is the use of specialist input (from ecological experts on fish, invertebrates, riparian vegetation, among others.; geomorphological experts; hydraulic experts and hydrological experts) during a workshop to define the main building blocks that will describe the monthly distribution characteristics of the modified flow regime (Hughes, 2001). This approach is known as the Building Block Methodology (BBM) and it has been described fully in King and Louw (1998) and King et al., (2000). Though the BBM has been known to produce reliable and high confidence results, it is too detailed (in terms of both time and resources). With the legislation (National Water Act no. 36 of 1998) which requires inclusion of a component that stipulates that some water has to be reserved to maintain the ecological functioning of the river, quicker methods are therefore required (Hughes, 2001).

2.6 Operating strategy/rules

Operating rules are statements on how to schedule water from a given resource at a given time (season) (Johnson, 1993). They are the policy instruments used to define operating conditions and procedures to implement when conditions are not ideal (Johnson, 1993). Relatively simple hierarchical operating rules are usually set during the planning stage (Basson et al., 1994). It is generally not economically feasible to develop and operate water resources to meet the demand all the times (Basson et al., 1994). This is especially the case in arid and semi arid regions where the water resources are scarce and limited

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(Basson et al., 1994). Operating rules of water supply are some of the few management tools available to cope with the demand (Basson et al., 1994). Efficient operation rules can make significant improvements in water supply reliability.

Operating rules are defined, either separately or in combination, as planned or target storage volumes or pool levels, and associated reservoir releases and diversion quantities, usually as a function of the time of the year (Johnson, 1993). These storage levels and release quantity criteria are based on the assumption that the systems' environment and objectives will not change in the immediate future (Johnson, 1993).

Most of the operating rules have been developed for systems supplied from reservoirs. These operating rules have been derived using simulation techniques (Loucks et al. (1981), Loucks and Sigvaldason, (1982), Lund and Guzman (1999), and others), optimization techniques (Labadie (1997), Stevens et al. (1998), Revelle (1999), Jenkins et al. (2004), Rosenberg and Lund (2006), and others) or simulation techniques linked to optimization techniques (Lund and Ferreira (1996), Ndiritu (2003), Ndiritu (2005) and and others). There are limited or no operating rules for water supply systems without reservoirs.

Smits et al. (2002) developed a modelling framework for deriving operating rules within the Sand River catchment in South Africa. The study derived different scenarios (operating rules) which can be used to schedule water resources in such a way that the resources can meet the demand. In this study like many others operating rules were derived for a water supply system with reservoirs. Water supply systems without reservoirs such as systems with run-of-river abstractions regardless of their size or scale, require operating rules to regulate the competing water uses or optimize the beneficial use of water and also account for ecological water requirements. Operating rules are used in daily reservoir simulation models to determine ecological reserve releases for river maintenance (Hughes et al., 1997; Hughes and Ziervogel, 1998).

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Hughes (2006) developed a simple model that simulates the water balances in small to medium sized water resource systems (without major storage) and compared the results with the standard information available on ecological reserve. This model was based on the use of monthly Flow Duration Curves (FDCs) to derive operating rules at different levels of assurance of supply. The model was aimed at deriving operating rules for three types of water uses which are streamflow reduction activities (afforestation), the effects of distributed farm dams and associated abstractions and run-of-river abstractions throughout a river basin. The latter study among others have either not separated the run-of-river abstractions for meeting the basic human water requirements as part of the total reserve from the ecological reserve or other run-of-river abstractions, for example, for commercial agriculture.

In river systems with low flows that are common in semi-arid areas of South Africa, the run-of-river abstractions form part of the water supply for basic human needs and is a competing user against ecological reserve. Thus, an urgent need exists to develop operating rules for a water supply system in which all or part of the water supply is from run-of-river abstractions for domestic use in rural villages where there is no or insufficient water supply from reservoir systems.

The concept of FDCs has been used in this study to derive operating rules for run-of-river abstractions for domestic water use at a daily time scale. This is the appropriate scale for scheduling domestic water use as it coincides with the scale of water abstractions and is particularly more pragramatic since there is no storage system to reserve water for a longer period. In this study FDCs have been derived from simulated daily runoff data for ungauged catchment unlike Hughes (2006) which were derived from WR90 (Midgley et al., 1994) monthly time series streamflow data.

Hughes (2006) recognized the limitations of using monthly flow time series data and proposed the need to disaggregate monthly WR90 data to daily time series data before deriving FDCs for each month. This is not applicable in ungauged catchments where such

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data is not available. In such situations, rainfall-runoff modelling should be done to generate daily streamflow data.

Hughes (2006) has listed a number of sources of uncertainties associated with the use of monthly flow time series data. He notes that one of the issues associated with using monthly flow data is that not all volumes of flow within a month are available for run-of-river abstraction when there is little or no storage involved. He explains that this is because the majority of the volume associated with high flows during the month will not be accessible to abstractors. To avoid such limitations, he separated the high flow and low flow components of the monthly flow volumes using a digital filter and assumed that low flows are available for run-of-river abstractors. He then derived the operating rules from time series data consisting of the net monthly flows after the effects of afforestration, farm dams, run-of-river abstractions and high flows had been accounted for.

Hughes (2006), however, recognized the fact that non-availability of daily flow data in most parts of the country makes it difficult to incorporate the disaggregation of monthly WR90 data into SPATSIM software that he used unless there is representative daily flows. This argument validates our approach, which is based on transferring model parameters from a neighbouring sub-quaternary catchment with hydrological homogeneity to generate daily simulated streamflow time series from rainfall-runoff modelling as having the potential to improve on the scale of resolution of the results.

This study developed a generic operating strategy for run-of-river abstractions that will serve the domestic water uses for rural villages that abstract water directly from rivers across the country, taking into account environmental flow requirements. Siloam Village in Nzhelele River Catchment has been used as a pilot study to facilitate the generation of the generic operating rules. In addition, the study will develop an operating strategy that integrates water quantity and quality. The water scarcity in these areas and the fact that people abstract water directly from rivers, without treatment, make both aspects of

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quantity and quality to be important in water supply operating strategy for such rural areas. It is also important to note that in such areas, there are no streamflow reduction activities like forestry and farm dams.

2.6.1 Incorporating water quality in operating rules

Considering water quality when developing operating rules is becoming a requirement due to the increasing demand for water, higher standards of living, depletion of resources of acceptable quality, and increasing water pollution due to agricultural and industrial expansions that are causing social and environmental predicaments all over the world (Kerachian and Karamouz, 2006).

Incorporating water quality in operating rules is done for different purposes such as maintaining the water quality target for downstream demand (Smith, 2002), meeting requirements for drinking water quality (Smith, 2002) and low flows management (Smith, 1993).

Studies that have incorporated water quality when developing operating rules include Nandalal and Bogardi (1995), Willey et al. (1996), Dai and Labadie (2001), Chaves et al. (2004), Kerachian and Karamouz (2006), Shirangi et al. (2008), among others. In all these studies operating rules were developed for systems with reservoirs. The operating rules were derived in such a way that either incorporated the water quality changes in the allocated water or stored water in the dam/reservoir (for example Kerachain and Karamouz, 2006), or water quality variables that changes/stratifies in reservoir (Chaves et al., 2004). Thus, these techniques take into account the existence of storage systems (reservoirs/dams) which do not exist in the case of run-of-river abstractions. These techniques can therefore not be applied to systems without dams/reservoirs where there is no storage. This leaves a gap in typical rural water supply schemes where there are no

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adequate water treatment facilities in most cases. Thus, a simple technique needs to be developed for incorporating water quality when developing operating rules in such areas.

Kerachian and Karamouz (2006) developed optimal operating rules for water quality management in reservoir-river systems using a methodology combining a water quality simulation model and a stochastic GA-based conflict resolution technique. In this study, simulation of the developed monthly reservoir operating and waste load allocation rules showed that the application of these rules reduces the TDS concentration in the allocated water as well as the salinity build-up in the reservoir. Smith (2002) incorporated water quality when developing operating rules for reservoir operation by using Artificial Neural Networks (ANN) to model the salinity, chloride, total organic carbon, bromate, total trihalomethane, temperature and Dissolved Oxygen at selected locations. Chaves et al. (2004) also incorporated water quality when developing operating rules for reservoir operation using a simple ANN model. Paredes and Lund (2006) incorporated water quality when developing operating rules by using linear programming techniques. The model developed in the latter study can be used to model any water quality variable that stratifies in reservoirs.

2.7. Unregulated river flow yield analysis

The yield of an unregulated river can be estimated through the use of Flow Duration Curves (FDCs). An unregulated river is a river that does not have upstream diversions (or additions) nor is regulated by an upstream reservoir, but the flows may have been affected by land use change (MacMahon and Adeloye, 2005). A Flow Duration Curve is a curve that shows a relationship between any given discharge value and the percentage of time that the discharge is equalled or exceeded (Smakhtin, 2001). Thus, the FDC shows the amount of water that can be available for use at a specific time, hence giving the yield of the river. FDCs constructed on the basis of daily flow time series provide the most detailed way of examining duration characteristics of a river (Smakhtin, 2001).

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The procedure for constructing FDC can be found in Vogel and Fennesy (1994), Smakhtin (2001), MacMahon and Adeloye (2005), Mays (2005), among others. FDCs have been used extensively in hydrological and water resource analyses including estimating unregulated river yield. For example studies by Mays and Tung (2001), MacMahon and Adeloye (2005) and Mays (2005) have indicated that FDCs can be used for estimating the yield in unregulated rivers.

2.8. Simulation of streamflow hydrograph in ungauged catchments

The use of rainfall-runoff models to predict streamflow in ungauged catchments is common practice throughout the world. Studies such as Pitman (1973), Post and Jakeman (1999), Dye and Croke (2003), Croke and Jakeman (2004), Chiew and Siriwardena (2005), Jazmin (2006), Quan (2006), Hammouri and El-Naqa (2007) among others, have used rainfall-runoff models to predict streamflow in ungauged catchments. The current study has only reviewed rainfall-runoff models that have either been developed and/or applied in South Africa or that have been applied in the current study. These include the Pitman model, the Variable Time Interval (VTI) model, Identification of unit Hydrographs and component flows from Rainfall, Evapotranspiration and Streamflow (IHACRES), ACRU, Mike 11 NAM and Australian Water Balance Model (AWBM) rainfall-runoff models.

The Pitman model is a monthly rainfall-runoff model developed by Pitman (1973) for water resources assessment in South Africa. Its data requirements are relatively limited; the minimum needed being a time series of monthly rainfall and mean monthly potential or reference evaporation (Hughes, 1996). The model is usually quite easy to calibrate. More details on descriptions of this model can be found in Pitman (1973) and Hughes (1995, 1996 and 1997). This model has been applied widely within the southern African region than any other hydrological model and has also been applied outside the region (Wilk and Hughes, 2002). The limitation of the Pitman model is that it can only be applied at a monthly time step and can therefore not be used in daily rainfall-runoff

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modelling.

The VTI (Variable Time Interval) model is a semi distributed rainfall runoff model. The VTI can be applied on a time step of 5 minutes (depending on the availability of rainfall intensity thresholds data) to one day (Hughes and Sami, 1994). Its limitation is that it requires a lot of greater resources in terms of data, experience, time and effort (Hughes, 1996). More details on descriptions of this model can be found in Hughes and Sami (1994) and. Hughes (1996).

Hughes (1996) described the applications of the Pitman and the VTI models in the Southern African region including South Africa, Namibia, Swaziland, Lesotho, Zimbabwe, Botswana, Malawi and Tanzania. The study found that the models are generally applicable in this region except in cases where rainfall data was inadequate.

IHACRES (Identification of unit Hydrographs and component flows from Rainfall, Evapotranspiration and Streamflow) is a daily rainfall-runoff model developed by Jakeman et al. (1990). Dye and Croke (2003) stated that this model can be used for rainfall-runoff modelling in South Africa when trying to avoid the problems that have been encountered in other models such as Pitman model and the VTI. Dye and Croke (2003) used this model to predict streamflow in two catchments in South Africa (Lambrechtsbos and Groot-Nylrivier catchments). The study found that the model can generate reliable results in small catchments and it has a tendency to overestimate high flows. The model is therefore suitable for the prediction of the effects of land use on low flows (Dye and Croke, 2003). The model description and the advantages can be obtained in Jakeman et al. (1990), Dye and Croke (2003) and Boughton (2005).

The Agricultural Catchment Research Unit (ACRU) is an agrohydrological distributed model that simulates daily runoff (Schulze, 1995). The ACRU model has been developed by the Bioresources and Environmental Engineering Hydrology School of the University of KwaZulu-Natal (Schulze, 1995). It is ideal for sub-catchment sizes not exceeding 30

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square kilometers (DWAF, 2006). The limitation of the sub-catchment size is due to the SCS (US Soil Conservation Service) method that is used to simulate runoff (DWAF, 2006). It is designed to be used in ungauged basins on the basis of parameters evaluated through default relationships with measurable catchment properties (soils, vegetation, management practices, among others.) (Schulze, 2000). It has been mostly applied in the temperate and humid parts of South Africa and has been frequently used for assessing the impacts of various land use modifications, specifically commercial afforestation (Hughes, 2005). The model has been less widely applied in the drier parts of the region and there appears to be very little documentation of the success of its application in semi-arid to arid basins (Hughes, 2005).

The Mike 11 Nedbør-Afstrømnings-Model (Mike 11 NAM) rainfall-runoff model forms part of the Mike 11 River modelling systems. The main inputs of the model are evaporation and rainfall data. MIKE 11 NAM rainfall runoff model includes an auto-calibration tool based on the shuffled complex evolution (SCE) method and also automatically calculates catchment areas and Thiessen mean area rainfall weights (DHI, 2002). The model parameters can be determined by the automatic calibration function (Madsen, 2000) or calibrated manually depending on the quality of the data.

The main outputs of the Mike 11 NAM model are catchment runoff (split into interflow, overland flow and baseflow), groundwater levels as well as information about other elements of the land phase of the hydrological cycle such as the moisture content and groundwater recharge (Madsen et al., 2000). The model has been applied in a number of studies including Shamsudin and Hashim (2002), Crăciun (2003), Tingsanchali (2005), Vaitiekūnienė (2005) and Keskin et al. (2007). The model has been accepted worldwide especially for water resources modeling and it has the ability to simulate the watershed physical processes in more detail (Shamsudin and Hashim, 2002). The model has been applied in a large number of engineering projects covering various climatic regimes (Madsen, 2000; DHI, 2004). Refsgaard and Knudsen (1996) also applied the Mike 11 NAM model in three Zimbabwean catchments. The model was found to produce a close

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fit between the modelled and the recorded flows.

The Australian Water Balance Model (AWBM) is a catchment water balance model that calculates runoff from rainfall at daily or hourly time increments (Boughton, 2004). It is one of the most widely used rainfall–runoff models in Australia and has been applied in semi-arid and arid areas (Boughton, 2004; 2006). There are two main versions; one for daily water yield and low flow studies, the other for continuous simulation of flood runoff at hourly time steps (Boughton, 2004). Boughton (2004) stated that there are at least three rainfall–runoff models with structures that have some similarity to the AWBM. These are the USDA SCS curve number method, the Probability Distributed Model (PDM) and the modification of the PDM model, the Probability Distributed Soil Moisture Model (PDSMM).

AWBM is part of the rainfall-runoff models in-built within the Rainfall Runoff Library (RRL) developed by the Cooperative Research Center for Catchment Hydrology at the University of Monash in Australia. There are 7 optimization methods within the RRL which are available for model calibration. These are the genetic algorithm, pattern search, SCE, pattern search multi start, Rosenbrock single start, uniform random sampling and the Rosenbrock single multi-start. The model has been compared with models such as the SFB (Sharifi and Boyd, 1994), the USDA SCS curve number method (Boughton, 1995), the PDSMM (Muncaster et al., 1997) and auto-regressive model (Metcalfe et al., 2002) and has been found to perform better than these models.

Rainfall-runoff modelling requires streamflow data for calibration and verification. Since such data is not available in ungauged catchments, regionalization techniques are used for the transfer of model parameters from gauged to ungauged catchments. Regionalization techniques that are commonly used include the model averaging framework (McIntyre et al., 2005 and Reichl et al., 2006), the use of parameter sets from the closest upstream and downstream catchments, a parameter regression approach (Hughes, 1989; Servat and Dezetter, 1993; Seibert, 1999; Merz and Bloschl, 2004 and Vogel, 2005) and using

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parameter values from the nearest gauged catchment (nearest neighbour approach) (Merz and Bloschl, 2004; Chiew and Siriwardena, 2005; and He and Bárdossy, 2007). The nearest neighbour approach has been found to produce the best results as compared to all the above methods in studies such as Merz and Bloschl (2004) and Chiew and Siriwardena (2005).

2.8.1 The selected models for the current study and their structures

The MIKE 11 NAM and AWBM were selected for rainfall-runoff modelling in the current study because they have low data requirements. Both the models are user friendly and easy to set up. Mike 11 NAM has also been selected because it has been accepted worldwide for water resources modelling and because of its ability to simulate the watershed physical processes in detail as explained above. It has also been recognized by the Directorate: Water Resource Planning Systems within the Department of Water Affairs of South Africa as one of their modelling tools. It was also available in the Department of Hydrology and Water Resources at the University of Venda. The Mike 11 NAM and AWBM have been applied in modelling ungauged catchments (for example Boughton (2004) and Vaitiekūnienė (2005)).

In addition AWBM has been adopted for rainfall runoff modelling in this study because it has a range of optimization methods. This makes it easier to choose an optimization method which selects the best appropriate model parameters for calibration. The model is also freely available for download from the Cooperative Research Center for Catchment Hydrology website (www.toolkit.net.au/tools/RRL).

The Mike 11 NAM model structure (Fig. 2.3) is an imitation of the land phase of the hydrological cycle (DHI, 2004). The model simulates the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages that represent different physical elements of the catchment, which are snow

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storage, surface storage, lower or root zone storage and groundwater storage (Madsen et al., 2002). Table 2.3 provides the description of the Mike 11 NAM model parameters.

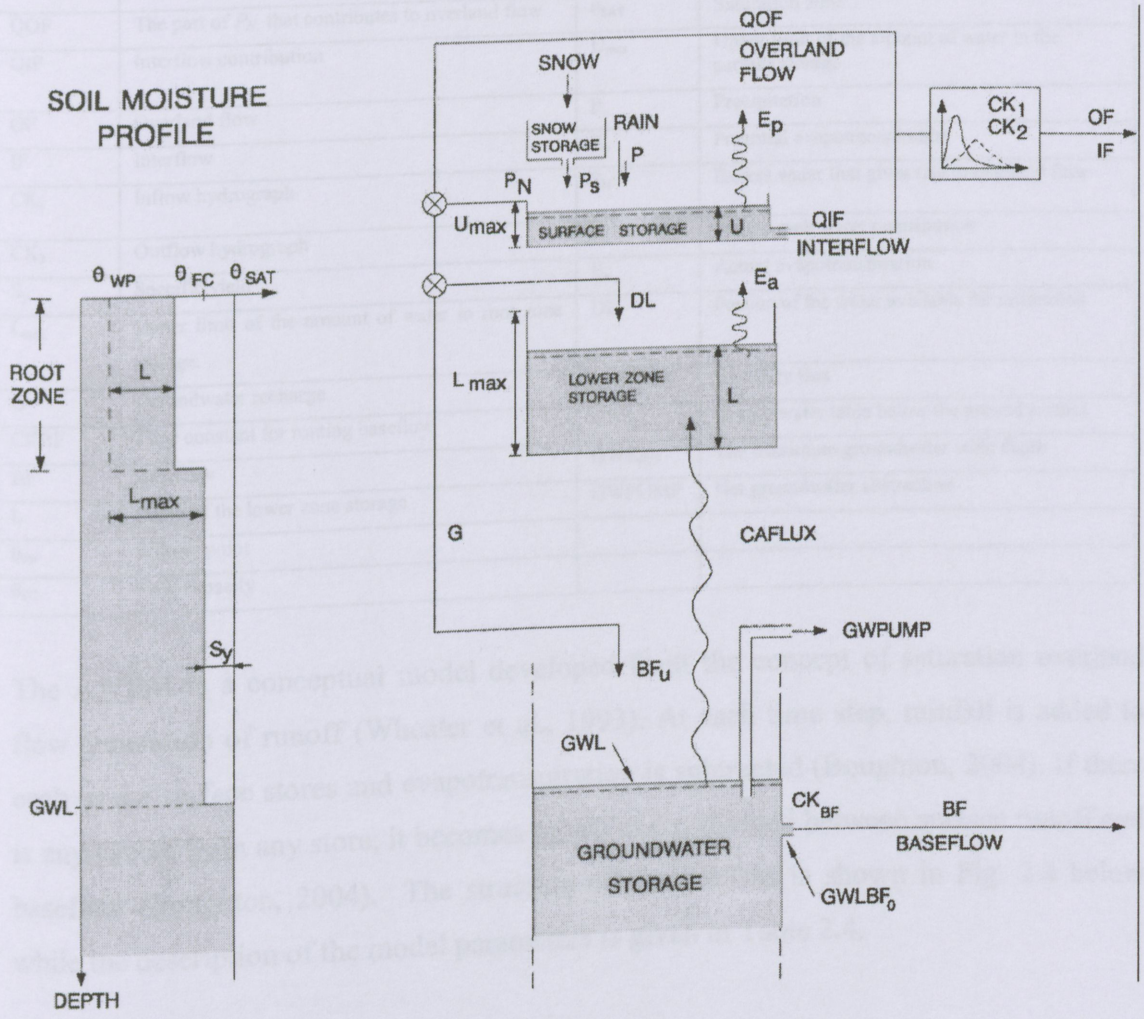


Figure 2.3: Mike 11 NAM model structure (DHI, 2004)

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Table 2.3: Description of the Mike 11 NAM model parameters (Adopted from DHI (2004)).

Parameter	Description	Parameter	Description
QOF	The part of P_N that contributes to overland flow	ϑ_{SAT}	Saturation zone
QIF	Interflow contribution	U_{max}	Upper limit of the amount of water in the surface storage
OF	Overland flow	P	Precipitation
IF	Interflow	E_p	Potential evapotranspiration
CK_1	Inflow hydrograph	P_N	Excess water that gives rise to overland flow
CK_2	Outflow hydrograph	P_S	Excess melt water contribution
S_y	Specific yield	E_a	Actual evapotranspiration
L_{max}	Upper limit of the amount of water in root zone storage.	DL	Portion of the water available for infiltration
G	Groundwater recharge	CAFLUX	Capillary flux
CKBF	Time constant for routing baseflow	GWL	Groundwater table below the ground surface
BF	Baseflow	GWL_{BF0}	The maximum groundwater table depth
L	Depth of the lower zone storage	GWPUMP	Net groundwater abstraction
θ_{wp}	Wilting point		
θ_{FC}	Field capacity		

The AWBM is a conceptual model developed from the concept of saturation overland flow generation of runoff (Wheater et al., 1993). At each time step, rainfall is added to each of the surface stores and evapotranspiration is subtracted (Boughton, 2004). If there is any excess from any store, it becomes runoff and is divided between surface runoff and baseflow (Boughton, 2004). The structure of the AWBM is shown in Fig. 2.4 below while the description of the model parameters is given in Table 2.4.

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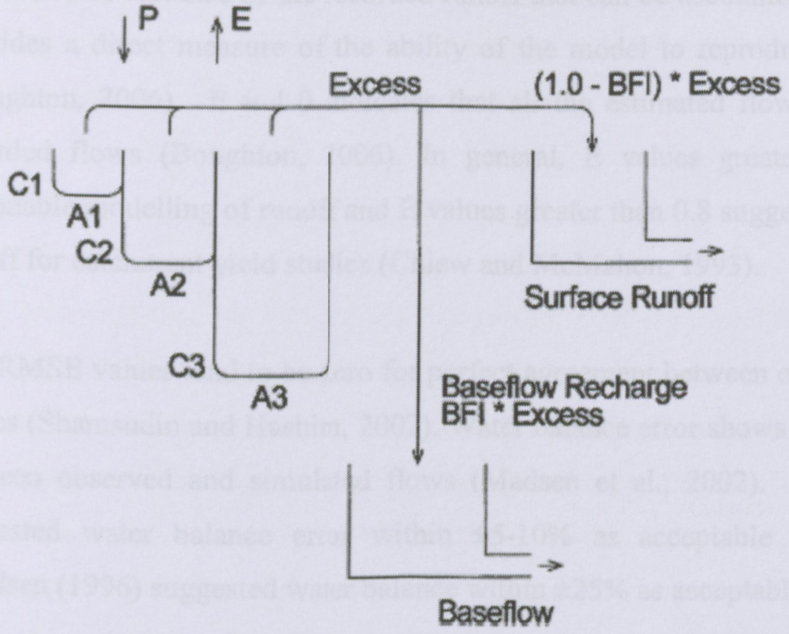


Figure 2.4: Structure of the AWBM model (Source: Boughton, 2006)

Table 2.4: Description of the AWBM model parameters

Parameter	Description
P	Precipitation
E	Evaporation
A_1	Partial area represented by C_1
A_2	Partial area represented by C_2
BFI	Baseflow Index
C_1	Surface storage capacity of A_1
C_2	Surface storage capacity of A_2
C_3	Surface storage capacity

2.8.2 Measures of model performance

The model performance measures used to define efficiency of calibration and verification of the models include the Nash Sutcliffe coefficient of efficiency (E), the overall root mean square error (RMSE), overall water balance error (OWBE), correlation coefficient (R) and percent bias (PBIAS). The Nash Sutcliffe coefficient of efficiency expresses the

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proportion of variance of the recorded runoff that can be accounted for by the model and provides a direct measure of the ability of the model to reproduce the recorded flows (Boughton, 2006). E = 1.0 indicates that all the estimated flows are the same as the recorded flows (Boughton, 2006). In general, E values greater than 0.6 suggest a reasonable modelling of runoff and E values greater than 0.8 suggest a good modelling of runoff for catchment yield studies (Chiew and McMahon, 1993).

The RMSE values tend to be zero for perfect agreement between observed and simulated values (Shamsudin and Hashim, 2002). Water balance error shows the average difference between observed and simulated flows (Madsen et al., 2002). Madsen et al. (2002) suggested water balance error within ±5-10% as acceptable while Refsgaard and Knudsen (1996) suggested water balance within ±25% as acceptable.

The R describes the degree of co-linearity between simulated and measured data (Moriasi et al., 2007). If R = 1, a perfect positive linear relationship exists between simulated and measured data (Moriasi et al., 2007). R values greater than 0.5 are considered acceptable (Van Liew et al., 2007). PBIAS measures the tendency of the simulated flows to be larger or smaller than the observed flows (Yapo et al., 1996). The optimal value is 0 % while positive values indicate a tendency to overestimate, and negative values indicate a tendency to underestimate the simulated flows (Yapo et al., 1996). Moriasi et al. (2007) suggested that PBIAS values acceptable should be within ±25%.

2.9 Summary

Literature review indicated that typical rural water supply schemes are facing a lot of challenges in terms of the adequacy and potability of the available water resources to meet the demand. This has been exacerbated by inadequate water supply infrastructure. These challenges force rural communities to abstract untreated river and groundwater for use without considering the health impacts and the environmental flow requirements.

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The review has identified critical water quality indicators to be considered when developing operating rules. Different methods that are used to estimate EWR together with their merits and demerits have also been reviewed. From the review, the method developed by Smakhtin et al. (2004) was found to be the most suitable method for the current study.

A methodology that can be used for unregulated river yield analysis was also established through literature review. Furthermore it was established that rainfall-runoff models are used to estimate streamflow in ungauged catchments by transferring model parameters from gauged to ungauged catchments using regionalization techniques. Rainfall-runoff models that have either been developed and/or applied in South Africa or elsewhere have been reviewed. The review established their strengths and weaknesses and provided motivation for the models that were selected to be used in the current study.

The review has shown that the existing operating rules/strategies have been developed mostly for water supply systems with reservoirs. The only operating strategy for run-of-river abstractions is that by Hughes (2006). The operating rules were derived from a time series data that consists of net monthly flows after the effects of afforestation, farm dams, run-of-river abstractions and high flows have been accounted for.

Literature review established that disaggregation of the monthly WR90 data to daily time series data before deriving FDCs for each month is not applicable in ungauged catchments where such data is not available and in situations where operating rules are to be developed at sub-quaternary catchment scales. It was also established that there are no operating rules for run-of-river abstractions that have been developed from daily flow time series. A need was particularly found for the development of an operating strategy for run-of-river abstractions for domestic water supply using simulated daily flow time series. Siloam Village has been used as a case study area for purposes of generating data for use in developing the strategy.

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CHAPTER 3: DATA COLLECTION AND ANALYSIS METHODS

3.1 Preamble

This chapter describes the data sets that were collected, how they were collected and what they were used for. It further describes the methods that were used to analyze the data in order to meet the objectives of the study.

3.2 Data collection methods

3.2.1 Data requirements for water balance modelling

Data sets that were collected include rainfall, evaporation, uncontrolled spills, downstream flow releases, dam water levels, storage-area relationship for Mutshedzi Dam, domestic abstractions, area under irrigation, crop factors, types of crops grown and the irrigation schedule. Evaporation, uncontrolled spills, downstream flow releases, dam water levels and storage-area relationship for Mutshedzi Dam were obtained from DWAF while rainfall data was obtained from the South African Weather Services (SAWS). Irrigation data and the crop factors were obtained from the farmers and Allen et al. (1998) respectively. The domestic abstractions were obtained from the Mutshedzi Water Treatment Plant. The station numbers for the rainfall, evaporation, downstream flow releases and uncontrolled spills are 0766327 (Mpsema Irrigation), A8E004 (Beaconsfield at Mutshedzi Dam), A8H011 (Beaconsfield at Mutshedzi River) and A8R004 (Mutshedzi Dam) respectively. These data sets were used in the computation of the inflows into the Mutshedzi Dam. The locations of these stations together with those used in rainfall-runoff modelling are shown in Fig. 3.1.

The crop factors, the area under irrigation, crops grown, irrigation schedule and the evaporation data from station number A8E004 were used to compute the irrigation water demand. This was done to determine the highest amount of water required for irrigation,

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and was also useful in establishing the significance of irrigation water use and its influence on the computed inflows to justify the exclusion of daily irrigation time series demand from the water balance. This was necessary because it was not possible to obtain the daily irrigation time series data.

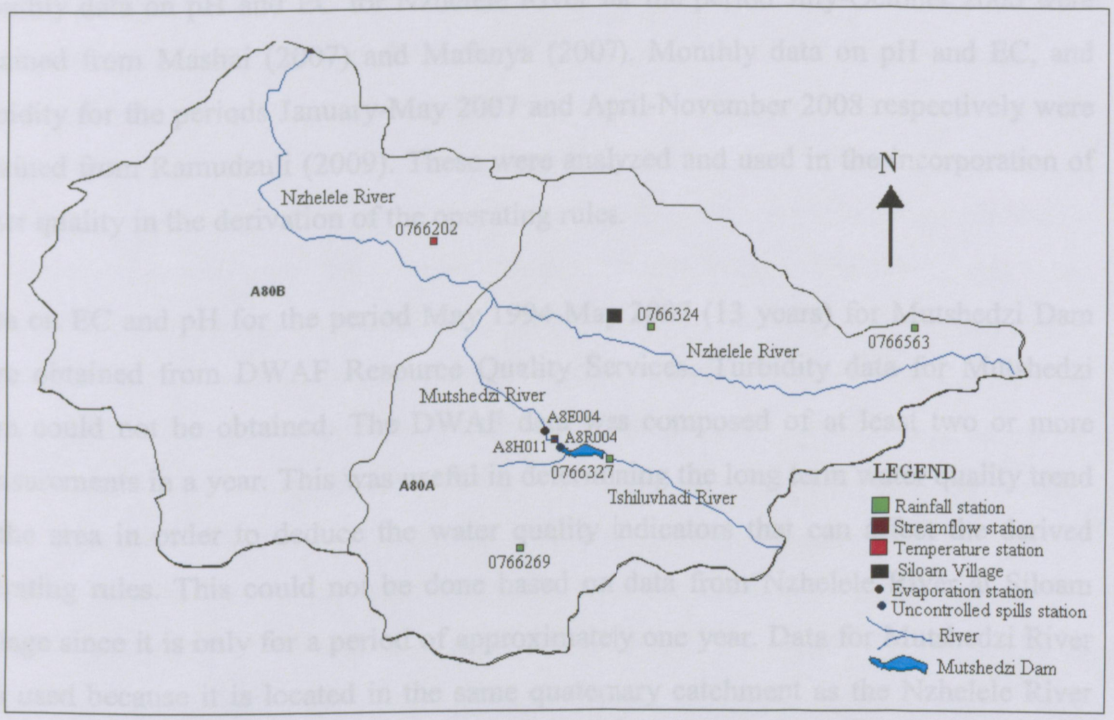


Figure 3.1: Locations of rainfall, evaporation, temperature and streamflow stations

3.2.2 Data requirements for rainfall-runoff modelling

Rainfall data for station numbers 0766327, 0766324 (Siloam), 0766269 (Joubertstroom) and 0766563 (Tate Bos) and evaporation data for station number A8E004 (Fig. 3.1) were collected from the SAWS and DWAF respectively. These were used as inputs into the Mike 11 NAM rainfall-runoff model. The evaporation data from A8E004 station together with the weighted areal rainfall computed in Mike 11 NAM rainfall-runoff model were also used for rainfall-runoff modelling with the AWBM. Temperature data for station number 0766202 (Rabali) located in the neighbouring quaternary catchment A80B was obtained from the Water Research Commission (WRC) temperature database (Schulze

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and Maharaj, 2003). This was used to extend the evaporation data for station A8E004 for use in rainfall-runoff modelling for Nzhelele River at Siloam Village.

3.2.3 Water quality data

Monthly data on pH and EC for Nzhelele River for the period July-October 2006 were obtained from Mashai (2007) and Mafenya (2007). Monthly data on pH and EC, and turbidity for the periods January-May 2007 and April-November 2008 respectively were obtained from Ramudzuli (2009). These were analyzed and used in the incorporation of water quality in the derivation of the operating rules.

Data on EC and pH for the period May 1994-May 2007 (13 years) for Mutshedzi Dam were obtained from DWAF Resource Quality Services. Turbidity data for Mutshedzi Dam could not be obtained. The DWAF data was composed of at least two or more measurements in a year. This was useful in determining the long term water quality trend of the area in order to deduce the water quality indicators that can affect the derived operating rules. This could not be done based on data from Nzhelele River at Siloam Village since it is only for a period of approximately one year. Data for Mutshedzi River was used because it is located in the same quaternary catchment as the Nzhelele River and is likely to have similar water quality characteristics.

3.3 Data analysis methods

3.3.1 Methods used to simulate streamflow hydrographs in Mutshedzi and Nzhelele Rivers sub-quaternary catchments

Performing unregulated river flow yield analysis requires a streamflow hydrograph to enable the derivation of flow duration curves for Nzhelele River. There is no such data in Nzhelele River (around where Siloam Village is located) since there is no streamflow gauging station. Because of this, runoff hydrographs were generated using the Mike 11

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NAM and AWBM rainfall runoff models. The AWBM was used for comparing the simulated runoff results with those obtained from Mike 11 NAM.

Since there is no streamflow data to calibrate the model, runoff simulation was performed for a nearby Mutshedzi River in the same quaternary catchment to obtain the model parameters. In order to achieve this, the quaternary catchment was delineated into two sub-quaternary catchments that drain the Nzhelele and Mutshedzi Rivers respectively. The model parameters including overland flow runoff coefficient, surface and root zone parameters, among others, were then obtained from the Mutshedzi River sub-quaternary catchment and transferred to the Nzhelele River sub-quaternary catchment for use in rainfall runoff modelling of the Nzhelele River at Siloam Village. The nearest neighbour regionalization approach was used to transfer model parameters from the ungauged Mutshedzi River sub-quaternary catchment (SQC) to the Nzhelele River SQC which are nested within an ungauged quaternary catchment. The nearest neighbour regionalization approach involves adopting model parameters from neighbouring catchment for transfer to the ungauged catchment of interest. It differs from the commonly used nearest neighbour regionalization approach involving a gauged quaternary catchment and an ungauged quaternary catchment. This approach ensures improvement in homogeneity of the estimated hydrological parameters since the two SQCs are located in one quaternary catchment and therefore have more or less similar hydrological characteristics.

The only stream gauging station (A8H011) in the A80A quaternary catchment, which was in operation from 1991 to 2000, was located immediately after the Mutshedzi Dam on the Mutshedzi River before it meets the Nzhelele River. It could therefore not be used in the surface water yield analysis of the Nzhelele River. Furthermore, the flows from this gauging station have been impacted on by the Mutshedzi Dam. Because of this, it was necessary to obtain a time series of inflows into the Mutshedzi Dam. This inflow time series was used to calibrate the Mike 11 NAM and AWBM rainfall runoff models to determine the model parameters highlighted above.

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(i) Determining inflow time series into Mutshedzi Dam

The conceptual diagram for the Mutshedzi Dam water balance is shown in Fig. 3.2. From Fig 3.2, I_{dam} is the inflow into the dam, Q_c are the domestic abstractions, Q_{irr} are the irrigation abstractions, Q_s are the uncontrolled spills, E is the evaporation, R is the rainfall and $D_{releases}$ are the downstream flow releases. These components have been used in the water balance equation below to compute inflow into the Mutshedzi Dam, I_{dam}.

$$I_{dam} = Q_d + Q_{irr} + Q_s + E \pm \Delta s - R + D_{releases} \quad (3.1)$$

The variables in the water balance equation are the same as those of the conceptual water balance diagram and have been explained above except for the change in storage (Δs).

Equation 3.1 was used to compute the inflow into the dam taking into account the estimated irrigation water demand. To compute the inflow into the dam excluding the estimated irrigation water demand, the following equation was used:

$$I_{dam} = Q_d + Q_s + E \pm \Delta s - R + D_{releases} \quad (3.2)$$

This was done to establish the significance of irrigation water use on the computed inflows and to justify the exclusion of daily irrigation time series demand from the water balance as explained in section 3.2.1.

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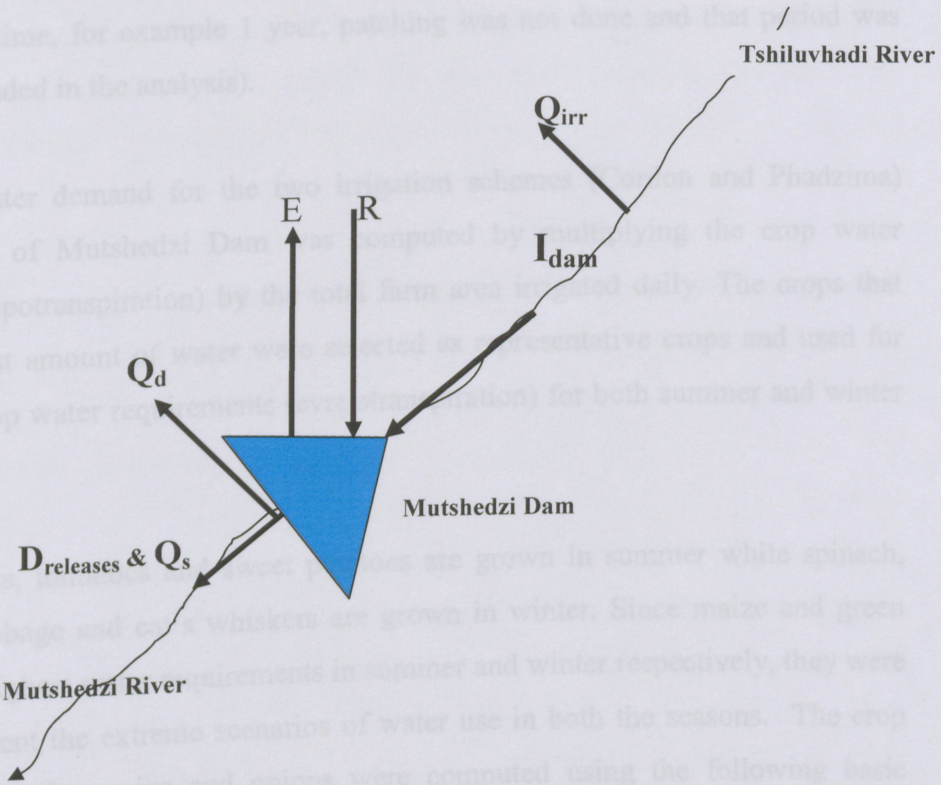


Figure 3.2: Conceptual diagram for the Mutshedzi Dam water balance

The daily water levels were used to compute the water storage time series of Mutshedzi Dam. The storage-area relationship for Mutshedzi Dam obtained from the DWAF was used to determine the area inundated for each daily water level. Each daily water level was multiplied by the area inundated to get daily storage. Daily rainfall and evaporation data which were in mm/day were converted to m^3/day by converting them to m/day and then multiplying the daily data by the area inundated (m^2). The daily downstream flow releases were converted from m^3/s to m^3/day by multiplying them by 86400 s/day. Daily rainfall, evaporation data and downstream flow releases were imported into Excel Spreadsheet while domestic water abstraction were manually entered into Excel Spreadsheet to be used in computation of the water balance.

Initial checking of all the data sets and minimum patching of evaporation data series using the arithmetic mean method were done. Minimum patching of daily domestic

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abstractions was also done where possible (i.e. in cases where there were missing data for a long period of time, for example 1 year, patching was not done and that period was therefore not included in the analysis).

The irrigation water demand for the two irrigation schemes (Cordon and Phadzima) located upstream of Mutshedzi Dam was computed by multiplying the crop water requirements (evapotranspiration) by the total farm area irrigated daily. The crops that require the highest amount of water were selected as representative crops and used for computing the crop water requirements (evapotranspiration) for both summer and winter seasons.

Maize, groundnuts, tomatoes and sweet potatoes are grown in summer while spinach, green onions, cabbage and cat's whiskers are grown in winter. Since maize and green onions have the highest water requirements in summer and winter respectively, they were selected to represent the extreme scenarios of water use in both the seasons. The crop water requirements for maize and onions were computed using the following basic formula:

$$ET_{crop} = k_c \times ET_o \tag{3.3}$$

where ET_{crop} = the water requirement of a given crop in mm/day, k_c = the crop factor and ET_o = the reference crop evapotranspiration in mm/day.

ET_o was obtained by multiplying the evaporation rates measured with an evaporation pan by the pan coefficient. This approach is referred to as the pan evaporation method by Allen et al. (1998). Daily irrigation demand was computed using the formula:

$$Q_{irr} = ET_{crop} \times A \tag{3.4}$$

where Q_{irr} = daily irrigation demand in m^3/day and A = area irrigated daily in m^2/day

The dam downstream flow releases were only available for the period 1991/02/13-

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2000/02/15 while the domestic abstractions were available from 1994/04/22-2007/10/31 with some years having completely no data. This has limited the computation of the water balance to the period 1994/04/22-1999/03/06. Though the computation would have been expected to continue up to 2000/02/15, this was not possible because there were no domestic abstractions data between this date and 1999/03/06.

(ii) Rainfall-runoff modelling for Mutshedzi and Nzhelele River sub-quaternary catchments

Delineation of the sub-quaternary catchments

The sub-quaternary catchments drained by the upper part of Nzhelele and Mutshedzi Rivers in quaternary catchment A80A were manually delineated from the 1:50000 topographical map and a topographical map obtained from the GRDM software and their respective areas determined.

The delineation was carried out based on:

- The location of ridges and valleys in each sub-quaternary catchment
- Flow direction of rivers and their tributaries
- The fact that the study was aimed at simulating the catchment runoff that gets into the Mutshedzi Dam and the point where the runoff can be accessed by the Siloam community for abstraction.

Mike 11 NAM model setup, calibration and verification

The sub-quaternary catchment area, weighted areal rainfall, evaporation and streamflow data were required for the model set up for the Mutshedzi sub-quaternary catchment. These data were input into the model and were used in the calibration and verification of the model. The weighted areal rainfall was automatically computed by the Mike 11 NAM rainfall-runoff model from point rainfall for station numbers 0766269 and 0766327 using

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Thiessen polygon method. The calibration to determine Mike 11 NAM rainfall-runoff model parameters was carried out using daily data for a period of 3 years (1994/04/22-1997/04/22). This was followed by verification using daily data for a period of 2 years (1997/04/23-1999/03/06). Three years is the minimum calibration period recommended by DHI (2004). Auto calibration was carried out using the Shuffled Complex Evolution optimizer in-built within Mike 11 NAM using the Root Mean Square Error as the objective function. Verification was performed to assess whether the calibrated parameter values can be used to successfully estimate streamflow for an independent test period that was not used to calibrate the model. The Nash Sutcliffe coefficient of efficiency (E), the overall root mean square error (RMSE), overall water balance error (OWBE), correlation coefficient (R) and percent bias (PBIAS) were used to define efficient calibration and verification of the model. Equations 3.5, 3.6, 3.7, 3.8 and 3.9 were used to compute the E, RMSE, OWBE, R and PBIAS respectively.

$$E = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \overline{Q}_{obs,i}\right)^2} \tag{3.5}$$

where Q_{obs} = observed flow (m^3/s); Q_{sim} = simulated flow (m^3/s) and $\overline{Q}_{obs}$ (m^3/s) is the mean of the observed flow, i= number of the day and n = total number of time steps.

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2\right]^{\frac{1}{2}} \tag{3.6}$$

where the variables are defined as in Equation 3.5.

$$OWBE = \frac{1}{n}\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right) \tag{3.7}$$

where the variables are defined as in Equation 3.5.

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$$R = \left[\frac{\sum_{i=1}^{n} \left(Q_{obs,i} - \overline{Q}_{obs,i}\right)\left(Q_{sim,i} - \overline{Q}_{sim,i}\right)}{\sqrt{\sum_{i=1}^{n} \left(Q_{obs,i} - \overline{Q}_{obs,i}\right)^2 \sum_{i=1}^{n} \left(Q_{sim,i} - \overline{Q}_{sim,i}\right)^2}} \right] \quad (3.8)$$

$$PBIAS = \frac{\sum_{i=1}^{n} \left(Q_{obs,i} - Q_{sim,i}\right)}{\sum_{i=1}^{n} \left(Q_{obs,i}\right)} \times 100 \quad (3.9)$$

where the variables are defined as in Equation 3.5.

Weighted areal rainfall computed from point rainfall for station numbers 0766327, 0766324, and 0766563; evaporation time series data and model parameters obtained from Mutshedzi sub-quaternary catchment calibration were used in Mike 11 NAM rainfall-runoff modelling for the Nzhelele River sub-quaternary catchment. The data for the period 1950/01/01-2000/07/31 was used in the simulation.

The measured daily evaporation data for station A8E004 used in the study was of a short record length from 1991/07/01-2000/07/31. It was therefore necessary to use an appropriate method to extend the length of the record. The Hargreaves equation (Eq. 3.10) (Hargreaves and Samani, 1985) was used to estimate the daily reference evaporation for Siloam Village. This method was selected for use because it only requires daily maximum and minimum air temperatures as well as estimates of extraterrestrial radiation. It can also estimate reference evaporation at a daily scale unlike other temperature based methods such as Thornthwaite (1948), Romanenko (1961) and Linacre (1977) which estimate reference evaporation on a monthly scale. This method produces better predictions for longer periods (Gavilan and Castillo-Llanque, 2009) and it is known to estimate daily ET_o accurately (Hargreaves and Allen, 2003).

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$$ET_o = 0.0023 R_a TD^{0.5} (T_a + 17.8) \quad (3.10)$$

where ET_o is the computed reference evaporation (mm/d); R_a is the water equivalent of the extraterrestrial radiation (mm/d), TD is the difference between the daily maximum and minimum temperatures. T_a is the mean daily temperature. R_a was computed using a series of equations found in Allen et al. (1998). The Hagreaves method was used by Hughes et al. (2006) when estimating evaporation for use in rainfall runoff modelling.

AWBM model setup, calibration and verification

The sub-quaternary catchment area, weighted areal rainfall, evaporation and streamflow data are also required for the AWBM model set up. These data were input into the model and were used in the calibration and verification of the model. The calibration to determine the AWBM rainfall-runoff parameters was carried out using daily data from the Mutshedzi sub-quaternary catchment for the same 3 year period used in Mike 11 NAM rainfall runoff calibration. This was followed by verification using daily data for the same 2 year period used in Mike 11 NAM rainfall runoff verification. Different trial calibration runs were carried out using the parameter optimization techniques mentioned in section 2.8. This was done in order to identify the technique which estimates the best model parameters. The Rosenbrock single start optimization technique (Rosenbrock, 1960) was selected for model calibration because it provided the best values of the measures of performance. The RMSE was used as the objective function in the calibration. The same measures of performances used with Mike 11 NAM results were used to define efficient calibration and verification of AWBM. The performances of the two models in rainfall runoff modelling in Mutshedzi River sub-quaternary catchment were then compared using the corresponding performance measures and the simulated and observed hydrographs.

The same weighted areal rainfall and evaporation time series data used with Mike 11 NAM, and AWBM model parameters obtained from Mutshedzi sub-quaternary

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catchment calibration were used in AWBM rainfall runoff modelling for Nzhelele River sub-quaternary catchment at Siloam Village. The simulated runoff hydrographs obtained from the two models and, the correlation between simulated runoff and areal rainfall were then compared.

3.3.2 Methods used to assess the availability and suitability of Nzhelele River water at Siloam Village

Since unregulated rivers have no storages, flow duration curves have been used for yield analysis at different percentages of time the discharge is equaled or exceeded (flow assurances). Daily runoff for the period 1950/01/01-2000/07/31 simulated using Mike 11 NAM and AWBM have been used to construct 366 one day FDCs. A one day FDC is a flow duration curve constructed from long term daily runoff data for each day of the year. The daily runoff for a period of 51 years were sorted out and arranged such that the discharge for each day of the year (for example 1 Jan 1950-1 Jan 2000) were grouped together to form one data set, resulting in 366 data sets each with 51 data points. These together with the computation of the percentage of time each discharge was equalled or exceeded was accomplished with a computer program (see Appendix A) written by Dr. John Ndiritu from the University of the Witwatersrand.

The 1 day flow duration curves for river flow have been used to derive 1 day flow time series (yields) equalled or exceeded at different levels of flow assurances. The percentage time a particular discharge/yield is equalled or exceeded is the assurance of supply of that particular discharge/yield event (Hughes, 1999 and 2001).

The total water requirements were compared with the total available water at different levels of assurance. The total water requirements are the sum of the domestic and the environmental water requirements in this study. If the total water requirement line crossed or was above the available water resources line at a specific level of assurance of supply, then there was no enough water to satisfy all requirements at that particular level

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of assurance. The supply was then considered at a different level of assurance, which was equivalent to practising water demand management. Otherwise, alternative sources of supply were recommended.

The LFR component of environmental water requirements was estimated using the procedure described in Smakthin et al. (2004). According to this method, LFR is approximated by the discharge, which is exceeded 90% of the time (Q_{90}). This was adopted as an estimate of the environmental water requirements based on the reasons given in section 2.5.

The water quality indicators (pH, EC and turbidity) were obtained from Mafenya (2007), Mashai (2007) and Ramudzuli (2009) and compared with the DWAF standards for domestic use and aquatic ecosystems to establish suitability for each of the uses. The water quality parameters were measured using the methods provided in Mafenya (2007), Mashai (2007) and Ramudzuli (2009). Available historical data on the water quality indicators (EC and pH) for Mutshedzi Dam were also analyzed to indicate the water quality status of the A80A quaternary catchment in which Siloam Village is located. These were also compared with the DWAF standards for domestic use and aquatic ecosystems to establish suitability for each of the uses. The required level of treatment was then recommended before water use.

3.3.3 Procedure for generating the operating strategy for Nzhelele River at Siloam Village

The run-of-river abstractions operating rules were derived based on the results of the water resources assessment. The run-of-river abstractions have been recommended to be operated in such a way that the available water above the environmental flow requirements can be supplied to the community for domestic use at a particular level of assurance of supply provided that the water meets the quality requirement for that use in accordance with DWAF (1996a, b). If the water does not meet the quality requirement for

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that use appropriate level of household treatment should be undertaken or the water recommended for a different type of use.

3.3.4 Procedure for generalization of the operating strategy

The procedures followed in developing the operating rules for Nzhelele River at Siloam Village have been used as a basis for developing the generic operating strategy that can be applied to any river system in which run-of-river abstractions are used to fully or partially supply the community with water.

3.4 Summary

A method for developing the operating rules for run-of-river abstractions for typical rural water supply schemes has been outlined. The approach involves the use of rainfall-runoff models to derive a streamflow hydrograph in ungauged catchments which is then used to derive FDCs. FDCs are then used to analyze unregulated yield and operate the system at given levels of assurance of supply for specific water requirements. Water quality which is an integral component of run-of-river abstractions for domestic use has been integrated into the developed operating rules, which also consider the environmental water requirements. The study further proposed the procedure for generalization of the operating rules so that the method can be applied to any river system in the country in which run-of-river abstractions are used to fully or partially supply the community with water.

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CHAPTER 4: SIMULATION OF STREAMFLOW HYDROGRAPHS IN MUTSHEDZI AND NZHELELE RIVER SUB-QUATERNARY CATCHMENTS

4.1 Preamble

This chapter presents the results and discussion of the computed inflows into Mutshedzi Dam and rainfall-runoff modelling for the Mutshedzi sub-quaternary catchment using the Mike 11 NAM and the AWBM. The chapter further presents the comparison of the performances of the Mike 11 NAM and the AWBM in rainfall-runoff modelling of Mutshedzi sub-quaternary catchment. The results of the rainfall-runoff simulation for the Nzhelele River sub-quaternary catchment using model parameters adopted from Mutshedzi sub-quaternary catchment has also been presented in this chapter.

4.2 Computed inflows into the Mutshedzi Dam

The inflows into the Mutshedzi Dam computed from the water balance equation (Eq. 3.2) using the downstream flow releases, domestic water abstractions, rainfall, evaporation, uncontrolled spills and dam water storage (see Appendix B) have been presented in Fig. 4.1. The inflow time series obtained was considered reasonable although 6.8% were negative. The negative flows summed up to only 7.3% of the sum of the positive flows. 90% of the negative flows were less than 10% of the mean flow. In Ndiritu et al. (2008), 17% of the inflows were negative and summed up to only 0.9% of the sum of positive flows. Their study found that 92% of the negative flows were less than 10% of the mean flow and were considered negligible and likely to be within the bounds of normal measurement errors. This value is comparable with that obtained in this study, though the percentage sum of the negative inflows to the total flows is lower than the 17% obtained by Ndiritu et al. (2008).

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Following this precedence, the negative flows in this study were considered negligible and likely to be within the bounds of normal measurement errors. All the negative flows were therefore converted to zero flows.

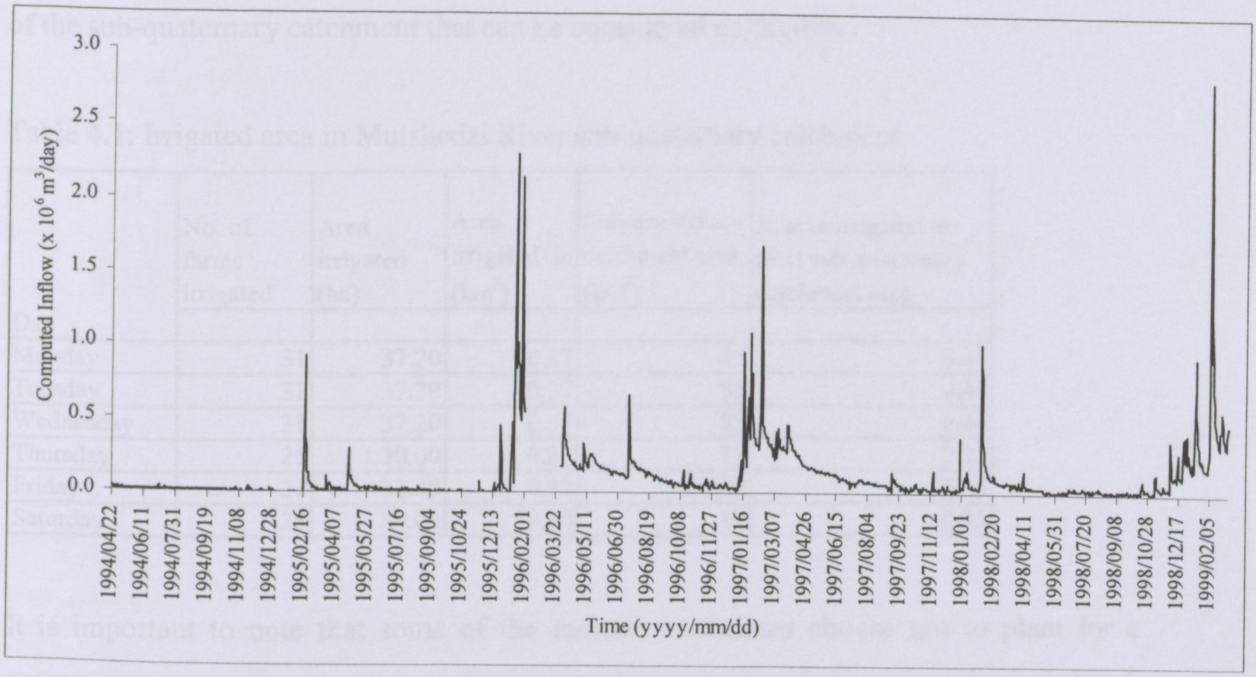


Figure 4.1: Computed inflow into the Mutshedzi Dam

The discontinuity observed in the inflow time series between 1996/02/01 and 1996/03/31 was because the domestic abstractions data for Mutshedzi Water Treatment Plant were not available for that period. It was therefore not possible to compute the inflow time series using the water balance equation during that period.

It was not possible to obtain the daily irrigation time series data since there is no monitoring of the irrigation abstractions in the study area. The daily irrigation time series could therefore not be included in the computation of the inflow time series for the Mutshedzi Dam. The two irrigation schemes that are located upstream of Mutshedzi Dam (Cordon and Phadzima irrigation schemes) have a number of farms under irrigation with each farm having an average area of 1.2 ha. The number of farms irrigated per day in

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both the schemes are provided in Table 4.1. The average area irrigated in a day ranges from 0.30-0.37 km^2 (Table 4.1). The area irrigated daily constitutes 0.35-0.44% of the total catchment area (Table 4.1). This is far much less than the total area of the sub-quaternary catchment (85 km^2). Thus irrigation water use takes place in a very small area of the sub-quaternary catchment that can be considered negligible.

Table 4.1: Irrigated area in Mutshedzi River sub-quaternary catchment

Day	No. of farms irrigated	Area irrigated (ha)	Area irrigated in (km^2)	Sub-quaternary catchment area (km^2)	% area irrigated to total sub-quaternary catchment area
Monday	31	37.20	0.37	85	0.44
Tuesday	31	37.20	0.37	85	0.44
Wednesday	31	37.20	0.37	85	0.44
Thursday	25	30.00	0.30	85	0.35
Friday	27	32.40	0.32	85	0.38
Saturday	25	30.00	0.30	85	0.35

It is important to note that some of the farmers sometimes choose not to plant for a season or a year. For example, information obtained from field visit indicated that 6 farmers in Cordon irrigation scheme never planted in 2008. This therefore makes the area irrigated daily in some seasons or years far much less than the average area that has been provided in Table 4.1. The canals that convey water to the irrigation schemes are also designed in such a way that the required amount of irrigation water is diverted from the canals into the farms and the unutilized water flows into the dam.

4.2.1 Estimation of the irrigation water demand time series

Further analysis involving the estimation of irrigation time series was done to show the insignificance of irrigation on estimation of the inflow time series of Mutshedzi Dam. It was not easy to estimate the actual daily time series irrigation water demand due to the nature of the irrigation schemes. In each scheme a number of different types of crops are planted within the allocated area (average 1.2 ha) in both summer and winter. No

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information was available on the area under which a different crop type was planted in both winter and summer since the farmers rely on their discretion to decide on which seasonal crop to plant in the unmeasured portion (area) of the farm. The information presented in Table 4.2 was therefore used to estimate the crop water requirements (evapotranspiration) from Eq. 3.3 for maize and green onion, which are the main summer and winter crops respectively, based on their crop factor (k_c) distribution over the life of the crop.

Table 4.2: Data needed to estimate crop water requirements for maize and green onion (adopted from Allen et al., 1998)

	Maize		**Green onion**	
Stage of growth	Crop factor (k_c)	Length of growing stages (days)	Crop factor (k_c)	Length of growing stages (days)
Initial	0.3	20	0.7	25
Development	1.15	35	1	30
Mid-season	1.15	40	1	10
Late season	1.05	30	1	5

The following assumptions which take into account the planting seasons for each crop were made in order to generate time series of irrigation water demand (Fig. 4.2):

- The summer crop (maize) is planted two times in the season from September and harvested in December and from January and harvested in April.
- Maize is only irrigated for 3 months and left to dry for one month.
- The winter crop (green onion) is only planted at the beginning of the winter season (May) and it is irrigated throughout the planting season.

The fact that no irrigation occur on Sunday from the information obtained from the community, was also considered when generating the irrigation water demand time

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series, computed from Eq. 3.4.

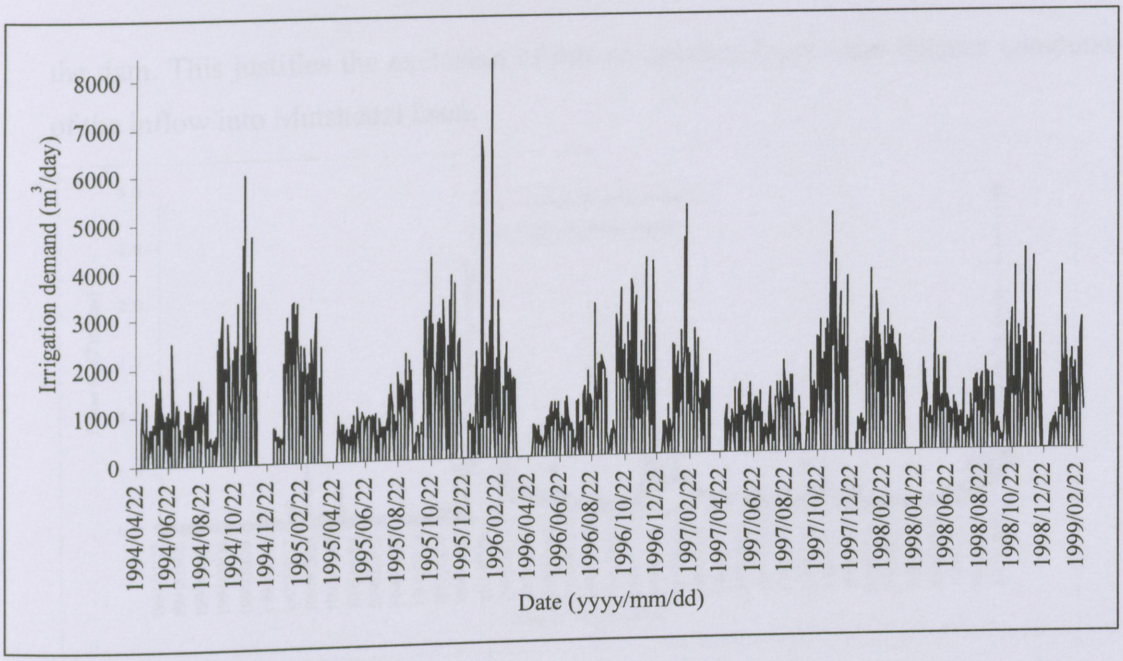


Figure 4.2: Estimated irrigation water demand

The estimated irrigation water demand ranges from 0-8363.5 m^3/day (Fig. 4.2) while the mean irrigation water demand is 957.5 m^3/day. It is important to note that the method used to compute the irrigation water demand did not consider the use of rainfall water during the rainy season. Thus, the computed irrigation water demand was overestimated especially during the rainy season.

4.2.2 Comparisons of computed inflow time series with and without irrigation

The inflows into the Mutshedzi Dam computed from the water balance equation in which the irrigation water demand was excluded was compared with the inflows into the dam computed with the irrigation water demand included (Fig. 4.3). The results show that incorporating the irrigation water demand in the computation has negligible effect compared to the scenario that excludes the irrigation water demand. Its exclusion increases the inflows by a maximum of 0.004 m^3/day in some of the days. This shows that the actual irrigation water demand is low and has negligible effect on the inflows into

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the dam. This justifies the exclusion of this component from water balance computation of the inflow into Mutshedzi Dam.

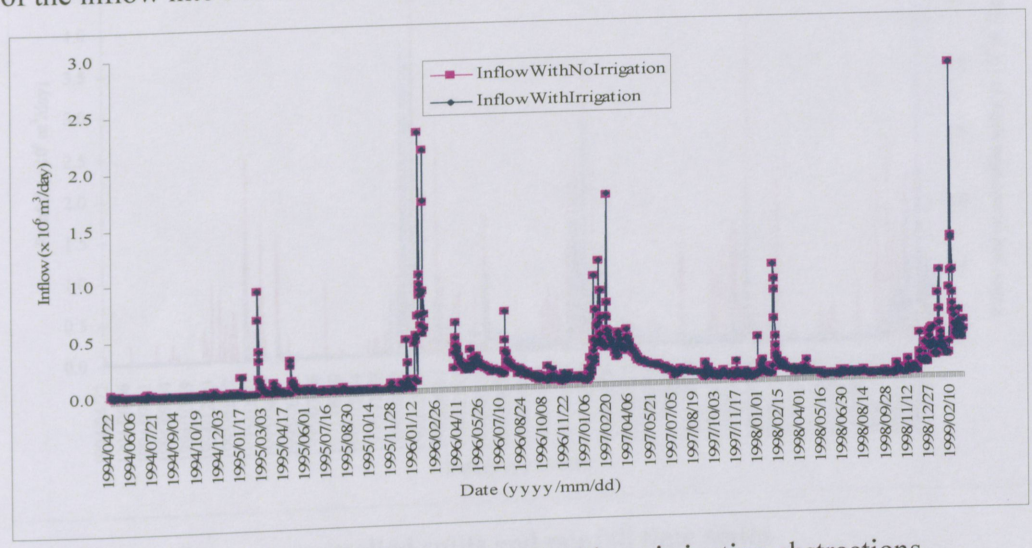


Figure 4.3: Comparison of inflows with and without irrigation abstractions

4.2.3 The realistic nature of the computed inflow time series for Mutshedzi Dam

Figure 4.4 below is the plot of rainfall, uncontrolled spills and computed inflows into the dam. The plot shows that the behaviour of the inflows is the same as the behaviour of the rainfall and uncontrolled spills as can be observed from the peaks that occur at about the same time. There is, however, some lag in the runoff response (inflows) and the uncontrolled spills. When the rainfall is high, the inflows and uncontrolled spills are high as expected and vice versa. This therefore means that the computed inflow time series is realistic.

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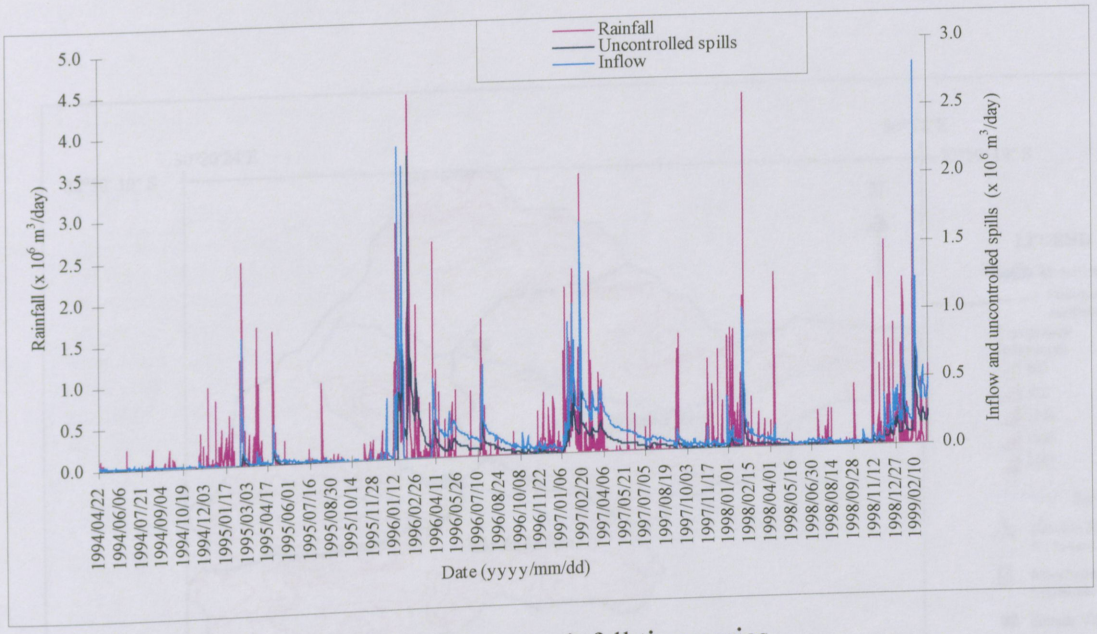


Figure 4.4: Inflows, uncontrolled spills and rainfall time series

4.3 Delineated Mutshedzi and Nzhelele sub-quaternary catchments

The delineated sub-quaternary catchments of the Nzhelele and Mutshedzi Rivers whose areas have been used in rainfall-runoff modelling are represented by A and B respectively (Fig. 4.5). Their estimated areas are 98.25 and 85 km^2 respectively.

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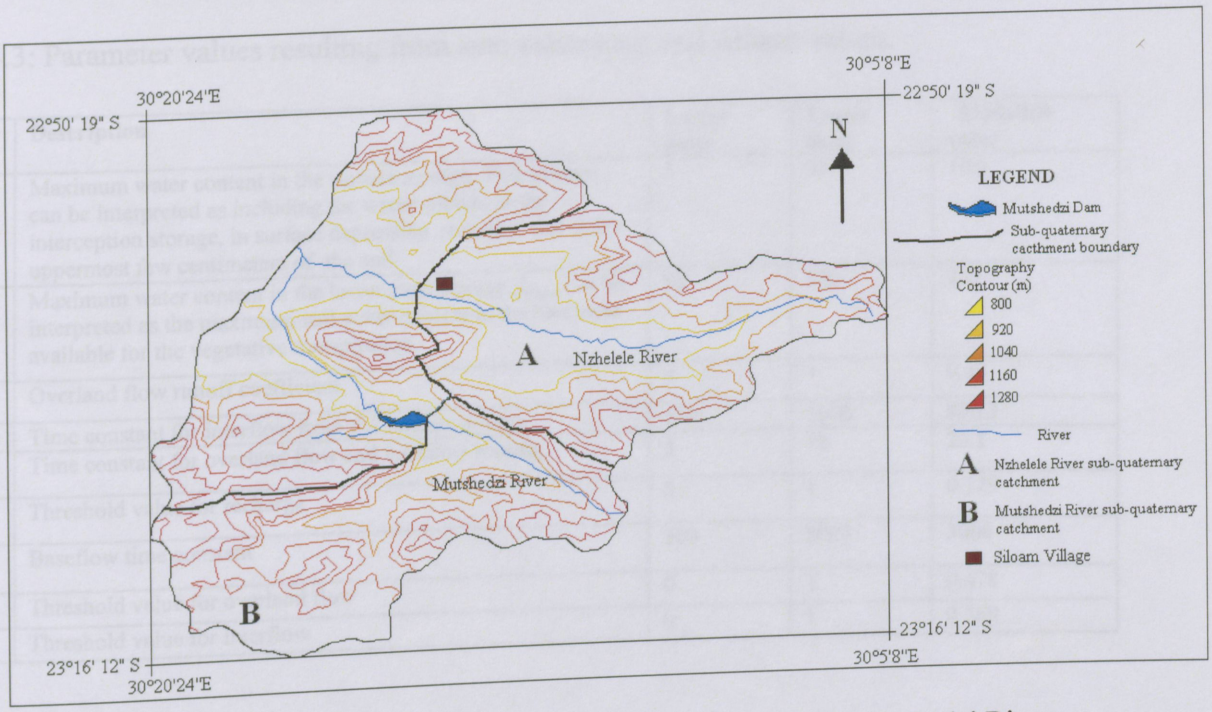


Figure 4.5: Delineated sub-quaternary catchments for the Nzhelele and Mutshedzi Rivers

4.4 Rainfall-runoff modelling for Mutshedzi sub-quaternary catchment

4.4.1 Mike 11 NAM rainfall-runoff modelling

The parameters obtained from the model auto calibration, their descriptions and acceptable limits are given in Table 4.3. The modelled parameters fall within the acceptable lower and upper limits of the individual parameter ranges. Several trials during the calibration revealed that the most sensitive model parameters are L_{max}, U_{max}, CQOF and CKIF. These findings are similar to those in Keskin et al. (2007). The parameters L_{max}, U_{max}, CQOF and CKIF define the base flow in the basin (Keskin et al., 2007). It was also found that the parameters TOF and TIF (Table 4.3) do not have much influence on the total runoff volume in the current study. This finding was also confirmed

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by Keskin et al. (2007) while calibrating a rainfall-runoff model for Yuvacik Dam Basin in Turkey.

Table 4.3: Parameter values resulting from auto calibration and default values

Parameter	Description	Lower limit	Upper limit	Modelled value
U_{max} (mm)	Maximum water content in the surface storage. This storage can be interpreted as including the water content in the interception storage, in surface depression storages, and in the uppermost few centimeters of the soil	5	35	10.5
L_{max} (mm)	Maximum water content in the lower zone storage. L_{max} can be interpreted as the maximum soil water content in the root zone available for the vegetative transpiration	50	350	267
CQOF (–)	Overland flow runoff coefficient	0	1	0.82
CKIF (h)	Time constant for interflow from the surface storage	500	1000	856.3
CK1,2 (h)	Time constant for overland flow and interflow routing	3	72	29.1
TG	Threshold value for recharge	0	1	0.129
CKBF (h)	Baseflow time constant	500	5000	3066
TOF	Threshold value for overland flow	0	1	0.478
TIF	Threshold value for interflow	0	1	0.569

The computed Nash Sutcliffe coefficient of efficiency (E) for the calibration and verification runs are 0.67 and 0.74 respectively. The E for the calibration run is slightly lower than the E for the verification run. This may have been because of the missing data between the periods 1996/02/01 and 1996/03/31 which may have affected the model calibration and resulted in a lower E value. However, the high E value for the verification period indicates that reasonably good model parameters were obtained during the calibration. The E values for both the calibration and verification were considered reasonable when compared to those obtained in other studies that used the Mike 11 NAM rainfall-runoff model for runoff simulation.

Shamsudin and Hashim (2002) reported that missing data, on site data acquisition and the nature of rainfall pattern affected calibration of the Mike 11 NAM rainfall runoff modelling for the Layang River, resulting in an E value of 0.75. The current study area is characterized by uneven rainfall distribution and missing data that could have affected the

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E value. They fall within the range 0.66-0.87 obtained by Vaitiekūnienė (2005) during the calibration of the Mike 11 NAM rainfall-runoff model for 66 catchments in the Lithuanian River Basin. In the latter study, the lower E values were due to inadequately distributed precipitation data and errors in the observed discharges.

The computed RMSE for the calibration and the verification runs are 0.96 and 0.92 m^3/s respectively. RMSE values in the ranges 0.067-0.92 and 0.05-1.03 m^3/s have been obtained in studies by Madsen et al. (2002) and Madsen (2003) respectively. Thus, the RMSE values obtained in this study are reasonable as they fall within the ranges obtained in other studies. The computed correlation coefficients (R) for both the calibration and verification runs are 0.82 and 0.86 respectively. Thus, the computed R for the calibration and verification runs are acceptable according to Van Liew et al. (2007) (see sub-section 2.8.2).

The OWBE (in %) for the calibration and verification runs are 9.89 and 9.13 m^3/s respectively. Madsen et al. (2002) indicated that the inherent uncertainties in measuring the catchment average rainfall and the corresponding runoff make it difficult to obtain the perfect water balance. According to Madsen et al. (2002) and Refsgaard and Knudsen (1996), the overall water balance error for both the calibration and verification runs obtained in this study are acceptable (see sub-section 2.8.2).

The computed PBIAS for the calibration and verification runs are -10.45 and -10.09% respectively. PBIAS values ranging from -17.99 to 0.10% have been obtained in a study by Guatam and Holz (2001). This shows that the PBIAS values obtained in the calibration and verification of Mike 11 NAM are comparable to those obtained in other studies though they indicate underestimation of simulated runoff. The PBIAS values are also acceptable as they fall within ±25% recommended by Moriasi et al. (2007). Simulated runoff and observed runoff for both the calibration and verification runs are given in Figs. 4.6 and 4.7 respectively.

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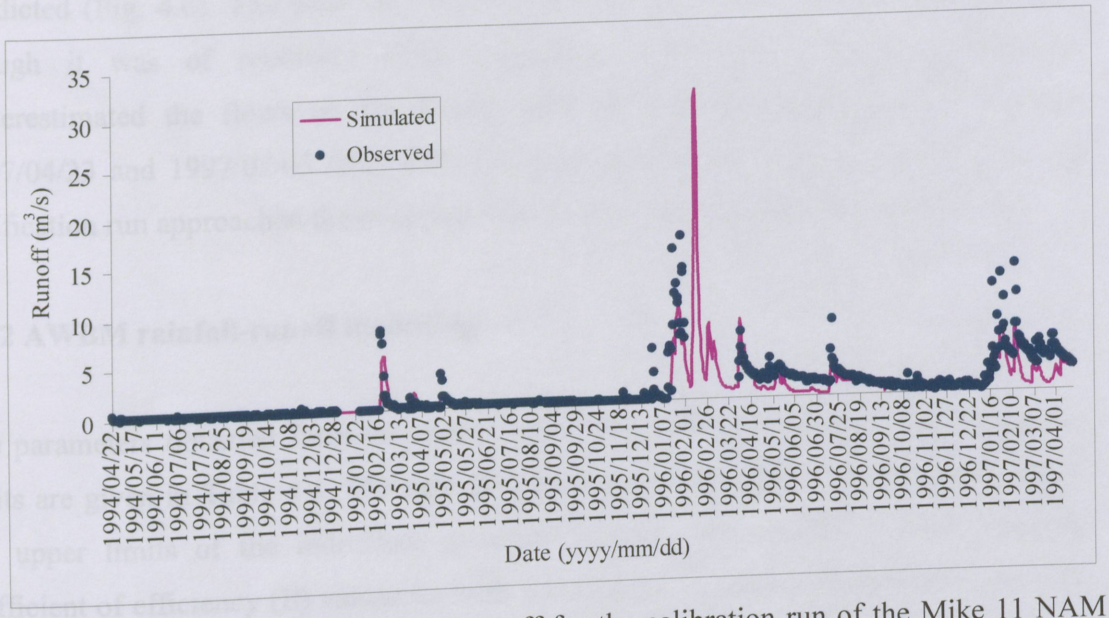


Figure 4.6: Simulated and observed runoff for the calibration run of the Mike 11 NAM RR model

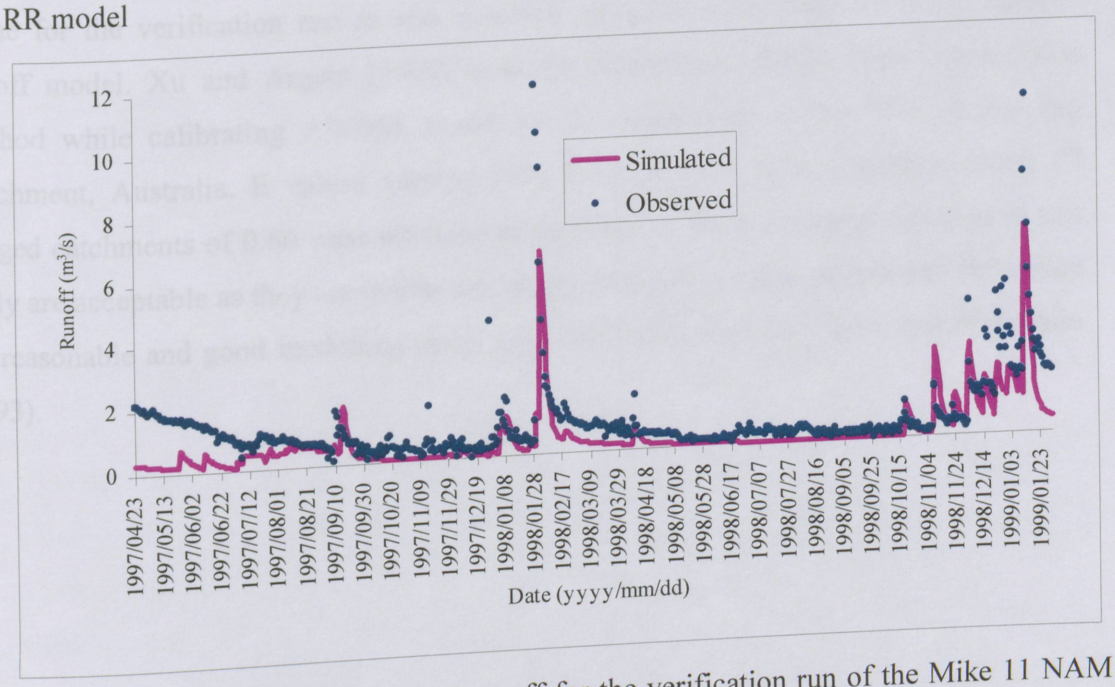


Figure 4.7: Simulated and observed runoff for the verification run of the Mike 11 NAM RR model

The Mike 11 NAM model calibration and verification runs underestimated most of the

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peak flows (Figs. 4.6 and 4.7). Most of the [illegible] for the calibration run were well predicted (Fig. 4.6). The peak flow which occurred on 1998/10/18 was well predicted though it was of relatively small magnitude (Fig. 4.7). The verification run underestimated the flows on the falling limb of a peak flow hydrograph between 1997/04/23 and 1997/07/09 (Fig. 4.7). The estimation of the rest of the low flows on verification run approached the observed values if not slightly underestimated them.

4.4.2 AWBM rainfall-runoff modelling

The parameters obtained from the model calibration, their descriptions and acceptable limits are given in Table 4.4. The modelled parameters fall within the acceptable lower and upper limits of the individual parameter ranges. The computed Nash Sutcliffe coefficient of efficiency (E) values for both the calibration and verification runs are 0.72 and 0.77 respectively. The E value for the calibration run is slightly lower than the E value for the verification run as was similarly obtained with Mike 11 NAM rainfall-runoff model. Xu and Argent (2005) used the Rosenbrock Single Start optimization method while calibrating AWBM model for 37 catchments in the Port Phillip Bay Catchment, Australia. E values varying from 0.16 to 0.85, with a median across 37 gauged catchments of 0.60 were obtained in their study. Thus, E values obtained in this study are acceptable as they are within the ranges obtained in other studies and fall within the reasonable and good modelling range of 0.6-0.8 described by Chiew and McMahon (1993).

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Table 4.4: Parameter values resulting from the calibration of AWBM rainfall-runoff model and default values

Parameter	Description	Lower Limit	Upper Limit	Modelled Value
A_1	Partial area represented by C_1	0	1	0.74
A_2	Partial area represented by C_2	0	1	0.26
BFI	Baseflow Index	0	1	0.67
C_1	Surface storage capacity of A_1	0	50	0.00
C_2	Surface storage capacity of A_2	0	200	126.92
C_3	Surface storage capacity	0	500	119.10
KBase	Baseflow recession constant	0	1	0.96
KSurf	Surface runoff recession constant	0	1	0.84

The computed RMSE for the calibration and verification runs are 1.01 and 1.14 m^3/s respectively. The RMSE values in the ranges of 0.01-2.36 and 0.20-4.50 have been obtained in studies by Bhadra et al. (2008) and Solaimani (2009). This shows that the RMSE values obtained in this study are reasonable as they fall within ranges obtained in other studies. The computed correlation coefficients (R) for both the calibration and verification runs are 0.85 and 0.88 respectively. The R values obtained during AWBM model calibration and verification are acceptable according to Van Liew et al. (2007) (see sub-section 2.8.2).

The OWBE (in %) for the calibration and verification runs are 3.34 and 4.37 respectively. The overall water balance error for both the calibration and verification runs are acceptable according to Madsen et al. (2002) and Refsgaard and Knudsen (1996) (sub-section 2.8.2).

The computed percent bias (PBIAS) for both the calibration and verification runs are -3.94 and -5.36 % respectively. This shows that the PBIAS values obtained in the calibration and verification of AWBM are acceptable as they fall within the acceptable

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values of ±25% according to Moriasi et al. (2007). They, however, indicate underestimation of simulated runoff. The AWBM overestimated most of the small to medium peak flows and underestimated the major peak flows in both the calibration and verification runs (Figs. 4.8 and 4.9). For example, the peak flows which occurred on 1995/03/28, 1995/08/12, 1996/12/22, 1997/09/15, 1997/12/09, 1998/10/20 and 1998/11/10, etc. were overestimated while the peak flows which occurred on 1995/02/20, 1996/01/24, 1996/07/17, 1998/12/15 and 1999/01/12 were underestimated. The model generally predicted the low flows correctly in the calibration and verification runs except for the flows on the falling limb of the peak hydrograph between April and early September 1997 which were underestimated (Figs. 4.8 and 4.9).

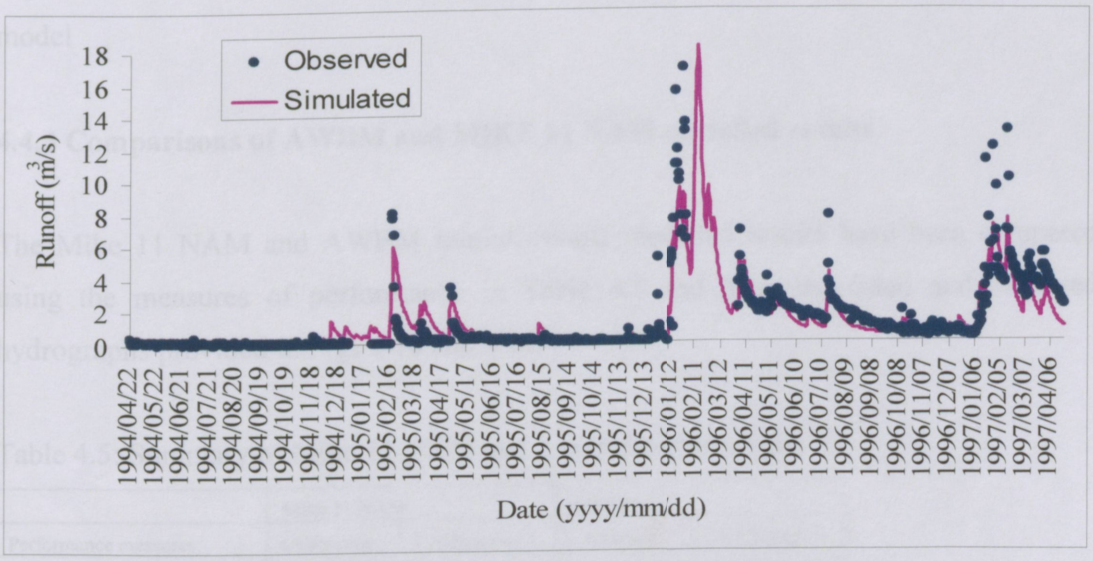


Figure 4.8: Simulated and observed runoff for the calibration run of the AWBM RR model

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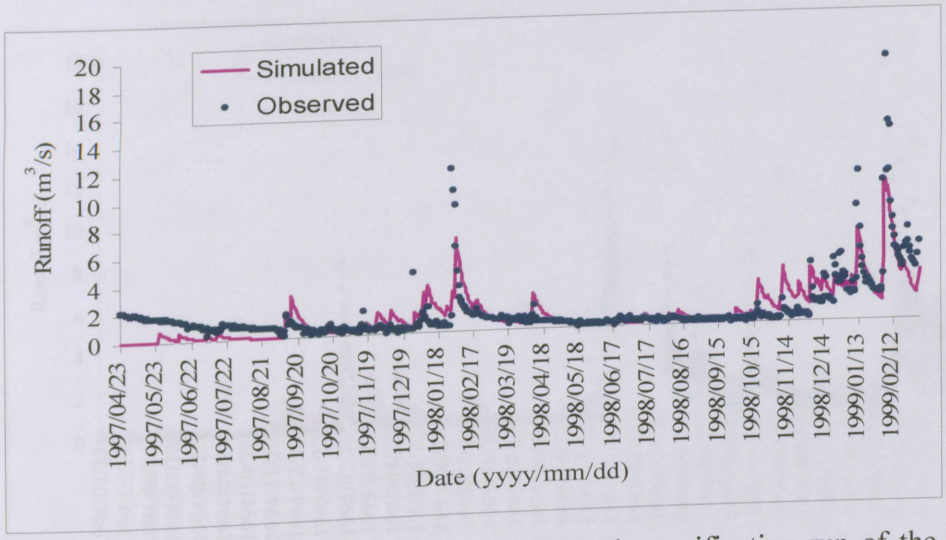


Figure 4.9: Simulated and observed runoff for the verification run of the AWBM RR model

4.4.3 Comparisons of AWBM and MIKE 11 NAM modelled results

The Mike 11 NAM and AWBM rainfall-runoff modelled results have been compared using the measures of performance in Table 4.5 and their simulated and observed hydrographs provided in Figs 4.10 and 4.11.

Table 4.5: Summary of Mike 11 NAM and AWBM performances

	Mike 11 NAM		AWBM	
Performance measures	Calibration	Verification	Calibration	Verification
Nash Sutcliffe coefficient of efficiency	0.67	0.74	0.72	0.77
RMSE (m^3/s)	0.96	0.92	1.01	1.14
Overall water balance error (%)	9.89	9.13	3.34	4.37
Correlation coefficient	0.82	0.86	0.85	0.88
PBIAS (%)	-10.45	-10.09	-3.94	-5.36

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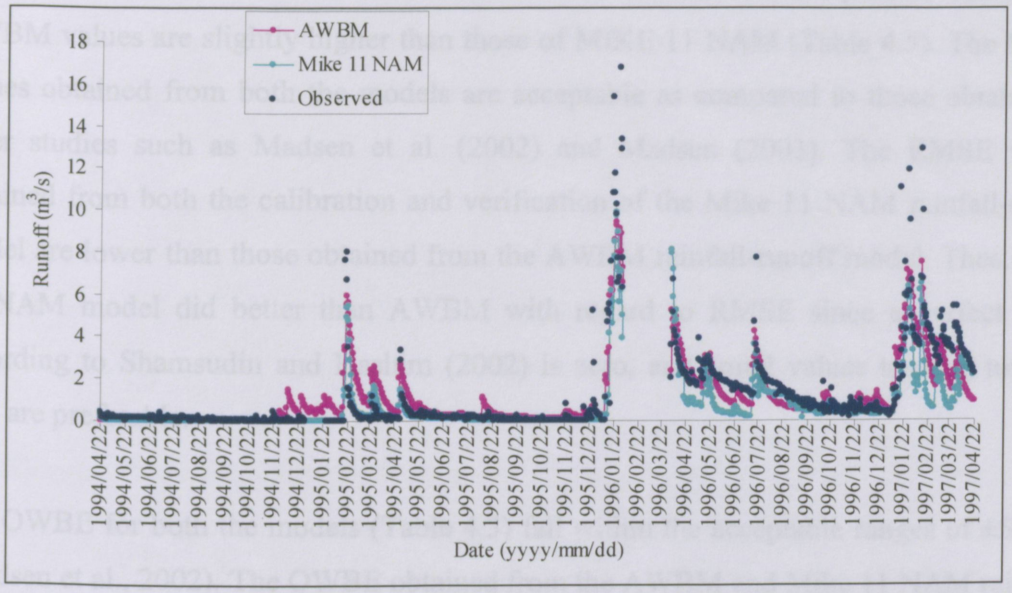


Figure 4.10: Comparisons of the Mike 11 NAM, AWBM and observed runoff hydrographs for the calibration run

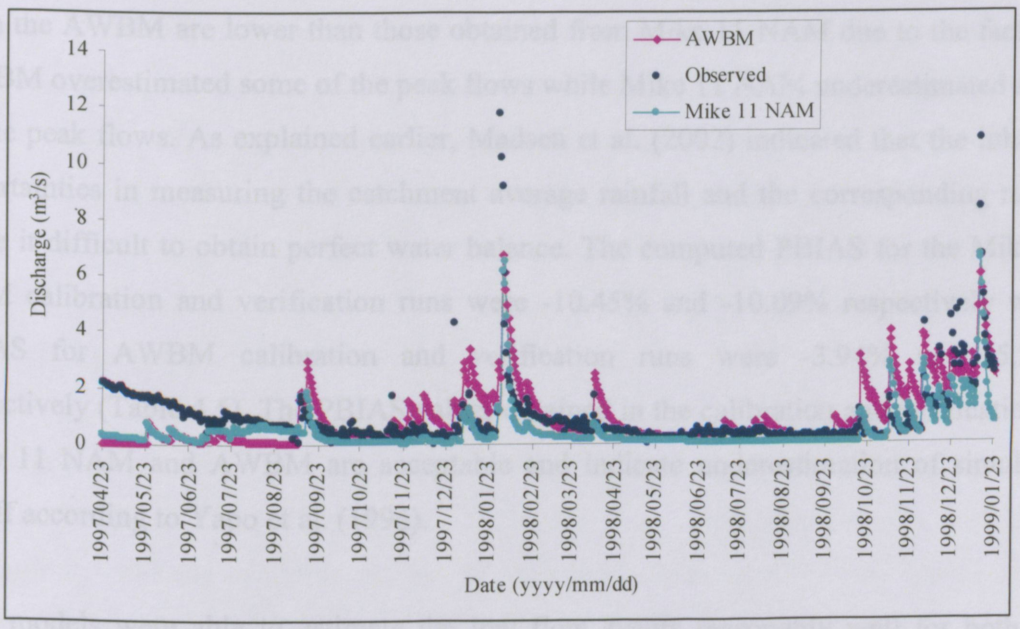


Figure 4.11: Comparisons of the Mike 11 NAM, AWBM and observed runoff hydrographs for the verification run

The E values for the calibration and verification runs for both the models are greater than

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0.6 and suggest a reasonable modelling of runoff according to Chiew and McMahon (1993). The E values for the two rainfall-runoff models are comparable though the AWBM values are slightly higher than those of MIKE 11 NAM (Table 4.5). The RMSE values obtained from both the models are acceptable as compared to those obtained in other studies such as Madsen et al. (2002) and Madsen (2003). The RMSE values obtained from both the calibration and verification of the Mike 11 NAM rainfall-runoff model are lower than those obtained from the AWBM rainfall-runoff model. Thus, Mike 11 NAM model did better than AWBM with regard to RMSE since a perfect value according to Shamsudin and Hashim (2002) is zero, and small values tending towards zero are preferable.

The OWBE for both the models (Table 4.5) fall within the acceptable ranges of ±5-10% (Madsen et al., 2002). The OWBE obtained from the AWBM and Mike 11 NAM rainfall-runoff models suggest that the models underestimated the simulated runoff since the results indicate that Q_{obs} is greater than Q_{sim} from Eq. 3.7. However, the OWBE obtained from the AWBM are lower than those obtained from Mike 11 NAM due to the fact that AWBM overestimated some of the peak flows while Mike 11 NAM underestimated some of the peak flows. As explained earlier, Madsen et al. (2002) indicated that the inherent uncertainties in measuring the catchment average rainfall and the corresponding runoff make it difficult to obtain perfect water balance. The computed PBIAS for the Mike 11 NAM calibration and verification runs were -10.45% and -10.09% respectively while PBIAS for AWBM calibration and verification runs were -3.94% and -5.36% respectively (Table 4.5). The PBIAS values obtained in the calibration and verification of Mike 11 NAM and AWBM are acceptable and indicate underestimation of simulated runoff according to Yapo et al. (1996).

Both models were able to estimate the low flow events reasonably well for both the calibration and the verification runs, except in a few cases where they underestimated the low flows (Figs. 4.10 and 4.11). Good and reasonable model performances (i.e. RMSE, E, R, PBIAS and OWBE) were obtained during calibration and verification of both the

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Mike 11 NAM and AWBM rainfall-runoff models. This indicates that reasonably good model parameters were obtained during the model calibration. Thus, the parameter sets obtained in calibration can be transferred to another sub-quaternary catchment with similar hydrological conditions for use in rainfall-runoff modelling. The results in Table 4.5 and Figs. 4.10 and 4.11 show that the AWBM and Mike 11 NAM rainfall-runoff models have generally comparable performances in the Mutshedzi SQC though the AWBM performed relatively better than the Mike 11 NAM. It was therefore decided to simulate the runoff hydrograph for the ungauged Nzhelele River SQC, which is within the same quaternary catchment, using both the models. The results were then compared.

4.5 Simulated streamflow hydrographs for the ungauged Nzhelele River sub-quaternary catchment at Siloam Village

Long term daily runoff for a period of at least 30 years that adequately captures the hydrological behaviour of the study area was required for yield analysis. Due to non-availability of long term observed evaporation data, a number of temperature based methods such as the Hamon and Blaney Criddle methods were tested to determine which one gives good estimates of daily evaporation. The comparisons of estimated evaporation using Hargreaves method and observed evaporation were found to give more reliable results as compared to the other methods. Fig. 4.12 shows the comparison of the estimated and observed evaporation between the period 1991/07/01 and 2000/12/31 when observed data was available.

The Hargreaves method was therefore used to estimate evaporation for a 50 year period (1950/01/01-2000/07/31). This was due to the fact that the temperature data used in the estimations was only available for the 50 year period mentioned above. The estimated evaporation are shown in Figs. 4.13 and 4.14.

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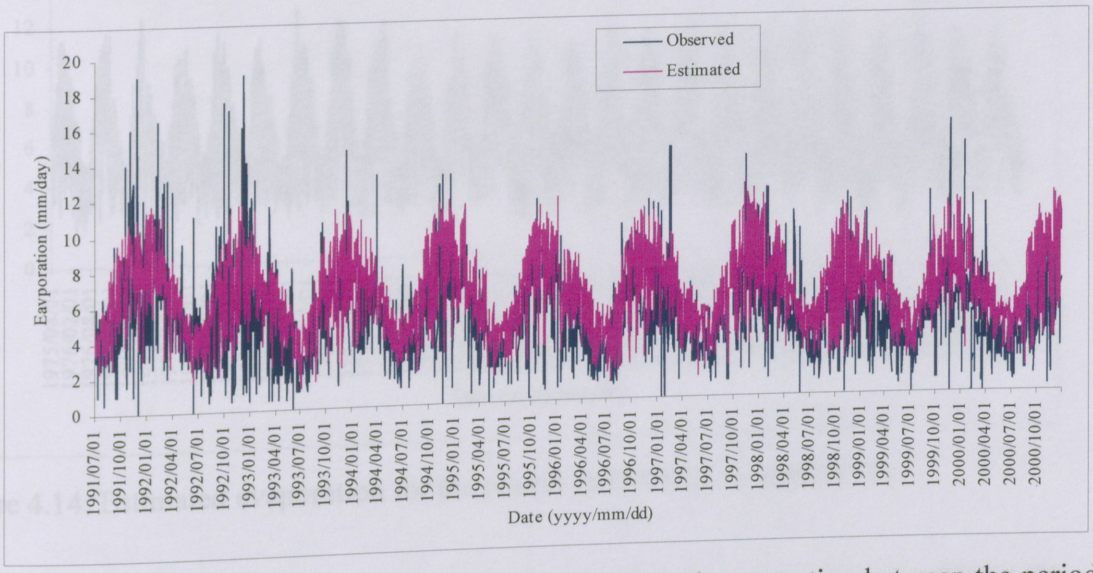


Figure 4.12: Comparisons of the estimated and observed evaporation between the period 1991/07/01 and 2000/12/31

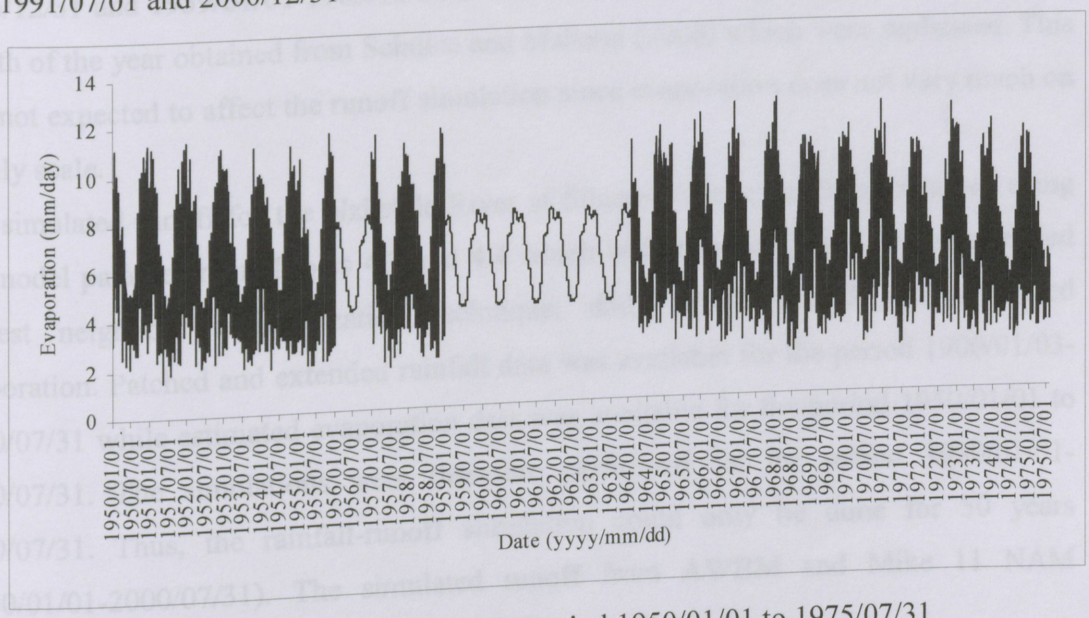


Figure 4.13: Estimated evaporation for the period 1950/01/01 to 1975/07/31

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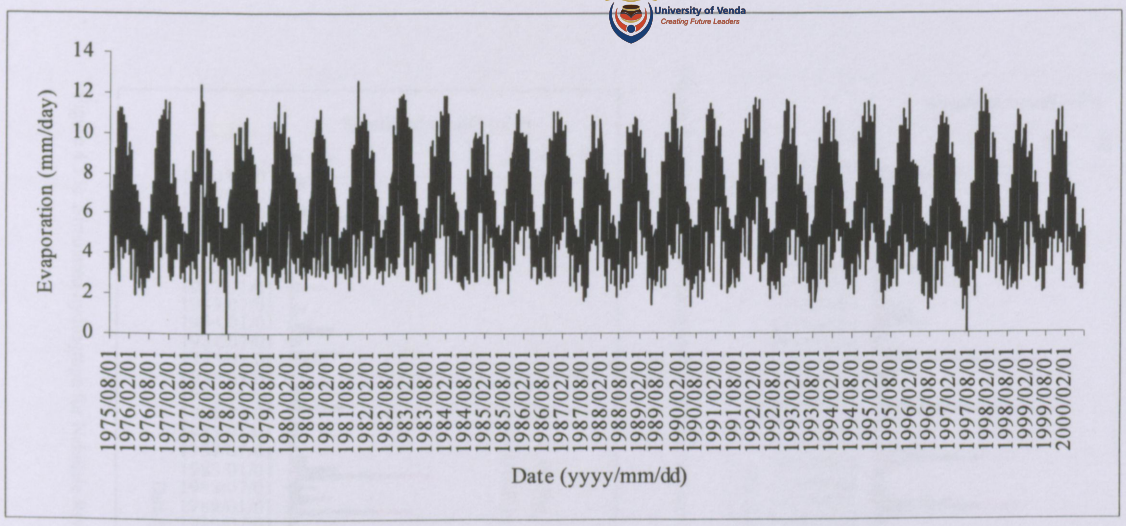


Figure 4.14: Estimated evaporation for the period 1975/08/01 to 2000/07/31

The behaviour of the evaporation time series (Fig. 4.13) between the periods 1956/01/01-1956/12/31 and 1959/01/01-1963/12/31 is due to the constant daily temperatures of each month of the year obtained from Schulze and Maharaj (2003) which were replicated. This was not expected to affect the runoff simulation since evaporation does not vary much on a daily scale.

The simulated runoff for the Nzhelele River at Siloam Village has been obtained using the model parameters in Tables 4.3 and 4.4 which were adopted based on the modified nearest neighbour regionalization technique, daily areal rainfall and estimated evaporation. Patched and extended rainfall data was available for the period 1900/01/03-2000/07/31 while estimated evaporation data was available for the period 1950/01/01 to 2000/07/31. The simulations were therefore performed for the period 1950/01/01-2000/07/31. Thus, the rainfall-runoff simulation could only be done for 50 years (1950/01/01-2000/07/31). The simulated runoff from AWBM and Mike 11 NAM rainfall-runoff models are provided in Fig. 4.15a-c.

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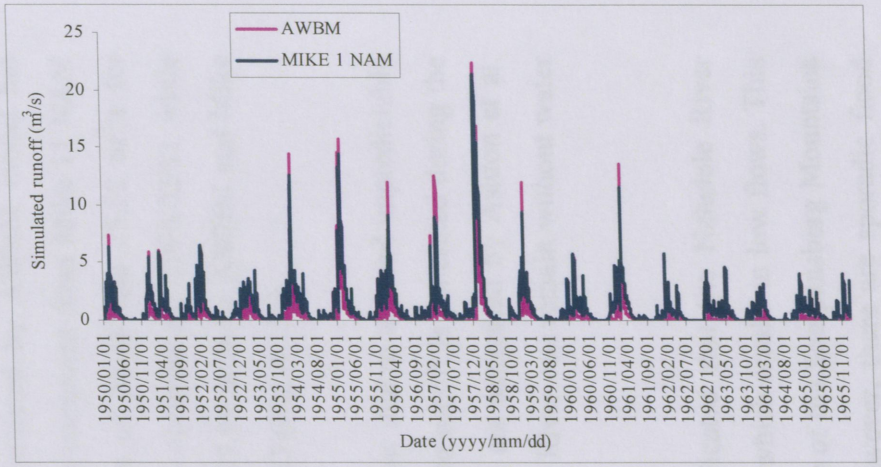


Figure 4.15a: Simulated hydrograph for Nzhelele River at Siloam Village for the period 1950/01/01-1965/12/31

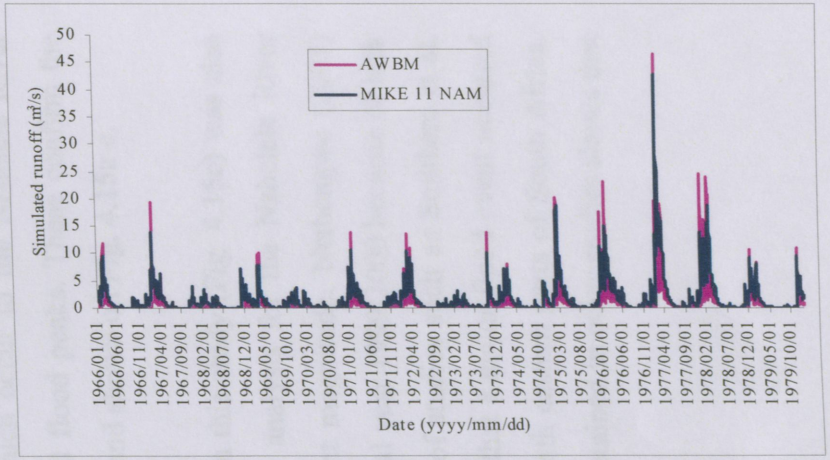


Figure 4.15b: Simulated hydrograph for Nzhelele River at Siloam Village for the period 1966/01/01-1979/12/31

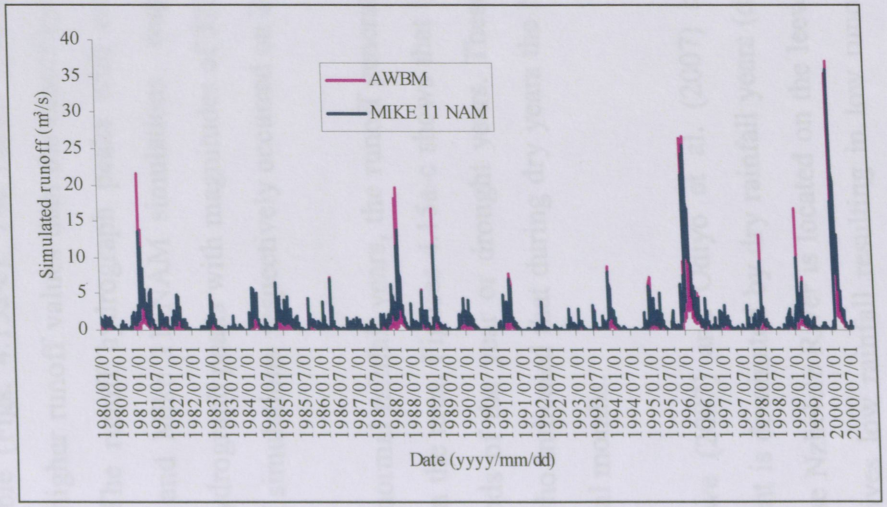


Figure 4.15c: Simulated hydrograph for Nzhelele River at Siloam Village for the period 1980/01/01-2000/07/31

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The runoff hydrographs simulated by both the AWBM and Mike 11 NAM models are comparable (Figs. 4.15a-c). The runoff hydrograph simulated by AWBM model has slightly higher runoff values than the runoff hydrograph computed from Mike 11 NAM model. The runoff hydrograph peaks with magnitudes of 26.13 and 25.52 m^3/s for AWBM and Mike 11 NAM simulations respectively occurred on 1996/02/11 while runoff hydrograph peaks with magnitudes of 37.07 and 35.99 m^3/s for AWBM and Mike 11 NAM simulations respectively occurred on 2000/02/23 (Fig. 4.15c).

During normal rainfall years, the runoff generation is low due to low and unpredictable rainfall in the area. Figures 4.15a-c shows that little or no runoff is generated during the dry periods of the year or drought years. These results are supported by Ashton et al. (2001) who indicated that during dry years the Nzhelele River can remain without water for several months.

Nethengwe (2007) and Odiyo et al. (2007) have indicated that the Nzhelele River Catchment is dominated by dry rainfall years (drought) which results in low flows. This is because Nzhelele River is located on the leeward side of the Soutpansberg Mountains and receives low rainfall resulting in low runoff. However, there are sporadic flood events with return periods greater than 1:15 years which occur in the Nzhelele River (Nethengwe, 2007). These contribute to the occasional flood peaks. These confirm the dominance of low flows and sporadic floods simulated and shown on Fig. 4.15a-c.

The 1995/96 hydrological year flood event predicted in this study (Fig. 4.15c) was also predicted by Nethengwe (2007) on performing flood analysis for the Nzhelele River downstream of the Nzhelele Dam, though of different magnitude. Nethengwe (2007) could not perform the flood analysis for the hydrological year 1999/2000 because of lack of streamflow data for that year. However, a number of studies such as Smithers et al. (2001) and Odiyo and Maluleke (2005) have reported that a major flood event occurred in February 2000 in the Limpopo Province and the north eastern parts of South Africa. The coincidence of the major flood peaks with those obtained in other studies shows that

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the AWBM and Mike 11 NAM models were able to simulate the runoff hydrograph for Nzhelele River at Siloam Village well.

Figures 4.16a-c and 4.17a-c show the correlation of the simulated runoff and the areal rainfall hydrographs for the Nzhelele River SQC for the period 1950/01/01 to 2000/07/31. The graphs show that the major peak rainfall events are well correlated with the major peak runoff events. This verifies the runoff simulated by the AWBM and Mike 11 NAM models for Nzhelele River at Siloam Village.

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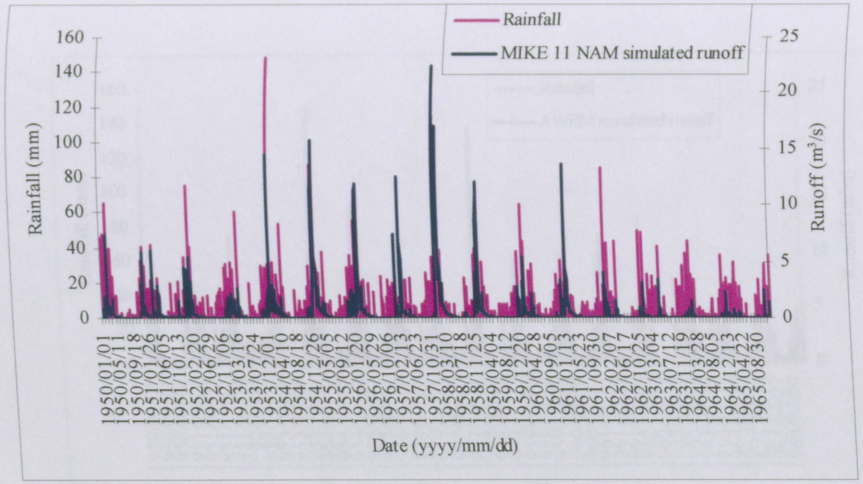


Figure 4.16a: Correlation of the simulated runoff (Mike 11 NAM) and the areal rainfall for the Nzhelele River SQC for the period 1950/01/01-1965/12/31

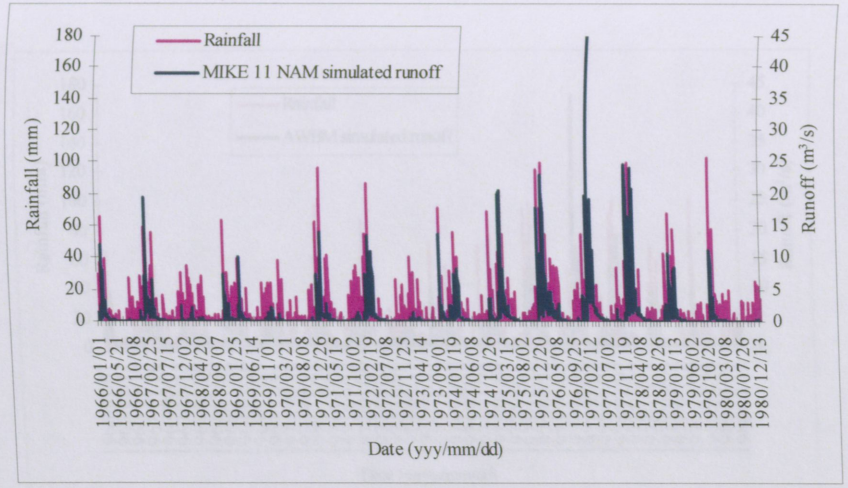


Figure 4.16b: Correlation of the simulated runoff (Mike 11 NAM) and the areal rainfall for the Nzhelele River SQC for the period 1966/01/01-1980/12/31

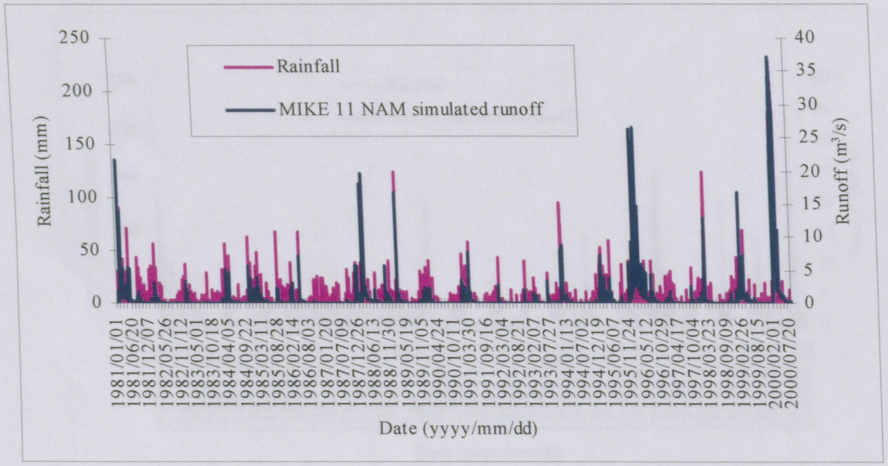


Figure 4.16b: Correlation of the simulated runoff (Mike 11 NAM) and the areal rainfall for the Nzhelele River SQC for the period 1981/01/01-2000/07/31

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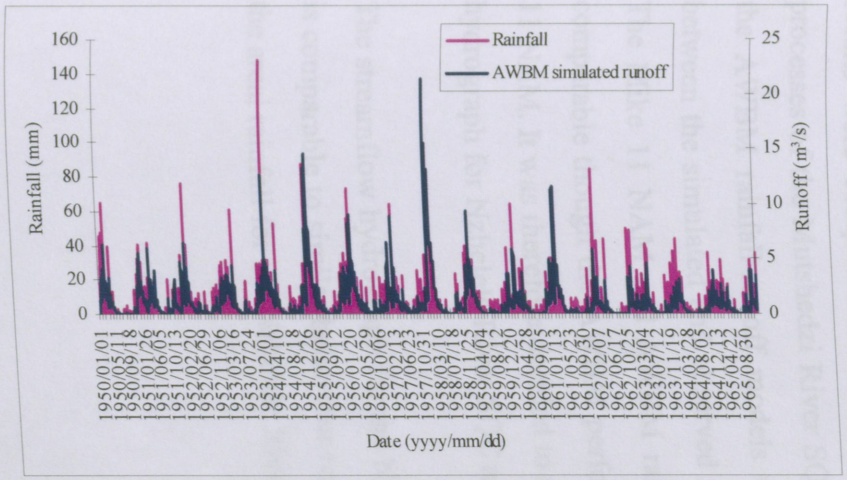


Figure 4.17a: Correlation of the simulated runoff (AWBM) and the areal rainfall for the Nzhelele River SQC for the period 1950/01/01-1965/12/31

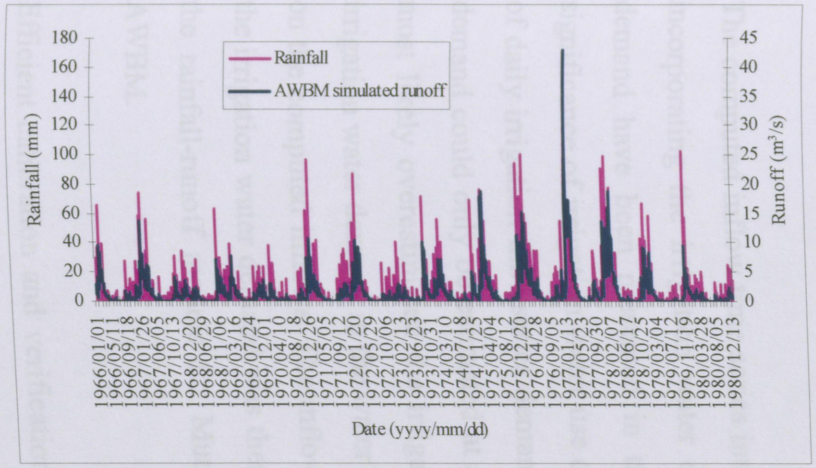


Figure 4.17b: Correlation of the simulated runoff (AWBM) and the areal rainfall for the Nzhelele River SQC for the period 1950/01/01-1965/12/31

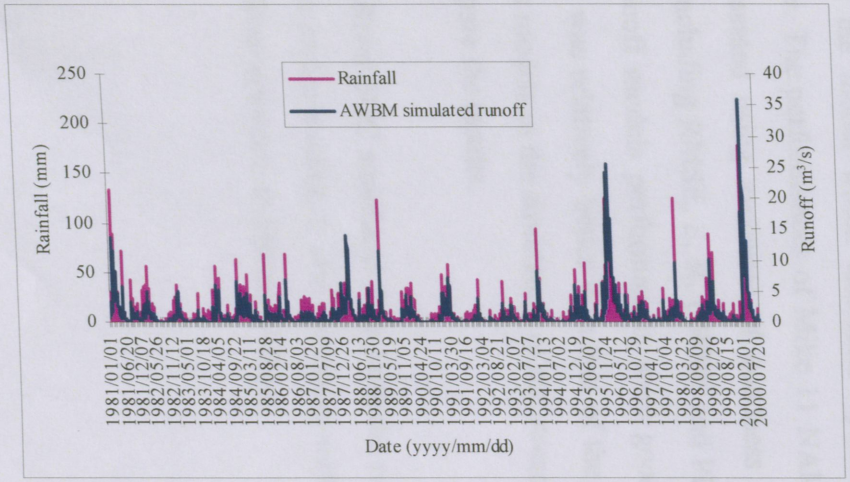


Figure 4.17c: Correlation of the simulated runoff (Mike 11 NAM) and the areal rainfall for the Nzhelele River SQC for the period 1981/01/01-2000/07/31

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4.4. Summary

The computed inflow time series into the Mutshedzi Dam using the water balance while incorporating the irrigation water demand and not incorporating the irrigation water demand have been presented in this chapter. This has been done to establish the significance of irrigation water use on the computed inflows and to justify the exclusion of daily irrigation time series demand from the water balance, since the irrigation water demand could only be estimated at a very coarse scale. Despite applying a method that most likely overestimated the irrigation water demand, the inclusion of the computed irrigation water demand in the water balance equation was found to have negligible effect on the computed inflows. The inflow time series computed without the incorporation of the irrigation water demand was therefore adopted for the calibration and verification of the rainfall-runoff models for Mutshedzi River SQC using the Mike 11 NAM and AWBM.

Efficient calibration and verification was achieved using both models. The two model results were compared in order to deduce the model which simulates hydrological processes of the Mutshedzi River SQC better. The performances of Mike 11 NAM and the AWBM rainfall-runoff models were assessed using measures of goodness of fit between the simulated and observed runoff including RMSE, E, R, OWBE and PBIAS. The Mike 11 NAM and AWBM rainfall-runoff models performances were good and comparable though the AWBM performance was relatively better than that of the Mike 11 NAM. It was therefore decided to use both models in the simulation of the streamflow hydrograph for Nzhelele River SQC and compare the results.

The streamflow hydrograph for the Nzhelele River SQC simulated from both the models is comparable to similar behaviour reported in earlier studies. It also correlates well with the areal rainfall for the Nzhelele River SQC from upstream to Siloam Village.

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5.1 Preamble

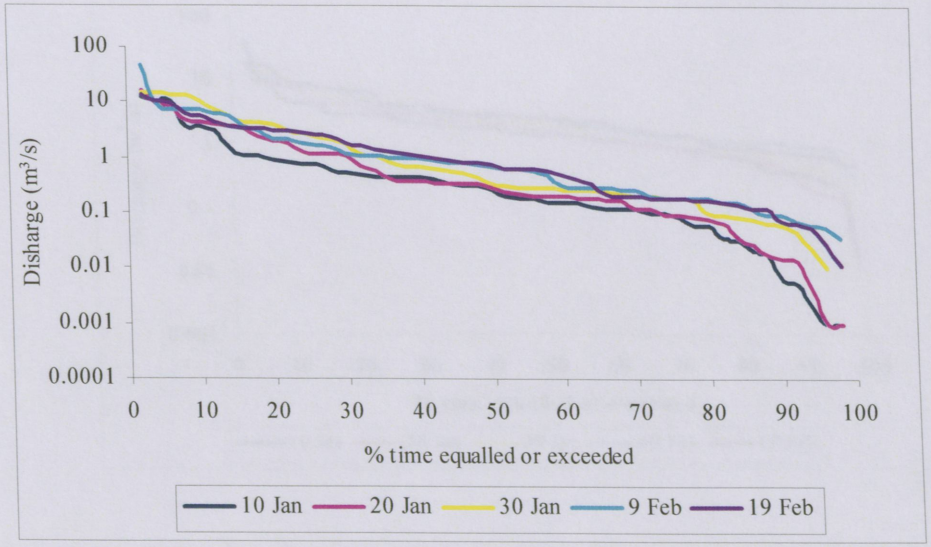
This chapter is aimed at assessing the availability and suitability of Nzhelele River water for domestic and environmental uses. The chapter presents the results of the unregulated river yield analysis for Nzhelele River SQC, the water requirements and the reconciliation with the available water. Assessment of the river water quality has been done to determine its suitability for domestic and environmental uses.

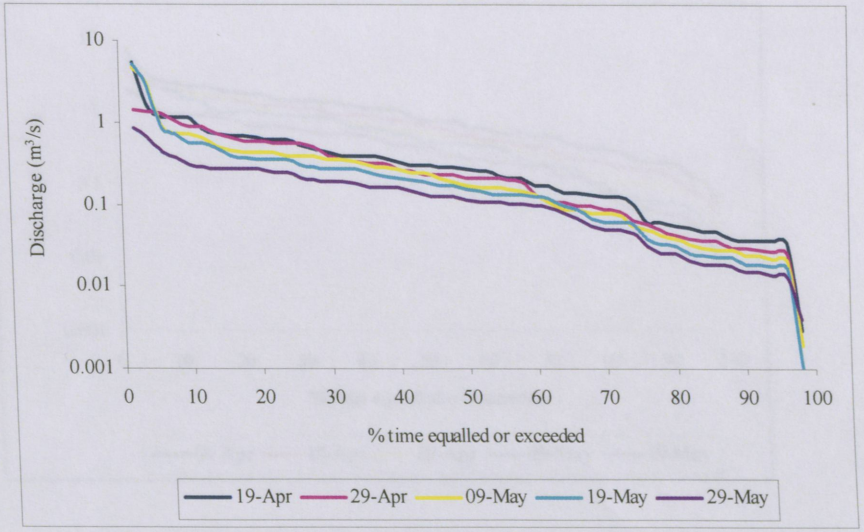
5.2 Unregulated river yield analysis for Nzhelele River sub-quaternary catchment

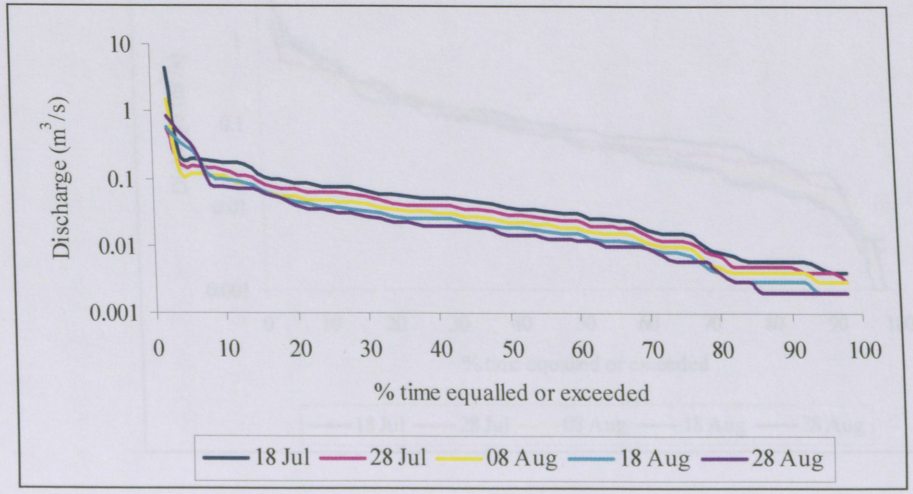
The one day FDCs for selected days that represent the wet and dry seasons of the year have been presented to show examples of the daily flow behaviour in Nzhelele River at Siloam Village (Figs. 5.1 and 5.2). The FDCs were constructed from the daily runoff for the period 1950/01/01-2000/07/31 simulated using Mike 11 NAM and AWBM. It was not possible to present the results of all the constructed 366 FDCs due to the length of the data used in the analysis. The FDCs have been plotted in a log-linear scale to obtain a clear view especially during periods of low flows.

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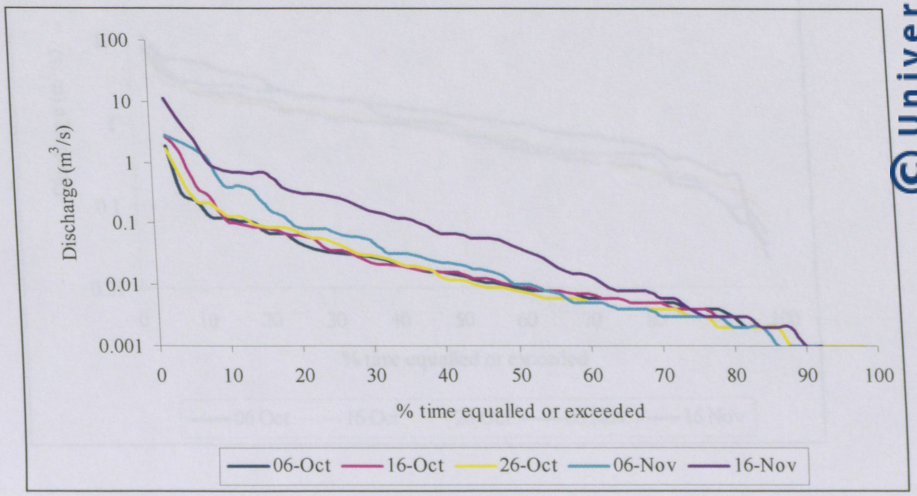
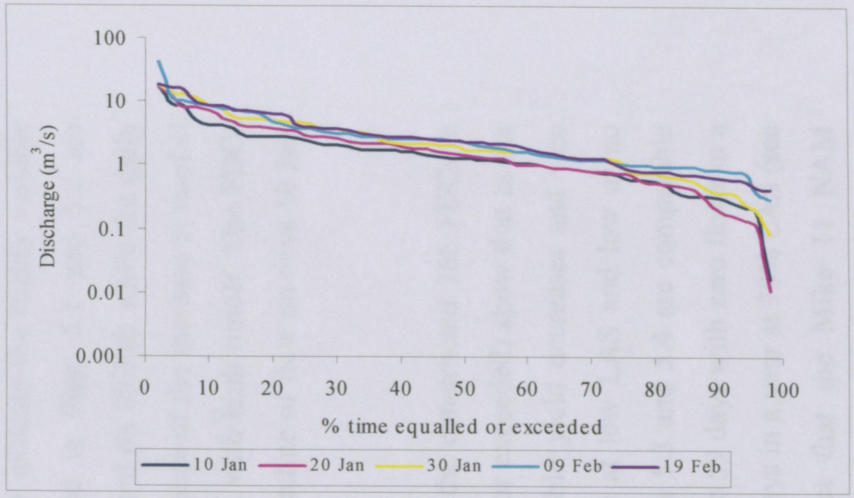
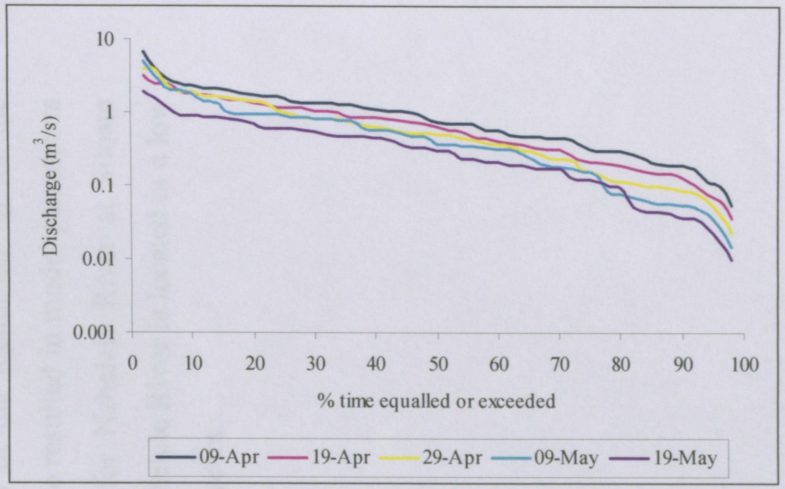
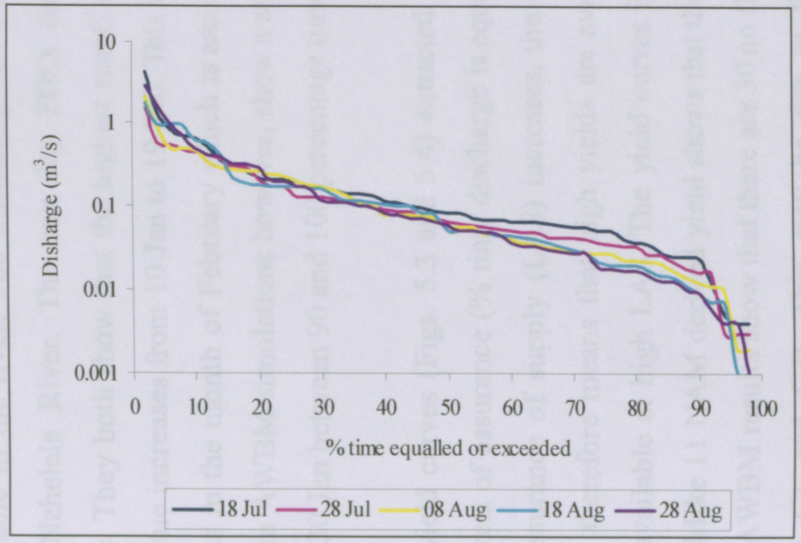


Figure 5.1: One day FDCs for Nzhelele River at Siloam Village (from Mike 11 NAM simulated runoff)

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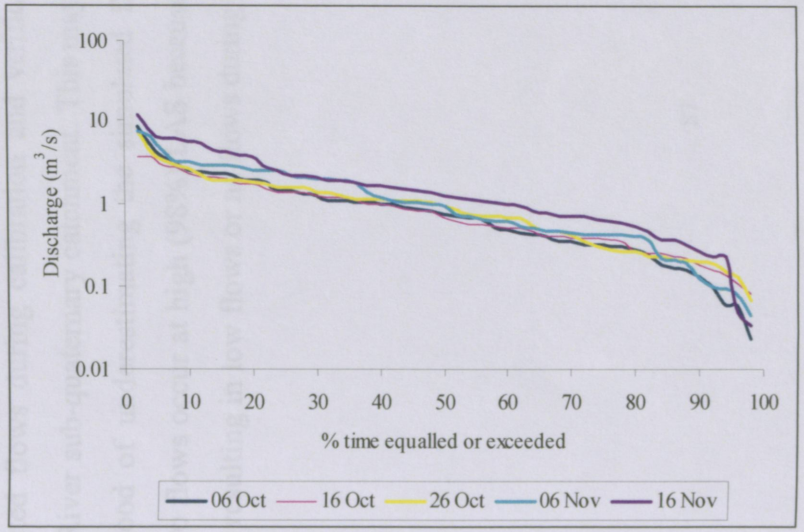


Figure 5.2: One day FDCs for Nzhelele River at Siloam Village (from AWBM simulated runoff)

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The FDC gives the amount of water (yield) that is available at different percentage times (levels of assurance). The variations in the FDCs display the variations in the amount of water available in the river. The fluctuating FDCs clearly indicate the highly variable nature of Nzhelele River. The one day FDCs displayed in Figs. 5.1 and 5.2 are comparable. They both show that the highest runoff occurred on 09 Feb while the daily runoff volume increases from 10 Jan to 19 Feb. This is because of the increase in rainfall which peaks in the month of February which is associated with high runoff. The FDCs derived from AWBM simulations however, show a steep decline of flow on days 10 Jan, 20 Jan and 30 Jan between 90 and 100 percentage times.

The daily yield curves (Figs. 5.3 and 5.4) extracted from the constructed 366 FDCs at relevant levels of assurance (% time discharge is equalled or exceeded) show that as the levels of assurance of supply (LAS) increases, the available yield decreases and vice versa. This therefore means that high yields are available at low LAS and low or no yields are available at high LAS. The yield curves in Figs 5.3 and 5.4 are comparable though the Mike 11 NAM derived yield shows that there are 59 days with zero flows in a year while AWBM results show that there are 30 no flow days in a year at 98% LAS (see Appendices C1 and C2). This may be due to the fact that the Mike 11 NAM underestimated flows during calibration and verification of the model set up for the Mutshedzi River sub-quaternary catchment. This may have resulted in model parameters with likelihood of underestimating the simulated flow for Nzhelele River at Siloam Village. Zero flows occur at high (98%) LAS because Nzhelele River is located in a low rainfall area resulting in low flows or no flows during dry years.

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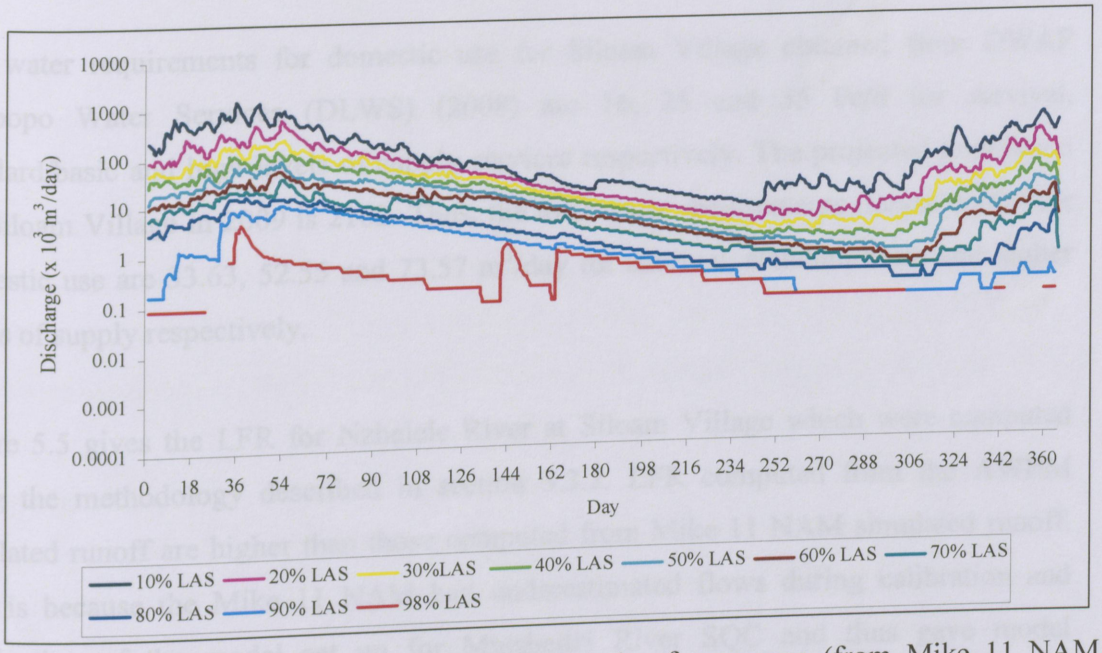


Figure 5.3: Daily yield curves at different levels of assurance (from Mike 11 NAM simulations)

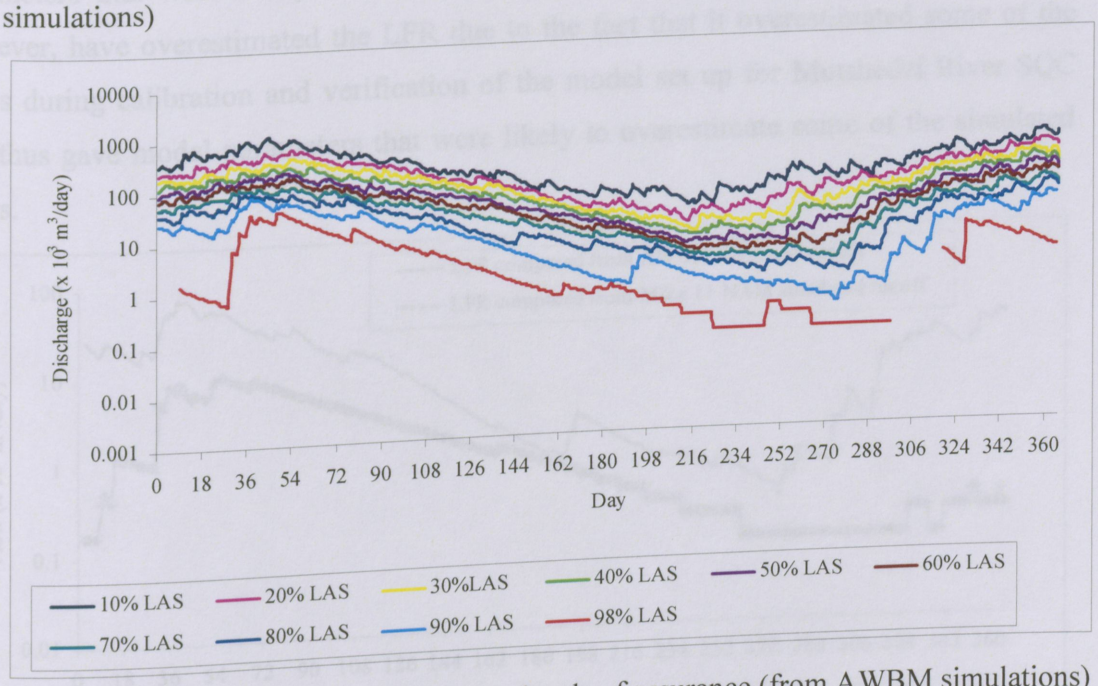


Figure 5.4: Daily yield curves at different levels of assurance (from AWBM simulations)

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5.3 Water requirements for domestic and environmental purposes

The water requirements for domestic use for Siloam Village obtained from DWAF Limpopo Water Services (DLWS) (2008) are 16, 25 and 35 l/c/d for survival, standard/basic and high levels of supply services respectively. The projected population for Siloam Village in 2009 is 2102. Thus, the total water requirements (target drafts) for domestic use are 33.63, 52.55 and 73.57 m^3/day for survival, standard/basic and higher levels of supply respectively.

Figure 5.5 gives the LFR for Nzhelele River at Siloam Village which were computed using the methodology described in section 3.3.2. LFR computed from the AWBM simulated runoff are higher than those computed from Mike 11 NAM simulated runoff. This is because the Mike 11 NAM had underestimated flows during calibration and verification of the model set up for Mutshedzi River SQC and thus gave model parameters that were likely to underestimate the simulated flows. The AWBM may however, have overestimated the LFR due to the fact that it overestimated some of the flows during calibration and verification of the model set up for Mutshedzi River SQC and thus gave model parameters that were likely to overestimate some of the simulated flows.

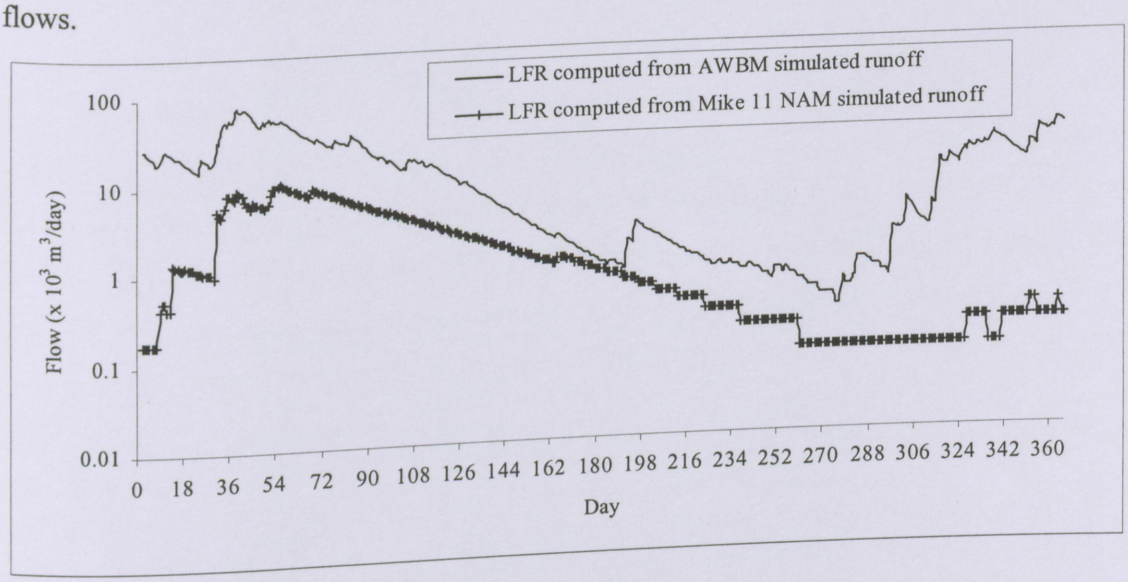


Figure 5.5: LFR for Nzhelele River at Siloam Village

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5.4 Reconciliation of the available water and the water requirements

Figure 5.6 shows the reconciliation of the available yield from AWBM simulated runoff with the domestic water requirements for survival (DS), standard/basic (DB) and high (DH) levels of supply services respectively, the LFR and the total water requirements (TWR). Similarly, Fig. 5.7 shows the reconciliation of the available yield from MIKE 11 NAM simulated runoff with the DS, DB and DH levels of supply services respectively, the LFR and the TWR. From Figs. 5.6 and 5.7, TWR1, TWR2 and TWR3 represent the total water requirements for DS and LFR, DB and LFR, and DH and LFR respectively.

Though the yields were estimated from AWBM and Mike 11 NAM simulated runoff, the figures show similar behaviour and supply conditions. It is important to note that the LFR and TWR values are different for the simulations from the two models. Figures 5.6 and 5.7 show that the TWR can be met at approximately 90% (1:10) LAS for all the levels of supply services. This is due to the fact that the current domestic water requirements are very low due to the current supply arrangements that have conditioned the community to low water use. This makes LFR more significant than domestic water requirements and explains the near collapse of the LFR and TWR curves on top of each other.

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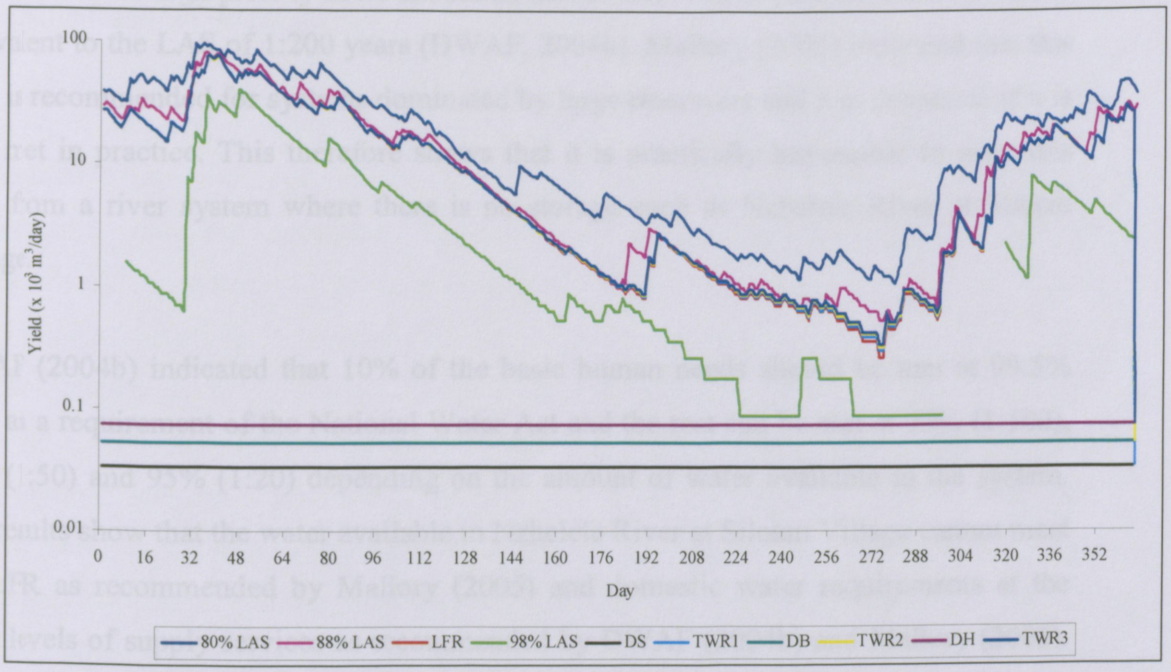


Figure 5.6: Available yield from AWBM simulated runoff compared with the domestic water supply at DS, DB and DH levels; the LFR and TWR

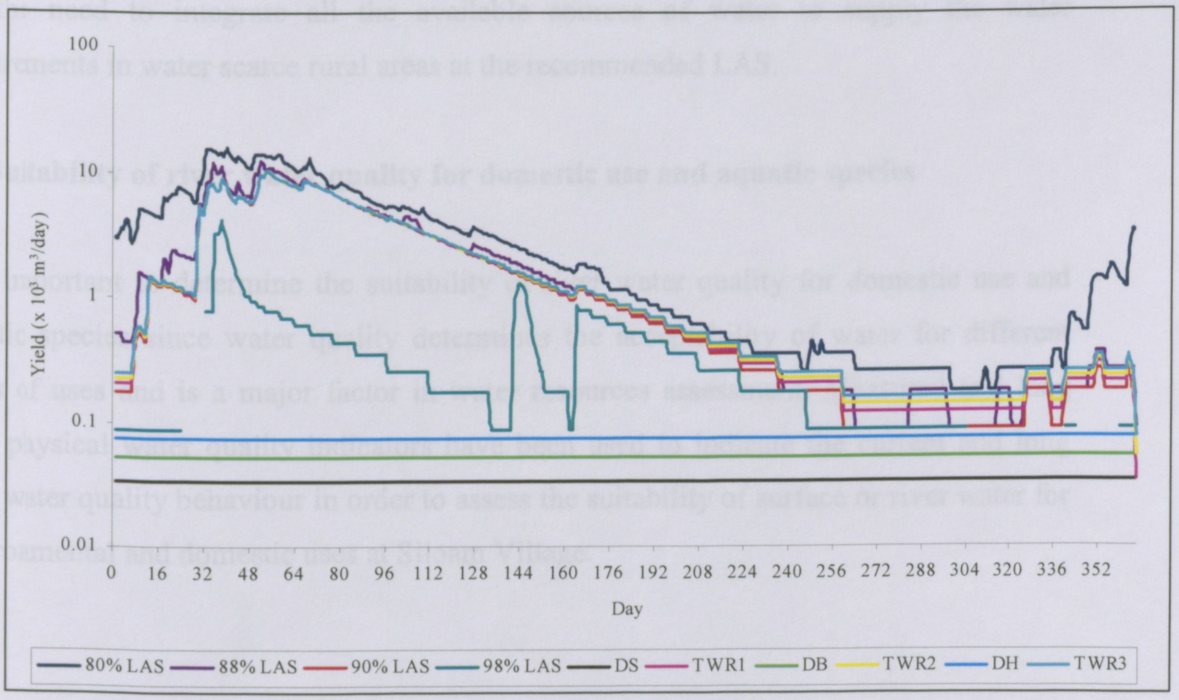


Figure 5.7: Available yield form MIKE 11 NAM simulated runoff compared with the domestic water supply at DS, DB and DH levels; the LFR and the TWR.

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The environment and the domestic water users are high priority users. The water requirements for high priority users should be met at 99.5% LAS (Mallory, 2005). This is equivalent to the LAS of 1:200 years (DWAF, 2004b). Mallory (2005) indicated that this LAS is recommended for systems dominated by large reservoirs and it is debatable if it is ever met in practice. This therefore shows that it is practically impossible to meet this LAS from a river system where there is no storage such as Nzhelele River at Siloam Village.

DWAF (2004b) indicated that 10% of the basic human needs should be met at 99.5% LAS as a requirement of the National Water Act and the rest can be met at 99% (1:100), 98% (1:50) and 95% (1:20) depending on the amount of water available in the system. The results show that the water available in Nzhelele River at Siloam Village cannot meet the LFR as recommended by Mallory (2005) and domestic water requirements at the three levels of supply services as recommended by DWAF (2004b) and Mallory (2005). Thus, if the domestic water requirements are to be met at these LAS, then other sources of supply would be required to supplement the domestic water requirements. This argues for the need to integrate all the available sources of water to supply the water requirements in water scarce rural areas at the recommended LAS.

5.5 Suitability of river water quality for domestic use and aquatic species

It is important to determine the suitability of river water quality for domestic use and aquatic species since water quality determines the acceptability of water for different types of uses and is a major factor in water resources assessment. Measured and long term physical water quality indicators have been used to indicate the current and long term water quality behaviour in order to assess the suitability of surface or river water for environmental and domestic uses at Siloam Village.

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5.5.1 Measured water quality

Figures 5.8-5.10 give the comparisons of the water quality indicators (pH, EC and turbidity) for two sites on Nzhelele River at Siloam Village with the DWAF standards for domestic water use and aquatic ecosystems. The comparison was done to establish the suitability of Nzhelele River water at Siloam Village for each of the water uses. Figure 5.8 shows the pH fluctuations in both the summer and the winter seasons. The pH values for Nzhelele River at Siloam Village for the periods August 2006 to March 2007 varies from 6.7-7.96 for both site 1 (S1) and site 2 (S2) (Fig. 5.8). These values were within the recommended DWAF standards of 6-9 (DWAF, 1996a) and 6.5-8.5 (DWAF, 1996b) for the domestic water use and aquatic ecosystem respectively. These pH values suggest that metals such as aluminium, cadmium, iron, copper, mercury, manganese, lead and zinc were either not present or were present at very low concentrations and were therefore unlikely to have detrimental effects on human health and aquatic ecosystems. This has been confirmed in a study by Ramudzuli (2009) which indicated that the above mentioned metals were within the recommended DWAF (1996a and 1996b) standards for domestic use and aquatic ecosystems.

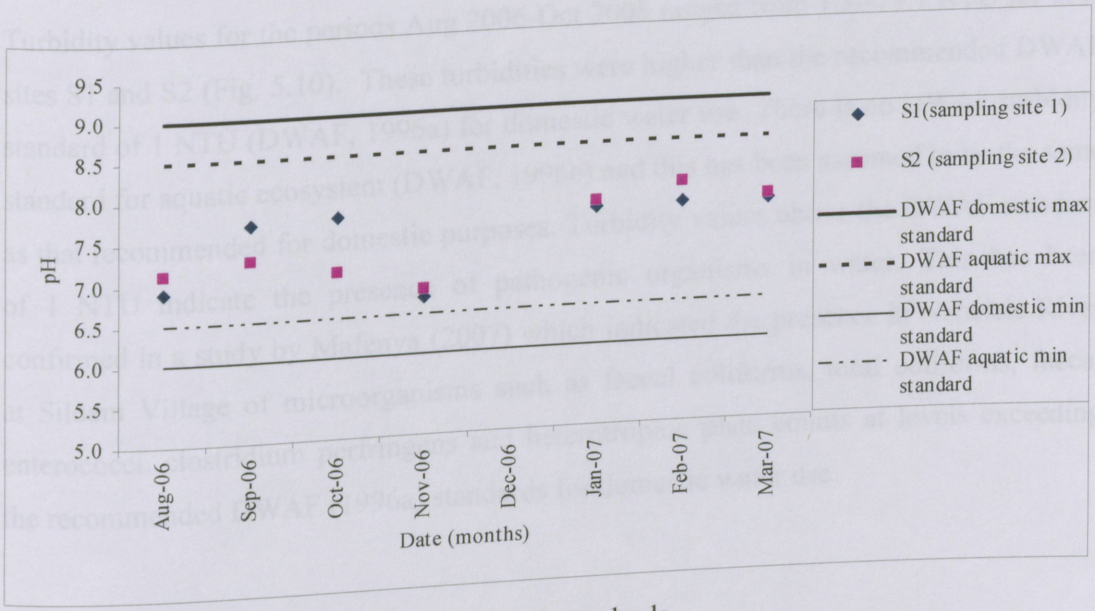


Figure 5.8: Comparisons of pH with DWAF standards

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The EC values for the periods Aug 2006-May 2007 varied from 8.75-12.95 mS/m respectively for both sites S1 and S2 (Fig. 5.9). They were lower than the recommended DWAF standard of 70 mS/m (DWAF, 1996a) for domestic use and South African guideline for unpolluted water of <70 mS/m (DWAF et al., 1998). Within these EC ranges, the ions that have been discussed in sub-section 2.4.1 were likely to be present in low concentrations which could not harm human life or aquatic ecosystems.

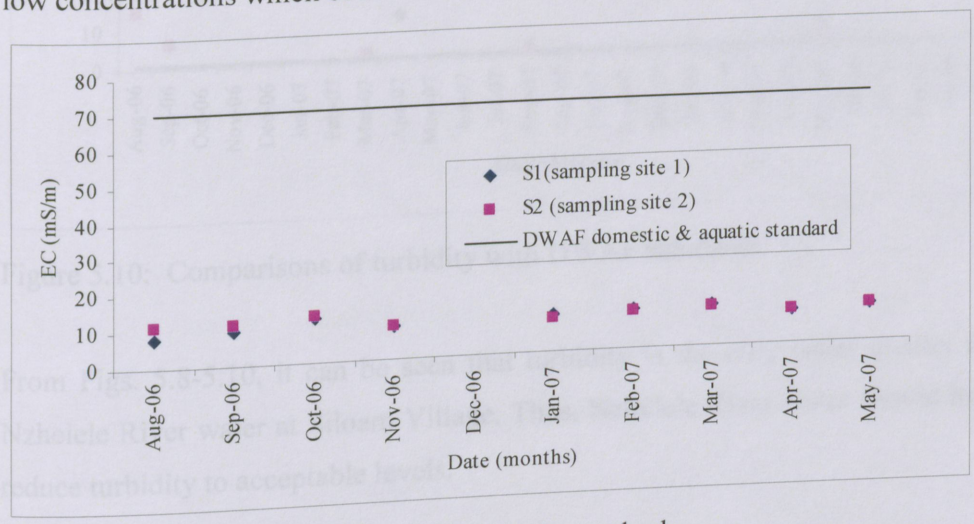


Figure 5.9: Comparisons of EC with DWAF standards

Turbidity values for the periods Aug 2006-Oct 2008 ranged from 1.3--79.7 NTU for both sites S1 and S2 (Fig. 5.10). These turbidities were higher than the recommended DWAF standard of 1 NTU (DWAF, 1996a) for domestic water use. There is no DWAF turbidity standard for aquatic ecosystem (DWAF, 1996e) and this has been assumed to be the same as that recommended for domestic purposes. Turbidity values above the DWAF standard of 1 NTU indicate the presence of pathogenic organisms in water. This has been confirmed in a study by Mafenya (2007) which indicated the presence in Nzhelele River at Siloam Village of microorganisms such as faecal coliforms, total coliforms, faecal enterococci, clostridium perfringens and heterotrophic plate counts at levels exceeding the recommended DWAF (1996a) standards for domestic water use.

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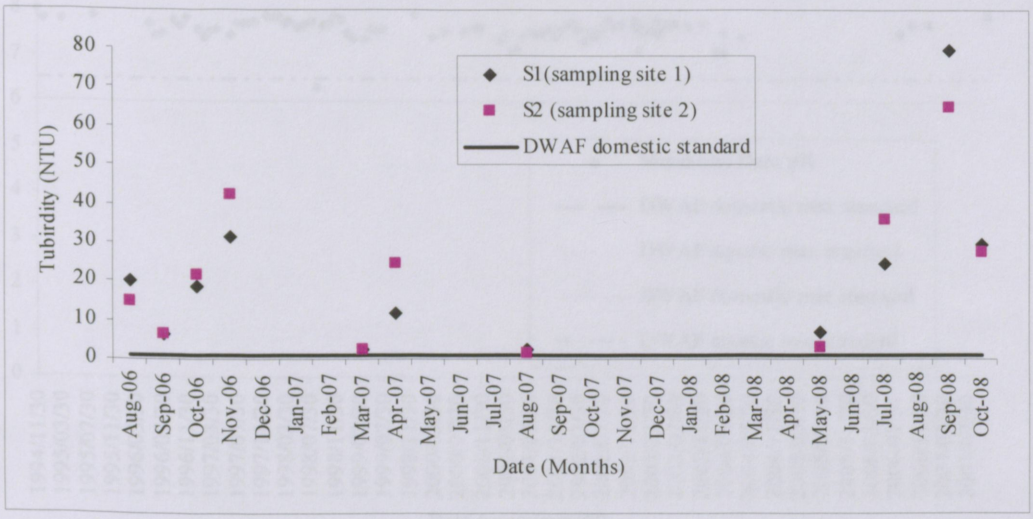


Figure 5.10: Comparisons of turbidity with DWAF standards

From Figs. 5.8-5.10, it can be seen that turbidity is the only water quality problem in Nzhelele River water at Siloam Village. Thus, Nzhelele River water should be treated to reduce turbidity to acceptable levels.

5.5.2 Long term water quality trends

Figures 5.11 and 5.12 show the pH and EC values respectively for Mutshedzi Dam for a period of 13 years (1994- 2007). Mutshedzi Dam lies in the same quaternary catchment A80A in which Siloam Village is located. The pH values for Mutshedzi Dam were within the DWAF recommended standard for domestic water use (DWAF, 1996a) and aquatic ecosystems (DWAF, 1996b), except for one value of 6.33 recorded on 1998/08/31 (Fig. 5.11) which was within the maximum acceptable values for both standards and the minimum acceptable value for domestic use but below the minimum acceptable value for aquatic species. However, the EC values were within the DWAF recommended standard of 70 mS/m for both the aquatic ecosystems and domestic water use (Fig. 5.12).

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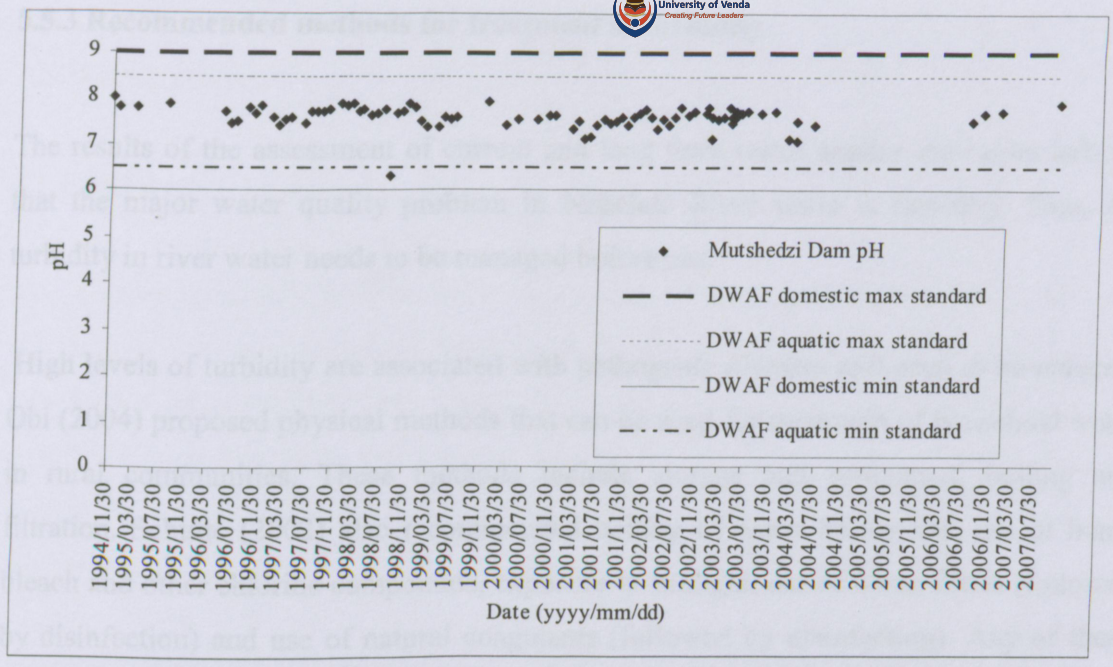


Figure 5.11: pH values for Mutshedzi Dam for a period of 13 years

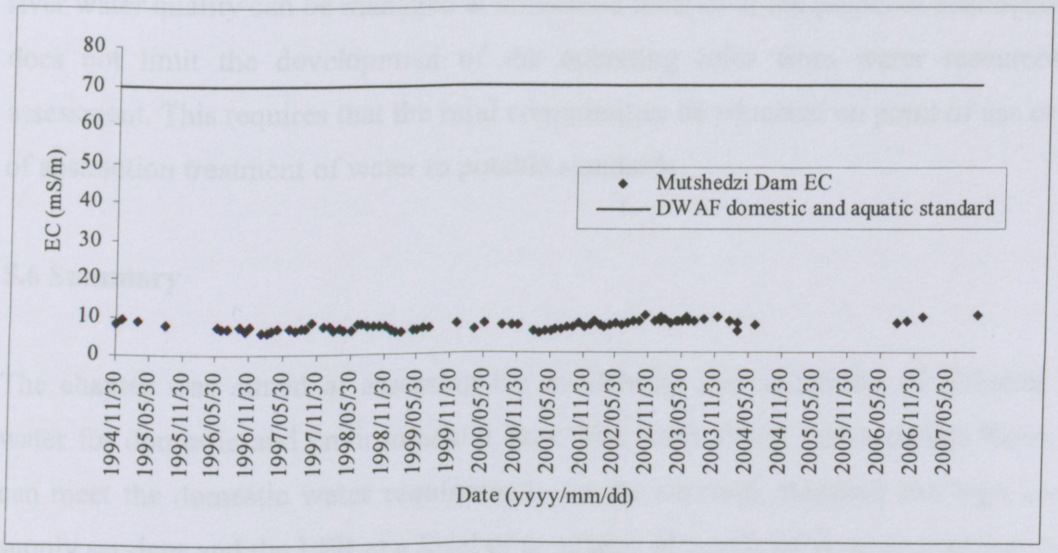


Figure 5.12: EC for Mutshedzi Dam for a period of 13 years

These water quality indicators (pH and EC) indicate that the general chemical water quality for the area is good. This has been confirmed by the measured values.

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5.5.3 Recommended methods for treatment of turbidity

The results of the assessment of current and long term water quality indicators indicate that the major water quality problem in Nzhelele River water is turbidity. Thus, the turbidity in river water needs to be managed before use.

High levels of turbidity are associated with pathogenic diseases and need to be reduced. Obi (2004) proposed physical methods that can be used for treatment of household water in rural communities. These methods include storage and settlement, boiling and filtration. Schutte (2002) also recommended boiling of water before use, use of home bleach and other chlorine compounds, exposure to sunlight, use of home filters (followed by disinfection) and use of natural coagulants (followed by disinfection). Any of these methods can be used to treat Nzhelele River water at Siloam Village before domestic use depending on what each household prefers or can afford. Thus, on the basis of turbidity river water quality can be managed at household level or at the points of abstraction. This does not limit the development of the operating rules from water resources yield assessment. This requires that the rural communities be educated on point of use or points of abstraction treatment of water to potable standards.

5.6 Summary

The chapter was aimed at assessing the availability and suitability of Nzhelele River water for domestic and environmental uses. The study found that Nzhelele River water can meet the domestic water requirements for the survival, standard and high levels of supply services and the LFR at a level of assurance of supply of up to approximately 90% (1:10). The domestic water requirements cannot be supplied at the recommended levels of assurance of supply of 99.5% (1:200), 99% (1:100), 98% (1:50) and 95% (1:20). High levels of turbidity in river water make Nzhelele River water unsuitable for domestic use until the turbidity is reduced to acceptable levels. However, this has been recommended to be done with the methods applicable at the household point of use.

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CHAPTER 6: OPERATING STRATEGY FOR RUN-OF-RIVER ABSTRACTIONS

6.1 Preamble

This chapter presents conceptualized and developed operating strategy for run-of-river abstractions for use in typical rural water supply schemes. The verification of the proposed strategy using Siloam Village as a case study has also been presented in this chapter. The chapter lastly presents the generic strategy that can be applied to any river system in which run-of-river abstractions are used to fully or partially supply the community with water.

6.2 Conceptual framework for the run-of-river abstractions operating strategy

When developing an operating strategy, the water demand and the available water resources and their sources should be assessed first and reconciled. The available water resources at given levels of assurance of supply can then be scheduled optimally to supply the water requirements. The water quality assessment is important to determine the suitability of the water for use or the need for treatment intervention. This is conceptually illustrated in Fig. 6.1 that shows the framework for an operating strategy for run-of-river abstractions in rural water supply schemes with no dams. In the conceptual diagram, water quality has not been considered for the dam water case because it is assumed that all dams are linked to water treatment plants.

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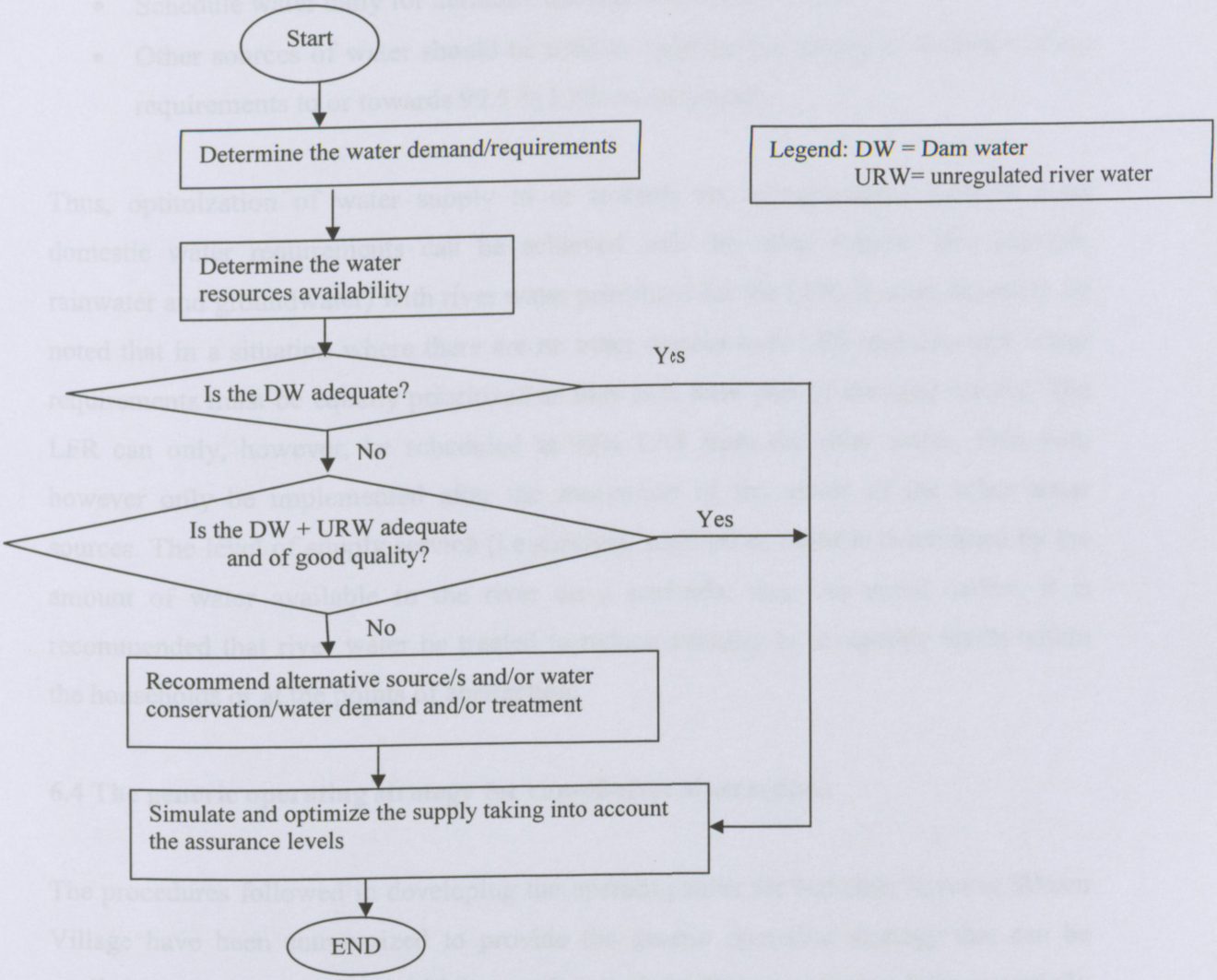


Figure 6.1: Conceptual framework for run-of-river abstractions operating strategy

6.3 Run-of-river abstractions operating rules for Nzhelele River at Siloam Village

Operating rules have been derived for daily scheduling of river water for domestic use taking into account the environmental water requirements. The derivations have been based on the results of the water resources assessment presented in Chapter 5. The rules are:

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- Schedule water daily for domestic use and LFR at 90% LAS.
- Other sources of water should be used to optimize the supply of domestic water requirements to or towards 99.5 % LAS on daily scale.

Thus, optimization of water supply to or towards the recommended LAS to meet domestic water requirements can be achieved with the other sources (for example rainwater and groundwater) with river water prioritized for the LFR. It must, however, be noted that in a situation where there are no other sources both LFR and domestic water requirements must be equally prioritized as they both form part of the total reserve. The LFR can only, however, be scheduled at 90% LAS from the river water. This, can, however only be implemented after the assessment of the yields of the other water sources. The level of supply service (i.e survival, standard or high) is determined by the amount of water available in the river on a particular day. As noted earlier, it is recommended that river water be treated to reduce turbidity to acceptable levels within the households or at the points of abstraction.

6.4 The generic operating strategy for run-of-river abstractions

The procedures followed in developing the operating rules for Nzhelele River at Siloam Village have been summarized to provide the generic operating strategy that can be applied to any river system in which run-of-river abstractions are used to fully or partially supply the community with water. The generic operating strategy is as follows:

1. Determine the existing water uses and their requirements.
2. Obtain or simulate daily streamflow and develop 1 day FDCs.
3. Derive yield curves from 1 day FDCs by extracting the discharges that have been equalled or exceeded at specific percentage times/levels of assurance of supply.
4. Reconcile the derived yield curves at different LAS with the existing water requirements to determine the LAS which meets the water requirements.

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5. Assess the suitability of river water for domestic and environmental uses and recommend household or point of abstraction treatment of water if necessary or possible; otherwise define alternative use for the water.
6. Determine the daily environmental low flow requirements (LFR) from the LFR tables.
7. Measure the flow at the point of interest.
8. If the measured flow is less than or equal to LFR, keep all the water in the river for LFR.
   - If the river is the only accessible source of water, the environment and the domestic users will share the available water according to weighted demands since they are both high priority users. This can be expressed mathematically as:

     If $Q(t) \leq DD + LFR(t)$ then allocate water as follows:

$$DS(t) = \frac{DD}{DD + LFR(t)} Q(t) \tag{7.1}$$

$$LFS(t) = \frac{LFR(t)}{DD + LFR(t)} Q(t) \tag{7.2}$$

where $Q(t)$ is the measured flow on day t, DD is the specified daily domestic demand, $DS(t)$ is the actual supply for domestic use on day t and $LFS(t)$ is the actual supply to the environmental flow on day t

9. If the measured flow is greater than the LFR but the difference between the measured flow and the LFR is less than the domestic water requirements, supply the difference to the domestic water users.
   - The domestic water requirements should be supplemented by other sources of supply such as groundwater and rainwater.
   - If the river is the only accessible source of water, the environment and the domestic users will share the available water according to weighted demands since they are both high priority users. This can be expressed mathematically

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as in Eqs. 7.1 and 7.2.

10. If the measured flow is greater than or equal to the LFR plus the domestic water requirements ($Q(t) \geq DD + LFR(t)$) then supply the domestic water demand ($DS(t) = DD$) and let the rest of the water (≥LFR(t)) flow down the river

- The level of domestic supply service will be determined by the available water after the LFR has been allocated.

6.5 Summary

The operating rule for Nzhelele River at Siloam Village is that river water can be scheduled daily for domestic use and LFR at approximately 89% LAS. Other sources of water such as groundwater and rainwater should be used to optimize the supply of domestic water requirements to or towards 99.5% LAS at daily scale. It has been recommended that the river water be treated within households to reduce turbidity and microbiological risks to acceptable levels.

The generic operating strategy has been derived by summarizing the procedure used in developing the operating rules for Nzhelele River at Siloam Village to provide the generic operating strategy that can be applied to any river system in which run-of-river abstractions are used to fully or partially supply the community with water.

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7.1 Conclusions

The first specific objective requiring determination of the typical characteristics of rural water supply schemes has been achieved through summarized examples in Table 2.2 based on thorough and comprehensive background literature review and field studies. The most important characteristics of rural water supply schemes that made it possible to define and motivate problems of inaccessibility, scarcity and non-potability of the available water resources have been extensively illustrated in the study. These included inadequate water supply infrastructure, use of untreated river and groundwater by rural communities without considering the health impacts and the environmental flow requirements, unknown or unreliable water requirements and lack of limited water storages (dams). As a result of these, the study showed that rural areas tend to rely on groundwater, harvested rainwater and run-of-river abstractions. The latter forms the subject of this study. Literature review has also shown that present operating rules largely assume water supply from dams (see sections 1.5 and 2.6). However, the current study has shown that many rural areas are not supplied from dams. Thus, approving hypotheses one and two of the study (see section 1.5).

The operating framework for run-of-river abstractions, typical in rural water supply schemes has been conceptualized and developed (see section 6.2), thus achieving the second objective. The framework can be used to optimally schedule the river water taking into account the level of assurance of supply and water quality requirements.

The developed operating strategy has been verified using Siloam Village as a case study. There was no daily streamflow data on Nzhelele River at Siloam Village to enable the derivation of the daily FDCs for developing the operating rules. Rainfall-runoff (RR) modelling was therefore performed for a nearby Mutshedzi River SQC within the same quaternary catchment to generate model parameters to transfer to the Nzhelele River SQC

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using the nearest neighbour regionalization technique. Measures of goodness of fit between the simulated and observed runoff with Mike 11 NAM and AWBM including RMSE, E, R, OWBE and PBIAS (Table 4.5) were good and comparable though the AWBM performance was relatively better than that of the Mike 11 NAM. Both models were therefore used in the simulation of the streamflow hydrographs for the Nzhelele River SQC at Siloam Village and the results compared. The streamflow hydrographs for the Nzhelele River SQC at Siloam Village simulated from both models were comparable and showed similar behaviour reported in earlier studies. They also correlated well with the areal rainfall for the Nzhelele River SQC from upstream to Siloam Village.

The findings of the study indicate that Nzhelele River water can meet the domestic water requirements for the survival, standard and high levels of supply services and the LFR at a level of assurance of supply of up to approximately 90% (1:10). The amount of water corresponding to this LAS can be supplied from the river at a daily scale without harming the aquatic ecosystems. This will hence contribute to efficient and reliable operation of the run-of-river system and thus approve the third hypothesis of this study (see section 1.5). The fact that the domestic water requirements cannot be supplied at the recommended LAS of 99.5% (1:200), 99% (1:100), 98% (1:50) and 95% (1:20), shows that the water supply cannot be fully ensured from Nzhelele River water in Siloam Village without considering additional sources of supply. High levels of turbidity in Nzhelele River water makes it unsuitable for domestic use until the turbidity is reduced to acceptable levels.

The operating rules for Nzhelele River at Siloam Village are that the river water can be scheduled daily for domestic use and LFR at approximately 90% LAS, and other sources of water should be used to optimize the supply of domestic water requirements to or towards 99.5% LAS on daily scale. It has been recommended that the river water should be treated within the households or points of abstraction to reduce turbidity and microbiological risks to acceptable levels. Thus, the third objective on the development

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of run-of-river abstractions operating rules for water supply in Siloam Village case study area has been achieved.

The procedure used in developing the operating rules for Nzhelele River at Siloam Village has been summarized to provide the generic operating strategy that can be applied to any river system in which run-of-river abstractions are used to fully or partially supply the community with water (see section 6.4). This achieved the fourth specific objective of this study (see sub-section 1.4.2).

7.2 Recommendations

Continuous monitoring of downstream water releases, domestic water abstractions and the irrigation water abstractions upstream of Mutshedzi Dam is recommended. This will increase the length of the period for computation of the inflow into Mutshedzi Dam using the water balance equation and will also improve the calibration and verification of the models.

The derived operating strategy will need to be updated in future to cater for the possible increase in water demand in the study area. Continuous monitoring of water quality is also recommended. This will aid in identifying any potential water quality problems in the future. Continuous monitoring of water quality will also help in updating the derived developed operating strategy.

The developed operating strategy for run-of-river abstractions should be applied in more case studies. This will help to improve on the verification and generalization of the strategy.

A study that involves the development of an integrated water supply scheme involving run-of-river abstractions and the other sources such as groundwater and rainwater is recommended. This will ensure that the total water requirements are met at or towards the

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recommended LAS throughout the year. A study on the social and economic consequences of the proposed generic operating strategy needs to be undertaken to determine the extent to which the strategy will impact on the socio-economic activities in the study area.

To facilitate implementation of the derived operating rules for Nzhelele River at Siloam Village, infrastructure such as an abstraction weir, transfer pipes and a reservoir (tank) should be provided. During the implementation of the strategy, the community should be trained on the importance of ensuring that their water systems are operated using operating rules. They should also be educated on the relevant home based or point of abstraction methods for treating river water for household use.

Monitoring of streamflow in unregulated rivers to provide natural streamflow hydrograph is also recommended. This would give more reliable results than rainfall-runoff modelling for use in deriving the 1 day FDCs in order to generate run-of-river abstractions operating rules. Monitoring streamflow will also aid in monitoring the compliance to the environmental flow requirements.

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```
!     ------------------------------------------------------------

!     This program obtains the exceedance magnitudes of each day of the year
!     input daily data
!     sp - initial probability of exceedance to include in analysis
!     pra      - interval in exceedance probability
!     fp - final exceedance probability

!     John  Ndiritu July 03 2009
!     ------------------------------------------------------------

      use MSFLIB

      integer  year(:),month(:),day(:)

      real mag(:),magSort(:,:),magRanked(:,:),magExceed(:,:)

      allocatable year,month,day,mag,magSort,magRanked,magExceed

      integer nyears,ndays,l1(2),u1(2),day2(366)
   real sp, pra,fp

!
   open(unit=1, file ='ComputationInfo.txt',status='old')
      read(1,*)nyears,ndays
      read(1,*)sp, pra,fp
      close(1)


      allocate(year(ndays),month(ndays),day(ndays),mag(ndays))
      allocate(magSort(nyears+1,366),magRanked(nyears+1,366))
      allocate(magExceed(100,366))

!
      open(unit=2,file='InputData.txt', status='old')
      read(2,*)
      do 10 i=1,ndays
      read(2,*)year(i),month(i),day(i),mag(i)
!     write(*,*) year(i),month(i),day(i),mag(i)
 10   continue
      close(2)


!   sort data into years and days
      im=1
      i = 1
```


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```
      j = 1
      id=day(1)
 20   k = day(j)
      magSort(im,k) = mag(j)
!     write(*,*) im,k,j,magSort(im,k)
      if(year(i).eq.year(i+1)) then
            i=i+1
            j=j+1
            goto 20
      elseif(j.lt.ndays) then
            im=im+1
            i=i+1
            j=j+1
            goto 20
      endif



!     do 200 i2=1,im
!     open file for recording output
!     open(unit=3,file='Output.txt',status='unknown')
!     write(3,210)(magSort(i2,k),k=1,366)
!210  format(366(f10.2,1x))
!200  continue


!     rank sorted data

      l1(1)=id
      u1(1)=366
      l1(2)=1
      u1(2)=id-1

      do 60 i2=1,2

      do 30 i=l1(i2),u1(i2)

      do 50 j2=1,im
      dummy=-1
      do 40 j=1,im
      if(magSort(j,i).gt.dummy) then
            dummy=magSort(j,i)
            k=j
      endif
40    continue
      magRanked(j2,i)=magSort(k,i)
```


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```
!       write(*,*)j2,i,magRanked(j2,i)
        magSort(k,i)=-2
50      continue

30      continue

60      continue
!       obtain magnitudes for selected percentage exceedances

!       check that provided range is valid and adjust if need be
        if((sp+100/(im+1)).gt.100) then
                sp = 100*(im/(im+1))
                fp = 100*(im/(im+1))
        elseif((fp+100/(im+1)).gt.100) then
                fp = 100*(im/(im+1))
        endif

!       obtain magnitudes  and take care of
!       the leap year extra day - day (number 60)
!       count number of leap years
        NLeapY=0
        do 130 i=0,im
        if(int((year(1)+i)/4).eq.float(year(1)+i)/4.0) NLeapY=NLeapY + 1
130     continue
        do 70 i = 1,366
        if(i.eq.366) then
                im2=NLeapY
        else
                im2=im
        endif
        j=0
        do 80 perc=sp,fp,pra
        j = j + 1
        rank = int(perc*(im2+1)/100 + 0.5)
        magExceed(j,i) = magRanked(rank,i)
!       write(*,*)i,perc,j,magExceed(j,i)
80      continue
70      continue

!       include days on first row of output file
        do 110 i=1,366
        day2(i)=i
110     continue

!       open file for recording output
        open(unit=3,file='Output.txt',status='unknown')
        write(3,120)(day2(i),i=1,366)
```


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```
120     format('Exceedance Pr',1x,366(i3,10x))

        j=0
    do 90 perc=sp,fp,pra
        j = j + 1
        write(3,100) perc,(magExceed(j,i),i=1,366)
90      continue
100     format(f3.0, 4x,366(f12.3,1x))
        close(3)

        end
```


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APPENDIX B: Data used to compute the inflow into Mutshedzi Dam

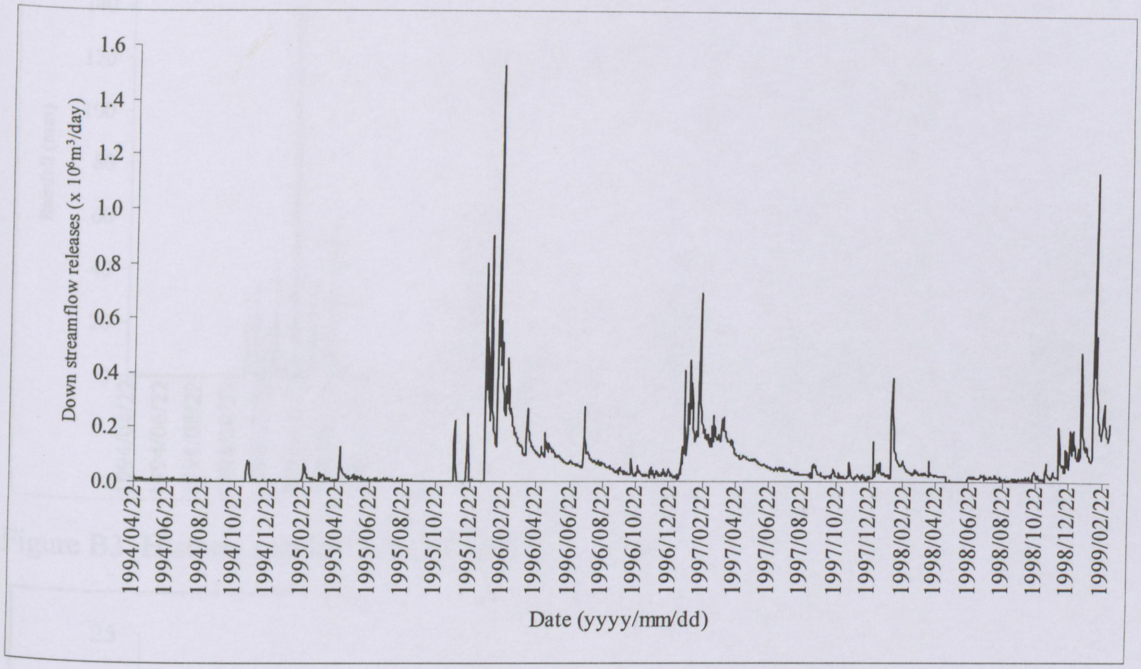


Figure B1: Downstream flow releases

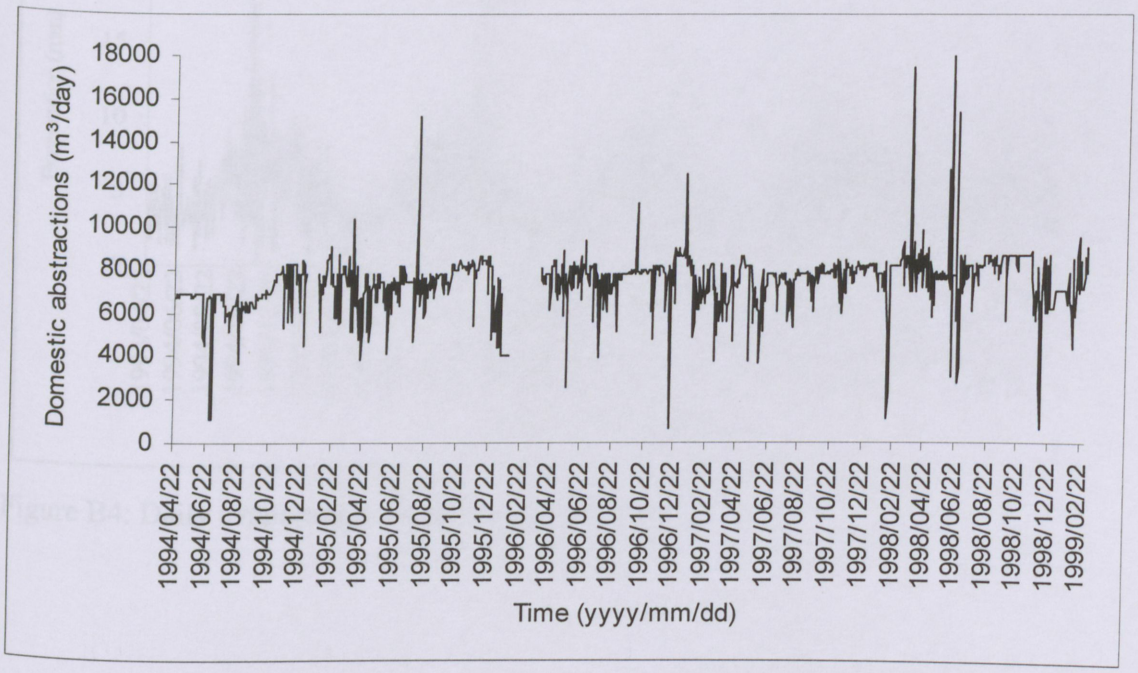


Figure B2: Domestic abstractions from Mutshedzi dam to Mutshedzi Water Treatment Plant

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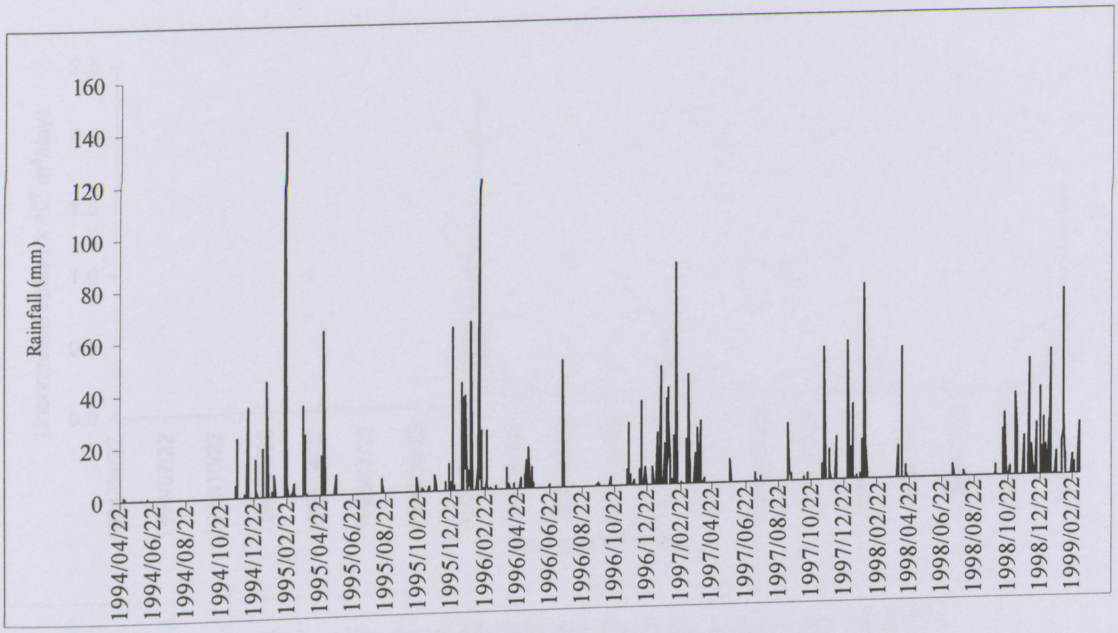


Figure B3: Historic rainfall data for station no. 0766327

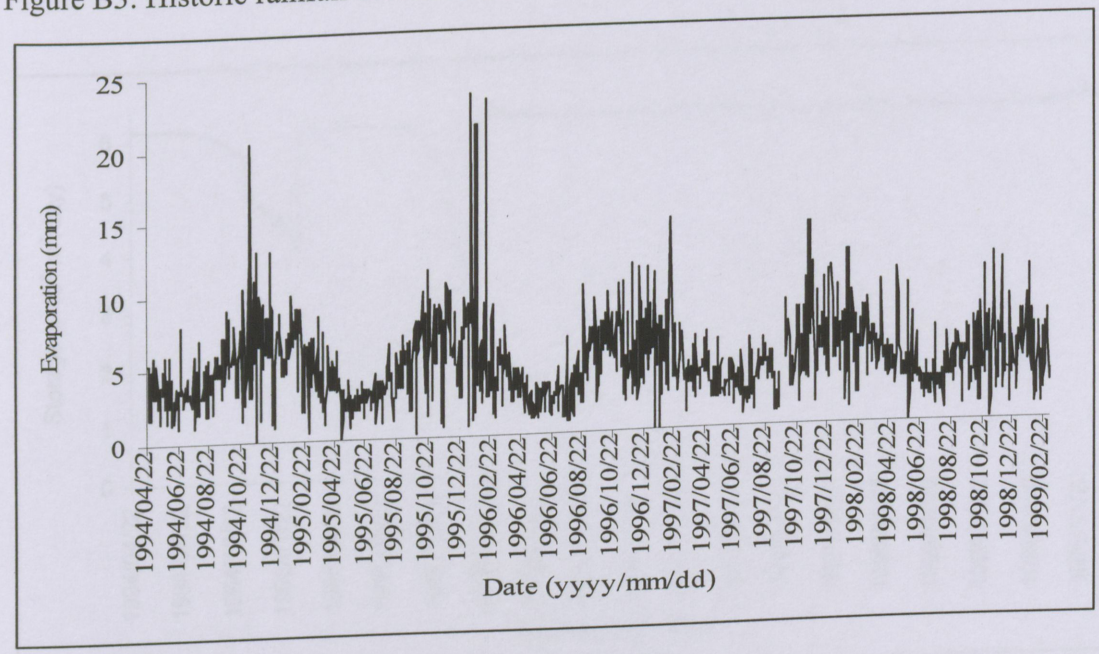


Figure B4: Daily evaporation for station no. A8E004

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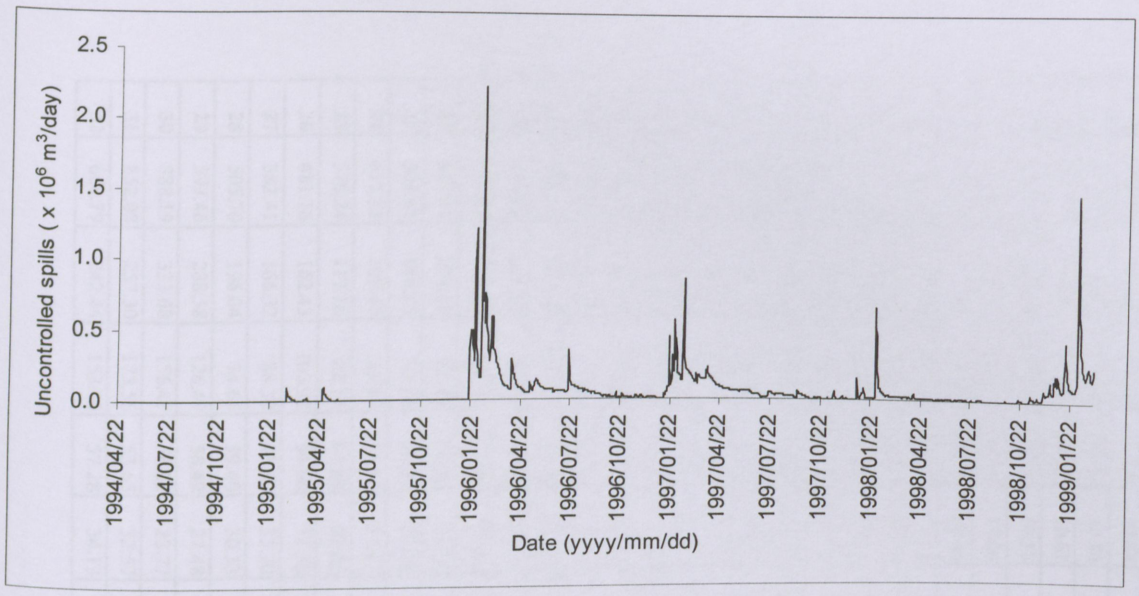


Figure B5: Uncontrolled spills from Mutshedzi Dam for station on A8R004

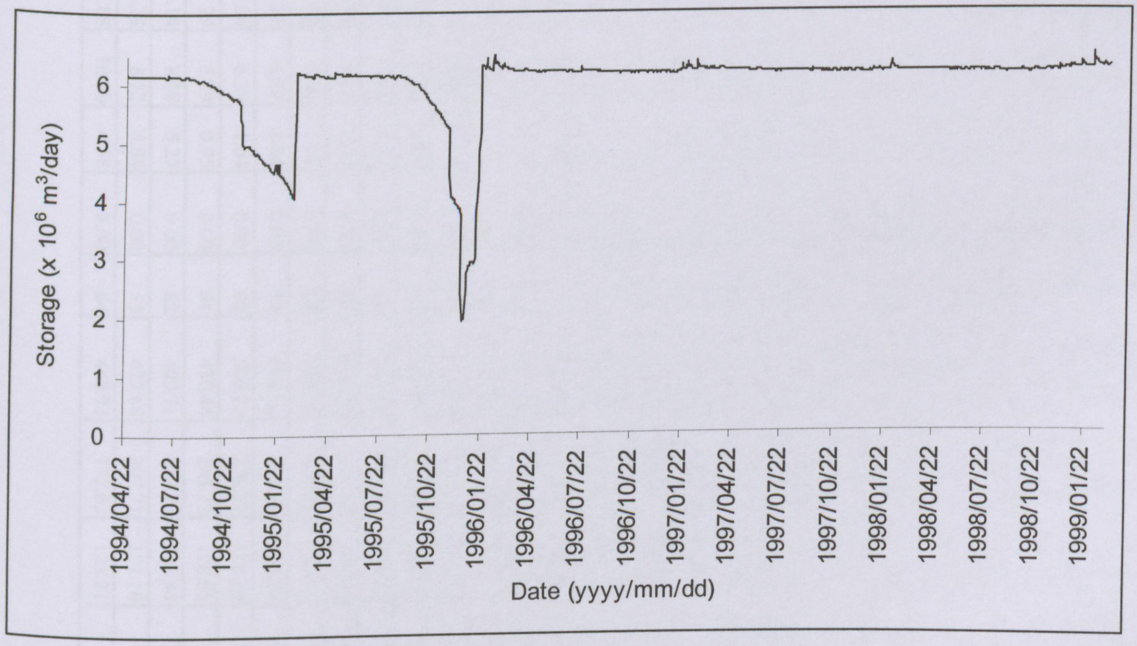


Figure B6: Historic storage trajectory for Mutshedzi Dam

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APPENDIX C: Yields derived from Mike 11 NAM and AWBM simulated runoff

Appendix C1: Yields derived from Mike 11 NAM simulated runoff

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
1	217.04	89.34	49.16	28.68	12.53	10.28	6.13	3.02	0.17	0.09	**33**	781.40	278.21	177.90	111.80	38.02	31.45	19.96	15.29	5.96	0.78
2	203.73	88.56	52.96	37.93	15.98	10.89	6.48	2.94	0.17	0.09	**34**	619.57	267.67	153.19	98.93	36.55	29.29	21.17	15.12	7.86	0.78
3	173.40	79.83	52.10	36.29	18.84	11.92	7.00	3.54	0.17	0.09	**35**	766.28	273.46	165.72	114.65	66.79	30.33	20.56	15.03	8.12	0.78
4	143.34	105.93	59.44	37.07	19.61	11.66	5.88	3.46	0.17	0.09	**36**	1406.51	232.85	170.21	106.36	59.62	30.24	20.48	14.95	7.60	3.28
5	190.34	107.05	55.30	34.04	19.18	11.32	5.70	4.15	0.17	0.09	**37**	1127.00	184.72	130.72	92.97	49.77	28.60	19.53	14.17	7.17	3.20
6	152.32	93.83	51.67	32.14	18.66	12.79	5.62	3.28	0.17	0.09	**38**	919.04	220.58	118.02	84.67	56.68	30.33	19.44	14.34	8.99	4.23
7	210.21	79.06	52.53	38.45	18.49	13.82	8.55	2.68	0.17	0.09	**39**	728.01	210.73	97.03	86.31	64.11	28.68	18.58	13.74	8.29	3.54
8	380.76	82.08	47.17	42.25	18.23	12.18	9.42	3.20	0.43	0.09	**40**	614.13	184.72	102.30	80.61	57.54	26.61	21.86	15.90	7.78	2.94
9	371.52	100.22	47.95	41.56	19.79	13.74	10.28	5.10	0.52	0.09	**41**	489.89	189.56	111.37	69.38	55.30	38.19	18.49	14.34	6.83	2.42
10	312.60	79.92	47.43	37.58	22.64	13.31	9.94	5.01	0.52	0.09	**42**	623.46	302.49	148.09	61.69	53.14	31.10	19.01	13.22	6.05	1.99
11	712.54	104.89	48.21	34.30	22.46	12.61	8.90	4.84	0.43	0.09	**43**	1069.03	416.28	189.82	75.60	47.09	26.18	19.44	12.44	5.70	1.64
12	570.84	82.25	48.21	31.10	21.17	12.61	9.16	4.84	0.43	0.09	**44**	1106.70	456.54	170.29	64.97	40.35	22.90	20.13	13.56	6.48	1.47
13	429.75	110.33	46.92	33.09	19.27	15.03	10.45	4.75	1.38	0.09	**45**	1371.77	390.01	169.95	123.98	54.26	23.59	19.35	12.61	6.22	1.30
14	638.58	142.47	48.30	32.49	24.28	13.56	11.15	4.67	1.30	0.09	**46**	940.12	309.92	185.33	119.23	56.33	28.25	18.92	11.92	6.22	1.12
15	591.06	166.92	72.23	36.46	23.67	13.22	10.37	4.49	1.30	0.09	**47**	695.35	244.60	185.59	123.81	51.32	26.70	18.23	11.32	5.88	1.04
16	537.49	258.16	76.90	36.20	23.07	12.53	9.42	4.41	1.21	0.09	**48**	614.82	247.10	177.21	108.00	58.41	23.07	17.45	10.97	5.79	1.04
17	426.21	227.06	63.59	31.71	22.46	12.53	8.55	4.32	1.21	0.09	**49**	469.84	248.57	155.35	89.51	58.32	38.45	16.68	10.71	5.62	0.95
18	419.04	194.75	60.65	40.18	21.95	17.97	9.94	6.22	1.30	0.09	**50**	492.65	270.78	155.09	91.32	64.11	42.94	17.02	14.17	6.31	0.95
19	360.37	208.74	100.92	37.50	21.51	17.54	10.45	5.96	1.21	0.09	**51**	480.12	263.95	165.46	91.84	60.05	46.57	15.81	13.82	7.78	0.86
20	373.68	161.83	88.13	31.36	25.49	17.11	10.45	6.39	1.21	0.09	**52**	816.39	307.24	199.41	126.84	73.18	49.16	18.58	14.08	9.50	0.86
21	475.80	152.41	79.32	49.08	25.40	18.49	13.48	6.83	1.21	0.09	**53**	828.14	357.96	212.11	117.24	66.61	50.28	32.92	14.17	9.24	0.86
22	467.94	194.49	92.45	54.26	25.75	18.06	12.79	6.83	1.12	0.09	**54**	742.18	566.18	202.69	112.84	79.49	49.94	35.16	13.56	9.94	0.78
23	509.41	144.55	72.75	46.57	27.22	20.82	12.53	7.52	1.12	0.09	**55**	909.10	459.04	222.22	97.29	64.80	45.10	34.13	13.65	10.02	0.78
24	617.33	109.47	83.46	65.92	37.41	23.16	12.53	7.34	1.12	0.09	**56**	740.02	419.39	188.44	90.03	54.43	41.39	30.41	13.31	9.59	0.78
25	570.24	117.16	82.77	63.85	42.85	22.90	11.75	7.17	1.04	0.00	**57**	663.90	364.44	148.35	113.53	52.53	39.66	26.35	13.05	9.24	0.78
26	481.16	162.43	100.92	54.60	38.36	24.36	11.49	7.00	1.04	0.00	**58**	706.75	348.28	133.75	112.75	45.96	35.51	28.25	13.91	8.99	0.78
27	382.41	166.32	88.30	43.89	33.70	23.07	11.23	6.83	1.04	0.00	**59**	608.95	302.14	130.20	104.54	39.31	35.94	24.45	13.56	8.73	0.69
28	505.70	196.04	74.65	39.40	30.33	22.03	15.64	6.39	1.04	0.00	**60**	500.77	276.22	118.20	88.91	39.40	32.92	20.04	12.44	8.47	0.69
29	597.46	288.58	126.49	56.42	27.48	21.25	15.29	5.79	0.95	0.00	**61**	430.44	245.72	128.65	93.14	37.58	32.14	17.02	11.84	8.29	0.69
30	888.19	333.68	156.47	58.32	28.77	22.90	18.14	8.38	5.27	0.00	**62**	409.71	232.76	143.94	83.89	36.98	27.73	16.07	11.58	8.04	0.69
31	852.08	257.30	175.56	53.65	32.57	23.67	17.28	8.12	4.84	0.00	**63**	427.68	207.71	131.16	75.60	36.03	24.02	14.86	11.32	7.86	0.69
32	660.79	242.44	153.45	57.28	34.13	22.46	17.88	10.80	4.58	0.00	**64**	448.93	172.63	125.71	71.71	35.08	24.71	13.05	10.54	7.69	0.60

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Appendix C1: Continues

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
65	426.56	182.13	113.01	85.71	34.13	24.11	12.53	10.20	7.52	0.60	**99**	121.22	82.68	47.26	32.49	26.44	15.29	12.36	5.36	4.15	0.26
66	359.86	146.36	105.32	81.22	43.11	28.60	14.43	10.37	7.34	0.60	**100**	128.04	81.48	45.27	34.99	26.96	14.95	12.44	5.18	4.06	0.26
67	378.17	199.76	99.45	80.61	36.81	27.91	18.92	11.23	8.73	0.60	**101**	161.40	75.95	43.55	35.42	26.09	14.60	12.01	5.10	3.97	0.26
68	454.12	192.84	104.28	76.12	35.68	27.22	19.09	10.97	8.38	0.60	**102**	166.41	71.71	42.25	30.33	25.23	14.26	11.23	5.44	3.89	0.26
69	413.77	181.53	96.94	65.06	34.13	22.46	17.88	12.96	8.38	0.60	**103**	143.08	71.37	41.21	29.81	23.07	13.91	10.71	5.27	3.80	0.26
70	337.13	155.69	101.61	62.12	35.51	26.09	17.02	11.40	8.12	0.52	**104**	130.90	69.38	39.92	33.44	23.85	13.65	10.71	5.18	3.72	0.26
71	259.89	144.98	87.96	58.75	31.28	25.83	14.43	10.20	7.86	0.52	**105**	107.74	67.65	38.88	32.31	23.24	13.31	10.37	5.10	3.63	0.26
72	215.74	127.53	87.52	59.18	30.15	25.57	12.96	9.94	7.69	0.52	**106**	96.77	65.92	37.76	31.02	22.81	13.05	10.11	4.92	3.54	0.26
73	262.48	140.83	83.89	55.30	29.12	24.97	12.18	9.76	7.52	0.52	**107**	88.73	60.13	36.55	29.46	23.16	12.70	9.76	4.84	3.46	0.26
74	253.84	128.74	75.51	53.40	28.17	24.36	11.49	9.16	7.34	0.52	**108**	77.24	56.76	35.51	26.61	23.50	12.44	9.50	4.75	3.37	0.26
75	248.75	124.85	68.08	51.24	27.39	24.19	11.06	8.38	7.17	0.52	**109**	64.89	54.86	35.34	27.39	23.24	18.23	10.97	5.18	3.28	0.26
76	207.79	128.65	64.80	51.41	31.62	24.11	10.63	7.86	7.08	0.52	**110**	98.06	56.25	38.19	29.38	23.16	14.77	10.71	4.75	3.20	0.26
77	188.27	157.59	71.19	52.53	30.93	23.50	10.20	7.86	6.91	0.52	**111**	86.31	52.79	38.36	28.68	22.64	14.43	10.45	4.41	3.20	0.26
78	189.73	137.38	79.32	53.91	30.24	22.81	9.85	7.69	6.65	0.43	**112**	77.07	51.58	33.26	26.35	22.12	12.01	10.20	4.32	3.11	0.17
79	176.77	128.48	80.01	53.31	29.55	22.20	9.50	7.78	6.48	0.43	**113**	70.33	51.15	32.14	24.28	21.51	11.06	10.02	4.23	3.02	0.17
80	217.64	120.87	78.71	51.49	29.72	21.60	11.06	8.29	6.31	0.43	**114**	65.92	54.60	35.08	25.32	21.08	13.48	9.68	4.15	2.94	0.17
81	227.40	113.79	76.81	49.94	29.03	21.00	12.01	8.04	6.13	0.43	**115**	74.13	53.91	38.88	26.18	20.65	15.81	9.42	4.06	2.85	0.17
82	242.09	108.00	67.82	48.47	28.34	20.56	12.10	7.78	5.96	0.43	**116**	79.92	52.70	37.41	25.57	20.13	13.74	9.24	3.97	2.85	0.17
83	280.20	121.22	78.54	47.17	27.65	20.04	11.58	7.60	5.79	0.43	**117**	77.93	51.41	36.29	24.97	19.70	12.61	8.99	3.80	2.76	0.17
84	242.09	114.65	71.88	42.68	27.04	19.53	10.02	7.43	5.70	0.43	**118**	91.41	50.37	39.83	24.45	19.27	12.27	8.81	3.72	2.68	0.17
85	214.44	109.56	89.25	52.44	33.44	19.35	9.24	7.26	5.53	0.43	**119**	80.09	50.63	34.30	23.85	18.84	12.01	8.29	3.63	2.59	0.17
86	194.49	105.49	92.79	51.24	28.77	19.09	9.07	7.08	5.36	0.35	**120**	78.88	51.49	33.44	23.33	18.40	11.75	7.43	3.63	2.59	0.17
87	186.62	102.04	87.18	50.03	32.66	20.22	8.81	6.91	5.27	0.35	**121**	79.49	49.94	41.90	26.27	17.97	11.49	7.00	3.54	2.51	0.17
88	186.97	107.31	78.36	47.69	30.93	19.79	8.64	6.39	5.18	0.35	**122**	73.27	47.17	35.86	25.14	17.54	11.58	8.04	3.46	2.42	0.17
89	164.76	96.42	66.44	44.32	29.55	19.27	8.47	6.22	5.01	0.35	**123**	71.63	45.53	31.02	23.67	17.11	12.44	7.86	3.37	2.42	0.17
90	140.83	91.15	72.92	46.66	30.33	18.49	8.21	6.05	4.92	0.35	**124**	64.45	43.80	30.33	22.46	16.76	11.92	7.69	3.28	2.33	0.17
93	160.01	113.62	63.33	43.55	26.01	16.24	7.69	5.62	4.58	0.35	**125**	55.12	42.34	29.64	20.74	16.33	10.89	7.52	3.20	2.25	0.17
94	168.57	116.38	58.84	42.51	25.32	15.72	7.52	5.53	4.49	0.35	**126**	48.99	41.39	27.82	20.30	15.98	10.20	7.34	3.11	2.25	0.17
95	134.01	102.30	54.95	39.83	24.71	15.29	7.34	5.36	4.41	0.35	**127**	56.68	40.44	28.25	20.22	15.81	14.00	7.26	3.63	2.16	0.17
96	136.94	97.80	51.93	35.42	24.11	15.12	7.17	5.27	4.23	0.35	**128**	64.54	39.74	27.65	19.70	16.24	13.05	7.08	3.54	2.16	0.17
97	127.09	83.81	49.51	34.13	23.59	16.07	7.78	5.44	4.15	0.26	**129**	62.99	36.55	30.84	22.20	15.72	12.18	6.91	3.46	2.07	0.17
98	124.16	77.67	47.61	33.26	28.25	15.64	12.70	5.44	4.32	0.26	**130**	61.26	38.10	30.33	23.07	15.21	11.49	6.74	3.37	2.07	0.17

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Appendix C1: Continues

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
131	59.79	37.15	29.29	22.72	14.69	10.97	6.57	3.28	1.99	0.17	**163**	24.97	15.55	12.10	10.20	6.83	6.05	3.11	1.56	0.95	0.09
132	58.41	36.29	30.93	22.81	15.12	12.36	6.39	3.20	1.99	0.17	**164**	23.07	15.21	11.92	9.94	7.17	5.88	3.37	1.64	1.12	0.86
133	56.16	35.51	29.72	22.81	14.77	12.10	6.22	3.11	1.90	0.17	**165**	21.69	14.86	11.66	9.94	7.00	5.79	3.28	1.81	1.12	0.78
134	52.36	34.73	30.50	24.02	14.77	12.27	6.13	3.11	1.90	0.09	**166**	20.56	14.52	11.40	9.68	6.83	5.62	3.54	1.81	1.12	0.78
135	54.26	33.96	29.20	22.29	14.43	12.01	5.96	3.02	1.81	0.09	**167**	19.70	14.17	11.06	9.24	6.74	5.53	4.23	1.81	1.12	0.78
136	51.84	33.18	27.13	20.39	14.08	11.75	5.88	2.94	1.81	0.09	**168**	19.01	13.82	10.80	9.07	6.39	5.36	3.89	1.73	1.04	0.78
137	51.84	33.18	27.04	19.70	13.74	11.49	5.70	2.85	1.73	0.09	**169**	18.40	13.56	10.54	8.81	5.96	4.92	3.37	1.73	1.04	0.78
138	50.63	32.49	26.01	19.27	14.43	11.23	5.62	2.76	1.73	0.09	**170**	17.88	13.22	10.45	8.64	5.88	4.41	2.94	1.73	1.04	0.69
139	49.42	30.93	25.23	18.75	13.74	10.97	5.44	2.76	1.64	0.09	**171**	17.37	12.96	10.20	8.47	5.70	4.32	2.85	1.64	0.95	0.69
140	48.64	30.76	23.67	18.32	13.13	10.71	5.36	2.68	1.64	0.09	**172**	16.93	12.61	9.94	8.29	5.62	4.15	2.51	1.64	0.95	0.69
141	47.17	29.89	22.64	17.88	12.61	10.45	5.18	2.59	1.56	0.09	**173**	16.50	12.36	9.76	8.04	5.44	4.06	2.51	1.56	0.95	0.69
142	46.14	29.03	22.12	17.54	11.92	10.20	5.10	2.59	1.56	0.86	**174**	16.16	12.10	9.50	7.86	5.36	3.97	2.42	1.30	0.95	0.69
143	47.43	28.34	21.60	16.93	11.66	9.94	5.01	2.51	1.56	1.21	**175**	15.72	11.75	9.33	7.60	5.18	3.89	2.42	1.30	0.86	0.60
144	40.61	27.99	19.44	16.42	11.40	9.33	4.84	2.42	1.47	1.30	**176**	15.38	12.01	9.07	7.43	5.10	3.80	2.33	1.12	0.86	0.60
145	36.63	26.96	18.75	15.47	11.15	9.16	4.75	2.42	1.47	1.21	**177**	15.03	11.92	8.99	7.26	4.92	3.72	2.25	1.12	0.86	0.60
146	35.77	26.35	19.61	15.12	10.89	8.99	4.67	2.33	1.38	1.04	**178**	14.69	11.75	8.64	7.08	4.84	3.63	2.25	1.12	0.86	0.60
147	34.91	25.66	19.70	14.77	10.63	8.73	4.58	2.25	1.38	0.78	**179**	15.12	11.40	8.47	6.91	4.75	3.54	2.16	1.12	0.78	0.60
148	30.50	25.06	19.27	14.43	10.45	8.55	4.41	2.25	1.38	0.60	**180**	20.39	11.23	8.29	6.83	4.92	4.06	2.33	1.12	0.78	0.60
149	27.04	24.45	17.63	14.08	10.20	8.38	4.32	2.16	1.30	0.43	**181**	22.81	10.97	8.12	6.74	4.84	3.97	2.33	1.12	0.78	0.60
150	25.57	23.76	16.59	13.74	9.94	8.47	4.23	2.16	1.30	0.35	**182**	22.29	10.71	7.95	6.57	4.75	3.89	2.25	1.12	0.78	0.52
151	24.97	22.46	16.24	13.39	9.68	8.29	4.15	2.07	1.30	0.26	**183**	21.77	10.54	7.78	6.39	4.67	3.80	2.16	1.04	0.78	0.52
152	24.45	21.00	15.72	13.13	9.07	8.12	4.06	1.99	1.21	0.26	**184**	21.25	10.28	7.52	6.31	4.49	3.72	2.16	1.04	0.69	0.52
153	23.85	19.87	15.38	12.79	8.64	7.78	3.97	1.99	1.21	0.17	**185**	20.74	10.02	7.34	6.22	4.41	3.63	2.07	1.04	0.69	0.52
154	23.33	19.18	14.95	12.53	8.47	7.43	3.89	1.90	1.21	0.17	**186**	21.34	10.37	7.26	6.13	4.32	3.54	2.07	0.95	0.69	0.52
155	26.09	18.75	14.60	12.27	8.29	7.17	3.80	1.90	1.12	0.17	**187**	20.82	10.11	7.08	5.96	4.23	3.46	1.99	0.95	0.69	0.52
156	33.35	18.32	14.26	11.92	8.04	6.83	3.72	1.81	1.12	0.17	**188**	20.39	9.94	6.91	5.79	4.15	3.37	1.99	0.95	0.69	0.52
157	32.57	17.88	13.91	11.66	7.86	6.39	3.63	1.81	1.12	0.17	**189**	19.87	9.68	6.74	5.70	4.06	3.28	1.90	0.95	0.69	0.43
158	31.88	17.45	13.56	11.32	8.12	6.74	3.54	1.73	1.04	0.17	**190**	19.44	9.50	6.57	5.53	3.97	3.20	1.90	0.86	0.60	0.43
159	31.10	17.02	13.31	11.06	8.04	6.65	3.46	1.73	1.04	0.17	**191**	18.92	9.24	7.08	5.36	3.89	3.20	1.81	0.86	0.60	0.43
160	30.41	16.68	12.96	10.80	7.86	6.48	3.37	1.64	1.04	0.17	**192**	18.49	9.07	6.91	5.27	3.80	3.11	1.81	0.86	0.60	0.43
161	29.72	16.33	12.61	10.54	7.69	6.31	3.28	1.64	1.04	0.17	**193**	19.09	8.90	6.83	5.10	3.72	3.02	1.73	0.86	0.60	0.43
162	27.39	15.90	12.36	10.37	7.00	6.13	3.20	1.64	0.95	0.09	**194**	19.61	8.64	6.65	4.92	3.63	2.94	1.73	0.78	0.60	0.43

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	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
195	18.14	8.47	6.48	4.84	3.54	2.85	1.64	0.78	0.60	0.43	**227**	8.21	4.06	3.11	2.33	1.64	1.38	0.78	0.35	0.26	0.17
196	16.85	8.29	6.31	4.75	3.46	2.85	1.64	0.78	0.52	0.43	**228**	8.81	3.97	3.02	2.25	1.64	1.38	0.78	0.35	0.26	0.17
197	16.50	8.12	6.22	4.67	3.37	2.76	1.56	0.78	0.52	0.35	**229**	8.55	3.89	2.94	2.25	1.64	1.30	0.78	0.35	0.26	0.17
198	16.16	7.86	6.05	4.49	3.28	2.68	1.56	0.78	0.52	0.35	**230**	8.29	3.80	2.85	2.16	1.56	1.30	0.78	0.35	0.26	0.17
199	15.72	7.69	5.88	4.41	3.20	2.59	1.56	0.69	0.52	0.35	**231**	8.04	3.72	2.85	2.07	1.56	1.21	0.69	0.35	0.26	0.17
200	14.95	7.52	5.79	4.41	3.20	2.59	1.47	0.69	0.52	0.35	**232**	7.86	3.63	2.76	2.07	1.47	1.21	0.69	0.35	0.26	0.17
201	14.34	7.34	5.79	4.32	3.11	2.51	1.47	0.69	0.52	0.35	**233**	8.04	3.54	2.68	1.99	1.47	1.21	0.69	0.35	0.26	0.17
202	14.00	7.17	5.96	4.23	3.02	2.42	1.38	0.69	0.52	0.35	**234**	7.95	4.06	2.85	1.99	1.47	1.21	0.86	0.35	0.26	0.17
203	13.65	7.00	5.70	4.15	2.94	2.42	1.38	0.69	0.43	0.35	**235**	7.69	3.89	2.76	1.99	1.38	1.21	0.86	0.35	0.26	0.17
204	13.39	6.83	5.27	4.06	2.85	2.33	1.38	0.69	0.43	0.35	**236**	7.43	3.80	2.68	1.90	1.38	1.12	0.86	0.35	0.26	0.17
205	13.05	6.65	5.18	3.97	2.85	2.25	1.30	0.60	0.43	0.35	**237**	7.17	3.72	2.68	1.90	1.38	1.12	0.86	0.35	0.17	0.17
206	12.79	6.57	5.01	3.80	2.76	2.25	1.30	0.60	0.43	0.35	**238**	6.91	3.63	2.59	1.81	1.30	1.12	0.78	0.35	0.17	0.17
207	12.44	6.39	4.92	3.72	2.68	2.16	1.30	0.60	0.43	0.35	**239**	6.74	3.54	2.51	1.81	1.30	1.12	0.78	0.35	0.17	0.17
208	12.18	6.22	4.84	3.63	2.59	2.16	1.21	0.60	0.43	0.26	**240**	6.57	3.46	2.42	1.73	1.21	1.04	0.78	0.35	0.17	0.17
209	11.92	6.13	4.67	3.54	2.59	2.07	1.21	0.60	0.43	0.26	**241**	6.39	3.46	2.42	1.73	1.21	1.04	0.78	0.35	0.17	0.17
210	11.66	5.96	4.58	3.46	2.51	2.07	1.21	0.60	0.43	0.26	**242**	6.22	3.37	2.33	1.64	1.21	1.04	0.78	0.35	0.17	0.17
211	11.40	5.79	4.49	3.37	2.42	1.99	1.12	0.52	0.43	0.26	**243**	6.05	2.76	2.33	1.64	1.21	0.95	0.69	0.35	0.17	0.17
212	11.15	5.70	4.41	3.28	2.42	1.90	1.12	0.52	0.35	0.26	**244**	6.13	3.20	2.16	1.56	1.12	0.95	0.69	0.35	0.17	0.17
213	10.89	5.53	4.23	3.20	2.33	1.90	1.12	0.52	0.35	0.26	**245**	6.31	3.11	2.07	1.56	1.12	0.95	0.69	0.26	0.17	0.17
214	10.63	5.44	4.15	3.11	2.25	1.81	1.04	0.52	0.35	0.26	**246**	6.22	3.02	1.99	1.56	1.12	0.95	0.69	0.26	0.17	0.17
215	10.37	5.27	4.06	3.02	2.25	1.81	1.04	0.52	0.35	0.26	**247**	9.07	3.72	2.07	1.47	1.21	0.95	0.69	0.26	0.17	0.09
216	10.11	5.18	3.97	3.02	2.16	1.73	1.04	0.52	0.35	0.26	**248**	15.72	5.10	2.51	1.56	1.30	0.95	0.69	0.43	0.17	0.09
217	9.94	5.10	3.89	2.94	2.16	1.73	1.04	0.52	0.35	0.26	**249**	14.86	4.92	2.42	1.56	1.21	0.95	0.69	0.43	0.17	0.09
218	9.68	4.92	3.80	2.85	2.07	1.73	0.95	0.43	0.35	0.26	**250**	12.44	4.84	2.33	1.47	1.12	0.95	0.69	0.35	0.17	0.09
219	9.42	4.84	3.72	2.76	1.99	1.64	0.95	0.43	0.35	0.26	**251**	10.71	4.32	2.33	1.56	1.21	0.95	0.60	0.35	0.17	0.09
220	9.24	4.75	3.63	2.68	1.99	1.64	0.95	0.43	0.35	0.26	**252**	13.82	4.58	2.25	1.73	1.30	0.95	0.60	0.43	0.17	0.09
221	8.99	4.58	3.54	2.68	1.90	1.56	0.95	0.43	0.35	0.26	**253**	16.24	4.23	2.25	1.73	1.30	0.95	0.60	0.35	0.17	0.09
222	8.81	4.49	3.46	2.59	1.90	1.56	0.86	0.43	0.35	0.26	**254**	15.90	3.54	2.16	1.64	1.21	0.86	0.60	0.35	0.17	0.09
223	8.64	4.41	3.37	2.51	1.81	1.47	0.86	0.43	0.26	0.17	**255**	12.27	3.46	2.51	1.64	1.21	0.86	0.60	0.35	0.17	0.09
224	8.38	4.32	3.28	2.51	1.81	1.47	0.86	0.43	0.26	0.17	**256**	15.12	4.23	2.42	1.73	1.21	0.86	0.60	0.35	0.17	0.09
225	8.21	4.23	3.20	2.42	1.73	1.47	0.86	0.43	0.26	0.17	**257**	15.03	4.41	2.51	1.81	1.12	0.86	0.60	0.35	0.17	0.09
226	8.47	4.15	3.20	2.33	1.73	1.38	0.78	0.43	0.26	0.17	**258**	14.69	4.32	2.42	1.73	1.12	0.78	0.52	0.35	0.17	0.09

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Appendix C1: Continues

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
259	14.34	4.15	2.33	1.64	1.12	0.78	0.52	0.35	0.17	0.09	**291**	9.59	4.67	2.68	1.38	0.78	0.60	0.35	0.26	0.09	0.09
260	14.00	4.32	2.76	1.64	1.04	0.86	0.52	0.35	0.09	0.09	**292**	17.54	4.84	2.94	1.30	0.78	0.52	0.35	0.26	0.09	0.09
261	22.20	4.15	2.68	1.64	1.04	0.78	0.52	0.35	0.09	0.09	**293**	22.64	4.49	2.85	1.21	0.69	0.52	0.35	0.26	0.09	0.09
262	19.27	4.06	2.68	1.56	1.04	0.78	0.52	0.35	0.09	0.09	**294**	22.46	6.31	2.85	1.30	0.78	0.60	0.43	0.26	0.09	0.09
263	17.11	3.80	2.59	1.56	1.04	0.69	0.52	0.35	0.09	0.09	**295**	20.22	6.65	2.76	1.21	0.78	0.52	0.35	0.26	0.09	0.09
264	15.55	3.72	2.51	1.56	0.95	0.69	0.52	0.26	0.09	0.09	**296**	17.71	6.48	2.59	1.21	0.69	0.52	0.35	0.26	0.09	0.09
265	14.43	3.63	2.16	1.47	0.95	0.69	0.43	0.26	0.09	0.09	**297**	15.38	6.74	2.51	1.21	0.69	0.43	0.35	0.26	0.09	0.09
266	12.36	3.37	1.99	1.47	0.95	0.69	0.43	0.26	0.09	0.09	**298**	13.56	7.60	2.42	1.12	0.69	0.43	0.35	0.26	0.09	0.09
267	11.75	3.28	1.90	1.38	0.95	0.69	0.43	0.26	0.09	0.09	**299**	12.10	6.39	2.42	1.12	0.69	0.43	0.35	0.17	0.09	0.09
268	11.49	3.37	2.33	1.56	0.95	0.69	0.52	0.26	0.09	0.09	**300**	12.10	6.22	2.59	1.12	0.69	0.43	0.35	0.17	0.09	0.09
269	14.86	5.27	2.25	1.56	0.86	0.69	0.52	0.26	0.09	0.09	**301**	11.32	6.83	2.68	1.47	0.69	0.43	0.35	0.17	0.09	0.09
270	21.95	6.31	3.02	1.47	1.04	0.69	0.60	0.26	0.09	0.09	**302**	10.11	6.83	2.51	1.47	0.69	0.43	0.35	0.17	0.09	0.09
271	20.91	5.36	2.94	1.47	0.95	0.69	0.52	0.26	0.09	0.09	**303**	9.94	7.00	3.20	1.47	0.69	0.43	0.35	0.17	0.09	0.09
272	20.13	4.92	2.94	1.38	0.95	0.69	0.52	0.26	0.09	0.09	**304**	20.56	7.95	3.20	1.38	0.69	0.43	0.35	0.17	0.09	0.09
273	16.24	4.75	2.85	1.38	0.95	0.60	0.52	0.26	0.09	0.09	**305**	18.14	7.17	3.11	1.38	0.69	0.43	0.35	0.17	0.09	0.00
274	13.05	4.67	2.76	1.38	0.95	0.60	0.52	0.26	0.09	0.09	**306**	22.29	7.43	3.28	1.64	0.69	0.35	0.26	0.17	0.09	0.00
275	12.61	3.80	2.85	1.30	0.86	0.60	0.52	0.26	0.09	0.09	**307**	39.31	7.95	3.46	1.99	0.78	0.43	0.26	0.17	0.09	0.00
276	11.84	3.97	2.76	1.30	0.86	0.60	0.52	0.26	0.09	0.09	**308**	38.19	7.78	3.28	1.90	0.86	0.43	0.26	0.17	0.09	0.00
277	10.28	4.15	2.59	1.47	0.86	0.60	0.52	0.26	0.09	0.09	**309**	37.15	7.60	4.67	1.90	0.86	0.43	0.26	0.17	0.09	0.00
278	10.11	4.23	2.51	1.47	0.86	0.60	0.43	0.26	0.09	0.09	**310**	36.37	7.43	4.67	1.99	0.86	0.43	0.26	0.17	0.09	0.00
279	9.85	3.89	2.51	1.38	0.86	0.60	0.43	0.26	0.09	0.09	**311**	40.18	16.50	6.05	1.99	0.86	0.43	0.35	0.26	0.09	0.00
280	10.54	4.06	2.42	1.38	0.78	0.52	0.43	0.26	0.09	0.09	**312**	54.69	17.28	5.44	1.90	0.86	0.60	0.35	0.17	0.09	0.00
281	17.02	4.92	2.59	1.38	0.86	0.60	0.43	0.26	0.09	0.09	**313**	64.20	20.48	5.88	3.63	0.95	0.60	0.35	0.17	0.09	0.00
282	15.12	4.49	2.59	1.38	0.86	0.60	0.43	0.26	0.09	0.09	**314**	48.04	26.09	5.96	3.63	0.86	0.52	0.35	0.17	0.09	0.00
283	14.17	4.06	2.51	1.30	0.78	0.60	0.43	0.26	0.09	0.09	**315**	52.70	25.40	6.57	4.15	0.86	0.60	0.35	0.17	0.09	0.00
284	13.48	3.80	2.42	1.56	0.86	0.60	0.43	0.26	0.09	0.09	**316**	64.89	27.39	10.45	4.41	1.30	0.69	0.35	0.26	0.09	0.00
285	15.12	4.92	2.68	1.56	0.86	0.60	0.43	0.26	0.09	0.09	**317**	56.07	22.81	15.38	4.67	1.47	0.78	0.35	0.26	0.09	0.00
286	11.92	7.60	2.68	1.56	0.86	0.60	0.43	0.26	0.09	0.09	**318**	67.05	24.36	13.05	4.49	2.51	0.95	0.52	0.26	0.09	0.00
287	11.84	7.52	2.59	1.47	0.86	0.60	0.43	0.26	0.09	0.09	**319**	72.58	23.07	12.61	5.10	3.20	1.12	0.60	0.26	0.09	0.00
288	9.42	7.34	2.42	1.47	0.78	0.60	0.35	0.26	0.09	0.09	**320**	64.71	28.25	13.91	5.88	3.72	1.21	0.52	0.26	0.09	0.00
289	8.81	6.57	1.99	1.47	0.86	0.60	0.43	0.26	0.09	0.09	**321**	63.33	27.56	14.08	5.70	3.63	1.21	0.52	0.26	0.09	0.00
290	10.02	5.62	1.99	1.38	0.86	0.60	0.43	0.26	0.09	0.09	**322**	48.56	32.23	15.98	7.34	4.15	1.21	0.52	0.26	0.09	0.00

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Appendix C1: Continues

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
323	99.62	26.35	14.00	5.70	3.72	1.21	0.52	0.26	0.09	0.00	**346**	175.13	87.35	24.28	11.75	6.05	3.20	1.99	0.52	0.17	0.00
324	166.92	23.16	11.92	5.36	3.63	1.21	0.52	0.26	0.09	0.00	**347**	226.54	104.63	23.93	12.10	7.52	3.28	1.99	0.52	0.17	0.00
325	195.70	21.95	15.03	7.95	3.63	1.12	0.60	0.26	0.09	0.00	**348**	196.65	90.89	25.32	14.95	7.08	3.02	1.90	0.52	0.17	0.00
326	160.27	29.89	14.08	10.37	4.23	1.99	0.60	0.26	0.17	0.00	**349**	203.73	77.93	30.67	16.33	8.73	4.49	2.33	0.78	0.17	0.00
327	126.84	27.65	12.53	9.50	4.06	2.59	0.60	0.26	0.17	0.00	**350**	157.59	72.84	34.91	17.63	9.07	5.53	2.33	1.30	0.17	0.00
328	95.73	25.83	14.08	9.42	4.84	3.02	0.60	0.26	0.17	0.00	**351**	137.89	98.50	41.90	25.92	9.24	5.62	2.42	1.38	0.26	0.00
329	76.03	22.90	14.17	8.90	4.75	3.02	0.52	0.26	0.17	0.00	**352**	146.36	86.83	52.88	21.51	12.10	5.27	2.33	1.38	0.26	0.00
330	65.15	22.38	11.75	9.59	5.53	2.94	0.52	0.26	0.17	0.00	**353**	180.75	81.30	48.38	19.44	11.15	5.18	2.68	1.38	0.26	0.00
331	55.21	21.86	16.16	10.89	5.79	3.11	0.78	0.26	0.17	0.00	**354**	174.36	62.12	46.92	24.71	10.45	5.70	2.68	1.30	0.17	0.00
332	60.65	28.51	20.22	10.02	5.88	3.02	0.95	0.26	0.17	0.00	**355**	183.00	70.85	47.87	22.98	9.59	7.43	3.89	1.30	0.17	0.00
333	59.18	24.88	19.27	9.33	5.27	3.20	0.86	0.26	0.17	0.00	**356**	194.83	90.63	54.95	38.45	18.14	7.86	4.49	1.73	0.17	0.00
334	63.24	24.28	15.98	8.81	4.92	3.54	0.86	0.26	0.17	0.00	**357**	243.39	162.52	59.27	38.97	17.80	7.69	4.58	1.73	0.17	0.00
335	88.04	49.16	19.35	12.27	7.26	3.46	2.07	0.26	0.09	0.00	**358**	299.38	167.10	49.68	36.63	17.28	7.17	4.41	1.56	0.17	0.00
336	114.31	49.68	23.24	11.15	7.34	3.28	1.99	0.35	0.09	0.00	**359**	356.66	173.49	47.17	28.68	15.81	6.74	4.32	1.38	0.17	0.00
337	97.55	40.09	23.50	9.24	6.31	3.02	1.99	0.35	0.09	0.00	**360**	385.08	142.65	45.19	27.73	15.64	7.43	4.49	1.30	0.17	0.09
338	80.35	47.43	23.07	12.36	5.79	3.02	1.90	0.35	0.09	0.00	**361**	333.07	118.28	43.55	27.13	14.52	7.17	4.15	1.21	0.17	0.09
339	109.38	38.36	23.50	11.84	5.27	2.94	1.64	0.26	0.09	0.00	**362**	259.72	100.05	40.26	22.98	13.65	6.91	4.06	1.12	0.17	0.09
340	105.06	37.24	18.58	11.32	4.58	2.85	1.38	0.26	0.17	0.09	**363**	222.65	86.75	39.66	20.91	13.56	9.59	3.97	2.25	0.26	0.09
341	97.46	37.07	16.50	10.28	4.15	2.76	1.81	0.43	0.17	0.09	**364**	184.64	99.96	51.67	30.33	15.12	12.01	5.88	3.20	0.17	0.09
342	102.99	29.98	19.79	12.10	5.79	3.80	2.51	0.69	0.17	0.09	**365**	167.10	103.33	50.98	29.46	14.69	11.58	6.13	3.11	0.17	0.09
343	133.32	34.39	22.72	11.75	5.53	3.63	2.16	0.69	0.17	0.09	**366**	268.10	38.71	28.77	11.15	7.17	2.85	0.52	0.00	0.00	0.00
344	153.27	48.64	20.30	10.89	5.36	3.46	2.07	0.60	0.17	0.09											
345	178.93	55.99	24.71	12.87	6.22	3.28	1.73	0.60	0.17	0.00											

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Appendix C2: Yields derived from AWBM simulated runoff

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
1	362.71	236.04	182.91	129.77	93.57	70.93	52.70	38.28	26.96	0.00	**33**	924.39	398.39	334.71	235.53	173.23	142.82	112.92	93.31	54.69	17.45
2	404.27	260.84	205.29	145.32	104.89	77.50	53.83	37.50	26.70	0.00	**34**	817.08	375.06	305.86	255.74	158.20	133.32	107.57	87.96	49.16	16.33
3	371.43	249.87	208.31	161.40	109.30	82.34	56.51	38.36	24.80	0.00	**35**	921.54	422.06	293.41	264.12	190.34	133.75	107.48	89.25	57.28	15.38
4	342.66	257.47	203.82	170.73	104.54	78.71	53.74	36.72	23.07	0.00	**36**	980.64	418.87	309.48	240.45	177.47	128.39	112.41	93.74	53.57	14.52
5	356.49	252.81	210.64	158.63	110.33	74.56	51.15	34.99	21.60	0.00	**37**	913.77	391.82	287.80	221.44	189.39	119.75	104.46	88.65	73.44	35.34
6	328.84	233.37	208.92	156.56	113.18	70.68	48.73	33.18	20.22	0.00	**38**	853.98	402.36	262.74	231.64	192.07	147.66	104.80	90.81	76.03	31.97
7	390.96	267.84	195.78	152.41	120.01	75.69	47.09	31.54	18.92	0.00	**39**	834.71	360.37	260.50	246.07	180.58	132.28	97.37	86.40	70.42	29.03
8	419.13	240.11	180.23	153.36	122.86	93.23	60.74	32.31	21.43	0.00	**40**	751.85	417.05	271.64	227.75	201.74	141.18	104.28	85.45	72.40	26.44
9	404.09	260.50	182.30	156.38	116.90	97.20	68.26	32.14	23.76	1.56	**41**	694.31	378.35	253.15	208.48	189.91	128.91	119.40	84.41	75.34	31.71
10	358.73	239.41	175.05	145.58	108.78	91.32	68.00	48.73	27.13	1.47	**42**	912.21	509.07	304.13	234.40	181.61	134.61	109.73	78.19	68.60	30.0
11	663.81	235.27	177.81	143.34	101.26	85.54	63.16	44.06	25.83	1.38	**43**	1021.33	564.71	359.77	221.79	168.83	122.43	101.09	73.53	62.81	28.86
12	599.18	251.16	181.87	139.88	102.38	80.52	66.44	46.57	24.62	1.30	**44**	1045.18	517.71	340.24	216.43	167.27	147.57	98.67	83.89	57.72	27.48
13	543.20	238.81	190.51	148.78	119.92	84.33	64.28	51.32	23.50	1.30	**45**	1126.92	476.50	351.73	250.30	187.92	136.68	92.88	79.66	53.22	26.7
14	719.37	243.65	180.84	158.89	127.53	97.72	66.96	53.22	22.46	1.21	**46**	1018.66	440.21	324.52	283.22	189.73	143.16	95.56	77.41	49.25	25.86
15	673.06	284.95	197.94	161.22	119.66	92.62	62.47	48.56	21.43	1.21	**47**	925.00	456.02	331.26	274.23	177.72	136.17	88.99	72.14	46.14	23.93
16	613.44	372.21	194.31	156.47	109.21	95.04	64.37	44.50	20.48	1.12	**48**	843.61	423.45	320.54	267.93	197.86	134.01	98.06	70.85	55.21	39.3
17	561.51	331.60	184.29	154.31	109.04	93.57	63.16	46.66	19.53	1.04	**49**	799.63	487.12	327.28	246.67	202.69	123.12	91.67	66.53	50.20	37.07
18	516.07	354.41	219.20	163.38	128.82	90.72	68.08	49.33	18.66	1.04	**50**	734.14	541.64	313.98	239.85	202.00	155.35	112.75	70.33	56.33	37.32
19	476.15	356.57	253.93	150.34	120.36	86.75	74.48	47.09	17.88	0.95	**51**	758.51	524.88	310.87	269.74	216.26	144.81	104.28	66.79	52.88	34.99
20	603.59	318.73	227.75	172.63	126.40	89.68	71.88	45.79	17.11	0.95	**52**	832.38	513.65	364.78	286.68	215.91	178.50	106.53	66.53	55.73	32.92
21	639.10	286.33	257.99	201.74	128.82	96.85	73.87	43.29	16.33	0.86	**53**	1002.24	545.36	419.30	274.84	206.32	179.02	101.61	71.80	52.70	31.10
22	571.28	314.50	251.77	186.97	140.49	99.53	76.72	40.95	15.64	0.86	**54**	927.94	597.02	412.82	275.70	207.79	165.20	113.36	83.46	51.93	29.38
23	616.46	281.75	231.21	199.15	159.58	120.53	81.65	39.05	14.95	0.86	**55**	987.03	565.49	403.92	264.12	210.82	169.34	120.10	78.28	55.04	27.7
24	592.27	337.31	216.43	209.43	171.76	118.02	80.44	51.24	21.60	0.78	**56**	912.38	535.08	395.02	247.54	207.71	156.82	111.37	73.44	52.19	26.35
25	530.84	322.88	229.56	193.97	164.25	125.45	81.99	47.09	20.74	0.78	**57**	837.13	580.52	391.22	232.16	191.81	146.45	103.68	68.69	49.59	24.97
26	576.63	382.15	224.55	204.85	153.53	136.43	75.95	50.46	19.87	0.69	**58**	784.25	563.67	368.58	212.80	177.64	138.59	107.31	64.97	47.17	23.76
27	559.18	349.40	211.51	185.85	140.92	127.44	79.92	47.09	19.01	0.69	**59**	720.75	530.76	383.53	199.15	165.28	128.91	99.01	61.34	44.84	22.55
28	576.29	332.12	199.67	174.53	148.87	129.77	75.77	44.06	18.14	0.69	**60**	666.23	530.24	366.60	229.13	162.43	121.31	95.39	64.45	42.77	21.43
29	702.95	437.70	309.92	188.78	148.35	120.79	74.13	52.19	20.91	0.60	**61**	619.92	492.22	340.59	273.11	153.01	114.39	92.62	60.57	40.78	20.48
30	740.53	438.91	324.35	192.41	153.36	137.81	111.97	64.89	32.57	7.52	**62**	635.99	465.61	357.87	276.48	147.31	108.09	85.02	57.02	38.45	19.53
31	655.60	402.36	292.64	177.72	141.96	128.39	104.37	60.83	30.50	7.17	**63**	671.33	428.11	323.40	259.89	138.15	101.61	78.28	53.83	37.07	18.58
32	583.20	371.78	335.40	190.60	153.45	121.56	100.40	58.84	45.01	6.91	**64**	664.42	416.19	304.82	245.89	132.88	104.37	72.23	50.89	35.42	17.71

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Appendix C2: Continues

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	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
61	619.92	492.22	340.59	273.11	153.01	114.39	92.62	60.57	40.78	20.48	**91**	313.46	249.96	219.97	122.17	87.61	75.25	46.57	34.99	19.70	7.86
62	635.99	465.61	357.87	276.48	147.31	108.09	85.02	57.02	38.45	19.53	**92**	306.46	245.03	203.99	137.81	81.04	70.42	51.84	35.16	18.58	7.43
63	671.33	428.11	323.40	259.89	138.15	101.61	78.28	53.83	37.07	18.58	**93**	332.29	258.16	184.12	130.38	76.81	66.44	49.25	33.09	17.45	7.00
64	664.42	416.19	304.82	245.89	132.88	104.37	72.23	50.89	35.42	17.71	**94**	358.13	251.86	167.01	121.05	72.92	63.16	46.31	31.28	19.01	6.65
65	606.79	413.77	318.90	225.59	124.24	97.98	67.74	48.21	33.78	16.93	**95**	358.21	235.53	170.64	118.20	76.81	60.31	43.63	29.55	18.06	6.31
66	556.42	387.07	294.71	226.28	148.09	98.24	78.97	60.39	33.44	16.16	**96**	334.28	223.69	160.44	114.74	73.44	55.56	41.21	27.99	17.19	6.05
67	596.59	384.65	304.13	225.33	159.49	112.67	91.41	57.28	31.19	15.47	**97**	312.85	213.49	156.73	113.36	82.34	62.73	42.42	28.86	16.42	5.79
68	702.78	400.29	286.85	207.96	143.77	105.93	85.28	54.52	29.46	14.77	**98**	293.50	212.28	150.94	108.35	77.85	59.79	47.95	30.07	16.59	6.91
69	640.14	369.96	267.75	192.93	156.04	115.43	87.96	52.27	32.66	14.08	**99**	302.92	212.80	137.55	103.16	73.44	56.94	43.80	28.51	15.55	6.65
70	585.53	361.50	260.76	189.73	147.14	118.37	83.72	49.94	31.28	13.48	**100**	321.49	200.10	160.53	99.79	69.81	55.21	43.37	27.04	14.69	6.39
71	537.84	335.15	240.28	177.72	138.84	108.09	89.08	50.80	29.89	12.87	**101**	337.392	188.2	152.24	115.1	69.72	53.05	40.18	25.7	13.82	6.1344
72	495.94	305.16	266.20	165.72	130.20	103.94	84.41	56.33	28.60	12.36	**102**	300.413	177.3	141.87	107.3	81.56	61.17	43.89	24.4	13.13	5.8752
73	458.96	308.88	247.88	159.93	122.34	96.60	80.01	53.48	27.39	11.84	**103**	291.514	170.6	133.14	108.7	82.34	58.92	41.9	24.9	13.82	5.616
74	431.74	289.35	231.29	154.66	118.28	90.12	74.56	50.80	26.18	11.32	**104**	270.605	206.3	138.59	102.9	75.95	55.21	40	23.6	13.22	5.3568
75	533.87	307.93	222.48	164.68	113.79	84.07	78.28	49.77	25.06	10.80	**105**	251.942	183.3	149.9	100.7	70.42	51.93	38.19	23.8	16.59	5.0976
76	502.42	321.06	222.13	159.49	121.91	104.46	76.90	65.06	30.84	10.37	**106**	235.267	167.8	142.21	91.32	72.49	51.75	37.93	21.9	15.9	4.9248
77	452.22	331.95	229.82	185.50	115.95	93.05	71.45	61.00	29.29	9.94	**107**	220.32	154.9	135.04	101.3	71.19	49.42	34.82	23.7	17.19	4.6656
78	418.09	297.48	227.75	175.13	109.04	83.29	66.70	57.28	27.91	9.50	**108**	206.755	143.6	125.8	96.42	66.61	51.93	43.11	27.7	16.42	4.4928
79	391.91	302.14	206.50	165.72	103.42	87.87	64.63	55.73	28.08	15.90	**109**	196.042	152.2	122.08	98.84	65.06	53.48	40.61	25.5	15.72	4.32
80	419.56	312.42	204.25	162.86	112.06	87.26	59.79	52.62	28.86	15.21	**110**	206.15	149.7	116.21	95.21	64.37	50.11	38.28	25.4	16.16	4.752
81	479.87	310.35	193.80	158.98	102.30	81.39	57.97	49.77	27.30	14.52	**111**	194.918	142.2	110.76	90.81	62.81	47.26	36.2	23.9	15.12	4.5792
82	434.16	293.24	200.97	151.03	92.62	75.00	54.86	47.17	34.73	13.91	**112**	182.736	135	106.01	86.66	59.62	44.58	34.21	22.5	14.17	4.4064
83	457.92	305.77	234.06	141.09	84.41	69.29	52.01	44.76	33.18	12.87	**113**	171.072	131.4	111.8	82.77	56.59	42.16	32.4	20.8	14.52	4.1472
84	456.28	281.75	217.64	132.28	80.35	64.28	49.33	42.51	31.71	12.01	**114**	165.974	129.6	108.43	83.72	64.02	48.12	33.35	21.9	14.43	3.9744
85	415.76	283.05	228.10	130.64	119.66	74.30	59.70	40.44	29.81	11.23	**115**	192.067	129.3	115.43	91.84	63.68	45.1	31.8	20.7	13.82	3.8016
86	373.59	278.29	221.10	124.16	110.76	69.38	55.81	38.53	27.65	10.54	**116**	179.885	119.2	108.52	87.7	59.79	42.34	30.41	18.8	13.22	3.7152
87	349.66	272.16	201.14	160.70	102.90	67.31	52.27	36.63	25.66	9.85	**117**	164.074	112.3	99.792	81.73	56.25	39.83	29.03	17.2	12.61	3.5424
88	333.16	261.62	188.35	149.47	95.90	69.64	48.99	34.99	23.93	9.24	**118**	166.838	120.4	101.43	80.09	60.13	38.53	30.07	18.1	12.1	3.3696
89	315.96	243.22	176.86	139.36	89.60	64.63	46.05	33.35	22.38	8.73	**119**	169.171	120.4	96.854	76.64	57.28	36.37	28.77	17.4	11.49	3.1968
90	299.98	241.49	166.41	130.38	96.25	80.70	50.03	33.00	21.00	8.29	**120**	155.606	114.1	92.534	72.92	54.6	34.39	27.56	16.6	11.06	3.1104

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Appendix C2: Continues

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
61	619.92	492.22	340.59	273.11	153.01	114.39	92.62	60.57	40.78	20.48	**91**	313.46	249.96	219.97	122.17	87.61	75.25	46.57	34.99	19.70	7.86
62	635.99	465.61	357.87	276.48	147.31	108.09	85.02	57.02	38.45	19.53	**92**	306.46	245.03	203.99	137.81	81.04	70.42	51.84	35.16	18.58	7.43
63	671.33	428.11	323.40	259.89	138.15	101.61	78.28	53.83	37.07	18.58	**93**	332.29	258.16	184.12	130.38	76.81	66.44	49.25	33.09	17.45	7.00
64	664.42	416.19	304.82	245.89	132.88	104.37	72.23	50.89	35.42	17.71	**94**	358.13	251.86	167.01	121.05	72.92	63.16	46.31	31.28	19.01	6.65
65	606.79	413.77	318.90	225.59	124.24	97.98	67.74	48.21	33.78	16.93	**95**	358.21	235.53	170.64	118.20	76.81	60.31	43.63	29.55	18.06	6.31
66	556.42	387.07	294.71	226.28	148.09	98.24	78.97	60.39	33.44	16.16	**96**	334.28	223.69	160.44	114.74	73.44	55.56	41.21	27.99	17.19	6.05
67	596.59	384.65	304.13	225.33	159.49	112.67	91.41	57.28	31.19	15.47	**97**	312.85	213.49	156.73	113.36	82.34	62.73	42.42	28.86	16.42	5.79
68	702.78	400.29	286.85	207.96	143.77	105.93	85.28	54.52	29.46	14.77	**98**	293.50	212.28	150.94	108.35	77.85	59.79	47.95	30.07	16.59	6.91
69	640.14	369.96	267.75	192.93	156.04	115.43	87.96	52.27	32.66	14.08	**99**	302.92	212.80	137.55	103.16	73.44	56.94	43.80	28.51	15.55	6.65
70	585.53	361.50	260.76	189.73	147.14	118.37	83.72	49.94	31.28	13.48	**100**	321.49	200.10	160.53	99.79	69.81	55.21	43.37	27.04	14.69	6.39
71	537.84	335.15	240.28	177.72	138.84	108.09	89.08	50.80	29.89	12.87	**101**	337.39	188.18	152.24	115.08	69.72	53.05	40.18	25.66	13.82	6.13
72	495.94	305.16	266.20	165.72	130.20	103.94	84.41	56.33	28.60	12.36	**102**	300.41	177.29	141.87	107.31	81.56	61.17	43.89	24.36	13.13	5.88
73	458.96	308.88	247.88	159.93	122.34	96.60	80.01	53.48	27.39	11.84	**103**	291.51	170.64	133.14	108.69	82.34	58.92	41.90	24.88	13.82	5.62
74	431.74	289.35	231.29	154.66	118.28	90.12	74.56	50.80	26.18	11.32	**104**	270.60	206.32	138.59	102.90	75.95	55.21	40.00	23.59	13.22	5.36
75	533.87	307.93	222.48	164.68	113.79	84.07	78.28	49.77	25.06	10.80	**105**	251.94	183.25	149.90	100.66	70.42	51.93	38.19	23.85	16.59	5.10
76	502.42	321.06	222.13	159.49	121.91	104.46	76.90	65.06	30.84	10.37	**106**	235.27	167.79	142.21	91.32	72.49	51.75	37.93	21.95	15.90	4.92
77	452.22	331.95	229.82	185.50	115.95	93.05	71.45	61.00	29.29	9.94	**107**	220.32	154.92	135.04	101.35	71.19	49.42	34.82	23.67	17.19	4.67
78	418.09	297.48	227.75	175.13	109.04	83.29	66.70	57.28	27.91	9.50	**108**	206.76	143.60	125.80	96.42	66.61	51.93	43.11	27.73	16.42	4.49
79	391.91	302.14	206.50	165.72	103.42	87.87	64.63	55.73	28.08	15.90	**109**	196.04	152.24	122.08	98.84	65.06	53.48	40.61	25.49	15.72	4.32
80	419.56	312.42	204.25	162.86	112.06	87.26	59.79	52.62	28.86	15.21	**110**	206.15	149.73	116.21	95.21	64.37	50.11	38.28	25.40	16.16	4.75
81	479.87	310.35	193.80	158.98	102.30	81.39	57.97	49.77	27.30	14.52	**111**	194.92	142.21	110.76	90.81	62.81	47.26	36.20	23.93	15.12	4.58
82	434.16	293.24	200.97	151.03	92.62	75.00	54.86	47.17	34.73	13.91	**112**	182.74	134.96	106.01	86.66	59.62	44.58	34.21	22.46	14.17	4.41
83	457.92	305.77	234.06	141.09	84.41	69.29	52.01	44.76	33.18	12.87	**113**	171.07	131.41	111.80	82.77	56.59	42.16	32.40	20.82	14.52	4.15
84	456.28	281.75	217.64	132.28	80.35	64.28	49.33	42.51	31.71	12.01	**114**	165.97	129.60	108.43	83.72	64.02	48.12	33.35	21.86	14.43	3.97
85	415.76	283.05	228.10	130.64	119.66	74.30	59.70	40.44	29.81	11.23	**115**	192.07	129.34	115.43	91.84	63.68	45.10	31.80	20.74	13.82	3.80
86	373.59	278.29	221.10	124.16	110.76	69.38	55.81	38.53	27.65	10.54	**116**	179.88	119.23	108.52	87.70	59.79	42.34	30.41	18.84	13.22	3.72
87	349.66	272.16	201.14	160.70	102.90	67.31	52.27	36.63	25.66	9.85	**117**	164.07	112.32	99.79	81.73	56.25	39.83	29.03	17.19	12.61	3.54
88	333.16	261.62	188.35	149.47	95.90	69.64	48.99	34.99	23.93	9.24	**118**	166.84	120.44	101.43	80.09	60.13	38.53	30.07	18.14	12.10	3.37
89	315.96	243.22	176.86	139.36	89.60	64.63	46.05	33.35	22.38	8.73	**119**	169.17	120.36	96.85	76.64	57.28	36.37	28.77	17.37	11.49	3.20
90	299.98	241.49	166.41	130.38	96.25	80.70	50.03	33.00	21.00	8.29	**120**	155.61	114.13	92.53	72.92	54.60	34.39	27.56	16.59	11.06	3.11

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Appendix C2: Continues

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
121	148.44	116.81	88.39	69.12	53.91	37.58	26.35	15.90	10.54	2.94	**151**	75.17	63.24	44.50	37.76	26.61	17.54	13.82	7.78	3.02	0.78
122	172.02	119.66	93.66	67.05	54.86	35.68	25.23	14.86	10.11	2.85	**152**	71.28	60.05	43.11	36.03	26.27	17.02	13.05	7.86	2.94	0.78
123	156.56	111.63	92.19	73.70	52.88	33.96	24.02	13.65	9.68	2.68	**153**	67.65	57.11	39.74	34.39	25.14	16.24	12.27	7.52	2.76	0.78
124	147.05	104.37	84.76	68.77	52.10	32.31	22.90	12.70	9.24	2.59	**154**	64.28	53.31	41.64	33.09	26.09	16.59	12.61	8.47	2.68	0.69
125	134.18	97.89	79.75	63.76	49.16	30.76	21.86	11.75	8.81	2.51	**155**	80.27	50.63	41.39	31.54	23.76	15.90	12.10	8.12	2.59	0.69
126	162.00	93.05	76.12	59.27	46.74	30.84	20.82	11.23	8.47	2.42	**156**	74.56	48.99	41.99	31.80	23.85	19.44	12.87	7.78	2.42	0.69
127	170.99	95.13	79.49	60.91	51.15	35.68	23.50	12.10	8.73	2.25	**157**	94.44	45.36	37.93	29.72	21.69	18.58	12.27	7.43	2.33	0.60
128	159.75	103.94	79.66	62.55	48.56	35.60	22.46	11.40	8.38	2.16	**158**	89.86	42.42	38.19	31.36	20.22	17.80	11.75	7.17	2.25	0.60
129	158.80	129.25	76.38	58.41	45.45	32.57	21.43	10.80	7.95	2.07	**159**	85.62	40.95	36.46	30.67	20.91	17.02	11.40	6.83	2.16	0.60
130	164.16	125.28	71.37	54.78	43.46	31.19	20.48	10.28	7.60	1.99	**160**	78.02	38.02	34.65	28.17	19.61	16.33	10.89	6.57	2.07	0.52
131	151.80	113.53	67.31	56.07	45.19	31.80	19.87	9.76	7.26	1.90	**161**	69.90	36.63	33.00	29.64	20.74	15.64	11.40	6.31	1.99	0.52
132	142.39	114.91	78.71	60.65	45.96	30.24	19.01	9.24	6.91	1.81	**162**	62.99	39.31	31.45	28.86	19.53	14.95	10.89	6.05	1.90	0.52
133	131.76	110.76	92.28	57.02	45.62	32.31	18.14	8.99	6.65	1.73	**163**	63.68	39.31	30.41	27.73	20.74	14.34	10.45	5.79	1.81	0.52
134	152.41	111.28	83.98	59.36	43.80	36.29	20.30	8.99	6.31	1.73	**164**	67.74	45.27	28.86	27.65	19.79	14.52	10.02	5.53	1.99	0.86
135	135.56	105.15	82.51	52.70	41.04	34.39	19.44	8.55	6.05	1.64	**165**	68.69	42.51	27.30	26.18	18.66	13.82	9.59	5.27	1.90	0.78
136	121.22	95.90	77.33	49.85	38.62	32.66	18.58	8.21	5.79	1.56	**166**	61.86	40.69	26.96	24.80	19.18	13.22	9.16	5.10	1.81	0.78
137	159.49	99.96	85.80	57.20	36.63	31.02	17.80	7.86	5.53	1.47	**167**	59.18	38.62	25.32	23.41	18.40	12.70	8.81	4.84	1.73	0.69
138	143.25	94.35	80.78	59.36	36.46	31.02	16.93	7.52	5.27	1.38	**168**	55.90	36.72	23.85	22.29	17.63	12.18	8.47	4.67	1.64	0.69
139	135.04	88.39	75.00	54.95	34.30	29.38	16.33	7.08	5.10	1.38	**169**	52.36	34.21	23.50	21.34	16.76	11.66	8.12	4.41	1.56	0.69
140	154.48	81.82	69.90	51.06	31.54	27.73	15.55	6.65	4.84	1.30	**170**	51.75	33.35	26.78	20.30	15.64	11.15	7.78	4.23	1.56	0.60
141	142.65	78.02	65.32	47.61	29.98	26.27	14.95	6.22	4.67	1.21	**171**	53.65	31.02	24.71	19.61	14.60	10.63	7.43	4.06	1.47	0.60
142	137.46	76.55	65.06	45.27	29.72	26.01	15.38	6.31	4.41	1.21	**172**	51.32	28.94	22.90	18.75	14.77	10.20	7.08	3.89	1.38	0.60
143	125.88	74.22	61.26	43.03	28.25	23.93	14.69	6.05	4.23	1.12	**173**	48.73	27.04	22.98	18.40	14.95	10.54	7.17	3.72	1.38	0.52
144	115.69	78.54	57.80	41.13	26.96	23.85	14.95	5.79	4.06	1.12	**174**	44.41	25.57	22.81	18.14	14.69	10.45	7.00	3.89	1.30	0.52
145	107.22	69.81	53.83	39.31	25.75	21.86	14.08	5.53	3.89	1.04	**175**	44.84	26.35	22.90	17.37	13.91	9.85	6.65	3.72	1.21	0.52
146	99.71	70.33	51.67	46.40	30.41	21.86	17.88	9.59	3.80	1.04	**176**	42.94	33.35	21.77	16.68	15.03	9.59	6.91	5.36	1.21	0.52
147	94.52	65.40	48.99	43.72	29.03	20.91	17.11	9.24	3.63	0.95	**177**	41.04	30.84	22.64	19.87	15.03	11.92	8.21	5.70	1.12	0.69
148	88.99	61.08	46.48	41.39	27.73	20.04	16.33	8.81	3.46	0.95	**178**	53.31	31.62	22.98	18.84	14.17	11.40	7.86	5.44	1.12	0.69
149	83.98	65.23	45.62	41.13	27.56	19.18	15.55	8.47	3.37	0.86	**179**	67.39	29.64	21.95	18.32	13.82	11.32	7.52	5.27	1.04	0.69
150	77.50	61.00	46.57	39.57	26.35	18.40	14.69	8.12	3.20	0.86	**180**	62.99	28.68	21.00	17.54	13.22	10.80	7.17	5.01	1.04	0.60

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Appendix C2: Continues

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
181	59.01	29.12	20.13	16.76	12.70	10.28	6.91	4.84	0.95	0.6	**211**	35.60	15.64	10.20	7.43	5.18	4.23	3.46	2.68	1.38	0.26
182	55.38	26.87	19.09	15.90	12.18	9.76	6.57	4.58	0.95	0.6	**212**	32.92	13.91	9.76	7.00	5.01	4.06	3.28	2.59	1.30	0.17
183	52.36	31.54	22.72	15.47	12.27	9.94	6.65	4.49	0.95	0.78	**213**	30.41	12.61	9.33	7.52	4.84	3.89	3.11	2.51	1.21	0.17
184	49.16	32.83	21.34	15.38	11.84	10.28	6.74	4.32	0.86	0.69	**214**	28.34	12.10	8.90	7.26	4.58	3.63	3.02	2.42	1.21	0.17
185	53.40	28.94	21.00	15.90	11.66	10.20	6.91	4.23	0.95	0.69	**215**	26.44	11.58	8.47	6.74	4.92	3.46	2.85	2.25	1.12	0.17
186	50.20	35.51	22.90	16.16	13.05	10.20	8.04	3.97	0.95	0.69	**216**	29.98	18.14	8.12	6.65	4.84	3.46	2.76	2.25	1.12	0.17
187	47.26	32.83	21.77	15.47	12.18	9.76	7.78	3.80	0.95	0.6	**217**	28.17	18.66	7.86	6.91	5.36	3.37	2.68	2.16	1.04	0.17
188	44.58	29.38	20.30	14.26	11.32	9.42	7.43	3.72	0.86	0.6	**218**	26.52	16.59	7.52	6.65	5.10	3.28	2.59	2.07	1.04	0.17
189	40.52	26.09	18.32	13.48	10.54	8.99	7.08	3.54	0.86	0.6	**219**	30.50	20.56	12.44	6.65	5.10	3.28	2.76	2.07	1.04	0.17
190	37.07	23.33	18.23	14.95	10.80	8.64	6.83	3.37	0.78	0.52	**220**	40.52	22.20	14.60	6.83	4.92	3.54	2.59	1.99	1.04	0.17
191	47.35	26.01	17.88	14.08	10.11	8.21	6.48	3.20	0.78	0.52	**221**	35.77	19.96	13.74	7.60	5.36	3.80	2.59	1.90	0.95	0.17
192	67.05	29.29	18.84	13.56	9.94	8.12	6.22	3.37	1.64	0.52	**222**	33.78	21.17	13.74	7.52	5.10	3.63	2.51	1.81	0.95	0.17
193	59.53	25.75	17.02	13.31	9.50	7.95	6.39	3.89	1.56	0.52	**223**	30.24	20.13	13.13	6.91	4.92	3.54	2.42	1.73	0.86	0.17
194	53.05	22.72	15.47	12.61	9.07	7.60	6.13	3.72	1.47	0.43	**224**	27.30	24.28	14.77	8.99	5.36	3.80	2.51	1.64	0.86	0.17
195	47.52	21.43	14.77	12.10	8.90	7.34	6.31	3.89	2.59	0.43	**225**	24.62	22.64	13.48	8.21	5.18	3.63	2.51	1.81	0.78	0.09
196	42.77	22.38	14.17	11.49	8.29	7.00	5.96	3.72	2.51	0.43	**226**	48.90	20.91	12.96	8.38	5.27	3.46	2.42	1.73	0.78	0.09
197	38.71	21.77	15.64	10.97	8.12	6.65	5.62	3.54	2.42	0.43	**227**	62.81	19.53	12.79	9.94	5.01	3.63	2.59	1.73	0.78	0.09
198	52.36	20.74	14.86	10.45	7.78	6.39	5.36	3.46	2.33	0.43	**228**	57.28	18.32	12.79	10.45	4.84	3.97	2.51	1.81	0.86	0.09
199	48.47	19.18	14.17	10.02	7.43	5.96	5.10	3.28	2.16	0.35	**229**	52.44	16.42	12.18	9.42	4.58	3.80	2.42	1.81	0.86	0.09
200	55.30	18.84	14.95	10.02	7.08	5.70	4.84	3.11	2.07	0.35	**230**	54.52	15.72	14.17	9.07	4.41	3.89	2.59	1.73	0.78	0.09
201	55.21	21.34	14.52	11.15	7.08	5.79	5.10	4.15	1.99	0.35	**231**	48.99	17.80	13.31	9.24	6.48	3.89	2.68	1.64	0.78	0.09
202	51.49	20.30	13.91	10.37	6.74	5.53	4.84	3.97	1.90	0.35	**232**	44.32	22.03	12.27	8.81	6.48	4.06	2.94	1.81	0.86	0.09
203	49.51	23.16	15.03	10.37	7.52	5.88	4.92	3.80	1.81	0.35	**233**	40.18	21.34	11.40	8.38	6.13	3.89	2.85	1.73	0.86	0.09
204	58.67	21.51	14.26	9.94	7.17	5.53	4.67	3.54	1.81	0.35	**234**	48.82	20.04	11.84	8.12	6.05	3.72	2.68	1.64	0.78	0.09
205	52.10	20.04	13.56	9.50	6.91	5.27	4.49	3.28	1.73	0.26	**235**	47.69	24.36	11.32	7.78	5.62	3.54	2.59	1.56	0.78	0.09
206	46.66	18.75	12.96	9.07	6.57	5.18	4.23	3.02	1.64	0.26	**236**	43.37	22.90	10.89	8.38	5.27	3.37	2.51	1.47	0.78	0.09
207	41.73	17.54	12.27	8.64	6.31	4.92	4.06	2.76	1.56	0.26	**237**	47.35	21.51	12.01	8.38	5.27	3.28	2.68	1.47	0.69	0.09
208	38.53	16.50	11.75	8.29	5.96	4.67	3.89	2.59	1.47	0.26	**238**	44.06	27.65	11.40	8.21	4.84	3.11	2.59	1.38	0.69	0.09
209	38.62	20.13	11.32	8.38	5.79	4.75	3.72	2.94	1.47	0.26	**239**	38.97	26.09	11.15	7.69	4.58	3.02	2.42	1.30	0.69	0.09
210	38.71	17.71	10.80	7.86	5.53	4.49	3.63	2.85	1.38	0.26	**240**	42.08	24.62	10.11	7.26	5.18	3.20	2.42	1.47	0.78	0.09

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Appendix C2: Yields derived from AWBM simulated runoff

	Yield (x 10^3 m^3/day) at different LAS											Yield (x 10^3 m^3/day) at different LAS									
Day	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**	**Day**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**98%**
1	362.71	236.04	182.91	129.77	93.57	70.93	52.70	38.28	26.96	0.00	**33**	924.39	398.39	334.71	235.53	173.23	142.82	112.92	93.31	54.69	17.45
2	404.27	260.84	205.29	145.32	104.89	77.50	53.83	37.50	26.70	0.00	**34**	817.08	375.06	305.86	255.74	158.20	133.32	107.57	87.96	49.16	16.33
3	371.43	249.87	208.31	161.40	109.30	82.34	56.51	38.36	24.80	0.00	**35**	921.54	422.06	293.41	264.12	190.34	133.75	107.48	89.25	57.28	15.38
4	342.66	257.47	203.82	170.73	104.54	78.71	53.74	36.72	23.07	0.00	**36**	980.64	418.87	309.48	240.45	177.47	128.39	112.41	93.74	53.57	14.52
5	356.49	252.81	210.64	158.63	110.33	74.56	51.15	34.99	21.60	0.00	**37**	913.77	391.82	287.80	221.44	189.39	119.75	104.46	88.65	73.44	35.34
6	328.84	233.37	208.92	156.56	113.18	70.68	48.73	33.18	20.22	0.00	**38**	853.98	402.36	262.74	231.64	192.07	147.66	104.80	90.81	76.03	31.97
7	390.96	267.84	195.78	152.41	120.01	75.69	47.09	31.54	18.92	0.00	**39**	834.71	360.37	260.50	246.07	180.58	132.28	97.37	86.40	70.42	29.03
8	419.13	240.11	180.23	153.36	122.86	93.23	60.74	32.31	21.43	0.00	**40**	751.85	417.05	271.64	227.75	201.74	141.18	104.28	85.45	72.40	26.44
9	404.09	260.50	182.30	156.38	116.90	97.20	68.26	32.14	23.76	1.56	**41**	694.31	378.35	253.15	208.48	189.91	128.91	119.40	84.41	75.34	31.71
10	358.73	239.41	175.05	145.58	108.78	91.32	68.00	48.73	27.13	1.47	**42**	912.21	509.07	304.13	234.40	181.61	134.61	109.73	78.19	68.60	30.24
11	663.81	235.27	177.81	143.34	101.26	85.54	63.16	44.06	25.83	1.38	**43**	1021.33	564.71	359.77	221.79	168.83	122.43	101.09	73.53	62.81	28.86
12	599.18	251.16	181.87	139.88	102.38	80.52	66.44	46.57	24.62	1.30	**44**	1045.18	517.71	340.24	216.43	167.27	147.57	98.67	83.89	57.72	27.48
13	543.20	238.81	190.51	148.78	119.92	84.33	64.28	51.32	23.50	1.30	**45**	1126.92	476.50	351.73	250.30	187.92	136.68	92.88	79.66	53.22	26.27
14	719.37	243.65	180.84	158.89	127.53	97.72	66.96	53.22	22.46	1.21	**46**	1018.66	440.21	324.52	283.22	189.73	143.16	95.56	77.41	49.25	25.06
15	673.06	284.95	197.94	161.22	119.66	92.62	62.47	48.56	21.43	1.21	**47**	925.00	456.02	331.26	274.23	177.72	136.17	88.99	72.14	46.14	23.93
16	613.44	372.21	194.31	156.47	109.21	95.04	64.37	44.50	20.48	1.12	**48**	843.61	423.45	320.54	267.93	197.86	134.01	98.06	70.85	55.21	39.74
17	561.51	331.60	184.29	154.31	109.04	93.57	63.16	46.66	19.53	1.04	**49**	799.63	487.12	327.28	246.67	202.69	123.12	91.67	66.53	50.20	37.67
18	516.07	354.41	219.20	163.38	128.82	90.72	68.08	49.33	18.66	1.04	**50**	734.14	541.64	313.98	239.85	202.00	155.35	112.75	70.33	56.33	37.32
19	476.15	356.57	253.93	150.34	120.36	86.75	74.48	47.09	17.88	0.95	**51**	758.51	524.88	310.87	269.74	216.26	144.81	104.28	66.79	52.88	34.99
20	603.59	318.73	227.75	172.63	126.40	89.68	71.88	45.79	17.11	0.95	**52**	832.38	513.65	364.78	286.68	215.91	178.50	106.53	66.53	55.73	32.92
21	639.10	286.33	257.99	201.74	128.82	96.85	73.87	43.29	16.33	0.86	**53**	1002.24	545.36	419.30	274.84	206.32	179.02	101.61	71.80	52.70	31.10
22	571.28	314.50	251.77	186.97	140.49	99.53	76.72	40.95	15.64	0.86	**54**	927.94	597.02	412.82	275.70	207.79	165.20	113.36	83.46	51.93	29.38
23	616.46	281.75	231.21	199.15	159.58	120.53	81.65	39.05	14.95	0.86	**55**	987.03	565.49	403.92	264.12	210.82	169.34	120.10	78.28	55.04	27.85
24	592.27	337.31	216.43	209.43	171.76	118.02	80.44	51.24	21.60	0.78	**56**	912.38	535.08	395.02	247.54	207.71	156.82	111.37	73.44	52.19	26.35
25	530.84	322.88	229.56	193.97	164.25	125.45	81.99	47.09	20.74	0.78	**57**	837.13	580.52	391.22	232.16	191.81	146.45	103.68	68.69	49.59	24.97
26	576.63	382.15	224.55	204.85	153.53	136.43	75.95	50.46	19.87	0.69	**58**	784.25	563.67	368.58	212.80	177.64	138.59	107.31	64.97	47.17	23.76
27	559.18	349.40	211.51	185.85	140.92	127.44	79.92	47.09	19.01	0.69	**59**	720.75	530.76	383.53	199.15	165.28	128.91	99.01	61.34	44.84	22.55
28	576.29	332.12	199.67	174.53	148.87	129.77	75.77	44.06	18.14	0.69	**60**	666.23	530.24	366.60	229.13	162.43	121.31	95.39	64.45	42.77	21.43
29	702.95	437.70	309.92	188.78	148.35	120.79	74.13	52.19	20.91	0.60	**61**	619.92	492.22	340.59	273.11	153.01	114.39	92.62	60.57	40.78	20.48
30	740.53	438.91	324.35	192.41	153.36	137.81	111.97	64.89	32.57	7.52	**62**	635.99	465.61	357.87	276.48	147.31	108.09	85.02	57.02	38.45	19.53
31	655.60	402.36	292.64	177.72	141.96	128.39	104.37	60.83	30.50	7.17	**63**	671.33	428.11	323.40	259.89	138.15	101.61	78.28	53.83	37.07	18.58
32	583.20	371.78	335.40	190.60	153.45	121.56	100.40	58.84	45.01	6.91	**64**	664.42	416.19	304.82	245.89	132.88	104.37	72.23	50.89	35.42	17.71

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Appendix C2: Continues

	Yield (x 10^3 m^3/day) at different LAS									
Day	10%	20%	30%	40%	50%	60%	70%	80%	90%	98%
301	110.76	83.81	51.93	40.00	32.92	25.57	15.29	8.99	1.90	0.00
302	99.19	78.11	48.47	37.32	31.71	26.27	21.25	9.50	3.97	0.00
303	109.21	78.36	50.11	39.92	31.19	24.45	19.96	8.99	3.54	0.00
304	153.19	73.53	52.10	37.07	29.38	25.75	18.84	8.47	3.20	0.00
305	138.76	79.75	46.66	34.13	28.34	24.62	18.23	8.04	2.85	0.00
306	159.24	93.66	63.24	41.04	30.33	23.24	17.71	8.12	2.59	0.00
307	167.70	92.10	69.12	43.29	30.67	24.62	16.59	7.52	2.33	0.00
308	150.68	87.26	68.43	52.19	32.57	25.23	18.66	7.00	2.16	0.00
309	186.45	90.29	70.68	55.12	32.23	25.49	22.20	12.01	2.16	0.00
310	164.85	114.39	64.97	49.59	30.41	25.66	19.79	10.89	1.99	0.00
311	180.92	139.54	83.46	59.01	38.28	27.48	19.79	13.13	1.90	0.00
312	171.59	124.16	77.67	54.09	43.55	27.13	19.87	13.91	3.63	0.00
313	178.24	113.88	94.35	52.62	45.10	38.97	20.82	13.74	3.37	0.00
314	193.45	118.63	99.79	55.47	41.39	37.58	21.00	12.36	3.20	0.00
315	201.14	113.10	94.52	71.19	44.24	35.94	31.36	18.32	11.06	0.00
316	206.58	130.29	91.58	83.12	42.60	35.77	31.88	20.22	10.02	0.00
317	200.62	140.23	94.44	80.09	46.66	36.46	29.46	18.92	9.16	0.00
318	243.04	142.21	104.28	76.38	55.73	36.20	30.41	23.07	9.42	0.00
319	222.74	130.98	102.99	80.09	63.42	41.99	31.10	25.49	11.75	2.25
320	213.41	163.21	105.93	85.02	62.81	42.34	29.64	23.85	11.15	1.99
321	193.10	145.24	97.20	80.61	63.07	38.45	27.48	22.29	10.54	1.81
322	230.95	160.36	104.54	76.20	63.42	50.20	27.13	23.41	10.02	1.64
323	220.49	144.29	97.55	74.48	62.12	50.20	29.46	22.20	9.50	1.56
324	329.70	130.38	97.55	74.04	58.32	49.16	29.55	21.69	11.32	1.38
325	309.05	159.49	110.76	72.58	55.38	44.84	27.30	20.65	13.56	1.30
326	310.78	159.24	108.00	76.03	55.21	45.10	33.26	24.19	12.61	1.21
327	276.05	142.73	105.67	72.84	55.30	47.61	38.79	23.50	15.72	1.12
328	246.33	140.40	111.89	81.56	54.52	47.35	36.89	23.41	14.95	7.86
329	220.84	129.08	116.38	84.41	51.75	43.89	34.30	22.38	14.17	7.52
330	198.98	145.76	105.75	83.20	59.36	44.41	33.61	22.64	15.72	7.08
331	180.06	157.08	117.59	92.97	52.53	42.51	30.93	20.74	15.03	6.74
332	224.38	152.06	133.32	100.14	58.92	43.98	29.29	19.53	14.34	6.48
333	236.22	142.30	118.80	95.30	54.86	41.82	27.91	24.88	16.07	6.13

	Yield (x 10^3 m^3/day) at different LAS									
Day	10%	20%	30%	40%	50%	60%	70%	80%	90%	98%
334	223.34	136.94	116.47	89.42	63.07	40.61	31.28	24.62	15.12	5.88
335	241.40	198.63	126.06	110.76	82.08	42.51	30.15	23.41	15.29	5.62
336	250.99	183.25	154.31	106.88	83.03	63.76	32.23	22.72	18.49	6.74
337	222.39	166.23	138.76	102.12	77.24	59.53	30.67	22.81	20.39	6.83
338	221.01	163.56	138.24	111.63	71.71	55.81	29.12	21.77	19.09	6.48
339	219.46	154.74	128.65	99.88	65.66	52.44	27.73	20.82	17.88	6.22
340	221.01	156.73	118.97	95.82	79.23	58.75	35.68	22.38	17.28	5.96
341	256.35	149.90	111.20	103.42	80.61	55.73	33.78	21.25	16.85	5.70
342	231.72	155.17	136.94	112.32	91.24	65.32	49.94	23.93	15.90	5.44
343	277.34	159.49	125.71	103.94	84.24	64.54	46.31	22.90	14.77	5.18
344	314.50	161.31	130.38	105.67	78.11	60.39	54.17	27.73	14.08	5.00
345	301.19	206.58	121.56	109.47	82.25	67.91	50.37	26.44	13.39	4.7
346	351.13	250.91	113.70	104.63	74.56	61.60	48.12	26.18	12.79	4.5
347	338.95	237.95	135.04	102.64	68.00	56.07	45.01	24.97	12.18	4.4
348	307.50	226.28	123.81	99.71	63.07	51.58	44.24	34.65	11.58	4.15
349	275.10	207.53	181.01	103.94	67.31	55.90	40.61	37.50	11.23	3.97
350	266.11	217.90	173.32	100.66	79.57	52.79	37.50	35.08	10.71	3.80
351	294.19	226.80	189.56	152.24	79.66	50.72	38.02	34.13	15.90	4.8
352	316.83	221.44	179.37	137.89	74.56	48.04	37.32	31.97	16.24	4.5
353	314.50	224.21	178.68	131.24	86.05	66.53	34.73	29.89	15.12	4.32
354	278.29	220.41	179.28	142.04	105.58	65.84	36.20	27.99	14.08	4.0
355	302.66	222.22	191.89	156.04	101.17	69.47	41.04	28.17	23.76	3.8
356	335.84	264.73	199.50	175.65	116.99	79.40	46.66	26.78	22.64	3.6
357	452.13	285.90	184.20	163.64	117.24	81.65	49.33	26.87	21.60	3.4
358	444.36	255.40	194.23	148.87	110.51	74.56	50.80	30.59	21.95	3.2
359	457.75	313.37	178.07	149.30	106.27	68.17	56.25	33.78	20.74	3.
360	472.95	309.05	181.01	142.82	104.28	86.40	61.34	45.96	22.64	2.94
361	469.41	294.88	168.74	126.32	96.16	78.80	56.07	45.27	21.43	2.76
362	427.94	303.26	153.19	115.69	88.99	72.14	58.84	46.31	28.86	2.68
363	384.65	277.00	163.12	127.53	99.27	82.60	56.16	47.26	27.56	2.51
364	347.33	264.56	194.66	144.98	112.84	86.40	53.22	43.72	26.27	2.42
365	330.57	265.51	188.61	136.94	106.01	79.23	49.85	40.52	25.14	2.33
366	417.57	213.32	113.53	87.09	73.01	70.24	37.67	36.20	0.00	0.00

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