Modelling Nutrient and Sediment Dynamics at the Catchment Scale

Report to the

Water Research Commission

on the project

Development of an Integrated Modelling Approach to Prediction of Agricultural Non-Point Source (NPS) Pollution from Field- to Catchment-Scales for Selected Agricultural NPS Pollutants

by

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i. GÖRGENS AHM (Editor), LORENTZ SA, VAN DER LAAN M, ANNANDALE JG, JOVANOVIC NZ, MATTHEWS N, GROVÉ B and LE ROUX JJ (2012). *Modelling Agricultural NPS Pollution and Economic-Environmental Trade-offs of Pollution Control Measures. (A Project Overview).* WRC Report No. TT 516/12.

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iii. JOVANOVIC NZ, PETERSEN C, BUGAN RDH and VAN DER WALT E (2012). *Modelling the Fate of Pesticides: Primary Processes, Non-Point Source Data Collection and Guidelines.* WRC Report No. 1516/2/12.

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EXECUTIVE SUMMARY

Background and Objectives

Agriculture has been recognised, both locally and internationally, as a significant contributor to non-point source (NPS) pollution of water resources. For this reason, progressively more attention has been given to identify NPS sources and to quantify the extent of the NPS pollution problems, so that appropriate steps might be taken to reverse, halt, or minimise their environmental impacts. Such steps might include bio-physical control measures at field- or farm-scale, or statutory and policy instruments. Bio-physical control measures yield benefits to the water environment, but they usually have a cost associated with them; therefore, it is also important to consider the economics of NPS pollution management.

To address this challenge, the Water Research Commission (WRC) has initiated and funded the long-term Research Project, "*An integrated modelling approach to predict agricultural NPS pollution from field- to catchment scale- for selected NPS pollutants*".

The Research Team was structured into Specialist Task Teams within the discipline areas of Sediments, Pesticides, Nutrients, Field-Scale Modelling, Economics, and Catchment-Scale Modelling. This document represents one volume out of four Research Reports that accompany the Final Project Overview Report. The overall objective is to present the main outputs produced by the Catchment-Scale Modelling Task Team.

Detailed Catchment Monitoring

Detailed monitoring took place in the Mkabela River catchment (a total area of about 40 km^2) near Wartburg in KwaZulu-Natal at point-, field- and catchment-scales during the period 2006 to 2009. Point observations comprised weather data; overland flow (at two Wischmeier runoff plots), sediment and nutrient yield; soil water tensions in transects to waterways; soil nitrate profiling and groundwater sampling. Field-scale observations at two flumes in field-draining waterways included runoff and concentrations of suspended solids and nutrients. Catchment-scale observations comprised discharge at multiple scales; concentrations of suspended solids and nutrients.

The results indicated rainfall variation between 450 mm and 750 mm per annum; air temperatures that vary between 4ºC and 44ºC; maximum hourly wind speed of 11 m/s and average at 1.2 m/s. Soil water tensions responded to rainfall events of more than 30 mm to a depth of 400 mm below surface in the soil profile. The loads of suspended solids and nutrients from overland flow were dependent on the growth stage of the sugar cane. Loads of suspended solids and nutrients were highly dependent on controls in the water flow path, including road crossings, farm dams and wetland areas. Concentrations of suspended solids and nutrients generally increased during runoff events.

Development of the *ACRU-NPS* Model

The *ACRU-NPS* model was developed in this Project to represent dominant NPS pollution dynamics and processes observed and modelled at the field scale in a range of local and international studies, including the outstanding fresh research reported by the Nutrients and Field-Scale Task Team under this Project.

ACRU is a deterministic agrohydrological model – under continuous development at the University of KwaZulu-Natal, South Africa – for the past three decades. *ACRU* includes the SCS algorithm that simulates daily discharge and peak runoff from daily rainfall. Sediment yield per unit area from a land unit is based on the Modified Universal Soil Loss Equation (MUSLE), in which the energy for sediment entrainment and transport is derived from the event discharge volume and peak flow rate and empirical soil erodibility, vegetative cover, slope and practice factors determine the sediment yield.

Inclusion of nutrient mass balance algorithms in *ACRU* in this Project enabled simulation of N and P losses in surface runoff, sediment, and leaching; N and P cycling in the soil-water-plant-animal system; and N and P mass balances in the catchment system. The resultant "*ACRU-NPS*" includes rainfall, irrigation, fertilisers, plants, and animal wastes as potential nutrient sources and simulates pollution management impacts on N and P transformations and transport. The most recent version of functions in the GLEAMS model was used as a guide in the development of *ACRU-NPS*.

New components and processes added to *ACRU* were a plant residue layer, a soil surface layer, plant matter removed, soil temperature, ammonification, nitrification, N plant uptake and fixation, volatilisation, denitrification, N adsorption and extraction, ammonium partitioning, immobilization, P mineralisation, P plant uptake, P adsorption and extraction, labile P partitioning, harvest, tillage, surface and evaporation transport, subsurface transport and crop stress recovery after moisture or nitrogen shortfalls.

The model details and structure are presented in the Report, including the model components; guidelines for parameter estimation; the results of the current-day simulation of the Mkabela catchment and conclusions on the merits and improvements of the model. Simulations of the full catchment included observed wetland, reservoir and buffer strip elements and processes in nutrient and sediment delivery, which demonstrated the pollution attenuation effects of these hydrological control elements in the catchment.

Application of the *ACRU-NPS* and SWAT Models to the Mkabela River Catchment

Two catchment-scale simulation models were configured for the Mkabela catchment, the application of which highlighted the merits and shortfalls of each. The two models were:

- *ACRU-NPS*, developed in this Project
- SWAT (Soil and Water Assessment Tool), developed by the USDA-ARS.

Each model configuration is described in detail in this Report.

ACRU-NPS was specifically verified against the observations at the lower flume at the small-catchment-scale. The most useful load observations at the flume occurred between October 2007 and March 2008. Observed nitrate loads were simulated successfully with *ACRU-NPS*, but phosphorus loads were under-simulated and sediment loads over-simulated.

The SWAT model was configured to include the nested subcatchments, but the number of observed events in which both streamflow and pollutant concentrations were measured at the larger scale were too limited for comprehensive calibration and verification. The SWAT simulations at the small-catchment-scale were all low in comparison with the measured loads at the lower flume.

These simulations have exposed specific challenges to the attainment of reliable simulations of the observed NPS pollution loads and fluxes. These can be summarised as follows:

- Simulations were improved with delineation of the subcatchments into small hillslope units and invoking a three layered soil system (SWAT);
- Simulated catchment outlets should coincide with control points in the stream/wetland/farm dam network (*ACRU-NP*S and SWAT);

- The physics and chemistry of important hydrological control elements, such as wetlands, farm dams and restrictions to flow must be included in the model configurations (*ACRU-NPS,* SWAT and in-situ observations);
- Site-specific vegetation parameters and land management parameters must be reliably derived to assure successful model performance (SWAT and *ACRU-NPS*);
- Delineation of sub-catchments into Hydrological Response Units to capture the diversity of land use is recommended (SWAT);
- Overland and channel roughness must be adequately represented (SWAT);
- The models must represent the site-specific processes of overland versus subsurface discharge and nutrient flux (*ACRU-NPS*).

The analyses of the simulation of various scenarios of alternative pollution control and management measures that could be applied to the catchment, demonstrated that the use of these two models could play an important role in providing decision support during catchment water quality management processes.

However, a number of the SWAT scenario simulations of pollution management alternatives produced counter-intuitive impacts on nutrient and sediment loads. These findings undermine confidence in SWAT, or, at least, in this particular configuration and require extensive further interrogation.

Conclusions

The Report presents eleven distinct conclusions under the headings:

- Data Collection and Model Developments
- Scenario Analyses

Lessons Learnt

The Report elaborates seven detailed Project Learnings under the headings:

- Research Design
- Multi-Team/Multi-Location Integration and Collaboration
- Approaches to Scaling
- Interfacing Natural Resource Management Needs and Scientific Realities

Recommendations for Further Research

The Report outlines sixteen research recommendations under the headings:

- Observations and Process Understanding
- Advanced *ACRU2000* Processes for Future Inclusion in *ACRU-NPS*
- Additional Model Developments and Comparisons

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- The Department of Soil, Crop and Climate Sciences University of the Free State, Bloemfontein for their extensive and thorough survey of the Mkabela catchment
- The Mgeni Water Board for advice and direction in nutrient monitoring
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ACRU	Agro-hydrological Catchment Research Model
ACRU-NPS	Agro-hydrological Catchment Research Model – Nitrogen, Phosphorus and Sediments or Non-Point Source
AP	Ambic 1 Phosphorus
ARC	Agricultural Research Council
AVSWATX	Geographical Interfaced Model of SWAT
AWC	Available Water Capacity
BP1	Bray 1 Phosphorus
CiP	Citric Acid Method
CN	Curve Number
CN%	Nitrogen content in a crop
CoP	Colwell Phosphorus
DEM	Digital Elevation Model
DP	Double Acid Phosphorus
F1	Flume 1
F2	Flume 2
FAO	Food and Agricultural Organization
GIS	Geographical Information System
GRT	Growth rate ratio
HRU	Hydrological Response Unit
HSG	Hydrological Soil Group
ISCW	Institute of Soil Climate and Water
KZN	KwaZulu-Natal
LAI	Leaf Area Index
MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MP	Mehlich III
MUSLE	Modified Universal Soil Loss Equation
NPS	Non-Point Source (pollution)
OP	Olsen Phosphorus
RP1	Runoff Plot 1 (measured at Flume 1)
RP2	Runoff Plot 2 (measured at Flume 2)

RUSLE	Revised Universal Soil Loss Equation
SLEMSA	Soil Loss Estimator of South Africa
SWAT	Soil and Water Assessment Tool
TP	Truog Phosphorus
UN	United Nations
USLE	Universal Soil Loss Equation

1. INTRODUCTION

1.1. Background and rationale

Agriculture has been recognised, both locally and internationally, as a significant contributor to non-point source (NPS) pollution of water resources. For this reason, in recent years, progressively more investment has been made in identifying agricultural NPS contributors and quantifying the extent of the NPS problems, so that appropriate steps could be taken to reverse, halt, or minimise their environmental impacts. Such steps might include bio-physical control measures at field- or farm-scale, or statutory and policy instruments. Bio-physical control measures yield benefits to the water environment, but they usually have a cost associated with them; therefore, it is also important to consider the economics of NPS pollution management.

To address this challenge, the Water Research Commission (WRC) initiated the following long-term, multi-scale, multi-disciplinary Research Project: "*An integrated modelling approach to predict agricultural NPS pollution from field- to catchment scale for selected NPS pollutants*" – the Catchment-Scale Task Team component of which is detailed in this Report.

As the Project title indicates, the primary aim was to develop an integrated modelling approach to prediction of agricultural NPS pollution from field- to catchment-scale for selected NPS pollutants. A secondary aim was to develop a modelling approach for examination of the economic-environmental trade-offs of agricultural pollution control measures, the effects of which were to be modelled by use of the field- and catchment-scale models. The specific objectives of the Project stated in the original TOR were as follows:

- Establishment of fate-of-NPS-pollutant and other requisite data sets at field-, laboratory-, and quaternary catchment-scale, suitable for model improvement, development and verification.
- Improvement of understanding of on-farm NPS pollution control measures and their modelling requirements.
- Establishment of an improved field-scale model for simulation of agricultural NPS pollution loadings for phosphorus, nitrogen, selected pesticides and sediments, as well as for simulating the beneficial impacts on nearby receiving waters of on-farm NPS pollution control measures.
- Establishment of an improved quaternary catchment-scale model for simulation of agricultural NPS pollution loadings for phosphorus, nitrogen and sediments, as well as for simulating the downstream benefits of on-farm NPS pollution control measures at the catchment-scale.
- Development of guidelines about model usage to examine economic trade-offs and feasibility of agricultural NPS pollution control measures at field- and catchment-scale.

1.2. Project scope and extent

The duration of the Project was from April 2005 to February 2012 and involved researchers from nine different institutions and organisations: the Universities of Pretoria, the Free State, KwaZulu-Natal and the Western Cape, respectively, as well as the Agricultural Research Council (ARC), CSIR, SA Sugar Research Institute (SASRI), CSIRO (Australia) and Aurecon, who provided project leadership.

The Project was structured into four parallel but overlapping phases to ensure research effort synergies and inter-linked research outputs:

- Phase One: Observation and monitoring of NPS pollution processes at point-, field- and catchment-scales (nutrients, sediments and pesticides).

- Phase Two: Developing field-scale NPS pollution predictive capability via a bio-physical field-scale model (nutrients and sediments), as well as an expert system (pesticides).
- Phase Three: Developing catchment-scale NPS pollution predictive capability via catchment-scale bio-physical models (nutrients and sediments).
- Phase Four: Developing economic-environmental trade-off modelling ability, supported by the above bio-physical models.

This Report documents the research conducted by the Catchment-Scale Modelling Task Team during Phases One and Three of the Project, including specific interfaces with Phases Two and Four.

1.3. Technology transfer

The Project yielded five published final reports: an Overview Report and four detailed technical accounts of the research on the field-scale bio-physical modelling, the field-scale expert system for pesticides, the catchment-scale modelling and the economic-environmental trade-off modelling, respectively.

vi. GÖRGENS AHM (Editor), LORENTZ SA, VAN DER LAAN M, ANNANDALE JG, JOVANOVIC NZ, MATTHEWS N, GROVÉ B and LE ROUX JJ (2012). *Modelling Agricultural NPS Pollution and Economic-Environmental Trade-offs of Pollution Control Measures. (A Project Overview).* WRC Report No. TT 516/12.

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x. MATTHEWS N, GROVÉ B and GöRGENS AHM (Editor) (2012). *Modelling Economic-Environmental Trade-Offs of Agricultural Non-Point Source Pollution Control Measures*. WRC Report No. 1516/4/12.

The Project also yielded 14 journal papers and presentations at conferences and symposia and at least three more are in progress. The Overview Report is not a detailed scientific presentation of the research conducted during this Project; rather, it presents a narrative of the Project, its challenges, its achievements and its learnings in the hope that a wider audience would find it accessible and useful.

1.4. Capacity building

Given the research nature of the Project, as well as the involvement of a number of academic and research institutions, a large capacity building component was maintained throughout and the Project supported 13 post-graduate students.

1.5. Project team composition

The Project Team was composed of four individual Task Teams, comprising one or more Specialists within each of the domains of agricultural nutrients, sediments, pesticides, field-scale bio-physical modelling, catchment-scale bio-physical modelling, and agricultural economics. As stated earlier, the Specialists were drawn from a range of academic and research institutions. The research consulting firm, Sigma Beta, was appointed to provide leadership, coordination and administration to the Research Team, with Professor André Görgens in the Project Leader role. In 2009 Sigma Beta was absorbed into Aurecon, a global professional consulting firm, who continued with the functions previously performed by Sigma Beta.

1.6. Structure of this Report

The overall objective of this Report is to present the main research outputs produced by the Catchment-Scale Task Team during the course of this Project. This volume is structured into four primary sections:

i. NPS pollution process data collection in the Mkabela River nested experimental catchment in KwaZulu-Natal.

ii. *ACRU-NPS* model: the details and structure of *ACRU-NPS* are represented, together with initial simulations which demonstrate the model results against the observed data from the Mkabela catchment. Also presented is the consideration of field-scale processes in catchment-scale models; the components of the *ACRU-NPS* model; guidelines for parameter estimation; the results of the simulation of the nested catchment headwaters and offers conclusions on the merits and improvement of the model.

iii. SWAT model*:* the details and structure of SWAT are represented, together with initial simulations which demonstrate the model results against the observed data from the Mkabela catchment.

iv. Model comparisons: The Report also presents a comparative critique of the configured catchment models, SWAT and *ACRU-NPS,* so that the merits and shortfalls of each can be identified. Results for the two model simulations are compared. Critique on each model simulation includes the strong and weak points of each model.

2. NESTED CATCHMENT MONITORING

Since the objective of the catchment monitoring of NPS pollution from agricultural sources in this study was to identify and quantify mechanisms of transport of nutrients, sediments and pesticides, including identifications of sources and pathways, it was important to make observations at various scales. A nested research catchment near Wartburg in KwaZulu-Natal, South Africa, was instrumented for multi-scale observation. At the Wartburg site, point-, field- and farm-scale observations were made in the headwaters of the Mkabela River catchment. Downstream, sampling stations in the Mkabela River were established and serviced for sediment and nutrient load analysis at increasing scales up to a large catchment scale (42 km^2).

This nested catchment approach allowed for:

- Identification and quantification of mechanisms of transport, sources and pathways of NPS pollutants;
- Observations against which to test bio-physical numerical models at various scales;
- Common reference points for the research team to develop solutions to NPS pollution generation and transport.

2.1 Mkabela River catchment monitoring

2.1.1 Mkabela catchment experimental set-up

2.1.1.1 Mkabela catchment location

After consultation with the local Mgeni Water Supply Board, the experimental catchment was established in the sugar cane growing region of the KwaZulu-Natal Midlands, one kilometre east of the town of Wartburg (30.68 DD East, 29.37 DD West) as indicated in Figure 1.

Vegetable cropping, pastures and forestry occur in the remainder of the catchment. The topography of the Mkabela catchment is a major determinant in the movement and behaviour of NPS pollution. A Digital Elevation Model (DEM) allows for catchment boundary delineation, and was created for the Mkabela catchment using pixel sizes of approximately 21 m x 21 m from 5 m contour intervals obtained from 1:10000 maps.

2.1.1.2 Mkabela land use

The land use delineation is shown in Figure 2 and comprises:

Cane:	26.4 km^2	(55%)
Forestry:	3.01 km^2	(6.3%)
Maize:	1.69 km^2	(3.5%)
Vegetables:	0.18 km^2	(0.4%)
Dairy:	0.5 km^2	(1.0%)
Grassland:	1.56 km^2	(3.3%)
Riparian/dams:	3.7 km^2	(7.7%)

The land use data derived from existing aerial photographs was supplemented by in-situ ground-truthing surveys. Of particular value was a survey conducted in May 2008. Here the nature of the main channel was evaluated during ground verification of land use. The results of this survey are summarized in Table 1. The observations of water velocity, turbidity and inundation are used directly in the derivation of reach characteristics of the models. Turbidity increases with flow velocity where local disturbance of the banks was noted and decreases where flow velocities were low, particularly through wetlands.

2.1.1.3 Mkabela land types

The Land Type, comprising associations of soil and relief, of the Mkabela catchment is evenly distributed throughout the catchment. The upper catchment is largely dominated by Bb110, the western slopes are generally Bb108, the eastern slopes Ac217 and Aa5, with a small area of Bb110 at the south west corner of the catchment. A detailed soil survey of the headwater research catchment and a hillslope-based soil survey of the catchment downstream were conducted by the Department of Soil, Crop and Climate Science, University of the Free State and are presented in Appendix A (Le Roux *et al.,* 2006).

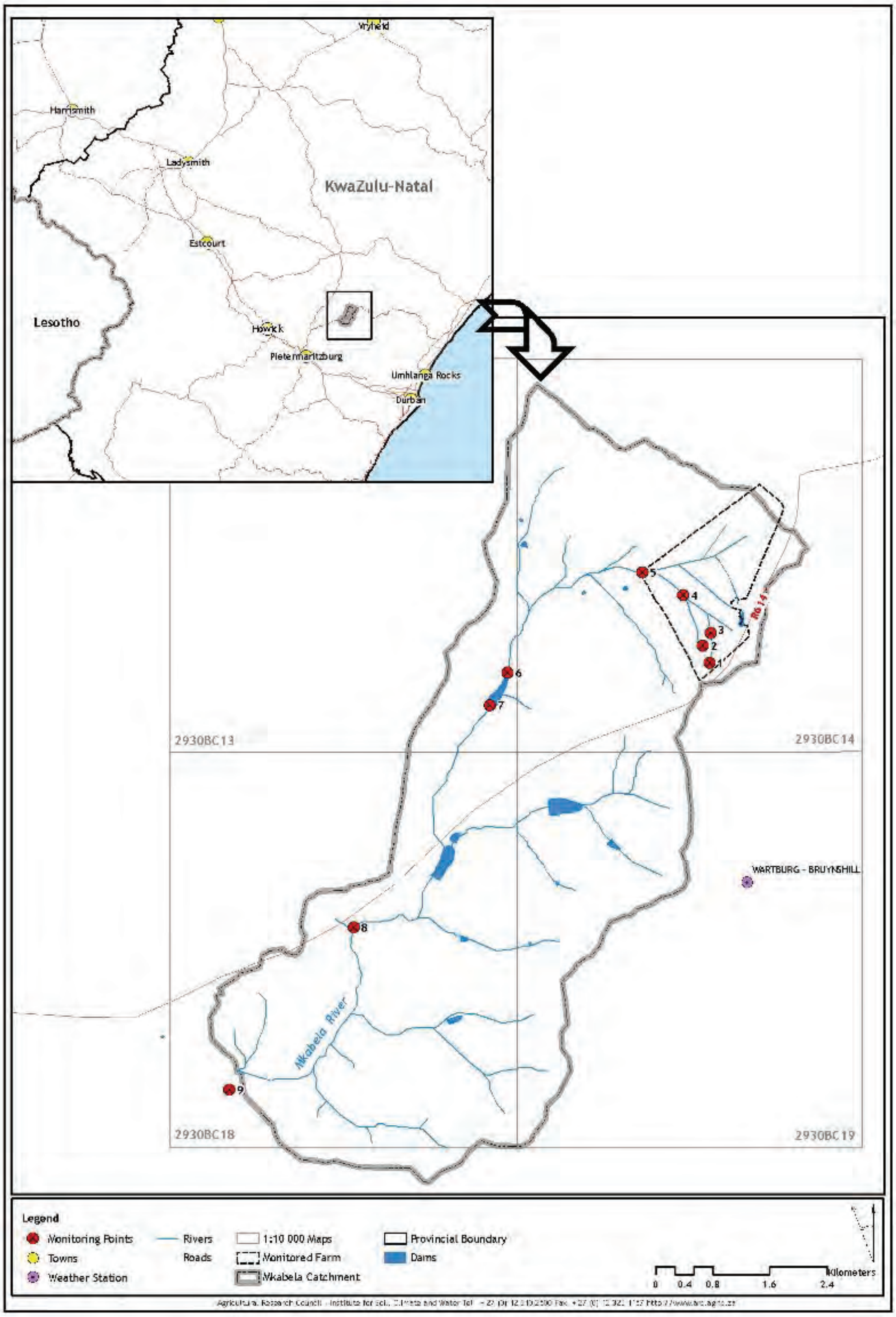


FIGURE 1 The Mkabela catchment showing nested sampling positions. (Germishuyse and le Roux, 2006)

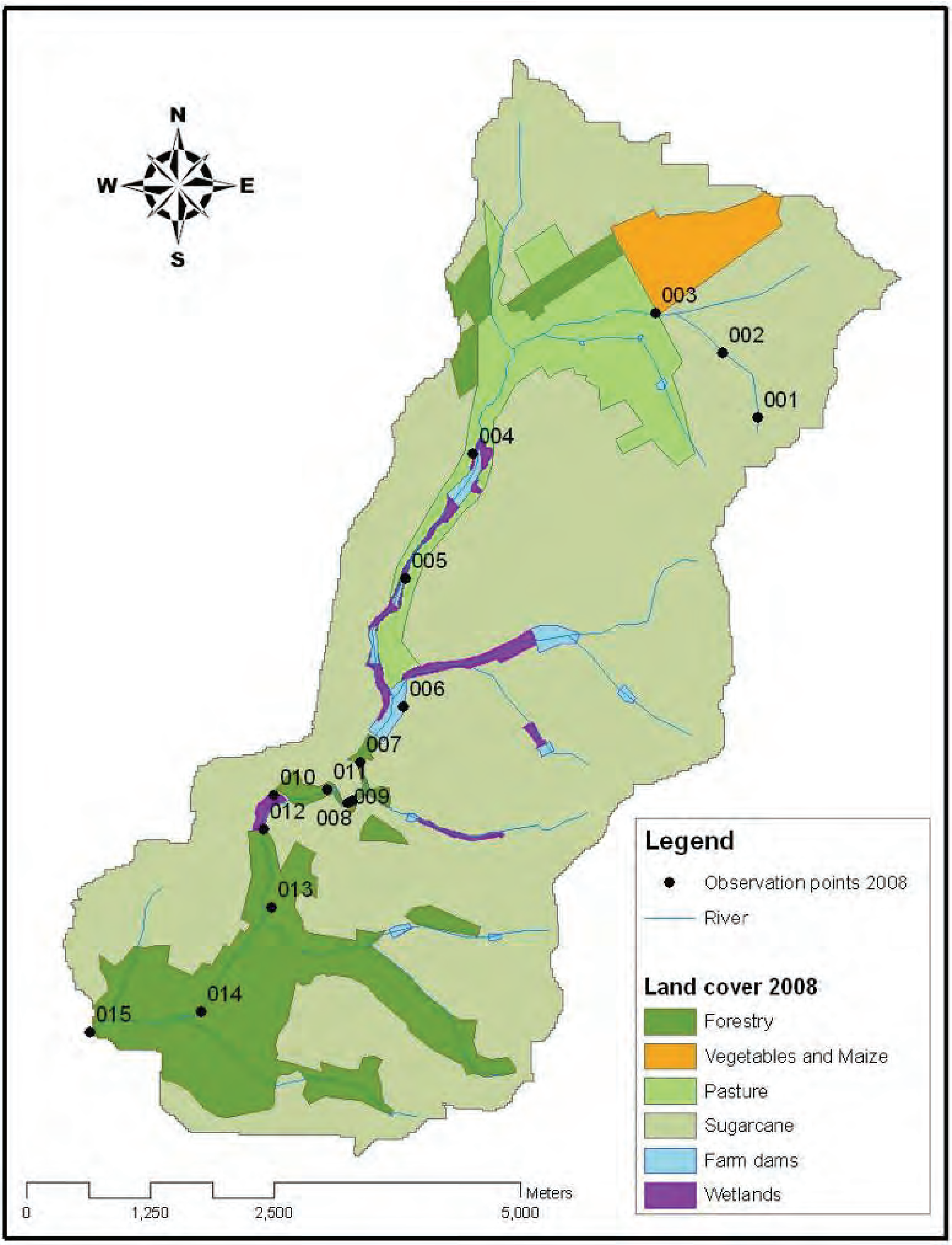


FIGURE 2 Land use in the Mkabela catchment.

TABLE 1 Land use and channel condition: 30 May 2008

Way-point (ref Fig 2)	Photo*	Channel and flow description	Land use description	Catchment area (ha)
1 (Flume 1)	1-3	Narrow, shallow and slow stream in grass waterway flowing towards flume 1	Sugarcane at Flume 1	17
2 (Flume 2)	4-7	Narrow, shallow and slow stream in grass waterway towards flume 2	Sugarcane at Flume 2	58
3 (Dirt road)	8-11 +35	Narrow, shallow and slow stream in grass waterway flowing under low water bridge/dirt road towards relatively large farm dam	Vegetable stand (cabbage) north of road and pasture south of road	330
4 (Dam inlet)	14-16	Relatively large farm dam surrounded by wetland	Pasture	888
5	17	Smaller (second) farm dam surrounded by wetland that extend downstream to bridge 1 into a third farm dam	Pasture	
6	18	Fourth farm dam adjacent to wetland (not used for grazing)	Sugarcane near stream adjacent to small wetland area	
7	20	Very small farm dam flowing under a low water bridge. From there the flow speed increases slightly	Small band of Black Wattles and Blue Gums adjacent to stream (surrounded by sugarcane fields)	
8	21	Flow velocity and discharge increases after tributary	Sugarcane west and trees mentioned above east of stream	
9	22-23	Channel widens to approximately 3 m and turbidity increases. A fire break extends into stream	Small band of Black Wattle and Blue Gum bush adjacent to stream (surrounded by pasture)	
10 (near Bridge 1)	28	Stream “flattens out” decreasing flow velocity through wetland before flowing into forestry area downstream	Sugarcane west and pasture east of stream	1500

Way-point (ref Fig 2)	Photo*	Channel and flow description	Land use description	Catchment area (ha)
11	24-27	Waterfall approximately 30 m. Water slightly more turbid	Small band of Black Wattle and Blue Gum bush adjacent to stream (surrounded by patch of natural grassveld within sugarcane)	
12	29	Water seems to be less turbid than waterfall after passing through the wetland before flowing into the forestry area	Poplar forest boundary	
13	30	Flow velocity and turbidity the same as above	Poplar forest with good ground cover	
14	31-32	Flow velocity decreases	Poplar forest with good ground cover	
15 (Bridge 2)	33-34	Flow speed relatively slow after passing through a wetland area under Poplar trees and deposition of sediment at outlet	Poplar forest with good ground cover	1310

*Available on request

2.1.2 Mkabela materials and methods

2.1.2.1 Mkabela climate

A full weather station was installed in the headwater research catchment in October 2007. The station comprised the following instrumentation:

- CR 200 Campbell Scientific data logger
  - RM Young wind sentry anemometer – model 03101
  - Vaisala Temperature/ RH probe – HMP 50-L
  - Texas Electronic Rain gauge – TES25 mm-L
- Apogee Silicon Pyranometer sensor.

The station was set up to record at hourly intervals. During the first year (October 2006-September 2007), 57 days of data were lost due to malfunction of the logger, while the remainder of the observation period (October 2007-2009) had no interruption.

2.1.2.2 Mkabela crop nutrients

Sugar cane nutrient requirements vary with age of the crop. Literature values for sugar cane nutrient uptake were extracted for use in bio-physical models and establishment of a mass balance. Farmer surveys were conducted to determine the land management during the period of observation.

2.1.2.3 Mkabela hydrological monitoring

Routine monitoring was conducted at various scales within the research catchment (Figure 1). Location of the sites where detailed monitoring was conducted in the upper headwater research catchment is shown in Figure 3.

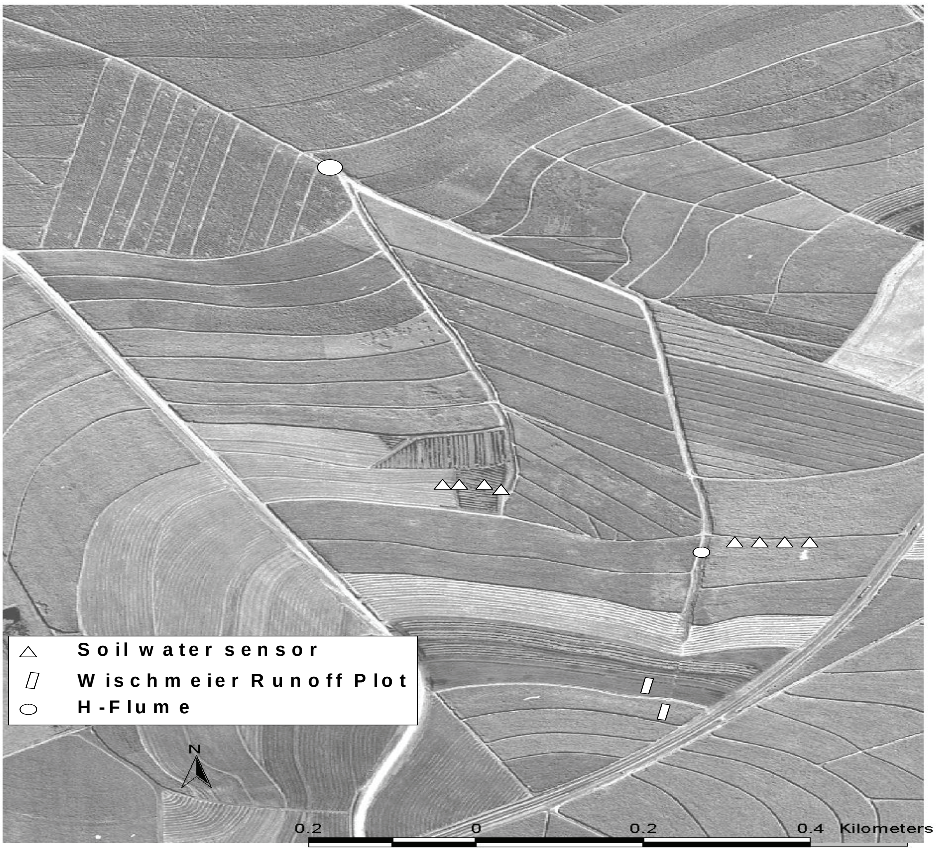


FIGURE 3 Layout of Instrumentation at the Mkabela Catchment, in the headwater sub-catchment.

The observation points and types of measurements consisted of the following:

- *Wischmeier runoff plots (22x2.4 m)*, where overland flow was sampled for sediment and nutrient analysis: The plots were established adjacent to one another, with the long axis perpendicular to the contours. The plots comprise a metal flow isolation boundary with a collector trough at the downslope end. Water is channeled to a flow baffle tank before discharging alternately into one of two tipping buckets (2litres) as shown in Figure 4. The number of tips and the timing is recorded via a magnetic switch onto an H07-002-04 HOBO event logger. The number of total tips is also recorded on a mechanical counter. The outflow from one of the buckets is directed into a splitter box, which has 5 equally sized outlets. One of these outlets discharges into a drum container, thus storing a sample of one tenth of the total runoff from the plot. The drum contents are thoroughly mixed before extracting a sample which is analysed to determine the average event sediment and nutrient concentrations.

FIGURE 4 Tipping bucket system, splitter box (left) and collector drum (right)

- *An upper flume* measuring runoff in a waterway and collecting samples automatically. This flume comprises a constructed H-Flume (Figure 5) with an ISCO sampler triggered by a specified flow volume, recorded by measuring the depth of flow in a stilling basin via a float and pulley apparatus.

FIGURE 5 Large H-flume in the headwaters of the Mkabela catchment

- *A lower flume* measuring runoff in a waterway and collecting samples automatically. This is identical to the upper flume, but designed for higher flows.
- Further downstream *a road crossing* is monitored.
- The inflow and outflow to *a farm dam* is measured.
- Further down the catchment monitoring occurs *at two bridge crossings* (Figure 1).

- At these *grab sampling sites*, the depth of flow was observed before, during and after certain events during 2005/2006 and samples were taken for sediment and nutrient analysis on each occasion.
- During the 2007-2008 monitoring period only *grab samples* were taken and concentrations of NO_3, P and suspended solids analysed.
- The *maize* was dryland and harvested every season around July/August. The *sugar cane* had a production cycle of some 18-20 months and was not irrigated.

2.1.2.4 Mkabela sediment analyses

In the laboratory, 200 ml or 100 ml of sample were shaken thoroughly and 5 ml of Hydrochloric acid was added to promote the flocculation of the suspended solids. To allow complete settlement of suspended solids, the mixtures were left overnight. After the sediments settled, the supernatant water was discarded carefully. The remaining wet sediments were oven dried overnight at 105°C. The sediment concentration was then determined as the dry mass of sediments divided by the volume of sample.

2.1.2.5 Nutrient analyses

Analyses of NO_3 and P were conducted with a HACH DR/2000 Direct Reading Spectrophotometer. Nitrate samples were generally analysed within one day of collection from the field. The Spectrophotometer was calibrated against known solutions of $KHPO_4$ and KNO_3 as detailed in Appendix B. The calibration results are presented in Figure 6 below.

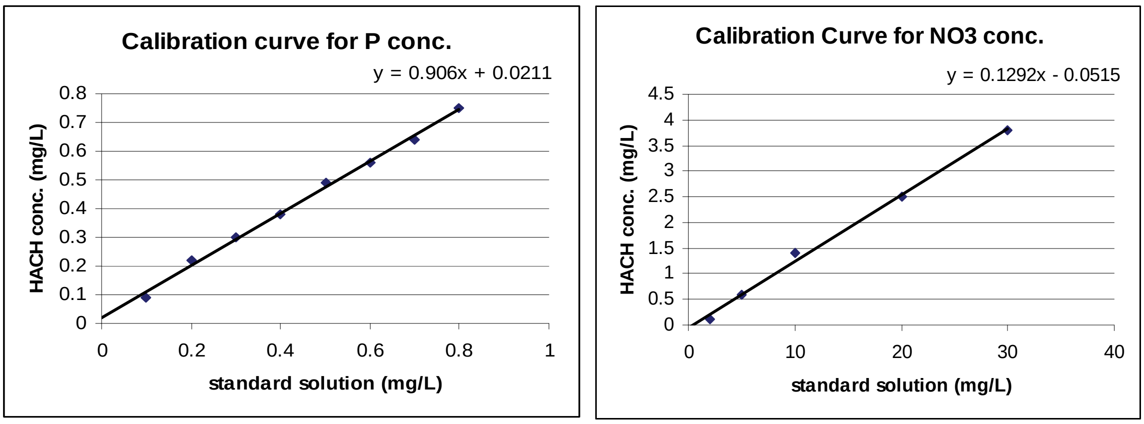


FIGURE 6 Calibration curve for P (left) and NO_3 right)

Values for field concentrations of P and NO_3 were derived by applying the inverse of the equations in Figure 6 to the measured values.

2.1.2.6 Soil water measurements

Soil water dynamics were monitored at 8 locations as indicated in Figure 3. Four of these locations comprise tensiometer nests in which automatic recording tensiometers had been installed in December 2006 at 300 mm, 600 mm and 1200 mm below surface. The nests were located in a transect across a waterway. A similar set of four nests of tensiometers (Watermarks) was installed in May 2007 in a drier location in the sugar cane area of the research catchment (Figure 3).

2.2 Mkabela continuous data sets

2.2.1 Mkabela local scale

2.2.1.1 Mkabela weather data

During the initial stages of the monitoring in the Mkabela catchment, a manual rain gauge was used to record rainfall events. Local meteorological stations were used to supplement the observations. In October 2006, an automatic recording meteorological station was installed and variables recorded at an hourly interval. The cumulative rainfall, solar radiation, ambient air temperature and wind speed are shown in Figures 7 to 10. The total rain recorded in the 2006/2007 and 2007/2008 hydrological years was 456 mm and 739 mm respectively. However, 57 days were not recorded in the 2006/2007 hydrological year and these values were patched with the use of local records.

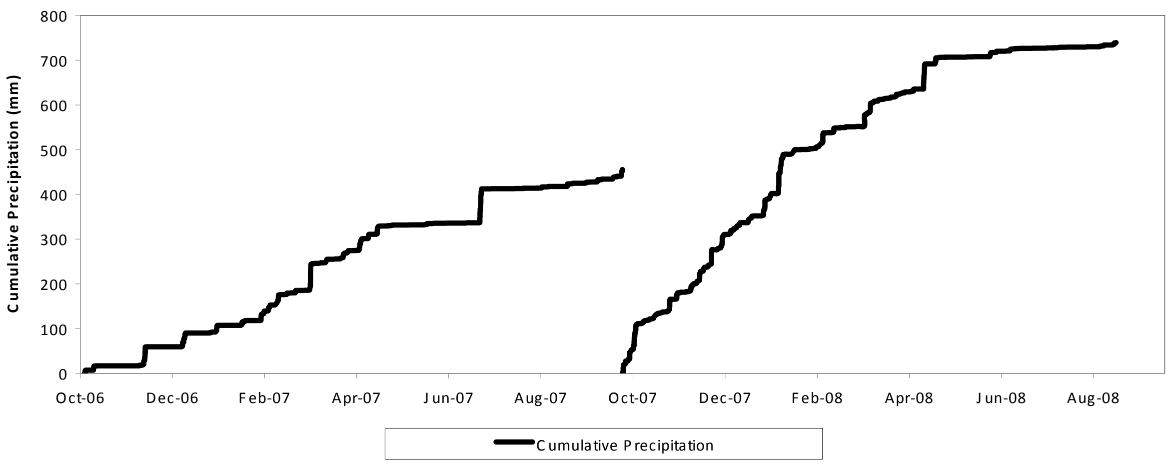


FIGURE 7 Cumulative rainfall for the Mkabela Catchment from 2006/7 (456 mm) and 2007/8 (739 mm) hydrological years.

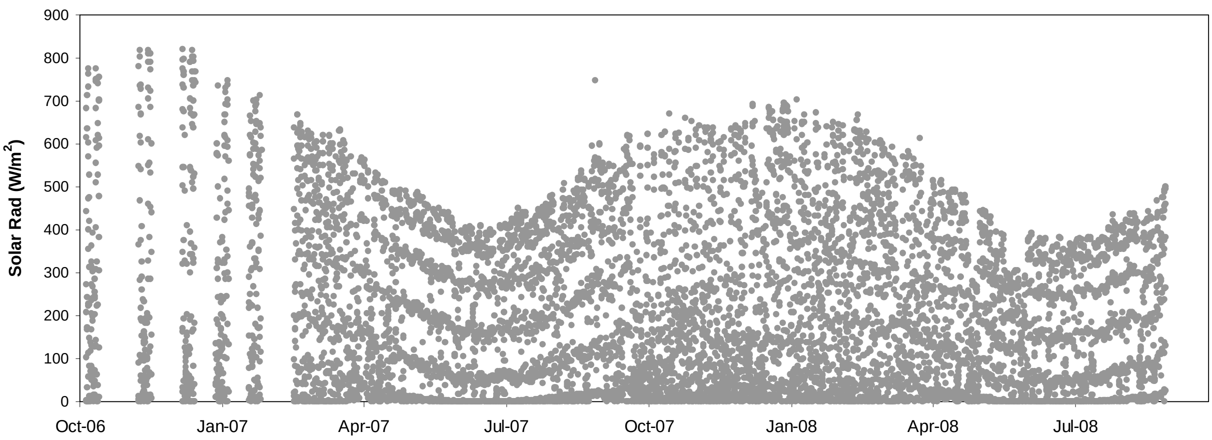


FIGURE 8 Hourly Solar Radiation for the Mkabela Catchment from October 2006 to September 2008.

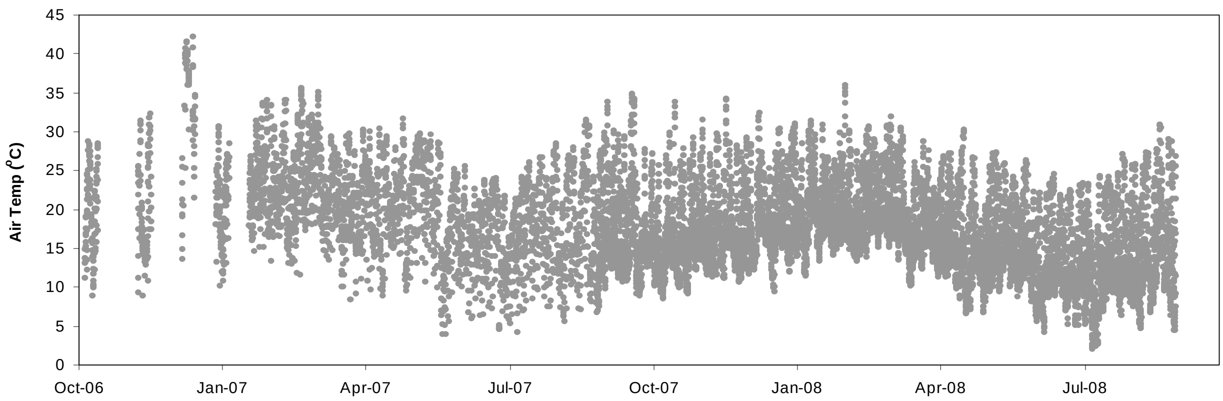


FIGURE 9 Hourly Temperature for the Mkabela Catchment from October 2006 to September 2008.

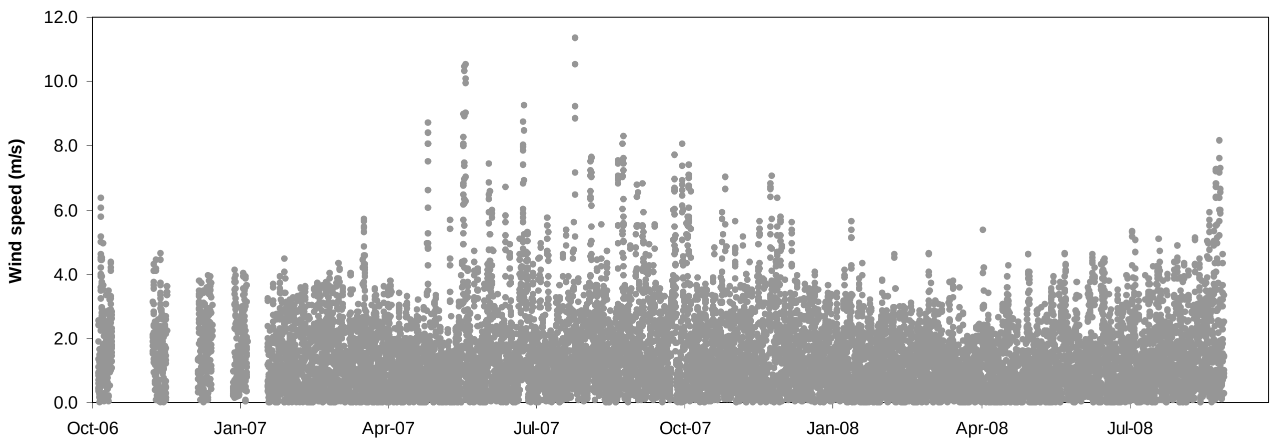


FIGURE 10 Hourly Wind speed for the Mkabela catchment from October 2006 to September 2008.

2.2.1.2 Mkabela crop nutrients

Organic fertilizers (in the form of commercially produced manure) are preferred to non-organic fertilizers (used prior to 2002). The Mkabela farmer did not use pesticides on his sugarcane, however weedacides and herbicides were applied to both maize and sugar cane. Table 2 describes the application schedules that are currently practiced.

Typical values for sugar cane nutrient uptake were provided by the SA Sugar Research Institute (Table 3).

TABLE 2 Weedicide and Fertilizer Application

Type	Sugarcane	Maize
Weedacides: Pre Planting		
Velpa K	2.4 L/ha	
MCPA	3 L/ha	
Tronic	0.5 L/ha	
Gardien		1.6 L/ha
Karate (Insecticide)		75 mL/ha
Weedacides**:** Post Emergence		
Cencor	3 L/ha	
Diuron	2 L/ha	
MCPA	3 L/ha	
Tronic	0.5 L/ha	
Gasaprin		3 L/ha
Turbo		1.5 L/ha
Fertilizers:	Organic fertilizers used since 2003, with a topdressing of LAN (150 kg/Ha) and manure	
At planting:		
321		200 kg/ha
LAN		200 kg/ha
Previous inorganic fertilizers used:		
Supets 10.5		
KCL	200 kg/ha	
LAN 28%	150 kg/ha	
	400 kg/ha	

TABLE 3 Nutrient Removal by 100t Sugar Cane Crop

Nutrient	Range (kg/100 ton crop)	Typical (kg/100 ton crop)
N	100-160	130
P	15-30	20
K	150-250	200
Ca	30-55	40
Mg	25-50	30
S	30-45	35

2.2.1.3 Runoff, sediments and nutrients

Typical examples of the responses are shown below for field-scale runoff and average sample concentration, while complete event analysis was completed for 18 events throughout the period of observation. These comprise 10 events in the wet season of 2005/2006, one event in the 2006/2007 wet season, one event in the dry season of 2007 and six events in the 2007/2008 wet season.

Typical examples of the runoff plot responses are shown for event 18 in Figure 11 for Runoff Plot 1 (RP1) and in Figure 12 for runoff plot 2 (RP2). RP1 consistently yielded more runoff than RP2, as its growth stage lags that of RP2. The average event concentrations of NO_3, P and suspended solids are similar for the runoff plots, but, with the higher runoff, RP1 yields higher loads than RP2. The loads are summarized for all eight events in Tables 4 (RP1) and 5 (RP2).

The summarized runoff plot data (Tables 4 and 5) show the total event rainfall; the antecedent 7-day rainfall (P_{-7}); the overland flow as a volume (mm) and as a percent of the rainfall; the average event concentration of the event discharge collected and the event load for NO_3, P and suspended solids. The surface runoff comprises a very small proportion of the rainfall, ranging between 0.2 and 3% of the event rain. The runoff observed at a larger scale (see Section 2.2.2) ranges between 1.6 and 68% of the rainfall, indicating the large proportion of subsurface contribution to event runoff.

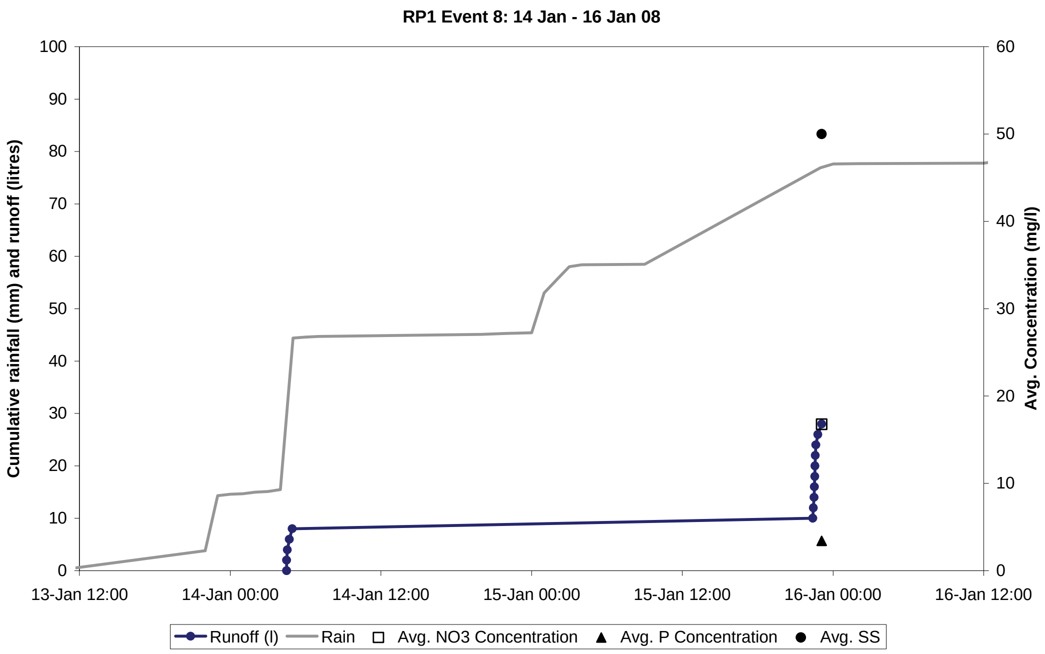


FIGURE 11 Runoff from RP1 and rainfall for event 8: 13-16 January 2008.

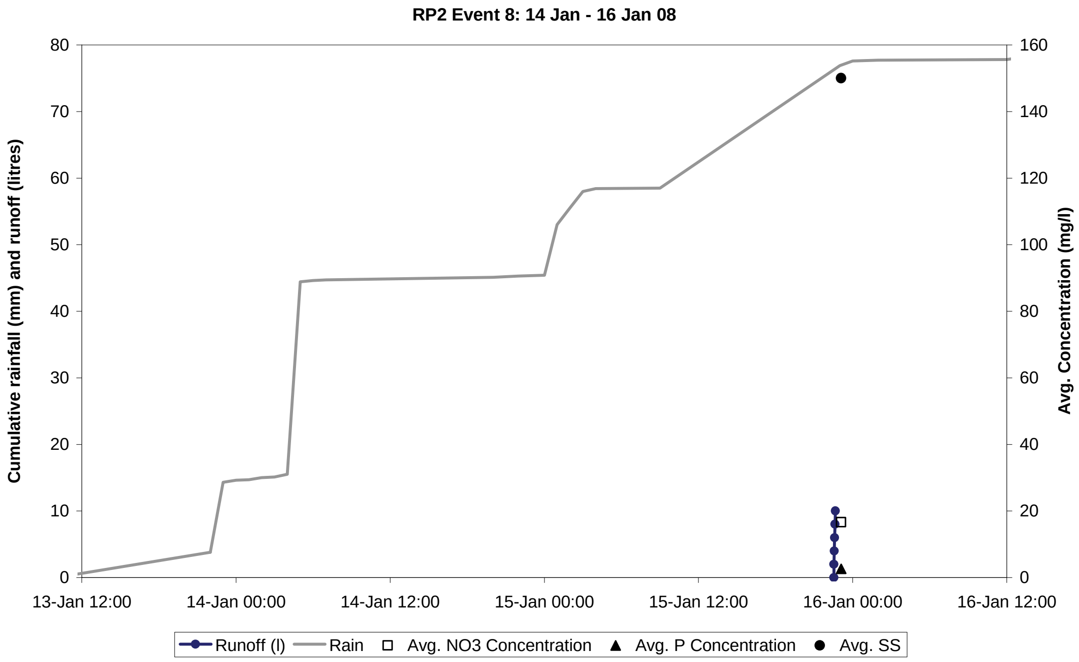


FIGURE 12 Runoff from RP2 and rainfall for event 8: 13-16 January 2008.

The NO_3 mass loads from the runoff plots range between 0.1 to 4.7g from RP1 and are consistently lower in RP2. The NO_3 loading observed is equivalent to 0.0015t/ha for the period October 2007 to February 2008. The total P load for RP1 amounts to 5.6×10^{-5}t/ha and the suspended solids load is 0.03t/ha for the observed period.

TABLE 4 Runoff Plot 1: Rainfall/Runoff And Mass Loading For Events: Nov 2005-Jan 2008

Event	Date	Rain	P_{-7}	Runoff		Concentration			Load		
						NO_3	P	SS	NO_3	P	SS
		mm	mm	mm	%	mg/l	mg/l	mg/l	g	g	g
1	6-Nov-05	22.00		3.35					2.226		
2	18-Nov-05	18.00		0.80					0.284		
3	10-Dec-05	30.00		3.67					2.309		
4	1-Jan-06	47.00		5.45					3.861		
5	18-Jan-06	29.00		2.25					0.811		
6	6-Feb-06	13.00		2.58					1.331		
7	3-Mar-06	17.40		0.40					0.076		
8	12-Mar-06	18.00		0.84					0.008		
9	28-Mar-06	16.00									
10	28-Apr-06	11.00									
11	21-Dec-06	60.00	4	0.33	0.66						
12	28-Jun-07	50.60	4.3	0.08	0.16						
13	8-10 Oct 07	47.00	67.6	0.29	0.62	24.2	3.01	200	0.35	0.042	2.8
14	1-9 Nov 07	30.80	9.2	0.12	0.4	16.7	0.96	600	0.1	0.006	3.6
15	30-Nov-07	30.40	20.8	0.79	2.58	124.2	2.46	1900	4.72	0.093	72.2
16	7-Dec-07	14.90	11.6	0.21	1.39	62.3	0.8		0.62	0.008	0
17	4-Jan-08	14.20	1.5	0.25	1.75	62.3	2.18	4550	0.75	0.026	54.6
18	14-16 Jan 08	61.40	12.4	0.58	0.94	16.8	3.4	50	0.47	0.095	1.4

TABLE 5 Runoff Plot 2: Rainfall/Runoff And Mass Loading For Events: Nov 2005-Jan 2008

Event	Date	Rain	P_{-7}	Runoff		Concentration			Load		
						NO_3	P	SS	NO_3	P	SS
		mm	mm	mm	%	mg/L	mg/L	mg/L	g	g	g
1	6-Nov-05	22.0		2.51					1.65		
2	18-Nov-05	18.0		0.36					0.15		
3	10-Dec-05	30.0		1.82					1.07		
4	1-Jan-06	47.0		2.65					1.83		
5	18-Jan-06	29.0		0.44					0.18		
6	6-Feb-06	13.0		0.87					0.40		
7	3-Mar-06	17.4		0.65					0.15		
8	12-Mar-06	18.0		0.69					0.01		
9	28-Mar-06	16.0									
10	28-Apr-06	11.0									
11	21-Dec-06	50.0	4.0	1.65	3.31			533			42.6
12	27-28 Jun 07	50.6	1.3	0.37	0.73						
13	1-10 Oct 07	67.6	21.8	0.29	0.43	11.2	3.01	200	0.16	0.042	2.8
14	1-Nov-07	7.1	9.2	0.04	0.58	18.2	0.97	150	0.04	0.002	0.3
15	30-Nov-07	24.7	20.8	0.12	0.5	50.7	2.07	5250	0.3	0.012	31.5
16	7-Dec-07	14.9	11.6	0.08	0.55	39.1	1.74	200	0.16	0.007	0.8
18	8 -16 Jan 08	85.8	12.4	0.29	0.34	16.7	2.63	150	0.23	0.037	2.1

2.2.1.4 Soil profile nitrate content

Profiles of nitrate content in the soil at 10 locations were extracted in May 2008. The locations and details of these analyses are presented in Appendix C. Most profiles show nitrate contents between 5 and 10 mg/kg (Figures 13 and 14), but a harvested field below RP2 had a high surface nitrate content (25 mg/kg), possibly due to recent fertilization. The nitrate content of the profile inside RP1 had a high nitrate content below 200 mm.

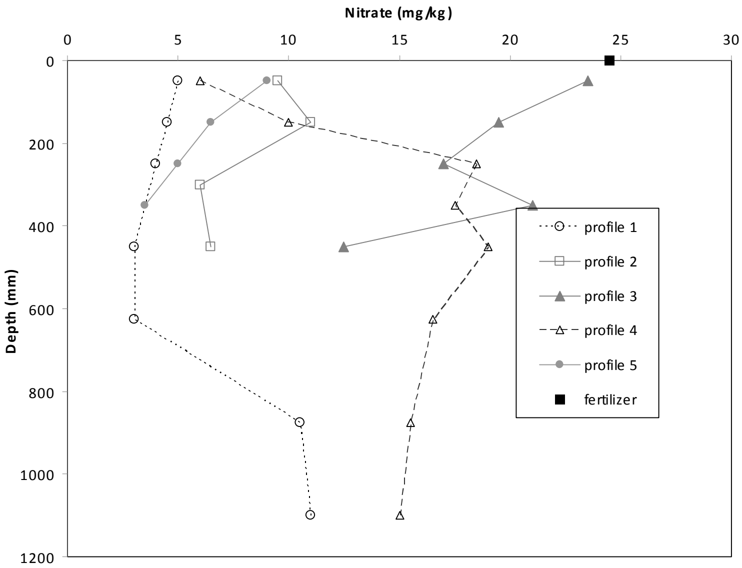


FIGURE 13 Soil Profile Nitrate Variation: Profiles 1-5, May 2008

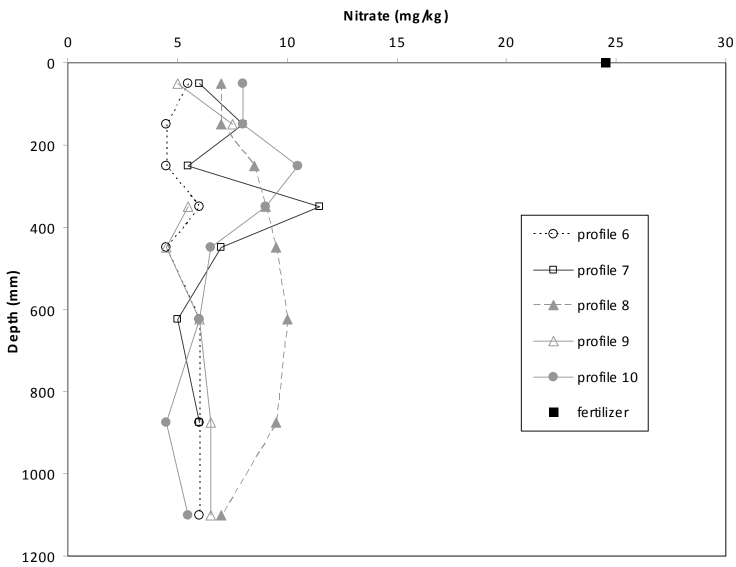


FIGURE 14 Soil Profile Nitrate Variation: Profiles 6-10, May 2008.

2.2.1.5 Soil water dynamics

Excellent results have been obtained from the tensiometer soil water tension records. A typical example is shown in Figures 15 to 18 for stations 5 to 8. The profiles near the waterway (Nests 1 and 2) have considerably lower tensions (wetter) than those further from the waterway (Nests 3 and 4), indicating the accumulation of moisture adjacent to the waterways. Considerable wetting occurs at all profiles in the upper 400 mm due to rainfall on 5 January 2008 (25 mm).

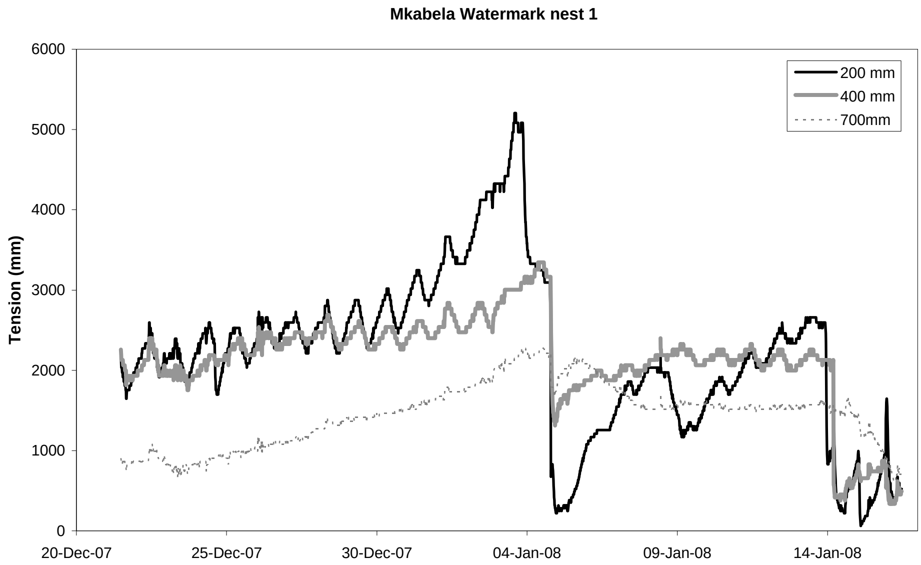


FIGURE 15 Soil Water Tension Variation: Nest 1, from 20 Dec 2007- 17 January 2008.

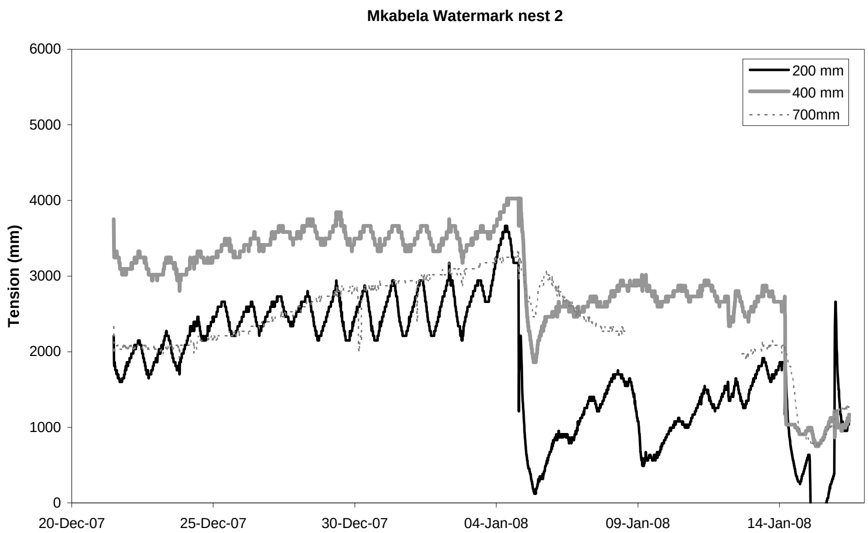


FIGURE 16 Soil Water Tension Variation: Nest 2, from 20 Dec 2007- 17 January 2008.

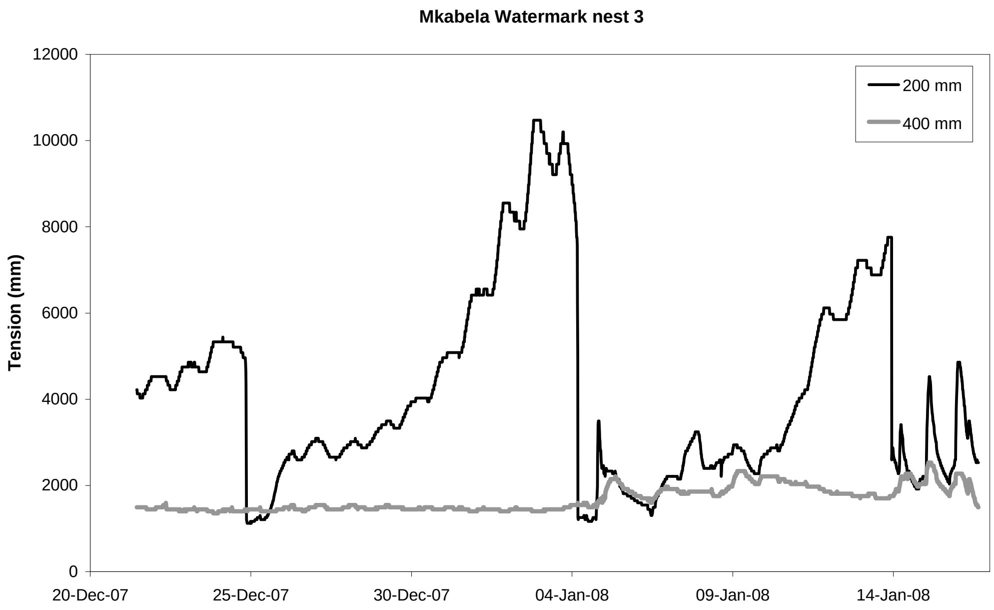


FIGURE 17 Soil Water Tension Variation: Nest 3, from 20 Dec 2007- 17 January 2008

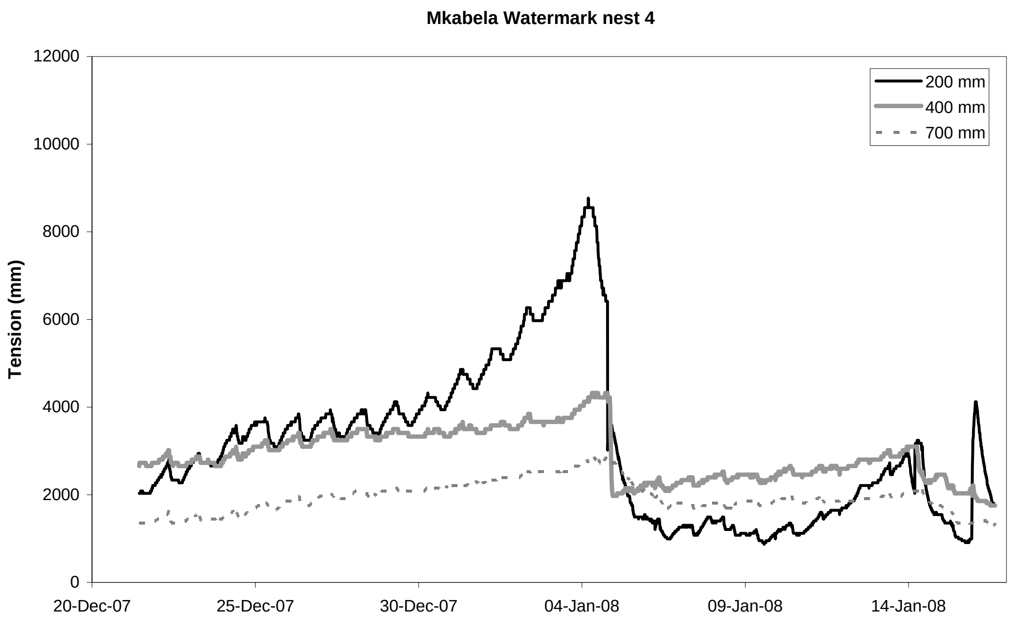


FIGURE 18 Soil Water Tension Variation: Nest 4, from 20 Dec 2007- 17 January 2008.

2.2.2 Mkabela field-scale

2.2.2.1 Rainfall and runoff

Runoff at the field scale is monitored at Flume 1 and Flume 2 (Figure 19, Table 6). The rainfall and runoff characteristics of the flumes are shown for Flume 1 in Figure 19 and for Flume 2 in Figure 20 for October 2006 to September 2008.

The events selected for load analysis are shown with the Flume 2 runoff in Figure 20. The maximum runoff rates for the upper flume range between 0.2 and 0.55 m^3/s while those in the lower flume range between 1.2 and 1.4 m^3/s. It seems that a rainfall event of 30 mm or more will generate these peak flows.

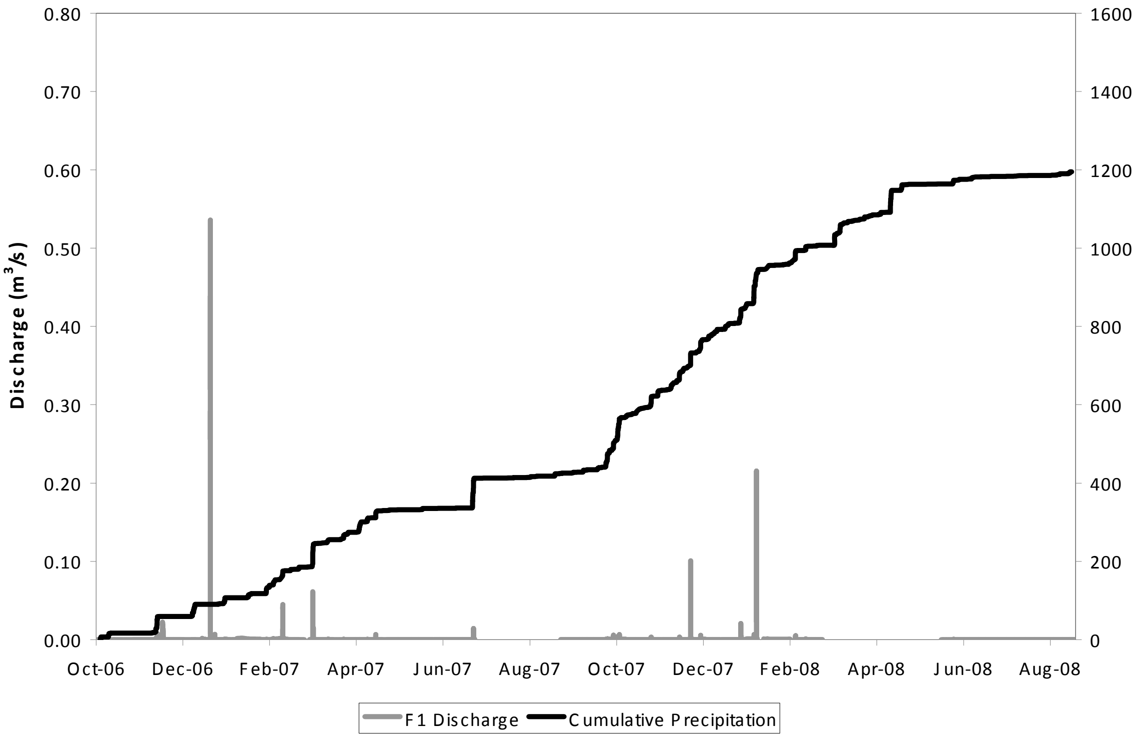


FIGURE 19 Rainfall/Runoff at Flume 1 (F1) of the Mkabela Catchment for October 2006 to September 2008.

2.2.2.2 Sediment and nutrient loads

The complete time series of observed flows and concentrations for Flume 1 (F1) and Flume 2 (F2) are shown in Figures 19 to 28. Concentrations of NO_3 and P were measured at the flumes during the period October 2007 to March 2008. These data were used to derive event loads for the flume stations, whereas suspended solids were measured from December 2006 onwards.

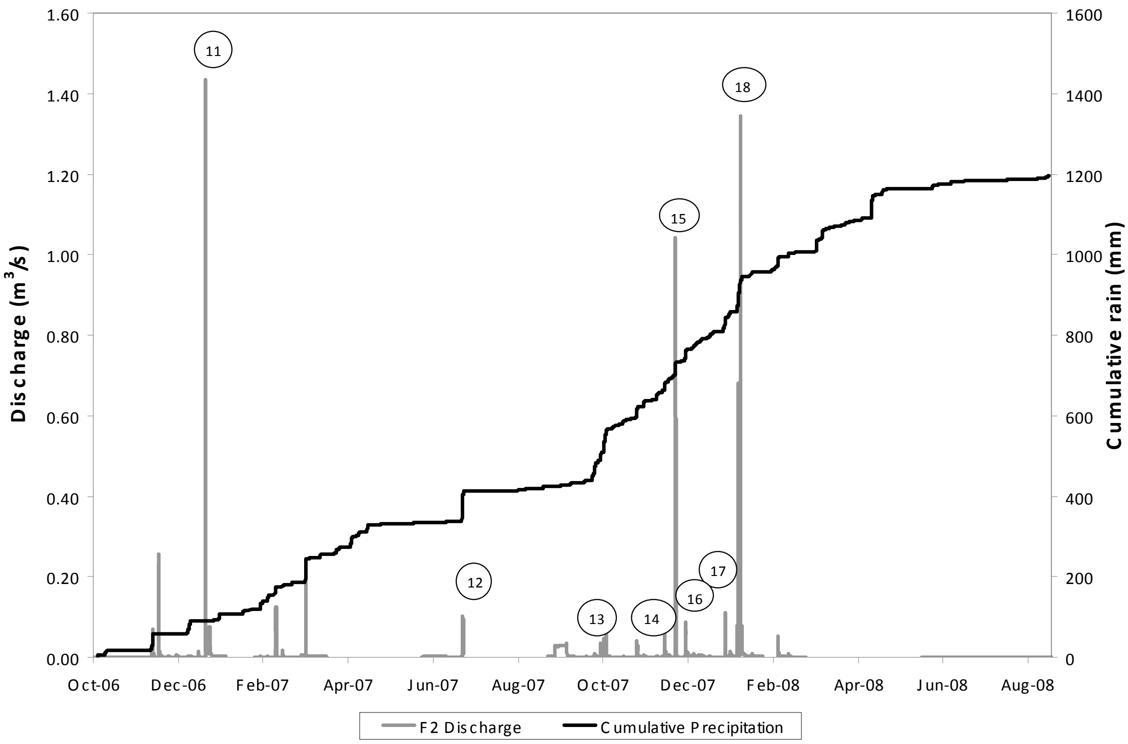


FIGURE 20 Rainfall/Runoff at Flume 2 (F2) of the Mkbala Catchment for October 2006 to September 2008. Labelled events are estimated separately.

It is clear from responses to the events that concentrations of NO_3, P and suspended solids all increase during the high flows of the high rainfall events. This reflects the significant uptake of mass of these species during an event. No dilution of these species during high flows is evident. A complete set of runoff and NO_3 responses for the selected events are shown in Table 6 for Flume 1 and Table 7 for Flume 2. Mass loadings have been derived for these by disaggregating the response hydrographs and determining the incremental mass, ΔM, for each segment by:

$$\Delta M = Q.C.\ \Delta t$$

Where Q is the average discharge, C the average concentration and Δt the incremental time for a specific load segment. The loads at F1 are always less than F2 by 5 to 10 times and yet the catchment area of F2 is only 3.5 times that of F1. This reflects the increasing contribution to discharge and mass transport nearer the lower slopes of the small catchment. Runoff ranges between 1.6% and 28% at F1 and between 2.7% and 33% at F2. Clearly, antecedent conditions affect the runoff and mass loading. Tables 6 and 7 list the summarized datasets.

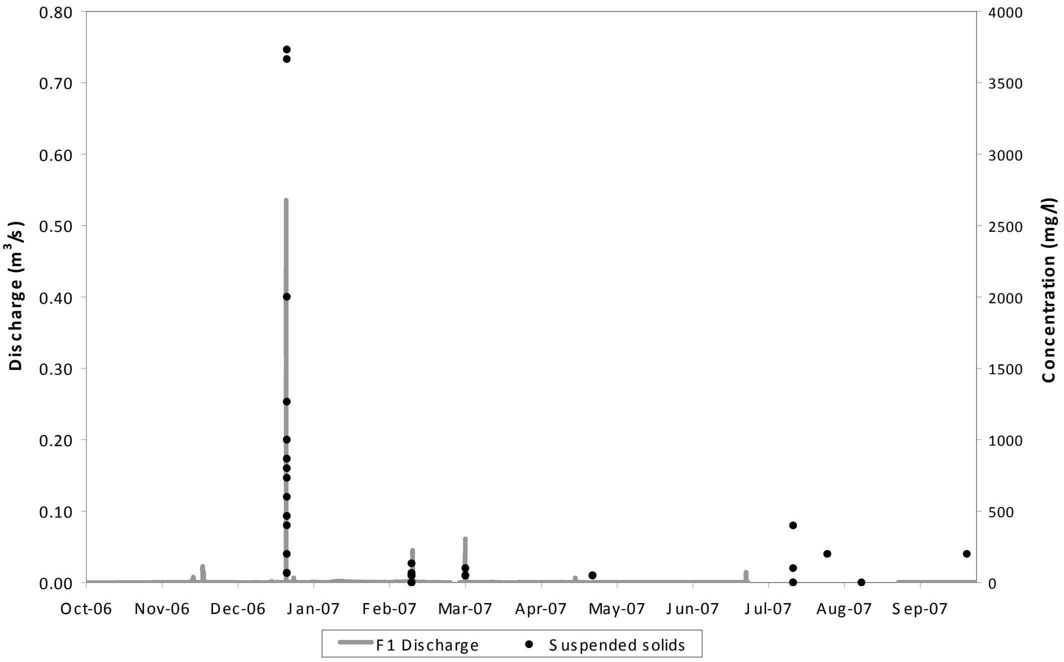


FIGURE 21 Runoff and Suspended Solids Concentrations at Flume 1 (F1) of the Mkabela Catchment for October 2006 to September 2007.

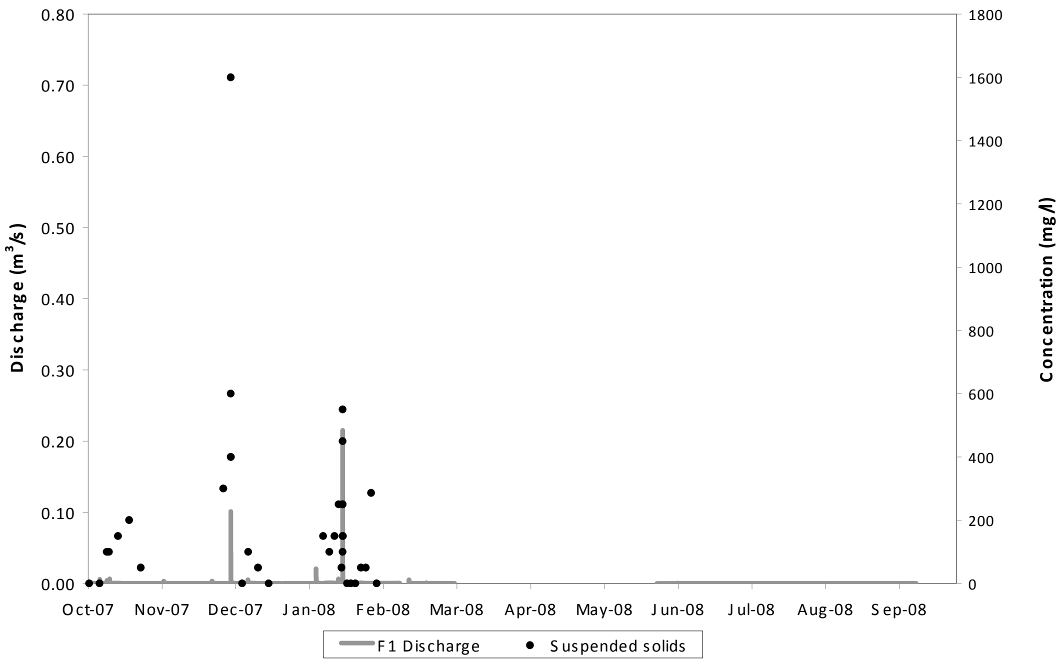


FIGURE 22 Runoff and Suspended Solids Concentrations at Flume 1 (F1) of the Mkabela Catchment for October 2007 to September 2008.

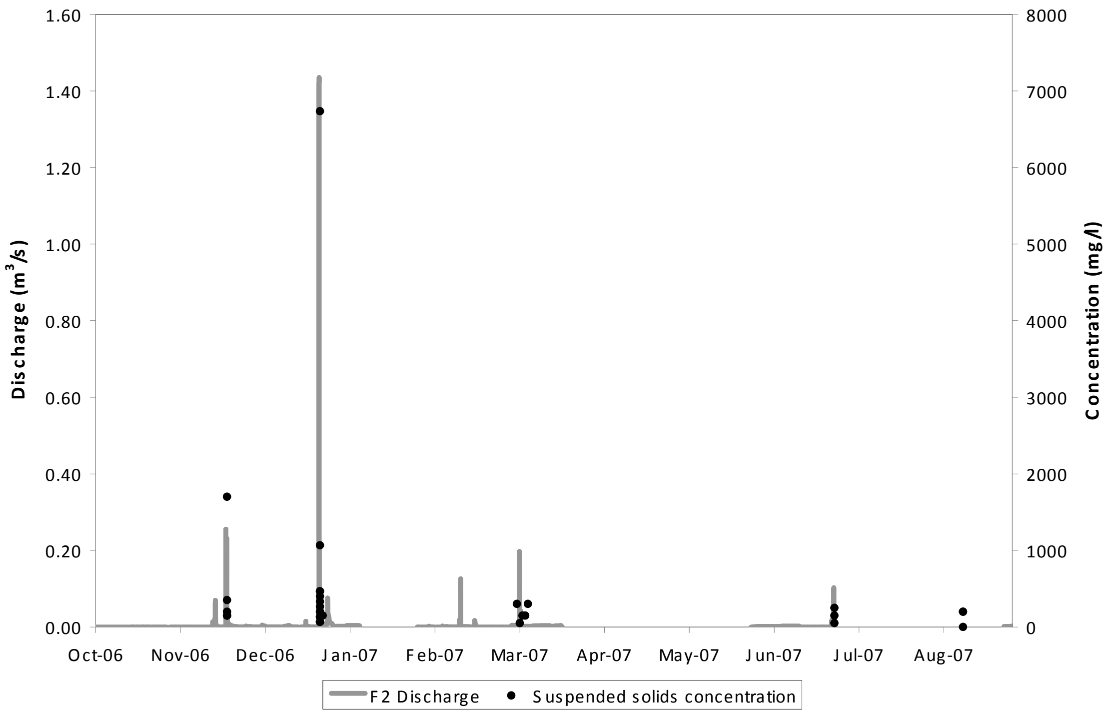


FIGURE 23 Runoff and Suspended Solids Concentrations at Flume 2 (F2) of the Mkabela Catchment for October 2006 to September 2007.

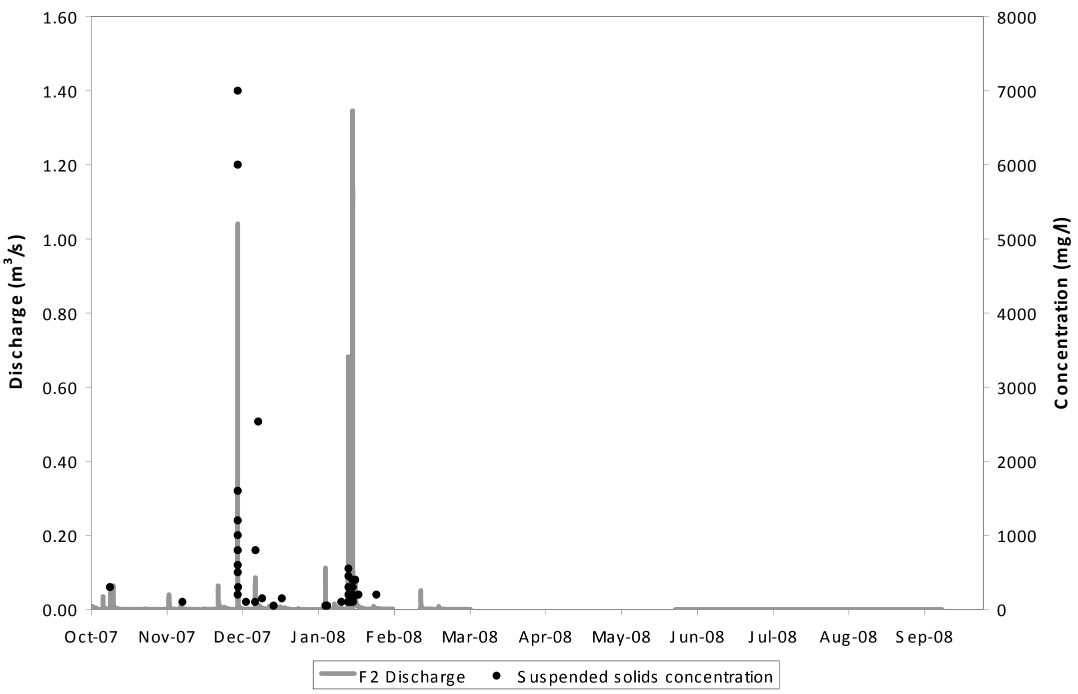


FIGURE 24 Runoff and Suspended Solids Concentrations at Flume 2 (F2) of the Mkabela Catchment for October 2007 to September 2008.

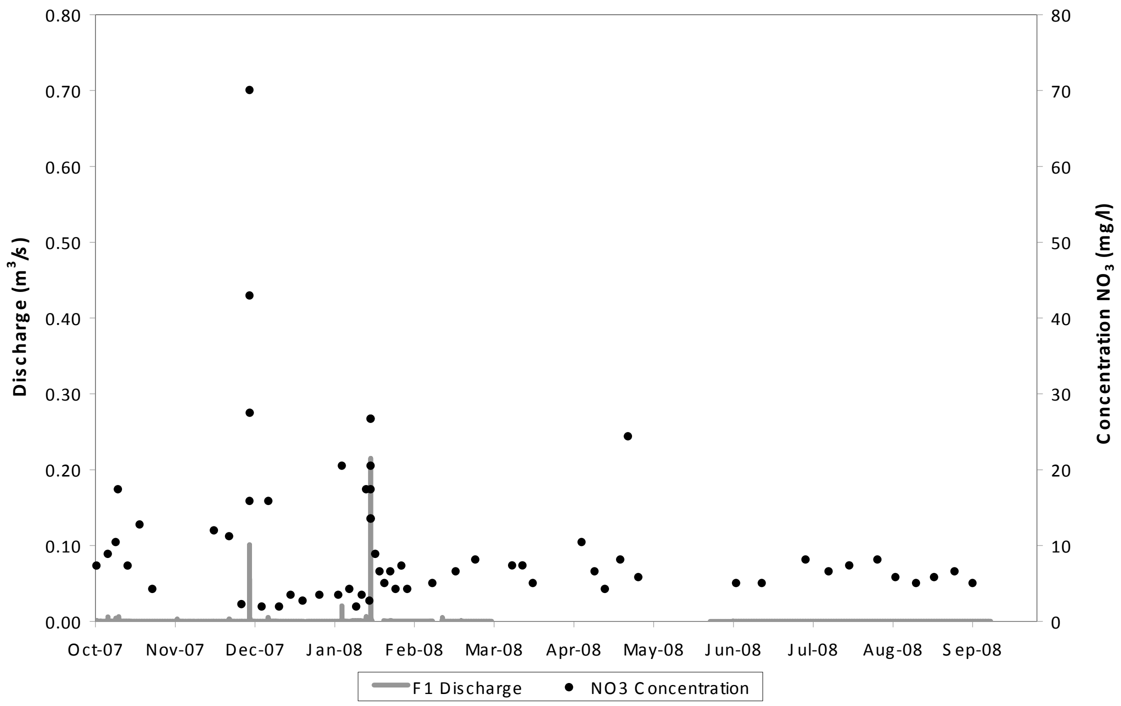


FIGURE 25 Runoff and Nitrate Concentrations at Flume 1 (F1) of the Mkabela Catchment for October 2007 to September 2008.

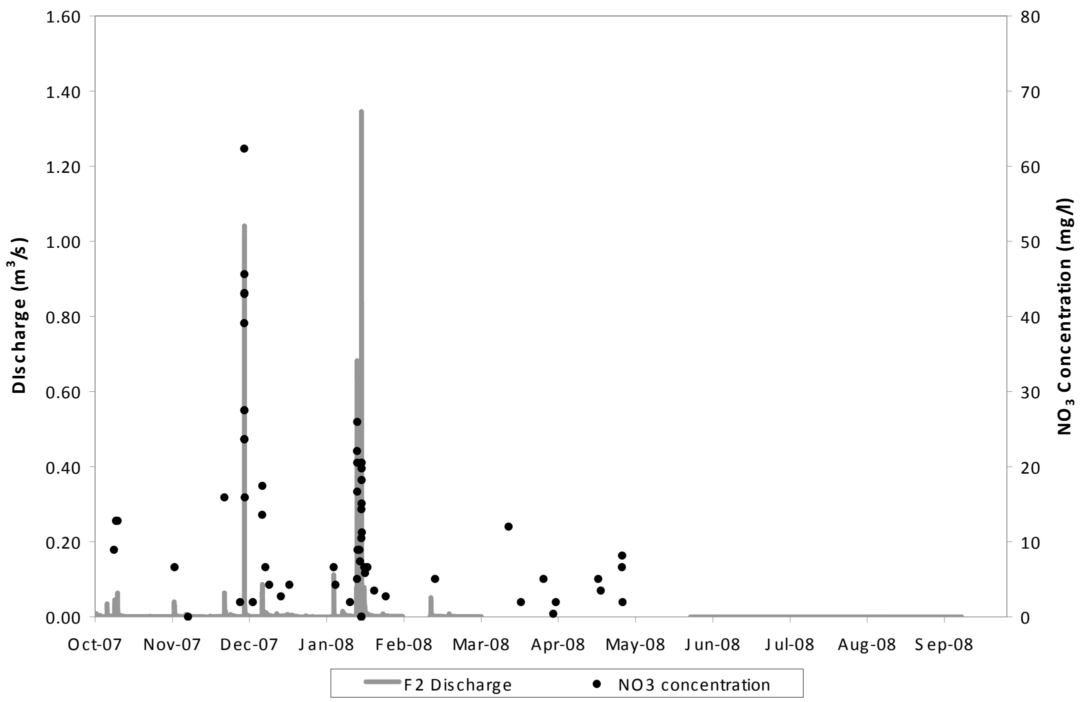


FIGURE 26 Runoff and Nitrate Concentrations at Flume 2 (F2) of the Mkabela Catchment for October 2007 to September 2008.

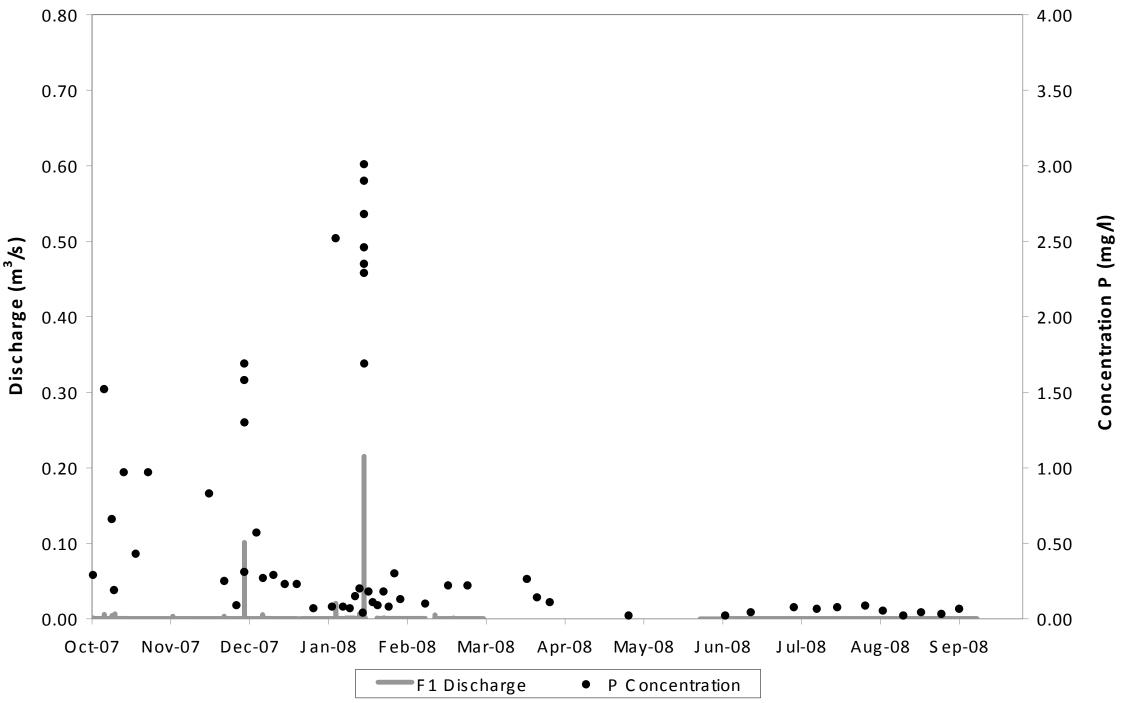


FIGURE 27 Runoff and P Concentrations at Flume 1 (F1) of the Mkabela Catchment for October 2007 to September 2008

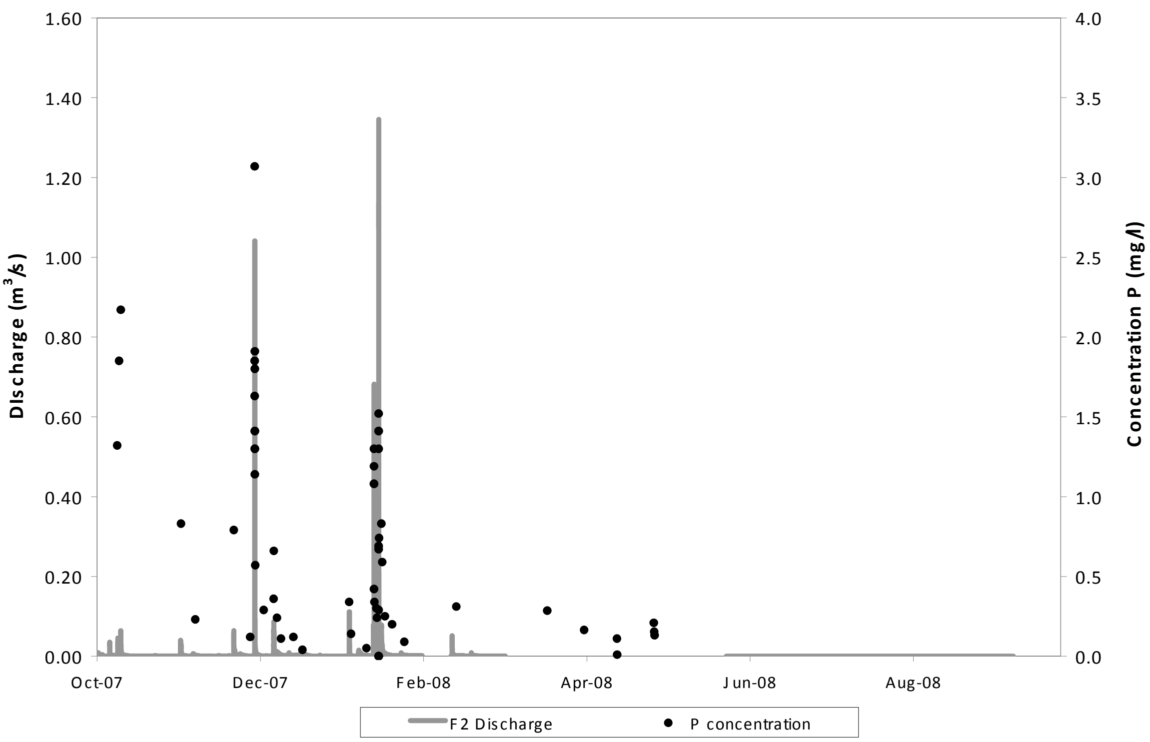


FIGURE 28 Runoff and P Concentrations at Flume 2 (F2) of the Mkabela Catchment for October 2007 to September 2008

TABLE 6 Flume 1: Rainfall/Runoff and Flume Loading for Events 1-18

Event	**Date**	**Rain**	**P$_{-7}$**	**Runoff**		**Load**		
						NO_3	P	SS
		mm	Mm	mm	%	kg	kg	kg
1	06-Nov-05	22.0				0.39		
2	18-Nov-05	18.0				0.19		
3	10-Dec-05	30.0				0.73		
4	01-Jan-06	47.0				3.01		
5	18-Jan-06	29.0				1.10		
6	06-Feb-06	13.0				0.23		
7	03-Mar-06	17.4						
8	12-Mar-06	18.0				0.23		
9	28-Mar-06	16.0						
10	28-Apr-06	11.0				0.00		
12	08-Oct-07	28.3	67.6	0.44	1.6	0.79	0.51	7
14	01-Nov-07							
15	30-Nov-07	33.5	20.8	2.19	6.5	14.70	0.45	289
16	07-Dec-07	17.3	11.6	0.64	3.7	1.70	0.03	11
17	04-Jan-08	20.4	15.5	0.57	2.8	2.00	0.24	
18	16-Jan-08	32.3	54.4	9.03	28	31.70	3.33	424

TABLE 7 Flume 2: Rainfall/Runoff and Mass Loading for Events 1-18

Event	Date	Rain	P_{-7}	Runoff		Load		
						NO_3	P	SS
		mm	mm	mm	%	kg	kg	kg
1	06-Nov-05	22						
2	18-Nov-05	18						
3	10-Dec-05	30						
4	01-Jan-06	47				8.52		
5	18-Jan-06	29				2.72		
6	06-Feb-06	13						
7	03-Mar-06	17.4				0.41		
8	12-Mar-06	18						
9	28-Mar-06	16				0		
10	28-Apr-06	11						
13	08-Oct-07	28.3	67.6	0.8	2.7	4.1	0.7	130
14	01-Nov-07	25	9.2	1.2	4.9	4.7	0.6	80
15	30-Nov-07	33.5	20.8	11.3	33.8	171.9	8	7850
16	07-Dec-07	17.3	11.6	2.1	12	18.1	0.6	950
17	04-Jan-08	20.4	15.5	1.9	9.1	7.1	0.4	50
18	16-Jan-08	32.3	54.4	8.3	25.6	81.6	4.9	700

2.2.3 Mkabela catchment-scale

2.2.3.1 Catchment nitrate loads: Nov 2005-Apr 2006

The resultant unit area loading of segments of the Mkabela catchment are summarized in Table 8.

The influence of the dirt road crossing, where water and sediments are delayed in a roadside cutting, prior to discharging over the road, is easily recognized by the drop in sediment loading at this sample point. The loading rate between the Dam In and Dam Out point also generally indicates a negative loading (retention of Nitrate) through the dam. However, the events 6 November 2005 and 10 December 2005 show a positive NO_3 yield/area in the dam. This is likely due to the flushing of nutrients from the dam on these occasions. Beyond the dam, NO_3 loading rates increase, often the large catchment areas reflect loading rates/unit area as high as in the small catchment served by the flumes. Clearly, structures such as wetland, impoundments and dams have a large influence on fluxes in the catchment.

TABLE 8 Large-Catchment NO_3 (kg) Loads: November 2005-April 2006

	06-Nov-05	18-Nov-05	10-Dec-05	01-Jan-06	18-Jan-06	06-Feb-06	03-Mar-06	12-Mar-06	28-Mar-06	28-Apr-06
Dirt Road	0.267	0.09	0.376	0.41	0.09	0.39	0.03	0.01	0	0.03
Dam In	0.081	0.54	1.875	2.83	1.16	0.42	2	1.41	0.07	0.05
Dam Out	1.051	0.21	6.726	0.43	0.34	0.085	0.71	1.24	0.02	0.02
Bridge 1	42.34	20.9	25.97	21.4	6.42	0.923	3.37	1.86	0.62	0.01
Bridge 2	74.17	35.0	58.23	61.6	6.5	2.09	5.87	4.77	0.61	0.73

2.2.3.2 Catchment sediment, nitrate and phosphorus loads: Oct 2007-Sep 2008

Suspended solids dynamics are shown in Figures 29 and 30. Nitrate responses are shown in Figures 31 and 32 and P responses in Figures 33 and 34. Notable is the drop in concentration after the road crossing sampling point, which is the outlet of the sugar cane catchment. Between the road crossing and the reservoir (dam in) sampling point there is a wetland, which should reduce the concentrations of NO_3 and P. The concentrations at the “dam in” sampling point are not always higher than the “dam out” concentrations, indicating that the reservoir may not always function as a NO_3-N and P sink. Between the “dam out” sampling point and the Bridge 1 station, concentrations increase and, since discharge increases downstream, the loads are clearly increasing with added contributions lower in the catchment. This same trend is evident between the Bridge 1 and Bridge 2 sampling points.

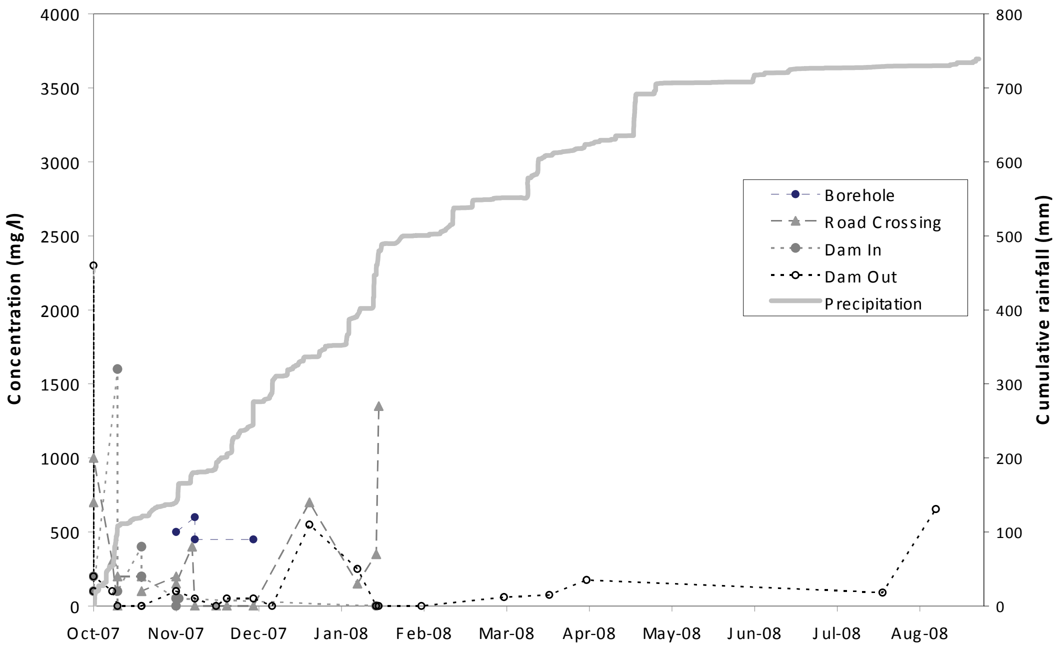


FIGURE 29 Rainfall and Suspended Solids responses from the Road Crossing to the Dam Out, including the groundwater stations of the Mkabela Catchment for October 2007 to September 2008.

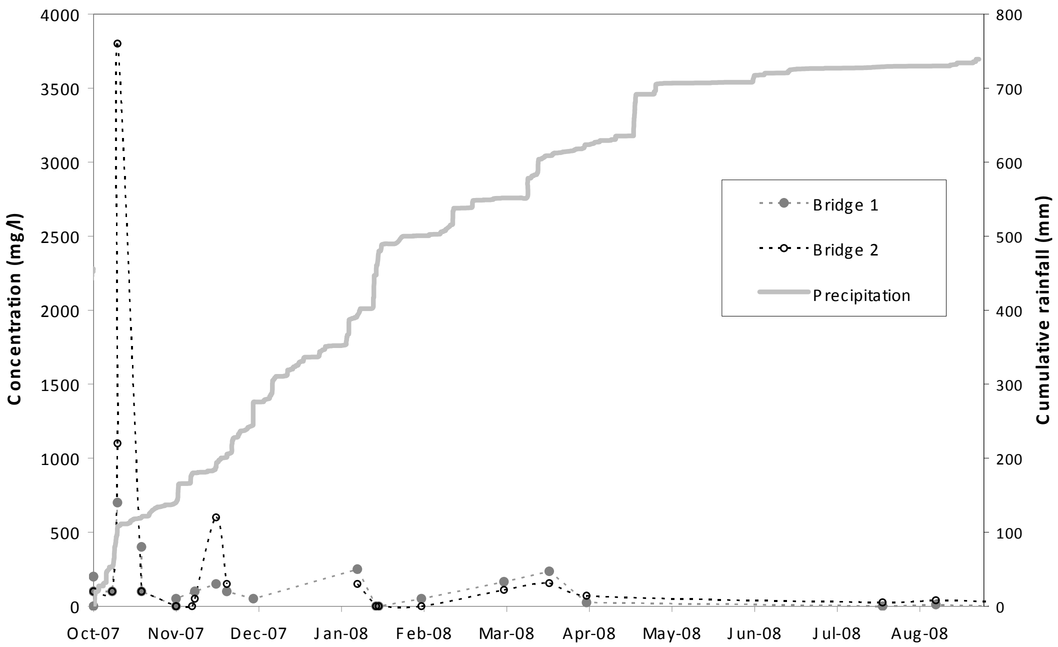


FIGURE 30 Rainfall and Suspended Solids responses from the Bridge 1 to the Bridge 2 stations of the Mkabela Catchment for October 2007 to September 2008.

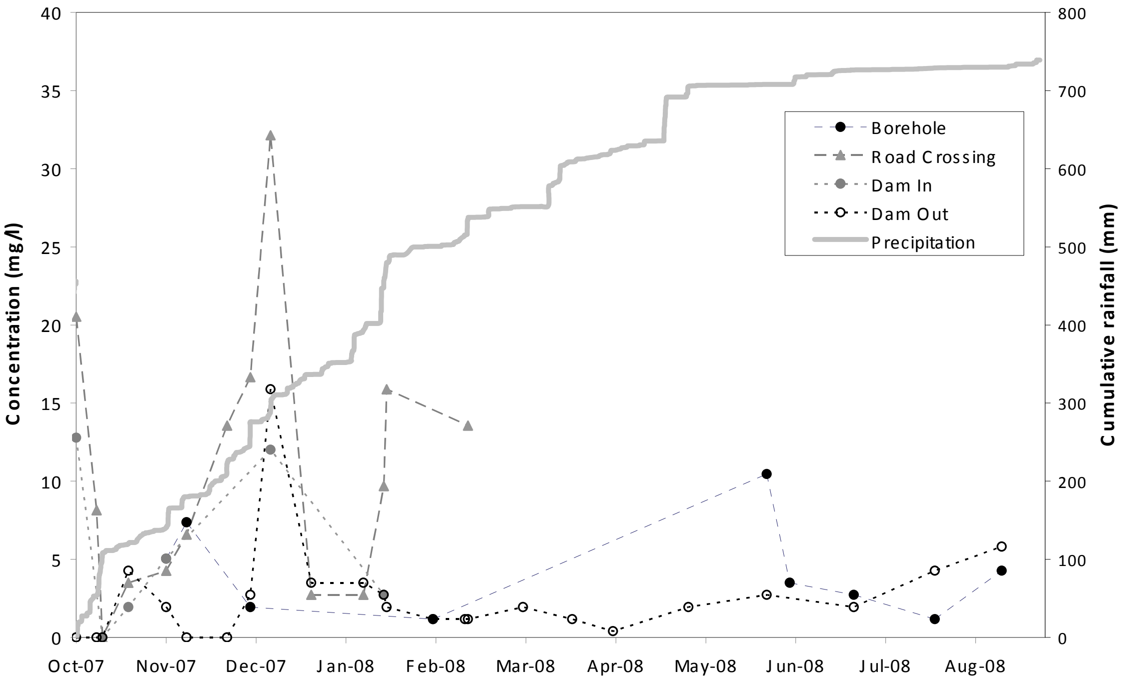


FIGURE 31 Rainfall and Nitrate responses from the Road Crossing to Dam Out and groundwater stations of the Mkabela Catchment for October 2007 to September 2008**.**

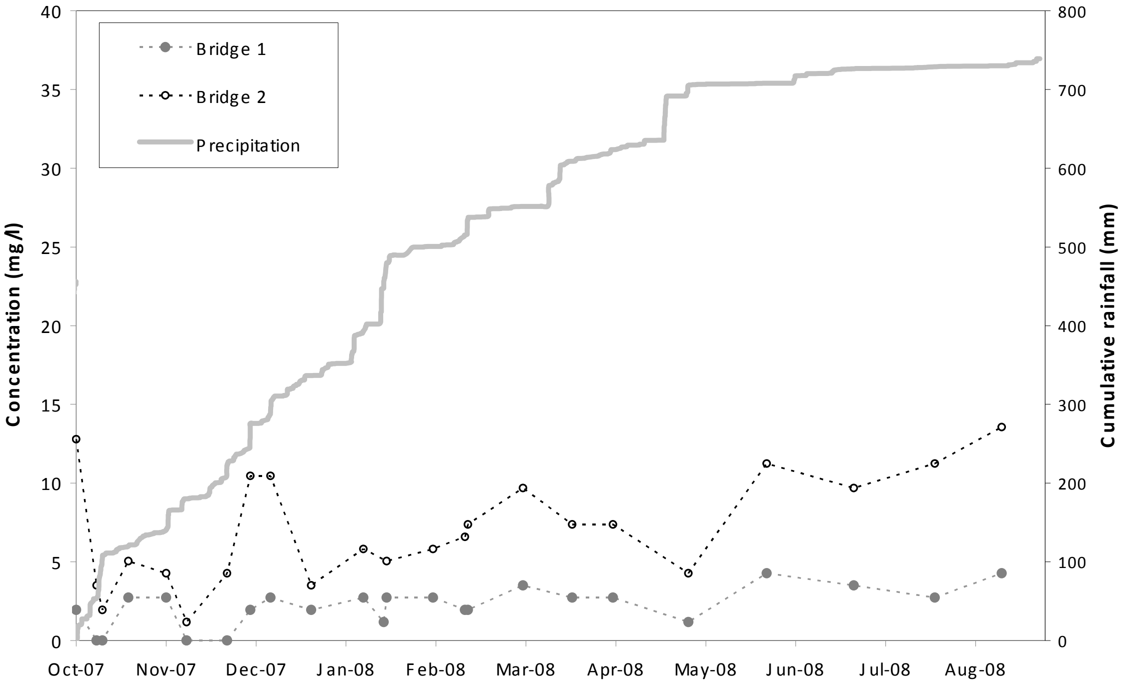


FIGURE 32 Rainfall and Nitrate responses from the Bridge 1 to the Bridge 2 stations of the Mkabela Catchment for October 2007 to September 2008.

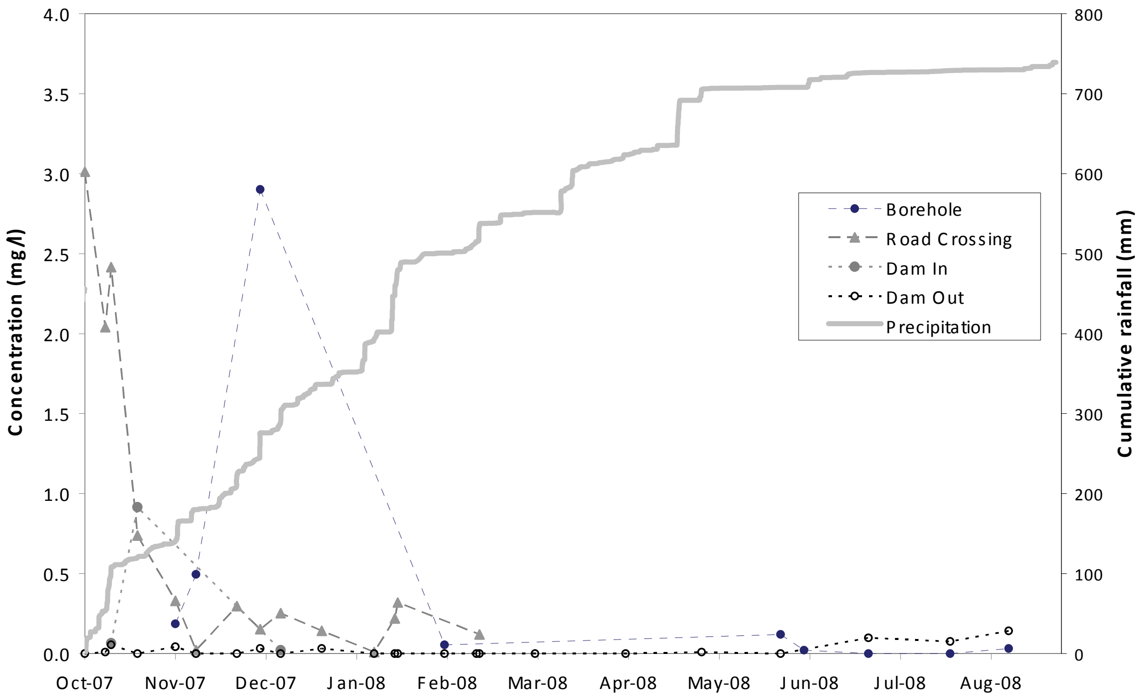


FIGURE 33 Cumulative Rainfall and P Concentrations from the Road Crossing to the Dam Out, (including the Groundwater) stations of the Mkabela Catchment for October 2007 to September 2008.

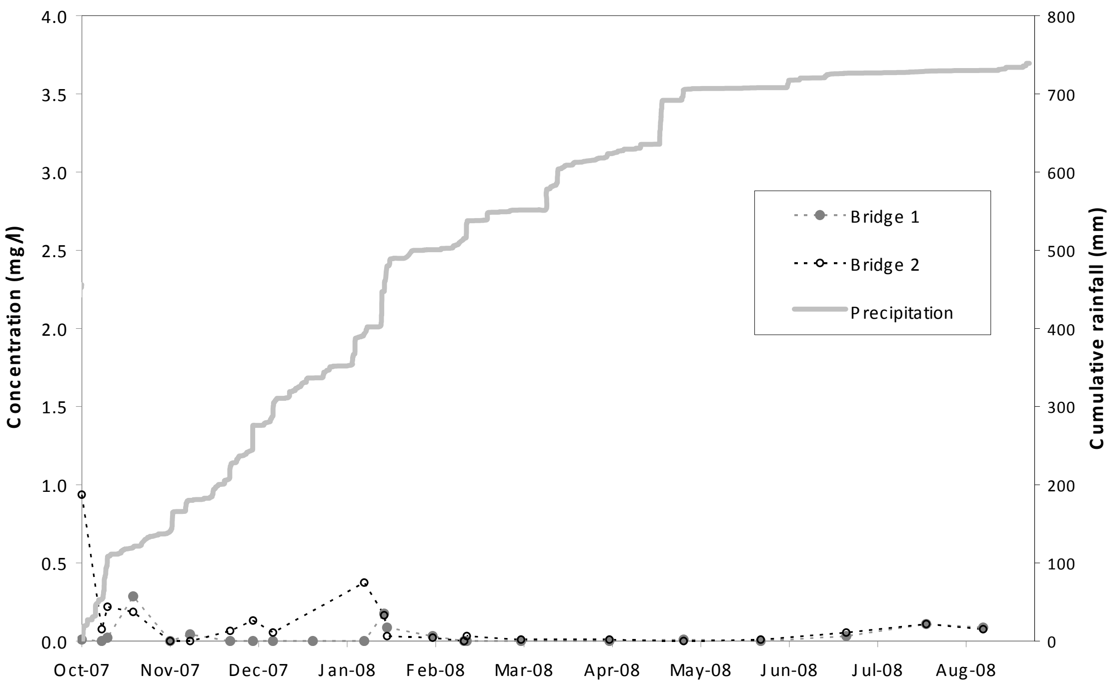


FIGURE 34 Rainfall and P responses from the Bridge 1 to the Bridge 2 stations of the Mkabela Catchment for October 2007 to September 2008.

Groundwater samples were extracted on selected occasions during the observation period and analysed for sediments, NO_3 and P (Figures 29, 31 and 33). These concentrations appear to decrease during the wet season, except for a peak observation of NO_3 during the high flow event of 30 November 2007 and a peak observation of P during December 2007. There is a need for more dynamic monitoring of these variations.

2.3 Conclusions

The following main conclusions about the Mkabela catchment processes could be drawn, based on the data collected in this Project:

- A comprehensive set of meteorological variables was assembled which indicated annual rainfall variation between 450 mm/a and 750 mm/a, temperatures ranging between 4ºC and 44ºC, maximum hourly wind speeds of 11 m/s, with an average of 1.2 m/s.
- Soil water tensions in the soil profile responded to rainfall events of more than 30 mm to a depth of 400 mm below the surface.
- The yields of suspended solids and nutrients from overland flow were dependent on the growth stage of the sugar cane. Significant increases in runoff and nutrient yield were observed at the field- and small-catchment-scale compared to the point-scale, indicating a predominance of subsurface discharge from the sugar cane land use.
- The proportion of load increase between the upstream Flume 1 and downstream Flume 2 is higher than the equivalent increase in area between the two flumes, indicating a higher response to runoff and mass loading in the lower, flatter slopes of the small catchment draining to Flume 2.
- Yields of suspended solids and nutrients were highly dependent on controls in the water flow-path, including road crossings, farm dams and wetland areas. Occasional high flow events yielded increased loading from farm dams as these were disturbed by the high rate of change in water volume. Concentrations of all NPS species drop significantly after the Road Crossing sampling station. However, these increase again downstream after the Dam-Out station, reflecting increasing loading with increasing contributing area.
- Suspended solids and nutrient concentrations generally increased during an event.
- Groundwater responses appear to be affected by event loadings.

3. DEVELOPMENT OF THE *ACRU-NPS* MODEL

This chapter reports on the details and structure of the *ACRU-NPS* model development, as well as the initial simulation results in comparisons against observed data. It details the consideration of field-scale processes in catchment-scale models; the components of the *ACRU-NPS* model; guidelines for parameter estimation; the results of the simulation of the nested catchment headwaters and offers conclusions on the merits and improvement of the model.

3.1. Field-scale processes of relevance for inclusion in catchment models

In the design of catchment-scale models, it must be recognised that certain processes reflect a dominant response of nutrient dynamics at different scales. Nevertheless, it is important to capture sufficient complexity properly to account for the mass balance at a catchment scale. In efforts to accomplish this, two different general approaches have been applied. The first comprises the coupling of detailed field-scale model simulation output to catchment-scale models (Andresson *et al.,* 2005). The second is integrating simplified process descriptions into the catchment-scale model (Campbell *et al.*, 2001). It is important to avoid simplification which will inhibit the ability to conclude source-pathway-response modelling, and likewise, to include processes for which parameters can be determined at the catchment scale. Therefore, the second approach is adopted in this study, in which nutrient process responses from the GLEAMS model are incorporated into the *ACRU* hydrological model to yield the *ACRU-NPS* model. Including the sediment yield capabilities inherent in the *ACRU* model, the nutrient module can be assigned the acronym *ACRU-NPS*.

The vertical leaching of organic N and P attached to colloidal particles is currently not simulated in the field-scale SWB-Sci model, the *ACRU-NPS* or SWAT models. A significant movement of N and P via vertical leaching and/or lateral flow may potentially be missed by excluding this process, especially under systems receiving high loadings of organic material. Similarly, the simulation of N and P leaching via macropore flow is highly challenging to model and not currently included in SWB-Sci. The movement of nutrients by macropore flow and in lateral hillslope transects are processes to be incorporated into the future *ACRU-NPS*.

3.2. *ACRU-NPS*

3.2.1 Nutrient processes

Professor Ken Campbell of the Agricultural and Biological Engineering Department at the University of Florida, Gainesville, USA, visited the School of Bioresources Engineering and Environmental Hydrology (SBEEH) at the University of KwaZulu-Natal (then University of Natal) from July 2000 to June 2001. During this time, the objective of Professor Campbell's work was to add a nitrogen (N) and phosphorus (P) module (*ACRU-NP*, currently referred to as *ACRU-NPS*) to the *ACRU* model, based on transformation and transport concepts used in the GLEAMS model.

The goals of the *ACRU-NPS* module were to enable the *ACRU* model to simulate:

i. N and P losses in surface runoff, sediment, and leaching,

ii. N and P cycling in the soil-water-plant-animal system, and

iii. N and P mass balances in the watershed system.

The module includes rainfall, irrigation, fertilizers, plants, and animal wastes as potential nutrient sources and represents management impacts on N and P transformations and transport. Since the GLEAMS model (Knisel and Davis, 1999) includes most of these capabilities in its current version it was used as a guide in development.

The *ACRU-NPS* module was developed using an object-oriented programming technique. New component objects were added to *ACRU* to represent a soil surface layer including plant matter dynamics. Process objects were developed to model soil temperature, snowfall, snowmelt, ammonification, nitrification, N plant uptake and fixation, volatilisation, denitrification, N adsorption and extraction, ammonium partitioning coefficient, immobilization, P mineralisation, P plant uptake, P adsorption and extraction, labile P partitioning coefficient, harvest, tillage, surface transport, evaporation transport, and subsurface transport. Process objects also were developed to handle nutrient inputs and to initialise nutrients. Numerous data objects were created to facilitate data input and output, and to hold nutrient status information. Considerable time was spent on the object-oriented design of the module, this was followed by a period of intensive coding, and finally the integration of the *ACRU-NPS* module into the *ACRU* model. The processes included in the current version of *ACRU-NPS* are detailed in Figures 35a and 35b.

The nineteen algorithm descriptions summarizing the nutrient component of the *ACRU-NPS* module are presented in Appendix E.

3.2.2 Sediment processes

Sediment yield per unit area, (SS) from a land unit is based on the Modified Universal Soil Loss equation (MUSLE) through the following algorithm (Lorentz and Schulze, 1995):

$$SS = \alpha(Q.q_p)^{\beta}.K.LS.C.P \qquad 23$$

where α and β are climate and catchment specific constants,

Q is the volume of storm runoff generated by the hydrological module of *ACRU*,

q_p is the peak storm discharge generated by the hydrological module of *ACRU* ,

K is the soil erodibility factor, which varies in a range depending on the prevalent soil water content,

LS is the slope length and steepness factor,

C is the cover factor and

P is the practice factor.

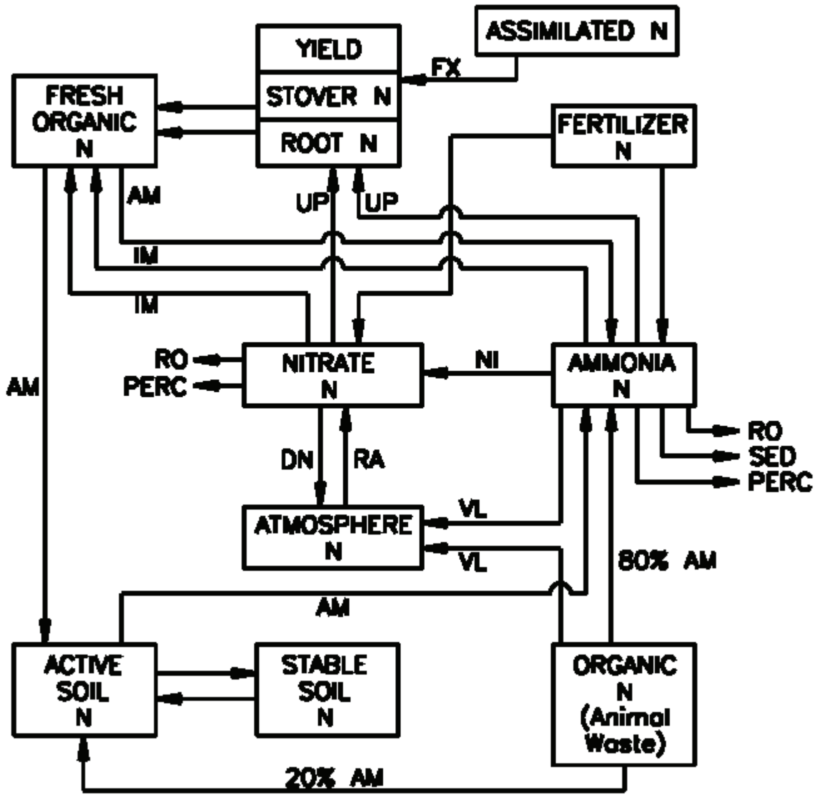


FIGURE 35 Nitrate processes included in *ACRU-NPS* (Campbell et al., 2001)

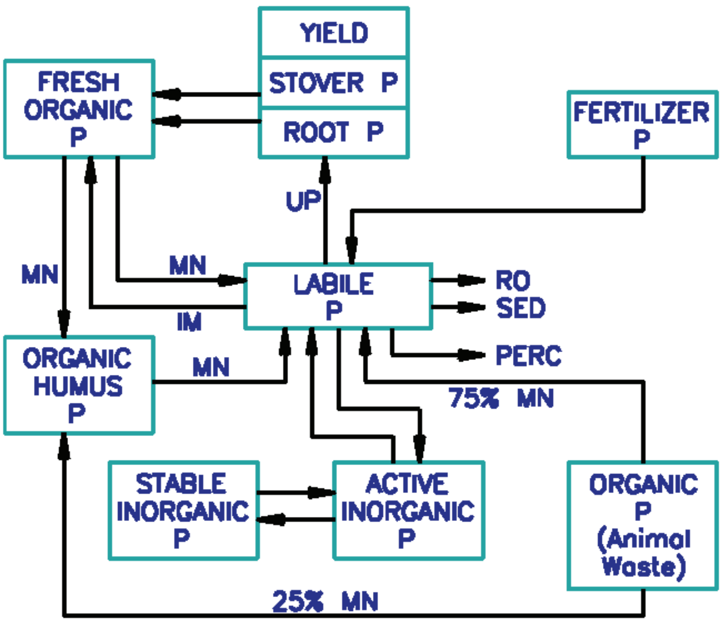


FIGURE 36 P processes included in *ACRU-NPS* (Campbell et al., 2001)

3.2.3 Crop Yield Processes

A crop growth algorithm has been included in the *ACRU-NPS* model so that the economic analysis of fertilization and land use practice can include the benefits of improved yield against the costs of possible increases in nutrient release to streams.

The daily crop growth is limited by either water or nitrogen stress, whichever is the most severe. On a daily basis, the water stress is determined by comparing actual transpiration against potential transpiration. The nitrogen stress is determined by comparing the nitrogen uptake (driven by transpiration uptake and prevalent soil water nitrogen concentration), against the nitrogen demand (driven by the crop growth). The processes inherent in estimating the nitrogen stress are detailed in Figure 37.

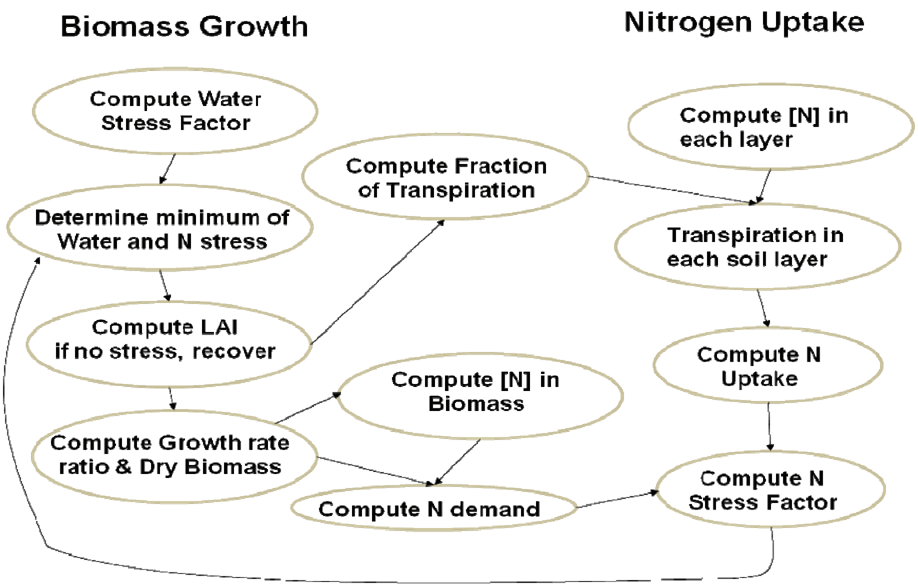


FIGURE 37 Water and nitrogen stress and crop growth processes.

The crop growth is determined by tracking the daily crop Leaf Area Index (LAI), which is calculated relative to a known crop potential LAI (BaseLAI) for each stage of growth. The actual LAI increment is reduced from the potential LAI, on any day in which water or nitrogen stress are experienced. If the LAI is reduced through water or nitrogen stress, the subsequent permissible transpiration is reduced by a fraction (FractionTranspiration) determined as:

$$FractionTranspiration = \frac{1 - e^{-0.5LAI}}{1 - e^{-0.5BaseLAI}} \qquad 24$$

If the crop has been previously stressed, and neither water or nitrogen stress conditions exist on a particular day, then the LAI is allowed to recover fractionally towards the potential.

The daily crop growth ratio (GRT) is defined as the ratio of LAI to BaseLAI and is used to generate the incremental Dry Matter BioMass, based on a potential crop yield. The GRT is also used to determine the required nitrogen concentration (CN%) for a particular stage of growth from, CN% = $C1.GRT^{C2}$, where C1 and C2 are crop specific parameters which regulate the yield response to nitrogen application. The nitrogen demand (DemN) is subsequently determined from CN% and compared to the uptake (UpN) to determine the nitrogen stress factor (StressFacN) for a particular day from:

$$StressFacN = 1 - \frac{UpFac}{UpFac + e^{3.39-10.39UpFac}}$$ 25

Where:

$$UpFac = 2\left(1 - \frac{UpN}{DemN}\right)$$ 26

This results in a stress factor being applied whenever the demand is greater than the uptake. The stress factor reduces rapidly and is effectively zero (no LAI or growth increment) for any day in which the uptake is less than 60% of the demand.

3.2.4 Processes at Control Structures

Control structures in the stream network, whether natural or man-made, have been shown to retardand attenuate the migration of sediments and nutrients through agricultural catchments, as is also the case for the Mkabela catchment (Chapter 2). Therefore, algorithms have been developed to route daily water discharge and sediments, nitrogen and phosphorus loads through farm dams, wetlands and riparian buffer strips. For each land segment the simulated daily discharge and sediment, N and P loads are read into a “network” spreadsheet and resultant output discharges and loads are calculated for each control feature in the catchment network.

3.2.4.1 Farm dams and wetlands

The water balance in farm dams and wetlands is controlled by a water balance including:

$$V_i = V_{i-1} + V_{in} - V_{evap} - V_{seep} - V_{out}$$ 27

where:

V_i = dam or wetland volume on day, i,

V_{i-1} = dam or wetland volume on day, i-1,

V_{in} = inflow volume on day, i,

V_{evap} = evaporation volume on day, i, controlled by an area-volume relationship for the impoundment (this can be enhanced for wetland vegetation transpiration),

V_{seep} = seepage volume from the base of the impoundment on day, i, controlled by an effective hydraulic conductivity and the impoundment area.

V_{out} = outflow volume on day, i, controlled by the storage volume in excess of the full volume. A user specified percentage of the seepage volume is added to the outflow volume.

The sediment load stored in the dam or wetland is determined by a mass balance of inflow sediment load and the change in sediment load in the water body due to settling of sediments. The mass of settled sediments is determined by calculating the sediment concentration at the end of each day (C_f) from:

$$C_f = (C_i - \overline{C})e^{-ks.d50} + \overline{C} \qquad 28$$

where:

C_i = sediment concentration at the start of the day,

$\overline{C}$ = a user specified equilibrium sediment concentration,

ks = a settling rate constant,

$d50$ = the 50 percentile particle size of delivered sediment, determined from,

$$d50 = e^{0.41Cl + 2.71Si + 5.71Sa} \qquad 29$$

where Cl, Si and Sa are the catchment parent soil clay, silt and sand textural fractions, respectively.

The mass balance of N and P loads in farm dams or wetlands is controlled by the inflow and is determined using a user specified settling velocity (v_{sett}) as $M_{sett} = v_{sett}.C_i.A_i$ where C_i *is* the initial concentration of N or P in the impoundment on day, i.

3.2.4.2 Riparian buffer strips

Sediment loss in buffer strips is controlled by the width (w) of the strip (Neitsch *et al.*, 2005a). For strip wider than 29 m, all the input sediment is trapped. The sediment output (Sed_{out}) for strips less than 29 m wide is calculated from the inflow sediment (Sed_{in}) as:

$$Sed_{out} = Sed_{in} - Sed_{in}\,0.367w^{0.2951} \qquad 30$$

N and P losses in buffer strips have been associated with strip width, (w), slope ($Slope$) and an empirical vegetation parameter (*Veg: 0 for grass and 1 for forest*) by Bereitschaft (2007), in which the Nitrogen output is given as:

$$N_{out} = N_{in} - N_{in}(24.6 + 55.3\log(w) - 0.5Slope^2 - 14.4Veg) \qquad 31$$

A similar relationship is used for P output from a buffer strip.

3.3. Guidelines for catchment-scale model inputs

For the *ACRU*-based estimation of P load in the Umgeni catchment Kienzle et al. (1997) made use of an estimation algorithm to determine fertilizer and soil P sorption coefficient using Land Type, climate, land use and topographical information (Figure 38). These were used in a simple isotherm calculation to account for the adsorbed and dissolved phases of P.

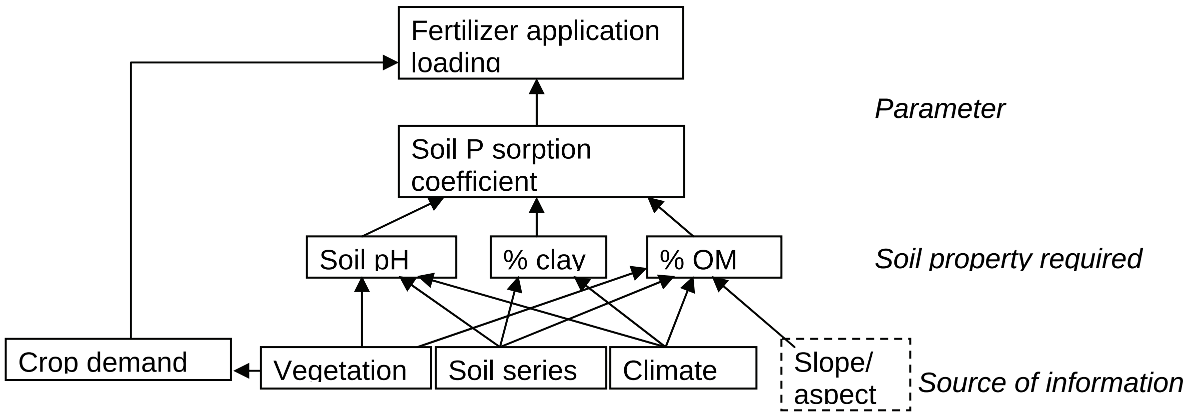


FIGURE 38 Flow chart for determining fertilizer application and soil P sorption coefficient in Kienzle et al., 1997.

Despite these early attempts at estimating these parameters, a field-scale model is useful to identify and determine dominant processes and to estimate parameters for inclusion in a catchment-scale model. The SWB-Sci model, developed at the University of Pretoria, was used for this purpose (Van der Laan et al., 2009).

3.3.1 Soil initialization

In order to run a simulation at the point- or field-scale with the SWB-Sci model, a comprehensive soil analysis would most likely be required to obtain the necessary inputs. N processes can be modelled without modelling P, but modelling P processes on their own is currently not possible. One of the key parameters affecting nutrient distribution and change in soils is the organic matter content. Percentage organic matter is an essential model input for each of the soil layers. Using hard-coded constants, the model divides organic matter into fast-cycling, slow-cycling and lignified fractions. Crop residues and organic fertilizers are also divided into fast-cycling, slow-cycling and lignified fractions, and must be parameterized by the user. Organic C is modelled in a highly mechanistic way and up to 3000 separate organic pools, each with its own half-life and C:N and C:P ratios, can be simulated.

3.3.2 Estimating Labile P pool size using standard soil P tests

The original work done by Jones et al. (1984) and Sharpley et al. (1984) only allows the estimation of *Labile P* pool size using the P soil test Bray 1 P (BP1), Olsen P (OP) and double acid P (DP). The most commonly used extraction methods in South Africa are BP1 (fertilizer industry) and Ambic 1 (AP) (Agricultural Research Council and Department of Agriculture). However, in the Western Cape the Citric acid method (CiP) and in KwaZulu-Natal the Truog (TP) method are also used. The OP method is mainly restricted to the Free State Department of Agriculture and the University of the Free State. The Bray 2 P (BP2) is also sometimes used in South Africa. Although much work has been done locally and internationally to compare various P extraction methods, much of this work has been restricted to unpublished reports (Schmidt et al., 2004). Equations for the estimation of *Labile P* using AP and BP2 results were therefore not possible for work done by Sharpley et al. (1984). After a study comparing BP1 and AP results from 12 localities in South Africa, Schmidt et al. (2004) reported the following relationship using linear regression analyses:

$$BP1 = 1.23085 \times AP1 + 3.8214 \qquad 32$$

An r^2-value of 0.91 was obtained where clay contents of the soils ranged from 8.4 to 47%. Van der Merwe (1978) reported very good correlation for the following relationship between BP1 and BP2 for a mixed batch of South African soils:

$$BP1 = 0.42 \times BP2 + 1.44 \qquad 33$$

Table 9 lists the current and suggested equations for the estimated labile P pool size, in South African soils.

TABLE 9 Current and suggested equations for the estimation of labile P pool size for South African soils. (All P_{lab} values are mg P/kg soil).

Soil Group	Observ.	r^2	Soil Group	Observ.	r^2
Slightly weathered	35		**Highly weathered acid tropical soils**		
P_{lab} = 0.56BP1 + 5.1[§]		0.79	(> 30% Al saturation)	32	
= 1.07OP + 4.1[§]		0.77	P_{lab} = 0.41BP1 + 5.55[†]		0.86
= 0.13DP + 11.4[§]		0.39	= 0.20TP + 5.62[†]		0.80
= 0.69AP + 7.2[l]			= 0.43CP + 4.21[†]		0.84
= 0.24BP2 + 5.9[l]			= 0.64MP + 5.72[†]		0.71
Highly weathered	20		= 0.50AP + 7.12[l]		
P_{lab} = 0.14BP1 + 4.2[§]		0.83	= 0.17BP2 + 6.14[l]		
= 0.55OP + 2.1[§]		0.74			
= 0.24DP + 2.9[§]		0.51	**Highly basic calcareous**		
= 0.17AP + 4.7[l]			(> 50 g kg^{-1} $CaCO_3$)	23	
= 0.058BP2 + 4.4[l]			P_{lab} = 0.69BP1 – 1.76[†]		0.35
Calcareous	23		= 0.96OP – 0.19[†]		0.90
P_{lab} = 0.55BP1 + 6.1[§]		0.76			
= 1.09OP + 3.2[§]		0.61			
= 0.10DP + 10.2[§]		0.84			
= 0.68AP + 8.2[l]					
= 0.23BP2 + 6.89[l]					

[§] Sharpley et al. (1984)

[†] Sharpley et al. (1989)

[l] New equations being proposed

Buys and Venter (1980) reviewed correlations between BP1 and BP2 from several studies done by the Fertilizer Society of South Africa and observed greater correlation for acid soils than for alkaline soils and soils treated with rock phosphate. Using these relationships, the equations in Table 9 are suggested for the estimation of *Labile P* in South African soils. Sharpley et al. (1989) later added additional equations using BP1 and OP for highly basic calcareous soils (free $CaCO_3$ > 50 g/kg), and additional BP1, OP, Colwell P (CoP), TP and Mehlich III P (MP) soil P test values for highly weathered acid tropical soils (Al saturation > 30%). These equations are also included in Table 9.

3.3.3 The use of Land Type data for P parameter estimation

While project-specific soil surveys can be implemented for field-scale analyses of nutrient dynamics, this would be impractical at a catchment-scale. A method is therefore required to allow for the spatial assignment of nutrient input parameters for the catchment-scale model. Since equations for estimating labile P have been assigned to slightly weathered, highly weathered and calcareous soils (Table 9), it would be expedient to develop a methodology of spatially representing these soils.

A convenient method is afforded through the Land Type Surveys of soils in South Africa. Land Type maps are available for the whole of South Africa at a scale of 1:250 000. Each Land Type map is accompanied by a Memoir, from which the Soil Form and Series of a specific area can be obtained. In addition, profile descriptions of representative soils and analytical data for particle size distribution, water retentivity, modulus of rupture, air-water permeability ratio, mineralogy, cation exchange properties, soluble salts, acidity, CBD-extractable Fe, miconutrients, P-status and P sorption can also be obtained from the Memoirs (Land Type Survey Staff, 1985). After obtaining the Land Type of an area of interest, the accompanying Memoir can be used to obtain Soil Form and Series. A method is therefore required to categorise the Soil Form and Series into the three required groups: slightly weathered; highly weathered; and calcareous.

3.3.3.1 Grouping Soil Forms as calcareous, slightly weathered or highly weathered

Jones *et al.* (1984) and Sharpley *et al.* (1984) observed that the most accurate estimation of *Labile P* using soil P tests was achieved when soils were divided into calcareous, slightly weathered or highly weathered groups based on the presence of $CaCO_3$ and degree of weathering (Sharpley *et al.,* 1984). Strict definitions of these soil groups were not provided, however. A system was therefore required to group South African Soil Forms as slightly weathered, highly weathered or calcareous in situations where it is impractical to perform soil analyses. In Table 10, the original Soil Forms classified according the Soil Classification Working Group (1977) and used for the Land Type maps are grouped into four classes. After identifying into which class a specific Soil Form falls, the following guidelines for each of the four groups were proposed by Van der Laan et al. (2009) to categorize RSA soils as slightly weathered, highly weathered or calcareous.

TABLE 10 Classification of Soil Forms into four classes grouping into slightly weathered, highly weathered or calcareous (Van der Laan et al., 2009)

Soil Form			
Class 1	**Class 2**	**Class 3**	**Class 4**
Kranskop	Arcadia	Katspruit	Champagne
Magwa	Inhoek	Fernwood	Nomanci
Inanda	Milkwood		Sterkspruit
Avalon	Mispah		Estcourt
Glencoe	Rensburg		Kroonstad
Griffin	Willowbrook		Constantia
Clovelly	Bonheim		Shepstone
Bainsvlei	Tambankulu		Houwhoek
Hutton	Mayo		Lamotte
Shortlands	Swartland		Cartref
Pinedene	Valsrivier		Wasbank
	Vilafontes		Longlands
	Oakleaf		Westleigh
	Glenrosa		Dundee

Class 1: Each of these Soil Forms are divided into soil series and classified as eutrophic, mesotrophic, distrophic, or calcareous. For the purposes of P modelling, eutrophic and mesotrophic Soil Forms are grouped as ‘slightly weathered’ and distrophic soils are grouped as ‘highly weathered’. Calcareous soil series are grouped as ‘calcareous’.

Class 2: The soil series of Soil Forms falling into this group are divided into calcareous and non-calcareous. Series that are defined as calcareous fall into the ‘calcareous’ group, while all non-calcareous soils be categorized as ‘slightly weathered’.

Class 3: Soil Forms in this group are classified as acid, neutral or alkaline. Acid Soil Forms are grouped as ‘highly weathered’, while neutral and alkaline soils should be grouped as ‘slightly weathered’.

Class 4: Soil Forms from this group can only be grouped as ‘slightly weathered’ or ‘highly weathered’ according to mean annual precipitation (MAP). In these instances, soil receiving an MAP of 500-750 mm will fall into the ‘slightly weathered’ group, while soils receiving over 750 mm of rainfall will fall into the ‘highly weathered’ group.

3.3.3.2 Spatial distribution of parameters for catchment-scale modelling

A spatial distribution of Soil Form and Series would allow the estimation of parameters through the algorithms described above. The Land Type Surveys afford such a spatial delineation through the binomial mode of Soil Form and Series classification. (Schulze, 2007; SIRI, 1987). In the Land Type Surveys, the Soil Form and Series are reported as a percentage of their occurrence in a particular terrain unit. The terrain units, range from a crest (Terrain Unit 1), a scarp (Terrain Unit 2), a midslope (Terrain Unit 3), a footslope (Terrain Unit 4) to a valley bottom (Terrain Unit 5). By identifying the spatial distribution of the Land Types and Terrain Units through a Digital Elevation Model (DEM), the spatial distribution of *labile* P can be derived from the algorithm shown in Figure 39.

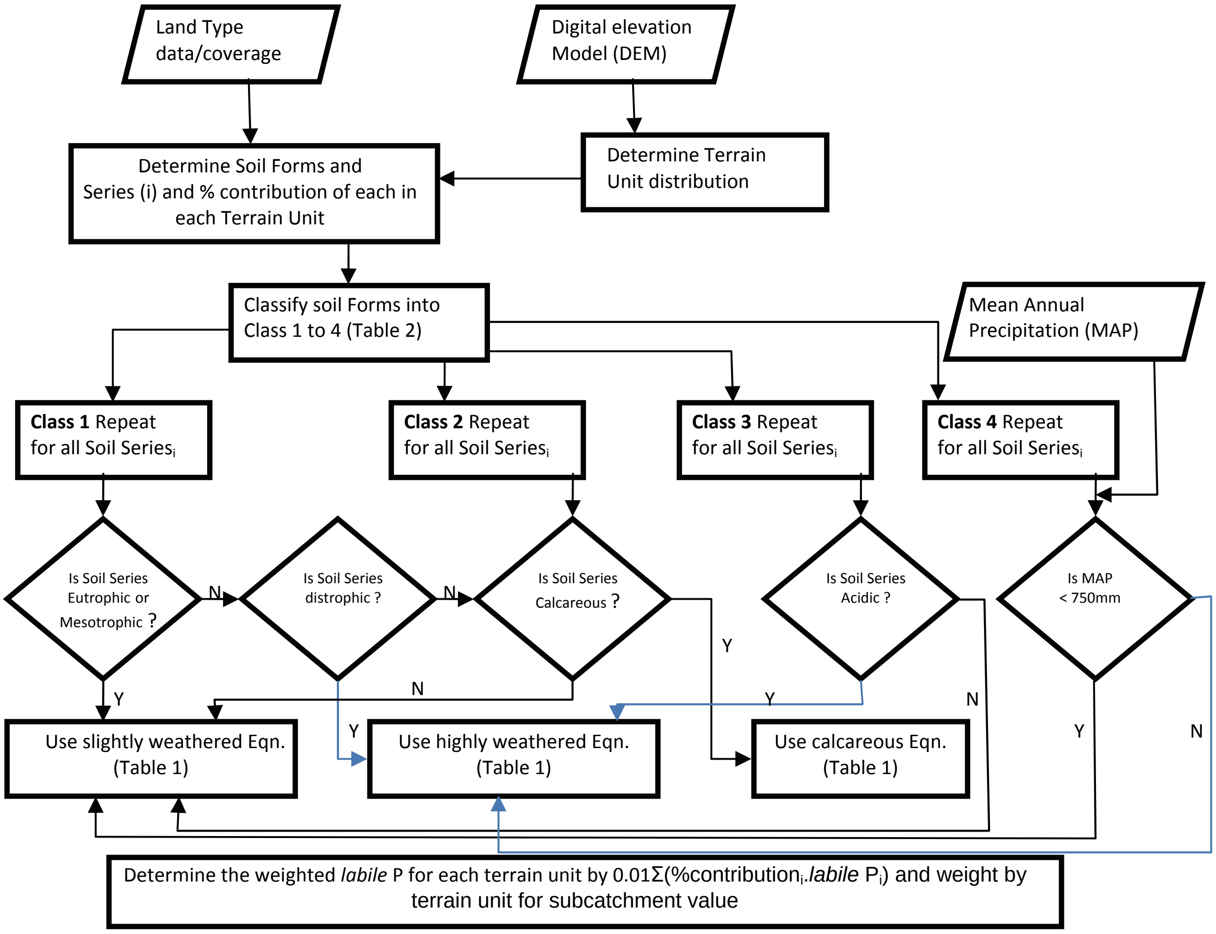


FIGURE 39 Flow chart for selection of labile P status in catchment-scale model

Since the Land Type inventories also report the percentage of clay content for each Soil Form:Series unit, this value can also be spatially represented in a similar way and used for input to the catchment scale model.

Soil P sorption, pH, Organic Carbon and texture can also be derived from Modal Profiles, reported as part of the Land Type Survey information. However, caution will need to be applied in interpolating between these profiles, which very often are sparsely distributed.

An example of the distribution of Land Types and Terrain Units is presented for the Mkabela catchment in Figure 40. As demonstration, the inventory for one of the Land Types, Ac217, is shown in Figure 41.

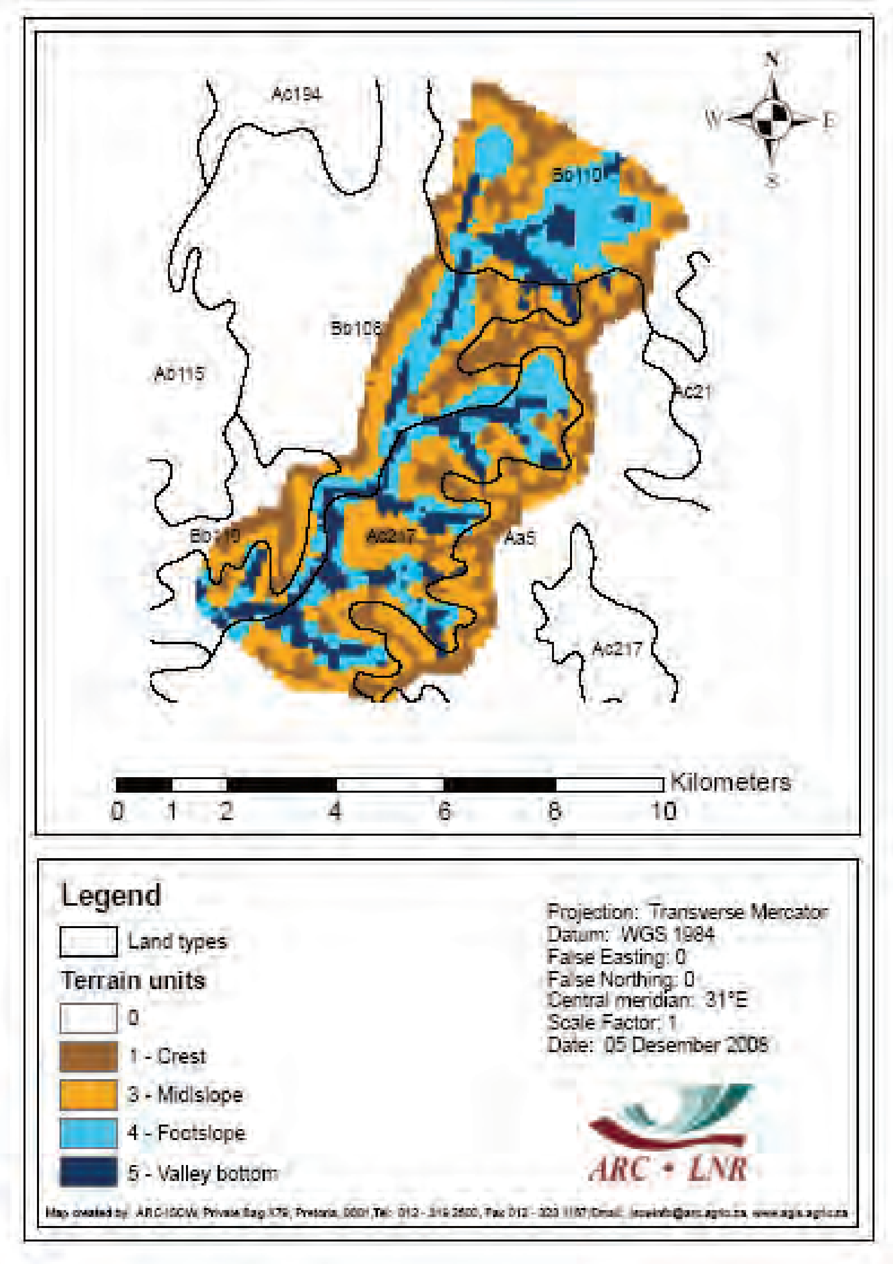


FIGURE 40 Distribution of Land Types and Terrain Units in the Mkabela catchment.

LAND TYPE / *LANDTIP* .... : **Ab217**
CLIMATE ZONE *KLIMAATSONE* ...... : 2775S
Area / *Oppervlakte* .... : 2785 ha
Estimated area unavailable for agriculture
Beraamde oppervlakte onbeskikbaar vir landbou : 56 ha

Occurrence (maps) and areas *Voorkoms (kaarte) en oppervlakte* :
3128 Umtata (2785 ha)

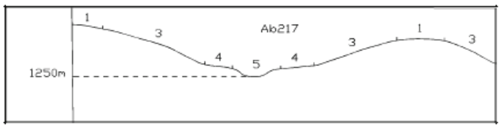
Inventory by *Inventaris deur* :
V G Roberts

Modal Profiles *Modale profiele* :
5010

Terrain uni *Terreineenhei*	1	3	4	5
% of land type *% van landtipe*	20	72	5	3
Area *Oppervlakte (ha)*	557	2005	139	84
Slope / *Helling (%)*	1 - 3	3 - 8	1 - 3	1 - 8
Slope length *Hellingslengte (m)*	250 - 1000	200 - 700	50 - 500	5 - 50
Slope shape *Hellingsvorm*	Y	Y-X	Z-X	X
MB0, MB1 (ha)	334	1845	139	28
MB2 - MB4 (ha)	223	160	0	56

Soil series or land classes *Grondseries of landklasse*	**Depth** *Diepte* (mm)	MB	ha	%	ha	%	ha	%	ha	%	**Total** *Totaal* ha	%	**Clay content %** *Klei-inhoud %* A	E	B21	Hor	**Texture** *Tekstuur* Class / *Klas*	**Depth limiting material** *Diepte-beperkende materiaal*
Rock / Rots		4	84	15							84	3.0						R
Msinga Hu26, Doveton Hu27	000-1200+	0	334	60	1644	82					1978	71.0	15-35		20-45	B	Lm-SaClLm-SaCl	so,R
Southwold Cv26	800-1200	0			140	7	56	40			196	7.0	15-25		20-35	B	fi/meSaClLm	so,R
Williamson Gs16, Saintfaiths Gs19	300-500	2	84	15	80	4					164	5.9	20-40			A	fiSaClLm-SaCl	so,R
Mispah Ms10	200-400	3	56	10	80	4					136	4.9	20-35			A	fiSaClLm	R
Airlie Pn27, Suurbraak Pn26	350-600	0			60	3	56	40			116	4.2	25-35		30-45	B	fi/meSaClLm-SaCl	gc
Katspruit Ka10	300-600	0					28	20	28	33	55	2.0	30-50		50-70	A	fiSaClLm-SaCl	gc
Stream beds/Stroombeddings		4							56	67	56	2.0						R

Terrain type *Terreintipe* : A3
Terrain form sketch *Terreinvormskets*



For an explanation of this table consult LAND TYPE INVENTORY (table of contents)
Ter verduideliking van hierdie tabel kyk LANDTIPE - INVENTARIS (inhoudsopgawe)

Geology: Grey mudstone, shale and sandstone of the Molteno Formation, Karoo Sequence.

Geologie Grys moddersteen, skalie en sandsteen van die Formasie Molteno, Opeenvolging Karoo.

FIGURE 41 Land Type inventory for Ac217 in the Mkabela catchment

The Land Type inventory assigns the Soil Series, Msinga (Hu26) and Doveton (Hu27) to 82% of the terrain unit 3 in Ac217 (Figure 41). Both these soils are of the Hutton (Hu) Form and so would fall into Class 1 of Table 10. Examination of the Series description for Msinga and Doveton reveals that they are mesotrophic (Soil Classification Working Group 1977) and thus classify as slightly weathered. The *Labile* P content can then be calculated using an appropriate equation from Table 9 and area-weighted with the results of the other Soil Series comprising the remaining 18% of the Terrain Unit. The weighted result can be applied to the land area covered by Terrain Unit 3 within Land Type Ac217.

3.3.4 Guidelines for selecting default parameters for catchment-scale models

A hierarchy of parameter estimation is proposed, in which the more detailed technique is preferred, if available. The parameters would be derived preferentially as follows:

i. Field-scale measurement – observation or survey
ii. Use of Land Type, land use, climate and Modal Profile data in algorithms
iii. Use of Land Type, land use and climate data in algorithms
iv. Default parameters.

Estimation of specific initial parameters is discussed below.

3.3.4.1 Initial soil nitrate and ammonium

According to the approach of SWAT (Nietsch *et al.,* 2002), the following equation can be used to estimate NO_3 concentration (mg/kg) when soil analysis data are not available:

$$NO_3 = 7e^{-d} \qquad 34$$

where d = layer lower boundary depth (m). For soil NH_4^+ concentration a default value of 2 mg/kg for all soil layers is suggested

3.3.4.2 Initial soil phosphorus

When no P input data is available, SWAT initializes the *Labile P* pool size at 25 mg/kg for the plough layer in cultivated land, and to 5 mg/kg for all other layers and uncultivated land (Cope *et al.,* 1981; Nietsch *et al.,* 2002). This is recommended for use when no other information is available. The *Active* and *Stable P* pools will then be initialized using this value. Further work to relate Soil Form and/or the cultivation history of a soil is suggested specifically for South African soils in order accurately to estimate soil P concentrations.

3.3.4.3 Soil clay content

Many of the Soil Forms that appear on Land Type maps are further divided into different Series based on the clay content of the soil. In these cases, it is possible to make use of Soil Classification Working Group (1977) to estimate the clay content of a specific soil.

3.3.5 The use of field-scale simulations in catchment-scale parameter estimation

Due to the mechanistic nature of SWB-Sci, and because much work has been done on a variety of crops in South Africa with the model, it seems plausible that the model could be used to indicate crop input parameters, such as potential yield and Leaf Area Index (LAI) under non-limiting conditions for the catchment-scale model. Additional parameters that could potentially be obtained through simulations with SWB-Sci include the extent of crop residue remaining on the land after harvest and the decline in soil organic matter over time due to cultivation. Simulated fluxes from Land Segments were used as input to a spreadsheet based model to evaluate the behaviour of nutrient and flow controls, including:

- wetland processes,
- farm dams and
- riparian zone buffer processes.

3.3.6 Guidelines for measurements of input parameters

Input parameters are described in Appendix F. Guidelines for methodologies for estimation of *ACRU-NPS* parameters to be used in South Africa are described in Appendix G. Appendix I lists the specific values of the input parameters for nutrient simulations.

3.3.7 Challenges in parameter estimation

3.3.7.1 Estimating parameters using Land Type maps

Caution should be practiced when using Modal Profiles from the Land Type maps, as these profiles were sampled under native vegetation. The effects of years of cultivation will therefore not be reflected using the Modal Profiles for parameters such as pH and soil test P.

3.3.7.2 Estimating parameters to predict P sorption

P modelling still closely follows the early approach developed by Jones *et al.* (1984) and Sharpley *et al.* (1984). These algorithms were developed using continental U.S. and Puerto Rican soils. Obtaining the required input parameters can therefore be challenging, when applying this approach to soils not classified according to the U.S. system, and for soils for which similar parameters are not available. It is crucial to use these equations to only model soils with properties within the range of soils used for the establishment of the original regression equations. Certain models, including the model ANIMO (Groenendijk and Kroes, 1999) utilize either Freundlich or Langmuir isotherms to determine P sorption. This approach is often deemed too mechanistic and inputs too difficult to obtain for inclusion in field to catchment scale models, however.

Numerous studies have been done in South Africa on P sorption kinetics (Johnston *et al.*, 1991; Henry and Smith, 2003; Henry and Smith, 2004). This work can potentially be adapted for local modelling purposes. Local research, similar to the work done by Jones *et al.* (1984) and Sharpley *et al.* (1984) is ultimately required to develop P modelling algorithms suited to South African soils.

4. *ACRU-NPS* MODEL SIMULATONS IN THE MKABELA CATCHMENT

4.1 Description of the Mkabela River catchment in the model context

In order to simulate the process of streamflow generation from rainfall on a catchment, the catchment is divided into homogenous sections, called sub-catchments. These sections have more or less homogeneous hydrological characteristics. These characteristics of importance in the subdivision of the Mkabela catchment include land cover, soil types and hill slopes (topology), as well as the dams on the main channel, riparian zones and wetlands. Figure 47a illustrates the Mkabela subcatchments' numbering system used in *ACRU-NPS* simulations. Table 11 lists the different sub catchment areas and dominant land use.

TABLE 11 Areas of subcatchments in the Mkabela River catchment used in *ACRU-NPS* modelling

Land Use	Catchment Numbers	Areas (km^2)
Sugarcane	1.1	2.58
Sugarcane	2.1	1.52
Forestry	2.3	0.25
Pasture	2.4	0.67
Vegetables: Cabbages	2.2	1.06
Sugarcane	3.1	1.91
Pasture	3.2	1.24
Sugarcane	4.1	2.21
Pasture	4.2	0.67
Forestry	4.3	0.35
Sugarcane	5.1	1.83
Pasture	5.2	0.36
Sugarcane	6.1	1.93
Pasture	6.2	0.33
Sugarcane	7.1	4.55
Sugarcane	8.1	2.77
Pasture	8.2	0.09
Sugarcane	9.1	3.84
Forestry	9.2	0.30
Sugarcane	10.1	7.85
Forestry	10.2	4.49
Total:		***40.63***

The main processes of streamflow generation, after a rainfall event, are simulated in the *ACRU* model. The simulation of these processes is governed by the bio-physical parameters (Schulze, 1995).

Simulation of the surface water resources of South Africa has been performed by SBEEH for pristine veld conditions, on a quinary catchment level, using the *ACRU* model. Quinary catchments are a subdivision of the well-known quaternary catchments into three subcatchments each. The simulations of the quinary catchments utilize input parameters originating from different research projects, each well-documented and published. The input and output from these simulations are available in the form of a quinary database. For the Mkabela catchment, some of the *ACRU* parameters, which have not been measured directly in the field, were extracted from this quinary database. Where this is the case, the background of these parameters is explained in the text to follow.

4.2 Climatic data

4.2.1 Rainfall data

Rainfall data for simulation over the monitoring period were extracted from the Mkabela research catchment meteorological station records. For the long term scenario modelling, a daily time series of rainfall was extracted from the quinary database of SBEEH, for the quinary U20G1 (SUBCAT nr 4690) for the period from 1950 to 1999. The daily rainfall for the quinary U20G1 originated from Lynch *et al.* (2003). The MAP from this time series is 820 mm. A graph of the annual totals indicates that the annual rainfall ranged from 400 mm up to 1400 mm (Figure 42). The flood of Sep 1987, which is well-known for the flood damage caused in KwaZulu-Natal, measured 90 mm of rain in the week before the peak rain event of 334 mm on 28 Sep 1987.

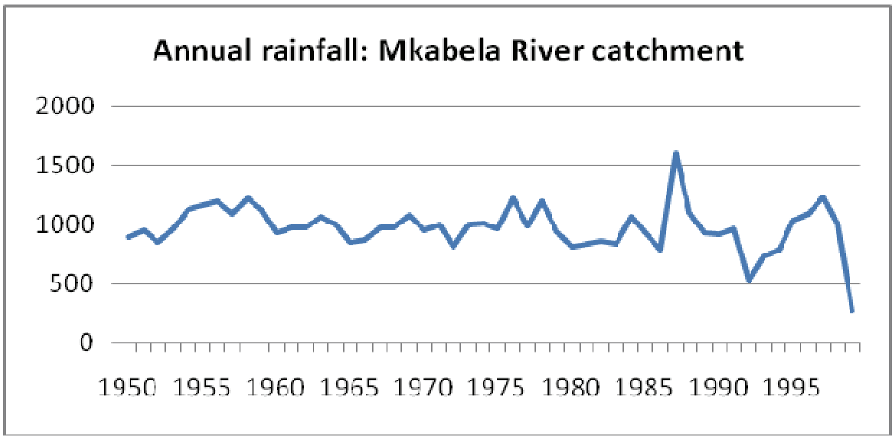


FIGURE 42 Annual rainfall (mm) estimated for the Mkabela catchment.

4.2.2 Evaporation

The evaporation in the *ACRU* model is an important influence on the simulations of the water cycle. Specification of a daily time series of the A-pan equivalent evaporation must be chosen with care. For the simulations over the observation period, the potential evapotranspiration (ETo) was determined from the Mkabela research catchment meteorological record. For the long-term scenario simulations, the A-pan equivalent evaporation (in the form of a daily time series) was extracted from the quinary database. Schulze (2009) explains the calculation of these evaporation time series: Procedures outlined by Schulze and Maharaj (2004) facilitate the generation of a 50-year historical series of daily maximum and minimum temperatures at any unmeasured location in the RSA at a spatial resolution of 1' x 1' latitude/longitude (~1.7 x 1.7 km).

The underlying database was made up of daily, quality-controlled records from over 970 temperature stations, extended to a common 50-year period, 1950-1999. Any infilling/extension of records took account of regionalised monthly temperature lapse rates from carefully chosen target stations at which similarities in variability of daily temperature value with the control station was a key factor (Schulze and Maharaj, 2004). This daily temperature series was then used in the generation of daily estimates of reference potential evaporation using the FAO (1992) approach to the Penman-Monteith equation and applying techniques adapted specifically to South Africa (Schulze and Maharaj, 2007). These evaporation time series are transformed within *ACRU* to A-pan equivalent evaporation using monthly conversion factors.

The specification of A-pan equivalent evaporation makes it unnecessary to specify other climatic data than daily rainfall. The time series is available over the period from 1950 until 1999.

4.3 Evaporation control parameters

The calculation of soil water evaporation and plant transpiration were separated (EVTR=2), as required by *ACRU-NPS*. The plant stress onset is determined by a constant of 0.4 (CONST=0.4). This constant is the fraction of the plant-available water of the soil horizon at which total evaporation is assumed to drop below the maximum evaporation during drying of soil. No enhanced wet canopy evaporation and no enhanced CO_2 levels were activated in the simulations. Unsaturated soil water redistribution was activated.

4.4 Soils data

The necessary parameters for the soils were extracted from Le Roux *et al.* (2006), who surveyed the soils in the catchment on a fine scale, especially in the headwater section of the catchment. This includes the depths of soil horizons, which were in turn used to calculate the initial soil water content as 50% of the soil horizon, called SMAINI and SMBINI (Table 12). *ACRU-NPS* also includes a soil surface layer, which was simulated with a depth of 1cm. The soil surface layer's properties were adapted from the Soil Form's A horizon. Where Le Roux *et al.* (2006) indicated more than two soil layers, the B1 and B2 soil horizons were combined (using depth-weighting) in the parameterizations.

TABLE 12 Depths (m) of soil horizons and initial soil water content for different Soil Forms

Horizon/Soil Type	Avalon (Av)	Westleigh (We)	Cartref (cf)	Glencoe (Gc)	Hutton (Hu)
A (DEPAHO)	0.33	0.264	0.25	0.297	0.347
B (DEPBHO)	0.67	0.536	0.5	0.603	0.704
A (SMAINI)	0.065	0.068	0.056	0.052	0.113
B (SMBINI)	0.135	0.145	0.131	0.101	0.238

Soil Textures were specified for Hutton Soil Forms (Hu) as clay soils, Westleigh Soil Forms (We) as loam soils and Avalon (Av) Cartref (Cf) and Glencoe (Gc) Soil Forms as sandy loam soils. These soil textures were used to parameterize the fractions of saturated soil water to be redistributed daily from the soil horizons to the subsoil (Schulze *et al.*, 1995). Other soil parameters are specified within *ACRU-NPS* along with the nutrient and soil parameters, discussed elsewhere.

4.5 Land cover parameters

4.5.1 Vegetation Parameters

The *ACRU-NPS* simulations utilize five different land cover types:

i. Sugarcane
ii. Plantations:
    a. Pine
    b. Wattle
iii. Pastures
iv. Vegetables: cabbages
v. Maize
vi. Fallow lands: Unimproved grasslands.

The last two land cover types will be used during scenario simulations.

Crop areas for each of these were listed along with monthly values of:

i) CAY: average monthly crop coefficients
ii) COIAM: coefficient of initial abstraction from rainfall before stormflow commences
iii) CONST: fraction of plant-available water of the soil horizon at which total evaporation is assumed to drop below maximum evaporation during drying
iv) COVER: C-factor in the MUSLE equation, used during estimation of sediment yield
v) ROOTA: % of roots that grows in the A-horizon of the soil (the remainder of the roots grows in the B-horizon)
vi) VEGINT: Interception loss (mm.rainday^{-1})
vii) ELAIM: leaf area index

The effective root depths were defaulted to the total soil depth. Percentages of surface mulch cover (PCSUCO) were extracted from the quinary database (i.e., 73%) for all land cover types, except for plantations, where it was set to 100%.

Appendix H lists the various land cover parameters used in *ACRU* for the different land types. Parameters were mostly sourced from the *ACRU* land cover database.

4.5.2 Irrigation

Irrigation of crops can currently not be included directly in the *ACRU-NPS* simulations, but it can be simulated in *ACRU*. To simulate irrigated crops, the *ACRU* model (excluding the *NPS* section) is utilized to identify the volume of irrigation needed. These volumes of irrigation water are then added to the rainfall during the *ACRU-NPS* simulations, to include irrigation on crops. To rectify the addition of irrigation water in the catchment during *ACRU-NPS* simulations, the difference between runoff with and without irrigation (as simulated in *ACRU*) is subtracted from the irrigated catchment's runoff (as simulated in *ACRU-NPS*).

4.6 Streamflow control parameters

The fraction of the total stormflow that will run off from the catchment on the same day as the rainfall event (QFRESP) is specified to be 0.4. The fraction of the groundwater store that becomes streamflow on a particular day (COFRU), was set to 0.009. Both values are recommended parameter values.

The effective depth of the soil from where stormflow is generated, is defaulted to the soil depth of the topsoil. Groundwater simulations were included. Monthly coefficients of initial abstractions COIAM, (which include interception, surface storage and infiltration into the soil, all of which are abstracted from rainfall before stormflow commences) were extracted from the quinary database for the crops, where these were not available for specific land covers.

Calculation of peak discharge was indicated, as required by sediment delivery modelling.

4.7 Dams, wetlands and riparian zones

Wetlands and riparian zones are currently not simulated in the *ACRU-NPS* model. However, these were included in this Project by reading the simulated streamflow, sediment yield and nutrient fluxes into a spreadsheet model, as described in Section 3.2.4.

4.8 Sediment yield

The MUSLE equation was utilized by the *ACRU* model to simulate the sediment yield from the catchments. In practical terms, these estimated yields are not similar to sediment productions. They merely are indications of higher and lower levels of sediment production. The parameters used to estimate sediment yields originate from the quinary database. Some of the land cover parameters are also utilized. Table 13 lists the sediment yield parameters.

TABLE 13 Parameters used to estimate sediment yield with the MUSLE equation in *ACRU*.

Parameter	Description	Value
SOIFC1	Max soil erodibility factor	0.29
SOIFC2	Min soil erodibility factor	0.29
ELFACT	Slope length and steepness. A value of null will default the slope to the average catchment slope	0
PFACT	Support practice factor. PFACT = 1: no conservation practice	1
ICOVRC	Option which indicates that no daily values are available for cover factors, and that monthly factors (COVER(i)) will be utilized.	0
SEDIST	The fraction of the event-based sediment yield from the catchment that reaches the outlet on the day of the event.	0.45
ALPHA	Runoff erosivity constant	8.934

No impervious areas were included in the simulations. No domestic abstractions were included. Analyses of crop yields are included in *ACRU-NPS* scenario simulations, and parameters are specified in the *ACRU-NPS*.

4.9 Calculations of soil and nutrient parameters

Values of soil and nutrient parameters were derived from various literature sources as summarized in Appendix G. Appendix I lists the calculated values of the nutrient parameters for the different soil types found in the Mkabela catchment.

4.10 Agricultural practices

Different sources were used to obtain estimates of manure and fertilizer applications. Tables 14, 15 and 16 list the rates of fertilizer and manure applications, as sourced from different data sources.

TABLE 14 Average rates (kg/ha) of fertilizer use in KwaZulu-Natal (FSSA, 2004; FAO 2005).

Crop	**N**	**P_2O_5**	**K_2O**	**P**	**K**
Maize	55	30	6	13	5
Sugar cane	92	57	133	25	110
Pastures	50	44	7	19	6
Vegetables/cabbages	170	159	120	70	100

TABLE 15 Manure rates and nutrient composition (Ministry of Agriculture KZN, South Africa, 2005).

Type of manure (WASCMP)	Rate (t/ha) (WASAPR)	Nutrients supplied (kg/ha)		
		N	**P**	**K**
Cattle	5	10	10	50
	20	40	40	200
Poultry	5	162	54	65
	20	648	216	260

It was assumed that poultry manure (5 t/ha) is applied on cabbages and cattle manure (20 t/ha) on sugarcane.

TABLE 16 Fertilizer rates (Source: farmer interviews).

Fertilizer rates (kg/ha)	**Sugarcane**	**Maize**
• Manure since 2003 for sugarcane • Topdressing LAN (28 % N)	150	
At planting • N:P:K (3:2:1) • KCL (50% K)		200 200
Before 2003 • Superphosphates (10.5 % P) • KCL (50% K) • LAN (28% N)	200 150 400	

It was assumed that 100 % of the total area under sugarcane, cabbages and pastures will receive a full nutrient loading of fertilizer every year. Simulations exclude fertilizing on forestry. The following application rates were determined:

- Sugarcane: for NH_4-N: 16.4 kg/ha/month
  for phosphorus (P): 8 kg/ha/month

  The parameterization indicates that the fertilizers are applied 5 times every year, on the 1st day of the month from August to December.
- Cabbages: for NH_4-N: 81 kg/ha/month

  for phosphorus (P): 27 kg/ha/month

  Fertilizers are simulated to be applied on cabbages twice every year, on the 1st day of the month in August and September.
- Pastures: for NH_4-N: 50 kg/ha/month

  for phosphorus (P): 33.35 kg/ha/month

  Simulations include fertilizing of pastures twice every year on the 1st day of the months of August and September.

Assumptions were made for the simulation of routine agricultural practices. Actual tilling in the catchment takes place before the planting of cabbages, as well as during the fertilizing of sugarcane with cattle manure (tilling between the sugarcane rows). During simulations it was assumed that all sugarcane fields are tilled in August, along with the application of cattle manure, to a depth of 15cm, using the “disk harrow in tandem” method. Model simulations incorporate tilling of cabbage fields, to a depth of 15cm, in August (during planting of cabbages), using the same tilling method. Pastures and forests are not tilled in the simulations.

Cabbages are harvested during the month of November, while sugarcane harvesting takes place from the beginning of May until the end of November of each year. Pastures and forests are harvested throughout every year. Sugarcane and forests were simulated as perennial plants (plants which last for several seasons), while cabbages and pastures were classified as non-perennials.

4.11 Evaluation of simulation outputs

4.11.1 Results of simulations over the observation period

Simulated times series of N and P loads indicate that higher P loads are likely to occur in the river system after high rain events at the beginning of the summer wet season, when sediment loads are higher than normal. These high loads occur as a result of P attaching itself to sediments, which are exported during the early rain events of the season, while plant development is still at the start of the growing season.

The *ACRU-NPS* model was configured for the 0.58 km^2 small-scale-catchment draining to Flume 2. Observed concentrations and loads at this observation station were used to verify the model outputs. A sugar cane crop was specified and soil characteristics were derived from the soil survey. Daily rainfalls, average temperature, humidity and wind speed data were extracted from the meteorological station records. The NO_3-N, P and suspended solids loads from the simulation outputs are compared with the loads estimated from six observed discharge events in Table 17 and Figures 43 to 46.

TABLE 17 Flume 2: Rainfall/Runoff and Mass Loading for Events 3-8.

Event	Date	Rain	P_{-7}	Runoff		Load		
						NO_3	P	SS
		mm	mm	mm	%	kg	kg	kg
3	8 Oct 07	28.3	67.6	0.8	2.7	4.1	0.7	130
4	1 Nov 07	25.0	9.2	1.2	4.9	4.7	0.6	80
5	30 Nov 07	33.5	20.8	11.3	33.8	171.9	8.0	7850
6	7 Dec 07	17.3	11.6	2.1	12.0	18.1	0.6	950
7	4 Jan 08	20.4	15.5	1.9	9.1	7.1	0.4	50
8	16 Jan 08	32.3	54.4	8.3	25.6	81.6	4.9	700

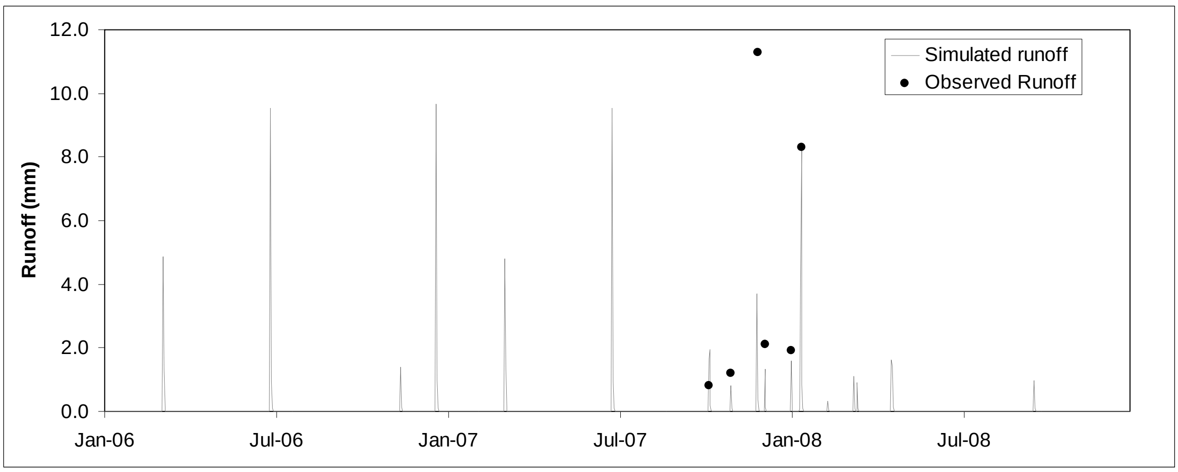


FIGURE 43 Simulated and observed daily runoff at Flume 2: January 2006-December 2008.

Daily runoff predictions were generally acceptable, except for the event of 30 November 2007, where the observed runoff far exceeded the simulated value, probably due to the vegetation cover being set too high in the model for this period.

Simulated nitrate-N loads were similar to those observed at the flume (Figure 44). Detailed comparison of the response during January 2007 to December 2008 shows simulated daily loads ranging from 0 to 100 kg from the 58 ha catchment. The simulated responses of nitrate-N load were dependent on the dates of fertilizer application, which were set to take place on the first of every month from August to December of each year. The few measured loads included one event yielding 39 kg nitrate-N (30 November 2007), which was adequately simulated. However, the simulated load of 8 October 2007 exceeded the observed load, since runoff and sediments were over-predicted for this event.

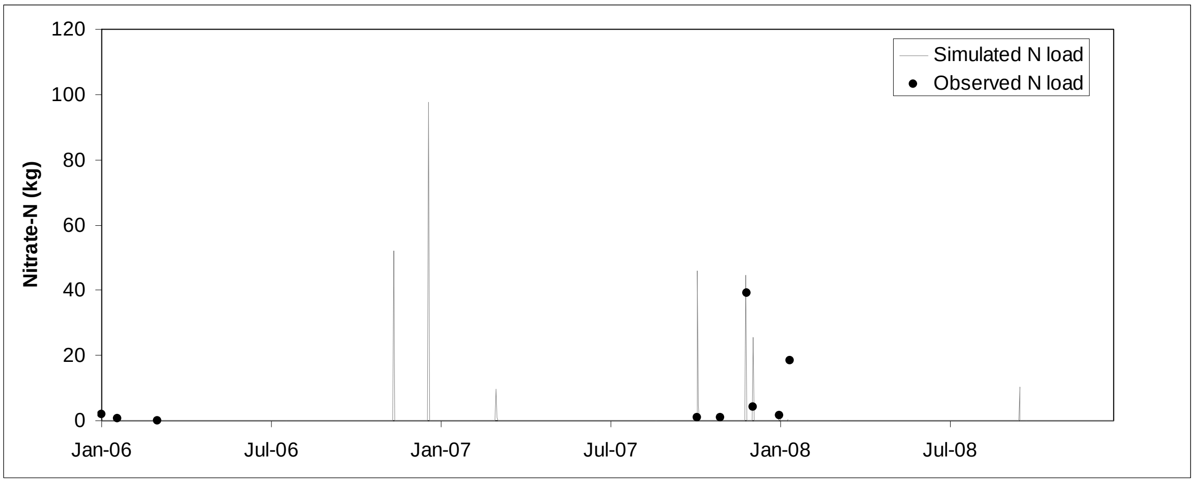


FIGURE 44 Simulated and observed daily Nitrate-N loads at Flume 2: January 2006-December 2008.

The simulated P load was lower than that observed for the 30 November 2007 event, but other events in late 2007 were over-predicted (Figure 45). The event of 16 January 2008 was under-predicted (Figure 45), although the runoff prediction was adequate (Figure 43). In this event, the sediment yield was also under-predicted – the field cover conditions considered in the model for this event were too high. The fertilizer application was an organic waste and was input to the model as such. However, even the addition of inorganic P to the model input failed to raise the P loads to those observed. It was noted that very little P was measured at the overland flow runoff plots, whereas, just a few hundred metres downslope, the P loads were high. It is conceivable that a significant load of P reached the measurement flume via the subsurface or in particulate form from an organic source. This dynamic P processes are not considered in the *ACRU-NPS* model and could explain its relatively weaker performance in simulating P loads.

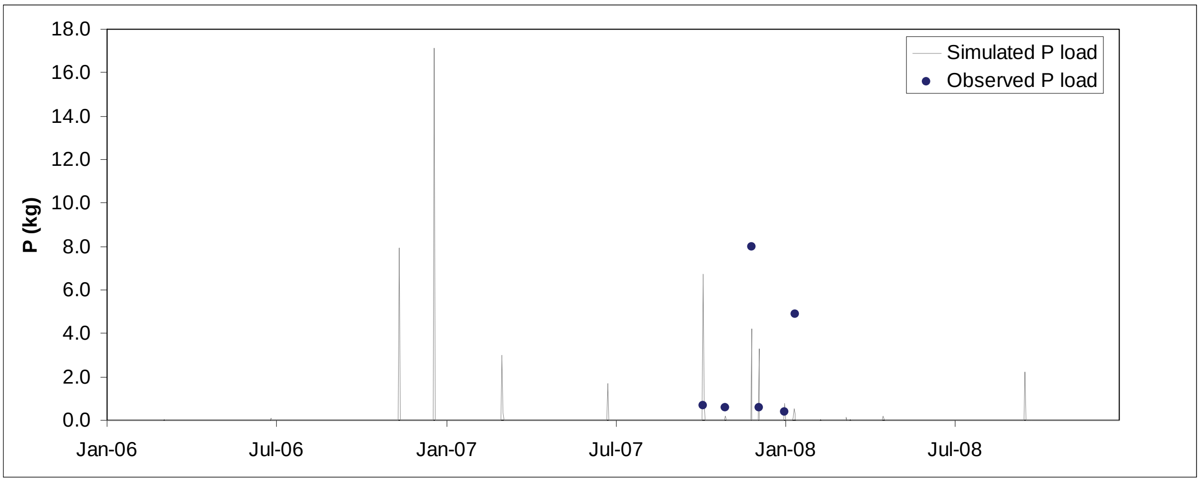


FIGURE 45 Simulated and observed daily Total-P loads at Flume 2: January 2006-December 2008.

Simulated daily sediment loads (Figure 46) were generally lower than those observed, except for the event on 30 November 2007. This could be due to a low antecedent water content elevating the soil erodibility in the simulation. Given the sandy soils of this catchment the maximum erodibility parameter was closer to the minimum than selected. The simulation highlighted the need to keep accurate record of crop cover conditions in the field. The overland processes were over-simulated and thus carried too much sediment. In contrast, it was observed in the Mkabela catchment that much of the water delivery at the small-catchment-scale is through subsurface pathways.

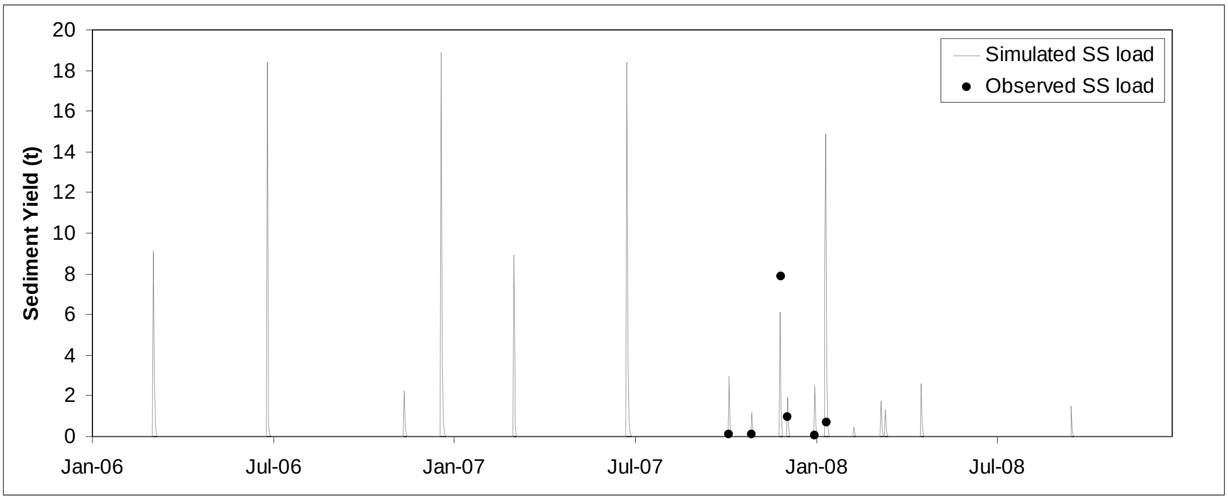


FIGURE 46 Simulated and observed daily suspended sediment loads at Flume 2: January 2006-December 2008.

4.11.2 Results of scenario simulations

Evaluation of the economic impacts of NPS in agriculture must necessarily compare the benefits of specific land use practices for crop yield against the costs of deteriorated water quality. The water quality impact may be assessed at the outlet of a farm unit or at some position in the stream network downstream of multiple source contributions. The prediction of water quality impacts immediately downstream of a source can be used to evaluate load reductions due to remediation at each source, while predictions in the stream network can be used to determine the relative contribution from each source and, in so doing, to direct remedial measures and assess their net effects.

For this purpose the *ACRU-NPS* model was modified to include:

- Algorithms to simulate nutrient and sediment production from land segments for various land uses (Section 3.2.1 and 3.2.2);
- A crop growth algorithm in which the crop yield is influenced by water and nitrogen stress (Section 3.2.3);
- Algorithms to simulate nutrient and sediment fate at controls and buffers in the stream network. These included provision for farm dams, wetlands and riparian buffer strips (Section 3.2.4).

With these modifications completed, a series of pollution control scenarios were tested, based on the catchment configuration and observations made in the Mkabela research catchment. The primary catchment land use (Figure 47) comprised sugar cane plantations, with small pockets of forestry (Wattle and Cyprus), a vegetable production farm and pastures located on toe slopes, in places acting as buffer strips between the cane and the riparian zones. For the purpose of the scenario modelling, the catchment was divided into land segments based on the dominant land use, as well as on the riparian network controls and buffers as illustrated in Figure 48.

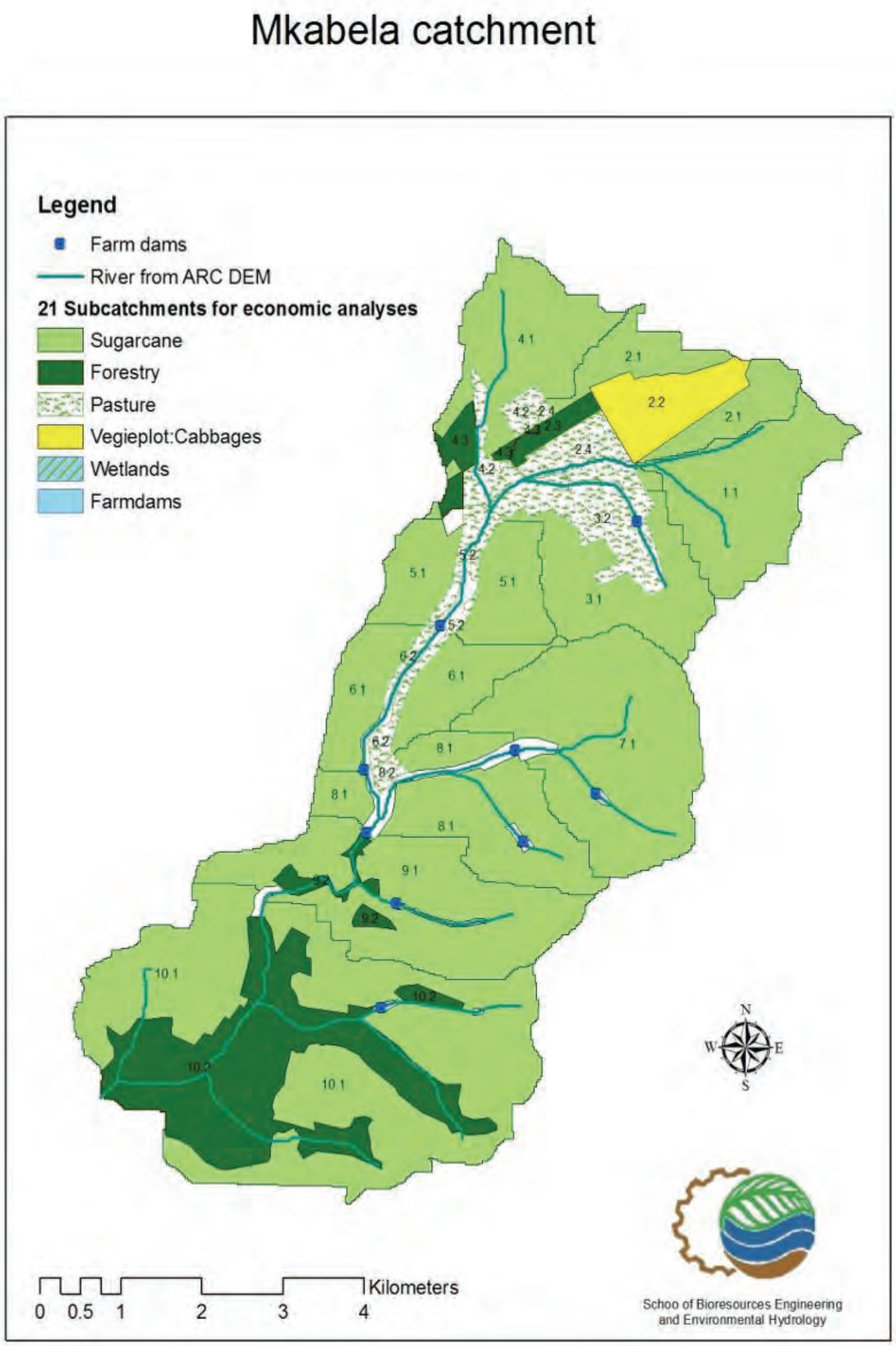


FIGURE 47 Mkabela catchment land use and subcatchment numbering

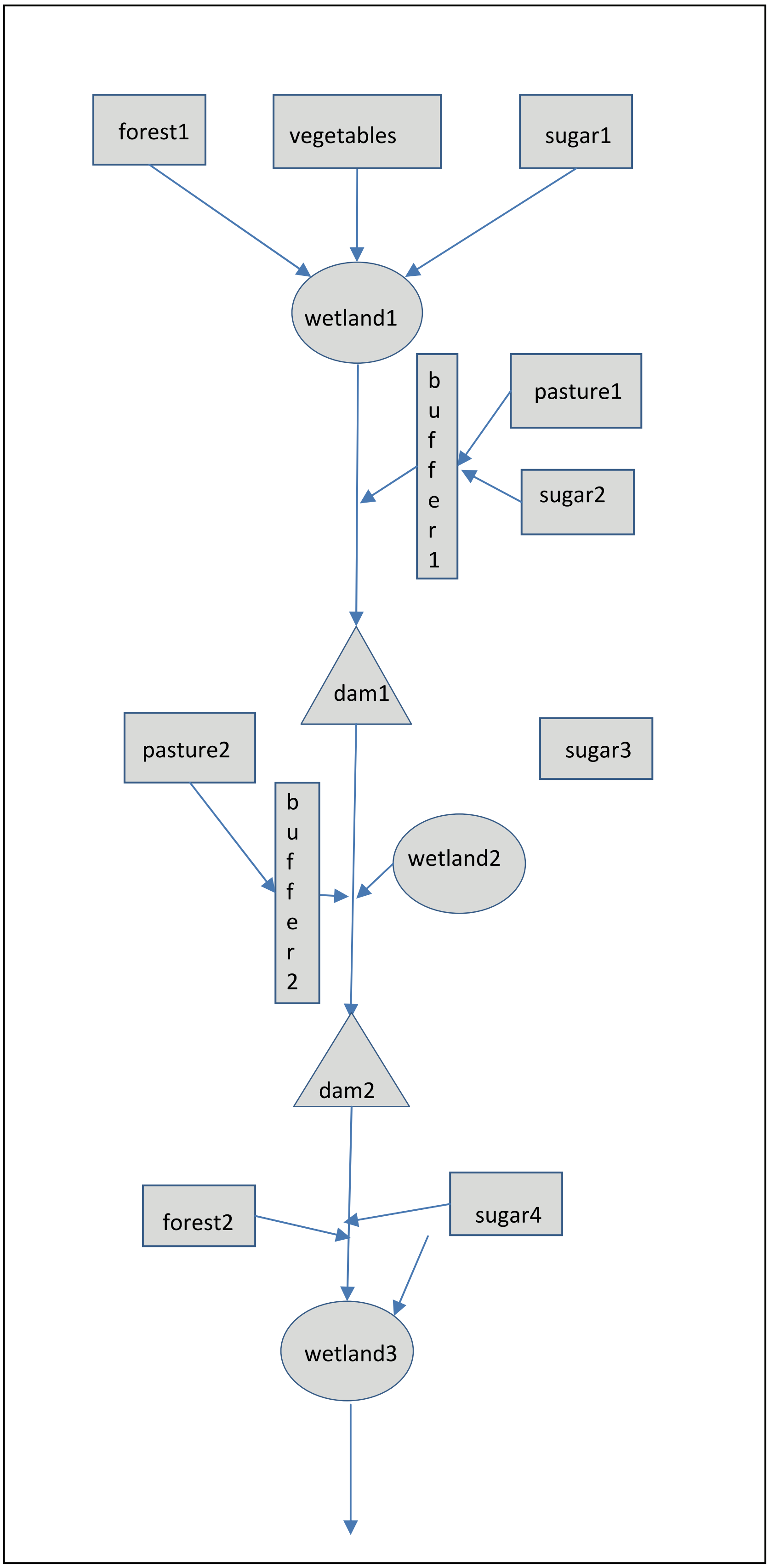


FIGURE 48 Mkabela catchment simplified network for scenario analysis

The scenarios comprised:

- **Base case:** current land use;
- **No contours:** current land use, assume no contours used in the sugar cane estates;
- **All sugar:** all land uses set to sugar cane;
- **Irrigation:** current land use, but with deficit irrigation applied to the sugar cane;
- **No buffers:** base scenario with farm dams and buffers removed.

All these scenarios were run with a series of fertilizer applications, comprising current fertilization practice (base), double (high), half (low-1/2) and a quarter (low-1/4) of the base fertilizer applications and finally, no fertilizer (zero) application. The resulting crop yields and sediment and nutrient loadings are analysed below.

4.11.2.1 Sugar cane yields

A 5-year sequence (2006-2011) was simulated to check crop yield response to fertilizer application. The effective yield of the sugar cane is controlled by the relationship between the growth rate ratio (GRT) and the nitrogen content (CN%) in the cane:

$$CN\% = C1.GRT^{C2} \qquad 35$$

The recommended value for C1=0.17 was used in the extended simulations, but the sensitivity of this relationship to resultant crop yield was tested using C1 values of 0.325 and then 0.525 as illustrated in Figure 49.

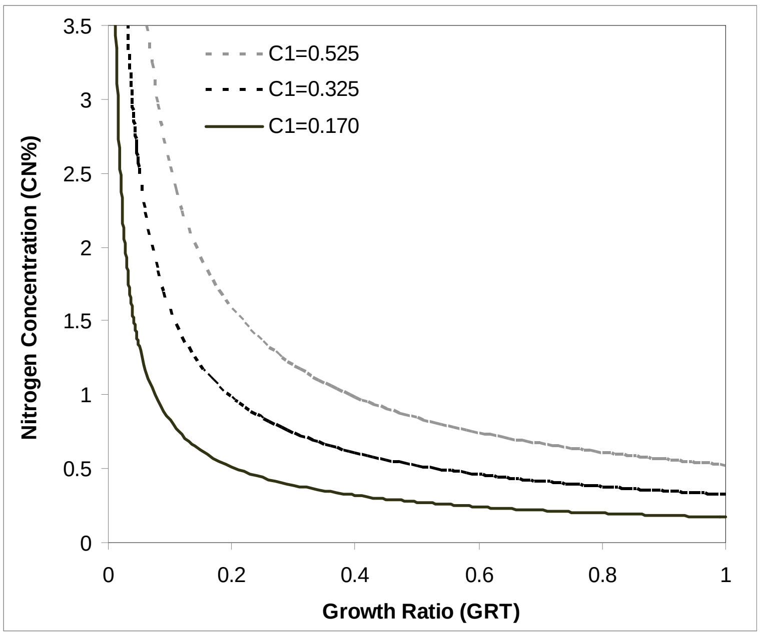


FIGURE 49 Sugar cane growth rate ratio and nitrogen content relationship for a range of C1 values.

Simulations of a single sugar cane land segment with the five fertilizer application rates revealed small differences in yield when using the recommended 0.17 value for C1 and potential yield of 67t/ha. Significant reductions in yield were, however, simulated when no fertilizer was applied (Figure 49). In addition, varying the C1 values and the potential yields modified the actual yield dependence on the fertilizer applications significantly (Figure 49).

A comparison of the *ACRU-NPS* generated sugar cane yields for the period 2006 to 2011 against the CaneGrow model estimates and reported average yields for South Africa shows that a C1 value of 0.325 results in reasonable yields and variation (Figure 50). While the relationship between sugar cane yield and nitrogen application has been shown to be dependant on the presence or absence of other nutrients (Miles, 2009, Miles 2010), it is assumed in these simulations that these are sufficiently available.

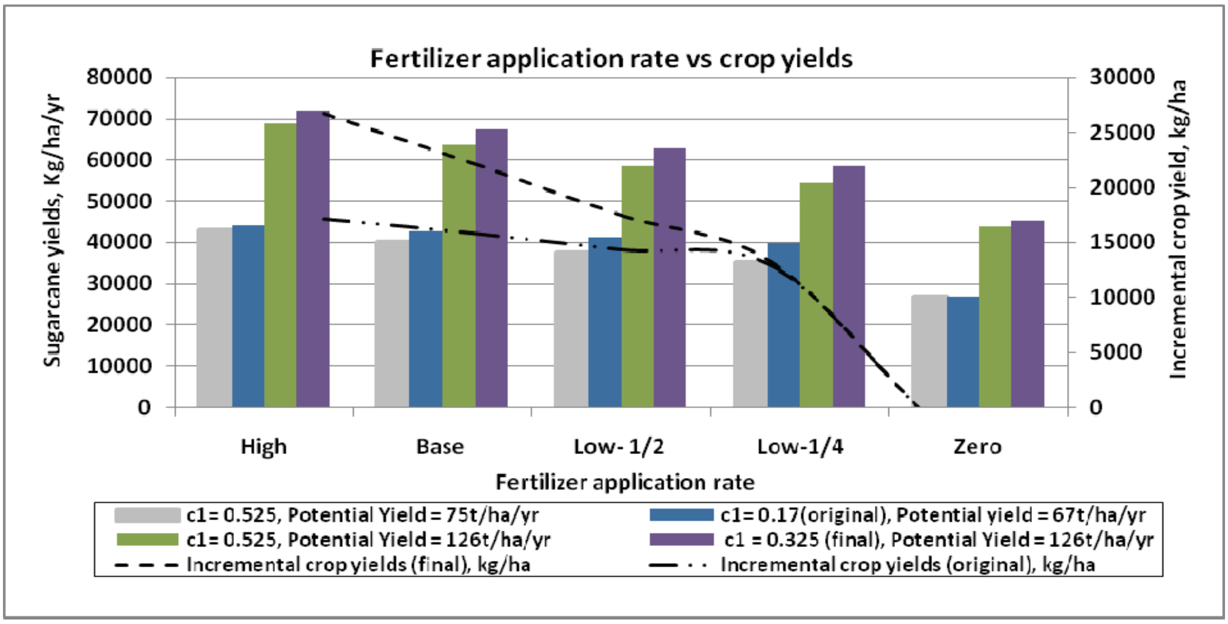


FIGURE 50 Comparison of sugar cane yield for various N fertilizer applications and potential yields, using values of C1 =0.17 (initial), 0.325 (final) and 0.525. The lines indicate the incremental crop yield for the different fertilizer applications against zero fertilizer.

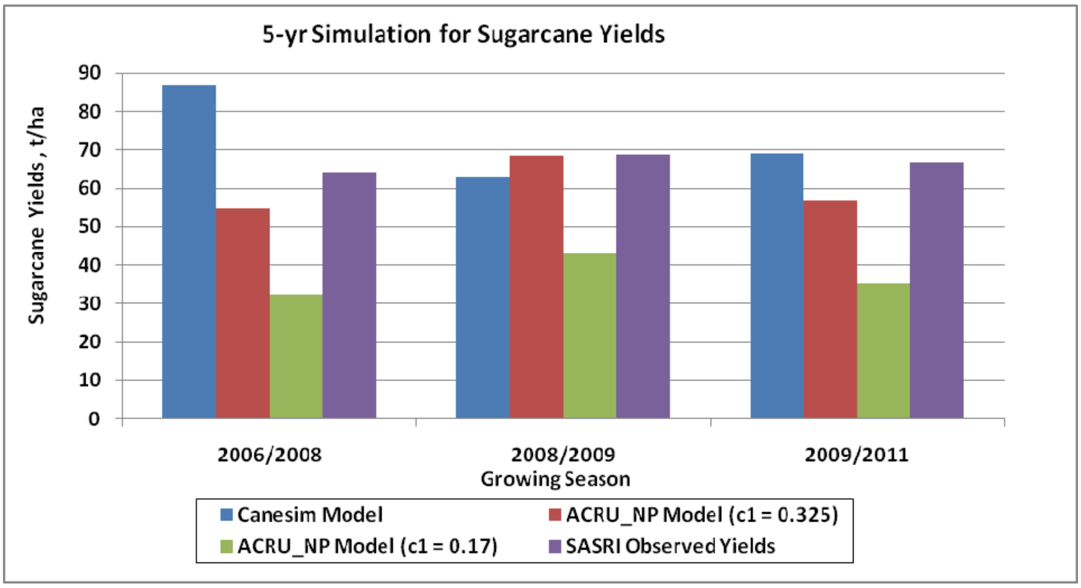


FIGURE 51 Comparison of sugar cane yields for 3 18-month retunes (production cycles) from 2006 to 2011 from simulations (CaneGrow, *ACRU-NPS* C1=0.17 and *ACRU-NPS* C1=0.325) and SASRI published average yields for the South African sugar industry.

A 50-year period, 1950-1999, was simulated to determine variation in crop yield and mass loads. A 50-year rainfall record was used to simulate 33 retunes (production cycles), each of 18 month duration. The maximum potential yield was set at 75 t/ha (Figure 51).

The Base application crop yields vary between 66 t/ha and 34 t/ha over the 50 year period. There is a marginal improvement in crop yield with the Double application rate and systematic, but small, decreases in yield with lower fertilizer application rates. Without fertilizer application, the crop yields are significantly lower than those from the Quarter application rate. However, there are two occasions when the crop yield without fertilizer exceeds the fertilized yields, the relatively dry years, 1955 and 1957. This is most likely because of the preservation (carry-over) of available water from a previous year's very low crop yield without fertilizer.

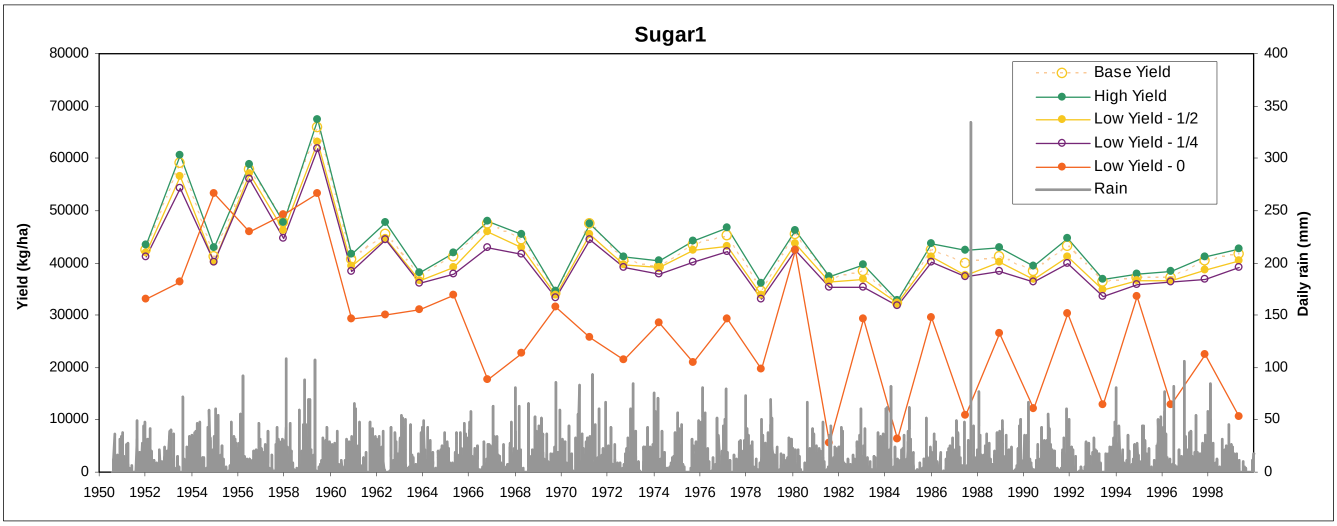


FIGURE 52 Sugar cane yields from Land Segment 1 for 50 year simulation. (File Yields_LS1_.xls)

4.11.2.2 Nutrient and Sediment Loads

i. <u>Off-field discharge and mass loads.</u>

Daily runoff and mass loads of sediment, nitrogen and phosphorus have been simulated for the sugar cane catchment, LS1. These daily values have been accumulated for each 18-month cropping period so that catchment loadings can be compared to resultant crop yield. Marginal reduction in runoff occurs with increasing fertilizer application rates as increases in plant water uptake are realised (Figure 52). Without fertilizer and with consequent reduction in plant water uptake, the runoff is generally higher than the fertilized scenarios. At the start of the simulation period, however, runoff from the unfertilized cane catchment is low due to the high water use in 1955, by a crop sustained by available soil water resulting from carry-over from a previous year's very low crop yield.

Different fertilizer applications do not appear to affect sediment yield significantly (Figure 53). However, this is understandable since the crop cover variable has not been adjusted for different crop yields.

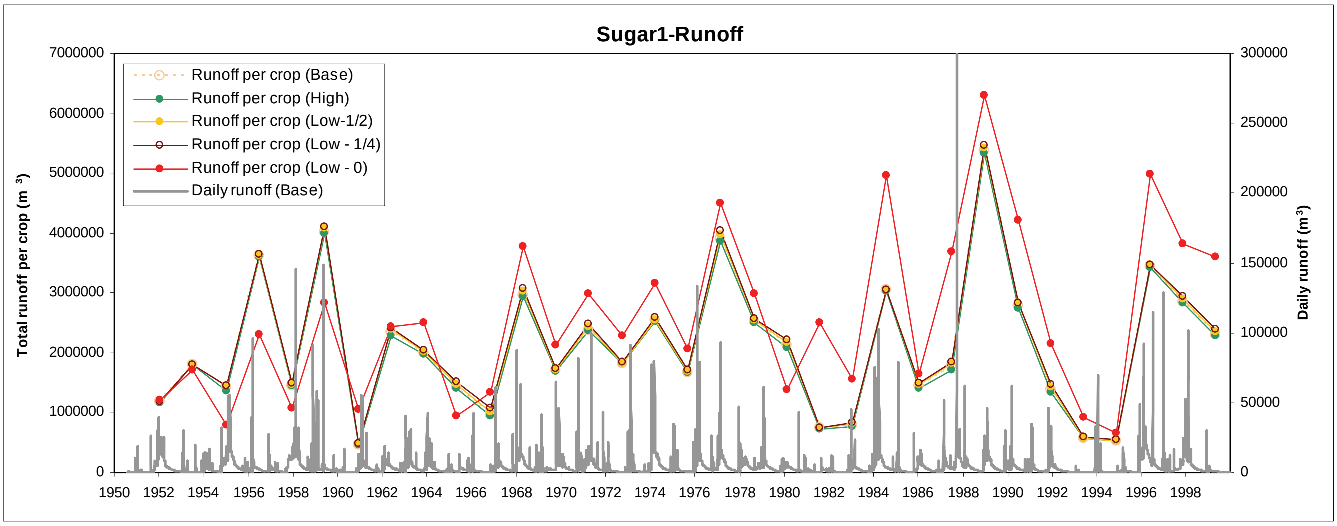


FIGURE 53 Runoff from Sugar cane Land Segment 1 for 50 year simulation, showing daily runoff for Base fertilizer application as well as Total Runoff for each crop retune for all fertilizer application rates, High to Low-0. (File Yields_LS1.xls)

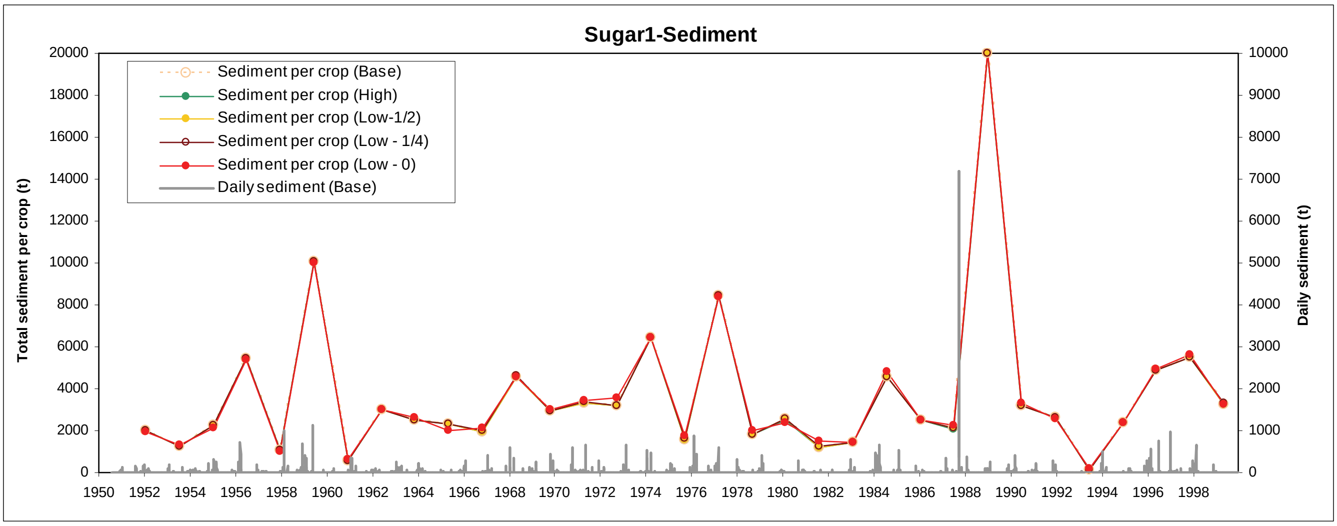


FIGURE 54 Sediment yield from Sugar cane Land Segment 1 for 50 year simulation, showing daily sediment yield for Base fertilizer application as well as Total Sediment for each crop retune for all fertilizer application rates, High to Low-0. (File Yields_LS1.xls)

Nitrogen and Phosphorus export vary significantly with varying fertilizer application (Figure 54 and Figure 55). The consequences of over-fertilization are very clear in the large mass loads resulting from a doubling of the application rate, compared to halving it.

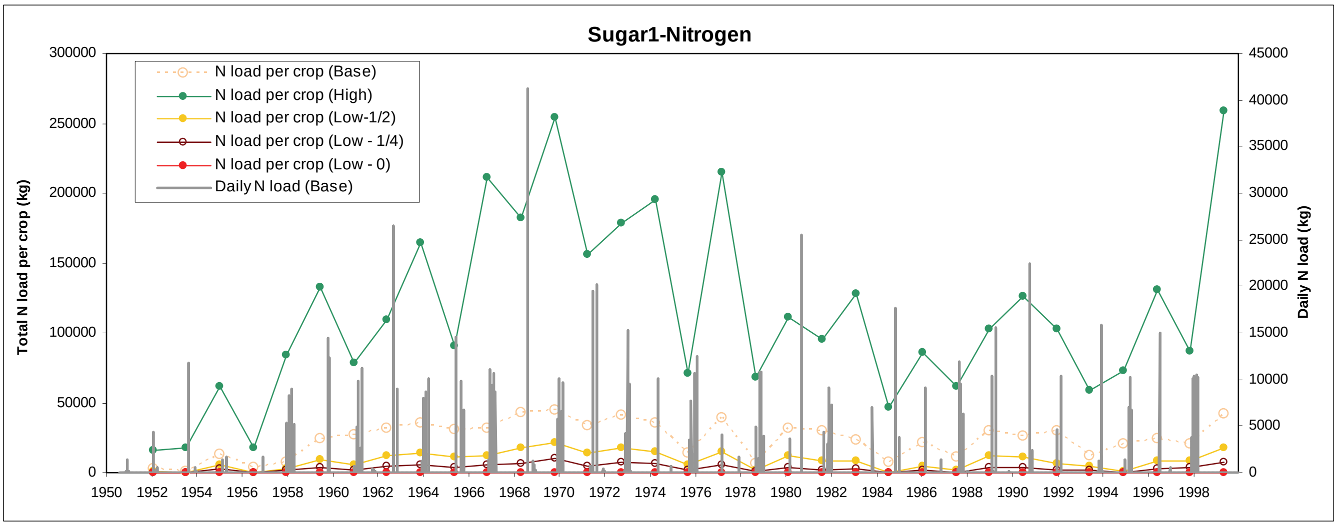


FIGURE 55 Nitrogen loads from Sugar cane Land Segment 1 for 50 year simulation, showing daily N load for Base fertilizer application as well as Total N for each crop retune for all fertilizer application rates, High to Low-0. (File Yields_LS1.xls)

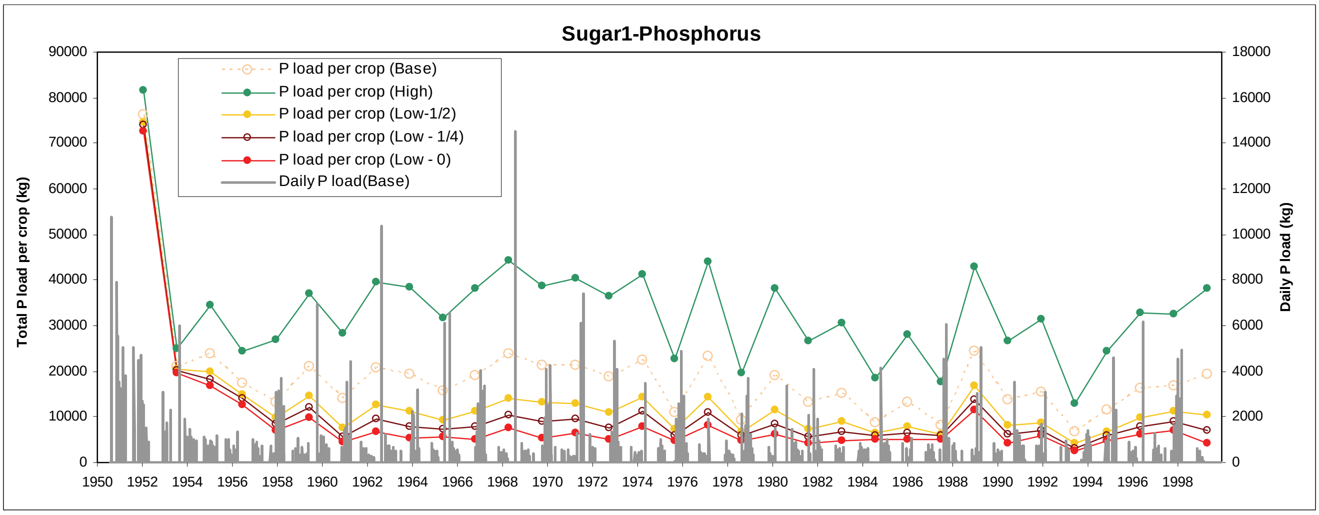


FIGURE 56 Phosphorus loads from Sugar cane Land Segment 1 for 50 year simulation, showing daily P load for Base fertilizer application as well as Total P load for each crop retune for all fertilizer application rates, High to Low-0. (File Yields_LS1.xls)

ii. <u>Nutrient and sediment loads through in-stream controls</u>

The sugar cane yield, discharge, sediment and nutrient loads were routed through the network controls (Figure 47b). The resultant inputs and outputs at the Dam1 and Wetland 3 controls are presented in Figures 56 and 57. A full set of results of the scenarios for the 1950-1998 simulations are presented in Appendix J.

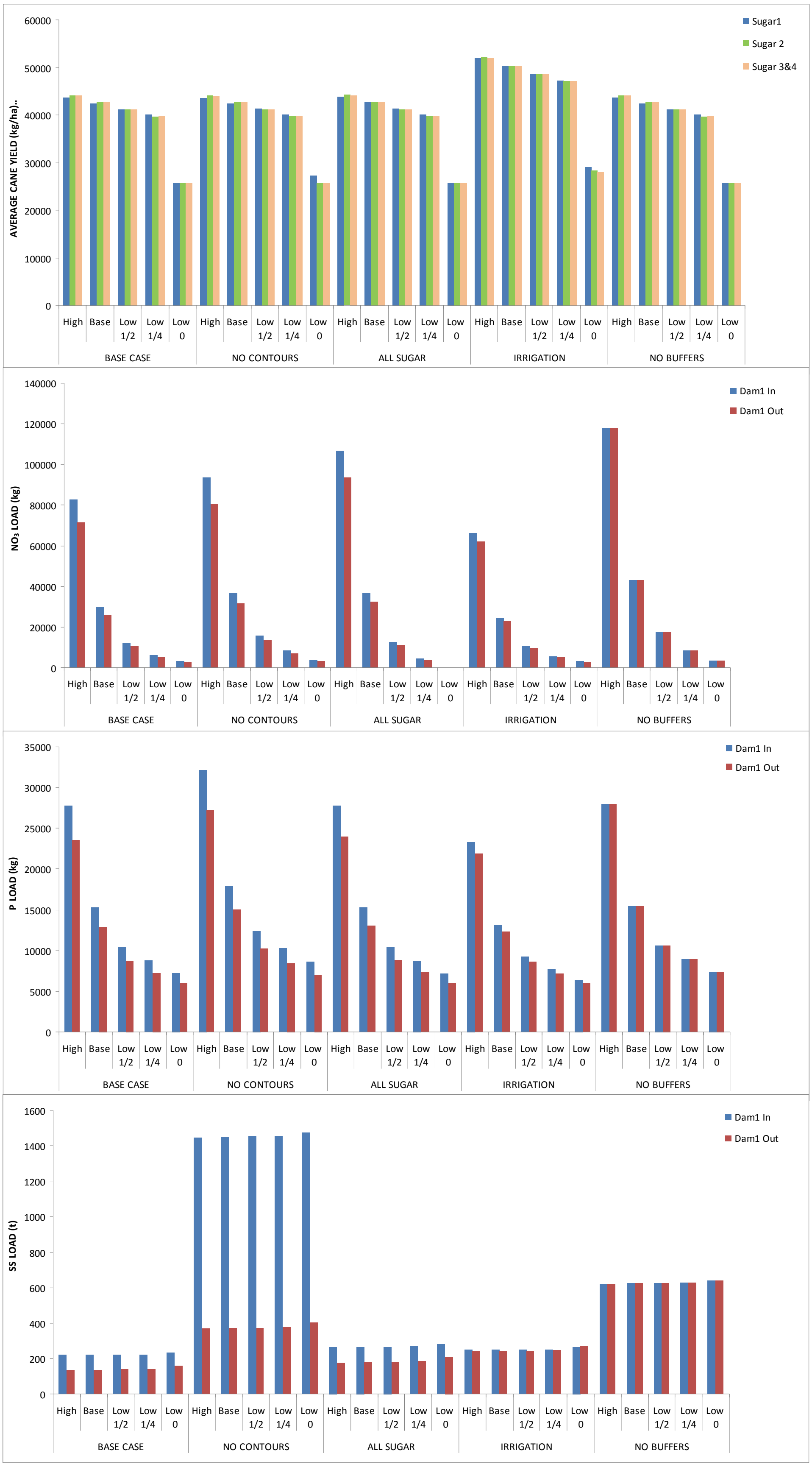


FIGURE 57 Scenario averages for cane yield (top), NO_3, P and sediment yields (bottom), into and out of Dam 1.

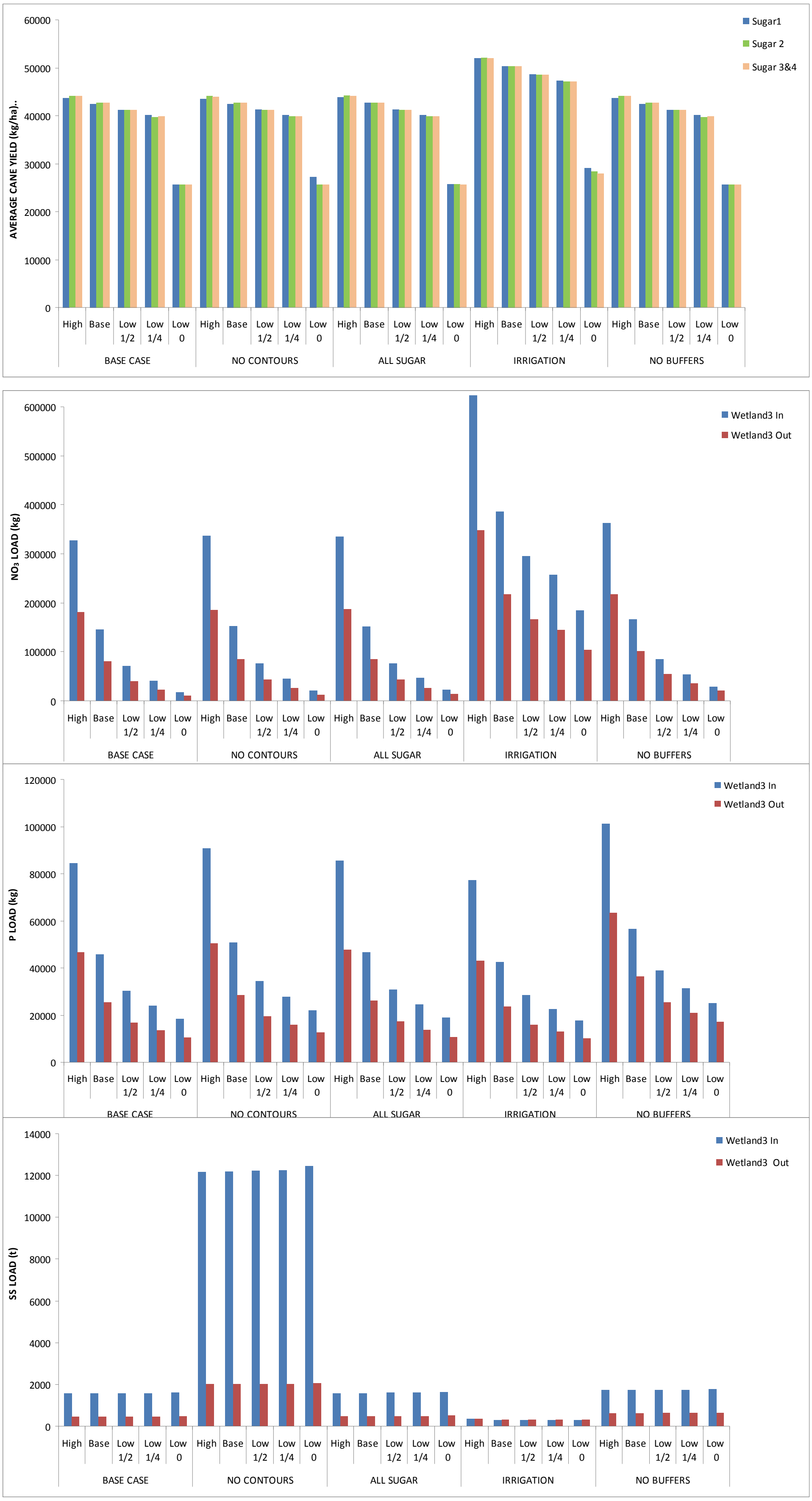


FIGURE 58 Scenario averages for cane yield (top), NO_3, P and sediment yields (bottom), into and out of Wetland 3.

5. SWAT MODEL SIMULATIONS OF THE MKABELA CATCHMENT

The Soil and Water Assessment Tool (SWAT) is a catchment-scale model that was developed at the US Department of Agriculture (USDA) Agricultural Research Service (ARS) to predict the impact of land management practices on water, sediment, and agricultural chemical yields on complex landscapes with varying soils, land use, and management conditions over long periods of time (Arnold et al., 1998). As part of this Task, SWAT was configured for the Mkabela River nested catchments. The intention was not to improve and augment SWAT as was done with *ACRU-NPS*; rather, the intention was to provide a comparative catchment-scale alternative to *ACRU-NPS*.

In SWAT, surface runoff volume is computed using the SCS curve number method which is empirically based and relates runoff potential to land use and soil characteristics (USDA Soil Conservation Service, 1972). Peak runoff rate is estimated with a modification of the Rational Method; where runoff rate is a function of daily surface runoff volume and a proportion of rainfall occurring until all of the catchment is contributing to flow at the outlet. The latter duration is estimated using Manning's Formula, considering both overland and channel flow. Sediment yield is computed with the Modified Universal Soil Loss Equation (MUSLE). In addition, loading functions estimate the daily organic N/P runoff loss based on the concentration of organic N/P in the top soil layer, the sediment yield, and the enrichment ratio.

Sediment and nutrient modelling with SWAT requires spatial data as well as attribute data for several parameters including topography, land cover, soil, climate and management. Due to the lack of data, research focused on improving simulations by revising or incorporating important model components for which appropriate input data exist. Input data requirements are listed as they are integrated within the geographically interfaced version of SWAT (AVSWATX) and the most sensitive parameters deserve special attention. Readers should note that the input data presented in this section are provided in the CD attached to this report. Please note the input data in the CD are presented in 'raw' format, i.e. in the same code as requested by the geographically interfaced version of SWAT (AVSWATX). The codes are defined in the SWAT2005 manual (Neitsch *et al.*, 2005a).

5.1 Topography

First of all, a digital elevation model (DEM) was created from 5 m contours obtained from 1:10 000 maps of the Surveyor-General. The DEM has a pixel size of approximately 20 m x 20 m and varies from 820 m a.s.l. at the catchment outlet to 1057 m a.s.l. in the upper reaches. Automated routines in AVSWATX calculated the slope and divided the catchment into homogenous sub-catchments from the DEM. Since the model cannot efficiently measure the geometric complexity at which the catchment is delineated, appropriate contributing source areas had to be delimited by the user (as area or percentage of the entire catchment). The number of sub-catchment links or outlets was manually limited across the catchment so that short channels and small sub-catchments were removed, while still representing all large streams in homogenous sub-catchments. For model calibration comparison of simulated outputs with observed flows and loads must be possible. Therefore, the flow measurement sites shown in Figures 1 and 2 were used to further subdivide the catchment into homogeneous sub-catchments. The final result is several tributary channels within 21 sub-catchments branching off the main channel, as shown in Figure 58. Next, hydrological parameters were derived from the land cover, as well as soil data, and added to the attribute data of the catchment.

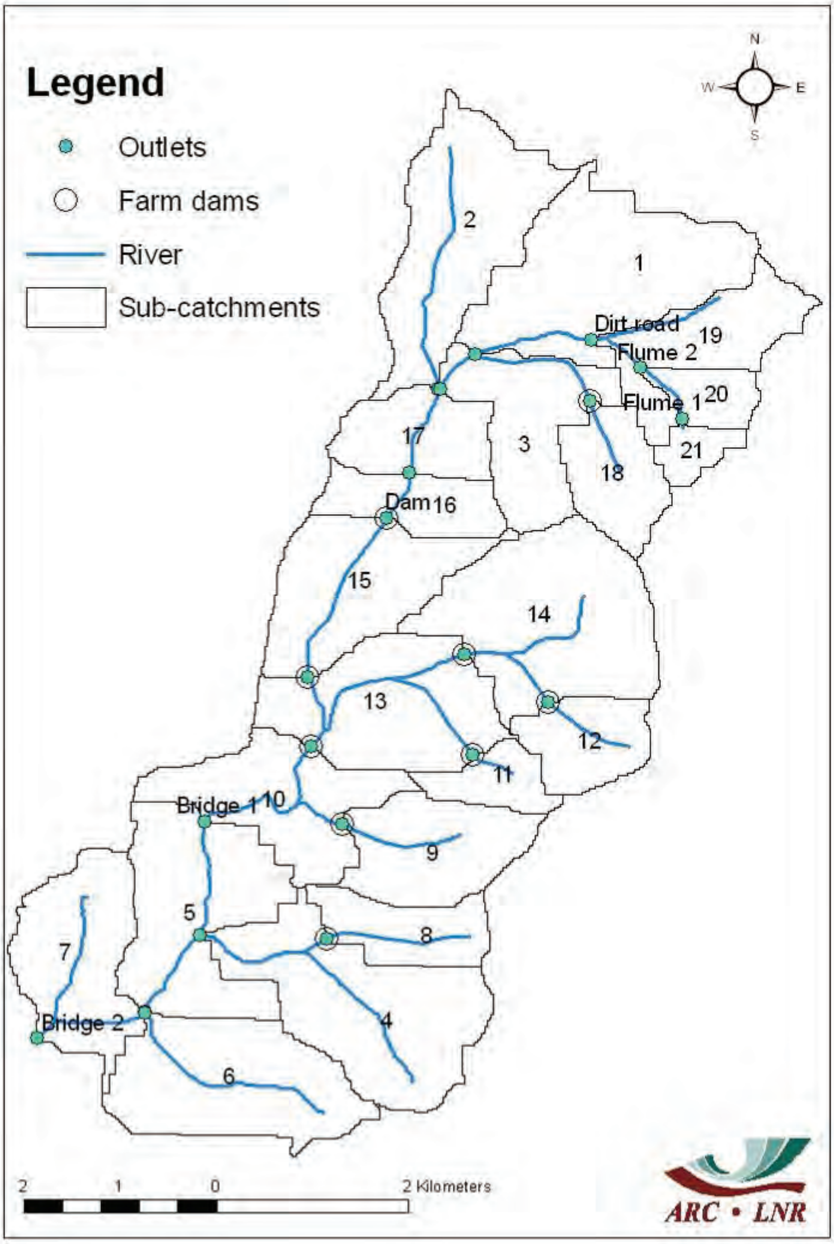


FIGURE 59 Sub-catchments of the Mkabela catchment, used in SWAT.

5.2 Land cover and hydrological structures

Of all erosion hazard factors the cover management code or land cover is the most important soil erosion factor in USLE-based models (Wischmeier and Smith, 1978). Plant cover is dominant over the effect of rainfall, slope and the soil profile. Therefore, site-specific vegetation parameters must be accurately derived to assure successful model performance. Initially, land cover data from the South African National Land Cover database (National Land Cover, 2000) was used. Subsequently, this land cover map was updated, using more recent Topomaps and SPOT 5 imagery with acquisition dates between 2005 and 2006. Figure 59 presents the adapted land cover map that portrays more current field conditions. In addition, river channel and flow observations were made from the upper catchment area to the catchment outlet in May 2008 (see Table 1 in Appendix K). Subsequently, nine outlets were incorporated in AVSWATX to represent nodes/outlets at the exit from farm dams, instead of simulating only one farm dam. AVSWATX further allows for impoundments such as wetlands located within sub-catchments to be modelled. Although all wetlands are incorporated/mapped on the adapted land cover map, they are too small to be represented amongst the larger land use/soil combinations. However, AVSWATX allows wetlands to receive loadings from a fraction of the sub-catchment area where they are located. Table 19 lists parameter information of the farm dams and wetlands in Mkabela catchment, whereas Figure 59 illustrates their geographical distribution.

TABLE 18 Parameter information used to model each of the farm dams and wetlands in Mkabela catchment.

Sub-catchment	Dam area (ha)	Dam volume (m^3)	Wetland area (ha)	Wetland volume (m^3)
5	-	-	2.79	41850
8	1.6	48300	-	-
9	0.6	17400	4.82	72300
10	-	-	2.63	39450
11	1.4	40800		
12	1.5	45900		
13	10.5	315600	22.46	336900
14	8.5	253500	-	-
15	3.0	88800	9.05	135750
16	5.9	175800		
17	-	-	4.78	71700
18	0.6	18600	-	-

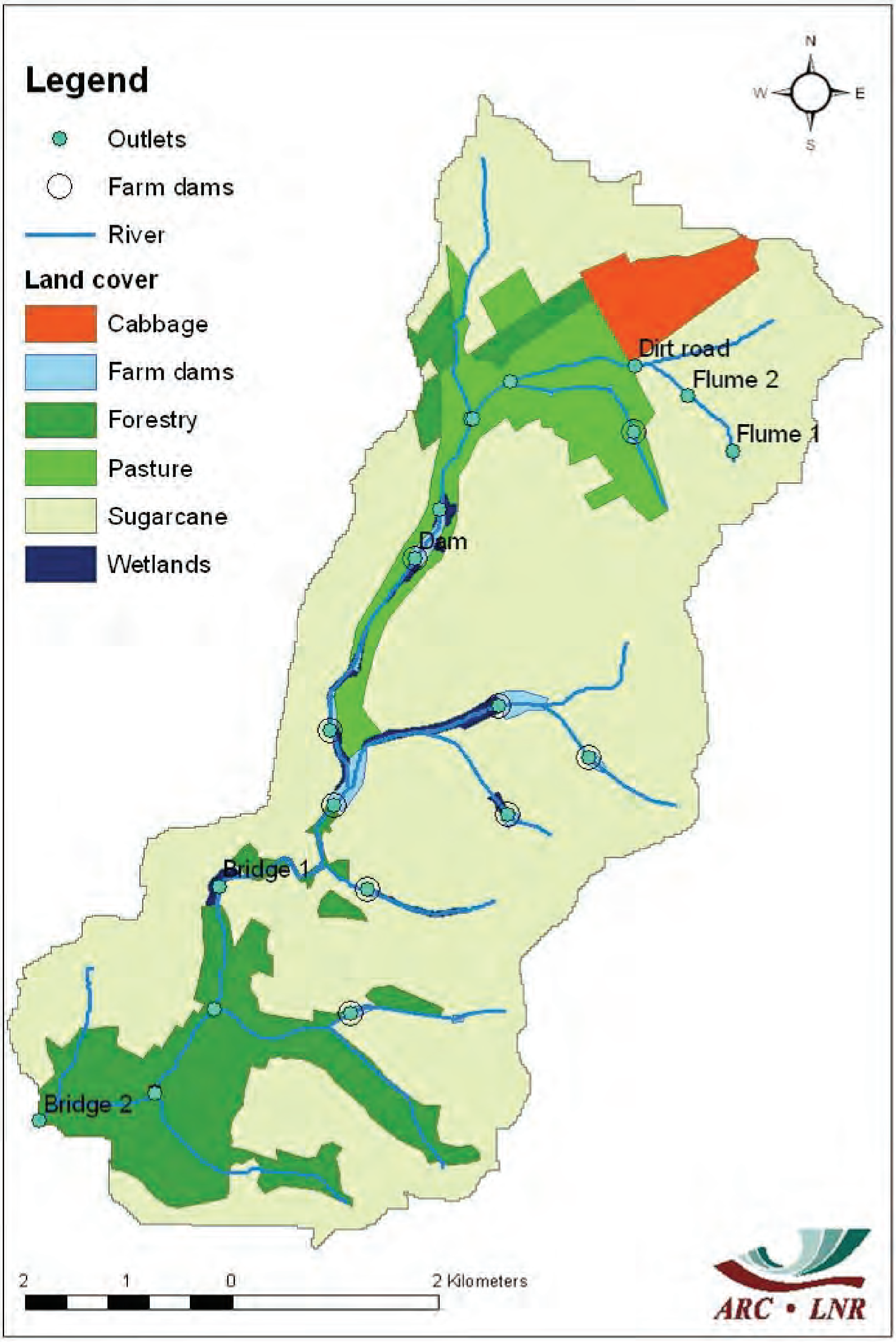


FIGURE 60 SWAT subcatchment outlets and land cover for the Mkabela catchment.

SWAT requires a fairly long list of land cover parameters that could not all be obtained directly from existing data for the Mkabela catchment. Instead, the land cover map was linked via a four character code to a database available in SWAT. Tables 2 and 3 in Appendix K contain the land cover parameter values used for the Mkabela catchment, as well as their definitions. The only parameter worth mentioning here is the Curve Number (CN); being the parameter that was modified in an attempt to calibrate the model (as a second possible improvement). The curve number determines the partitioning of precipitation between surface runoff and infiltration as a function of soil hydrological group, land use, and antecedent moisture condition (Mishra and Singh 2003). Since the CN is very sensitive in SWAT (Lenhart *et al.*, 2002), CN values for sugarcane in the SWAT database were adjusted according to values provided in the *ACRU* model database (CN2A = 39, CN2B = 50, CN2C = 68, CN2D = 75). These values are somewhat lower than the initial SWAT database values and were utilized in the calibration of the model. Since the remaining parameter values were obtained from the SWAT database, they will not be discussed. It should be noted that, due to a lack of data on crop rotation systems and timing of agricultural operations, phenological plant development had to be based on daily accumulated heat units (see Tables 2 and 3 in Appendix L).

5.3 Soil data

SWAT requires that each sub-catchment be characterized according to soil parameters which can be divided into physical and chemical characteristics (Neitsch *et al.*, 2005b). Information on chemical properties is optional, while the physical properties are a prerequisite. Physical properties of the soil govern the movement of water and air through the profile and have a major impact on the cycling of water within hydrological units. The main soil types (hillslopes and terrain units) in the Mkabela catchment and their soil parameter values are given in Appendix M, Table 1. Appendix M, Table 2 defines each of the soil parameters. Not all of the soil data listed in Appendix M was available for the Mkabela catchment. Therefore, parameter values were assigned to each individual soil component (hillslopes and terrain units) according to the soil descriptions given by Le Roux *et al.* (2006) if available; and supplemented by other sources of literature if needed. Following is a brief description of the methodology followed to assign parameter values for the soil map units (hillslopes) in Mkabela catchment. Descriptions are listed as they appear within Table 1 (Appendix M).

First, the initial soil components (6 hillslopes) provided by Le Roux *et al.* (2006) were divided into smaller soil units (18 units) using ARC-ISCW terrain unit data. Second, to account for soil variability with depth, up to three layers/horizons were incorporated into each soil component (instead of just one modelled previously). The new soil map with smaller soil components were prepared by overlay analysis of the terrain unit map and the soils map of Le Roux *et al.* (2006). As a result, the previous soil units (hillslopes) were divided into smaller units that display different soils according to each terrain unit inside the catchment (see Figure 60). The depth of each layer was obtained from the documentation of Le Roux *et al.* (2006).

SWAT requires that each sub-catchment be characterized according to its hydrological soil group (HSG) (see Tables 3 and 4 in Appendix L). HSG values (A, B, C, or D) were assigned to each dominant soil type within a given soil map unit or hillslope using the descriptions of Le Roux *et al.* (2006) and soil texture classes. General definitions for each HSG for use in verifying the relationship between texture and HSG were taken from Renard *et al.* (1994).

The two optional parameters, the fraction of porosity (void space) from which anions are excluded and the crack volume potential of soil, were set to default values of 0.5 due to a lack of data.

SWAT requires several additional parameter values that could not be obtained directly from existing soil data for Mkabela catchment. The available water capacity (AWC) is a key soil parameter that has been found to affect groundwater recharge estimates in simple water balance models (Finch, 1998). AWC was determined using soil texture classes and the documentation of Ashley *et al.* (1998) on AWC values for various textural classes of soils. Similarly, estimated values for hydraulic conductivity were derived from look-up tables (Morris and Johnson, 1967; Heath, 1983) based on soil texture in the top layer of each soil map unit. SWAT also requires bulk density and moist soil albedo parameter values that are not available in the soil survey data. Bulk density values were obtained from Lorentz

(2006; personal communication), whereas albedo values were assigned according to individual soil colour characteristics, on a subjective basis.

Percentage clay for each soil map unit was obtained from Le Roux *et al.* (2006), as well as the percentage particles smaller than 0.75 mm. The latter value was used as an indication of percentage fine sand and silt. Sand fraction values were added so that the combination of fraction values sum to 100. As recommended by Burns *et al.* (2004), rock content values were set to 0, given the lack of data. Organic carbon content is available from the soil survey data of Le Roux *et al.* (2006).

The K-factor may be estimated from data on the soil's particle size distribution, organic matter content, surface structure and profile permeability using the soil erodibility nomograph (Wischmeier and Smith, 1978). In the absence of soil analytical and experimental data, two alternative sources of soil information were used: Soil maps (1:50 000 and 1:250 000; Soil Survey Staff, 1973-1987) were used to obtain soil erodibility ratings for the individual soil series of the Binomial Soil Classification System of SA; and erodibility values were linked to corresponding soil series in the Land Type Inventories (Land Type Survey Staff, 1972-2006) in order to be spatially distributed on a scale of 1:250 000. Soil erodibility index values were utilized by using the Soil Loss Estimator of Southern Africa (SLEMSA; Elwell, 1976), providing a reasonable guide to the relative differences in the erodibility of major soils. SLEMSA soil erodibility units (F) were assigned on a scale of 1 to 10 based on an assessment of the surface soil texture, surface soil structure and profile permeability of the dominant soils (see Table 5 in Appendix M).

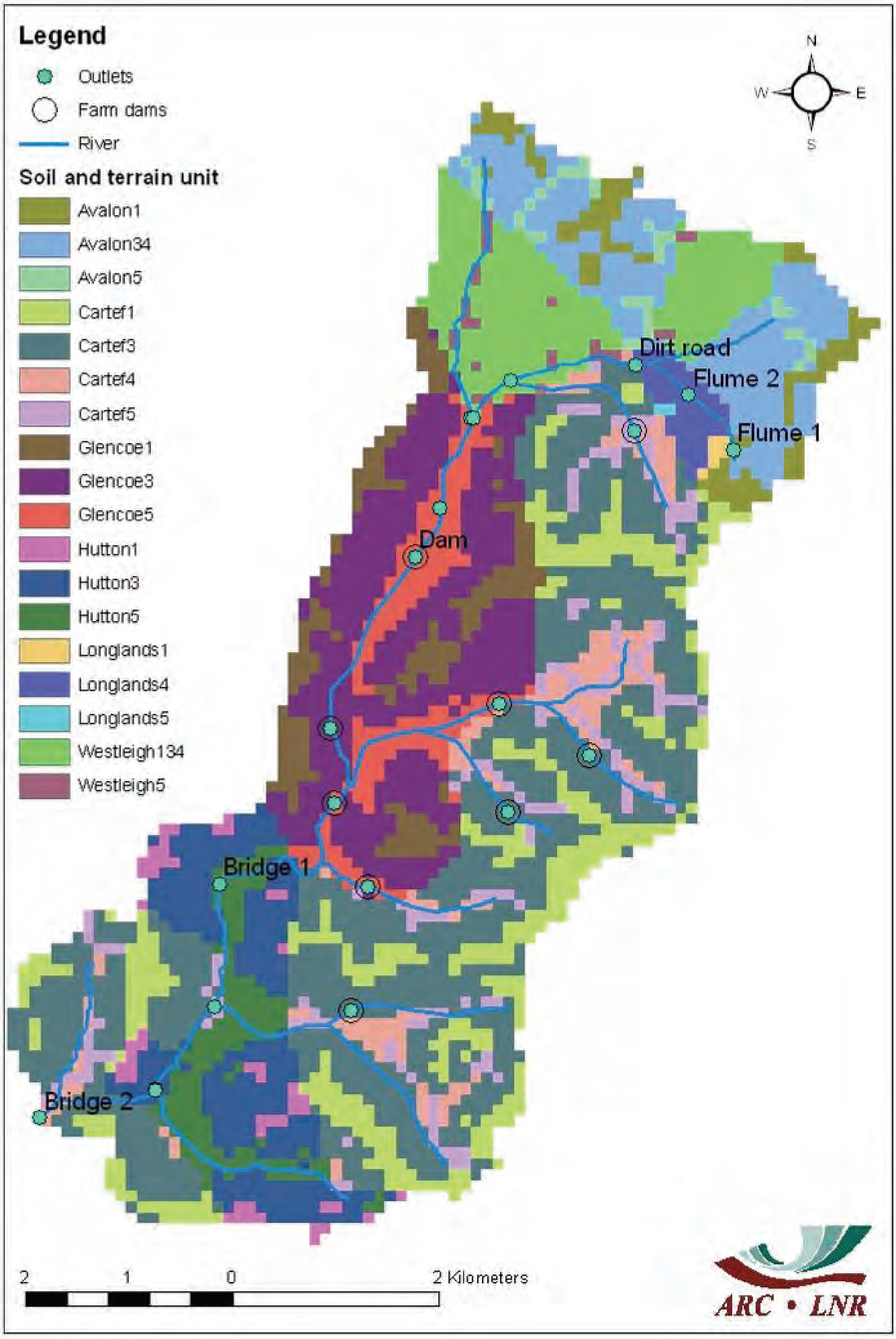


FIGURE 61 Adapted soils map of the Mkabela catchment for SWAT inputs

Subsequently, the SLEMSA F factors were used as a guide to the assignment of RUSLE K-factors to all Land Types of SA. It is noteworthy that the Land Type database does not contain individual soil profile information listing soil type and observed or measured soil attribute values. Although it was possible to state the number of soil types within each Land Type polygon with their proportions, the location of each soil type within a polygon was not available. To estimate a K value within a Land Type polygon, the K-values related to each soil type were weighted according to the area occupied by that soil type within the polygon. Therefore, the final K-values are an area-weighted average for a soil map unit.

Simulation results improved with delineation of the subcatchments into small hillslope units and invoking a three layered soil system (SWAT). However, ancillary soil information improved the simulated results to a lesser extent. At catchment scale, it seems as if the initial simulations overvalued certain spatial physical factors (e.g. soil variability) and disregarded important ones (e.g. hydrological structures).

5.4 Hydrological response units

In the initial SWAT configuration only one landuse/soil combination was defined per sub-catchment in the Mkabela catchment. However, lumping the main land cover and soil types disregard small but important land cover units, e.g. a vegetable plot and forest plantation in sub-catchment 1. To capture the diversity of land use a method was needed to account for the complexity of the landscape within the boundaries of the sub-catchments. According to Neitsch *et al.* (2000), the simulated net volume of runoff entering the main channel from the sub-catchment should be more accurate when the diversity in plant cover within a sub-catchment is accounted for.

The inclusion of multiple hydrological response units (HRUs) allows SWAT to account for this diversity. HRUs are portions of a sub-catchment that possess unique landuse/soil attributes. It is also worth mentioning that the geographically interfaced version of SWAT (AVSWATX) only provides HRU-related outputs (e.g. crop yield) when the user prompts the model to simulate multiple HRUs. Therefore, HRUs were incorporated into simulations of the current study to increase accuracy to the predictions of loadings from sub-catchments. Desired threshold values were specified for land use and soil that determine the number and kind of HRUs in each sub-catchment (land use/soil percentage within each sub-catchment, e.g. 10% and 5% respectively).

5.5 Surface and subsurface flows

5.5.1 Surface characteristics

In order to simulate the physical processes affecting the flow of water and transport of sediment in the channel network, SWAT also required information on the physical characteristics of the main channel and HRUs within each sub-catchment. The initial SWAT simulations neglected this element in the Mkabela catchment by simply accepting the default values provided in the SWAT database. However, these default values represent straight and uniform field or channel conditions that do not correspond to current conditions in the Mkabela catchment. Therefore, results were improved by adjusting/increasing Manning's roughness coefficient (n) for tributaries and the main channel to values of 0.065 and 0.14 respectively, representing (rougher) surface conditions observed during field observations in the catchment.

5.5.2 Subsurface flow

Models must represent the site-specific processes of overland versus subsurface discharge and nutrient flux. The monitoring results in the catchment (see Section 2.3) indicate significant increases in runoff and nutrient yield at the field- and small-catchment-scale compared to the point-scale, indicating a predominance of subsurface discharge from the sugar cane land use. As mentioned above, the available water capacity (AWC) is a key soil parameter that has been found to affect groundwater recharge estimates. In addition, SWAT partitions groundwater into two aquifer systems: A shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes no return flow to streams inside the watershed (Neitsch *et al.*, 2005a). Unfortunately, groundwater conditions in the Mkabela catchment could not be represented in the model with any certainty due to lack of data and groundwater's role remains speculative.

5.6 Climate data

The geographically-interfaced version of SWAT (AVSWATX) requires spatial data as well as attribute data for several climate parameters, including precipitation, temperature, solar radiation, dew point and wind speed, as follows:

- Precipitation:
  - Average total monthly precipitation (mm).
  - Standard deviation for daily precipitation in month.
  - Skew coefficient for daily precipitation in month.
  - Probability of a wet day following a dry day in the month.
  - Probability of a wet day following a wet day in the month.
  - Average number of days of precipitation in month.
  - Maximum 0.5 hour rainfall in entire period of record for month.
- Temperature:
  - Average or mean daily minimum air temperature for month (°C).
  - Average or mean daily maximum air temperature for month (°C).
  - Standard deviation for daily minimum air temperature in month.
  - Standard deviation for daily maximum air temperature in month.
- Solar radiation:
  - Average daily solar radiation for month (MJ/m^2/day).
  - Dew point:
- Average daily dew point temperature in month (ºC).
  - Wind Speed:
- Average daily wind speed in month (m/s).
  - Apart from the parameters, the model also requires the locations of the climate stations.

The foregoing required input values were calculated from daily values over a 30 year period (e.g. from 1 January 1977 to 30 June 2008). The data period and the length of record vary from station to station and not all the climate parameters could be measured at all the stations. In order to create a full record, the most complete and closest stations were selected and omitted values were replaced/patched with values from neighbouring stations. The assignment of a specific precipitation record to a given catchment was determined based on which weather station was closest to the catchment, as well as the number of years of record. Solar radiation data were obtained from the Cedara – AGR station no 13499. Data from several stations were interpolated by Thiessen Polygon analysis in AVSWATX to generate a spatial representation of the rainfall.

5.7 Management practices

In AVSWATX, the primary file used to summarize land use management practices is the HRU management file (.mgt), which includes input data for planting, harvest, irrigation applications, nutrient applications, pesticide applications, and tillage operations. The Mkabela land use management practices were incorporated in the SWAT configuration as follows:

- Specifying initial crop conditions prior to simulation;
- Specifying the application of nutrients to sugarcane and vegetables (the model can apply nutrients whenever the plant experiences a typical level of nitrogen stress);
- Specifying the application and source (deep aquiver in sub-catchment 1) of irrigation water applied to vegetables and pasture (the model can apply water as needed by the plant);
- Specifying harvesting operations for sugarcane (harvest only instead of harvest and kill), and forestry plantations (allows the plant to continue growing instead of frequent harvesting and killing).

The management practices applied in each sub-catchment, as well as the heat units at which they were applied, are given in Tables 1 and 2 in Appendix L. Since the operations data listed in Appendix L were not available for each HRU at specific times, parameter values were assigned to represent each management practice according to values provided in the SWAT database. Importantly, due to the lack of data on the crop rotation systems and timing of agricultural operations, phenological plant development is based on daily accumulated heat units. Detailed descriptions of the parameters are given in the SWAT2005 manual (Neitsch *et al.*, 2005a).

5.8 Calibration and validation

Calibration of the SWAT model in the Mkabela catchment focused mainly on the hydrological part of the model, by comparing observed rainfall-runoff events and loads with the equivalent simulated events.

Five model runs were conducted for the period of 1 July 2007 to 30 June 2008, to sequentially improve the initial coarse configurations, as follows:

- The initial soil components (6 hillslopes) were divided into smaller soil units (18 units) using ARC-ISCW terrain unit data, and up to three layers/horizons were incorporated into each soil component (instead of only one modelled initially);
- Incorporation of nine outlets that represent nodes/outlets at the exit from farm dams (instead of only one large farm dam in initial simulations);
- Incorporation of important hydrological control features, i.e. wetlands (excluded initially);
- Modification of the Curve Number (CN) of sugarcane (instead of using SWAT database default values);
- Delineation of sub-catchments into HRUs to capture the diversity of land use (instead of defining one land use/soil combination per sub-catchment initially);

- Adjustment of Manning's roughness coefficient (*n*) for HRUs and channels (representing rougher surfaces than previously simulated);
- Incorporation of important management practices, i.e. tillage operations, nutrient applications, irrigation scheduling, and harvesting operations (excluded in initial configurations).

Simulated outputs (flow and sediment concentration) were compared with the loads estimated from 6 observed discharge events (8-10-2007, 30-11-2007, 7-12-2007, 4-01-2008 and 16-01-2008) at two sub-catchment outlets (flume 1 and flume 2). Here nutrient and sediment loads from measured flow and concentrations were available for comparison with simulations. However, verification of the simulated loads at the larger scale (main catchment outlet/second bridge) was not possible. Furthermore, the observed events in which both streamflow and pollutant concentrations had been observed at the runoff plots could not be used for comparison with simulated results, because the runoff plots' areas were too small for simulation in AVSWATX. Lack of continuous monitoring of discharge and concentrations hindered a full verification of the model; nevertheless, useful outcomes were attained.

5.9 Scenario analyses of seven management practices

Seven management scenarios were simulated with the calibrated SWAT in order to provide insight into the effects of different control measures on NPS pollution in the Mkabela catchment, as follows:

S1 Whole catchment under sugar cane;

S2 Whole catchment under vegetables with standard soil tilling as specified in SWAT database;

S3 Whole catchment under vegetables with no till practices;

S4 Whole catchment under current land cover, but with zero nutrients applied;

S5a Whole catchment under current land cover/practices, but with 50 kg/ha mineral P and 100 kg/ha mineral N applied;

S5b Whole catchment under current land cover/practices, but with double above nutrients applied;

S6 Whole catchment under current land cover/practices, but with zero wetlands;

S7 Whole catchment under current land cover/practices, but with 1.5 m buffer strips surrounding cultivated fields.

Parameter values were assigned to represent each management practice or scenario according to values provided in the SWAT database. Since these parameter values were obtained from the SWAT database, they will not be discussed. Detailed descriptions of the parameters are given in the SWAT2005 manual (Neitsch *et al.*, 2005a).

5.10 Results, treatment of results and discussion

5.10.1 Comparison of simulated flow and sediment with observed values

For the limited number of observed events and sub-catchments/outlets in which both streamflow and pollutant concentrations could be measured (six events at the two flumes located in the upper sub-catchments), SWAT tracked most of the peak flow events (1:2 or 1:5 year). However, the peak flows were mostly over-predicted, whereas the majority of the low-flows were under-predicted.

Sediment concentrations for peak flow events were usually under-predicted, whereas the sediment concentrations for the majority of the low-flow periods were over-predicted. Continuous catchment-scale models such as SWAT are successful at predicting days on which soil loss did not occur;

however, they are usually less accurate at forecasting those days on which runoff or erosion did take place. Jetten *et al.* (1999) further states that, for models in general, goodness-of-fit correlation coefficients generally decrease (i.e. error increases) with shortening time scale (from annual to daily) for both runoff and soil loss. Since SWAT is not designed as a field-scale event-based model, long-term average results can be expected to be better simulated than results for individual time periods. Event-based catchment models perform better to predict peak discharge than continuous models such as SWAT, basically because the latter operate with large time steps and calculate peak flow independent of surface water depth (revised USLE, curve number). Therefore, simulated average sediment should be compared with long-term measured values.

Another possible explanation relates to inaccurate trap efficiencies of the 9 farms dams as simulated by SWAT in the Mkabela catchment. For example, small dams (e.g. 0.1ha surface area) seem to have similar trap efficiencies to large farm dams (e.g. 10ha surface area). Trap efficiencies of farm dams and their influence on NPS pollutants in the Mkabela catchment need further investigation. Importantly, the configuration was able to represent the farm dams as a series of storages where flow speed is reduced and sediment deposited. Van Oost *et al.* (2000) and Verstraeten *et al.* (2002) substantiate that hydrological structures such as farm dams influence migration of pollutants significantly. Lane *et al.* (1997) also emphasises the importance of channel processes as one of the dominant factors controlling sediment yield at a catchment scale (10^{-2} to 10^{2} km^2).

5.10.2 Simulated flow, sediment and nutrients for the observation period

Simulated outputs are displayed as a series of maps and graphs for flow, sediment yield and nutrients (organic N, NO_3, organic P and mineral P) of the Mkabela catchment during the observation period (January 2006-June 2008). First of all, Figures 61 to 66 illustrate the monthly average rates for the six monitoring points including flow, sediment concentration, organic N, NO^3, organic P and mineral P. Simulated monthly average flows range between 0.001 (at Flume 1 during the winter months) to 2.013 m^3/s (at the main catchment outlet in summer – Bridge 2). Monthly average sediment concentrations range between 0.004 (at Flume 1 during the winter months) to 4.911 mg/ℓ (at the Dam outlet in summer). Organic N, NO_3, organic P and mineral P range between 0 to 19.88 kg N, 0 to 236.69 kg N, 0 to 3.56 kg P and 0 to 0.76 kg P, respectively.

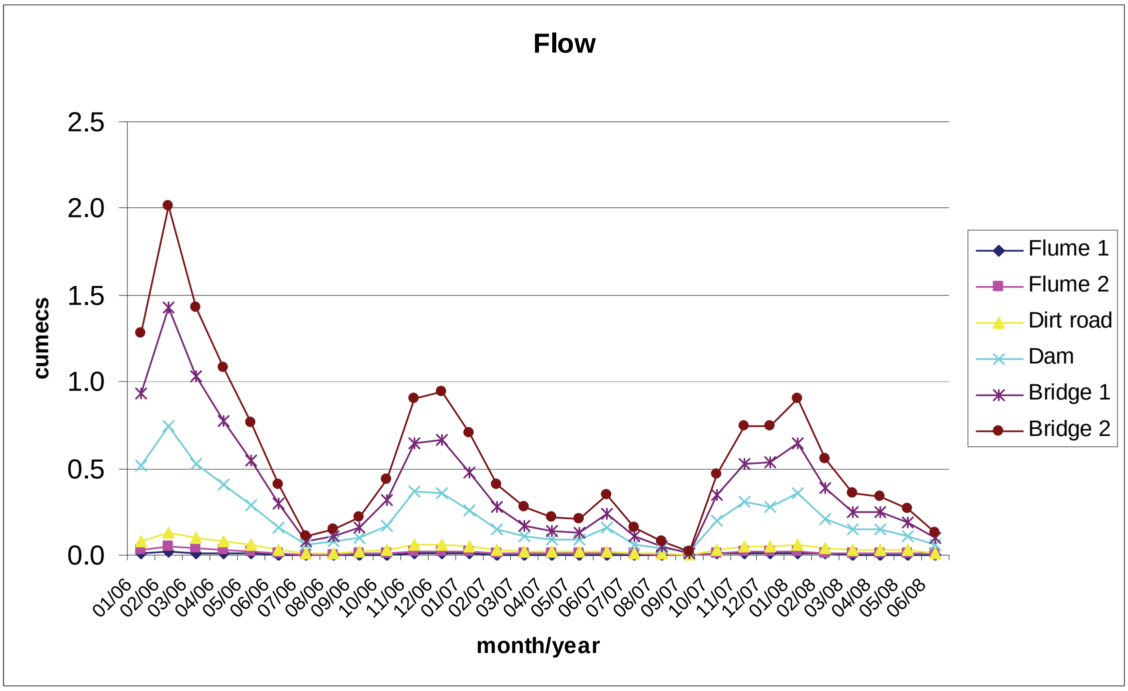


FIGURE 62 SWAT simulated monthly average flow rates of Mkabela catchment for January 2006-June 2008.

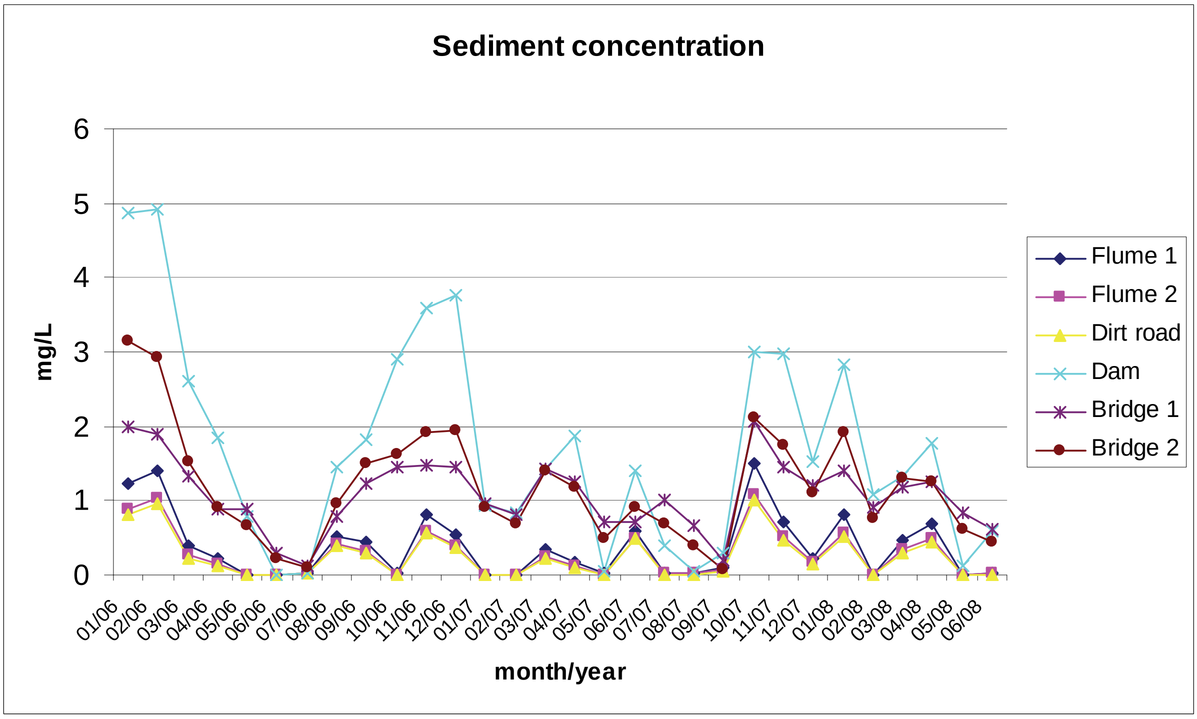


FIGURE 63 SWAT simulated monthly average sediment concentration output of Mkabela catchment for January 2006-June 2008.

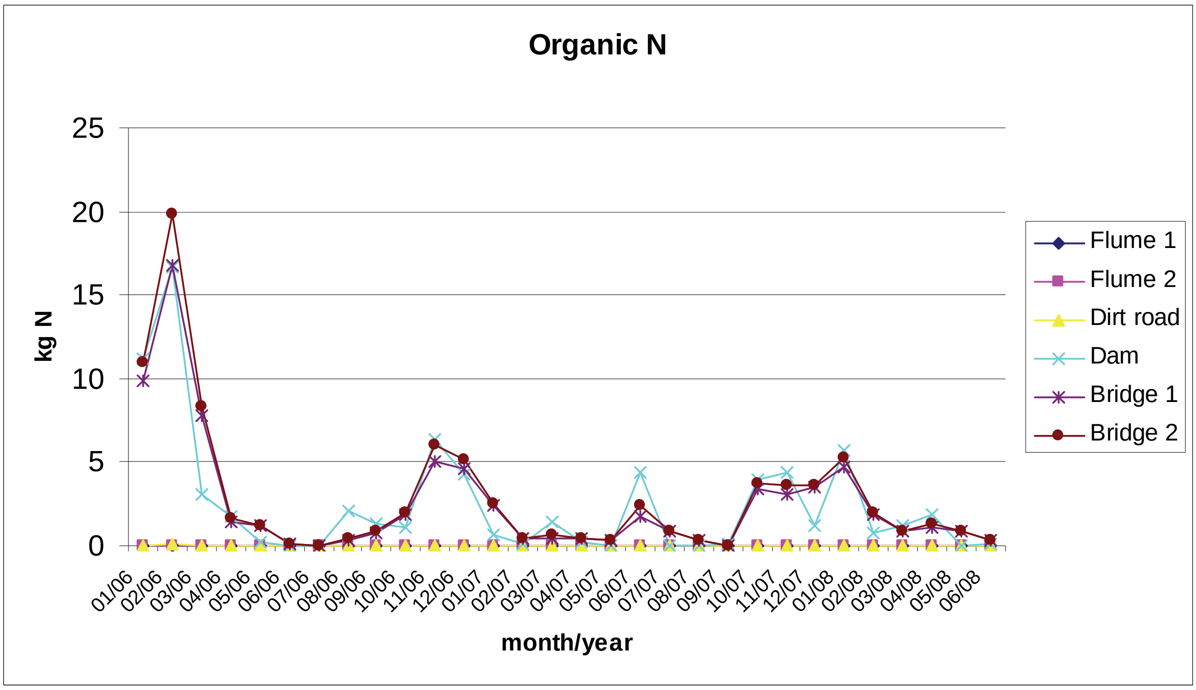


FIGURE 64 SWAT simulated monthly average organic N output of Mkabela catchment for January 2006-June 2008.

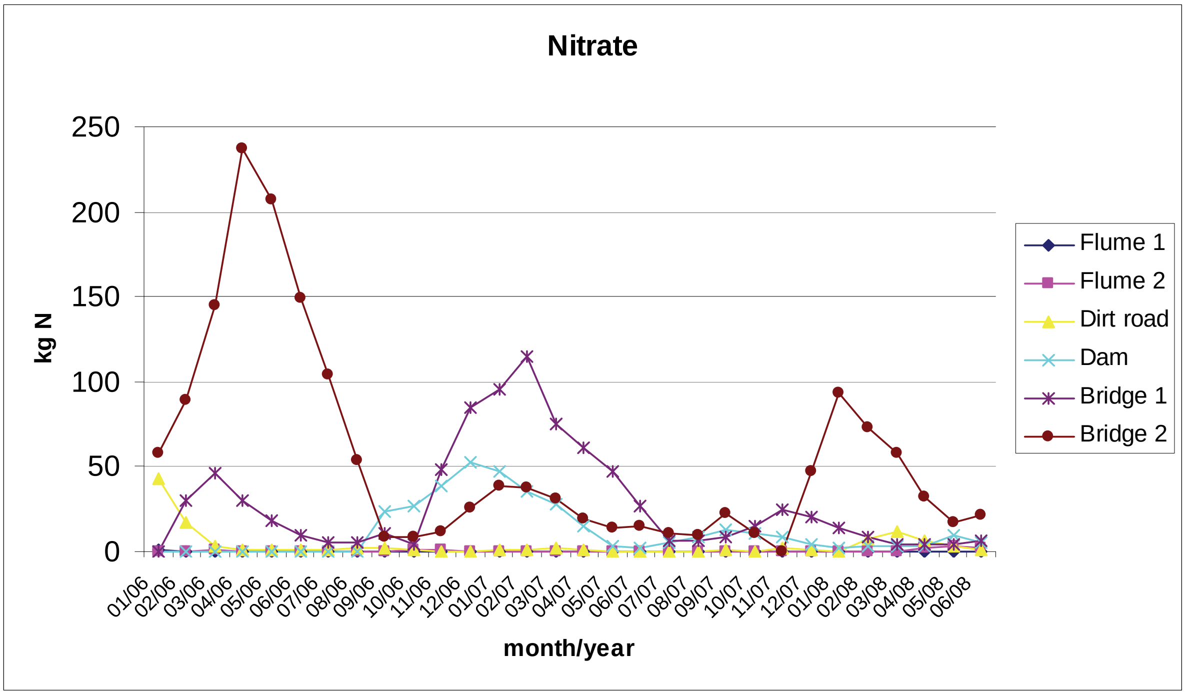


FIGURE 65 SWAT simulated monthly average nitrate output of Mkabela catchment for January 2006-June 2008.

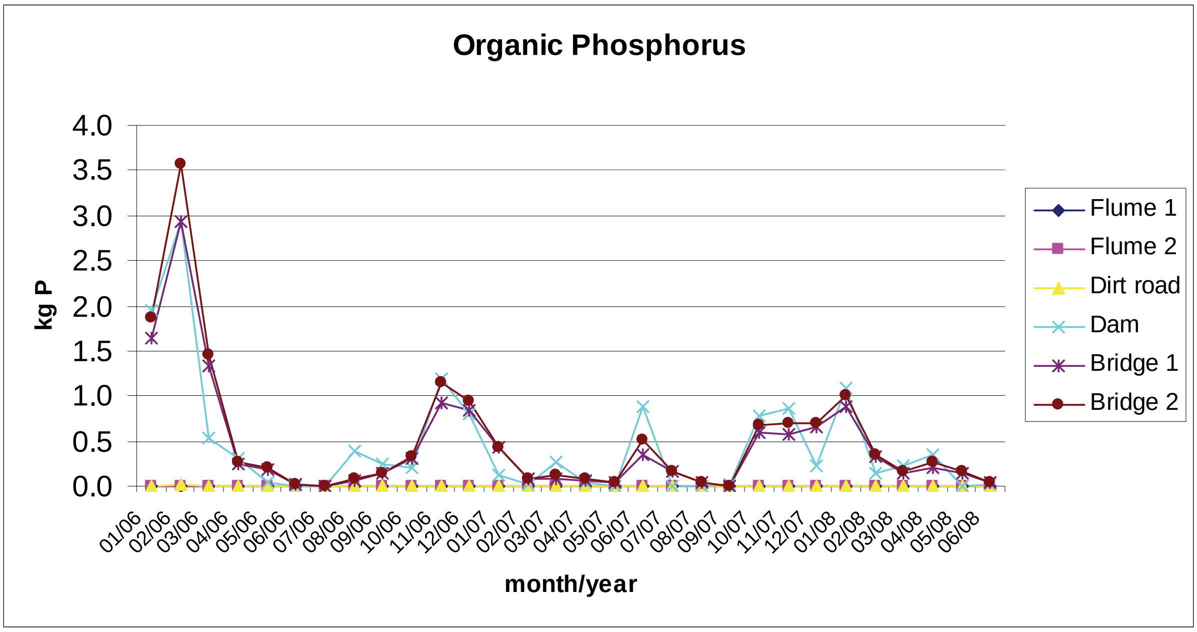


FIGURE 66 SWAT simulated monthly average organic P output of Mkabela catchment for January 2006-June 2008.

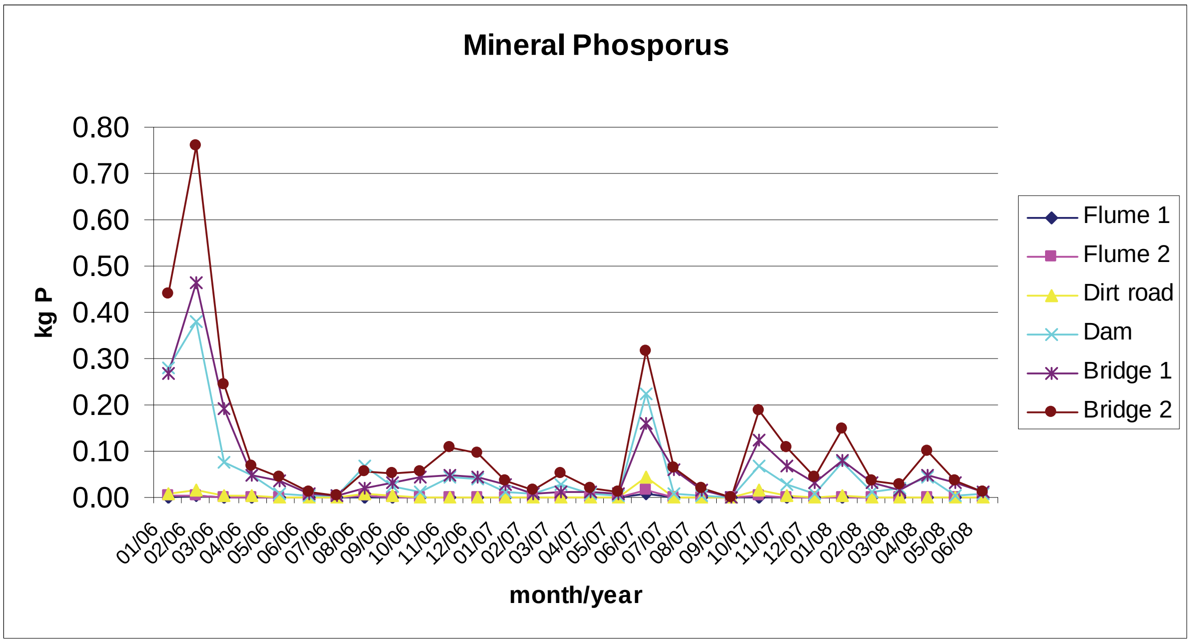


FIGURE 67 SWAT simulated monthly average mineral P output of Mkabela catchment for January 2006-June 2008.

Figures 67 to 72 depict cumulative loads over the same simulation period of all the sub-catchments for total runoff, sediment yield, organic N, NO_3, organic P and mineral P. It would be useful to accentuate the differences between the above graphs and the maps that follow. The above graphs show simulated output rates in outlets during monthly time-steps. In contrast, the maps below present simulated total accumulated outputs from sub-catchments into main-stem reaches over the whole simulation period of 30 months.

The simulated cumulative runoff ranges between 1018 mm (at sub-catchment 6) to 1225 mm (at sub-catchment 17). Cumulative sediment yields range between 0.008 t/ha (sub-catchments 8 and 9) to 2.556 t/ha (sub-catchment 1). Cumulative loads of organic N, NO_3, organic P and mineral P range between 0.022 to 5.667 kg N/ha, 0.390 to 0.986 kg N/ha, 0.002 to 0.788 kg P/ha and 0 to 0.274 kg P/ha, respectively.

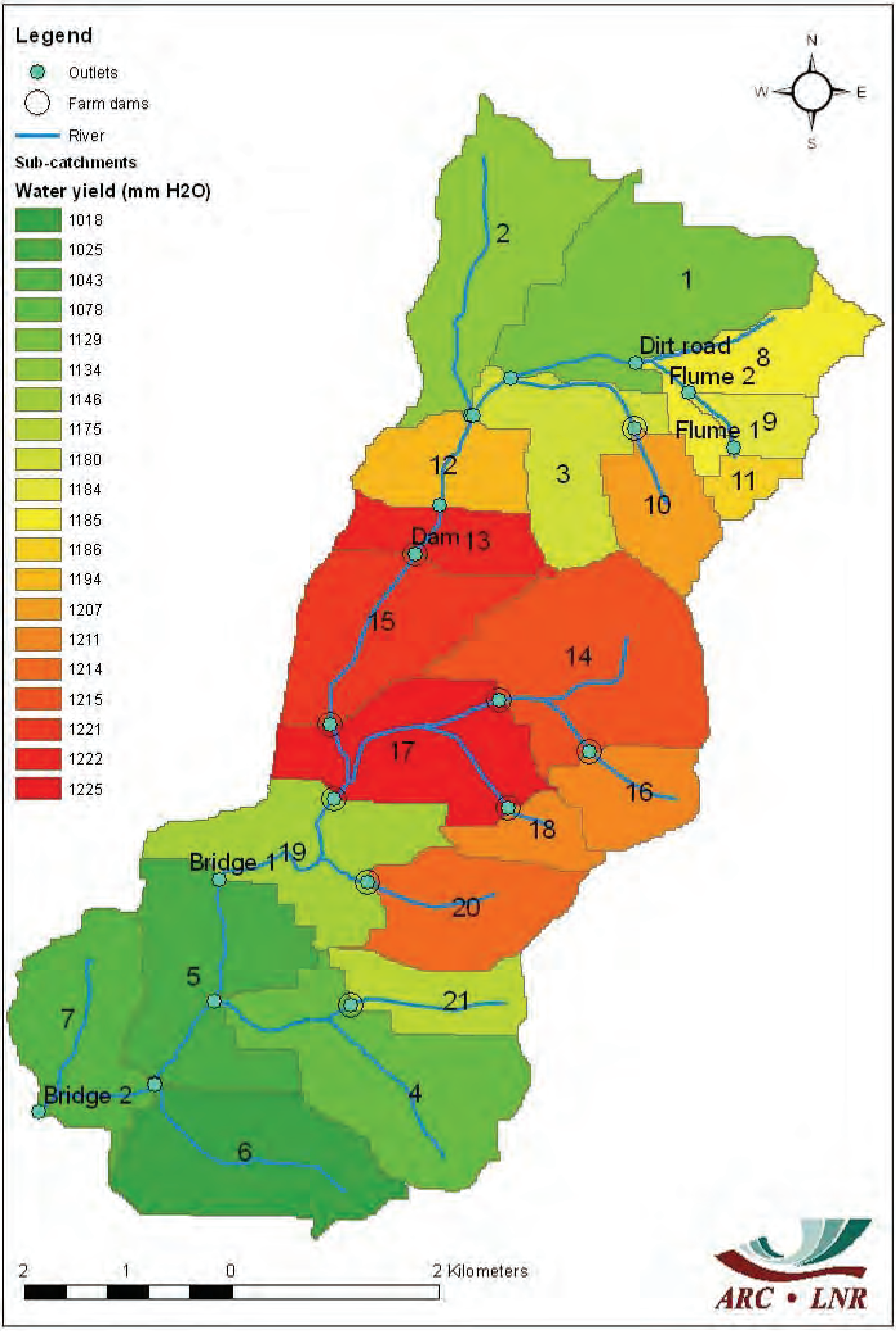


FIGURE 68 SWAT simulated cumulative runoff map of Mkabela catchment for January 2006-June 2008.

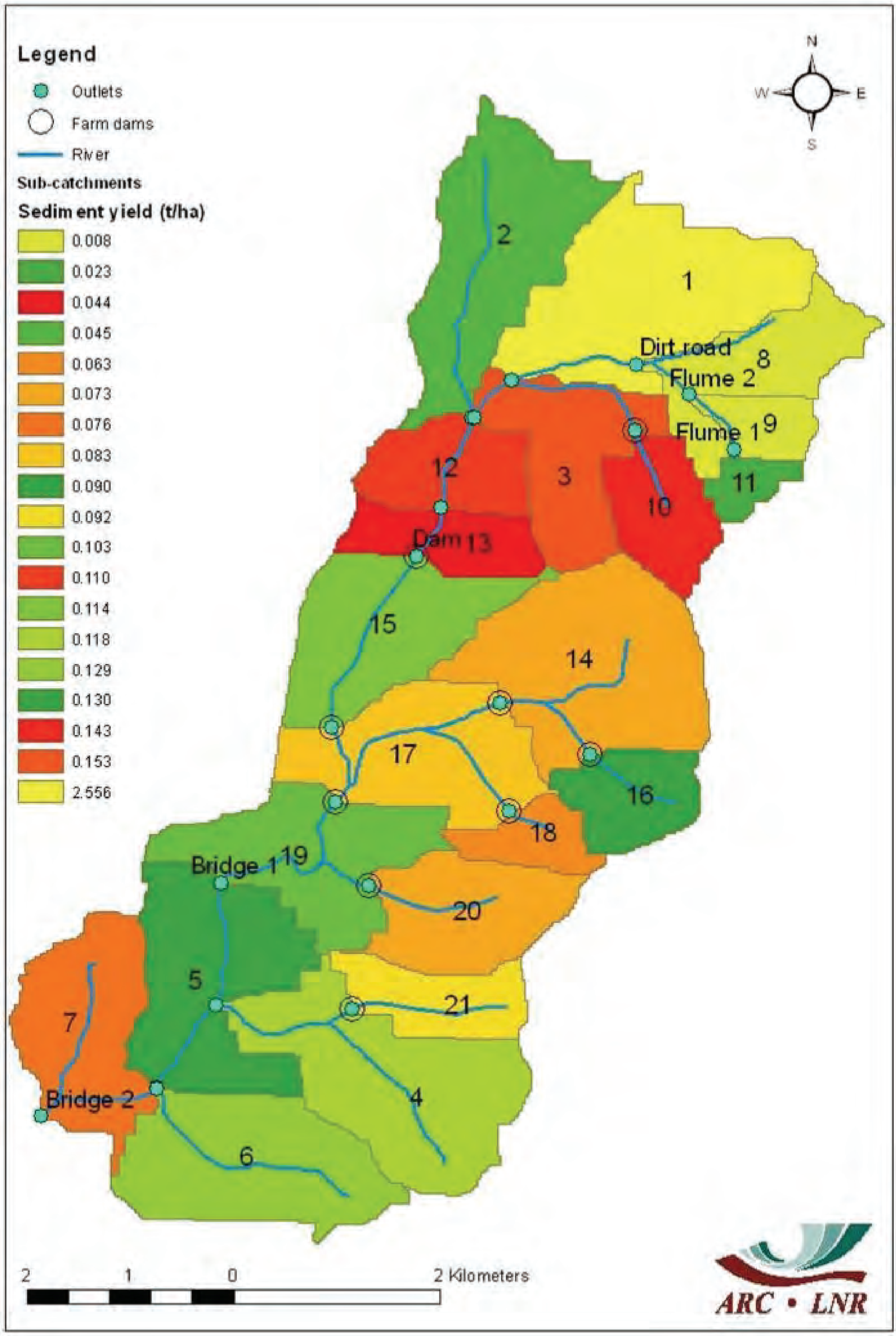


FIGURE 69 SWAT simulated cumulative sediment yield map of Mkabela catchment for January 2006-June 2008.

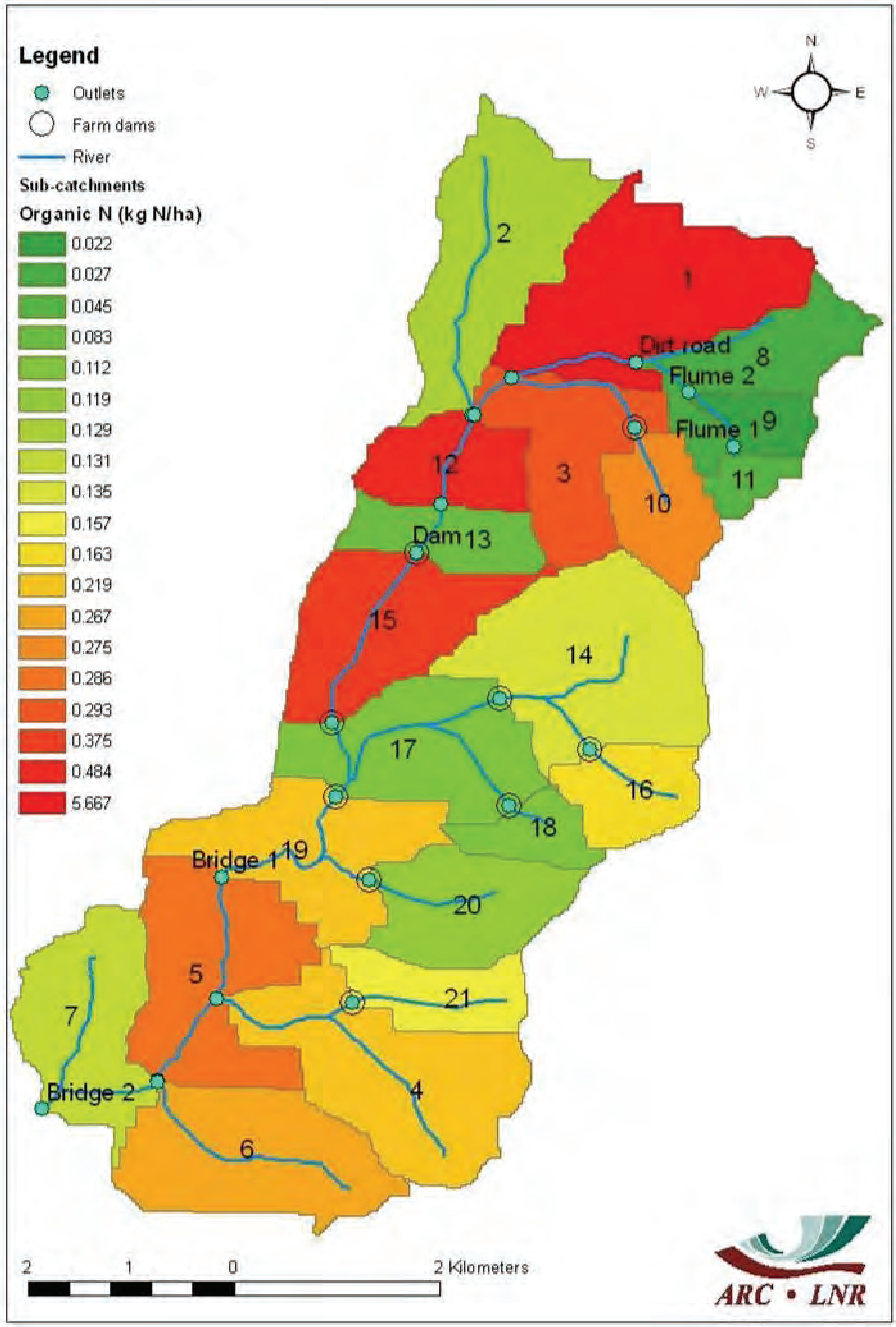


FIGURE 70 SWAT simulated cumulative organic N map of Mkabela catchment for January 2006-June 2008*.*

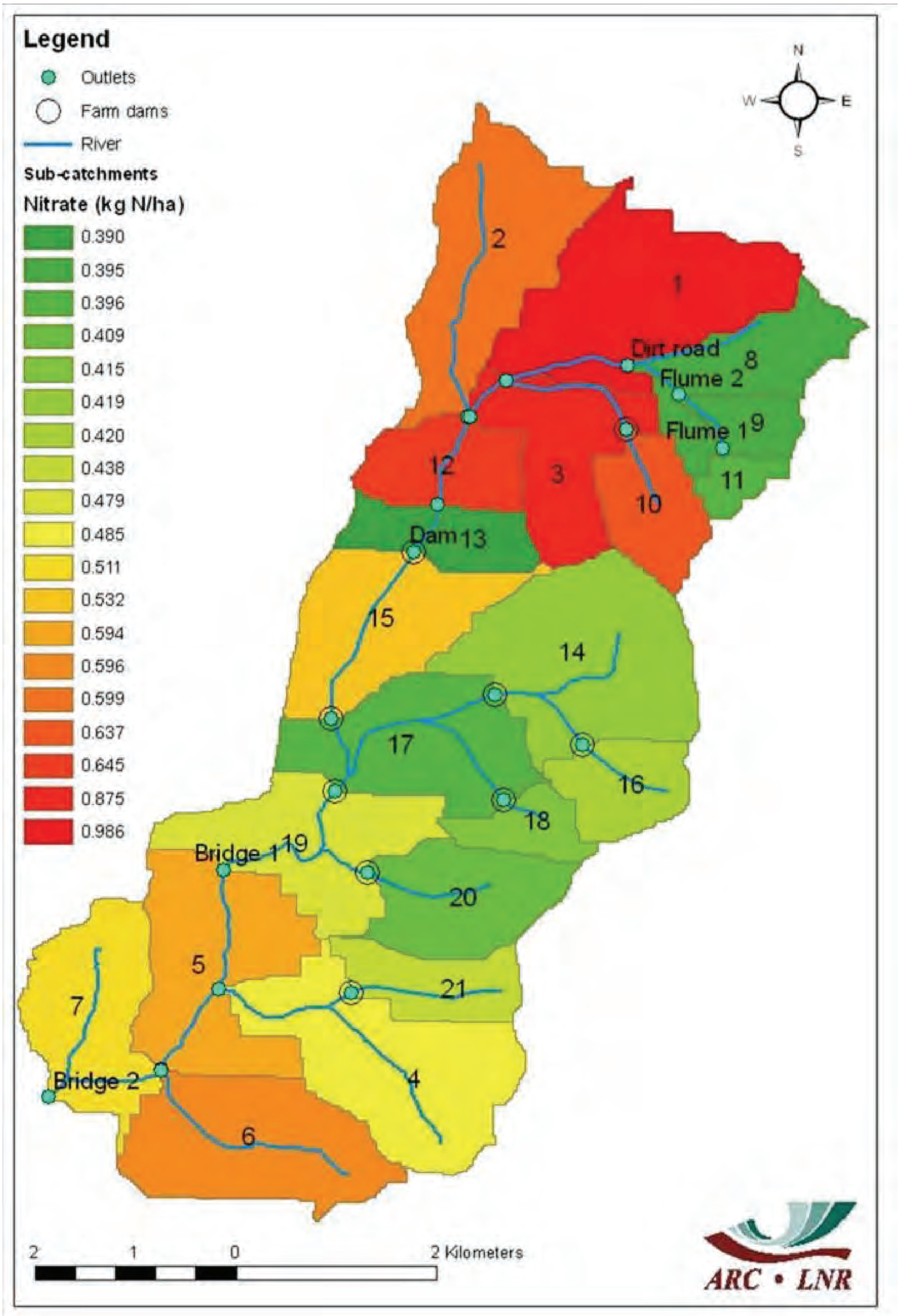


FIGURE 71 SWAT simulated cumulative NO_3 map of Mkabela catchment for January 2006-June 2008.

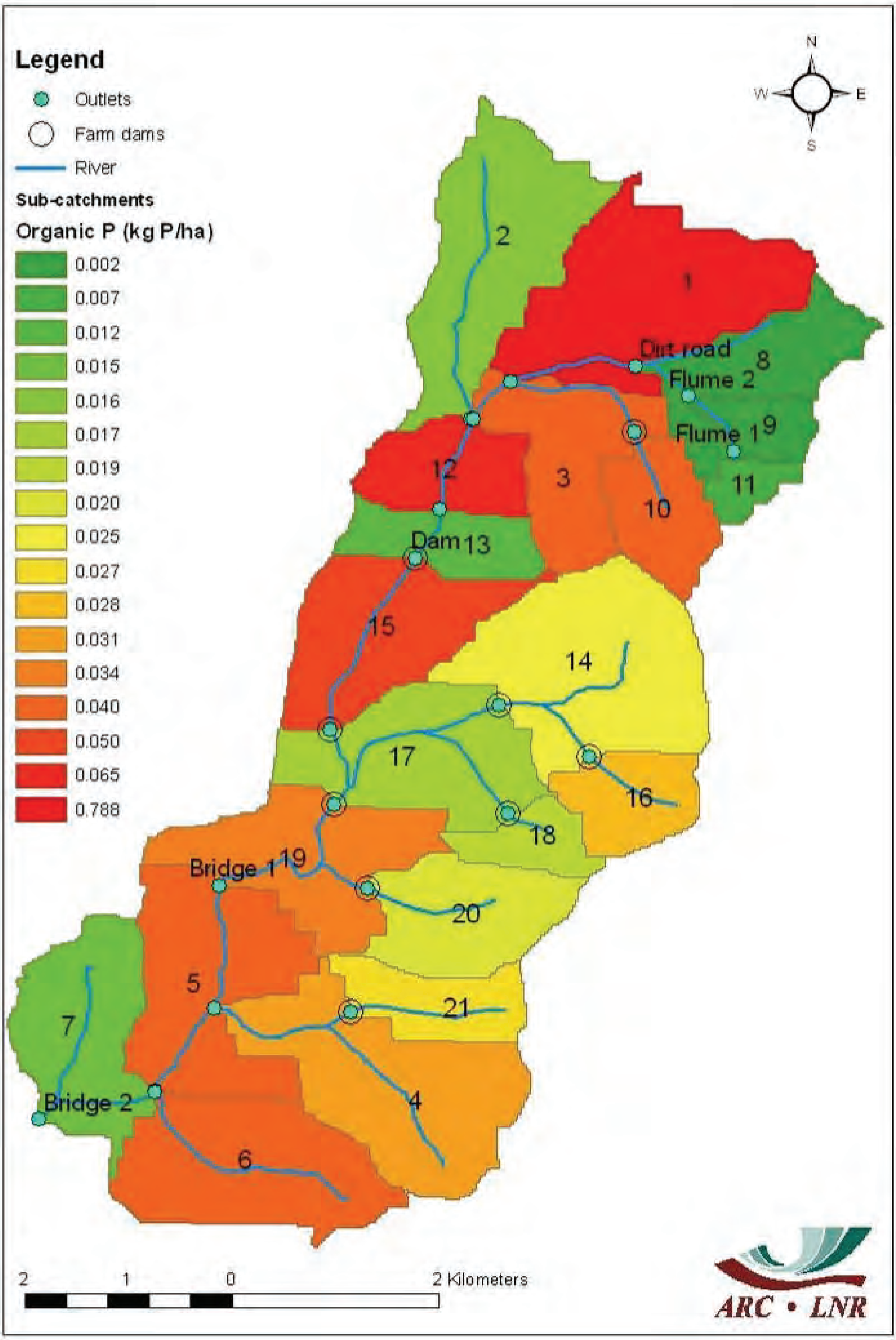


FIGURE 72 SWAT simulated cumulative organic P map of Mkabela catchment for January 2006-June 2008.

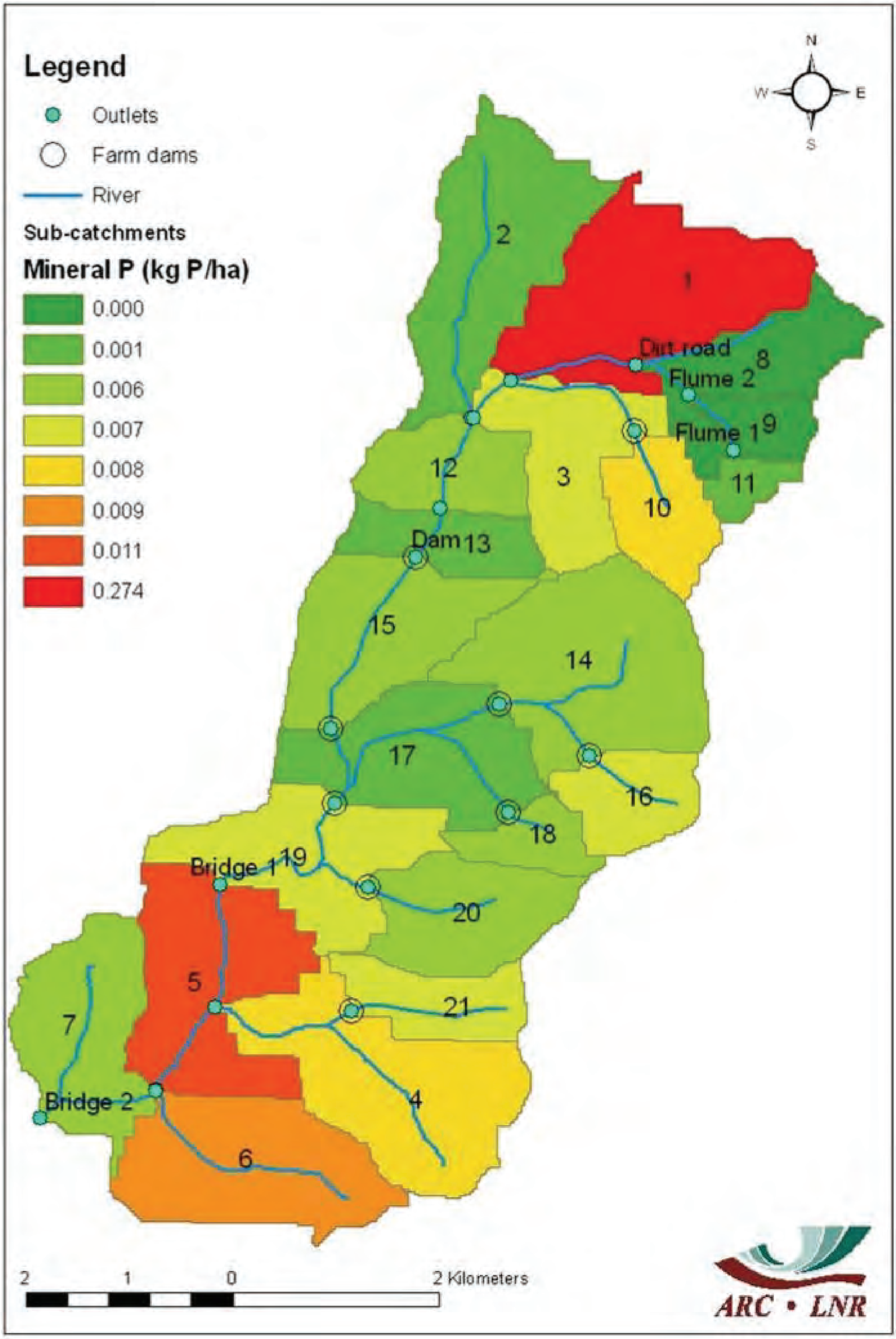


FIGURE 73 SWAT simulated cumulative mineral P map of Mkabela catchment for January 2006-June 2008.

The simulations illustrate a summer dominant erosion pattern which is mainly caused by intensive summer rainfall that possibly coincides with low vegetation cover. Sediment outputs are not necessarily related to the size of sub-catchments relative to the larger catchment; i.e. larger sub-catchments do not necessarily deliver more sediment and nutrients to the main channel.

It seems that simulated high sediment yield is not only slope-related, but that crop cover is equally important. Sub-catchment 1 under cabbage has a relatively flat slope and relatively poor crop cover; yet it has much higher sediment yield than some sub-catchments with steep slopes and good cover (e.g. forestry). Furthermore, the influence of lateral point-source contributions to and deposition in the downstream main-stem channel is quite evident.

Simulations results indicate that sub-catchments with a relatively high sediment yield contribute to high sediment loadings in the main-stem, which are subsequently routed to an outlet further downstream. As a result, incremental sub-catchments with low sediment yields could have high sediment concentrations simulated at their outlets. For example, Figure 62 illustrates that relatively high sediment concentration values (up to 4.911 mg/ℓ) are simulated for the dam outlet in sub-catchment 13. However, the sediment yield for the sub-catchment itself is relatively low (0.044 t/ha), as shown in Figure 68. Sub-catchment 1 has a relatively high simulated sediment yield under cabbage cultivation, subsequently contributing to high sediment loadings in the main-stem. Sediment is subsequently routed downstream to the dam outlet. Note that these relatively high concentrations are not captured/traced at the dirt road outlet adjacent to sub-catchment 1. The reason is that the dirt road outlet receives the loadings contributed upslope by sub-catchments 8, 9 and 11, and not from sub-catchment 1. The simulations mimic our understanding of the links between source areas of erosion (e.g. poor crop cover) on one hand and areas of deposition on the other (e.g. hydrological structures such as farm dams).

The relatively high NO_3 loads (up to 114.87 kg N) simulated at Bridge 1 during the 2006/2007 autumn season, shown in Figure 64, is also of interest. NO_3 loads are high despite sub-catchments 13 to 20 above Bridge 1 having hydrological control elements such as farm dams and wetlands where deposition of NPS pollutants occurs. NO_3 loads correspond with large rainfall events and the application of nitrogen to all sugarcane fields in the catchment, of which most occur above Bridge 1. Furthermore, high levels of nutrients correspond with low vegetation cover and subsequent low levels of nutrient uptake by plants during winter months.

5.10.3 Scenario analysis results and discussion

The relative differences of impacts of seven NPS pollution management scenarios in terms of flow, sediment and nutrients are depicted in Figures 74 to 79 for monthly averages of simulated flow, sediment yield and nutrients (organic N, NO_3, organic P and mineral P). The graphs present the simulated outputs for each scenario at the main catchment outlet. Sequences T3-T5 represent outputs from three consecutive calibration runs, with T5 the accepted final calibration results.

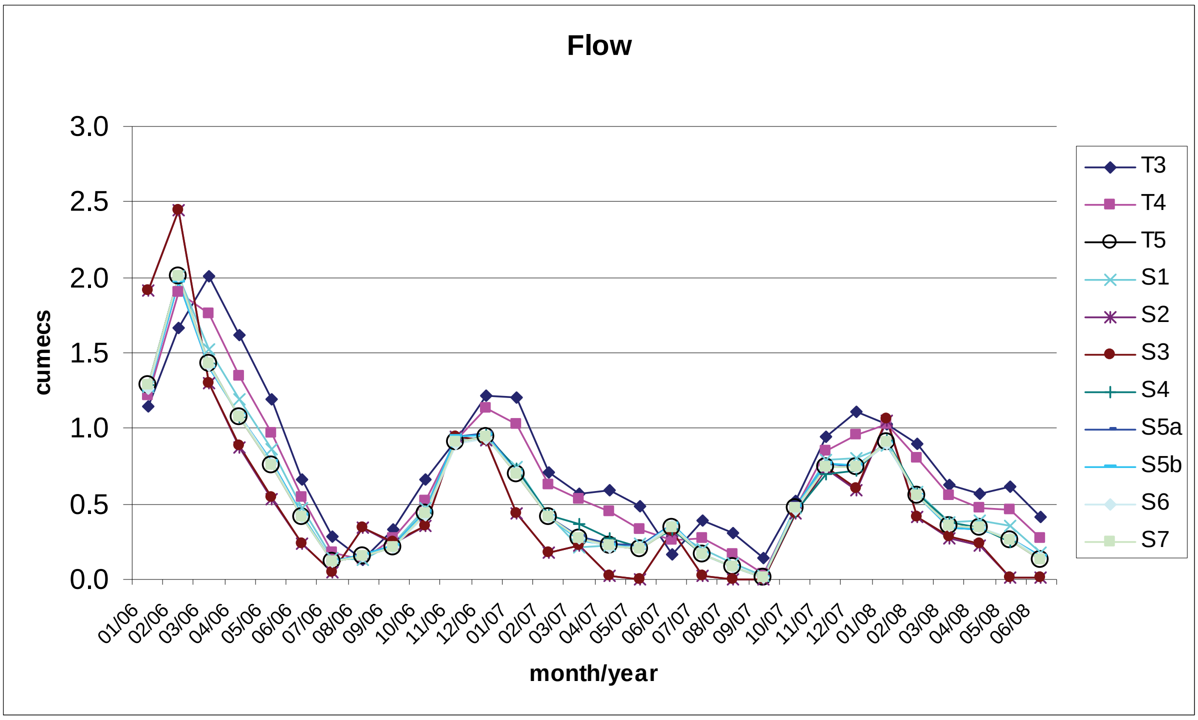


FIGURE 74 SWAT simulated monthly average flow rates at the catchment outlet for January 2006-June 2008 (T5 = final calibration run)

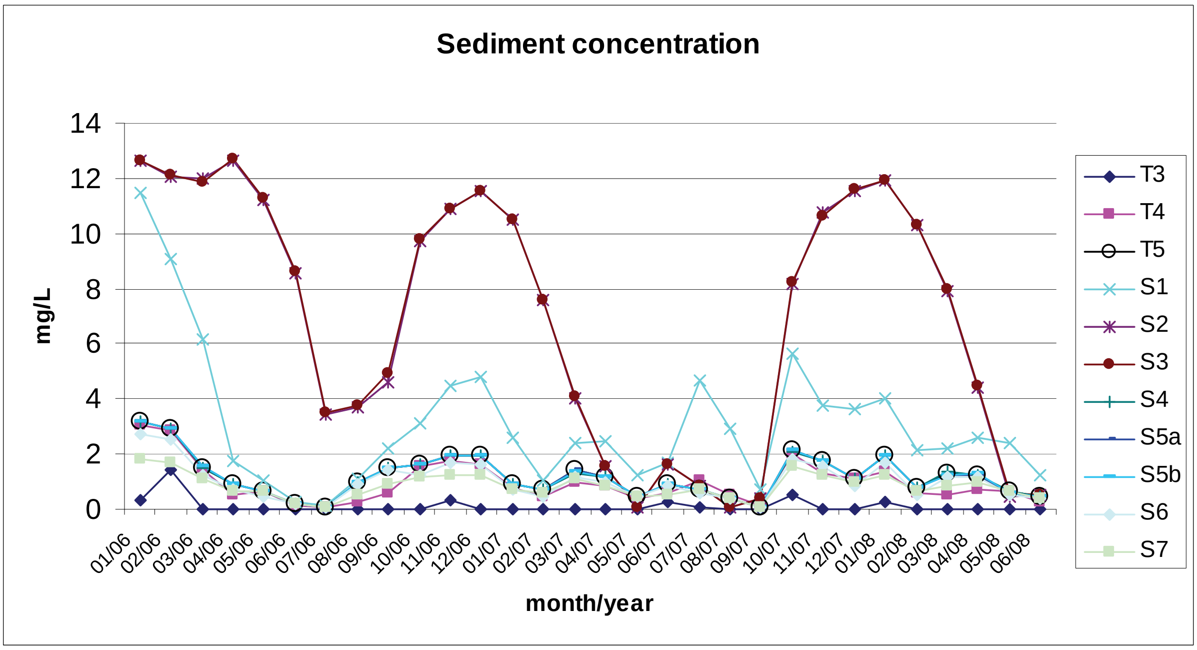


FIGURE 75 SWAT simulated monthly average sediment concentration output at the catchment outlet for January 2006-June 2008 (T5 = final calibration run).

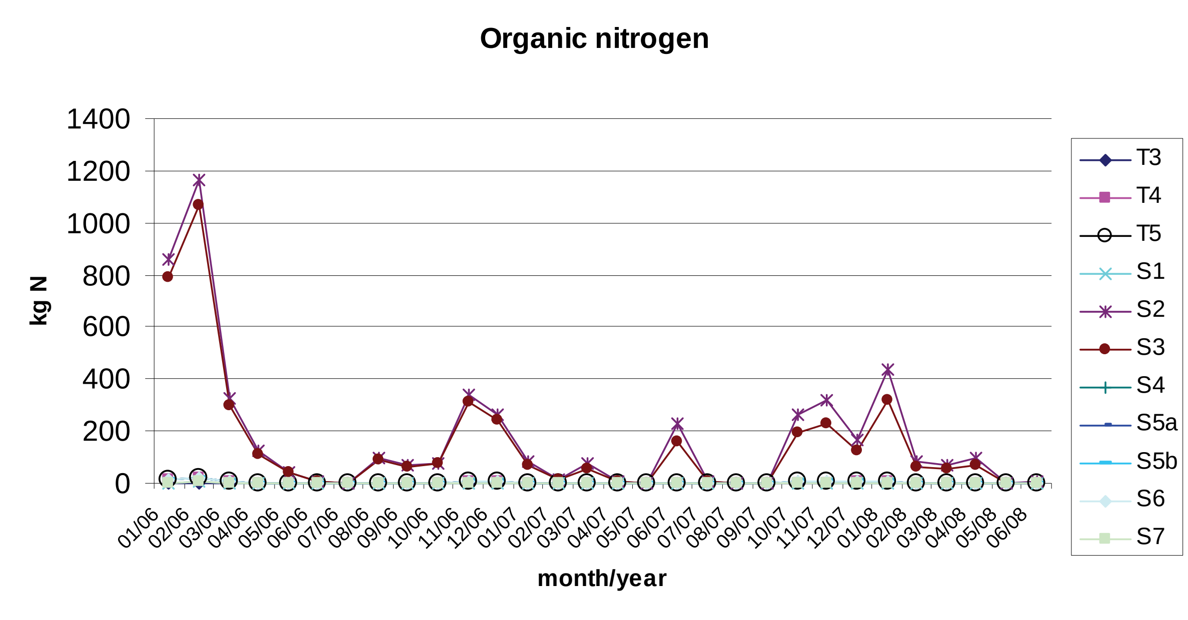


FIGURE 76 SWAT simulated monthly average organic N output at the catchment outlet for January 2006-June 2008 (T5 = final calibration run).

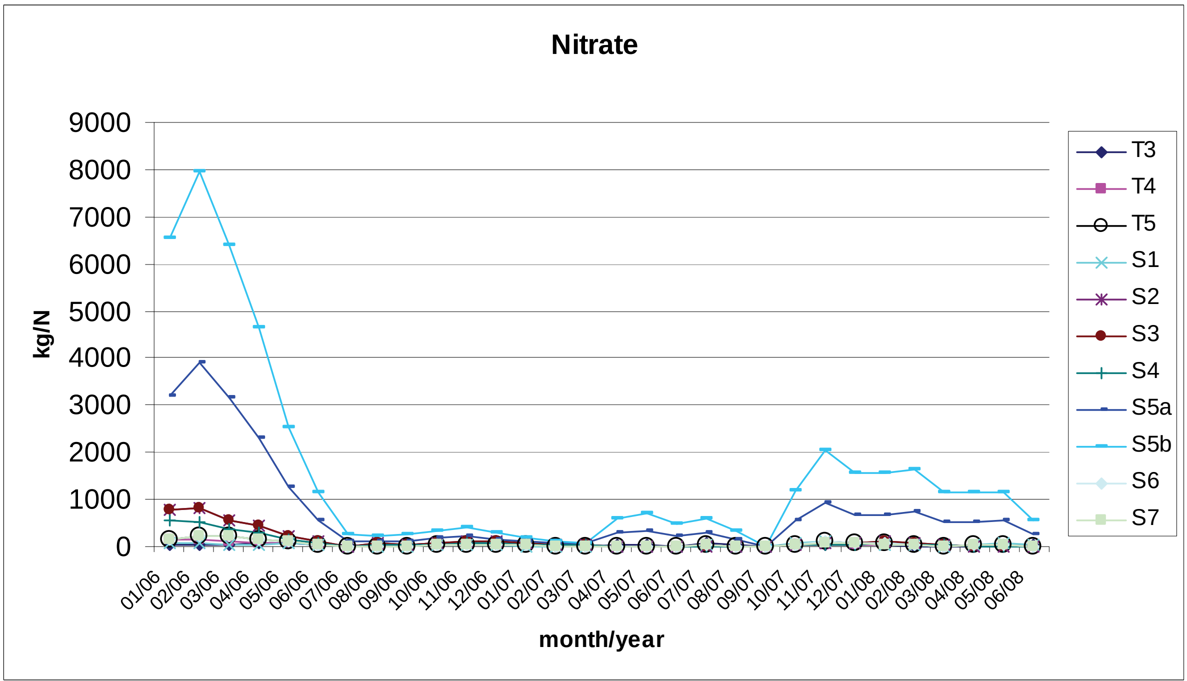


FIGURE 77 SWAT simulated monthly average nitrate output at the catchment outlet for January 2006-June 2008 (T5 = final calibration run).

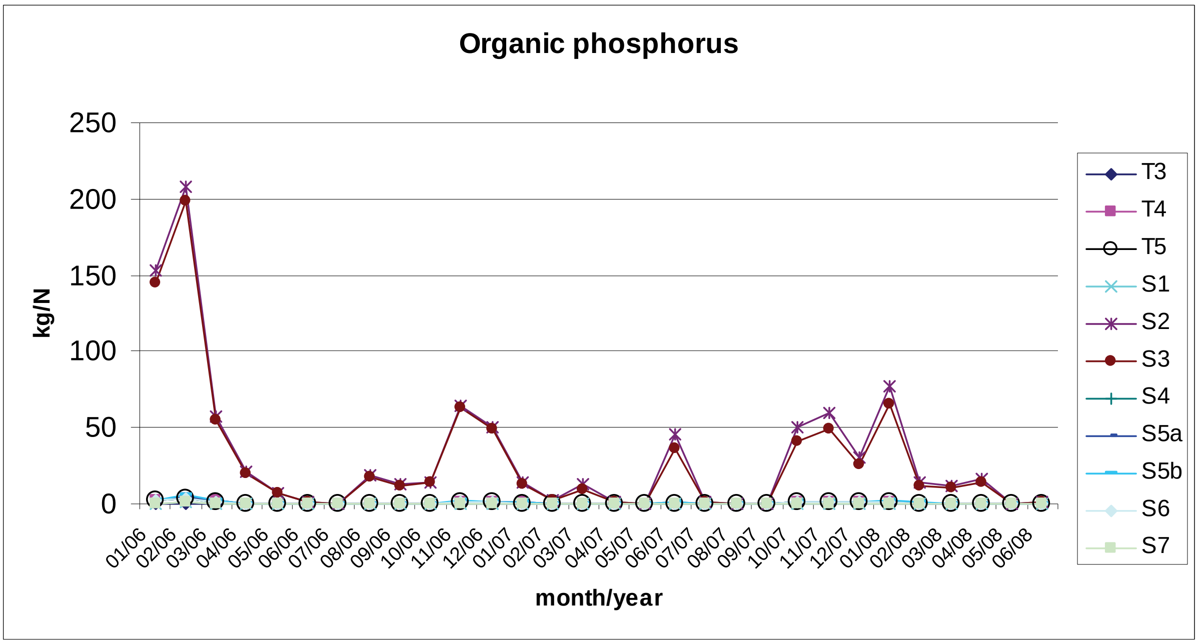


FIGURE 78 Monthly average organic P output at the catchment outlet for January 2006-June 2008 (T5 = final calibration run).

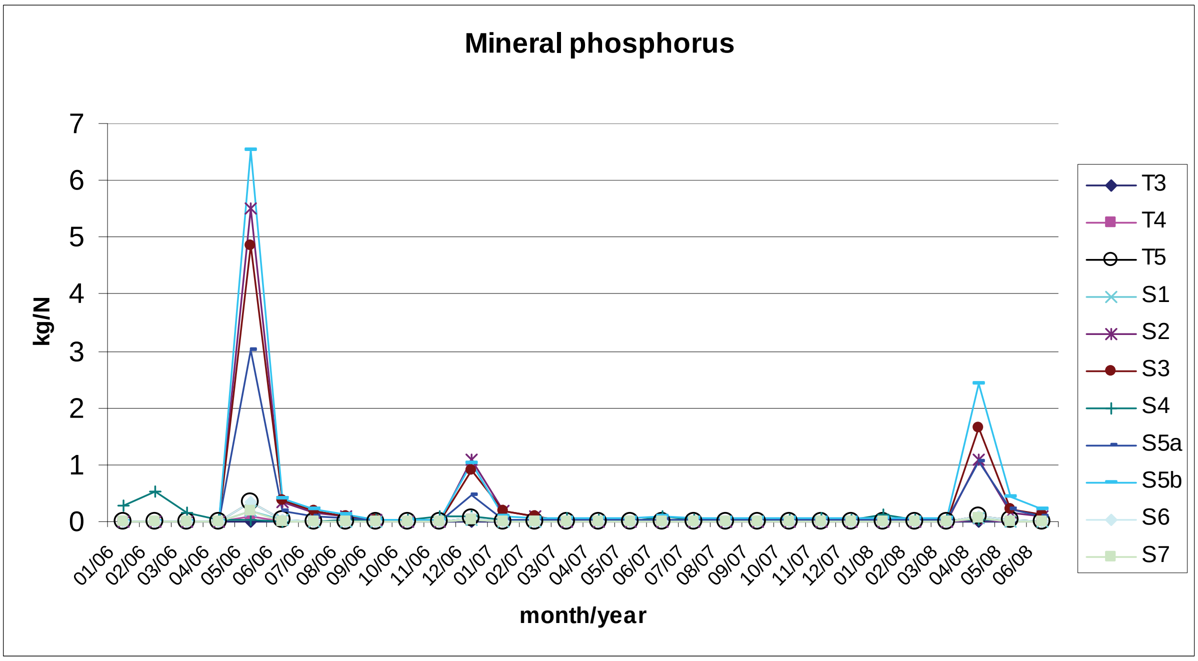


FIGURE 79 Monthly average mineral P output at the catchment outlet for January 2006-June 2008 (T5 = final calibration run).

For comparative purposes, results are further interpreted in terms of the average of the scenarios mentioned above over the whole observation period at the main catchment outlet (see Table 20). The so-called "Template" column refers to the final template scenario (T5 in the foregoing Figures 74 to

79) that is most representative of current land cover and management practices, and including farm dams and wetlands. S1 to S7 refer to the scenarios described in Section 5.9).

TABLE 19 Scenario averages over the simulation period Jan 2006-Jun 2008

	Template(T5)	**S1**	**S2**	**S3**	**S4**	**S5a**	**S5b**	**S6**	**S7**
Flow (m^3/s)	0.56	0.58	0.50	0.51	0.56	0.56	0.56	0.56	0.56
Sediment (mg/ℓ)	1.18	3.10	6.85	6.88	1.18	1.18	1.18	1.00	0.84
Nitrogen (kg N)	55.4	35.3	302	276	92.0	747	1540	55.9	52.5
Phosphorus (kg P)	0.62	0.19	33.6	30.4	0.99	1.87	3.54	0.63	0.22

As expected, simulated sediment yields at the catchment outlet increased more than five times when replacing other land uses with cabbage (S2 and S3). The main reason is that cabbage fields have less ground cover than other land uses in the Mkabela catchment, i.e. sugarcane, forestry and pasture. Various studies across SA have shown that poor vegetation cover coinciding with erosive rains contributes significantly to sediment yields (e.g. Snyman, 1999; Smith *et al.*, 2000; Ströhmenger *et al.*, 2004; Le Roux *et al.*, 2008a). Sediment yields also doubled when other land uses were replaced with sugarcane (S1). Despite being a soil conserving crop, sugarcane is usually more prone to erosion than forestry plantations with sound ground cover – which in this case was replaced by sugarcane.

Doubling the nutrients applied throughout the catchment (S5a and S5b), simply doubled N and P rates at the catchment outlet. Of all the scenarios, the buffer strip scenario (S7; including buffer strips and USLE P-value of 0.5) produced the lowest overall pollutant outputs.

The results for the remaining scenarios are somewhat puzzling. Worth mentioning is the little difference between outputs from cabbage with till (S2) and cabbage without till (S3). Likewise, it is quite surprising that the simulated outputs for the scenario excluding wetlands (S6) did not differ much from those for the template scenario including wetlands (T5). It is likely that SWAT did not simulate the wetlands processes effectively, or that the configuration was not appropriate. Another possible reason is that the monthly time-step at which average monthly values were reported, would obscure outputs from single large rainfall events. It is also puzzling that higher nutrient outputs were simulated for the scenario (S4) where no nutrients are applied, than for the template scenario where typical quantities of nutrients were applied.

5.10.4 Questions regarding crop yield simulation in AVSWATX

From an economics point of view, there is a focus on the impacts of management practices on HRU-related crop yield outputs (single land use and soil effects. Although AVSWATX calculates crop yield and reports it in the so called HRU output file for each HRU, the output volumes become very large rendering it impractical to determine the impact of individual HRUs in the larger catchment. Therefore, AVSWATX was configured to accumulate HRU outputs, such as crop yield, into a sub-catchment format.

One of the economic-related questions was whether fertilizer application rates influence the simulated crop yield in the expected manner. Although not shown here, results from the scenario analysis above indicate that when fertilizer application rates were doubled, simulated crop yield for cabbage increased on average by 30% (for most HRUs). In contrast, crop yield for sugarcane increased on average by only 2%. The reason for the difference in crop yield increase between cabbage and sugarcane is not obvious and requires additional interrogation of the SWAT routines involved.

6. MERITS OF EACH MODEL

6.1 Critique of the configured *ACRU-NPS m*odel

i. The simulation of NPS species for the Mkabela catchment met with mixed success, which may be attributed to:

- Uncertain initial fertilizer status in response to historical application rates by the farmer, particularly the P content.
- Poor linking of upslope subsurface fluxes to profiles lower in the catena. Comparison of the observations at surface runoff plots and at flumes indicates a dominance of subsurface discharge. However, the model simulates high sediment yield (overland phenomenon) and low P, which may be derived from an organic source and have a significant below-ground pathway.

ii. Simulations against observations for the larger catchment scale will most certainly result in similar deficiencies as the SWAT model, in which specific land features and structures had a dominant influence on the simulation of sediment and nutrient load retention – as had become evident from the monitoring results in the Mkabela catchment. Lack of continuous monitoring of discharge and concentrations at the larger scale have also hindered successful model verification.

iii. The *ACRU2000* modelling system has land segment surface and subsurface linkage capabilities which are not currently linked to water quality processes, but would improve the simulation of solute translation in properly defined catena response characteristics.

6.2 Critique of the configured SWAT model

i. SWAT simulation results for the Mkabela at the catchment scale remain speculative due to the lack of load data for comprehensive calibration and verification. Unfortunately, a major limitation to long-term use of SWAT in SA is the lack of long-term nutrient and suspended solids data for calibration and validation.

ii. A number of the scenario simulations produced counter-intuitive impacts on nutrient and sediment loads. These findings undermine confidence in the model or, at least, in this configuration and require extensive further interrogation.

iii. Due to a lack of data on the crop rotation systems and timing of agricultural operations, phenological plant development had to be based on daily accumulated heat units. The lack of knowledge about crop rotation systems and agricultural operations can lead to serious errors in both spatial output patterns across the catchment and the total catchment output (Vigiak *et al.*, 2006).

iv. Simulation results were displayed on a monthly time-step. However, monthly averages might obscure simulated outputs from single large rainfall events. For this purpose, results need to be displayed on a daily time step. As mentioned above, the disadvantage of daily results is that the output file volumes become very large and is difficult to comparatively summarise into a single report.

6.3 Comparisons of model benefits

The *ACRU-NPS* model offers the following benefits:

- a large database of default input parameters derived for South African conditions

- a linkage capability to other models, input data and geographical information systems
- recent developments which enable simulation of lateral translation of surface and subsurface water fluxes
- allows for addition of in-stream, impoundment and wetland processes
- well-suited to scenario modelling
- the code and original developers and programmers are available for introducing any freshly required modifications.

The SWAT model has the following benefits:

- a direct link to GIS input for deriving Hydrological Response Units
- offers wetland, in-stream and impoundment routines that have been tested in the USA and elsewhere
- a set of default values, although these may not always be applicable to southern Africa, as was discovered with the sugar cane variables
- well-suited to scenario modelling.

7. CONCLUSIONS

7.1 Data collection and model developments

i. Successful, albeit limited, observations were made of the transport mechanisms, sources and pathways of the pollutants at various scales in the nested, instrumented Mkabela River catchment.

ii. The *ACRU-NPS* model has been modified to include crop yield associated with water and nitrogen stress and output from the model has been used to simulate the effects of control structures in the catchment.

iii. Two simulation models (*ACRU-NPS* and SWAT) were fully configured for the Mkabela catchment to estimate the nutrient and sediment loads associated with different sources, pathways and controls.

7.2 Scenario analyses

iv. The analyses by simulation of various scenarios of alternative pollution control and management measures that could be applied to the catchment, demonstrated that the use of these two models could play an important role in providing decision support during catchment water quality management processes.

v. Farming with vegetables, which is either tilled or not tilled, can lower the quality of the water resources by enhancing sediment yields, and by increasing loads of both nitrogen and phosphorus in the rivers.

vi. Limiting the current level of nutrient application to crops will not enhance the river water quality significantly.

vii. Over-fertilizing of crops lead to significant deterioration in the quality of receiving water resources.

viii. Significant reductions in N, P and sediments occur in wetlands with large storage. Wetlands which have been canalised do not play an important role in the mitigation of sediments in the water resources of this specific catchment.

ix. Farm dams generally reduce the downstream movement of sediments and nutrients. However, extreme events mix the reservoir sediments and solutes and result in larger outflow loads than inflow loads on these occasions.

x. Buffer strips surrounding cultivated fields can enhance the quality of the downstream receiving water resources of the catchment.

xi. There is evidence of P migration in the subsurface.

8. LESSONS LEARNT

8.1. Research design

i. Research design could have included more case studies with associated observations of water, sediment, nutrient and pesticide dynamics. Significant time and energy went into observing only two research sites and a small number of land uses rather than a cross section of many land uses and crop types. Clearly, the second option would have suited the field-scale team, but multiple research sites were infeasible for catchment-scale observations.

8.2. Multi-Team/Multi-Location integration and collaboration

ii. The team benefited from interaction between field-scale nutrient research and the catchment-scale model development. More frequent scientific interaction earlier in the project would have been beneficial. The lack of appropriately detailed measurements in the Mkabela research catchment for small-scale verifications limited the interaction between field- and catchment-scale process algorithm development.

iii. Research of non-point source pollution from field- to catchment-scales requires multidisciplinary integration and continuous collaboration. Research efforts stagnate without frequent communication and comparison/distribution of input data and simulated outputs. Another challenge in this regard relates to the timescale of the Project (over 5 years). Long-term projects require research to be conducted intermittently, making it a challenge to keep focussed and up to date with other teams. An additional challenge is the timeous comparisons of one’s own research findings with those of other teams, especially when they operate at different locations and scales.

8.3. Approaches to scaling

iv. Dividing the Project Team into smaller Teams to focus on specific scales was important. The nested catchment was an ideal site for interaction of the Teams and to study mass transport dynamics from point- to field- to catchment-scales. However, insufficient detail in measurement at the field-scale, particularly soil profile nutrient dynamics, as well as infrequent observation of discharge at the larger scale, limited some aspects of model testing. Because the Project budget was insufficient for these additional observations, they were done on an ad hoc basis. Nevertheless, significant contributions to the understanding of the fate of nutrients and sediments from source to catchment-scale were made from observations in the catchment and from applying the models to this catchment.

v. Models such as SWAT and *ACRU-NPS* can be defined as distributed lumped-parameter models that aggregate representative processes over the scale at which outputs are simulated However, aggregating landuse/soil combinations disregard small but important sediment- or nutrient-producing areas (e.g. a small vegetable plot). This should be catered for through sub-catchment delineation into hydrological response units (HRUs) to capture the diversity of land use within sub-catchments. HRUs are portions of a sub-catchment that possess unique land use/soil attributes (Neitsch et al., 2000). Inclusion of multiple HRUs allow simulations to account for this diversity and to identify small but important source areas of erosion, e.g. a cabbage farm with relatively poor crop cover with higher (20 to 50 times) sediment and nutrient rates than areas with good canopy and ground cover (forestry).

8.4. Interfacing natural resource management needs and scientific realities

vi. The development of bio-physical models in this Project which do not only predict sediment and nutrient delivery at different scales of interest, but also associated crop yields, ought to be invaluable to agricultural production and environmental management stakeholders. Inclusion of sufficient scientific complexity into the models to allow for realistic predictions of NPS pollution loads as well as crop yields has been a primary intention of this Project. However, such a claim will have to be tested against different cropping and agricultural pollution control/mitigation systems.

vii. Given their complex nature and input requirements, the models developed by the scientists in this Project cannot be handed over for general use by natural resource managers, but the Team has demonstrated how useful scenarios can be developed to inform agricultural production and environmental management decision-making.

9. RECOMMENDATIONS FOR FURTHER RESEARCH

9.1. Observations and process understanding

i. Observations are required at a smaller time resolution at the larger scale in order to estimate event nutrient and sediment loads in the nested catchment and thus an accurate evaluation of the losses or gains through the network.

ii. In-situ and laboratory observations and quantification of the subsurface migration of phosphorus and assessment of surface and subsurface phosphorus species pathways from field to stream.

iii. Observations and quantification of subsurface controls of water and nutrient pathways in land forms.

iv. Observation and quantification of nutrient and sediment detention, retention or reaction in specific controls in stream networks, including farm dams, wetlands and buffer strips subject to a range of rainfall/runoff events.

v. Verification of nutrient uptake processes under various stressed and unstressed conditions.

vi. Observation and quantification of water and nutrient movement in the vadose zone, recharge to groundwater and subsequent migration. The use of hydropedological surveys could be used to enhance the definition of nutrient pathways.

9.2. Advanced *ACRU*2000 processes for future inclusion in *ACRU-NPS*

vii. Through GIS mapping and grouping of soil profile behaviours based on topography, soil type, geology and land use, it is possible to assemble detailed information of the near-surface soil horizons. Since it is here that significant partitioning of and responses in water and solute fluxes occur, it would be prudent to capture these processes in a catchment model.

viii. However, where deeper and more complex pathways are difficult to simulate in detail, model processes can resort to response functions derived from knowledge of the general behaviours of these complex features. In addition, the application of the SWAT model demonstrated the difficulty in models to translate discharge, solutes and sediments from upper slopes in a catchment to lower zones in the soils catena.

ix. The lateral flow discharge processes and land segment linking options, recently developed in the *ACRU2000* model, could serve as a foundation for linking the N-P and sediment yield processes to allow for simulation of surface and subsurface solute and sediment movement for typical catchment catenas, identified by GIS analysis.

x. These lateral flow processes are summarised in what follows. Based on the combination of hydrometric, geophysical and tracer sampling techniques, certain dominant mechanisms have been identified in research catchment studies. Incorporation of these dominant mechanisms into catchment rainfall/runoff models is desirable, particularly where they modify low flow responses. The observations and analyses of hydrological processes in research catchments have led to the following general enhancements to the *ACRU* agrohydrological model, depicted in Figure 80:

- Inclusion of a variable depth saprolite or intermediate layer between the soil B horizon and the groundwater store.

- A saturated threshold response, based on the water retention characteristic of the intermediate layer material to allow for the initiation of lateral discharge to downslope land segments or stream, as well as seepage into a groundwater store.
- The lateral responses from the intermediate layer and groundwater store need to be controlled by time distribution of discharge response functions, typical of geology, slope and soil characteristics.
- SCS generated runoff needs to be split between quickflow, retarded quickflow and macropore flow. The macropore component is discharged into the intermediate layer via similar response function control as lateral discharges from the intermediate layer and groundwater store.
- Root access is required to the intermediate layer, specified as a percent of total root mass. Transpiration occurs from the intermediate layer in response to the atmospheric demand and soil retention status.

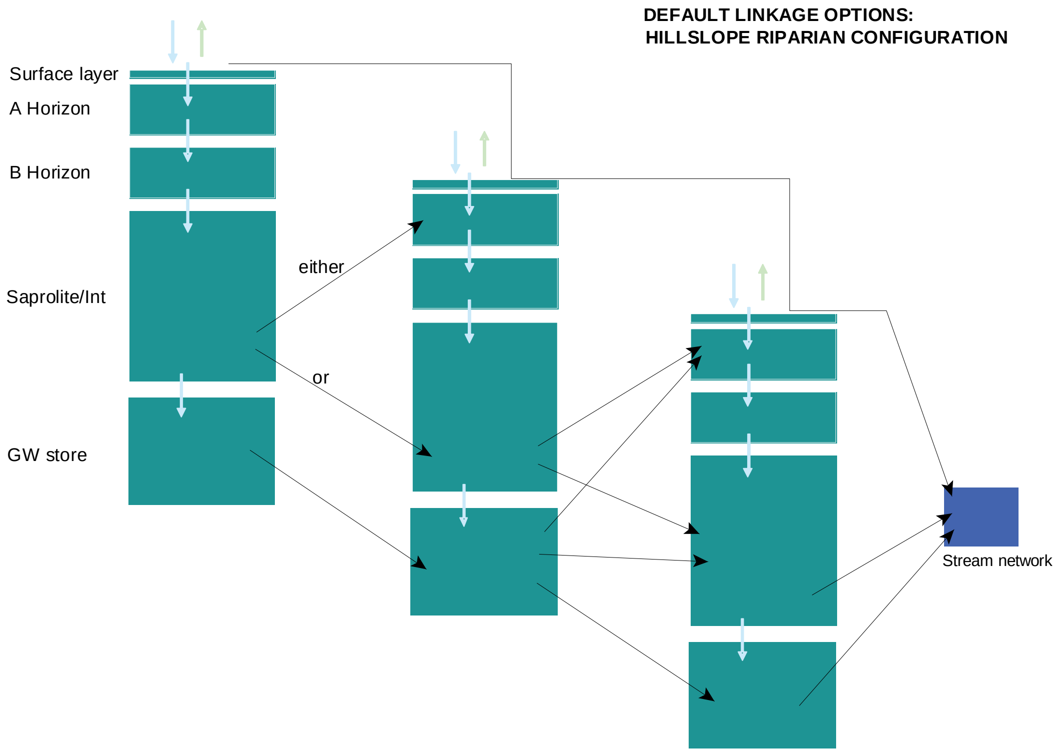


FIGURE 80: Lateral flow processes and land form network structure in *ACRU*2000*.*

9.3. Additional model developments and comparisons

x. Continued development of the use of land type and hydropedological surveys to estimate model parameters for water, sediment and nutrient simulation.

xi. Development of response functions to simulate the time distribution of water and nutrient migration in surface and subsurface flows. These response functions should be developed from in-situ observations as well as simplified from local or field scale algorithms.

xii. Verification of simulated nutrient uptake and crop yield responses to water and nutrient stress and recovery through observation.

xiii. Include in the modelling, secondary effects of scenario options, such as: effect on vegetation cover and yield in scenarios in which erosion is enhanced; effect on the yield of the removal or inclusion of in-field remedial measures and visa versa, the effect on sediment yield and nutrient loads resulting from stressed crop growth.

xiv. Use and evaluation of the model systems in ungauged basins.

xv. Comparison of specific model features, such as the wetland, buffer and small dam routines; the Green-Ampt infiltration versus the SCS runoff generation options (both inherent in *ACRU-NPS* and SWAT) and subsurface processes simulations.

xvi. Evaluation of sensitivity of simulated sediment and nutrient loading to disaggregation versus lumping of land segments.

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APPENDICES

(Presented on the CD in the Sleeve inside the Back Cover)
