Predicting the Impact of Farming Systems on Sediment Yield in the Context of Integrated Catchment Management

by

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EXECUTIVE SUMMARY

1 MOTIVATION

Land disturbances associated with agriculture are one of the major sources of sediment. It is increasingly accepted worldwide that erosion control should be linked to both soil (on-site erosion) and water (off-site sediment) conservation initiatives. Predicting the on- and off-site impacts of agricultural practices and erosion control measures requires models in which we have some degree of confidence. Verification of these models, therefore, is critical. Models predicting the off-site effects of farmland erosion at the small catchment scale have found limited application in South Africa to date. The focus of this project was to verify selected models predicting the impact of farming practices on sediment yield at the hillslope to small catchment scale.

2 OBJECTIVES

The overall aim of the project was to verify the performance of selected models in predicting the impact of farming practices on sediment yield at the small catchment (<10 km^2) scale in order to get an indication of the degree of confidence with which the off-site impacts of agricultural practices and erosion control measures can be predicted with the selected models. In order to achieve this aim, the following specific objectives were identified:

1. To improve international and South African methodologies for predicting the impact of selected land uses on sediment yield in local catchments.
2. To assess the impact of the following land uses on sediment yield: communal grazing, communal cropping, commercial grazing and pristine areas.
3. To assess the impact of quality, availability and the spatial distribution of input data on the accuracy of sediment yield prediction results.

The emphasis of the first objective was on verifying the performance of the selected models by comparing model predictions against measured data with those using the best available model input data (model verification). Verification was done by comparing model predictions against observed soil water contents at selected points in the catchments and runoff and sediment yield discharged at the catchment outlets.

The focus of the second objective was to get some indication of the ability of the selected models to predict sediment yield for typical South African agricultural practices by assessing the impacts through land management scenario predictions for the land uses occurring in the catchments.

Since the models will be applied in research catchments with detailed data, assessment of the impact of the availability and the spatial and temporal resolution of input data on the accuracy of sediment yield prediction results was verified (objective 3) in order to assess the performance of the models with input data with coarser spatial and temporal resolutions.

3 RESEARCH APPROACH

3.1 Role of sediment yield prediction in Integrated Catchment Management

Sustainable development of water resources in the context of Integrated Catchment Management implies the adoption of three successive steps in water management, namely identification of the system characteristics, prediction of the behaviour of the system and management of the system. This study concentrated mainly on the second step by verifying models that are being used to predict how the processes leading to sediment yield will respond to management practices of selected agricultural land uses.

Predictions at the hillslope and small catchment scale provide evaluations of the effectiveness of alternative land management treatments in terms of erosion and sediment delivery to the stream systems. Such knowledge obtained provides the opportunity for effective control when problems recognized at coarser scales indicate the need for remedial action. The selection of good agricultural practices and/or conservation measures, identified through scenario predictions at the hillslope and small catchment scale, should be integrated with the land user's socio-economic environment by matching the predicted sediment yield with *inter alia* the compatibility with existing farming practices, economic viability and farmer aspirations in implementing site specific erosion control measures. This study focused on detailed hillslope and small catchment scale modelling intended to study the impacts of agricultural practices on the spatial and temporal variation in runoff, erosion on and sediment delivery from hillslopes and ephemeral gullies, and sediment supply from small catchments.

3.2 Selected models

Many sediment yield models were developed for specific conditions and purposes and it is important to recognise their limitations in order to select a suitable model for the intended purpose. An overview of the various model types was undertaken. Two models were selected for verification in this study. The Water Erosion Prediction Project (WEPP) erosion model, developed by the United States Department of Agriculture – Agricultural Research Service and the Purdue University, USA, is a process erosion model, based on modern hydrological and erosion science. The 1999.5 and 2002.7 versions of the WEPP Windows interface model were applied in this study. The Agricultural Catchment Research Unit (*ACRU)* agrohydrological modelling system was developed in the School of Bioresources Engineering and Environmental Hydrology of the University of Natal, South Africa. The sediment yield module of the *ACRU* model is based on the Modified Universal Soil Loss Equation, where sediment yield is computed as a function of factors representing the hydrology, soil, vegetation, slope, and land management. The *ACRU* model was modified to account for upslope contributions of subsurface water to the soil profile in slopes lower down the hillslope. The research catchments were then subdivided topographically where upslope subcatchments contributed to subcatchments lower down the slope. This modified model is referred to as the research version of the *ACRU* model.

3.3 Study sites

Three sites were selected for this study, namely the Weatherley (near Maclear) and Zululand (near Empangeni) research catchments, and the Kokstad research site which consists of several camps to monitor the impact of sheep stocking rates on veld condition.

At the Zululand catchment, the footslopes and valley bottoms are the most susceptible to erosion since most of the storm flow is generated through runoff from these areas, giving support to the variable source area concept. The Zululand catchment is also spatially highly heterogeneous in terms of topography and land use, making it ideal to verify the incorporation of spatial discretization by models.

The Weatherley research catchment has the advantage that a detailed soil map was available, detailed monitoring of soil water tension and runoff was done, and the pristine grassland was converted to forestry in 2002. Unlike Zululand, the topography of Weatherley is simple, but has a complex soil pattern and a marsh where deposition can occur before the channel system.

3.4 Data assembling and organisation

Detailed time series data were collected during 1998 to 2002 on climate, rainfall, soil water content, runoff and sediment yield. The time series data was captured and is housed in a relational database system that has been developed by the School of Bioresources Engineering and Environmental Hydrology. Model input data were collected on topography, soil, land cover and management, and the stream system, and are kept as GIS map coverages at both the Institute for Soil, Climate and Water and the School of Bioresources Engineering and Environmental Hydrology.

Data organisation for the WEPP model was done on the basis of hillslopes and stream channels. The amount of hillslopes at Weatherley was mainly determined by the soil pattern, and at Zululand by land management. For the *ACRU* model, the data was organised according to catchment and subcatchment modelling units for the Weatherley and Zululand research catchments. The Weatherley catchment was divided into subcatchments that represent an area of macropore flow, grassland and marsh. The Zululand catchment was divided into subcatchments representing areas of the crest, midslope and footslope terrain units.

4 RESULTS AND DISCUSSION

4.1 Model verification

Verification of model performance was conducted against various measured components of the soil water balance, hydrology and sediment yield. Firstly, the simulated evapotranspiration was compared to that measured using the Bowen Ratio technique over a stretch of grassland in the Weatherley catchment from July to December 2002. Secondly, the soil water content status was compared to that measured using a neutron probe as well as that converted from tensiometer measurements at selected soil profiles in the catchments. Thirdly, the simulated and observed runoff responses at the catchment outlet were compared. Finally, the simulated sediment yields were compared against those derived from runoff related concentrations of suspended solids discharged at the catchment outlet.

Evapotranspiration

Both the WEPP model and *ACRU* model under-predicted evapotranspiration during winter and early spring. This could be due either to poor estimates by the equipment over the colder, dry period or an inherent fault in both models to predict evapotranspiration during dry, cool seasons. Nevertheless, evapotranspiration was satisfactorily predicted during the summer (wet) months and the poor evapotranspiration predictions during the dry season should have a relatively small effect on the predicted sediment yield.

Soil water content

The soil water contents predicted by the WEPP model were most often in close agreement with the measured values at the upslope (crests and midslopes) soil profiles during the wet season. The ability of the WEPP model to predict the rapid responses of the surface soil to rainfall events was also clearly illustrated throughout the wet seasons. The WEPP model could predict the hydrological water balance for the freely drained soils at the upslope positions satisfactory due to the sophisticated infiltration and overland flow model components.

The WEPP model was unable to accurately predict the frequency of saturated or near saturated soil conditions for the hydromorphic soil profiles at the downslope (footslopes and valley bottoms) positions during the wet seasons since the WEPP model did not effectively account for the soil saturation encountered at the foot of the hillslopes. The WEPP model considers mainly infiltration excess overland flow (rain intensity is larger than the rain infiltration into the soil) and does not explicitly consider saturation excess overland flow (a rising water table prevents further rain infiltration at the saturated surface soil) and interflow (exfiltration of water at a downslope position after having infiltrated upslope and flowed laterally within the soil profile). The subsurface drainage and lateral flow component of the WEPP model uses simple storage routing techniques to predict flow to the subsurface soil layers and downslope soil layers.

The Weatherley catchment was configured in the *ACRU* model to comprise grassland and macropore dominated grassland zones at the upslope (crests and midslopes) subcatchment discharging into a wetland zone at the downslope (footslopes and valley bottoms) subcatchment. The water contents in the wetland zone B-horizon were replenished by the upslope contributions, which, in the research version of the *ACRU* model applied in this study, include the near surface macropore zone contribution as well as baseflow contributions from both the grassland and macropore zones.

The research version of the *ACRU* model predicted the soil water content satisfactorily for the A-horizon at all of the positions on the hillslopes, reflecting the ability of the model to predict the rapid changes in water content in this part of the profile. The water content was under-predicted for the B-horizon in all the profiles, except for those in the riparian zone. The observation of elevated water contents in the riparian zone due to conditions promoting saturated and interflow has justified the simulation of upslope near-surface runoff and baseflow contributions to the B-horizon of the riparian zone in the Weatherley catchment.

Runoff

Although some predicted daily runoff by the WEPP model was in close agreement with the measured daily runoff, the variability in predicted runoff was high compared to the recorded daily runoff. The WEPP model predicted runoff for only a few rainfall events which coincided mostly with large and high storm intensity events. No runoff was predicted for several days during the wet seasons although daily runoff was recorded. On the other hand, daily runoff was over-predicted by several orders for some of the rainfall events. The rapid decline in simulated runoff after every large event might also not have taken effective account of the receding limb of the hydrograph measured at the weirs which could extend into the day after the event.

The WEPP model could not satisfactorily predict runoff because it considers mainly infiltration excess overland flow resulting most often in catchment-scale overland flow conditions. The partial area overland flow conditions which occurred during most of the storm events in the catchments were not adequately simulated by the WEPP model since it could not satisfactorily simulate the saturation excess overland flow and interflow occurring along the streams and footslopes of the hillslopes.

The research version of the *ACRU* model with the upslope contributions to the riparian zone provided an accurate simulation of the runoff observed at the downstream weir for the Weatherley catchment. However, the maximum daily flows recorded were generally larger than those predicted by the *ACRU* model and the simulated discharge recedes much faster than that observed. This could be due to the

ACRU model's inability to simulate the retarded through flow, accumulating in the lower parts of the slope after events. Nevertheless the final base flows some days after an event were successfully simulated.

The rapid responses recorded at the H-flume of the W17 catchment in Zululand were not adequately simulated by the *ACRU* model. Attempts to increase the variation between peak flow and baseflow, by increasing the percentage of rapid discharge from each event in the simulated flows, resulted in a poor representation of the sustained flows observed between rainfall events. This was evidence of the inability of the model to represent the rapid initial response, but sustained seepage from flow accumulations at the toe of hillslopes, observed in small catchments.

Sediment yield

As with runoff, the WEPP model did not satisfactorily predict sediment yield at both the downstream weir of the Weatherley catchment and the H-flume of the W17 catchment in Zululand. The variability in predicted sediment yield compared to the recorded daily suspended sediment load was high, which closely followed the same trends as with runoff discussed previously. This was to be expected since the hydrological component of the WEPP model is the primary input to the erosion and sediment yield component. It was illustrated that the predicted daily sediment yield was in close agreement with the recorded daily suspended sediment load for events in which the runoff was predicted accurately.

The daily sediment yield predicted with the *ACRU* model was in closer agreement with the measured daily suspended sediment load than the sediment yield predicted with the WEPP model. The *ACRU* model most often over-predicted the daily sediment yield. The over-predictions may be exacerbated by the fact that there were no measurements made over some of the apparently high daily sampled suspended sediment events. A comparison of simulated and measured daily suspended sediment yield reveals that the predicted sediment yields were evenly spread about the 1:1 line of equal simulated and observed yield. However, the variability was high, which can be attributed to the lack of detail of prevalent cover conditions, inability of the model to capture the effects of events of different intensity and to the variability in the simulated hydrology, which drives the erosion and sediment transport.

When the predicted and sampled daily sediment yield was summed on a monthly basis, the correlation between predicted and measured monthly totals was better than on a daily basis. This supports the notion that both the WEPP model and *ACRU* model simulate long-term sediment yields adequately, but fail to reproduce observed daily sediment yield consistently. The effect that the models predicted long-term sediment yields (annual or monthly basis) more accurately than on a daily basis is supported in the literature.

4.2 Parameterisation effects

Rainfall frequency

Rainfall data with a high temporal resolution is essential to run the WEPP model in South Africa, and the WEPP model was extremely sensitive to the rainfall input file since surface runoff, erosion and sediment delivery are simulated from both rainfall amount and storm intensity. The decrease in storm intensity when 15- and 60-minute time step rainfall data were used as a substitute for the 1-minute rainfall data was reflected in the under-prediction of sediment yield. The high recording frequency of rainfall time series data needed and the time-consuming process in preparing the rainfall input data for the WEPP model would severely limit its application in South Africa mainly to research projects with some focus on storm intensities. The *ACRU* model is a daily time step simulation model; therefore no other time steps were attempted.

Topography and soil

The effects of catchment configuration in the WEPP model were analysed through the amount of hillslopes and stream channels in the catchment, and the amount of overland flow elements (OFE) along hillslopes. An OFE is an area on the hillslope with relatively homogeneous soil and land management. The sediment yield predicted on the basis of a high spatial representivity of soil, slope and land management through several OFEs along the hillslope was comparable to where several OFEs were lumped into one OFE. This was in contradiction to what was expected from the rather complex and spatially variable hillslope flow mechanisms and water fluxes along the hillslope catena. This result confirms previous results on model verification in that the WEPP model did not adequately take account of the specific hillslope flow path mechanisms that occur in the Weatherley and Zululand catchments which give rise to partial area overland flow conditions.

The effects of catchment discretization were analysed for the research version of the *ACRU* model by simulating the catchment as a distributed configuration of cascading response units, in contrast to the case in which the whole catchment is taken as a single lumped unit. The predicted sediment yield from the lumped, full catchment was higher than from the case of the distributed zones, in which sediment is generated only from a single response unit adjacent to the riparian zone. This was because the whole of the catchment was deemed to be producing sediment in the lumped case, whereas, in the distributed example, only the near stream zones contributed sediment. The advantage of sediment yield models simulating the catchments as a distributed configuration of response units over models in which the whole catchment is taken as a single lumped unit was illustrated by the close match to the measured sediment yield for the distributed case and the poor match in the lumped simulations. The simulation of the catchments as a distributed configuration of response units would be important at the small catchment scale or catchments where partial area overland flow conditions exist.

4.3 Simulation of scenarios

Extreme events

An advantage of the WEPP model is that single storm events could be simulated in addition to the continuous simulation mode. Simulation of extreme events with a 20-year return interval at the Weatherley and Zululand catchments indicated that up to 30 and 60%, respectively, of the long-term average annual sediment yield could be delivered from hillslopes and small catchments in a single event. For the same event at Weatherley, the research version of the *ACRU* model applied in this study predicted that 50% of the long-term average annual sediment yield was delivered during the extreme event.

Land management practices

Both the WEPP model and *ACRU* model predicted a small increase in sediment yield when land in a pristine condition (natural erosion) was utilised for animal production, but a dramatic increase was predicted when rangeland was converted to arable land under conventional cultivation practices (Figures 1 and 2).

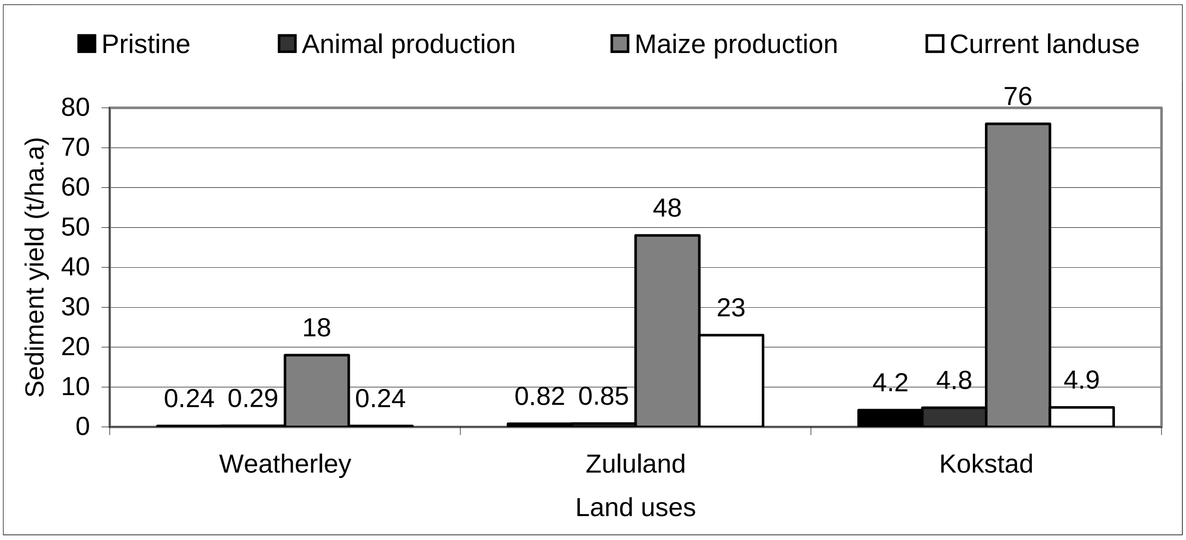

Figure 1. WEPP model predicted sediment yield for selected farming systems.

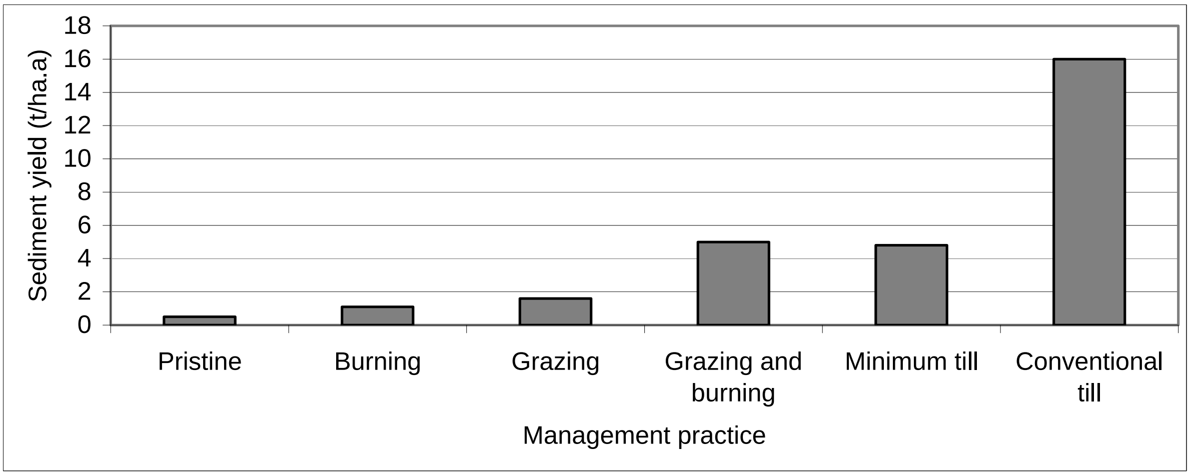

Figure 2. *ACRU* model predicted sediment yield from the Weatherley catchment for selected farming practices.

It was predicted that the utilization of land for grazing purposes produced acceptable erosion rates which were less than the soil loss tolerance value (10-15 t/ha.a). Predicted erosion rates were also in the range of the soil loss tolerance value when no- and minimum tillage practices were applied during a maize cropping system, but it was predicted that a maize cropping system under conventional cultivation practices produced unacceptably high erosion rates which exceed the soil loss tolerance value (Figures 1, 2 and 3).

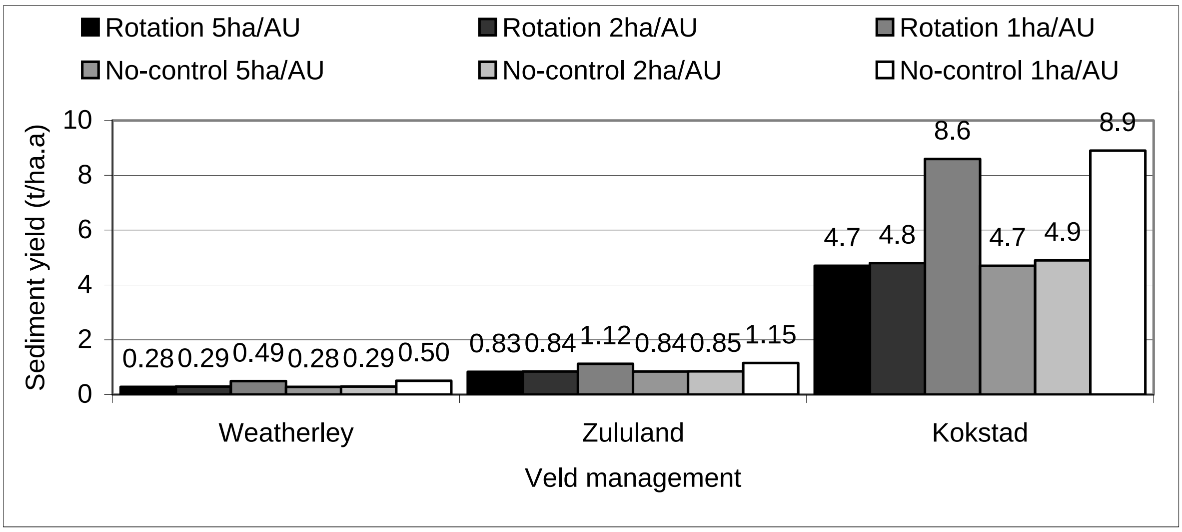

Figure 3. WEPP model predicted sediment yield for selected tillage practices and biological erosion control measures.

The WEPP model predicted that the use of vegetative erosion control measures (vegetative filter strips and riparian buffer zones) was as effective as conservation cultivation methods (no- and minimum tillage) in decreasing sediment delivery to the stream systems from agricultural land under conventional cultivation (Figure 3).

The impact of the various land management scenarios was compared on a relative basis since the comparisons were based on predicted sediment yield values and not on absolute values based on measured field data.

5 CONCLUSIONS

- The results from this study on model verification clearly demonstrate that sediment yield models that ignore soil saturation encountered at the foot of a hillslope due to saturation excess overland flow and/or interflow may well fail to predict important erosional features within a catchment. Sediment yield models based mainly on infiltration excess overland flow will fail to predict erosion and sediment delivery from partial area overland flow conditions localised at hydrologically sensitive areas, which are most often in close proximity to streams. It is to be expected that large areas in the eastern parts of South Africa, e.g. Mpumulanga, the eastern Free State, KwaZulu-Natal and the Eastern Cape, would give rise to partial area overland flow conditions due to the steep terrain and the (often) abrupt hydraulic transition between soil horizons. Therefore, sediment yield models applied at the hillslope and small catchment scale should take account of the specific hillslope flow path mechanisms that occur in a small catchment.
- In small catchments, the intensity of the rainfall event is significant in determining the resulting sediment yield. Simulations on a daily time step result in a smaller simulated discharge and peak flow and the resulting predicted energy for erosion and sediment transport is thus lower than the prevailing condition. Caution should therefore be exercised when applying sediment yield models operating at a daily time step on small catchments where variation in rainfall intensity dominates the sediment delivery process.
- Neither the WEPP model nor the *ACRU* model, and most of the sediment yield models, were designed to take account of headcut erosion, sloughing of gully sidewalls, subsurface / pipe erosion or the effects of seepage on erosion in concentrated flow channels, because they lack a sidewall failure and piping mechanism component. These processes could occur in small catchments such as those used in this study, which could severely under-predict erosion and sediment yield when the gullies are active. This is obviously a severe limitation if sediment yield models that do not take account of gully and pipe erosion are to be applied to plan soil conservation and water quality programmes in catchments where gullies are the dominant source of sediment.

- The focus of sediment yield predictions at the small catchment scale is to evaluate the severity of erosion under different management systems and may be intended as design tools for the selection of conservation practices. The application of the selected models provides major advantages in predicting the impact of agricultural management practices on sediment yield; most notably the capability of estimating spatial and temporal distributions of sediment yield and sediment delivery from hillslopes and small catchments on a daily, monthly or average annual basis. This has the benefit of analysing the impact of farming practices on sediment yield throughout the season according to the discharge volume or rainfall and the type of land use and management practices (harvest, fallow, cultivation, etc).
- The WEPP model is a powerful tool in predicting the impact of agricultural practice scenarios, because prediction results were visually presented along a hillslope or in a catchment through the Windows interface, and the various agricultural practice scenarios could easily be simulated in great detail through the use of default files from the extensive agricultural operational (e.g. burning, grazing, planting, harvesting, herbicide application, etc.) and tillage implement databases. However, this study has shown that the practical difficulties of obtaining the required detailed input data on climate and plant management that are mostly not readily available will limit the implementation of the model in South Africa. The application of the *ACRU* model is likely to be more successful in predicting sediment yield for South African conditions since much of the data gathering for the model has been incorporated in predefined data sets for various regions and climate, vegetation and soil types. These data sets aid the user in selecting proper inputs and increase the ease of input selection. Furthermore, the soil, vegetation, slope and management erosion-related parameters are derived from the Revised Universal Soil Loss Equation (RUSLE), model which is a well established and documented model with an extensive database.
- Both the WEPP model and the research version of the *ACRU* model predicted a small increase in sediment yield when land in a pristine condition (natural erosion) was utilised for animal production, but a dramatic increase was predicted when rangeland was converted to arable land. It was predicted that the utilization of land for grazing purposes produced acceptable erosion rates which were less than the soil loss tolerance value. Predicted erosion rates were also in the range of the soil loss tolerance value when no- and minimum tillage practices were applied during a maize cropping system, but it was predicted that a maize cropping system under conventional cultivation practices produced unacceptably high erosion rates which exceed the soil loss tolerance value. The WEPP model predicted that the use of vegetative erosion control measures (vegetative filter strips and riparian buffer zones) was as effective as conservation cultivation methods (no- and minimum tillage) in decreasing sediment delivery to the stream systems from agricultural land under conventional cultivation.

6 RECOMMENDATIONS ON FUTURE RESEARCH NEEDS

- A study to evaluate available approaches and methodologies on the integration of the susceptibility of the biophysical environment with the land user's socio-economic environment is of prime importance. The selection of good agricultural practices and / or conservation measures, identified through scenario predictions as illustrated in this study, should be matched with the social acceptability and economic viability of the intended land users.
- Prediction capabilities should be explored where both infiltration excess and saturation excess runoff are simulated for sediment yield predictions. Close collaborative research between soil scientists and hydrologists is needed in identifying typical landscapes and soil types where infiltration and saturation excess runoff and macropore flow conditions will dominate.
- The use of riparian buffer zones should be evaluated as a land management practice to manage the impact of upland agricultural practices on the sedimentation of the water resources.
- The possibilities that low-level remote sensing hold for cost-effectively acquiring geo-referenced land-based data, such as leaf area indexes, bare soil, land management, marsh / riparian areas, and detailed Digital Elevation Models, should be explored.

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Mr R Dube	Water Research Commission (Chairman)
Mr H Maaren	Water Research Commission (Chairman, deceased)
Mr HM du Plessis	Water Research Commission
Mr SK Armour	KwaZulu-Natal Department of Agriculture
Dr RMB Auerbach	Rainman Landcare Foundation
Prof GR Basson	University of Stellenbosch
Dr SA Lorentz	University of Natal, Pietermaritzburg
Mrs O Mwanyama	Isineke Developments
Mr TS Newby	Agricultural Research Council
Mr ACT Scheepers	University of the Western Cape
Mr PJ Strumpher	National Department of Agriculture

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LIST OF ACRONYMS

ACRU	Agricultural Catchment Research Unit
AMSL	Average Meters above Sea Level
SBEEH	School of Bioresources Engineering and Environmental Hydrology
BPCDG	BreakPoint Climate Data Generator
CALSITE	CALibrated SImulation of Transported Erosion
CPIDS	Crop Parameter Intelligent Database System
DEM	Digital Elevation Model
GIS	Geographic Information System
ICM	Integrated Catchment Management
IDW	Inverse Distance Weighting
ISCW	Institute for Soil, Climate and Water
MAE	Mean Annual A-pan Evaporation
MAP	Mean Annual Precipitation
MUSLE	Modified Universal Soil Loss Equation
OFE	Overland flow element
RUSLE	Revised Universal Soil Loss Equation
SASA	South African Sugar Association
SAWS	South African Weather Service
SCS	Soil Conservation Services
SLEMSA	Soil Loss Estimator for Southern Africa
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WRC	Water Research Commission

LIST OF SYMBOLS

α_{sy}, β_{sy} location specific MUSLE coefficients.

β rainfall induced turbulence factor

C USLE crop management factor

D_c detachment capacity by rill flow

D_f rill detachment rate

D_i interrill sediment delivery to rill

F_{nozzle} adjustment factor to account for sprinkler irrigation nozzle impact energy variation

G sediment load

I_e effective rainfall intensity

K USLE soil-erodibility factor

K_{iadj} adjusted interrill erodibility

K_r baseline rill erodibility parameter

K_{radj} adjusted rill erodibility parameter

LS USLE slope length and slope gradient factor

q flow discharge per unit width

q_o inflow discharge per unit width

q_p peak runoff rate

Q_v storm runoff volume

δ excess rainfall rate

δ_{ir} interrill runoff rate

P USLE erosion-control practice factor

R_s spacing of the rills

SDR_{RR} interrill sediment delivery ratio

T_c sediment transport capacity

τ_c rill detachment threshold parameter of the soil

τ_f flow shear stress acting on the soil particles

v_f particle fall velocity

w rill width

x distance downslope

Y_{sd} sediment yield from an individual storm

CHAPTER 1
INTRODUCTION

1.1 SCOPE

The major sources of sediment yield are natural erosion and land disturbances associated with urbanisation, mining, silviculture and agriculture. Although erosion rates associated with silviculture, surface mining and urbanisation are much higher than from agricultural sources, these activities only occupy a small percentage of the land attributed to agricultural activities (Elliot, Ward, Lane and Laflen, 1989).

Erosion was historically associated with loss of topsoil and agricultural potential, and reductions in reservoir storage. Lately, off-site impacts such as increased flooding due to reduced river channel capacities and deterioration of river health because of increased turbidity and pollution with pesticides and fertilisers contained in the sediment-laden flows, have become more important internationally (Elliot et al., 1989). Worldwide it is increasingly accepted that erosion control should be linked to both soil (on-site erosion) and water (off-site sedimentation) conservation initiatives. Several countries have incorporated “clean water strategies” into agricultural policies, legislation and programmes. Erosion control by biological measures such as riparian and wetland buffer zones or strip cropping, in addition to engineering measures, has become more popular as it is less expensive to establish and maintain. Forecasting both the on- and off-site impacts of agricultural practices and erosion control measures requires models in which we have some degree of confidence. Verification of these models, therefore, is critical (Wilcox and Simanton, 1998).

South Africa has broad scale maps (Predicted Water Erosion Map for South Africa (Pretorius, 1998) and Sediment Delivery Potential Map of South Africa (Verster, 1992)) to identify broad areas where the risk of erosion is high. These maps are of limited use in erosion predictions and control at a small catchment (<10 km^2) scale (Wilcox and Simanton, 1998). Erosion predictions at this scale were mainly done by the use of the Universal Soil Loss Equation (USLE) technology that is not suited to predict the off-site impacts of erosion (Lane, Renard, Foster and Laflen, 1992). According to Elliot et al. (1989), models predicting the off-site effects of farmland erosion at the small catchment scale have very limited application in South Africa.

1.2 OBJECTIVES

The overall aim of the project was to verify the performance of selected models in predicting the impact of farming practices on sediment yield at the small catchment scale in order to get an indication of the degree of confidence with which the off-site impacts of agricultural practices can be predicted with the selected models. In order to achieve this aim, the following specific objectives were identified:

1. To improve international and South African methodologies for predicting the impact of selected land uses on sediment yield in local catchments;
2. To assess the impact of the following land uses on sediment yield: communal grazing, communal cropping, commercial grazing and pristine areas;
3. To assess the impact of quality, availability and the spatial distribution of input data on the accuracy of sediment yield prediction results.

The emphasis of the first objective was on verifying the performance of the selected models by comparing model predictions against measured data with best available model input data (model verification). As the focus of the project was on the application of the models rather than on model development, no model calibration or modifications of model source codes were intended. The verification of model predictions against observed soil water contents at selected points in the catchments and runoff and sediment discharged at the catchment outlets are presented in Chapter 4, Model Verification.

The focus of the second objective was to get some indication of the ability of the selected models to predict sediment yield for typical South African agricultural practices by assessing the impacts through land management scenario predictions for the land uses occurring in the catchments. The aim of the study was not to engage in actual assessment measurements of the impacts. The predicted impacts of various land management scenarios are presented in Chapter 6, Simulation of Scenarios. The simulated values are relative (i.e. they were not absolute) and could only be used to compare different options.

Since the models were applied in research catchments with detailed data, assessment of the impact of the availability and the spatial and temporal resolution of input data on the accuracy of sediment yield prediction results were verified (objective 3) in order to assess the performance of the models with input data with coarser spatial and temporal resolutions. The parameterisation effects are presented in Chapter 5.

The models are discussed in Chapter 7 with respect to their ability to conceptualise the processes of sediment generation and delivery and the application of the models under South African conditions. The implications of the research results and recommendations for further research are presented in Chapter 8, Conclusions and Recommendations.

The research focused on the field and small catchment scale (1 ha-10 km^2) and not at the plot scale (1-100 m^2) or at the large catchment scale (>10 km^2).

CHAPTER 2
LITERATURE REVIEW

2.1 ROLE OF SEDIMENT YIELD PREDICTION IN INTEGRATED CATCHMENT MANAGEMENT

A water resource includes not only the water but also the three components of habitat (sediments, in-stream and riparian) and aquatic biota, as well as the physical, chemical and ecological processes which link these components of the aquatic environment. It is also important to recognize that land and water degradation, together with their subsequent impacts on land and water users, cannot easily be separated or managed independently of one another (Department of Water Affairs and Forestry, 1996).

The conceptual basis of Integrated Catchment Management (ICM) relies on recognition that the different components of the hydrological cycle (atmospheric precipitation, evapotranspiration, infiltration, seepage, runoff and erosion) are intimately linked to one another; therefore, they cannot be managed effectively as separate or disconnected units. The term ICM represents a systems approach to the management of natural resources, in particular water resources, within the bounds of a geographical unit that is based on the catchment area. Management actions could be focused on land, to constrain the impacts of land-based activities on water resources, as well as on the water itself, to ensure adequate storage, distribution and rehabilitation where necessary (Department of Water Affairs and Forestry, 1996). This study will focus on the impacts of diffuse sources from land-based activities on water resources, in particular sediment delivery caused by agricultural land use.

Sustainable development of water resources in the context of Integrated Catchment Management implies the adoption of three successive steps in water management:

- *Identification* of the system characteristics, which involves the specification of the characteristic features of the water resource system relevant to the different problems encountered. These features consist of the bio-physical, economic, social and environmental characteristics of the system;
- *Prediction* of the behaviour of the system, which corresponds to determining how the system will respond to certain actions taken by man (including changes in agricultural land use and practices); and
- *Management* of the system, which involves selection and implementation of the best strategy to attain certain objectives, where management decisions are based on the previous steps of identification and prediction (Department of Water Affairs and Forestry, 1996).

This study concentrated mainly on the second step by evaluating the use of sound scientific data and tools (models) that could be used to predict how the erosion and sediment delivery processes will respond to certain agricultural land uses and management practices.

According to Rutherfurd, Hairsine and Walker (1996), prediction tools were developed that are designed to help managers identify the major prevailing erosion factors and processes in a catchment and to decide which type of intervention should be used, and where to apply it. These range from complex physically and process-based simulation models, such as those used in this study, to the application of simple empirical predictors (Dickinson and Collins, 1998).

2.2 SCALE ISSUES

Scaling is arguably more relevant to model building and application for predicting sediment yield than to actual measurements. It is essential to be aware of the limitations inherent in converting the data collected from small areas / time periods to large areas / time periods. At coarser scales, additional processes are also generally observed that can rarely be predicted at a more detailed scale, for example the development of discrete channels, gullies and valleys (Kirkby, 1998). Integration of data from various scales remains a major challenge in sediment yield predictions.

Available sediment yield models cover a wide range of temporal and spatial scales. Regarding time, a model can be classified as:

- Long-term average annual model;
- Daily model;
- Event model;
- Continuous simulation model.

On the spatial scale, a model can be classified as:

- Plot;
- Hillslope;
- Field;
- Small catchment (<10 km^2);
- Large catchment;
- Grid model (Valentin, 1998).

Changes of scale in time and space generally go together, because a higher time resolution requires better understanding of hydrological and sediment transport processes, which, in turn, implies a more detailed spatial scale. At scales from the single erosion plot to the hillslope catena, overland flow hydrographs are critical. At the small and large catchment scale, topography, soil and vegetation patterns become more important, and it is essential to consider periods from single storm events up to several decades over which these patterns may change. In this process of up-scaling, some of the distributed variables must be replaced by average values (not necessarily arithmetic averages) (Kirkby, 1998).

Local decision-making may work well at the agricultural field and small catchment scale, but it becomes increasingly difficult in larger catchments where a strategic view must be taken by a central catchment authority (Rutherfurd et al., 1996). Predictions at the plot to the hillslope scale provide evaluations of the effectiveness of alternative land management treatments in terms of erosion and sediment delivery. Such knowledge obtained provides the opportunity for effective control when problems recognized at coarser scales indicate the need for remedial action. At the large catchment scale both hydrology and sediment transport is affected by spatial variability in factors such as land management, soil type, topography and channel characteristics (Ciesiolka and Rose, 1998). The details of micro-topography are most generally integrated at the large catchment scale to make use of available data at the broader scale. This generally consists of topographic data from maps or digital elevation model (DEM), together with data on soil and vegetation types, based on thematic maps or remote sensing (Kirkby, 1998). Figure 2.1 illustrates the focus of erosion predictions at different scales for farming systems research to reduce sediment yield caused by agricultural practices.

Overall, the sources of sediment in large catchments, and the management approaches thereof, can be crudely split between hillslope and in-stream sources (Rutherfurd et al., 1996). The modelling of sediment sources and sinks in large catchments consists of two major components:

- *Upland catchment* model that simulates the supply of sediment to major streams; and
- *In-stream* model that can infer sediment sources (sediment re-entrainment and bank erosion) and sinks within a river reach (Jakemann, Green, Zhang, Beavis, Evans, Dietrich and Barnes, 1998).

This study focused on detailed upland catchment modelling.

The detailed simulations for upland catchments are generally too demanding in data requirements to be widely applicable at the large catchment scale (Kirkby, 1998). Recent sediment yield model developments are focussing on developing a suite of models that contain two components:

- A model that predicts sediment yields at the large catchment scale from limited data to identify homogeneous erosion units; and
- A model for detailed simulations at the hillslope to small catchment scale to predict sediment yields for various agricultural practices at selected small catchments.

Large catchments are divided into sub-catchments / grids to predict 'hot spots' of sediment sources as well as sediment sinks (Kirkby, 1998). Such predictions are made with a sediment yield model, mostly geographic information system (GIS)-based, developed for simulating large catchments in a spatially distributed manner. Examples of such models applied in South Africa are CALSITE (**cal**ibrated **si**mulation of **t**ransported **e**rosion) and the *ACRU* (Agricultural Catchment Research Unit) model (Dickinson and Collins, 1998). ‘Benchmark’ sub-catchments / grid areas should be selected as representatives of the large catchment under study whose physiographical characteristics and functioning are considered as typical or representative of a certain hydrological region (Bricquet and Claude, 1998). These sub-catchments / grid areas are modelled in detail with models developed for the hillslope to small catchment scale, where a series of points down a hillslope or ephemeral gully are connected by kinematic routing of overland flow, subsurface flow, and grain-size selective

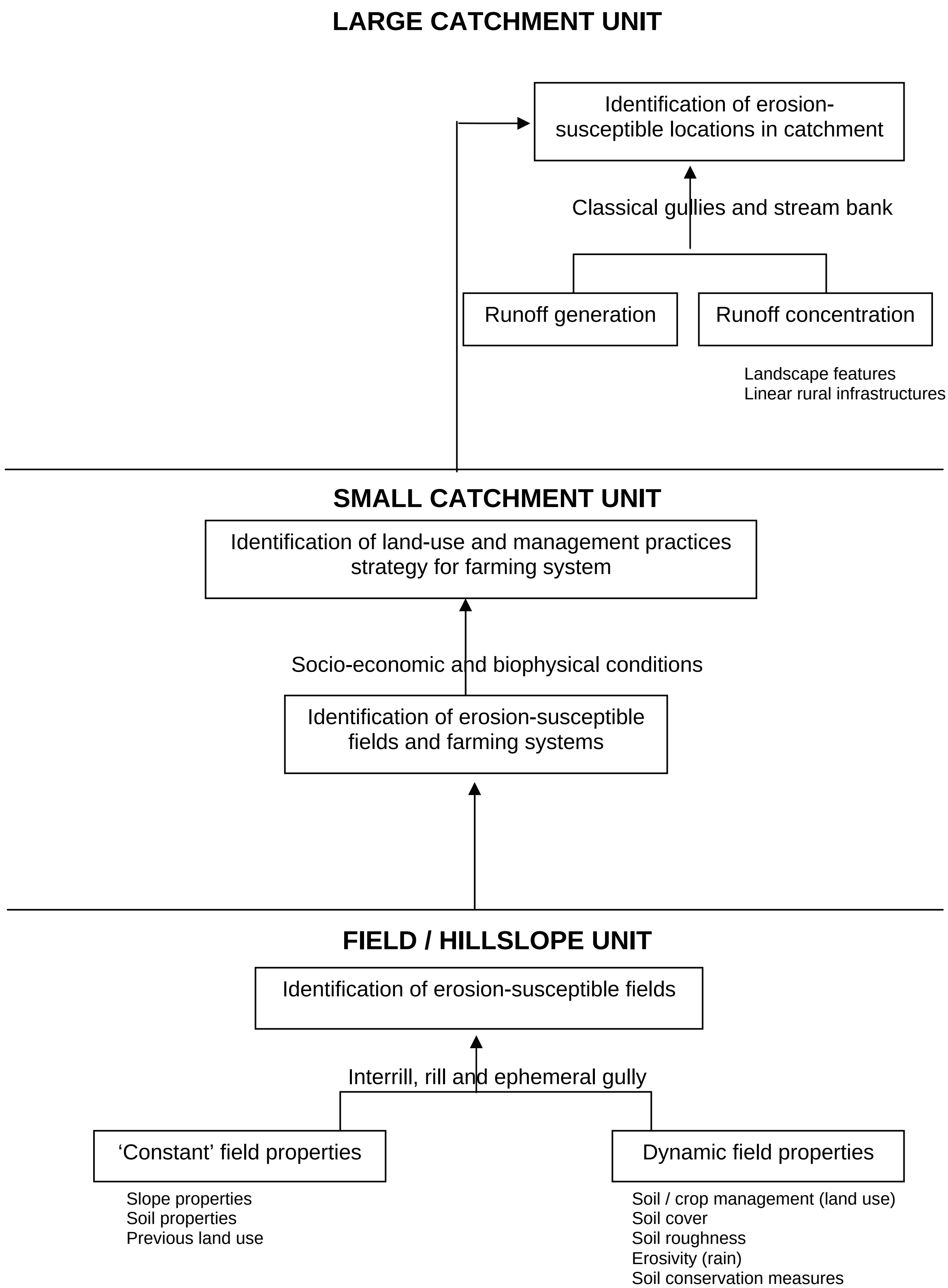

Figure 2.1. Erosion predictions at different scales for farming systems research.

sediment transport (Kirkby, 1998). The predictions are intended to study the impacts of agricultural practices on the variation in discharge and sediment, temporal and spatial variation in overland flow, erosion on hillslopes and ephemeral gullies, and ultimately the sediment supply from small catchments to main streams of the large catchment (Agus, Gintings, Kurnia, Adurachman and van der Poel, 1998).

2.3 MODELS FOR EROSION PREDICTION

2.3.1 Overview of Model Types

The range of management problems facing erosion and sedimentation across the country means that there are few universal rules that can be defined in managing soil loss and sediment yield. There is an increasing range of decision-making tools that are attempting to close the gap between management and research. They include the use of sediment yield models to predict future changes in erosion and sediment delivery in catchments and streams due to human interventions to assist managers in where to direct their works most effectively. These models may be experienced-based or they may be sophisticated numerical models (Rutherfurd et al., 1996).

As there are many types of sediment yield models developed for specific conditions and purposes, it is important to know their limitations in order to choose the correct model for the intended purpose (Morgan, 1995). Figure 2.2 summarises model development over time. In general, models become more process-based and tend to be more spatially distributed. Spatially-lumped models apply to a sub-catchment as a unit (weighted average parameter value for the sub-catchment); semi-distributed models apply to elements that are hydrologically homogenous (parameter value change along a hillslope), and distributed models are grid-based (parameter value for each pixel of grid overlain on area). The new generation models also simulate on a storm event basis, or at breakpoints thereof, whereas earlier models give long-term annual rates.

2.3.2 Empirical Models

Formal research on water erosion was begun in the 1940s when various statistical equations were developed. As these equations were developed with different factors, the results were difficult to compare. With this basis and a large body of experimental plot data (more than 10 000 plot-years), the Universal Soil Loss Equation (USLE) model (Wischmeier and Smith, 1965) was developed to overcome the difficulty of comparing results of the various equations. The statistically-derived USLE model is used to compute sheet (interrill) and rill erosion as a function of factors presenting climate, soil, topography and land use (Lane et al., 1992). The Revised Universal Soil Loss Equation (RUSLE) model (Renard, Foster, Weesies, Mccool, and Yoder, 1997) is an improved, computerised version of the USLE. Elwell (1978) has also developed a model similar in concept to the USLE model, the Soil Loss Estimator for Southern Africa (SLEMSA) model (Elliot et al., 1989). The USLE, RUSLE and

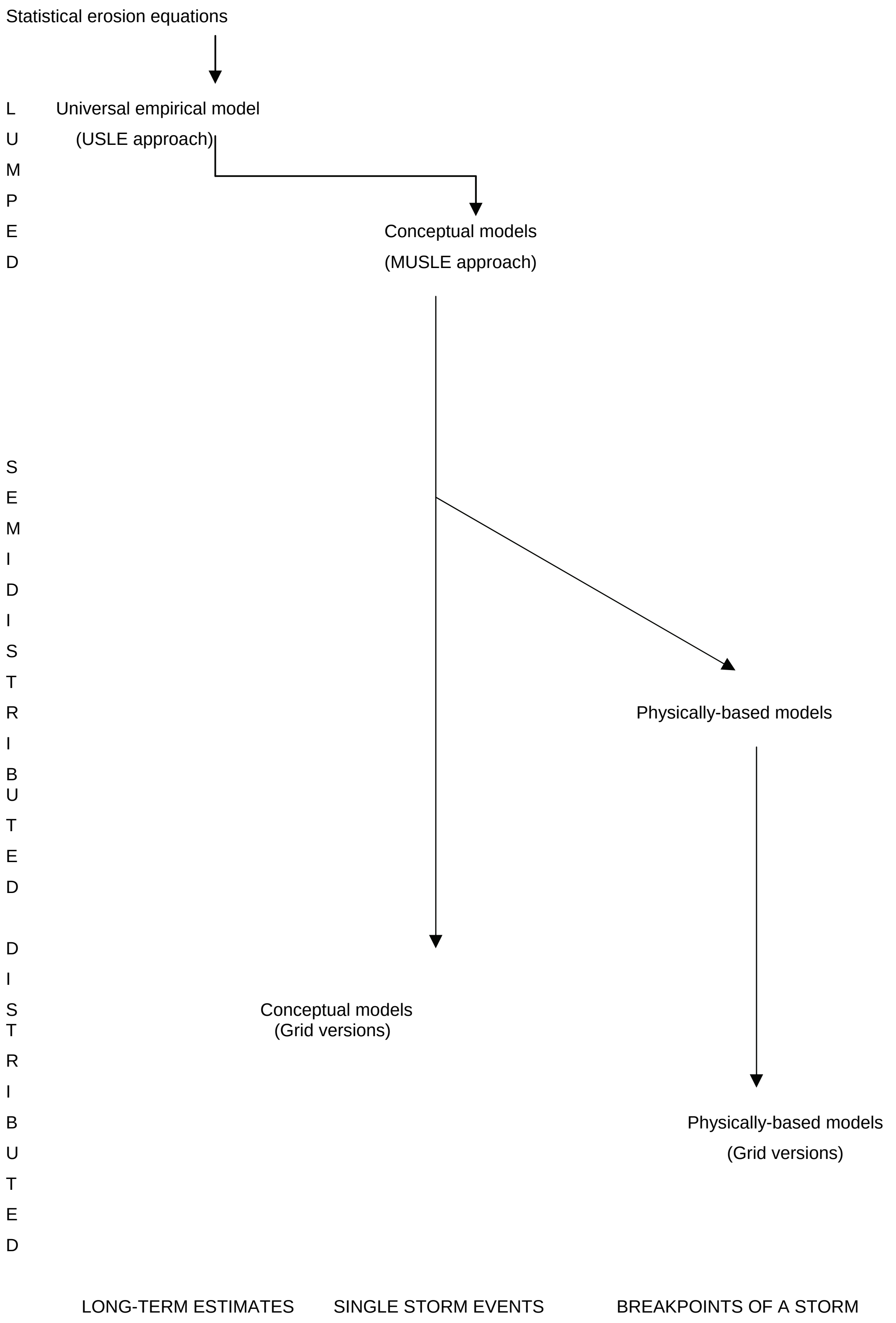

Figure 2.2. History of erosion model development.

SLEMSA soil loss models were developed specifically for evaluating average annual soil loss; that is, neither USLE, RUSLE nor SLEMSA models are useful for predicting deposition, sediment yields from complex shaped hillslope profiles, sediment size information, or temporal and spatial distributions of erosion (Nearing and Nicks, 1998). Another limitation is that they were developed to provide long-term erosion estimates, thus failing to take account of extreme meteorological events such as flooding (Wilcox and Simanton, 1998).

2.3.3 Conceptual Models

To determine the sediment yield at a downstream point, the gross erosion (soil loss) needs to be multiplied by a sediment delivery ratio term (sediment yield / soil loss). Numerous empirical delivery ratio concepts have been developed, but because of the empirical nature of these methods, relations should be applied with extreme caution. A prediction technology known as sediment-runoff models overcomes some of the problems of determining a delivery ratio by replacing the rainfall erosivity factor with a hydrological factor (storm runoff / peak storm runoff).

Although conceptual models like the Modified Universal Soil Loss Equation (MUSLE) model (Williams, 1975) account for the delivery process of a catchment, they should not be used to route the sediment yield from the catchment through the streams to a downstream point, or to predict gully erosion (Elliot et al., 1989). Most of the conceptual models are spatially-lumped models, but have lately become distributed (grid-based).

2.3.4 Physically-based Models

Subsequent advances in hydrology and erosion have provided the means of developing physically-based models based on infiltration theory, hydrodynamics of overland flow, interrill, rill and ephemeral gully sediment detachment, transport and deposition processes (Lane et al., 1992). Physically-based models provide several advantages over empirical and conceptual models, including most notably:

- Capabilities for estimating spatial and temporal distributions of net soil loss and sediment yield;
- More reliable extrapolation to ungauged areas; and
- The ability to better predicts off-site delivery of sediment, including particle size information (Nearing and Nicks, 1998).

Physically-based models calculate in addition to conceptual models erosion from concentrated flows in ephemeral gullies, deposition in backwater and impoundments, deposition in concave slopes, and the enrichment of the fines caused by deposition. However, erosion occurring in classical gullies (dongas) and perennial streams is not considered, nor is stream bank erosion or erosion from wave action (Lane et al., 1992). Unlike conceptual models, physically-based models do take account of erosion and deposition in ephemeral gullies. Ephemeral gullies develop where overland flow concentrates and result essentially from hydraulic erosion by concentrated overland flow. Classical gully erosion is less controlled by overland flow intensity but more by factors controlling piping and mass movement (i.e. slumping and soil fall). This implies that prediction of the exact location and the volume eroded by classical gullies is more difficult than that of ephemeral gullies (Poesen, Vandaele and Wesemael, 1998).

2.4 SELECTED MODELS

Many sediment yield models were developed for specific conditions and purposes and it is important to recognise their limitations in order to select a suitable model for the intended purpose. A theoretical evaluation of various models applicable at the field and small catchment scale was undertaken. These models include the Agricultural Catchment Research Unit (*ACRU*) model (Schulze, 1995a), Areal Nonpoint Source Watershed Environmental Response Simulation model (Beasley, Huggins and Monke, 1980), Chemicals, Runoff and Erosion from Agricultural Management System model (Knisel, 1980), European Soil Erosion Model (Morgan, Quinton and Rickson, 1994), Griffith University Erosion Sedimentation System model (Rose, Williams, Sanders and Barry, 1983), and the Water Erosion Prediction Project (WEPP) model (Nearing, Foster, Lane and Finkner, 1989).

The 1999.5 and 2002.7 versions of the WEPP Windows interface erosion model (National Soil Erosion Research Laboratory, 1999; 2002) were selected for this study. The WEPP model represents a new generation technology for predicting soil erosion on and sediment delivery from hillslopes and small catchments and is based on modern hydrological and erosion science. The WEPP model is a process model since it not only simulates the erosion and sediment transport and deposition processes, but also the processes that determine the status of the factors influencing the erosion and sediment transport and deposition processes. Therefore, it is argued that the WEPP model can be used in ungauged areas with more confidence. The WEPP model computes spatial and temporal distributions of soil loss and deposition, and provides explicit estimates of when and where in a catchment or on a hillslope that erosion is occurring so that conservation measures can be selected to most effectively control soil loss and sediment yield. The model includes options for single storm, continuous simulation, single crop, crop rotation, irrigation, contour farming, and strip cropping. The user interface programs and databases, such as a crop parameter and a tillage implement database, make the WEPP model a very powerful tool for users involved in soil and water conservation and environmental assessment.

A research version of the *ACRU* agrohydrological modelling system was also selected for this study. The *ACRU* model has the advantage, in South Africa, that the model builders can be directly consulted, and the components used in the *ACRU* model have been extensively researched for southern African conditions. The *ACRU* model represents the dominant components of catchment scale hydrology and sediment yield with a minimum of complexity. The *ACRU* model, therefore, requires a minimum of data to represent the catchment hydrology and sediment yield. In addition, much of the data gathering for these models has been incorporated in predefined data sets for various regions and climate, vegetation and soil types. These data sets aid the user in selecting proper inputs and increase the ease of input selection.

2.4.1 WEPP model

2.4.1.1 MODEL OVERVIEW

The WEPP model was developed by the United States Department of Agriculture – Agricultural Research Service and Purdue University at the National Soil Erosion Research Laboratory, West Lafayette, Indiana, USA. The WEPP model is based on modern hydrological and erosion science and simulates the erosion processes of detachment and transport by raindrop impact on interrill areas, detachment, transport, and deposition by overland flow in rill channels; detachment, transport, and deposition by concentrated flow in channels, and deposition in impoundments. In addition to the erosion components, it also includes a climate component that uses a stochastic generator to provide daily weather information, a hydrology component that is based on a modified Green-Ampt infiltration equation and solutions of the kinematic wave equations, a daily water balance component, a plant growth and residue decomposition component, and an irrigation component.

2.4.1.2 HYDROLOGY

The primary purpose of the the WEPP model surface hydrology component is to provide the erosion and sediment transport and deposition component with the duration of rainfall excess, the rainfall intensity during the period of rainfall excess, the runoff volume and the peak discharge rate. A secondary purpose is to provide the amount of water that infiltrates into the soil for the water balance, crop growth and residue decomposition calculations that are in turn used to update the infiltration, runoff routing and erosion parameters. The hydrological processes in the WEPP hillslope model include infiltration, runoff routing, soil evaporation, plant transpiration, snowmelt and seepage (Stone, Lane, Shirley and Hernandez, 1995).

Infiltration is computed using an implementation of the Green and Ampt equation and modified by Mein and Larson (1973) for unsteady intermittent rainfall. The infiltration process is divided into two distinct stages: one in which the surface is ponded with water and another without surface ponding. During an unsteady rainfall, the infiltration process may change from one stage to the other and then revert back to the original stage. The rainfall excess rate is conceptualised as occurring only when the rainfall rate is greater than the infiltration rate. The volume of rainfall excess is reduced to account for depression storage and runoff is assumed to begin only after the depression storage has been satisfied. For runoff events that produce a partial equilibrium hydrograph, the rainfall excess volume is reduced to account for water infiltrating during the recession of the event (Flanagan et al., 1995; Stone et al., 1995).

Overland flow processes are conceptualised as a mixture of broad sheet flow occurring in interrill areas and concentrated flow in rill areas. A peak discharge approximation based on the kinematic wave model is used when the model is run in the continuous simulation mode. Infiltration and rainfall excess on multiple overland flow elements (OFE, which is an area of homogeneous soil and land management) are approximated by either averaging the infiltration parameters and treating the multiple OFEs as a single OFE or by computing a simple water balance to determine if runoff occurs. For multiple OFEs, an equivalent depth-discharge coefficient for the kinematic wave model is computed based on the equilibrium storage of water on a cascade of OFEs (Stone et al., 1995). Once the peak runoff rate and the duration of runoff have been determined from the overland flow routing, steady-state conditions are assumed at the peak runoff rate for erosion calculations. Runoff duration is calculated so as to maintain conservation of mass for total runoff volume (Flanagan et al., 1995).

The antecedent soil moisture deficit with the onset of an event affects the infiltration component when the model is run in the continuous simulation mode. The soil moisture deficit is computed as the difference between effective porosity and initial volumetric water content. The soil water balance and percolation components of the WEPP model are designed to use inputs from the climate, infiltration, and crop growth components to estimate soil water content in the root zone and evapotranspiration losses throughout the simulation period. The time step in predicting evapotranspiration and percolation is 24 hours. Redistribution of water within the soil profile is accounted for by the Ritchie evapotranspiration model (Ritchie, 1972) and by percolation from upper to lower layers based on a storage routing technique. The model maintains a continuous water balance on a daily basis by taking account of precipitation, snow melt, precipitation interception by vegetation, surface runoff, evapotranspiration, percolation loss below the root zone and subsurface lateral flow (Flanagan et al., 1995; Savabi and Williams, 1995).

The infiltration component of the WEPP model is linked with the evapotranspiration and percolation components to maintain a continuous water balance. Infiltrated water is added to the upper layer’s soil water content and routed through the lower soil layers. Soil water in each layer is subjected to percolation and/or evapotranspiration. The upper layer soil water content is being used to establish initial moisture conditions for the infiltration component (Green and Ampt model). Daily leaf area index, root depth, total plant biomass and residue cover are entered as inputs to the evapotranspiration component from the crop growth component. The plant growth water stress factor is computed by considering water supply and demand (Savabi and Williams, 1995).

Subsurface stormflow can make up a significant portion of hillslope water yield with the presence of inhomogeneities in the soil, occurrence of soils of high permeability, whether inherent in the soil matrix or due to structural or biotic macropores, and/or a steep hydraulic gradient, whether due to the slope steepness or to the build-up of groundwater mounds on shallow slopes. In the WEPP model, it is assumed that the soil layer with water content in excess of field capacity (water held at 33 kPa tension for most soils) is subjected to percolation to a lower layer and to lateral flow (Savabi, Skaggs and Onstad, 1995).

The channel hydrology component computes infiltration, evapotranspiration, soil water percolation, canopy rainfall interception and surface depressional storage in the same manner as the hillslope hydrology component. Channel water balance calculations are performed after the channel runoff volume has been computed. The channel water balance and percolation routines are identical to those used in the hillslope component (Flanagan et al., 1995).

Hydrological inputs to the impoundment component include precipitation event generated runoff volume and flow rate. The hydraulic simulation section numerically integrates an expression of continuity using an adaptive time step that increases when the inflow and outflow rates are relatively constant. A predicted outflow hydrograph including the time, stage and outflow at each time step is then generated (Flanagan et al., 1995).

2.4.1.3 SEDIMENT YIELD

The WEPP model simulates the erosion processes of detachment and transport by raindrop impact on interrill areas; detachment, transport and deposition by overland flow in rill channels; detachment, transport and deposition by concentrated flow in channels; and deposition in impoundments. The WEPP hillslope model computes soil loss along a slope and sediment yield at the end of a hillslope by calculating interrill and rill erosion and deposition along the hillslope profile. The WEPP watershed model calculates channel erosion and deposition, and deposition in impoundments, but the procedures do not consider classical gully erosion.

The WEPP model uses a steady-state, sediment continuity equation to estimate net detachment or deposition:

$$dG/dx = D_f + D_i \qquad (1)$$

where

G = sediment load ($kg \cdot m^{-1} \cdot s^{-1}$)

x = distance downslope (m)

D_f = rill detachment rate ($kg \cdot m^{-2} \cdot s^{-1}$)

D_i = interrill sediment delivery to rill ($kg \cdot m^{-2} \cdot s^{-1}$)

Separate relationships are used for calculation of D_f depending upon whether conditions exist that will lead to detachment (transport capacity exceeds sediment load and shear stress exceeds critical shear stress) or deposition (sediment load exceeds transport capacity). In the case of rill detachment:

$$D_f = D_c \cdot (1 - G/T_c) \qquad (2)$$

where

D_c = detachment capacity by rill flow ($kg \cdot s^{-1} \cdot m^{-2}$)

T_c = sediment transport capacity ($kg \cdot m^{-1} \cdot s^{-1}$)

When hydraulic shear stress of the rill exceeds the critical shear stress for the soil, detachment capacity D_c, is expressed as:

$$D_c = K_{radj} \cdot (\tau_f - \tau_c) \qquad (3)$$

where

K_{radj}	=	adjusted rill erodibility parameter ($s \cdot m^{-1}$)
τ_f	=	flow shear stress acting on the soil particles (Pa)
τ_c	=	rill detachment threshold parameter of the soil (Pa).

The baseline rill erodibility (K_r) and critical shear stress are adjusted within the WEPP model as a function of temporally varying factors, such as buried residue, dead and live roots, soil surface sealing and crusting, and as the soil dries from saturation to field capacity. For the case of deposition in rills, the governing deposition equation is:

$$D_f = \beta \cdot v_f / q \ (T_c - G) \qquad (4)$$

where

β	=	rainfall induced turbulence factor
v_f	=	particle fall velocity ($m \cdot s^{-1}$)
q	=	flow discharge per unit width ($m^2 \cdot s^{-1}$)

Sediment load is normalised to transport capacity at the end of the OFE when there is water discharge from the OFE, and is normalised to transport capacity at the top of the OFE when there is no discharge from the plane. The flow discharge per unit width (q) is calculated from:

$$q = q_o + \delta \cdot x \qquad (5)$$

where

q_o	=	inflow discharge per unit width ($m^2 \cdot s^{-1}$)
δ	=	excess rainfall rate ($m \cdot s^{-1}$)
x	=	distance downslope (m).

The WEPP model applies an interrill sediment delivery function of the form:

$$D_i = K_{iadj} \cdot I_e \cdot \delta_{ir} \cdot SDR_{RR} \cdot F_{nozzle} \cdot (R_s / w) \qquad (6)$$

where

K_{iadj}	=	adjusted interrill erodibility ($kg \cdot s \cdot m^{-4}$)
I_e	=	effective rainfall intensity ($m \cdot s^{-1}$)
δ_{ir}	=	interrill runoff rate ($m \cdot s^{-1}$)
SDR_{RR}	=	interrill sediment delivery ratio
F_{nozzle}	=	adjustment factor to account for sprinkler irrigation nozzle impact energy variation
R_s	=	spacing of the rills (m)
w	=	rill width (m).

The base interrill erodibility (K_i) values for cropland and rangeland soils are adjusted (K_{iadj}) in the WEPP model for factors that influence the resistance of the soil to detachment, such as live and dead root biomass, soil freezing and thawing, and mechanical and livestock compaction. F_{nozzle} is adjusted to 1.0 for natural rainfall conditions. SDR_{RR} is computed as a function of the random roughness of the soil surface, the fall velocity of the individual particle size classes of sediment, and the particle size distribution of the sediment.

Sediment transport capacity, as well as sediment load, is calculated on a unit rill basis. The transport capacity, T_c, as a function of flow shear stress is calculated using a simplified transport equation of the form:

$$T_c = k_t \cdot \tau_f^{3/2} \qquad (7)$$

where

k_t = transport coefficient ($m^{0.5} \cdot s^2 \cdot kg^{-0.5}$)

τ_f = hydraulic shear stress acting on the soil (Pa).

Transport capacity at the end of the slope is computed using a modification of the Yalin (1963) equation. These modifications included in the WEPP model use a weighted average of the sediment transport capacity for each particle size class, where the weighted function is the mass fraction of sediment within each class (Flanagan and Nearing, 2000; Foster, Flanagan, Nearing, Lane, Risse and Finkner, 1995).

The WEPP watershed model channel erosion routines are similar to those of the hillslope model with major differences being that the flow shear stress is calculated using regression equations which approximate the spatially-varied flow equations, and only entrainment, transport and deposition by concentrated flow are simulated. Channel erosion is based on the steady-state sediment continuity equation. Sediment load in the channel is a function of the incoming upstream load (from hillslopes, channels and impoundments) and the incoming lateral load (from adjacent hillslopes and impoundments), and the ability of the flow to detach channel bed material or soil particles. Detachment of soil in a channel is predicted to occur if the channel flow shear stress exceeds a critical value and the sediment load in the flow is below the sediment transport capacity. Deposition is predicted to occur if channel sediment load is above the flow sediment transport capacity.

Impoundments can significantly reduce sediment yield by trapping as much as 90% of incoming sediment, dependent upon particle size, impoundment size, and inflow and outflow rates. The watershed model impoundment component calculates outflow hydrographs and sediment concentration for various types of outflow structures suitable for both large (e.g. farm ponds) and small (e.g. terraces) impoundments including culverts, filter fences, straw bales, drop and emergency spillways, and perforated risers. Conservation mass balance and overflow rate concepts are used to predict sediment outflow concentration (Ascough II, Baffaut, Nearing and Flanagan, 1995; Flanagan et al., 1995).

2.4.2 *ACRU* Model

2.4.2.1 MODEL OVERVIEW

The *ACRU* agrohydrological modelling system was developed in the School of Bioresources Engineering and Environmental Hydrology (formerly the Department of Agricultural Engineering) of the University of Natal, Pietermaritzburg, South Africa (Schulze, 1995a). It is a daily time step, catchment-scale model with runoff generated using a SCS curve number approach, modified for South African conditions. The SCS curve number equation is a procedure developed by the Soil Conservation Services (SCS) of the United States Department of Agriculture for estimating stormflow depths and volumes from small catchments (Schulze, 1995c). The model incorporates a multi-layered soil profile water balance and groundwater store. Sediment yield is generated using the Modified Universal Soil Loss Equation, MUSLE.

The streamflow generation water balance of the effective rainfall comprises evapotranspiration losses from the soil; rapid, event-based runoff and slower baseflow from a groundwater store. Evapotranspiration losses are based on a number of optional methods for estimating the reference potential evaporation. Vegetation parameters control the process of water loss due to transpiration. The process is also subject to plant stress, based on soil water content. Rapid event discharge is controlled by the antecedent water content prevalent at a specified depth in the soil profile. The volume of discharge generated by an event is estimated using an SCS equation, modified for South African conditions. The flux of this volume to the catchment outlet is controlled by a release rate parameter, which permits a specified fraction of the event water to reach the river each day. In the profile, the water is moved up and down between two soil horizons (A and B), based on the field capacity, porosity interchange rate parameter and the volumetric water content differences between the horizons. Water released from the lower soil horizon (B) reaches a groundwater store and baseflow is released from this store to the catchment outlet on a daily basis at an exponential rate of decay, dependent on the volume in storage and a decay rate constant.

Catchment hydrology has been successfully simulated by the *ACRU* model in catchments with areas of up to 50 km^2 using lumped estimated of the parameters, averaged over different land uses and soils, and the model is well documented (Schulze, 1995c). However, when considering sediment yield, the source of the eroded material is critical in order to estimate the resultant stream sediment load and to design remedial measures. The source of sediment is clearly linked to the source of surface and near-surface runoff. Hence, a research version of the *ACRU* model was developed, which includes the spatial distribution of water and sediment generation, particularly in terms of the topography of hillslopes.

2.4.2.2 HYDROLOGY

While catchment hydrology has been successfully estimated by the *ACRU* model using area-weighted, lumped parameters, when considering sediment yield, the source of the eroded material is critical in order to estimate of the resultant stream sediment load and to design remedial measures. The source of sediment is clearly linked to the source of surface and near surface runoff. Hence, a research version of the *ACRU* model was developed, which included the spatial distribution of water and sediment generation, particularly in terms of the topography of hillslopes. To this end the *ACRU* model was linked to a GIS distribution of source areas during a study from 1995 to 1997 (Howe and Lorentz, 1995). In that work, the antecedent moisture in each location was updated using a "Topmodel" algorithm (Bevin, Lamb, Quinn, Romanowicz and Freer, 1995), which takes into account flow accumulation, gradient of the hillslope on which the location is situated, as well as the hydraulic characteristics of the soil profile. The major features included in that work were:

- The spatial distribution of land use and sediment source areas;
- Topmodel update of antecedent moisture at each location;
- Infiltration / runoff by Green-Ampt infiltration;
- Macropore feature for rapid arrival of water at the soil-bedrock interface; and
- Accumulation of perched water table on the soil-bedrock interface prior to percolation into the bedrock aquifer store.

Subsequent to much of the data analysis of the Weatherley research catchment in the North Eastern Cape, the "Topmodel" approach of surface topology related flow accumulation was modified to allow for distinct flow generation zones, pathways and fluxes. The use of source zone streamflow generation, rather than surface topographically related flow accumulation, was also justified in other research (McDonnell, Freer, Hooper, Kendall, Burns, Bevans and Peters, 1996; McGlynn, McDonnell, Kendall and Hooper, 2001; Uhlenbrook and Leibundgut, 2002). The current approach, used in this study included:

- Flow generation based on a hillslope section contributing areas instead of on a grid basis;
- Near-surface discharge due to accumulation of macropore generated water above a hydraulic discontinuity in the profile and delivery of this discharge to the riparian zone B horizon (Figure 2.3);
- Baseflow contributions from the macropore zone and grassland profiles to the riparian zone (Figure 2.3); and
- Time distributed arrival of subsurface water based on hillslope criteria (Lorentz and Hickson, 2001).

2.4.2.3 SEDIMENT YIELD

The sediment yield module of the *ACRU* model is based on the Modified Universal Soil Loss Equation (MUSLE), where erosive and transport energies are derived from the product of peak stormflow and runoff volume for daily rainfall events (Williams, 1975).

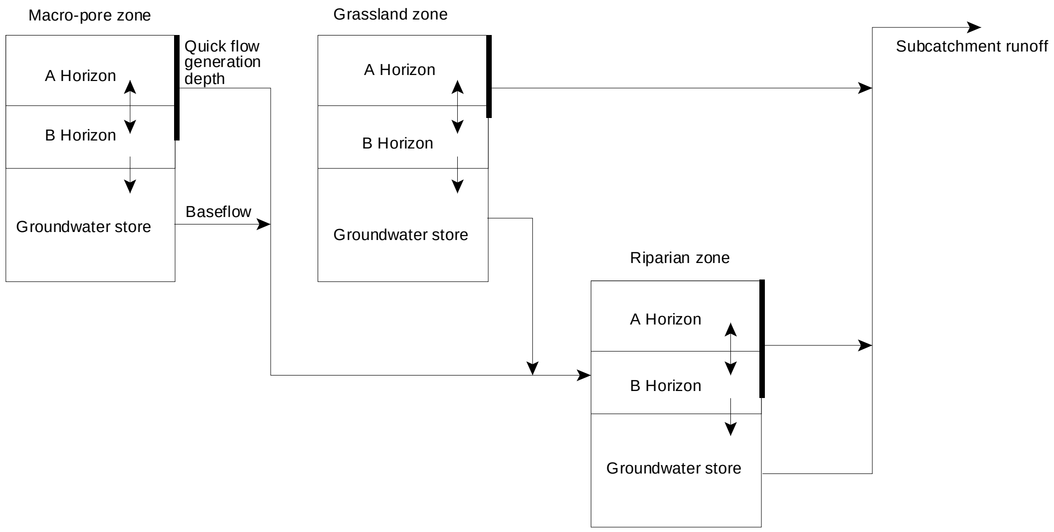

Figure 2.3. Schematic subcatchment streamflow generation zones and pathways simulated in the topological version of the *ACRU* model (macropore zone only applies to Weatherley).

The sediment yield processes are simulated in a combined / lumped manner by applying the following fundamental equation:

$$Y_{sd} = \alpha_{sy}(Q_v \times q_p)^{\beta sy} \cdot K \cdot LS \cdot C \cdot P \qquad (8)$$

where

Y_{sd}	=	sediment yield from an individual storm (tonne)
Q_v	=	storm runoff volume (m^3)
q_p	=	peak runoff rate ($m^3 \cdot s^{-1}$)
K	=	soil-erodibility factor ($tonne \cdot h \cdot N^{-1} \cdot ha^{-1}$)
LS	=	slope length and slope gradient factor
C	=	crop management factor
P	=	erosion-control practice factor
α_{sy}, β_{sy}	=	location specific MUSLE coefficients.

Estimates of Q_v and q_p are predicted by the hydrological component of the *ACRU* model. Although Q_v and q_p are highly correlated with one another, Q_v is related to more to the detachment process while q_p is associated with sediment transport (Williams and Brendt, 1977). The factors K, LS, C and P in the *ACRU* model are directly taken from the RUSLE model with the soil erodibility factor in appropriate SI units. In the *ACRU* model, various options are offered to estimate these parameters, depending on the level of data and information available. These options have been developed from the USLE model and RUSLE model manuals and, for modelling in southern Africa, from local experimental observations. The MUSLE coefficients, α_{sy} and β_{sy}, are location specific and must be determined for specific catchments in specific climatic zones (Lorentz and Schulze, 1995).

CHAPTER 3
RESEARCH CATCHMENTS AND MODEL DATA

3.1 SELECTION OF RESEARCH CATCHMENTS

The focus of this project was to verify models predicting sediment yield at the small catchment scale. Sixteen catchments (<5 km^2) were evaluated by applying the following criteria:

- Availability of instrumentation and monitoring systems for collecting climate, soil water content, runoff and sediment yield data;
- Infrastructure and instrumentation to operate the monitoring systems;
- Availability of historic climatic, soil water content, runoff and / or sediment yield data;
- Availability of other data such as DEMs, detailed soil maps and land use maps; and
- Different geographic environments.

The sites selected for this study were the Weatherley and Zululand catchments and Kokstad hillslope. Although the selected sites might not have the highest erosion rates (see Table 3.1 for the climate erosivity, soil erodibility and slope steepness and length erosion ratings), they were the most suitable with regard to the above criteria. This is especially true for the installed instrumentation and existing infrastructure to operate the monitoring system, as this can be very expensive to set up.

Table 3.1 Erosivity of climate, erodibility of soil, slope steepness and length erosion ratings of Weatherley, Zululand and Kokstad research areas

Catchment	Climate erosivity erosion rating	Soil erodibility erosion rating	Slope steepness and length erosion rating*
Weatherley	High	Moderate to high	Moderate to high
Zululand	Very high	Very low	High to very high
Kokstad	High	Low to moderate	Moderate to high

* The qualitative descriptions for the slope steepness and length erosion ratings in the Table referred to the combined USLE slope steepness and length factor (LS) and not to either slope steepness or lengths of hillslopes.

The Kokstad research site consists of several camps to monitor the impact of sheep stocking rates on veld condition. The camps also include a system of USLE runoff plots to monitor, in addition to veld degradation, the impact of stocking rates on runoff and erosion.

At the Zululand catchment, most of the storm flow is generated through runoff from the foot slopes and valley bottoms, giving support to the variable source area concept (Mulder, 1984). This characteristic was a good test on how the selected models handle hillslope subsurface hydrology and erosion in riparian areas. A relatively new phenomenon in the catchment is that riparian areas are drained and cultivated for vegetable gardens and amadumbe. The riparian areas are the areas that are the most susceptible to erosion in the Zululand catchment landscape and it is expected that sediment yields will increase. The Zululand catchment is also spatially highly heterogeneous in terms of topography and land use. This is ideal to verify the incorporation of spatial discretisation by models.

The Weatherley catchment has the advantage that a detailed soil map was made, detailed monitoring and study of soil water tension and runoff were done, and the pristine grassland was due to be converted to forestry in 2000. Unlike Zululand, the topography of Weatherley is simple, but has a complex soil pattern and a marsh where deposition before the channel system can occur.

3.2 CATCHMENT DESCRIPTION

3.2.1 Weatherley Research Catchment

The Weatherley catchment is located in the Umzimvubu catchment in northern Eastern Cape Province on the eastern coastal escarpment of South Africa. The research catchment is located approximately 5 km south west of Maclear (31^{o} 06' 00" S, 28^{o} 20' 10" E) at an altitude of approximately 1 300 m above mean sea level and is 1.5 km^2 in extent.

The research catchment was chosen for its typical Molteno-Elliot formation hillslope profile and has been described in detail by Lorentz and Hickson (2001). A detailed hillslope and nested sub-catchment experiment has been initiated in the research catchment, representative of the soils, geology, topography and climate of the region. The hydrological experiment was designed for the long-term observation of hillslope processes prior to and following afforestation (Esprey, 1997; Lorentz and Esprey, 1998; Hickson and Lorentz, 1999).

The area has a Mean Annual Precipitation (MAP) of 740 mm and a Mean Annual A-pan Evaporation (MAE) of 1488 mm (Esprey, 1997). Average daily temperatures range from 11°C in the winter to 20 °C in the summer, with severe frost and snow falls at higher altitudes in winter (Lorentz, Pretorius, Thornton-Dibbs and Goba, 2003). A monthly summary of rainfall, evaporation and daily temperatures is presented in Figure 3.1.

The topography is strongly undulating irregular land within an area of lowlands and hills with moderate to high relief (Roberts, Hensley, Smith-Baillie and Paterson, 1996). Elevations of the catchment range from 1340 m to 1260 m AMSL at the lower weir outlet. The slopes are steep, with an average of 12% on the eastern and southern slopes where the sandstone outcrop forms a bench, and 18% on the western slope were the outcrop is not as well defined. Evidence of other sandstone layering is present elsewhere on the upper half of the hillslopes (Lorentz et al., 2003).

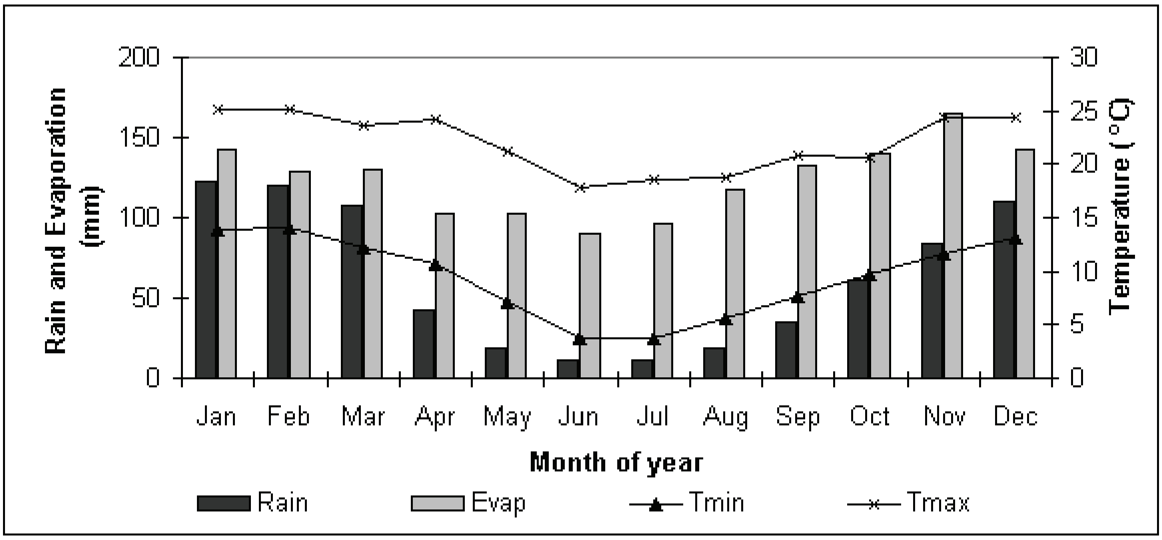

Figure 3.1. Rainfall, evaporation and temperature (minimum and maximum) data for the Weatherley catchment.

The geology of the area consists mainly of mudstone, shale and sandstone of the Molteno Formation, as well as brownish-red and grey mudstone and sandstone of the Elliott Formation, Karoo sequence. Two prominent dolerite dykes transect the area running north to south on the western side of the catchment and north-east to south-west on the eastern side of catchment (Roberts et al., 1996).

A very complex soil system exists with large spatial variation. A detailed soil survey was carried out by the Institute for Soil, Climate and Water (ISCW) and 16 different soil forms were identified within the 1.5 km^2 catchment boundary (Roberts et al., 1996). A feature of soils of the catchment is the varying degree of wetness as expressed in the soil colour. This ranges from soil mottling, thin horizons with bleached sand grains, other subsurface horizons with signs of wetness, to well-developed E and G horizons. The soils of the catchment include red to yellow apedal mesotrophic soils as well as neocutanic soils with signs of wetness together with hydromorphic soils.

The land cover at Weatherley is predominantly Highlands Sourveld grassland, which is generally in a moderate hydrological condition with a basal cover of 50-75% on the hillslopes (Esprey, 1997). The grassveld is dominated by *Themeda triandra* and *Tristachya leucothrix*. Wetland conditions exist along the entire reach of the stream and range in width from 100 to 400 m, being widest where marshy conditions are associated with lines of seepage from the hillslopes (Lorentz et al., 2003).

The instrumentation network in the catchment is extensive and has been systematically developed since 1995. Instrumentation of the catchment was described in detail by Lorentz and Hickson (2001) and Lorentz et al. (2003). The instrumentation network includes transects of automatic recording tensiometers and groundwater observation stations, and neutron probe access tubes in an upper and lower sub-catchment, each served by a crump weir. The main transect, comprising 11 stations, runs east-west, from the crest of the eastern slope in the lower sub-catchment, down into the wetland, across the stream and up the western slope. A similar transect runs west-east in the upper sub-catchment and a final transect runs from the southern slopes of the upper sub-catchment, parallel with the stream, to intersect with the main transect in the lower sub-catchment. Complete weather stations are located near the upper and lower weirs and there is an additional rain gauge on the crest of the eastern hillslope. Five surface water runoff plots (20 x 3 m) with tipping buckets were established in September 2000 on the upper and mid-slopes to supplement soil water content measurements along selected hillslopes for the verification of the model components on soil water budgeting and hillslope hydrology. As a further part of this project, an ISCO water sampler was installed at the lower crump weir on February 9th 2000. The sampler was flow related, collecting sediment concentration samples at 2400 m^3 intervals during low flows and at 4000 m^3 intervals during high intensity events. The daily suspended sediment load was calculated from the sediment concentration samples.

According to Kirkby (1998), processes affecting the soil water balance and overland flow along the hillslope are critical at the small catchment scale. Selected hillslopes were chosen where detailed data collection was carried out for soil water budgeting simulations at profiles along a hillslope. The land use, topography (slope length and height), soil horizons and position of the tensiometers for the selected hillslopes are illustrated in Figures 3.2 to 3.4. (When these figures are studied, the reader should be aware that the Y-axis indicates the height of the soil surface (m) from the lowest point of the hillslope.)

Three hillslopes were selected: hillslope 1 (Figure 3.2) and hillslope 2 (Figure 3.3) are on the western and eastern slopes respectively in the lower part of the catchment, while hillslope 3 (Figure 3.4) is on the southern slope of the upper part of the catchment. Transects of the hillslopes extend along the tensiometer nests as summarised in Table 3.2.

Table 3.2. Tensiometer nests along the hillslopes at the Weatherley catchment

HILLSLOPE	CATCHMENT	TENSIOMETER NEST	
		Top of hillslope	Bottom of hillslope
1	Lower	11	8
2a	Lower	1	4
3	Upper	8	4

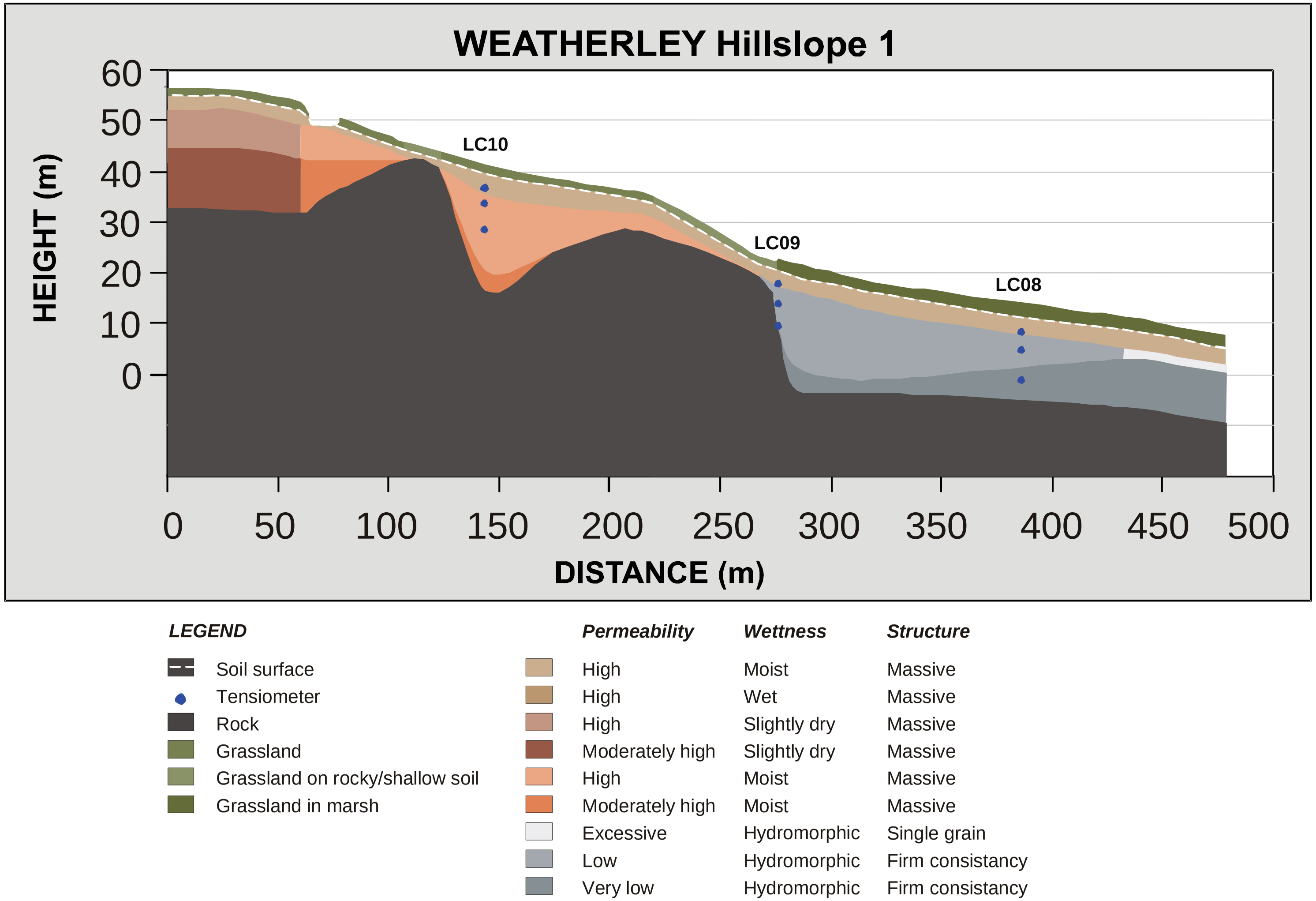

Figure 3.2. Illustration of the topography, soil and land use for Hillslope 1 at Weatherley catchment (lines are smoothed).

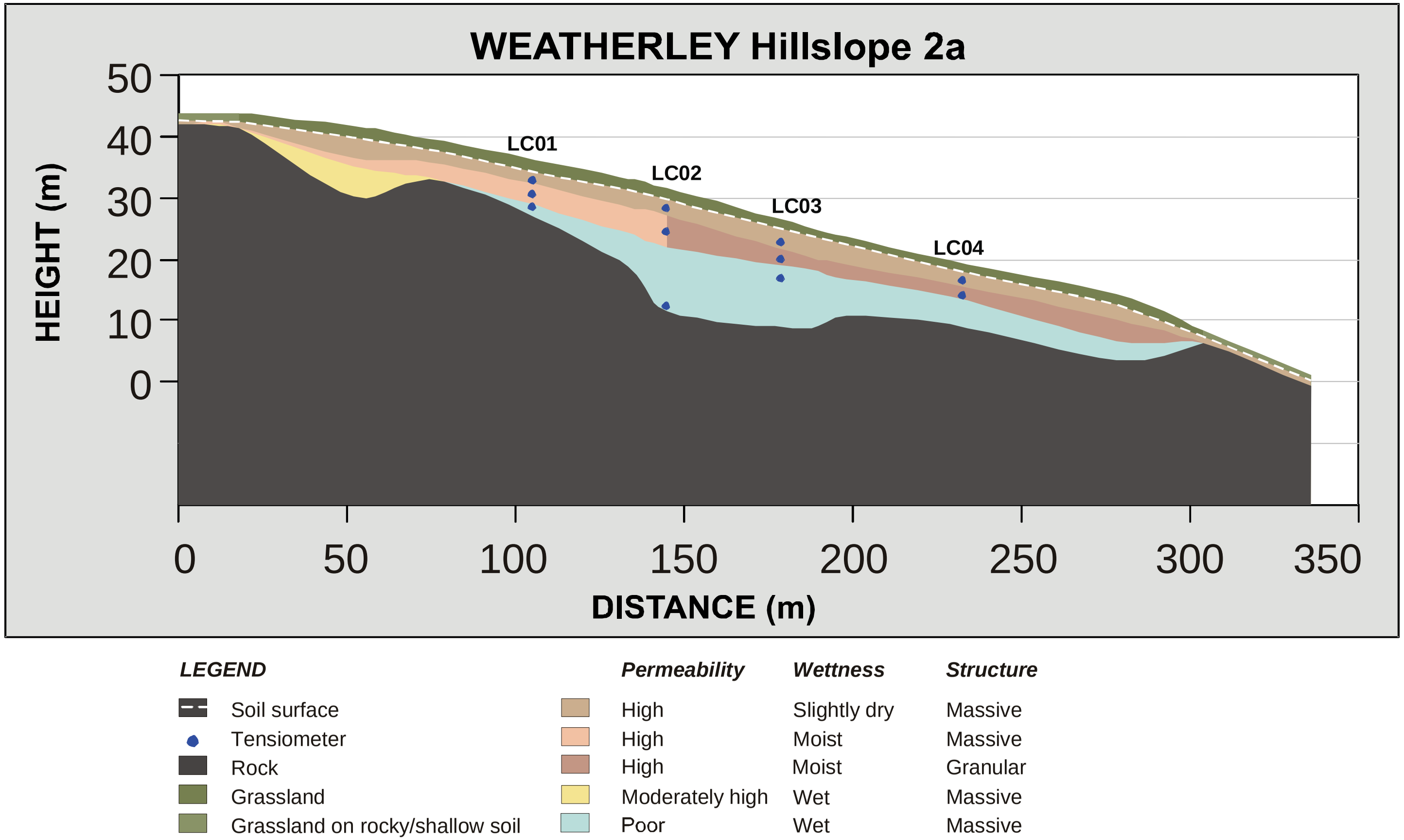

Figure 3.3. Illustration of the topography, soil and land use for Hillslope 2a at Weatherley catchment (lines are smoothed).

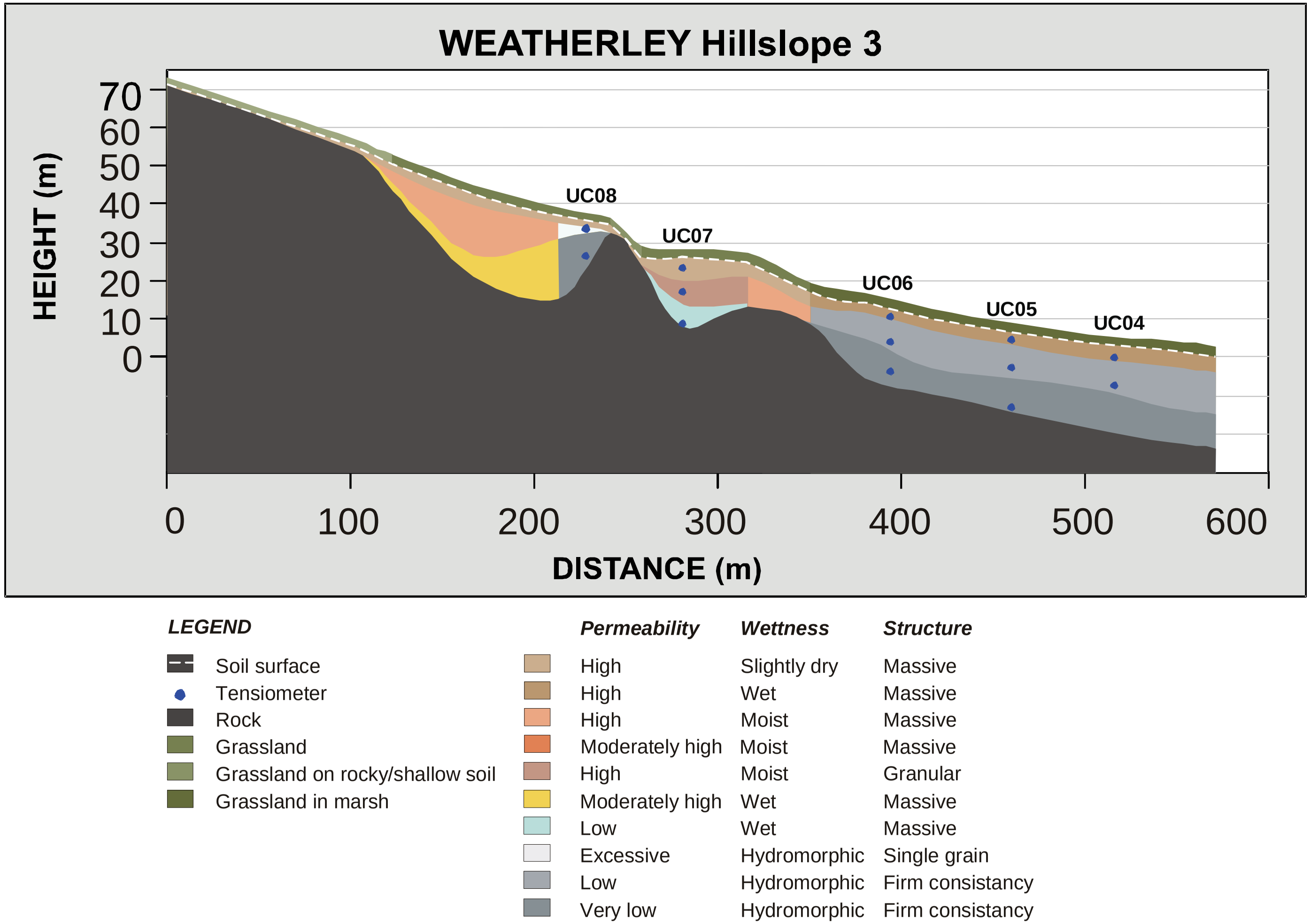

Figure 3.4. Illustration of the topography, soil and land use for Hillslope 3 at Weatherley catchment (lines are smoothed).

The topography and vegetation pattern at hillslopes 1 and 3 can broadly be grouped in the upper 60% section of the hillslope which is characterised with moderate steep (crest) to steep (midslopes) slopes. Large areas of shallow soils and bare rock are found at hillslope 3. The lower 40% of the hillslope extends into the marsh area (footslopes) with flatter slopes. The biomass production of the grass in the marsh area is higher than on the crests and midslopes. Hillslope 2a extends from the watershed to the rock outcrop on the eastern slope of the catchment which is characterized by a crest in the landscape with flat to moderate steep slopes. Large areas of shallow soils and bare rock are found at the top end of the hillslope.

The qualitative descriptions of the soil horizons; permeability, wetness and structure; were derived from the soil morphological characteristics and clay content observed during soil augering along the hillslope transects, and from saturated soil hydraulic measurements documented in Lorentz et al. (2003). The soil forms occurring at the upper section of the hillslopes are Hutton, Clovelly and Avalon. The sandy loam soils are typically characterised by slightly dry to moist soil horizons with no or few signs of wetness and a gradual transition in soil texture between the soil horizons which indicates high to moderately high permeability. The soil forms in the middle section of the hillslopes are mainly Tukulu and Longlands with moist soil horizons with few signs of wetness and a gradual transition in soil texture between the soil horizons which indicates a high to moderately high permeability. The surface soil and upper subsoil are underlain by a higher clay content soil horizon with signs of wetness which is an indication of poor permeability. The soils in the lower section of the hillslopes are of the Katspruit and Kroonstad soil forms. These soils are typically characterised by very wet soil horizons with many signs of wetness, a greyish soil matrix colour and a firm consistency in the subsoils which indicates low to very low permeability. The transition in soil texture between the surface and sub-horizons is abrupt. The Kroonstad soil form has an E-horizon between the surface and subsoil which is a light-coloured structureless horizon with a very high permeability due to the sandy horizon in which removal of colloidal matter has taken place due to lateral flow initiated above the low to very low permeable subsoil. The wetness and permeability qualitative classification of the various soil horizons was confirmed by tensiometer measurements that are discussed in section 4.1.1.1.

Ephemeral gullies are channels that develop where overland flow concentrates and result essentially from hydraulic erosion by concentrated overland flow. It is not only the characteristics of the ephemeral gullies, such as slope steepness and erodibility, that affect the sediment supply from hillslopes to the stream system, but also the condition of the surface that causes backwater effects. Plates 3.1 and 3.2 illustrate the typical ephemeral gullies occurring in the Weatherley catchment.

3.2.2 Zululand Research Catchment (W1H017)

The Zululand research catchment is located in the Ngoye hills near Empangeni and Richards Bay metropolitan area that belongs to the physiographic region of the Natal Coastal Belt. The research catchment (W1H017) is part of the nested Ntuze research catchments of the University of Zululand in the Ngoye hills.

Plate 3.1. Channel at the lower reaches of the stream at Weatherley, showing that it is open, straight and with little vegetation to cause backwater effects for potential deposition. Manning's roughness coefficient is relatively low as the channel is clean and the bed is rock. Enlargement of the channel occurs on the sides as critical shear stress (minimum shear stress of water that initiates erosion) of the rock is very high. In conclusion, the channel has a high transport capacity for sediments and high erosion rates occur at the channel sides.

Plate 3.2. Channel at the upper reaches of Weatherley which is winding and sluggish. A high Mannings roughness coefficient is caused by the dense grass favour deposition. Erosion is not very active and occurs both laterally and vertically as the erodibility of the channel bed and sides are the same. The capacity for sediment transport and channel erosion is low due to the good grass cover and high root mass.

The mean annual precipitation of the catchment is 1321 mm. Maximum daytime temperatures often exceed 40°C during the summer while winter nighttime temperatures drop to 10°C on average. The mean annual potential (A-pan) evaporation is 1750 mm. A monthly summary of rainfall, evaporation and daily temperatures is presented in Figure 3.5.

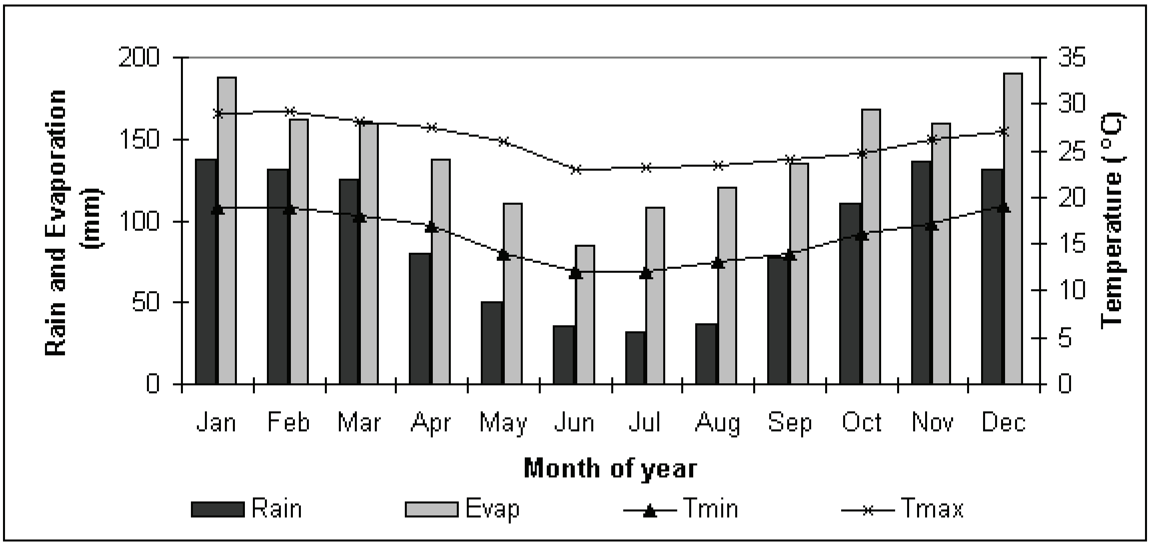

Figure 3.5. Rainfall, evaporation and temperature (minimum and maximum) data for the Zululand catchment.

The catchment forms the headwaters of the Ntuze River. The drainage area upstream of the weir at W1H017 is approximately 0.7 km^2 (70 ha). The topography is typical of the rolling Zululand coastal hills. Elevations range from 330 m in the western hills to some 258 m AMSL at the weir outlet, and slopes range between 10 and 20% (Lorentz, Rienks, Jetten, De Roo, Kelbe and Snyman, 1997).

The Ngoye hills, with typical Bornhardt structures, are underlain by the Ngoye overthrust unit (Mfongosi group). The drainage patterns that developed in the granite-gneiss are rhomboidal as a result of the characteristic parallel joint system present in the granite (Mulder, 1984). The soils in the catchment are weakly developed with mainly coarse sand clayey loam texture and high infiltration rates.

The catchment falls within a developing informal rural subsistence community that is showing a rapid increase in population density. There have been significant changes in the land use, for instance from 1988 until 1995 the sugarcane production in the catchment increased from 2% to about 16%. Other crops that are grown in small-scale vegetable gardens are beans, pumpkin, cabbage and amadumbe (taro). Stock farming in this area is generally used for commercial, subsistence and traditional purposes. The number of cattle has declined dramatically as stock farming has given way to commercial sugarcane and other cash crops. Some riparian areas have recently been drained and cropped with banana trees and amadumbe (Lorentz et al., 1997).

Two hillslopes were selected, one consisting mainly of grassland (Figure 3.6) and the other with predominantly sugarcane (Figure 3.7). (When these figures are studied, the reader should be aware that the Y-axis indicates the height of the soil surface (m) from the lowest point of the hillslope and that the soil horizon depths are 1/400 times the value of the Y-axis.) The hillslopes are characterised by steep slopes at the crests and midslopes and moderate steep slopes at the footslopes and valley bottoms. The footslopes are cultivated with vegetable gardens. The undisturbed channels have dense riparian vegetation with a high root mass causing backwater effects (Plate 3.3). However, the upper reaches of the streams have been drained and cultivated for vegetable gardens (Plate 3.4).

The qualitative descriptions of permeability, wetness and structure of the soil horizons were derived from the soil morphological characteristics and clay content observed during soil augering along the hillslope transects, and from saturated soil hydraulic measurements. The Magwa soil form occurs at the crests and midslopes. The soil is characterised by moist soil horizons with no signs of wetness and a gradual transition in texture between the soil horizons which indicates high permeability. This was confirmed by the high saturated soil hydraulic conductivities and tensiometer measurements discussed in section 4.1.1.2. The soils at the footslopes are of the Kroonstad soil form. These soils are typically characterised by very wet soil horizons with many signs of wetness, a greyish soil matrix colour and a firm consistency in the subsoils which is an indication of low to very low permeability. A very sandy (5% clay) E-horizon occurs between the surface and subsoil which is a light-coloured structureless coarse sandy horizon. The very high permeable E-horizon has developed from the removal of colloidal matter that has taken place due to lateral flow initiated above the low to very low permeable subsoil. The wetness and permeability qualitative classification of the various soil horizons were confirmed by tensiometer measurements that are discussed in section 4.1.1.2.

Soil water tension was monitored at one hillslope consisting mainly of grassland (three tensiometer nests) and one under sugarcane (four tensiometer nests). Three runoff plots (20 x 3 m) were installed next to the tensiometer nests at the hillslope consisting mainly of grassland. However, few measurements were made due to repeated vandalism of the tipping bucket switch mechanisms and loggers. Runoff and rainfall were monitored at the compound V-notch weir using an Ott chart recorder, which has been automated by installing a logger and encoder. An automatic recording tipping bucket rain gauge was installed to record rainfall at 1-minute time steps. An ISCO sampler was installed at the weir. The sampler was flow related, collecting sediment concentration samples at 1200 m^3 intervals during low flows and at 2000 m^3 intervals during high intensity events. The daily suspended sediment load was calculated from the sediment concentration samples. The dense riparian vegetation near the weir caused the deposition of sediment during small and moderate rainstorms. Therefore, it was decided to construct an additional monitoring point upstream of the

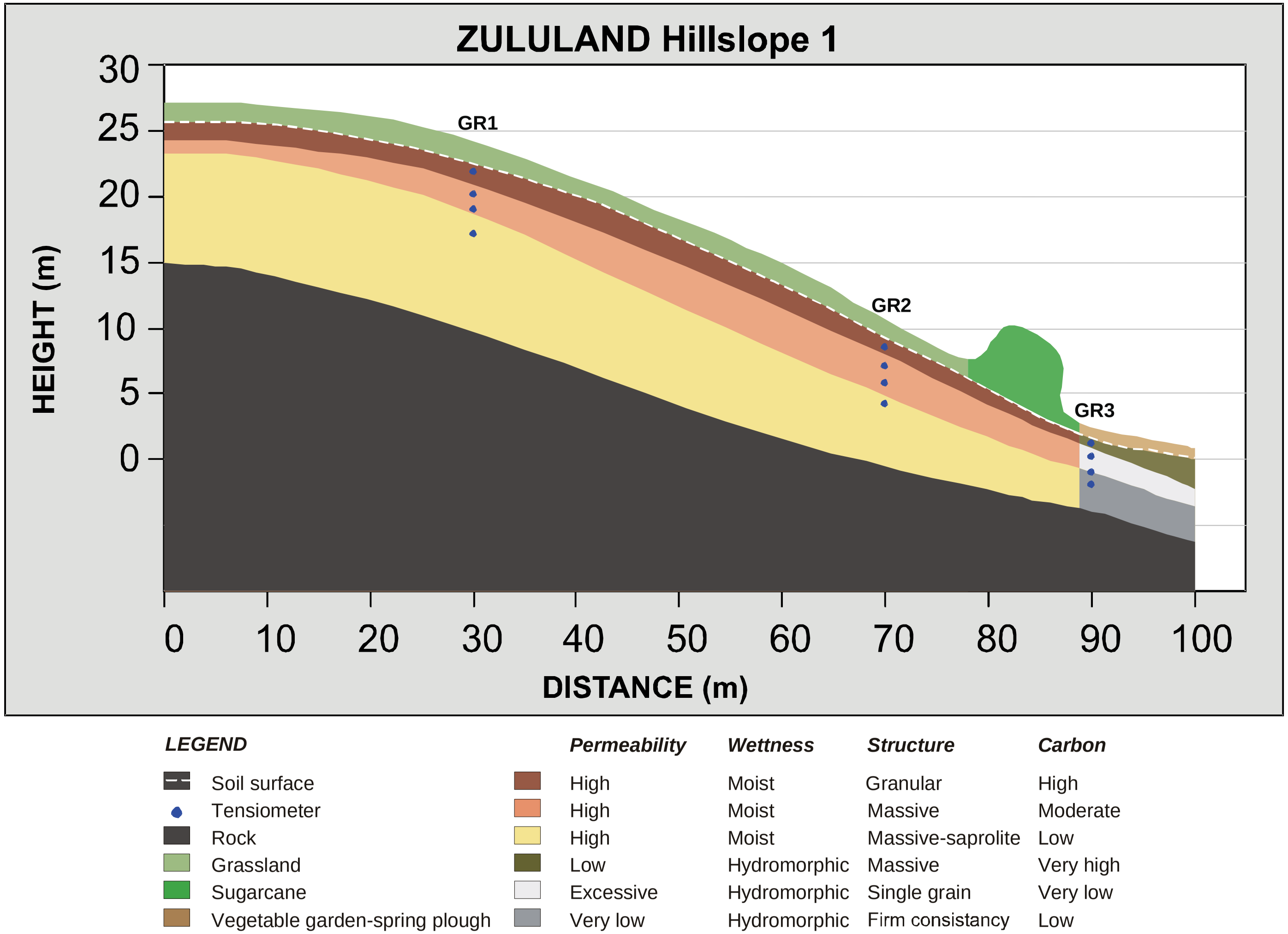

Figure 3.6. Illustration of the topography, soil and land use for Hillslope 1 at Zululand catchment (lines are smoothed).

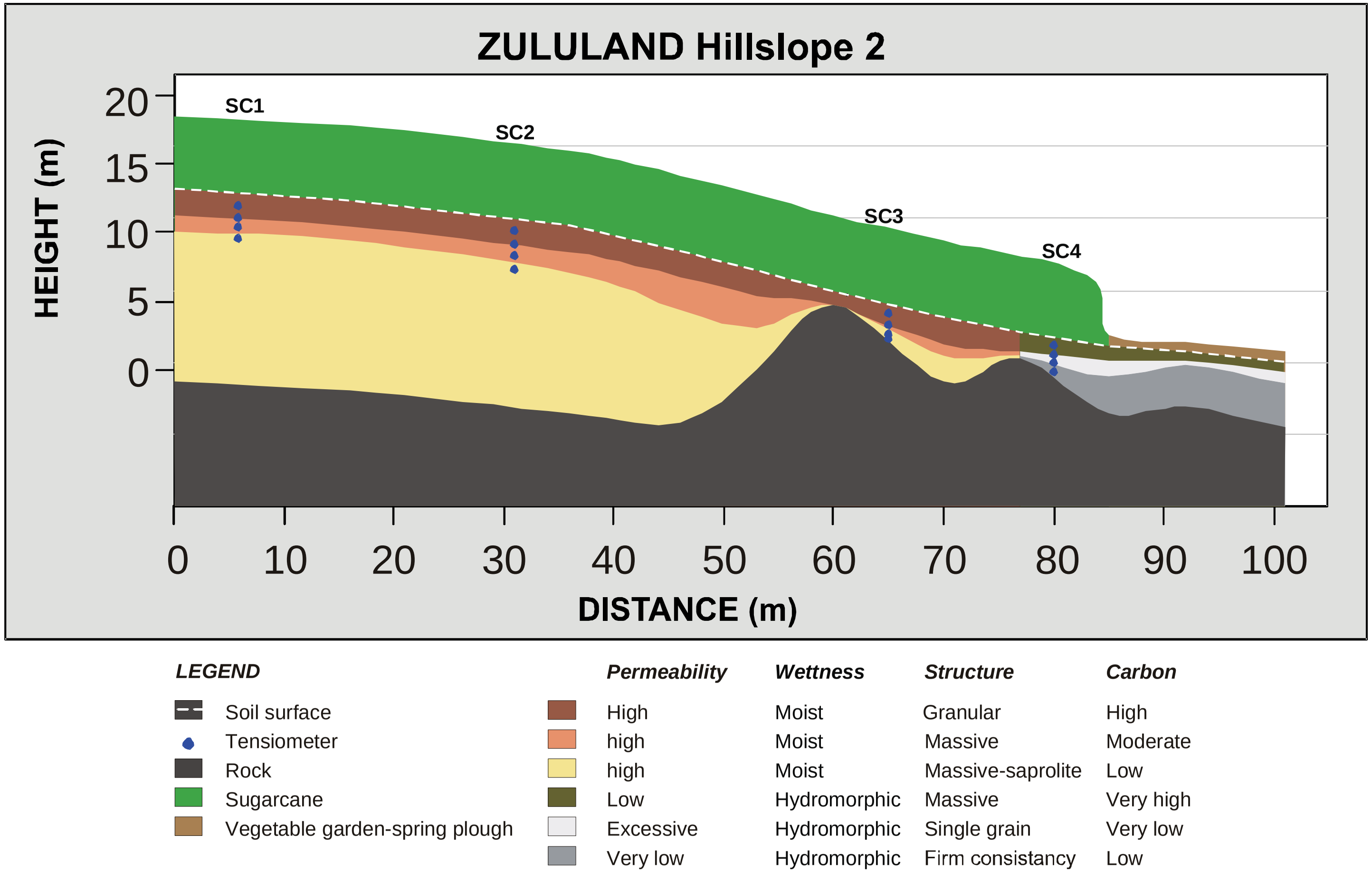

Figure 3.7. Illustration of the topography, soil and land use for Hillslope 2 at Zululand catchment (lines are smoothed).

dense riparian vegetation. This weir is a small structure with an H-flume, sump, ISCO-sampler and an encoder and logger. Suspended solids have been monitored at the H-flume since September 2001.

Plate 3.3. The very dense vegetation in this channel at the Zululand catchment causes backwater effects. The deposition potential of sediment is very high, but will decrease during high flows when the water pushes down the vegetation. Erosion is very low due to the very thick vegetation cover and high root mass.

Plate 3.4. An example where the riparian area is drained and cultivated for vegetable gardens in the upper reaches of a stream in the Zululand catchment. The immature plants do not have a good canopy cover and hence present a high potential erosion area. The ground surface cover is relatively low, which does not allow for enough protection against erosion. The fruit (bananas) in the field has a better cover (higher canopy and surface cover). Overall, this field has a high erosion potential and sediment transport capacity.

3.2.3 Kokstad Research Site

The Kokstad hillslope is located at the Kokstad Agricultural Research Station on the eastern coastal escarpment of South Africa. The research site is on the road to the Adam Kok monument (off the Underberg road), about 5 km from Kokstad.

The mean annual precipitation and potential (A-pan) evaporation are 780 and 1600 mm respectively. Most of the precipitation is summer rainfall. Average daily temperatures range from 11°C in the winter to 20°C in the summer, with severe frosts and infrequent snowfalls. A monthly summary of rainfall, evaporation and daily temperatures is presented in Figure 3.8.

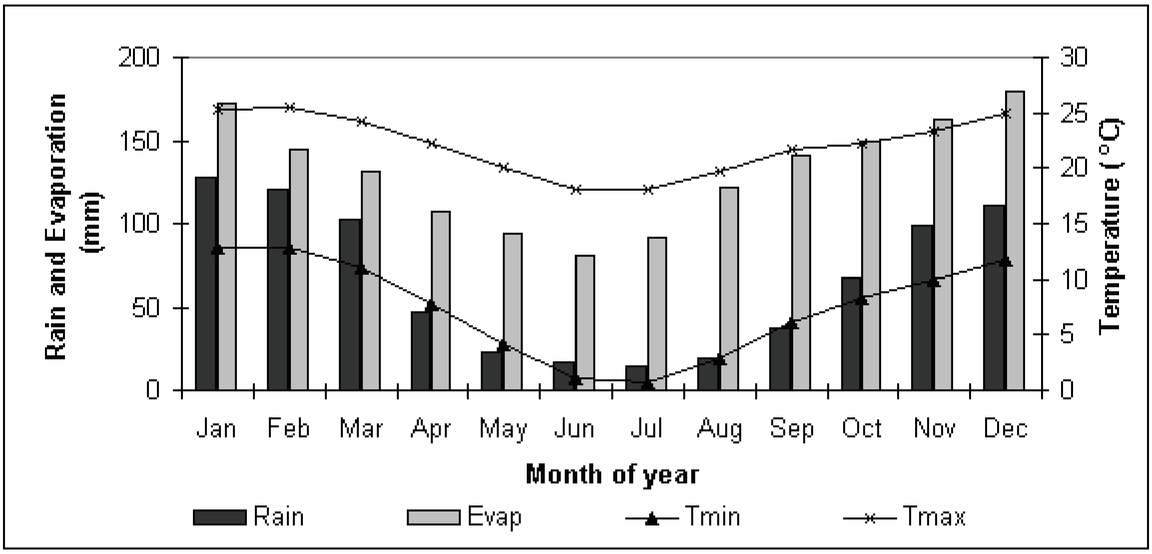

Figure 3.8. Rainfall, evaporation and temperature (minimum and maximum) data Kokstad research site.

The research site is situated on a slope ranging from 16–43%. The hillslope is part of an area where the land is undulating irregularly and consists of lowlands, hills with moderate relief and outstanding high mountains.

The geology of the area consists mainly of grey, green and brownish-red mudstone and yellow and grey fine-grained sandstone of the Adelaide Formation, Beaufort Group, with dolerite intrusions. The hillslope consists mainly (up to 80%) of red and yellow coloured apedal soils with patches of shallow rocky soils.

The research site consists of several camps to monitor the impact of sheep stocking rates on veld condition. The veld is described as Highland Sourveld. The grassveld is dominated by *Themeda triandra* and *Tristachya leucothrix*.

The hillslope at Kokstad has been instrumented with three automated tensiometer nests and three automated runoff plots located in the upper part of the slope. Manual runoff plots were located on the midslope. The runoff plots were designed to split the outflow, which is then discharged into a tipping bucket mechanism before running into a buried drum collector. Sediment samples were collected from the drum and analysed. A tipping bucket rain gauge was positioned in the upper part of the slope and automatic rainfall data was recorded.

The selected hillslope (Figure 3.9) comprises six camps under a range of sheep stocking rates. The camp system is situated on the midslope that consists mainly of well-drained slightly dry to moist red and yellow apedal soils with patches of shallow rocky soils. The upper 40% of the hillslope, which is above the camp system, is characterised by shallow rocky soils. The slopes are steep.

3.3 ASSEMBLING OF MODEL PARAMETER DATA

3.3.1 Modelling Units

Initial input data were collected for topography, soil, land cover and management, and the stream system. Data organisation for the WEPP model was done on the basis of catchment modelling units. A catchment comprises hillslope, channel and impoundment units. A hillslope is an area extending from the crest (watershed) down to the valley bottom (stream). A hillslope consists of overland flow elements (OFEs). An OFE is an area of homogeneous soil and land management. The spatial variability of soil and land management is accounted for by OFEs along the hillslope. Channels are ephemeral gullies that develop where overland flow concentrates and result essentially from hydraulic erosion by concentrated overland flow. The WEPP model allows the user to simulate many types of non-uniformities on a hillslope through the use of OFEs. The various hillslopes and OFEs in the Weatherley and Zululand research catchments were identified and delineated in the ArcView environment from a combination of the terrain unit, soil and land use maps. The number of hillslopes at Weatherley was mainly determined by the soil pattern, and at Zululand by land management.

The research version of the *ACRU* model has been developed as a module of the *ACRU* model. It therefore requires the standard input information required by the *ACRU* model input menu-builder as detailed in Smithers and Schulze (1995). The Weatherley and Zululand research catchments were simulated in a distributed mode through the use of catchment and subcatchment modelling units. The Weatherley catchment was divided into subcatchments that represent an area of macropore flow, grassland and marsh. The Zululand catchment was divided into subcatchments representing areas of the crest, midslope and footslope terrain units.

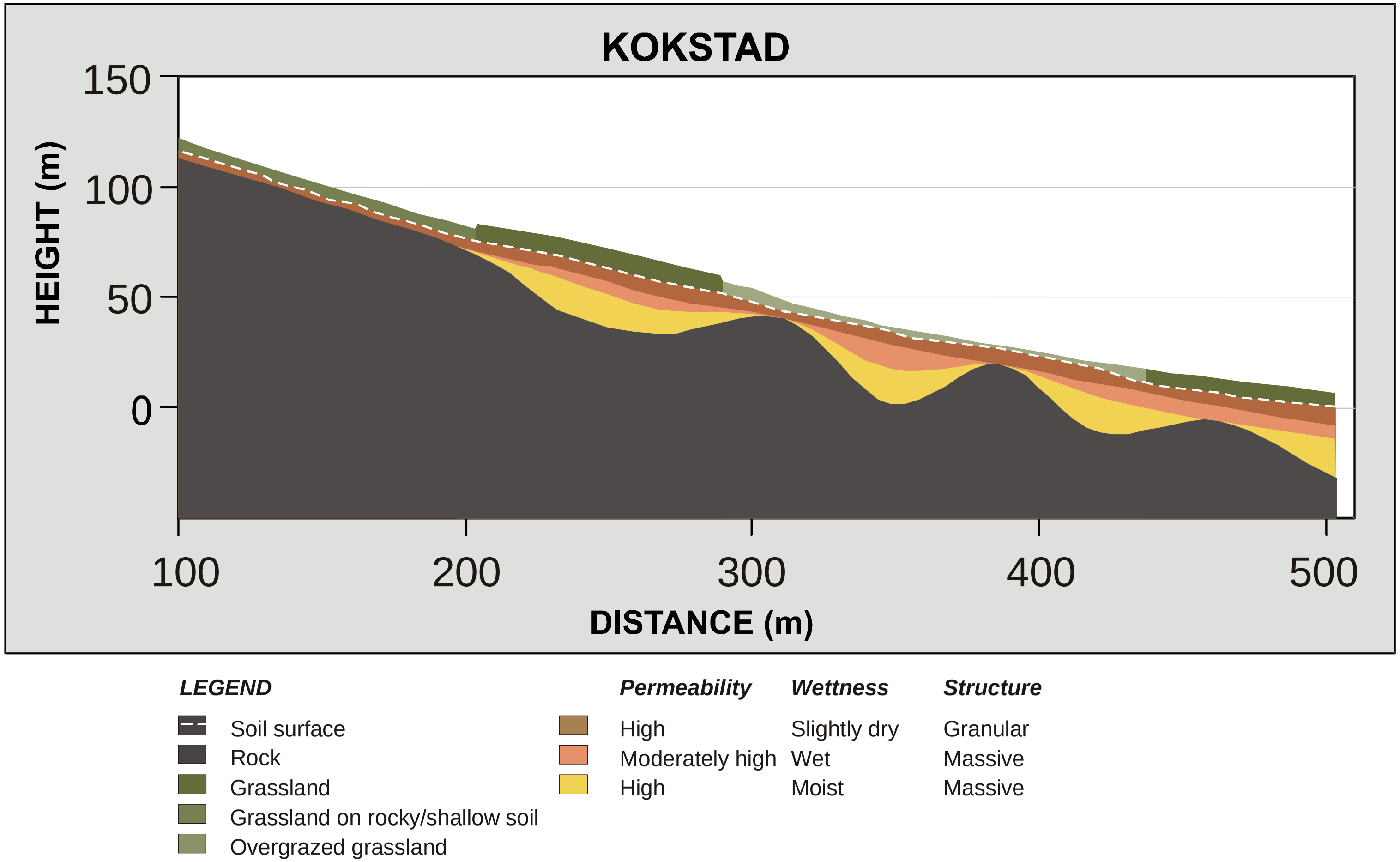

Figure 3.9. Illustration of the topography, soil and land use for the Kokstad hillslope (lines are smoothed).

3.3.2 Climate

One-minute time step rainfall data (1998-2002) for the Weatherley research catchment were supplied by the University of Natal - School of Bioresources Engineering and Environmental Hydrology (SBEEH). Except for December 2001, the rainfall record was such that no correction or patching of rainfall was necessary. For the Zululand research catchment (W1H017), rainfall OTT charts, one recorded for W017 and four neighbouring stations, were supplied by the University of Zululand – Department of Hydrology. OTT charts for all five stations were manually digitised. Extensive data checking and patching of rainfall data between the five stations (according to ranking) were done to acquire a good rainfall record for the period 1998 to 2000. SBEEH provided 1-minute time step rainfall data recorded at the weir of W017 for 2001 and 2002. This record was such that no correction or patching of rainfall was necessary. Rainfall data (1-minute time step) for the Kokstad research site was collected by the KwaZulu-Natal Department of Agriculture and then by SBEEH and was supplied by SBEEH. For the year 2000 and part of 2001 the data is not that reliable, as the MC loggers gave download errors.

The station information and weather data for Weatherley, Zululand and Kokstad research sites were downloaded from the National Agromet Databank at ISCW, as well as from the South African Sugar Association (SASA) and South African Weather Service (SAWS). Table 3.3 summarises the stations from which climate data were used (driver stations) and the stations used to check climate data of driver stations and to patch missing data.

The specific data that were downloaded for 1998-2002 included:

- Maximum temperature
- Minimum temperature
- Wind speed and direction
- Radiation / sunshine duration when radiation was not available
- Relative humidity
- Dry bulb temperature
- Wet bulb temperature

As dew point temperature was not monitored, it was derived either from relative humidity and temperature or from wet and dry bulb temperatures (see Appendix 1 for the formulas used). The radiation for Zululand was calculated from the sunshine duration at Heatonville and Mtunzini (see Appendix 1 for the formulas used).

Table 3.3. Summary of stations from which climate data were used (Driver) and stations used to check climate data of driver stations and to patch missing data (Check/Patch)

CATCHMENT	PURPOSE	INSTITUTION	NAME	NUMBER	LAT	LONG	ALT (m)
Weatherley	Driver	ISCW *	Weatherley	30193	-31.1000	28.3330	1325
	Check/Patch	ISCW	Somerton	21865	-31.0936	28.2311	1289
	Check/Patch	ISCW *	Wildebees	30087	-31.1196	28.1279	1289
	Check/Patch	ISCW	Funeray	30149	-31.3883	28.0833	1550
	Check/Patch	ISCW *	Tree Fern P	30148	-31.0401	28.1419	1174
Zululand	Driver		Zululand		-31.7550	28.8333	260
	Check/Patch	SASA	Mtunzini	0011	-31.7000	28.9330	36
	Check/Patch	SASA	Heatonville	460	-31.8000	28.7167	200
	Check/Patch	SAWS	Mtunzini	30281	-31.7000	28.9500	38
Kokstad	Driver	ISCW	Kokstad	12890	-30.5167	29.4167	1372
	Check/Patch	SAWS	Matatiele	02075310	-30.35	28.8	1490
	Check/Patch	ISCW	Beginsel	19711	-30.2833	29.0667	1463
	Check/Patch	ISCW	Fort Donald	30439	-30.68	29.55	1259

* Station owned by North East Cape Forests (NECF). Data was managed by ISCW until March 2000 but is now done by SBEEH.

Data from stations close to the Weatherley station were used to patch the missing data over the five years (Table 3.3), as long-term historical data was not available. Long-term mean ten-daily maximum (Tx) and minimum (Tn) temperature values were derived from long-term mean temperature surfaces created by ISCW and a relationship between the stations was determined by plotting these points (Appendix 1). Somerton and Weatherley's long-term mean Tx and Tn 10-daily values are very similar. Thus Somerton data was mainly used to patch the missing data at Weatherley, but even Somerton did not report data for some periods and in that case the other stations were used. When these stations were used a factor was added for the difference between the stations, which was the difference between the long-term mean 10 daily values for the two stations.

No climate data were collected at the station near the Zululand site for the years 1998-2002. Instead three stations close to the Zululand station were used to create the data for this period. These stations include Heatonville and Mtunzini (both SASA stations) and Mtunzini (a SAWS station) (Table 3.3). Again, long-term mean ten-daily Tx and Tn values were derived from long-term mean temperature surfaces and a relationship between the stations was determined by plotting these points (Appendix 1). For all these stations, factors were calculated to incorporate the difference between the stations. The station in best agreement with Zululand was used in each case.

The BreakPoint Climate Data Generator (BPCDG) program (Zeleke, Winter and Flanagan, 1999) was used to create the climate input file for the WEPP model. The following four input files were created:

1. Rainfall
2. Temperature
3. Radiation, dew point temperature and wind tables
4. Station information

The first file of the BPCDG program requires information on the rainfall storm pattern, which includes information on the amount of rainfall, and beginning and end times for the storm intensity slope breaks. Although programs were developed as part of this project in an attempt to prepare the rainfall storm file with the written programs (see Appendix 1), the only viable option was to manually plot cumulative rainfall amount (y-axis) against time (x-axis) for each rainfall event. The intensity slope breaks were identified from these plots and the rainfall amount and beginning and end times for each slope break were determined. Once the four input files were prepared for the BPCDG program, the program was run to identify any data errors. If the run was successful, an output file was produced in the correct format for the WEPP model, which was then imported into the WEPP model.

Daily values of rainfall, measured in the catchment, were input to the *ACRU* model. Monthly means of daily maximum and minimum temperatures, average monthly relative humidity, together with regionalised wind speed, were input to the *ACRU* model, where the Linacre 1977 option was invoked to derive reference potential evaporation.

3.3.3 Topography

The digital elevation model (DEM) for the Weatherley catchment, derived from a combination of air photo interpretation and *in situ* survey, was supplied by SBEEH.

In a previous WRC project, the Hydrological Research Unit of the University of Zululand produced the DEM for *inter alia* the Zululand catchment (W017). This DEM from IDRISI was obtained from the University of Zululand and translated into ArcView Spatial Analyst environment. Kelbe, Snyman and Mulder (1996) described the production and evaluation of the DEM in detail. The topographical image of the research catchment was captured through IDRISI by digitizing the 10-m contours from a 1:5000 topographical map of the Ntuze produced in 1982 by the Department of Survey and Mapping, Natal University. Several intermediate (5-m) contours, from other sources and ortho-photos, were also digitized for problematic areas in the catchment. The vector image of the topographical contours was used to create a Digital Elevation Model in IDRISI. The DEM were smoothed in IDRISI by using a weighted average of the central pixel and the eight surrounding pixels. The raster-based image was created at a spatial pixel resolution of 10 m by 10 m (0.01 ha).

Contours (1-m intervals) were generated from the DEMs for the Weatherley and Zululand catchments in an ArcView Spatial Analyst environment. The generated contours were superimposed over the delineated hillslopes. The slope length and steepness for a slope section with uniform steepness were determined and imported into the WEPP model's slope input file. The slope steepness and length were determined in the field at the Kokstad hillslope with an inclinometer and distance wheel for slope sections with similar steepness. The same method was applied at the selected hillslopes at the Weatherley (3 hillslopes) and Zululand (2 hillslopes) catchments.

Average slope steepness was calculated in an ArcView Spatial Analyst environment for each of the modelling units for the *ACRU* model. The slope length was derived internally to the *ACRU* model in a default option, which uses the slope gradient to estimate the slope length.

3.3.4 Soil

The Institute for Soil, Climate and Water (ISCW) carried out a detailed soil survey at the Weatherley research catchment (Roberts et al., 1996). Soil observations were made every 90 m on a grid system for the whole catchment area and every 30 m on a grid system of the neutron probe grid lines as well as within the upper catchment. At each auger point a soil profile description was completed. A total of 28 modal profiles were described and the soil samples analysed for various soil physical and chemical properties. The modal profile descriptions, soil analytical data, soil observations description and the soil map legend were documented by Roberts et al. (1996). The soil hydraulic characteristics were determined by SBEEH and documented by Lorentz and Hickson (2001).

As part of this project, a detailed soil survey at the Zululand research catchment was carried out by ISCW. Soil observations were made every 100 m on a grid system for the whole catchment area. Seven soil profiles were described. At each auger point a soil profile description was completed and selected soil samples analysed. Soil boundaries between freely drained soils and hydromorphic soils were determined using a soil auger, contour lines and visual aids as seen in the field. The soil hydraulic characteristics were determined by ISCW. Due to the fact that soil depth varies considerably in a soil-mapping unit of the freely drained soils, these units were further divided according to depth classes. Estimate maps of the depth of the A, B and C horizon in the Zululand catchment were generated by interpolating 64 sampling points, which exclude the hydromorphic soils, within the area using the Inverse Distance Weighting (IDW) technique in a ArcGIS Spatial Analyst environment. The depths, classified into groups, were overlaid with the soil map of the area and dissolved to form several units for each horizon map.

A detailed soil map of the veld grazing trials at the Kokstad Research Station was produced by the KwaZulu-Natal Department of Agriculture. In characterizing the Kokstad hillslope, soil samples were collected during this project at 20-m intervals along the hillslope. A representative soil sample from each soil layer was selected for soil physical and chemical analysis. The soil hydraulic characteristics were determined by SBEEH.

Soil information from the soil unit maps, modal profiles and soil observations were used to parameterise the soil input file of the WEPP model for each OFE. An option was used to have the WEPP model calculate the interrill and rill erodibility and critical shear based on other soil input parameters, as data collection of these parameters would be too expensive. The soil input parameters for generating the hydrology in the *ACRU* model were determined from soil hydraulic characteristics, while the soil erodibility parameter was calculated from a relationship similar to the K-nomograph of Wischmeier, Johnson and Cross (1971) but modified for use in the *ACRU* model. Where the K-factor is soil moisture dependent, an upper and lower limit were input to the *ACRU* model.

3.3.5 Land Management

A land use map for Weatherley was not produced as the catchment is presently under grassland. The main differences in canopy and ground cover and biomass production are mostly between the steep areas (crests and midslopes) with freely-drained soils and the marsh area (footslopes) with hydromorphic soils. Differences in plant model input parameters were accounted for in the models according to terrain and soil, with higher canopy and ground cover and biomass production in the hydromorphic soils along the footslopes and valley bottoms.

Three land use maps are presented in Lorentz et al. (1997) for the years 1991, 1993 and 1995 for the Zululand research catchment. These maps show the increasing enlargement of sugarcane and eucalypt plantations. During fieldwork at the Zululand catchment it was observed that some changes in land use occurred since 1995 when the last aerial photo was taken of this area. It was decided that a land use map would be produced from digital multispectral images (0.5 X 0.5 m resolution) that are taken from an airborne platform. As the condition of the sugarcane fields differs in the catchment due to different levels of management, and thus also input data on soil cover for the models, it was decided to take multispectral images late in the year when the sugarcane was more mature.

A detailed land management map (1:3000) was obtained from the KwaZulu-Natal Department of Agriculture on the two-camp veld grazing system at the Kokstad research site.

The WEPP plant growth model accounts for water and temperature stresses on biomass production and was designed so that parameters (described in Appendix 2) may be adjusted for each different plant, variations within plant varieties and for various management practices such as conserved area, burning, grazing, herbicide application, cultivation, planting and harvesting. Difficulties were experienced with the collection of information required to parameterise plant and land management for South African conditions. A number of pasture and crop scientists were contacted via e-mails, telephonic conversations and individual visits in order to obtain information on the plant parameters for the specific areas of the research sites (see Appendix 2 for consultation details). In addition, extensive literature searches and studies were conducted, including the Crop Parameter Intelligent Database System (CPIDS). Data on selected plant parameters were also collected at the experimental sites during August (start of growing season) and March–April (end of growing season).

The prepared climatic, topographic and soil input files for the selected hillslopes at Weatherley (3), Zululand (2) and Kokstad (1), were thoroughly examined to ensure that the model input data were correct and accurate before the plant-management input files were prepared. This task was necessary for the reason that the plant-management input files require a number of parameters of which most are not readily available. These files were constructed by using an existing rangeland / cropland default file in the database with comparable rainfall and temperatures to the sites that are being studied. Model builders have been consulted to help prepare a suitable file for the database by supplying specific descriptions of the research sites by e-mail. A sensitivity analysis was conducted on one of the hillslopes at the Weatherley catchment to rate the plant parameters according to their impact on model outputs. Much emphasis was focused on the accuracy of the parameters for which the model outputs are sensitive.

Once the plant-management files were prepared, the plant growth was simulated with the May 1999 WEPP model version. However, some difficulty with this version was experienced during the simulations for rangeland conditions. The model developers were notified of these problems and recommended that the April 2001 WEPP model version should be used where these problems in the model have been corrected. However, the rangeland input files of the April 2001 Windows Interface have been changed to cropland plant growth routines, causing the files for cropland management to differ considerably from the files for rangeland conditions prepared in the May 1999 Windows Interface. Dr John Laflen, from the National Soil Erosion Research Laboratory, gave some guidance and other supporting information in preparing newly constructed plant-management files from those prepared with the 1999 model version. Dr Laflen has been working on parameterizing rangeland scenarios using the cropland parameters.

The model output of plant growth was viewed to examine how reasonable the growth was in terms of plant canopy development, biomass production, growth initiation and plant senescence. Simulations have been interactively conducted to alter parameter values until satisfactory growth initiation, plant senescence, biomass production, canopy development and residue production were obtained for the specific hillslopes. It was important that the predicted plant growth be acceptable before the soil water contents could be predicted and verified.

In the *ACRU* model, the vegetation parameters controlling the water balance include average monthly crop coefficients, leaf area, plant canopy interception loss and effective rooting depth. In the Weatherley catchment, these parameters were specified as default options available in the *ACRU* model for veld in fair condition. In the Zululand catchment, the parameters were calculated for the subsistence cropping and the sugarcane from the tabled values in the *ACRU* model manual.

Average monthly cover factors, C-factors, controlling erosion loss, were calculated from canopy cover, canopy height, surface vegetation and mulch cover and surface roughness data collected during field work. These factors were estimated for maximum growth periods and for periods immediately after veld burning in the Weatherley catchment. The vegetation recovers rapidly after burning, so the C-factors were elevated for September and slightly for October only.

3.3.6 Stream Channel System

Various measurements were made of the channels for input data for the WEPP model's channel component. These measurements include *inter alia* channel geometry, roughness and characteristics of the erodible layers in the channel.

3.4 DATA SETS

The collection of detailed time series data, for model verification and as model input data; and soils, topography, land cover, land use and stream channel information for model input parameters, was time consuming and costly. Therefore, it is important that the data sets that were produced from the time series data monitoring, maps, surveys, fieldwork and consultation during the project are stored safely and are easily accessible. The time series data monitored during this project was captured and housed in a relational database system that has been developed by the School of Bioresources Engineering and Environmental Hydrology using Microsoft Access as the database management system and standard Structured Query Language. The database management system is described in Lorentz and Hickson (2001) and Lorentz et al. (2003). Soil surveys, DEMs, aerial photographs and land use maps of the study sites are kept at both ISCW and SBEEH in the form of GIS coverages and reports. The WEPP model input data are housed at ISCW as field forms (hard copy and in digital format) and model input data files, while the model menu-builder files for the *ACRU* model are kept at SBEEH.

CHAPTER 4
MODEL VERIFICATION

The verification of the soil water budgeting, runoff and sediment yield components of the WEPP model and the research version of the *ACRU* model against observed soil water contents at selected points in the catchments, and runoff and sediment discharged at the catchment outlets, relates to the first objective. The verified models will give an indication of the limitations and the degree of confidence with which the off-site impacts of agricultural practices and erosion control measures can be predicted with the WEPP model and the research version of the *ACRU* model. Sound sediment yield predictions are dependent on sound runoff predictions, which in turn are reliant on good hillslope and catchment hydrological predictions. The focus of the study was on the verification of the models rather than the description of the catchment processes. Consequently, this study draws on catchment processes described in other WRC studies, most notably the work done by Dr Lorentz and his team at the University of Natal and the Hydrological Research Unit at the University of Zululand.

4.1 SOIL WATER BUDGETING AND RUNOFF

The study of hillslope flow path mechanisms is a vital component of hydrology, erosion and sediment yield at the hillslope to small catchment scale. Mechanisms of rapid and slow responses at the hillslope scale affect the magnitude of sediment delivery from hillslopes to the stream system, as well as the magnitude of storm flow peaks and sediment yield at the small catchment scale. Mechanisms of lateral flow, accumulation, redistribution and residence times of water on the hillslope will influence the nature, location and magnitude that land use practices will have on the hydrology, erosion and sediment yield. Conversely, changes in land use practices may affect all these hillslope mechanisms. The dominant flow generation mechanisms on the selected hillslopes have been identified and described from the examination of subsurface soil moisture sensor signals, rainfall and runoff data in studies by *inter alia* Lorentz et al. (2003), Lorentz and Hickson (2001) and Kelbe, Mulder, Bodenstein, Hatting and Verwey (1992). The mechanisms are summarised from these studies at the Weatherley and Zululand research catchments.

4.1.1 Typical Hydrological Processes

4.1.1.1 WEATHERLEY RESEARCH CATCHMENT

Streamflow generation mechanisms have been described in a number of studies throughout the development of the Weatherley catchment (Esprey, 1997; Lorentz and Esprey, 1998; Hickson and Lorentz, 1999; Lorentz and Hickson, 2001). A study of tensiometer responses along the main transect from nest 1 to nest 10 in the lower catchment reveals the dominant mechanisms of streamflow generation. The descriptions have been generalised and are illustrated in Figure 4.1 and described in Table 4.1.

A comparison of soil water fluxes is summarised for an upslope position, nest 1, and one at the toe, nest 4, of Hillslope 2a (see Figure 3.3). At nest 1, during the wet season the soil profile responds rapidly to rainfall events and remains close to saturation for much of the record. There is evidence of a near-surface perched water table in the macropore zone, either after intense events or when the near-surface layers have a high antecedent moisture content or low antecedent capillary pressure head. During the dry season the capillary pressure head near the surface increases continuously in response to evapotranspiration demands. The lower layers in the profile are unsaturated and it is likely that all downslope accumulation of water from this location has ceased. At the toe of Hillslope 2a (nest 4), during the wet season, upslope lateral flow accumulates after a significant rainfall event and ponded water prevails in the profile thereafter. Subsequent rainfall events serve only to replenish the depth of ponding periodically. During the dry season, the soil profile remains unsaturated. However, the profile is not as dry during this period as it is in the soil profile near the crest of the slope at nest 1. This reflects a continuous accumulation of soil water to the base of the slope section throughout the year. This could occur either by lateral movement of unsaturated water or the saturated accumulation of a shallow perched layer at the soil-bedrock interface.

The soil water fluxes for an upslope position, nest 10, and one at the toe, nest 8, of Hillslope 1 (see Figure 3.2) were also compared. At nest 10, no perched water tables and no groundwater on soil/bedrock interface are evident during the wet season. Little macropore discharge in the near-surface layers occurs, even during intense events. Significant wetting to deep horizons does take place with unsaturated redistribution of soil water to bedrock. A slow delivery of unsaturated water to the lower slopes also occurs. During the dry season the capillary pressure head increases in response to evapotranspiration demands. At nest 8 at the toe of Hillslope 1, the profile is recharged from the upslope zone and a rise in groundwater levels occurs due to water infiltrating during the wet season. Some flow in near-surface macropores does occur, but it is normally associated with the resident groundwater rising into the macropore layers. There is generally soil matric pressure continuity between upper and lower layers.

A series of ranked data, comparing nest 1, near the crest of the eastern hillslope (Hillslope 2a), with nest 4 at the toe of the hillslope section, is presented in Figure 4.2. A comparison using the data set of November 1999 to March 2002 indicates that the deeper part of the profile (700 mm) at nest 4 is predominantly wetter than the 800 mm depth at nest 1, confirming that the accumulation of water at the toe of the slope is a dominant feature of the hillslope water fluxes. The 700 mm level at nest 4 is ponded almost 60% of the time, while the 800 mm level at nest 1 is saturated for only 35% of the period. The profile at nest 1 exhibits dry conditions (> 2000 mm / 20 kPa), for longer periods than even the near surface (250 mm depth) at nest 4.

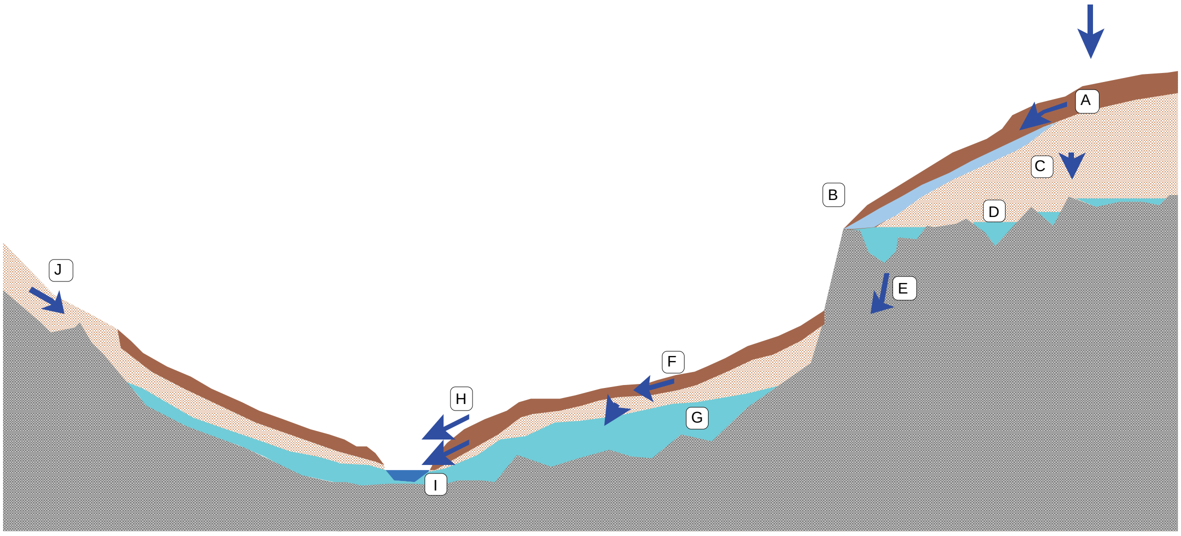

Figure 4.1. Schematic diagram of dominant flow processes and flow pathway zones at the Weatherley catchment (depths of the soil profiles are exaggerated 4x the vertical scale) (after Lorentz and Hickson, 2001).

Table 4.1. Summary of flow mechanisms and their occurrence at Weatherley research catchment (after Lorentz and Hickson, 2001)

CODE	DESCRIPTION	OCCURRENCE
A	Rapid lateral flow near the surface due to macropore conductance. Local perched water table of short duration. Matric pressure head discontinuity with deeper perched water table, D.	In upper slope segments in downstream catchment during high intensity events and some low intensity events with large volumes (>30 mm).
B	Accumulation at the toe of the slope segment with emergence and flow over bedrock.	In upper slope segments in downstream catchment.
C	Slow percolation to water tables perched on bedrock.	In all slope segments for most events except low intensity and volume.
D	Water tables perched on bedrock and in bedrock hollows.	Disconnected from soil water in upper slopes of eastern side of downstream catchment, but connected in lower slopes and in upstream catchment during moderate to intense events.
E	Seepage of groundwater through fractured bedrock.	Assumed to occur in all slope segments.
F	Rapid macropore, lateral flow in flatter marsh slopes and infiltration to marsh groundwater.	Vertical recharge is more rapid than lateral movement in lower slopes of downstream catchment and in upstream catchment, except when groundwater rises into macropore layers.
G	Marsh groundwater level fluctuation.	Rapid for most events in lower downstream catchment. Slower, but connected in upper catchment.
H	Exfiltration, surface runoff and macropore discharge to stream.	In downstream catchment. Exfiltration not observed in upstream catchment.
I	Groundwater discharge into stream.	Occurs in upstream and downstream catchments. Some near stream groundwater ridging during intense events.
J	Unsaturated redistribution of soil water to bedrock. No groundwater on soil/bedrock interface.	In upper parts of western slope. Generates slowly to soil/bedrock water table downslope.

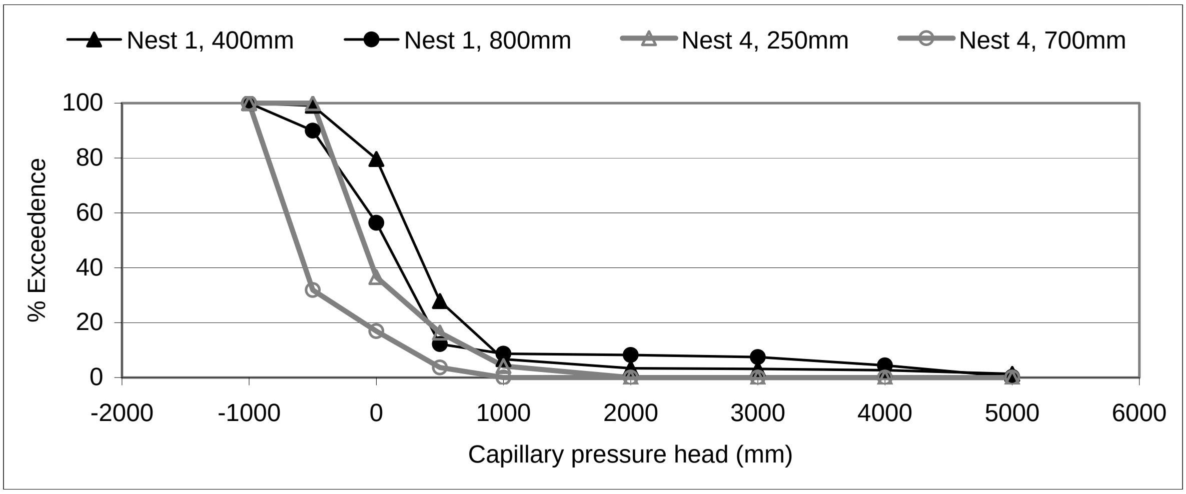

Figure 4.2. Comparison of ranked soil capillary pressure head between nest 1 on the crest and nest 4 at the toe of Hillslope 2a for the record from November 1999 to March 2002 (after Lorentz et al., 2003).

Similar ranked capillary pressure head data for the same monitored period are shown for nest 8 (riparian) and nest 10 (upper midslope) on Hillslope 1 on the western slope of the lower catchment in Figure 4.3. The riparian zone at the foot of the steep western hillslope is very wet, with the 700 mm level inundated 70% of the time and the 350 mm level 60% of the time. In stark contrast the midslope soil profile at nest 10 is practically never saturated at the 400 and 700 mm depths (Figure 4.3).

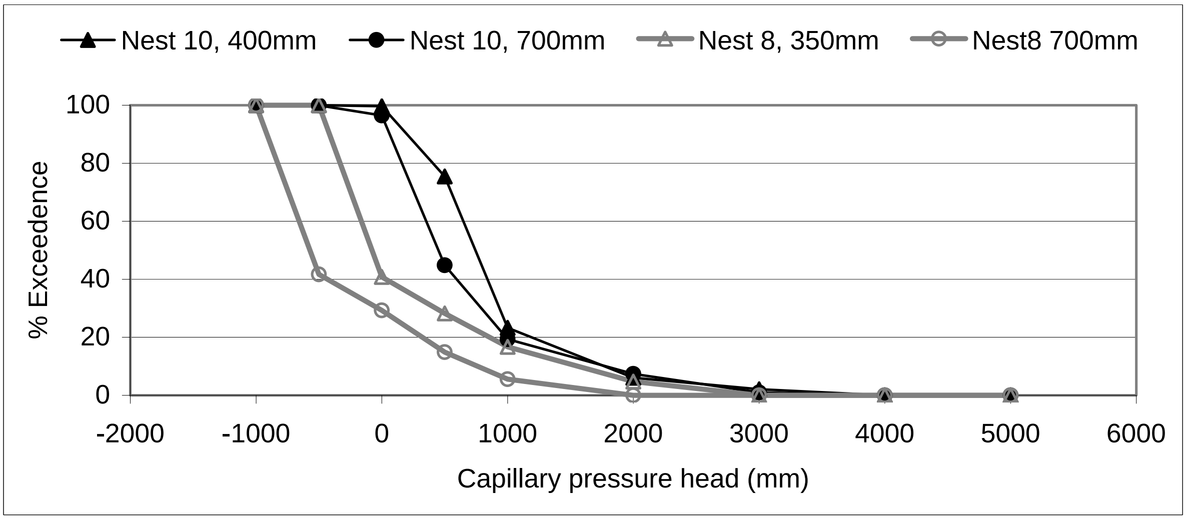

Figure 4.3. Comparison of ranked soil capillary pressure head between nest 10 on the upper midslope and nest 8 at the toe of Hillslope 1 for the record from November 1999 to March 2002 (after Lorentz et al., 2003).

The comparison of ranked soil capillary pressure head between nest 1 and nest 4, as well as the comparison between nest 10 and nest 8, confirm the general mechanisms described above and give an indication of the duration of the wetting phenomena leading to the mechanisms described.

Upscaling from the plot and hillslope processes described above to the catchment scale is illustrated by two events: a first intense event on 17 March 2001, and a second and much longer event recorded from 8-14 April 2001. In the first 12-hour event, some 23 mm of rain fell within an hour. The runoff plots at nest 2 on Hillslope 2a and nest 10 on Hillslope 1 responded immediately, while the runoff plot at nest 5 in the marsh area in the lower catchment appears to have a lagged response of half an hour, an intense response compared to the other plots, yielding 120 *l*, before its hinge mechanism failed (see Figure 3.2 for layout of runoff plots and tensiometer nests). It is clear that surface runoff ceases some 3 hours before the peak runoff is recorded at the weir. The receding limb of the hydrograph continues for another 9 hours beyond the peak. Near-surface soils wet up rapidly at the crest of the catchment at nest 1 (Hillslope 2a). However, there is little response in the deeper horizon and no effect on the groundwater during the 12-hour duration of the runoff event. On the other side of the valley, at nest 10, the near surface soils do not wet up as rapidly as at nest 1 and the deeper horizons do not indicate the arrival of a significant wetting front besides some moderate decreases in tension 8 hours after the start of the event. The groundwater response at nest 10 is dramatic, with the pressure transducers indicating a rapid rise in the observation well, a subsequent rapid decline after the first rain and then a shorter rise after an additional amount of rain just prior to 7 pm. This rapid and significant fluctuation of the water in the observation well is not substantiated by similar behaviour in the tensiometers. This seems to suggest that the observation wells, slotted from the bedrock interface to the surface, are receiving a rapid supply of water from the surface or macropores.

During the second and much longer event recorded from 8-14 April 2001, the runoff plots did not respond at all to 8.4 mm on 8 April but responded rapidly to 32 mm on 10 April. Again, the surface runoff ceased with the rain, but the yield of water to the stream continued to increase for at least half an hour after cessation of the rainfall and the surface runoff. The response of near-surface soils is, again, rapid. However, the deeper horizons are also affected and water reaches the observation well at nest 1, causing a rise in the water table. The dramatic behaviour of the groundwater is evident again at nest 10. These two events illustrate the wealth of data being assembled for the verification of models required in sediment yield analysis.

4.1.1.2 ZULULAND RESEARCH CATCHMENT

The dominant mechanisms of streamflow generation at the Zululand research catchment were revealed by a study of tensiometer responses along two hillslopes, one consisting mainly of grassland (see Figure 3.6) and one under sugarcane (see Figure 3.7). Analyses of the tensiometer responses showed that the hillslopes under grass and sugarcane respond in a similar fashion. A tensiometer response sequence for the sugarcane hillslope (Hillslope 2) and the streamflow generation mechanisms is summarised. The tensiometer responses have been summarised in the general behaviour of the Zululand cane field hillslope illustrated in Figure 4.4 and described in Table 4.2.

On the crest (top) of the hillslope (nest 1) the soil profile is deep (some 5 m) and well drained. Although the response to all rainfall events is rapid, there is no evidence of water being perched in the upper layers. The upper tensiometer at 330 mm depth responds rapidly to rainfall, but does not reach saturation or ponded conditions, indicating an unsaturated wetting front. The response at 1000 mm is slower, but becomes progressively wetter with each event, reaching saturated conditions for short periods after a rainfall event when antecedent moisture content is high. Some saturated lateral flow could occur for short periods after these events.

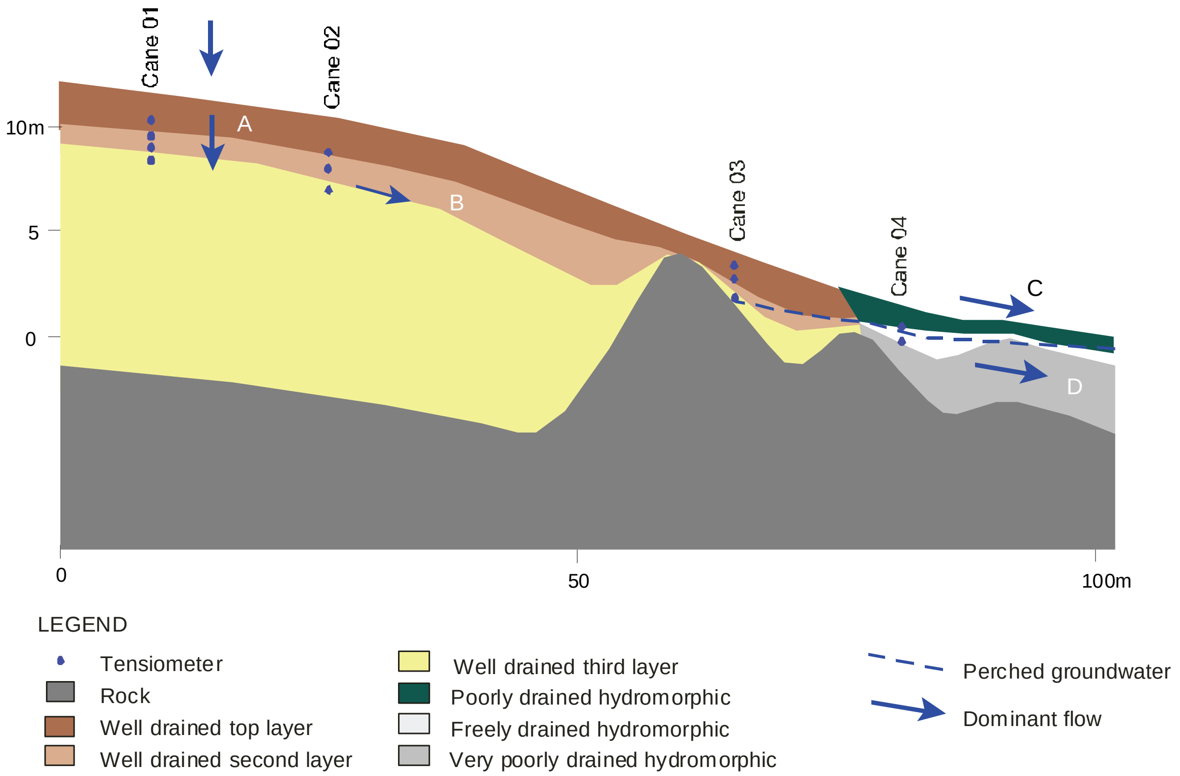

Figure 4.4. Cross section of the hillslope at the cane site, showing the soil profile, tensiometer locations and directions of dominant flow at the Zululand catchment.

Table 4.2. Summary of streamflow generation mechanisms and their occurrence at the Zululand research catchment (after Lorentz et al., 2003).

CODE	DESCRIPTION	OCCURRENCE
A	Rapid infiltration into freely drained profile.	In upper section of the hillslope in deep soil profile of well drained soils.
B	Saturated lateral subsurface flow.	In upper section of the hillslope in deep soil profile during intense events with high antecedent moisture content.
C	Saturated overland flow.	In lower, flatter hillslopes during high intensity events with high antecedent moisture content.
D	Perched water table from upslope flow accumulation.	Progressive accumulation during a series of rainfall events. Ponded depth decreases rapidly between events.

In the upper midslope at nest 2, the soil profile is still deep and the soil capillary head response to rainfall is very similar to that at nest 1. At the toe of the slope (nest 4), the hillslope profile is flatter and the soils are poorly drained. Here water accumulates so that ponded conditions are evident at about 500 mm below the surface at the start of the rainy season. Further rain then causes the ponding to rise to 350 mm below the surface. It is clear that these conditions would give rise to rapid saturation excess overland flow (surface flow occurs because the soil at the surface is saturated) in this part of the slope provided the antecedent moisture content is high (Lorentz et al., 2003). Studies by Mulder (1984) on similar hillslopes and soils with grass cover on a runoff plot at the University of Zululand have shown that there is little or no significant surface flow on the crests and midslopes due to the very high infiltration rates. Nearly all the storm flow component from these plots was derived from surface runoff associated with bottom land (footslopes and valley bottoms) variable source areas.

A comparison of ranked soil capillary pressure head between nest 1 at the upper midslope and nest 3 at the toe of Hillslope 1 (see Figure 3.6), consisting mainly of grassland, for the record May 2000 to March 2002, is presented in Figure 4.5. Similar ranked capillary pressure head data for the same period is shown for nest 2 at the upper midslope and nest 4 at the toe of Hillslope 2 (see Figure 3.7) under sugarcane in Figure 4.6.

Analyses of the ranked data illustrate similar trends in capillary pressure head for the two hillslopes, indicating that the soil horizons at the toe of the hillslopes are for the most part wetter than those at their crests, confirming that the accumulation of water at the toe of the slope is a dominant feature of the hillslope water fluxes. The subsurface soil horizons are also saturated for longer periods than the surface horizons.

On the crest and upper midslopes of the hillslopes, soil tension does not reach saturation or ponded conditions (negative capillary pressure head <2% of period), indicating a well-drained soil profile and unsaturated wetting conditions. On the other hand, at the toe of the hillslopes where the slope is flatter and the soils are poorly drained, ponded conditions are evident due to water accumulation, especially in the subsurface soil horizon. The 300 and 800 mm levels at nest 3 of Hillslope 1 are ponded almost 23% and 71% of the time respectively, while the 300 and 500 mm levels at nest 4 of Hillslope 2 are saturated for 23% and 61% of the period. These conditions would give rise to rapid saturation excess overland flow in this part of the hillslope, provided the antecedent moisture content is high.

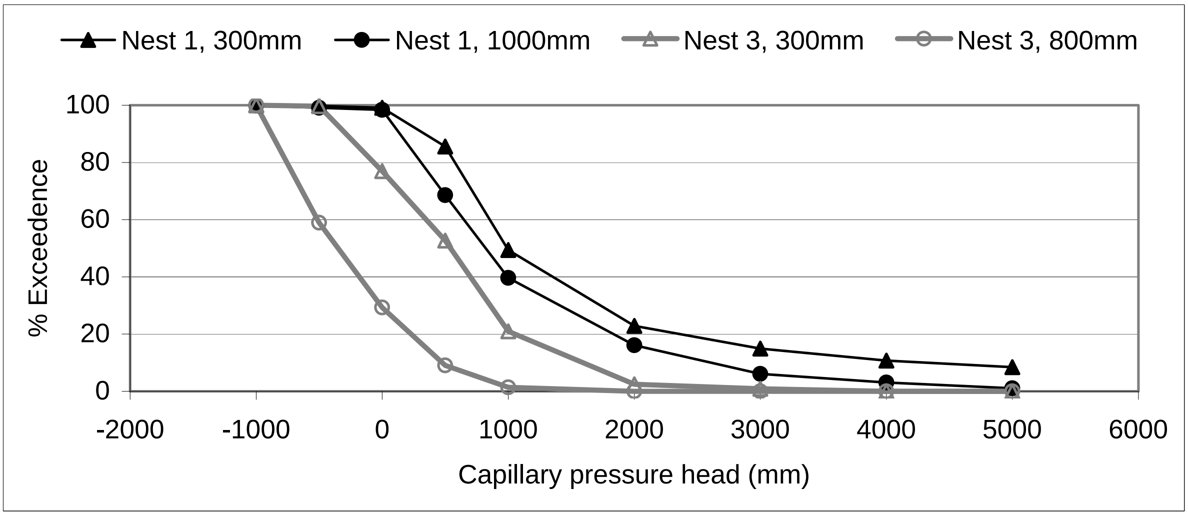

Figure 4.5. Comparison of ranked soil capillary pressure head between nest 1 on the upper midslope and nest 3 at the toe of Hillslope 1 for the record May 2000 to March 2002.

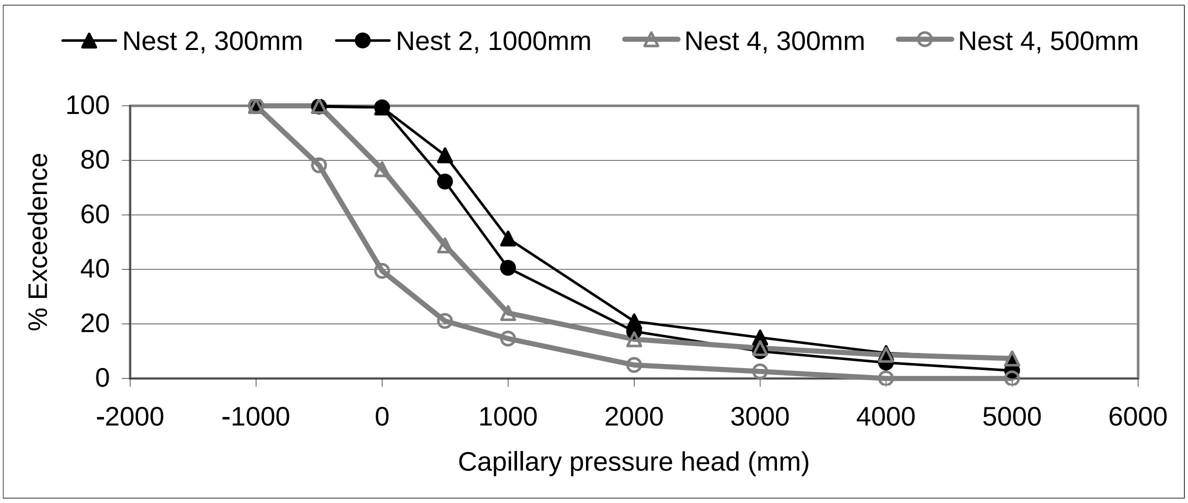

Figure 4.6. Comparison of ranked soil capillary pressure head between nest 2 on the upper midslope and nest 4 at the toe of Hillslope 2 for the record May 2000 to March 2002.

According to Mulder and Kelbe (1992), the storm hydrograph at the W017 weir usually comprises three components, namely surface flow, interflow and baseflow, with each component having a characteristic recession value. The peak flow and runoff occurring during the day of the event could most often be related to the surface runoff from the footslopes and valley bottoms plus some portion of the percolation from the deep water storage on the crests and midslopes. This initial runoff is followed by the recession curve that begins a long time after the peak when it is obvious that only baseflow is contributing to the discharge. The baseflow component of discharge cannot be compared directly with the predicted daily runoff as all of the percolation is considered to be deep storage which will drain out over time.

4.1.2 WEPP model

The main variables affecting water erosion are precipitation and surface runoff. Accurate surface runoff predictions are important, as it is the primary input to the erosion component that drives the transport of soil detached by raindrops, detachment of soil by concentrated flow and transport and deposition functions. Verification of the hydrological component of the WEPP model was conducted against daily and monthly runoff data for the Weatherley research catchment at the upper and lower weir, and for the Zululand research catchment at the H-flume.

The antecedent soil moisture deficit in the upper soil layer with the onset of an event affects the infiltration component and the scale of surface runoff and erosion when the model is run in the continuous simulation mode. The soil moisture deficit is computed as the difference between effective porosity and daily initial volumetric water content. The water balance component maintains a continuous balance of the soil moisture within the root zone on a daily basis. Verification of the soil water budgeting component of the WEPP model was conducted against daily soil water measurements for surface and subsurface soil horizons at selected soil profiles for hillslopes at the Weatherley research catchment (see section 4.1.1.1) and Zululand research catchment (see section 4.1.1.2).

4.1.2.1 EVAPOTRANSPIRATION

One of the most important determinants in soil water content prediction with the WEPP model is an accurate prediction of evapotranspiration (Laflen, 2002; Personal communication). Evapotranspiration (ET) is a dominant hydrological process between rainfall events that has a major influence on the moisture distribution in the soil profile. The WEPP model uses the Penman-Monteith equation to predict reference potential ET (Penman, 1963). Daily leaf area index, root depth, total plant biomass and residue cover are entered as inputs to the evapotranspiration component from the crop growth component. As the evapotranspiration prediction may be subject to uncertainty from inputs from *inter alia* the crop growth component, the WEPP model was verified using measured data from the Weatherley research catchment. A comparison of model-predicted and measured evapotranspiration is presented in Figures 4.7 (daily values) and 4.8 (monthly averaged values) for the period July to December 2001. Total evaporation was measured by the CSIR using the Bowen ratio energy balance technique, which includes all evaporation above the surface of the grassland (interception, plant transpiration and soil evaporation) and takes cognisance of both the atmospheric conditions and the character of the grass and soil surface (Jarmain, 2003; Personal communication). The calculated Penman-Monteith reference plant evaporation is also included in the graphs.

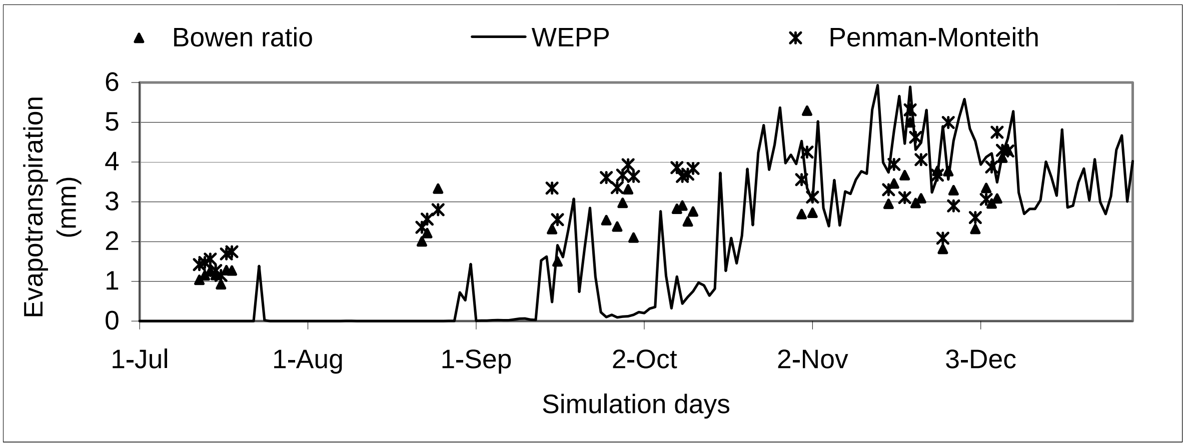

Figure 4.7. Comparison of daily total evapotranspiration values as predicted with the WEPP model, measured with the Bowen ratio technique and estimated by the Penman-Monteith equation.

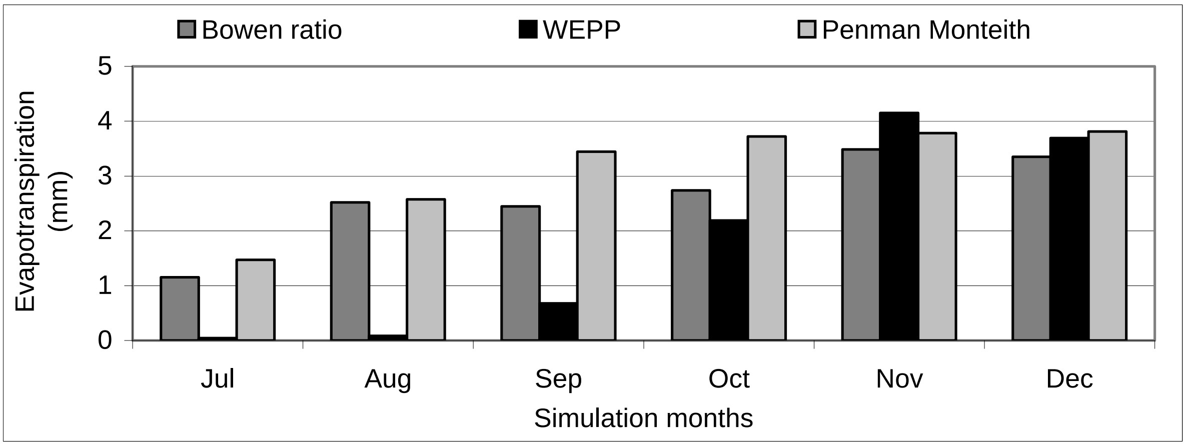

Figure 4.8. Comparison of monthly averaged total evapotranspiration values as predicted with the WEPP model, measured with the Bowen ratio technique and estimated by the Penman-Monteith equation.

Total evaporation measured with the Bowen ratio energy balance technique ranged from around 1 mm during the dry winter months to 3-4 mm per day during the wet season (Figures 4.7 and 4.8). The comparison of model predicted evapotranspiration and that determined with the Bowen ratio indicates that the model under-predicts evapotranspiration during winter and early spring. This is attributed to the fact that the leaf area index values are zero when the grass is dormant during the winter (Figure 4.9) and the soil moisture content of the surface soil is below residual moisture content where no more water can be evaporated from the soil. Daily plant transpiration is predicted from daily potential evapotranspiration calculated from the Penman-Monteith equation and daily leaf area index, which is calculated from the maximum leaf area index potential and above-ground vegetative biomass (Arnold, Weltz, Alberts and Flanagan, 1995; Savabi and Williams, 1995). No plant transpiration is predicted when the grass is dormant as the leaf area index values are zero when the above-ground live biomass dies off with the occurrence of frost (Figure 4.9). The only contribution to evapotranspiration during this period is soil evaporation. The results illustrated in Figures 4.7 and 4.8 imply that the soil water content could be over-predicted for several days in the winter when a significant rainfall event occurs during the dormant period of the grass. The same implies for early spring rainfall when the daily leaf area index is still low. However, these situations should be likely to have a relatively small effect on soil erosion.

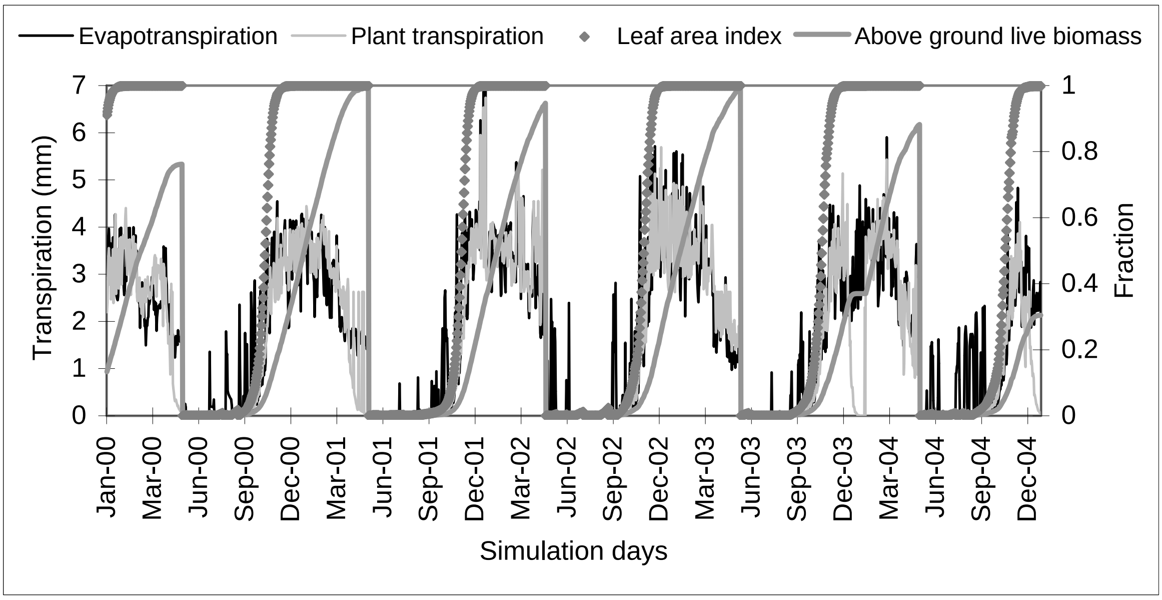

Figure 4.9. Daily values of total evapotranspiration and plant transpiration (mm), and leaf area index and above-ground live biomass as the fraction of maximum potential value predicted by the WEPP model for the period 1998 to 2002 at a soil profile at Weatherley.

4.1.2.2 SOIL WATER CONTENT

The relationships between predicted and measured soil water contents for an upslope position and one at the toe for Hillslope 2a (see Figure 3.3) and Hillslope 1 (see Figure 3.2) at the Weatherley research catchment are discussed. Similar relationships are discussed only for Hillslope 2 (see Figure 3.7) at the Zululand research catchment since analyses of the tensiometer responses at Hillslopes 1 and 2 showed that they respond in a similar fashion (see section 4.1.1.2). The reader is referred to sections 4.1.1.1 (Weatherley catchment) and 4.1.1.2 (Zululand catchment) in which the tensiometer responses and soil water fluxes are summarised for the specific nests under discussion. The comparisons of daily volumetric water content predicted by the WEPP model for a soil layer at the indicated depth and that calculated from the logged tension (average of last hour of day) at the indicated depth of the tensiometer cup are illustrated in Figures 4.10 to 4.21. The average tension of the last hour of the day is considered in view of the fact that the WEPP model computes the soil water balance at the end of each day, taking into account all the precipitation events in the 24-hour period. Daily rainfall (>5 mm) is also included in the figures to indicate increases in soil water contents due to rainfall events. The soil water content time series data calculated from soil water tension for the nests at the Weatherley catchment are expanded with water content data calculated from neutron probe measurements.

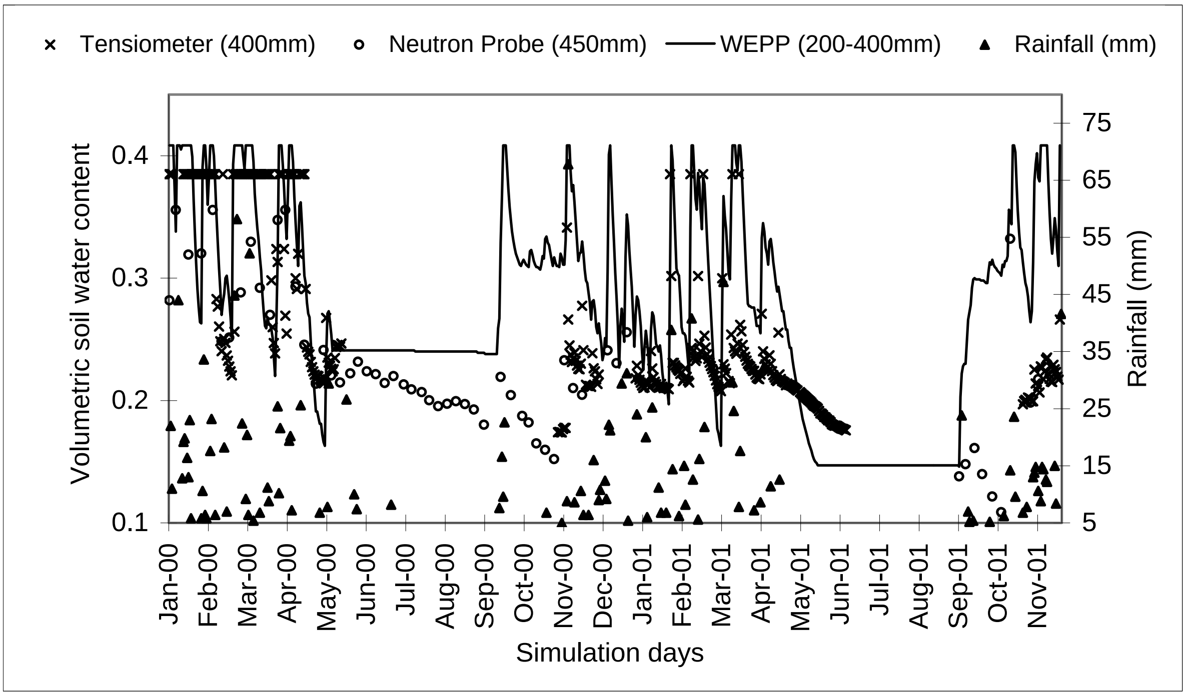

Figure 4.10. Comparison of WEPP model predicted, and tensiometer and neutron probe measured soil water contents for nest LC01 at Weatherley Hillslope 2a for the 400 mm soil depth.

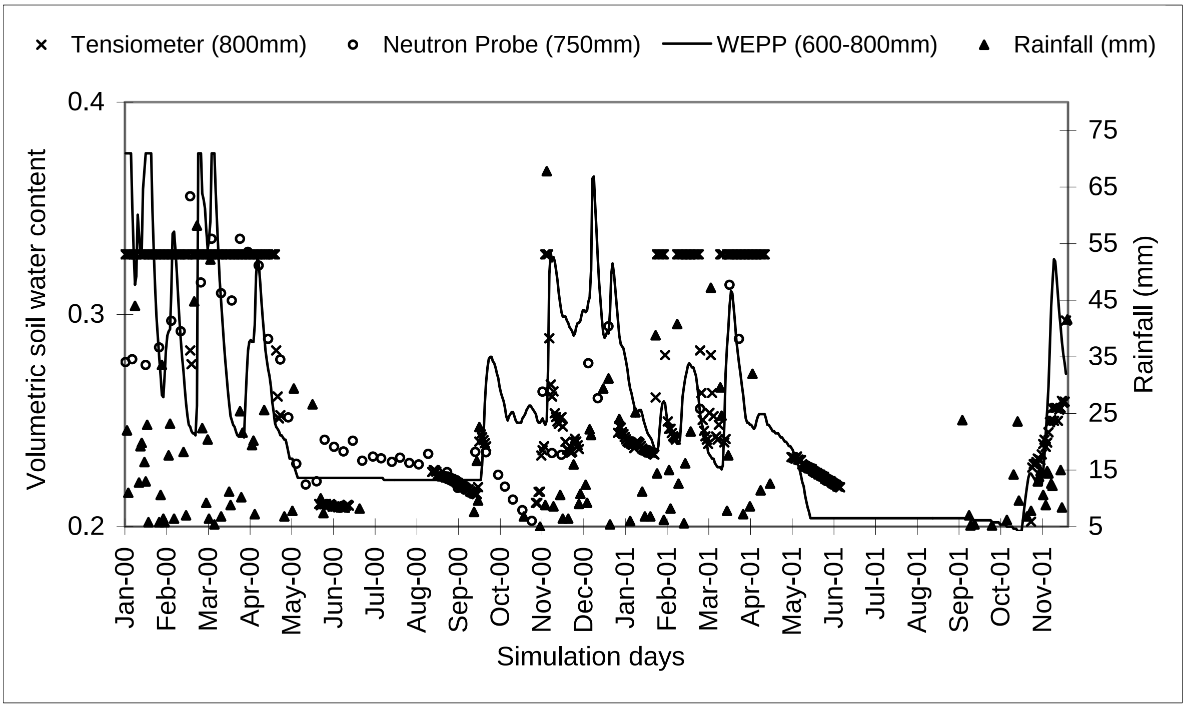

Figure 4.11. Comparison of WEPP model predicted, and tensiometer and neutron probe measured soil water contents for nest LC01 at Weatherley Hillslope 2a for the 800 mm soil depth.

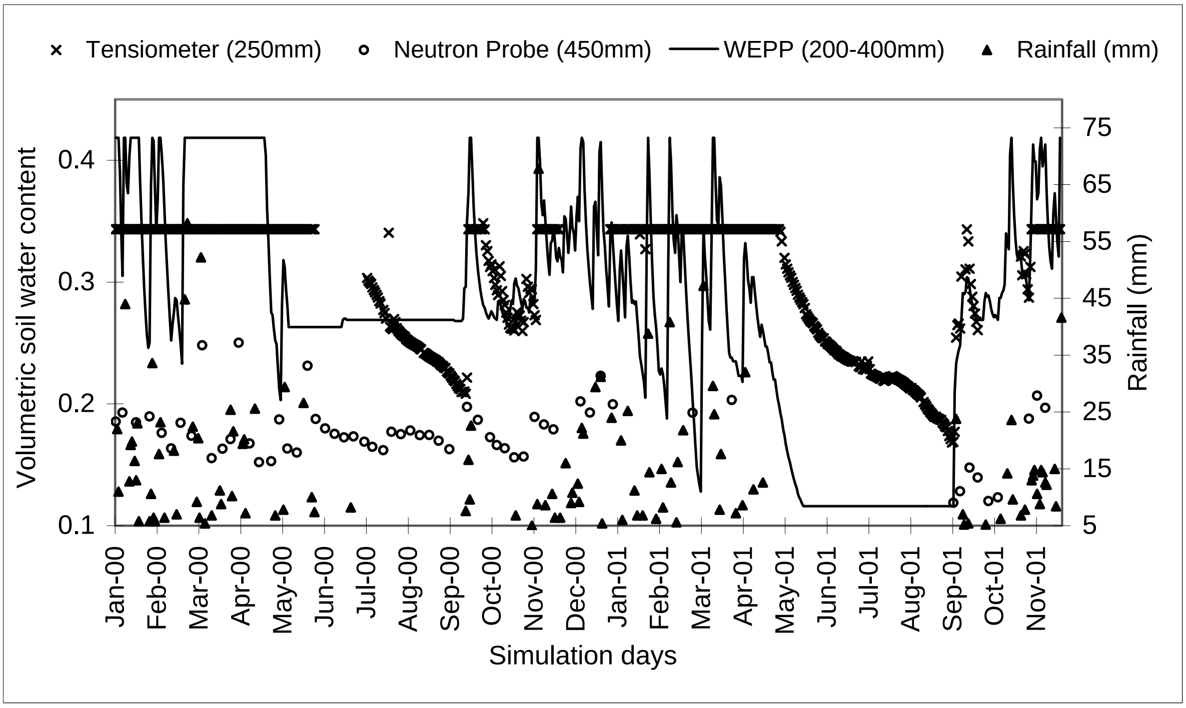

Figure 4.12. Comparison of WEPP model predicted, and tensiometer and neutron probe measured soil water contents for nest LC04 at Weatherley Hillslope 2a for the 250 mm soil depth.

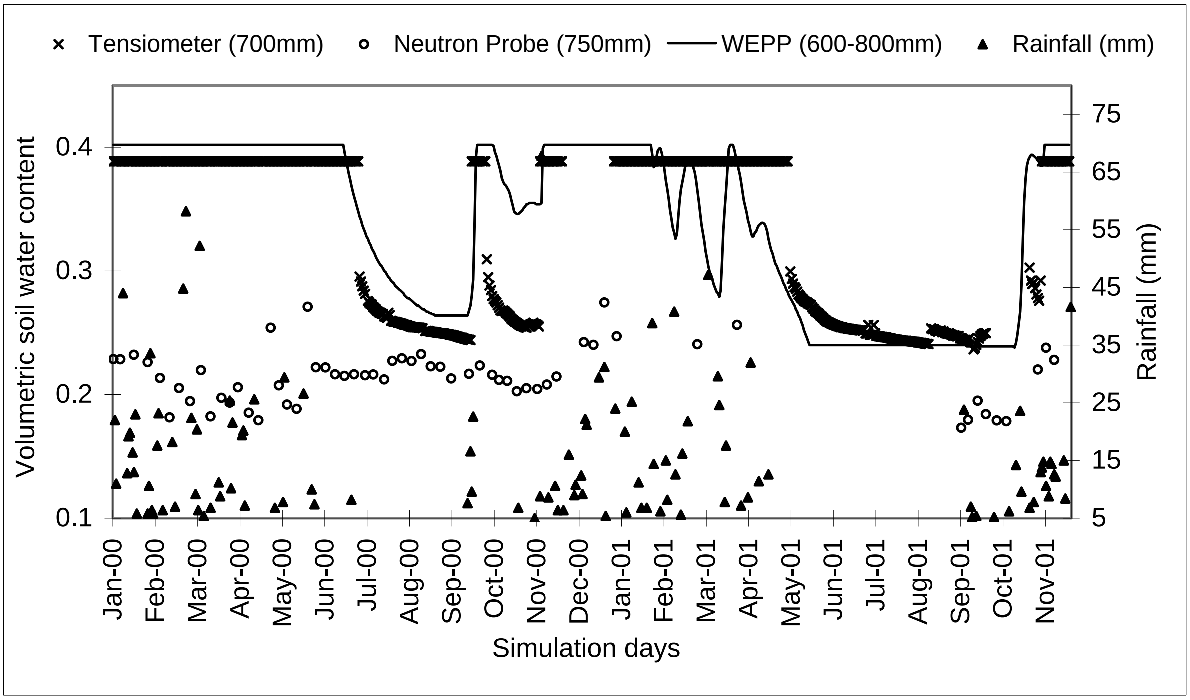

Figure 4.13. Comparison of WEPP model predicted, and tensiometer and neutron probe measured soil water contents for nest LC04 at Weatherley Hillslope 2a for the 700 mm soil depth.

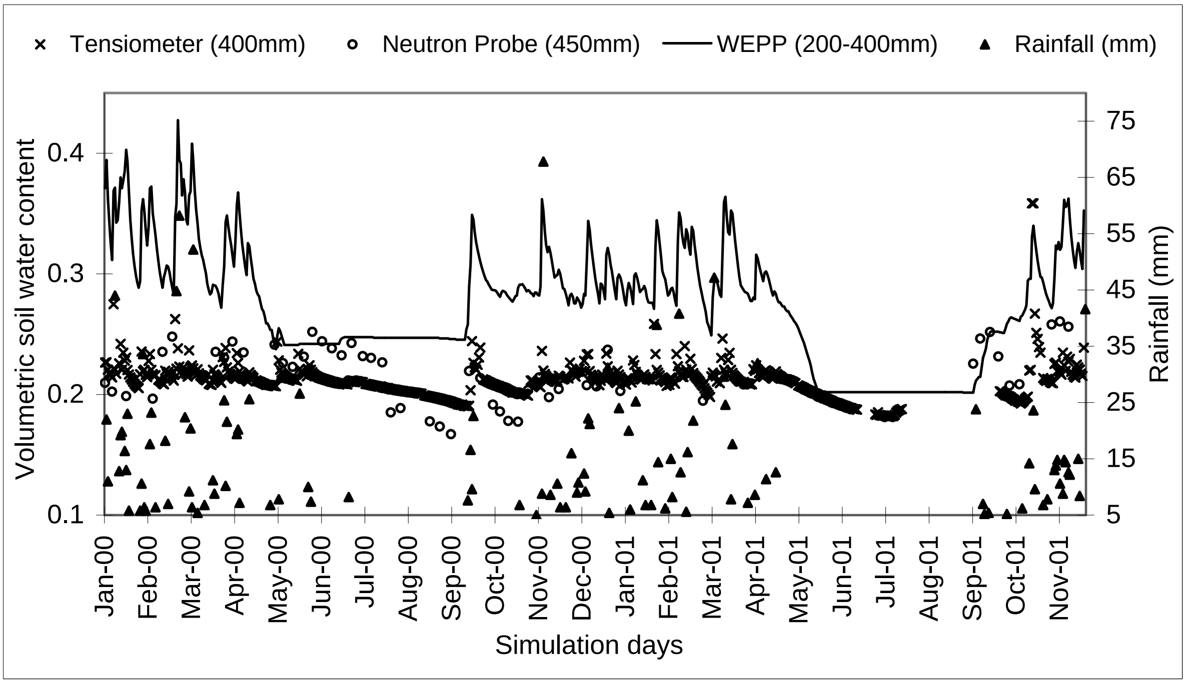

Figure 4.14. Comparison of WEPP model predicted, and tensiometer and neutron probe measured soil water contents for nest LC10 at Weatherley Hillslope 1 for the 400 mm soil depth.

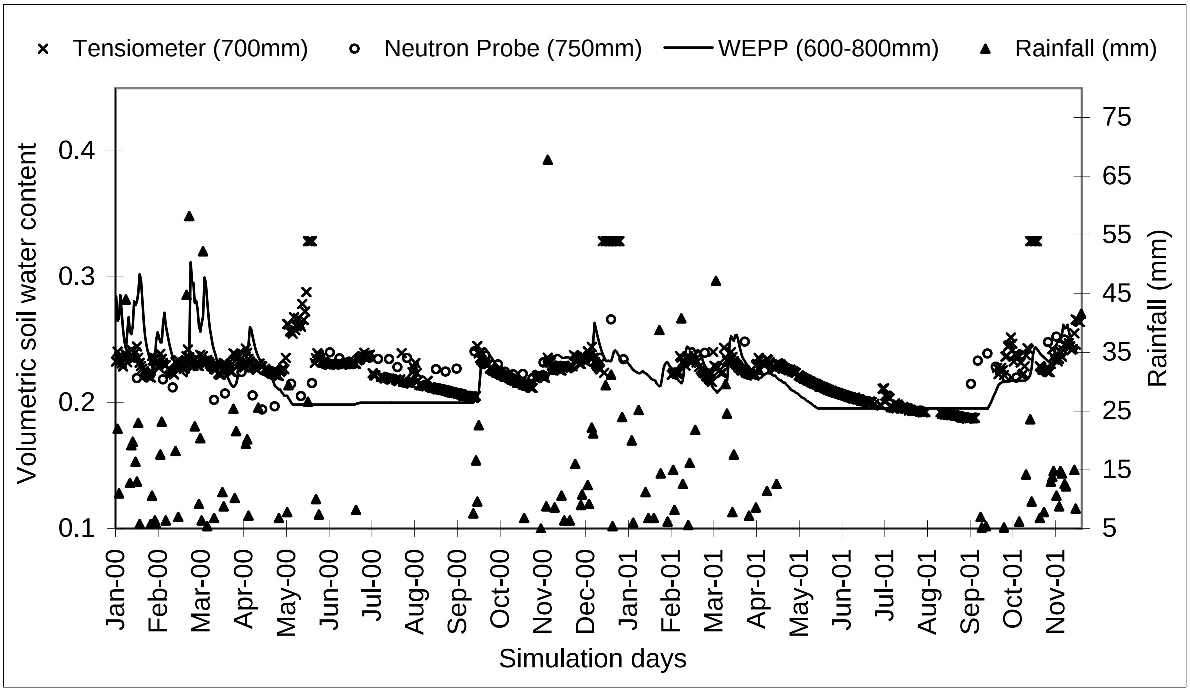

Figure 4.15. Comparison of WEPP model predicted, and tensiometer and neutron probe measured soil water contents for nest LC10 at Weatherley Hillslope 1 for the 700 mm soil depth.

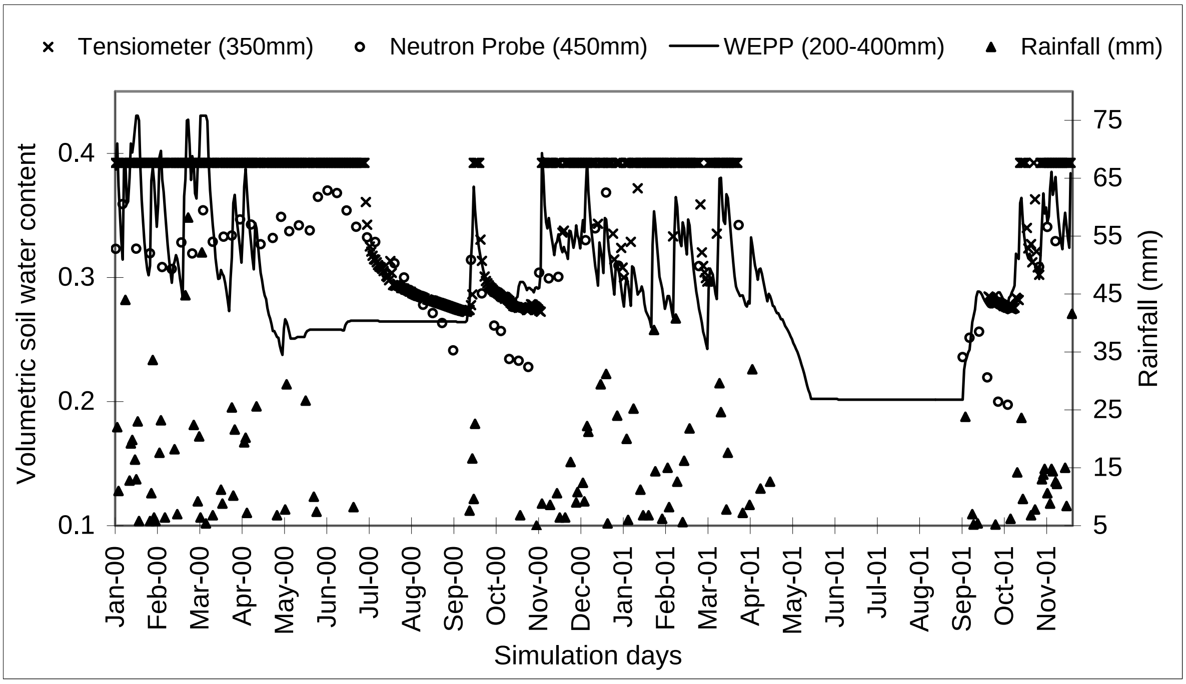

Figure 4.16. Comparison of WEPP model predicted, and tensiometer and neutron probe measured soil water contents for nest LC08 at Weatherley Hillslope 1 for the 350 mm soil depth.

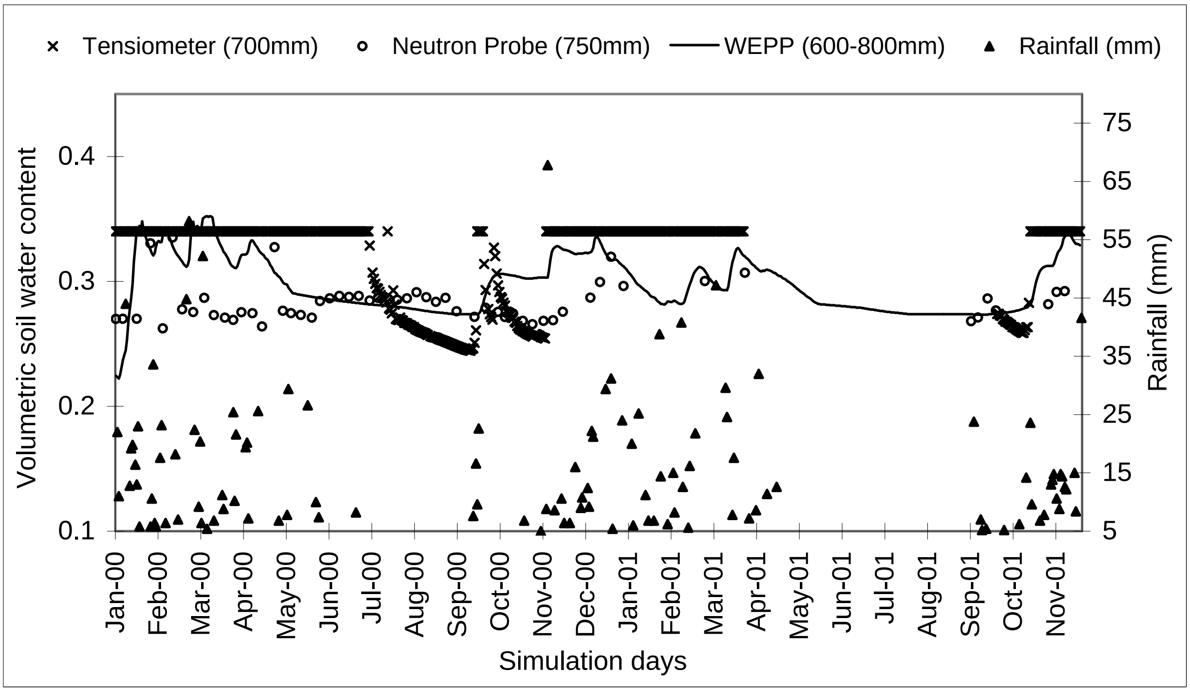

Figure 4.17. Comparison of WEPP model predicted, and tensiometer and neutron probe measured soil water contents for nest LC08 at Weatherley Hillslope 1 for the 700 mm soil depth.

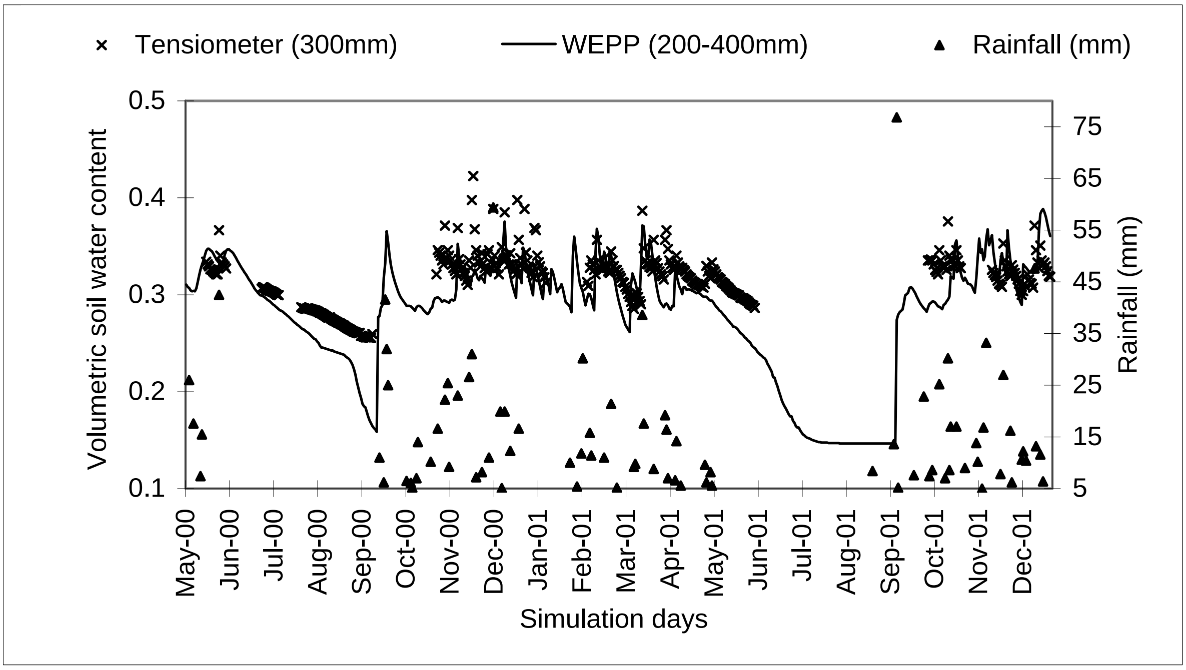

Figure 4.18. Comparison of WEPP model predicted and tensiometer measured soil water contents for nest SG02 at Zululand Hillslope 2 for the 300 mm soil depth.

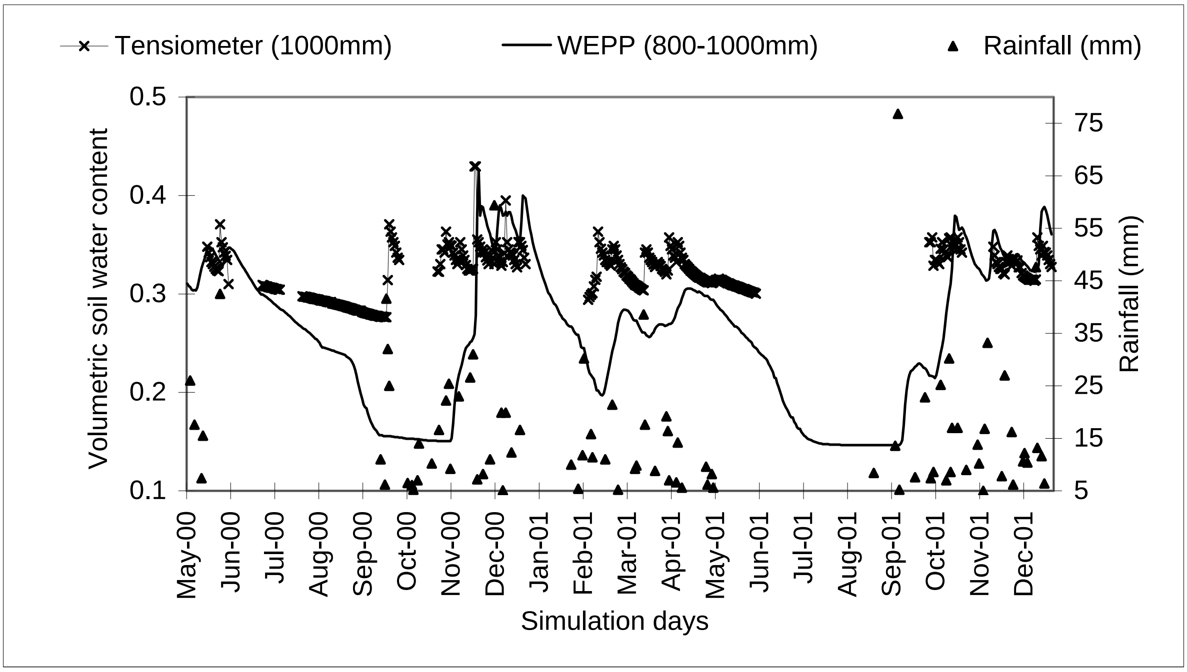

Figure 4.19. Comparison of WEPP model predicted and tensiometer measured soil water contents for nest SG02 at Zululand Hillslope 2 for the 1000 mm soil depth.

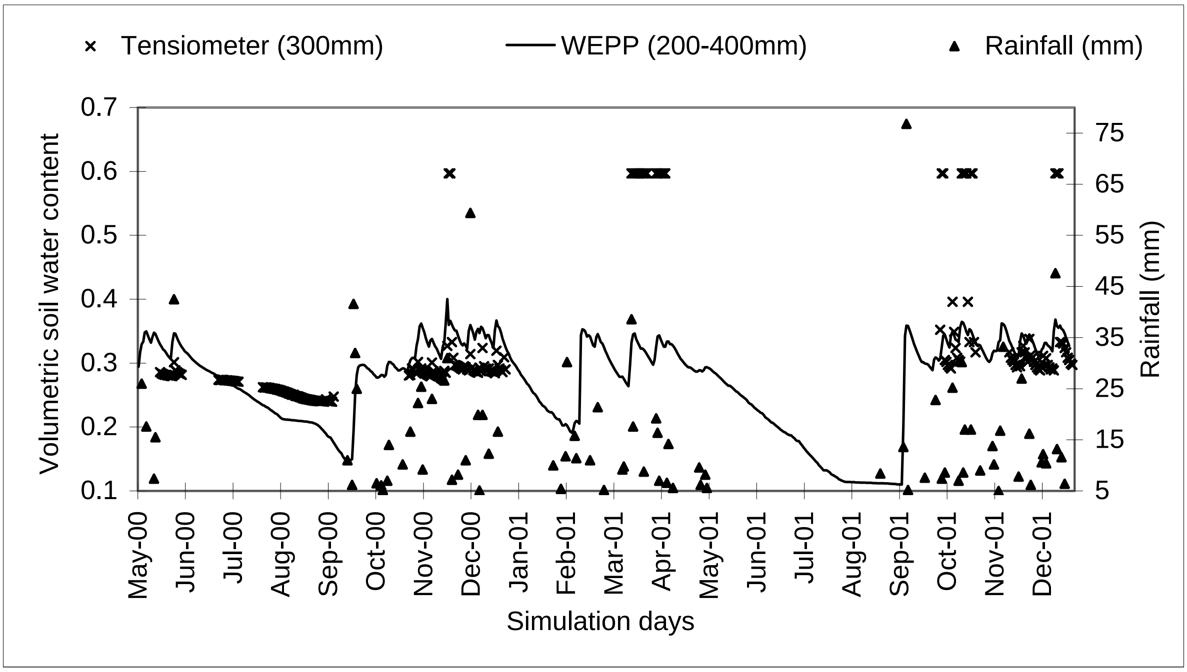

Figure 4.20. Comparison of WEPP model predicted and tensiometer measured soil water contents for nest SG04 at Zululand Hillslope 2 for the 300 mm soil depth.

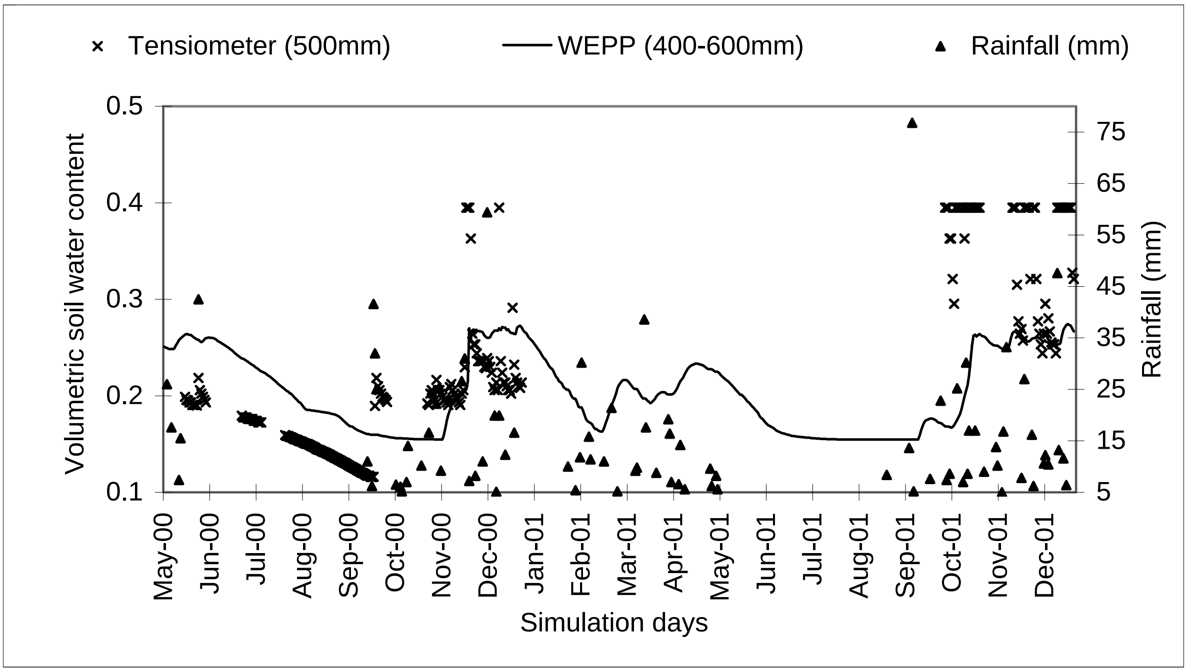

Figure 4.21. Comparison of WEPP model predicted and tensiometer measured soil water contents for nest SG04 at Zululand Hillslope 2 for the 500 mm soil depth.

When the predicted and measured soil water contents were compared, it is also important to analyse the difference between effective porosity and the volumetric water content, since the antecedent soil moisture deficit with the onset of an event affects the infiltration component and the scale of surface runoff and erosion. The WEPP model predicts total porosity from soil bulk density. Soil bulk density is calculated by the model from the soil input data (% sand, % clay, % organic matter and cation exchange capacity) and from changes in the density due to tillage and rainfall consolidation (Alberts, Nearing, Weltz, Risse, Pierson, Zhang, Laflen and Simanton, 1995). Volumetric water contents are predicted in the soil water balance component (see section 4.1.2.1).

The predicted and measured soil water contents for an upslope position, nest 1, and one at the toe, nest 4, of Hillslope 2a (Figures 4.10 to 4.13) at the Weatherley catchment were compared. The WEPP model was able to predict saturated conditions measured during the wet seasons, except in the subsurface soil for the dryer 2000/2001 season. Saturated conditions were less frequently predicted for the very wet period during January to April 2000 compared to that recorded by the tensiometers for the upslope position, nest 1. On the other hand, saturated condition was predicted for almost the whole period of measured saturated conditions for nest 4 at the downslope position. The same effect, although on a smaller scale, could be seen for the drier 2000/2001 wet season. This indicated that the WEPP model was able to redistribute soil water downslope along the relatively short hillslope for periods when field capacity of the soil horizons was exceeded. The ability of the WEPP model to predict the rapid responses of the surface soil to rainfall events were clearly illustrated throughout the wet season of 2000/2001 at nest 1 and at the beginning of the 2000/2001 wet season at nest 4. During the dry season, the soil moisture was predicted satisfactorily, with the exception of the surface soils during the winter of 2000. Two significant rainfall events occurred during this period (4 and 18 May 2000). The soil water contents were over-predicted, as the WEPP model predicted no plant transpiration for grass that was dormant (see discussion on evapotranspiration).

A comparison of predicted and measured soil water contents is summarised for an upslope position, nest 10, and one at the toe, nest 8, of Hillslope 1 at the Weatherley catchment (Figures 4.14 to 4.17). Of the four soil horizons verified, the soil water contents were predicted satisfactorily for only the subsurface soil at nest 10. The variation of water content at LC10 (whether measured by the neutron probe or implied from conversion of tensiometer tensions) is low. Generally the water contents range from a maximum of 0.25 to a low of 0.17 at the 400mm depth and from a saturated high of 0.32 to a low of 0.20 at the 700mm depth. Of significance, however, is the slow response to rainfall events compared to those at LC1 and LC2 for instance. The water contents derived from the neutron probe measurements vary more than those converted from tensions at the 400mm level, indicating that the water retention characteristic used to convert the tensions had too steep a pore size distribution index. Nevertheless, the main factor limiting the fluctuation of water contents at this site at both depths is the lack of macropore structure and behaviour at LC10. Water moves into the profile in a slow, uniform wetting front. The material is homogeneous and deep with a lower saturated hydraulic conductivity than that at the opposite slope. Surface runoff from this part of the slope can be expected to be rapid, and infiltration slow, reflected by the low predominant water contents at the 400mm depth.

The WEPP model over-predicted the soil water contents for the surface soil at the upslope position, whereas it under-predicted water contents at both the surface and subsurface soil at the downslope location at nest 8. No saturated conditions were predicted for the freely drained upslope soil profile which is in accordance with measured tensiometry data. Saturated conditions were predicted for only a few days for the hydromorphic soil profile at the downslope position at the riparian area. This is in contrast to the measured soil tension indicating saturated conditions for most of the year. There could be several reasons why the WEPP model could not satisfactorily predict the soil moisture distribution along the hillslope. The WEPP model considers only Hortonian flow or flow which occurs when the rainfall rate exceeds the infiltration rate. It does not explicitly consider variable partial area responses or interflow (Stone et al., 1995). Interflow is the exfiltration of infiltrated water at a downslope position after having flowed laterally within the soil profile. The percolation and subsurface lateral flow component of the WEPP model uses simple storage routing techniques to predict flow through soil layers. The water content exceeding the corresponding field capacity is subjected to drainage to the succeeding layer in the profile and to the downslope overland flow element (Savabi and Williams, 1995). In contrast to the upslope soil profile at Hillslope 2a, saturated and very wet conditions do not occur frequently at the freely drained upslope soil profiles, which reduces the probability of drainage of water to downslope soil horizons when the water content exceeded the corresponding field capacity at the upslope soil horizons. Secondly, the slope length of Hillslope 1 is long, which promotes re-infiltration of overland flow along the slope. The WEPP model has a sophisticated infiltration and overland flow component which is very sensitive to infiltration (Stone et al., 1995). Thirdly, the subsurface drainage component of the WEPP model is not very sophisticated in taking account of the flow in near-surface soil horizons when resident groundwater rises into these layers (Savabi et al., 1995). The WEPP model over-predicted the response of the surface soil of nest 10 to rainfall events (Figure 4.14). Furthermore, the WEPP model constantly over-predicted the soil water content when compared to measured data, due to the fact that it under-predicted the hydraulic conductivity of the surface soil and the internal drainage of the soil profile. It is expected that surface runoff will also be over-predicted.

The predicted soil water contents were compared with measured water contents for a soil profile at the upper-midslope / crest position, nest 2, and one at the footslope, nest 4, of a hillslope under sugarcane at the Zululand catchment (Figures 4.18 to 4.21). No saturated conditions were predicted for the freely drained upslope soil profile, which is in accordance with measured tensiometry data, or for the hydromorphic soil profile at the downslope position at the riparian area, which is in contrast with measured soil water tension data. The predicted soil water contents were in close agreement with the measured values at the upslope soil profile during the wet season. The WEPP model was also able to accurately predict the responses of the soil horizons at the 300 and 1000 mm depths for the significant rainfall events, except for the subsurface soil during the rainfall events on 18, 19 and 20

September 2000. The prediction of soil water contents for the hydromorphic soil profile at the downslope position was not as satisfactory as for the freely drained soil profiles on the crests and midslopes. Although the WEPP model could predict soil moisture satisfactorily for most of the period, the WEPP model was unable to predict soil water contents for the subsurface soil during the wet period of September to December 2001. The WEPP model was also not able to simulate the response of the hydromorphic soil profile to big rainfall events. This is of concern as it was shown by Mulder (1984) that there is little or no significant surface flow on the crests and midslopes due to the very high infiltration rates, and nearly all the storm flow component was derived from surface runoff associated with soil profiles at the footslopes and valley bottoms. Furthermore, the erodibility for soils in the Zululand catchment is very low, meaning that sediment yield is mainly produced from bottomland soils during big events. The slopes are very steep, causing lateral flow at the lower midslopes and footslopes. The WEPP model considers only Hortonian flow and does not consider variable partial area responses, as the subsurface lateral flow component of the WEPP model uses simple storage routing techniques to predict flow through soil layers. The water content exceeding the corresponding field capacity is subjected to drainage to the succeeding layer in the profile and to the downslope overland flow element (Savabi and Williams, 1995). In addition, the soils on the crests and midslopes have very high infiltration rates which promotes re-infiltration of overland flow along the slope. The WEPP model has a sophisticated infiltration and overland flow component which is very sensitive to re-infiltration (Stone et al., 1995).

4.1.2.3 RUNOFF

The runoff (water discharge at the catchment outlet / catchment area) predicted by the WEPP model was compared with the daily runoff recorded at the upper and lower weir at the Weatherley research catchment for the period 1999 to 2001 (Figures 4.22 and 4.23). The WEPP model predicted runoff for only a few rainfall events that coincided mostly with the big events. Although some predicted daily runoff was in close agreement with the runoff measured for that day, the variability in predicted runoff was very high compared to the recorded daily runoff. No runoff was predicted for numerous days during the wet seasons although measured daily runoff was most often higher than 0.5 mm/day. On the other hand, daily runoff was over-predicted for certain rainfall events in the order of 10 to 15 times the recorded runoff (see values indicated in Figures 4.22 and 4.23). It is also evident that the WEPP model find it much more difficult to predict days on which runoff will occur than days on which it will not occur. The rapid decline of predicted runoff after every large event might not take effective account of the receding limb of the hydrograph measured at the weirs which could extend into the day after the event. Consequently, models tend to do a better job of estimating the runoff for monthly periods than for daily intervals, compared to observed data. The predicted and recorded daily runoff was summed on a monthly basis and is shown in Figures 4.24 and 4.25. The predicted monthly runoff varied considerably in relation to the measured monthly runoff during the wet seasons. No definitive trend could be identified when monthly predicted runoff was compared with the recorded runoff, except that no runoff was predicted in dry months. The amount of rainfall events or predicted runoff

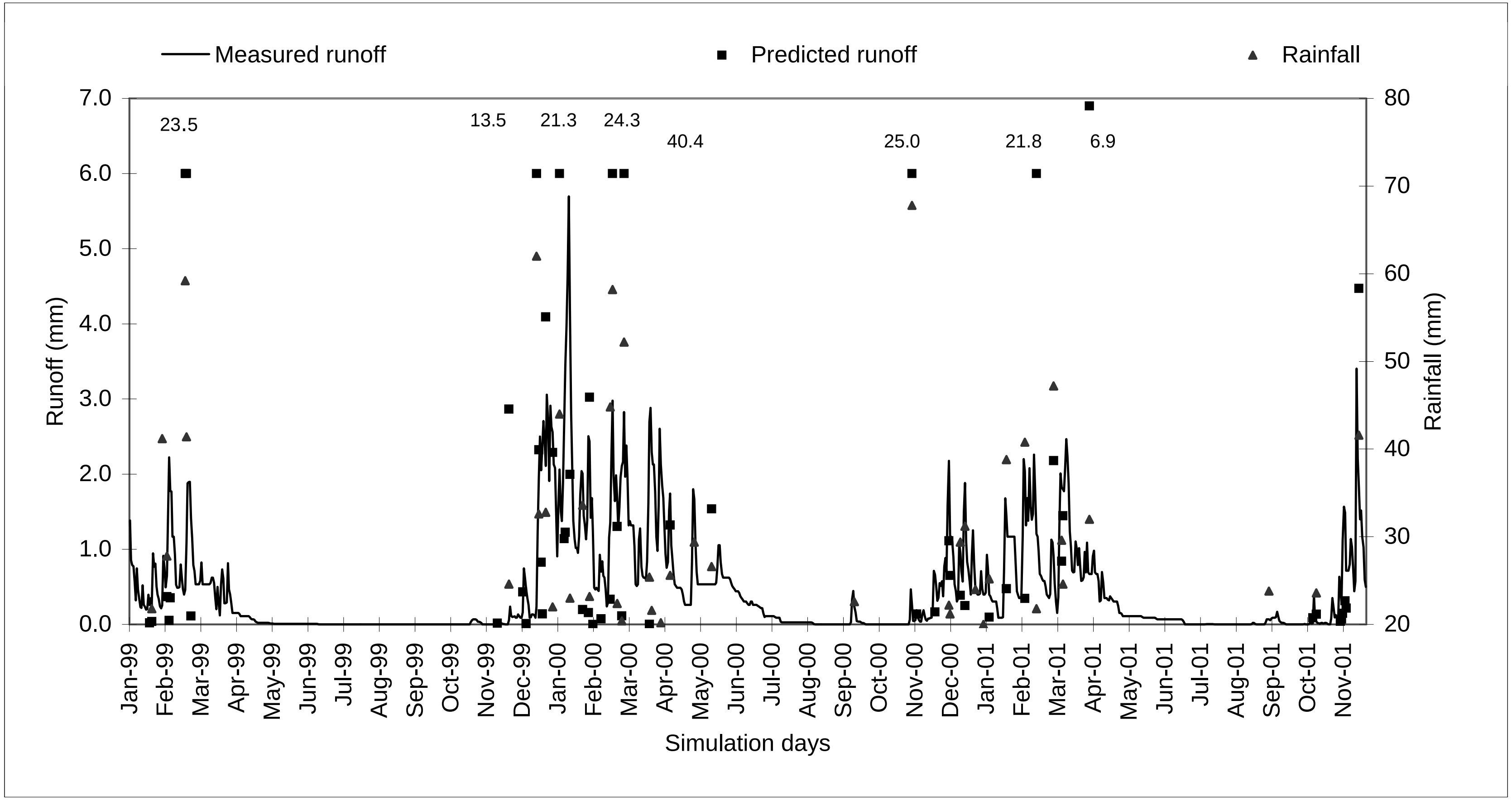

Figure 4.22. Comparison of WEPP model predicted and measured daily runoff for the upper weir at the Weatherley catchment for the period 1999 to 2001.
* The values in the graphs are off-scale peak heights.

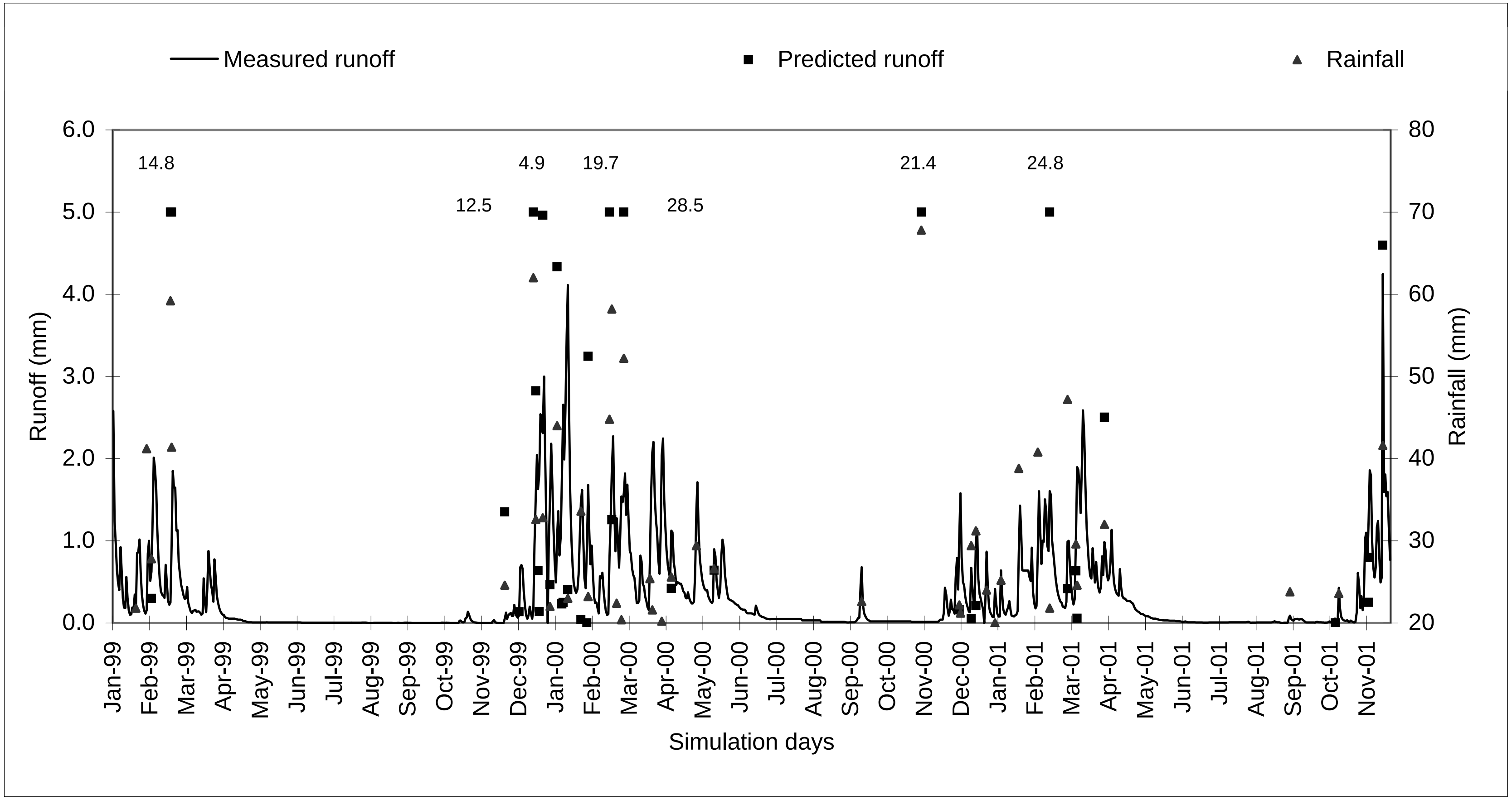

Figure 4.23. Comparison of WEPP model predicted and measured daily runoff for the lower weir at the Weatherley catchment for the period 1999 to 2001.

* The values in the graphs are off-scale peak heights.

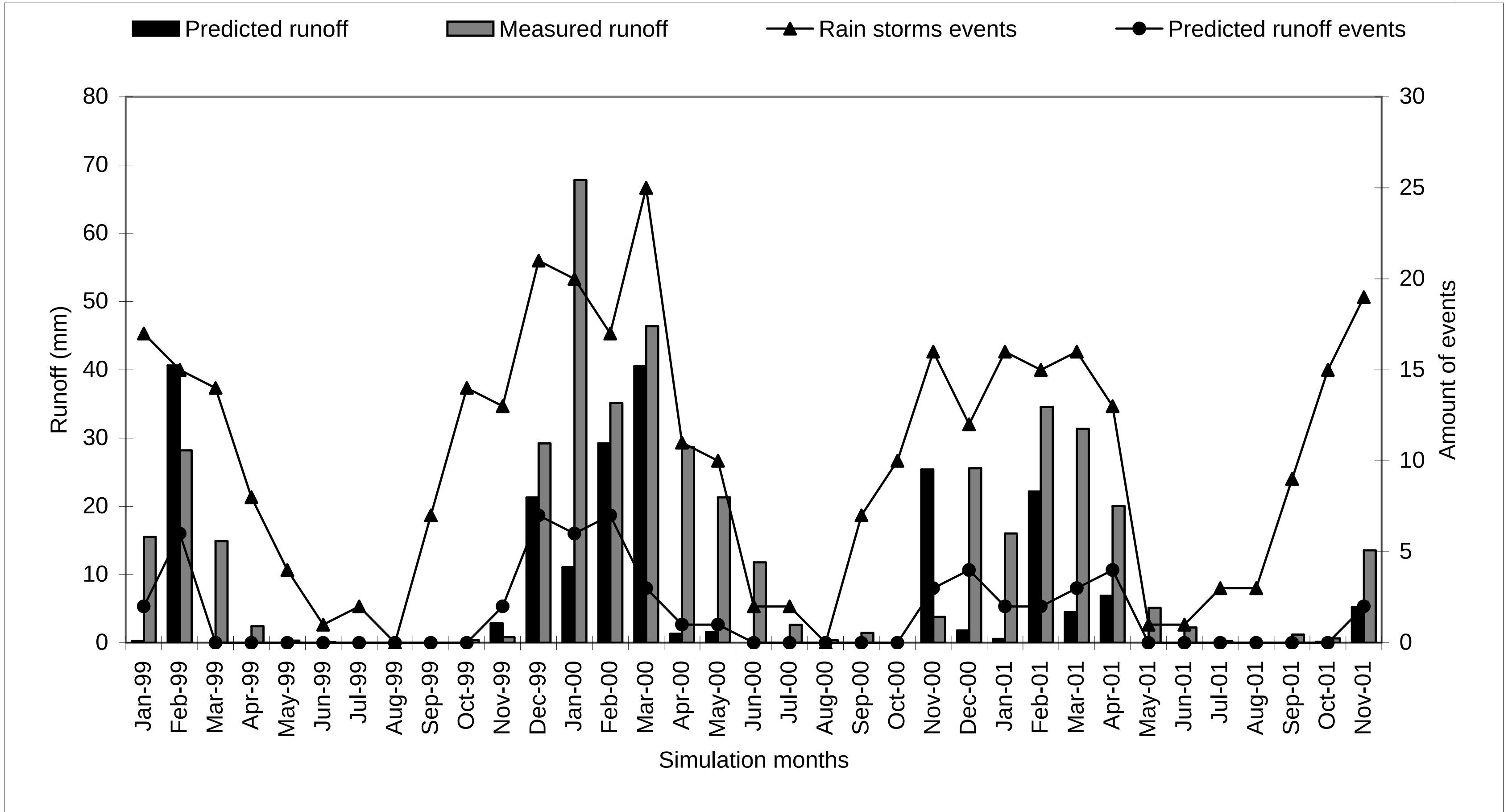

Figure 4.24. Comparison of WEPP model predicted and measured monthly runoff and the amount of rainfall events (>0.5 mm) and predicted runoff events for the upper weir at the Weatherley catchment for the period 1999 to 2001.

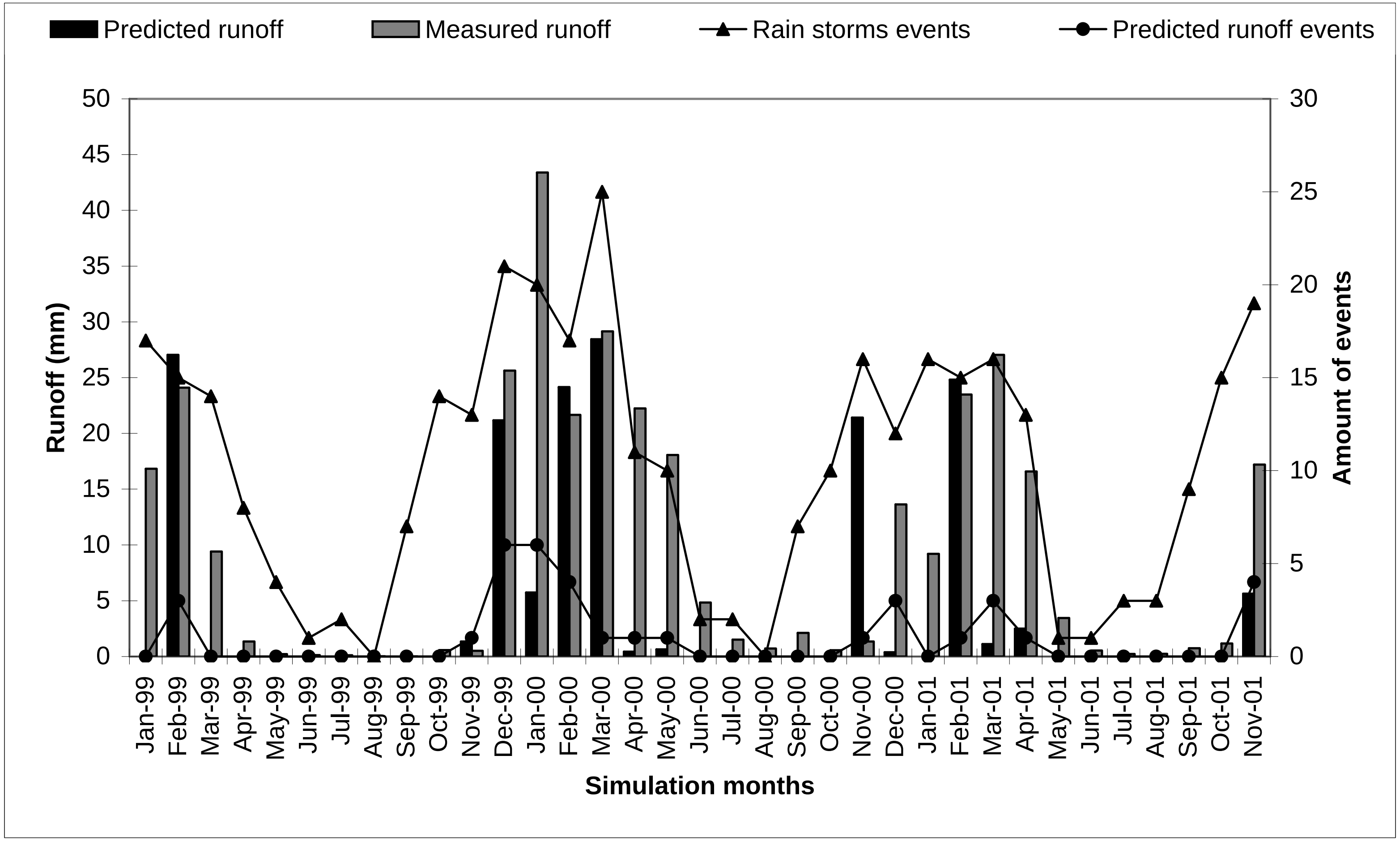

Figure 4.25. Comparison of WEPP model predicted and measured monthly runoff and the amount of rainfall events (>0.5 mm) and predicted runoff events for the lower weir at the Weatherley catchment for the period 1999 to 2001.

events could not explain the high variability between predicted and measured runoff. With the exception of three months, the WEPP model under-predicted runoff, as much as 5-8 times lower for certain months. When the daily runoff was summed over the period January 1999 to November 2001, the WEPP model predicted less than half of the measured runoff: 215 v. 462 mm at the lower weir and 165 v. 338 mm at the upper weir. This could be ascribed to the fact that the WEPP model predicted few runoff events from the amount of rainfall events occurred; e.g. only 36 and 55 runoff events for the 359 rainfall events during 1999 to 2001 for the lower and upper weirs respectively. Although most of the runoff was predicted during the big events, no clear relationship between rainfall and runoff amount is illustrated in Figures 4.22 and 4.23, e.g. low runoff was predicted for high rainfall amounts and *vice versa*. This could be ascribed to the fact that the WEPP model takes both rainfall amount and storm intensities into account when simulating infiltration excess and runoff (Figure 4.26).

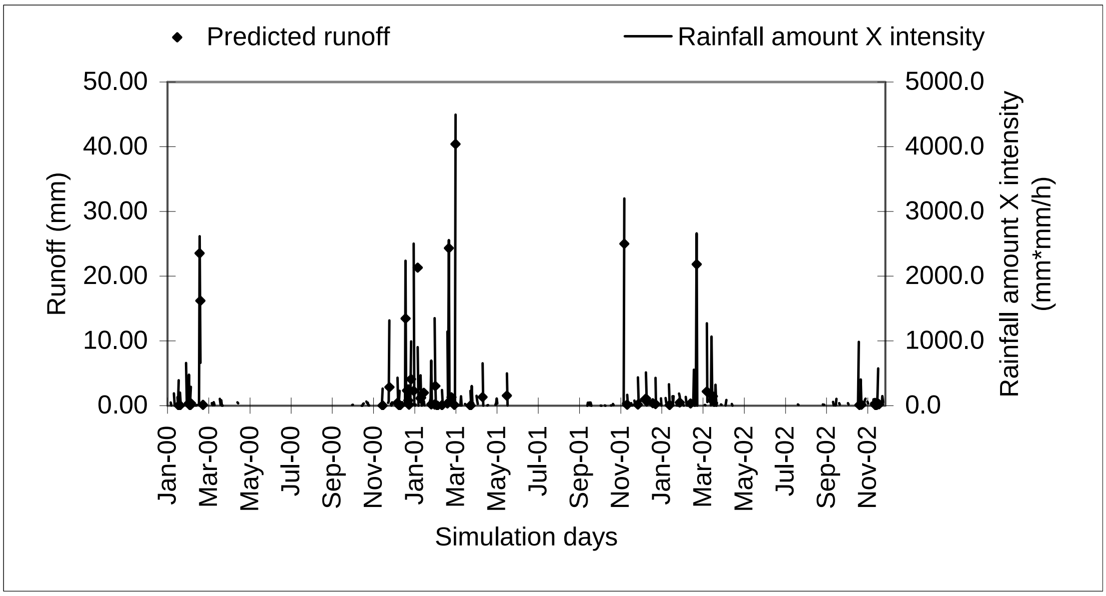

Figure 4.26. Comparison of WEPP model predicted daily runoff at the upper weir and the daily total of the product of rainfall amount and storm intensity for breakpoint rainfall at the Weatherley catchment for the period 2000 to 2002.

Figure 4.26 demonstrates the close relationship between predicted daily runoff and the product of rainfall amount and storm intensity. The predicted runoff events were highly dependent on both the rainfall amount and storm intensity that characterised the burst-effect of rainfall excess. The amount of predicted runoff was also related to the magnitude of the rainfall flux expressed as a combination of rainfall amount and storm intensity. This demonstrated that the WEPP model was extremely sensitive to the rainfall input data. The model runs in basic time steps of breakpoint rainfall, using rainfall intensity to take account of short duration bursts of intense rainfall, which have a significant effect on overland flow runoff. Rainfall excess was simulated by the WEPP model as the portion of the rainfall which ponds on the surface during the period when the rainfall rate exceeds the infiltration capacity. The time intensity distribution of rainfall excess was transformed into a time intensity distribution of runoff (the hydrograph) by the kinematic wave model. The WEPP model considers only Hortonian flow or flow which occurs when the rainfall rate exceeds the infiltration rate. It does not explicitly consider variable partial area response or interflow, as the subsurface lateral flow component of the WEPP model uses simple storage routing techniques to predict flow through soil layers. The water content exceeding the corresponding field capacity is subjected to drainage to the succeeding layer in the profile and to the downslope overland flow element (Savabi and Williams, 1995; Stone et al., 1995). This limitation had a profound effect on runoff predictions made with the WEPP model for the Weatherley catchment. The WEPP model poorly simulated the mechanisms of lateral flow, water accumulation at the toe of hillslopes and in the marsh area, the residence times of water on the hillslope and macropore flow. Consequently, the WEPP model was unable to accurately predict runoff from the catchment, which will most probably influence sediment yield predictions.

The runoff predicted by the WEPP model was compared with the daily runoff recorded at the H-flume installed at the Zululand research catchment for the period September 2001 to December 2002. The WEPP model predicted runoff for only few rainfall events. The predicted runoff for the four events did not correlate with the recorded daily runoff. Some of the runoff events were under-predicted, while the other events were over-predicted by a factor of 7-15. The predicted and recorded daily runoff was summed on a monthly basis. Apart from the predicted runoff events of October 2001 and July 2002, no runoff was predicted which was in contradiction with measured runoff. Measured daily runoff was seldom lower than 1 mm/day for the period September 2001 to April 2002, whereas for the minimum runoff recorded for July to December 2002 was 0.2 mm/day. When the prediction results were analysed, no runoff was predicted from the hillslopes, except for the days when runoff events were predicted. The effect of the limitations in the WEPP model discussed in the previous paragraph was amplified at the Zululand research catchment by the very high infiltration rates (80 mm/h and higher) and water storage capacities of the soils on the crests and midslopes. Consequently, infiltration excess overland flow on the crests and midslopes would seldom occur and only during very intense rainstorms. The soils on the crests and midslopes occupy the largest area of land, whilst the footslopes cover a narrow area along the streams. The runoff predicted at the H-flume was unsatisfactory since the WEPP model was unable to simulate the contribution of subsurface flow to surface runoff associated with footslopes and valley bottom partial source areas.

4.1.3 *ACRU* model

The different zones identified by soil water response observations are presented in Figure 4.27 for the Weatherley catchment. The catchment configuration comprised grassland and macropore dominated grassland zones discharging into a wetland zone as demonstrated in Figure 4.27. The upper catchment wetland zone discharges into the lower catchment wetland zone. The Zululand W17 catchment was divided into subcatchment response units based on the occurrence of crest, midslope, footslope and riparian units. The conventional linking of subcatchments was used in the Zululand catchment. There was no linking of baseflow discharge from upslope subcatchments into the A-horizon of lower slopes subcatchments as was used in the Weatherley catchment.

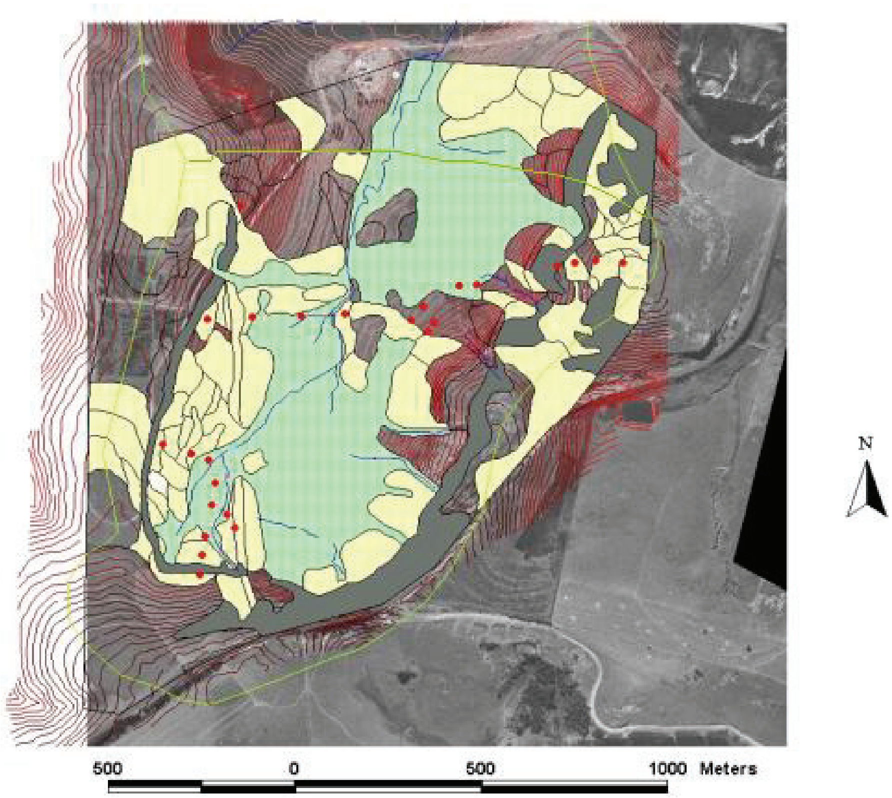

Figure 4.27. Topological *ACRU* hydrological response units in the Weatherley subcatchment including macropore zones (yellow), grassland (orthophoto grey), rock outcrop (grey) and wetland (green).

Verification of the model performance was conducted against various measured components of the hydrological water balance. Firstly, the predicted evapotranspiration was compared with that measured using the Bowen Ratio technique over a stretch of grassland in the Weatherley catchment from July to December 2002. Secondly, the soil water content status was compared with both that measured using a neutron probe and as well as that converted from tensiometer measurements. Thirdly, the predicted and observed runoff responses were compared and, finally, the predicted sediment yields were compared against those derived from runoff related concentrations of suspended solids.

4.1.3.1 EVAPOTRANSPIRATION

Evapotranspiration (ET) is a key component of the long-term water balance in a catchment and is made up of vegetation transpiration and evaporation from the soil. The *ACRU* model predicted ET was compared to values measured with the Bowen ratio equipment and estimated with the Penman-Monteith equation over a period from July to December 2002, (Figure 4.28). As with the WEPP model, the *ACRU* model under-predicted the ET during the winter. This could be due either to poor estimates by the equipment over the colder period or an inherent fault in both modelling systems to predict ET during dry, cool periods.

Equipment

Estimates of actual evapotranspiration using the Bowen Ratio during the monitoring period were often as high as the Penman-Monteith estimates of potential ET during the winter period, which lends some doubt to the validity of the winter Bowen Ratio measurements representing the actual ET.

Model

The *ACRU* model does not simulate dormant vegetation during the winter, but the vegetation coefficients were reduced during the winter, as was the predicted potential evaporation. Clearly there is a need for detailed soil water measurements during the winter to determine whether the vegetation continues to extract water from the deeper horizons or whether water evaporation at the soil surface continues to occur during the winter months. There was also evidence of reduced ET predicted in the *ACRU* model during the early part of October. This reduction was not observed through the measurements and could mean that the reduction in predicted ET during rain days is too severe in the model. In general the total monthly ET was predicted more accurately during the summer than during the dry period of winter and early spring as is shown in Figure 4.29.

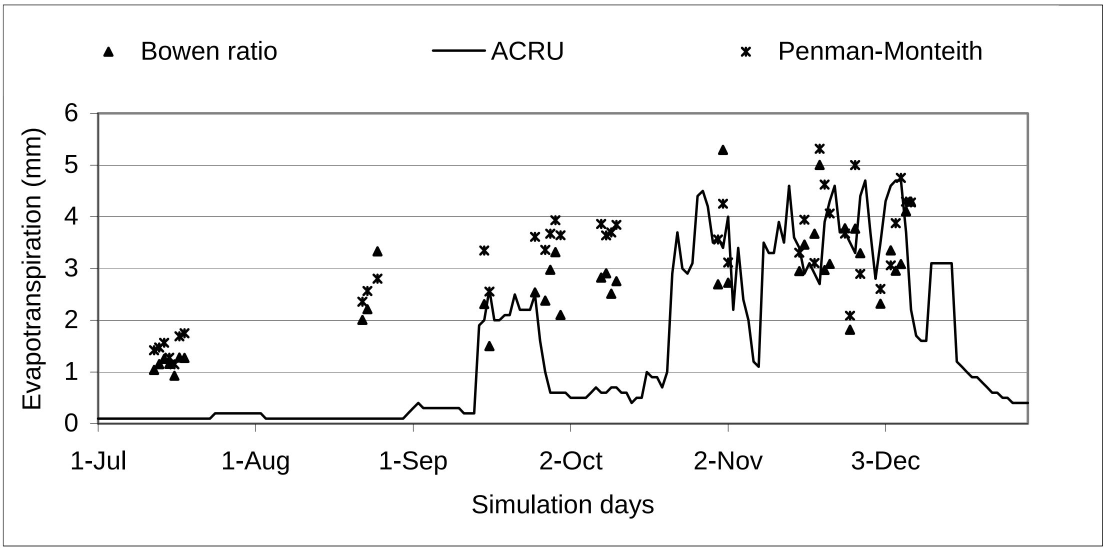

Figure 4.28 Comparison of daily actual evapotranspiration values as predicted with the *ACRU* model (solid line), measured with the Bowen ratio technique (triangles) and estimated by Penman-Monteith equation (crosses).

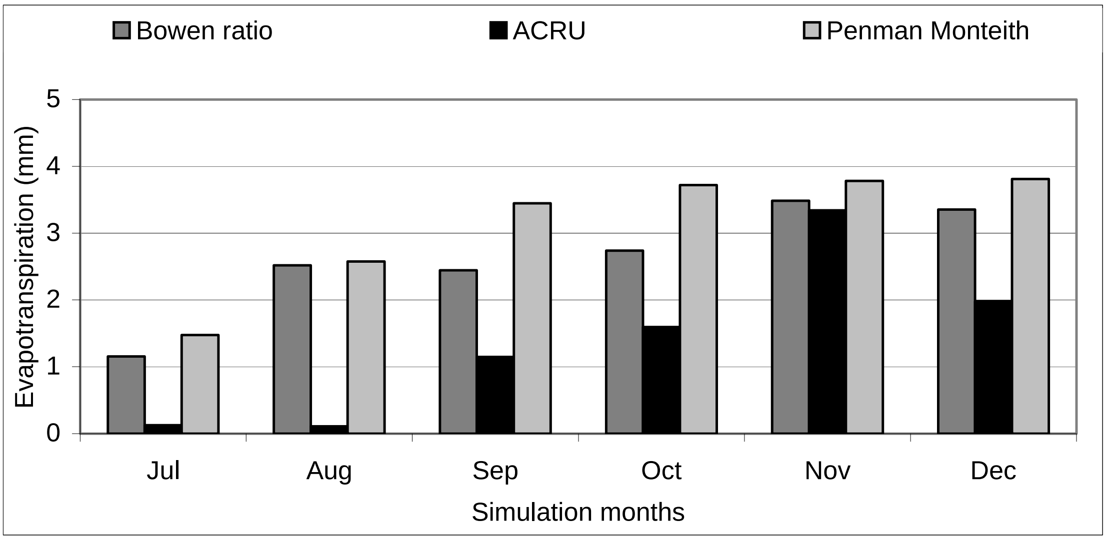

Figure 4.29 Comparison of monthly averaged daily evapotranspiration values as predicted by the *ACRU* model, measured with the Bowen ratio technique and estimated by the Penman-Monteith equation.

4.1.3.2 SOIL WATER CONTENT

Predicted and observed soil water dynamics were compared for the *ACRU* model simulations for the same positions as described in section 4.1.2.2. In the *ACRU* model, the soil water content was controlled primarily by the specified porosity, field capacity and wilting point of the two-layered system. The soil water content was predicted accurately for the A-horizon at all of the positions on the slope (Figures 4.30, 4.32 and 4.34). Variations of water content in the A-horizon were faithfully reproduced, reflecting the ability of the model to predict the rapid changes in water content in this part of the profile. The predicted water contents decreased to less than those measured using the neutron probe as was indicated during June to September 2000 at the 400mm depth (Figure 4.31). In the upper slopes of the lower catchment (LC01 to LC04), there was considerable accumulation of moisture at the toe (LC04) where the bedrock outcrops (Figures 4.30 to 4.33). There was no accumulation of water predicted in the *ACRU* model here (Figure 4.31 and 4.33), since this slope section has been considered as a single subcatchment response unit. For all the profiles except LC08, near the stream in the lower catchment, the B-horizon water content was under-predicted (Figures 4.31, 4.33 and 4.35). The water contents in the riparian zone B-horizon (Figure 4.37) were replenished by the upslope contributions, which, in the modified *ACRU* model include the near surface macropore zone contribution as well as baseflow contributions from both the grassland and macropore zones. Much of the under-prediction of the B-horizon in the model can be attributed to a field capacity (FC) value being specified which was too low. The field capacities used were those derived from water retention characteristics of the B-horizon of the profile. However, *in-situ* effective field capacities may be a function, *inter alia*, of the characteristics of the interface between the soil and bedrock, which may limit drainage, rather than the water retention capabilities of the soil. Elevated water content in the B-horizon may not increase the runoff potential significantly, if a similar dynamic in soil water content is available in the deficit volume as may be available with a reduced FC. The variation in the predicted water contents in the upper part of the profile at LC10 was larger than the measured variation. This was due to the nature of the hydraulic characteristics of the profile as described in the discussion of the WEPP model results.

In the Zululand transect, only the profile at the toe of the slope was compared to predicted values. Here an upslope contribution to the B-horizon in the riparian zone has not been considered. Nevertheless, the water contents were accurately predicted (Figures 4.38 and 4.39). There were occasions, though, where it was apparent that the profile becomes saturated for short intervals. This was not predicted in the *ACRU* model as these water content fluctuations may occur within a day, the time step at which the *ACRU* model simulates.

The observation of elevated water contents in the riparian zone has justified the simulation of upslope near surface runoff and baseflow contributions to the B-horizon of the riparian area in the Weatherley catchment. In the Zululand catchment, the measured field capacity appears to be representing the in-field conditions adequately.

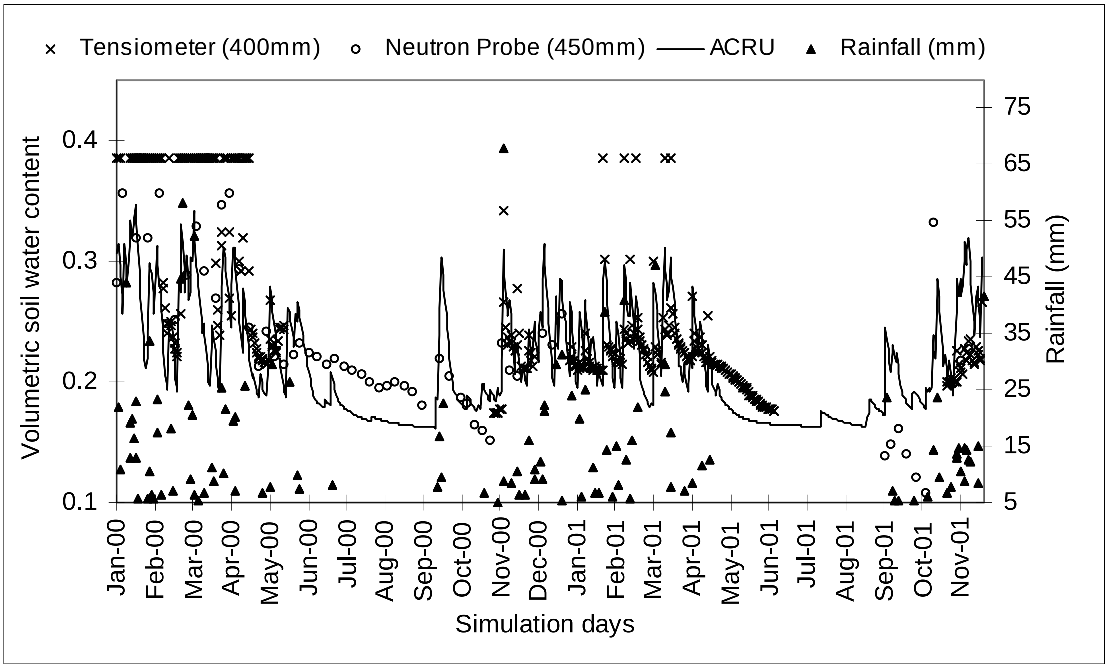

Figure 4.30. Comparison of *ACRU* model predicted A-horizon soil water content, and tensiometer and neutron probe measured soil water content for nest LC01 at Weatherley Hillslope 2a for the 400 mm soil depth.

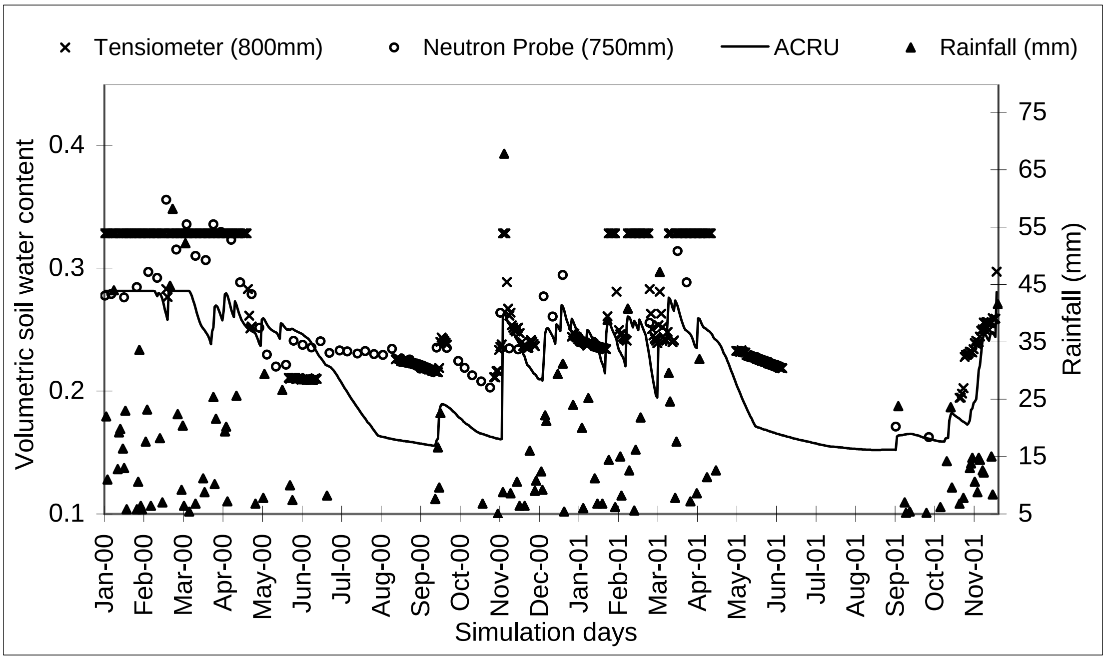

Figure 4.31. Comparison of *ACRU* model predicted B-horizon soil water content, and tensiometer and neutron probe measured soil water content for nest LC01 at Weatherley Hillslope 2a for the 800 mm soil depth.

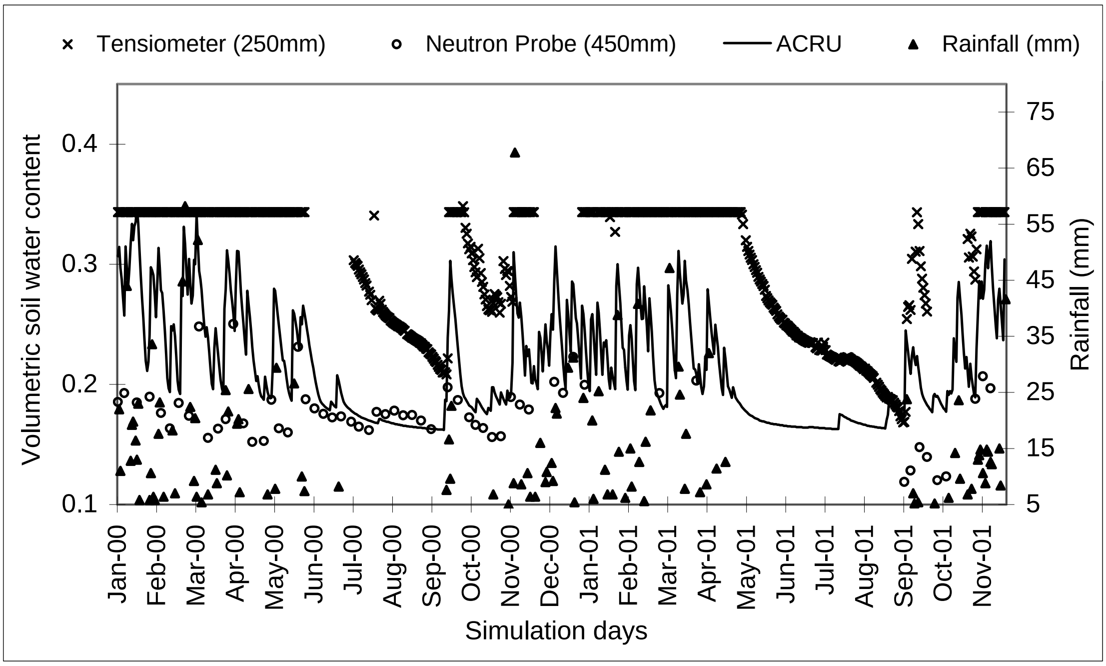

Figure 4.32. Comparison of *ACRU* model predicted A-horizon soil water content, and tensiometer and neutron probe measured soil water content for nest LC04 at Weatherley Hillslope 2a for the 250 mm soil depth.

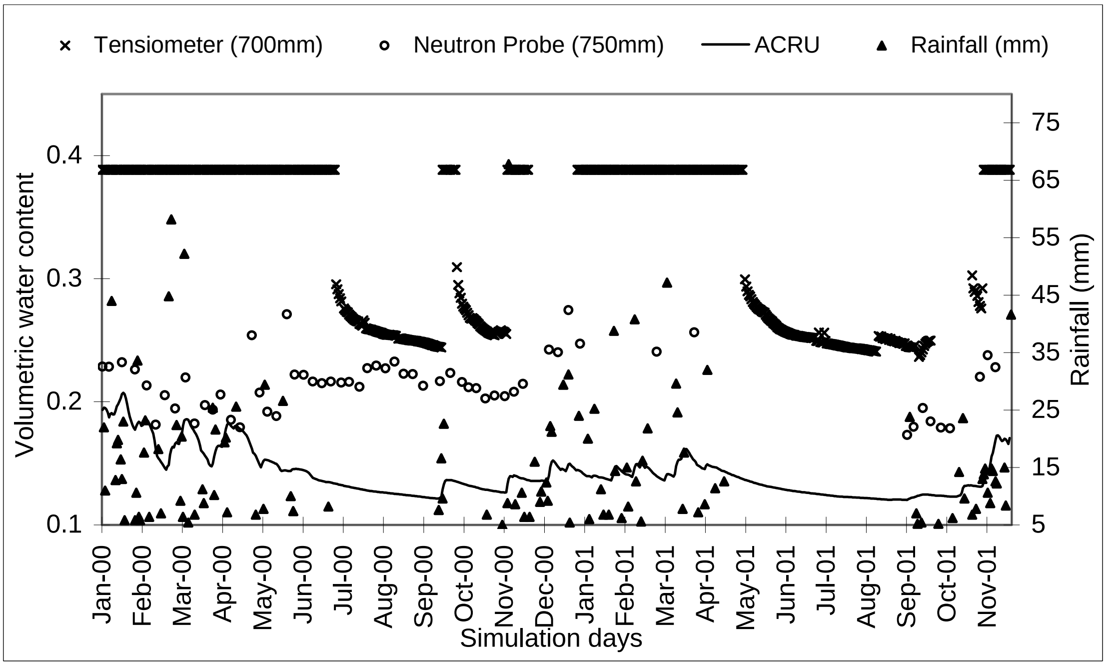

Figure 4.33. Comparison of *ACRU* model predicted B-horizon soil water content, and tensiometer and neutron probe measured soil water content for nest LC04 at Weatherley Hillslope 2a for the 700 mm soil depth.

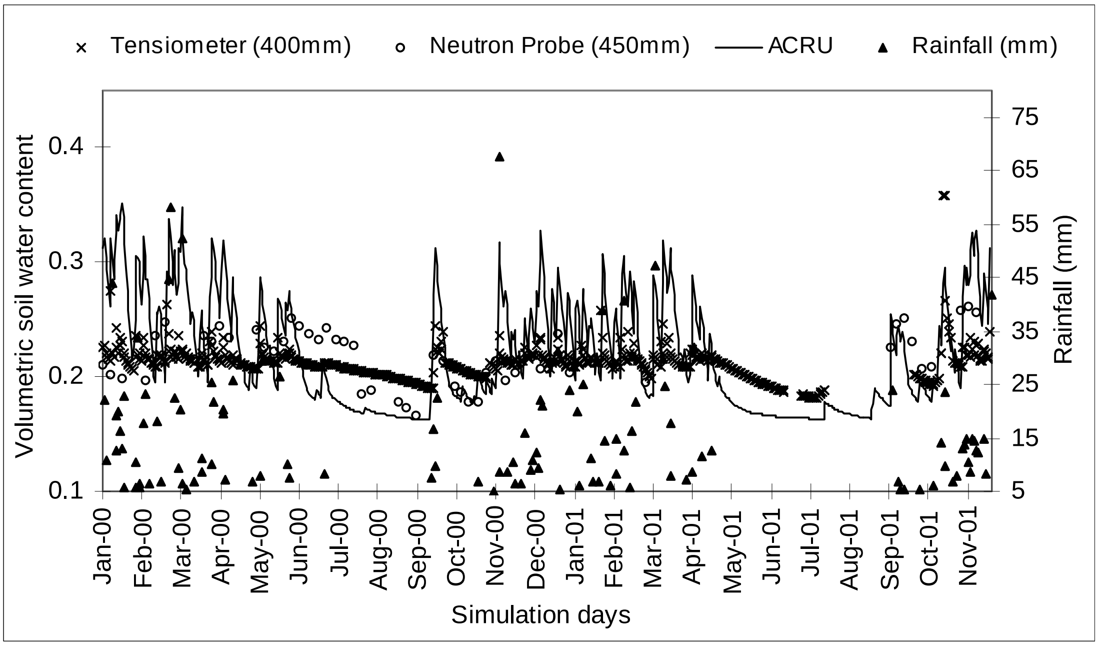

Figure 4.34. Comparison of *ACRU* model predicted A-horizon soil water content, and tensiometer and neutron probe measured soil water content for nest LC10 at Weatherley Hillslope 1 for the 400 mm soil depth.

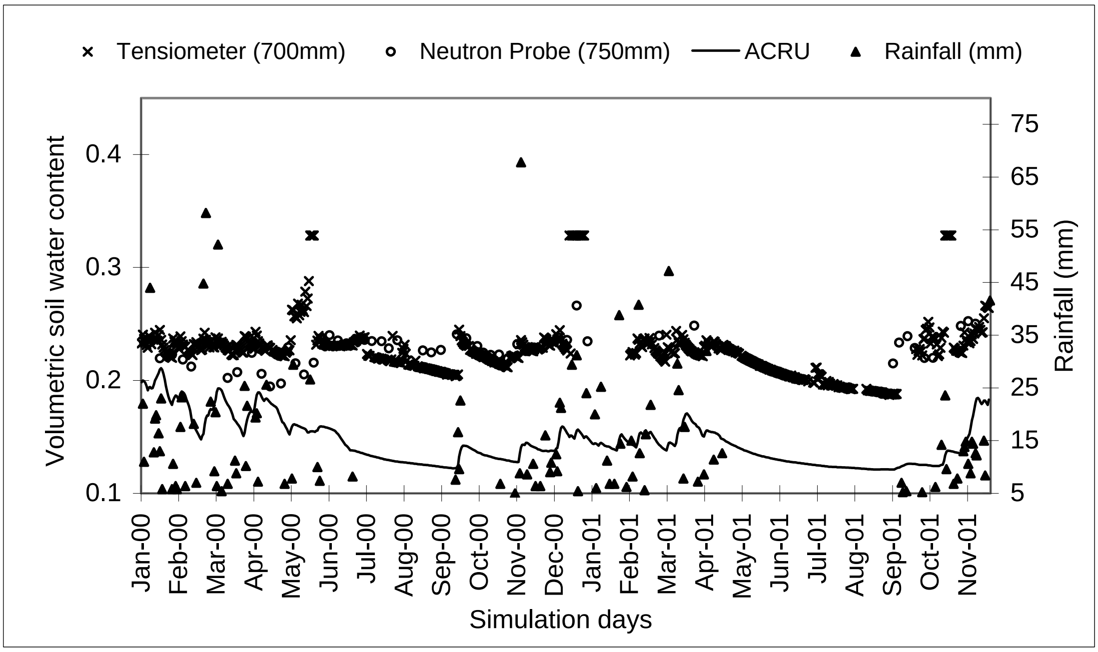

Figure 4.35. Comparison of *ACRU* model predicted B-horizon soil water content, and tensiometer and neutron probe measured soil water content for nest LC10 at Weatherley Hillslope 1 for the 700 mm soil depth.

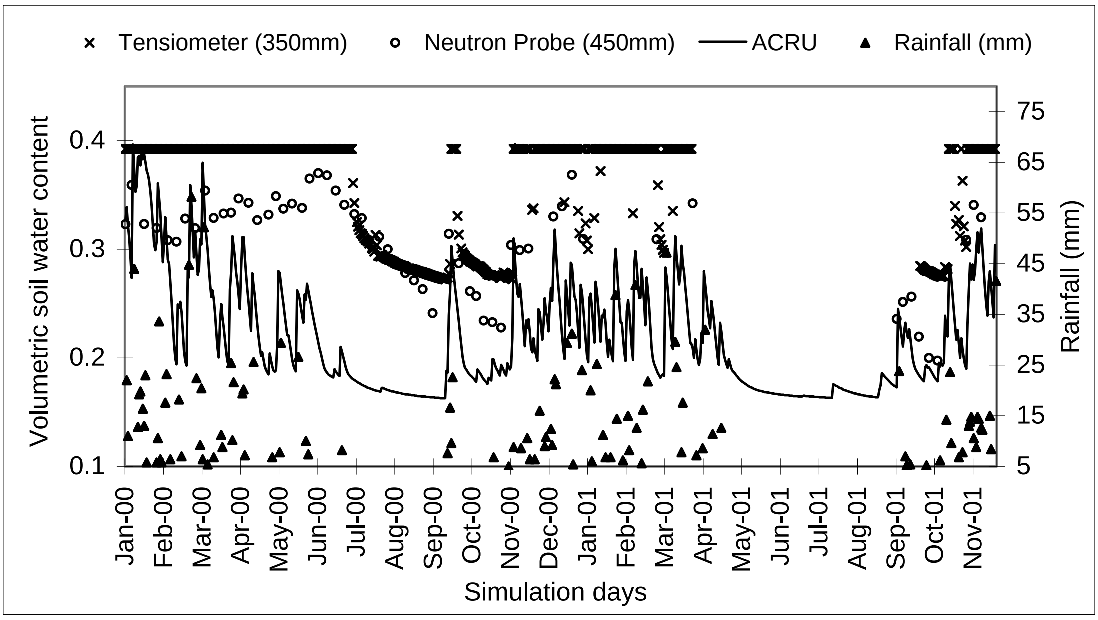

Figure 4.36. Comparison of *ACRU* model predicted A-horizon soil water content, and tensiometer and neutron probe measured soil water content for nest LC08 at Weatherley Hillslope 1 for the 350 mm soil depth.

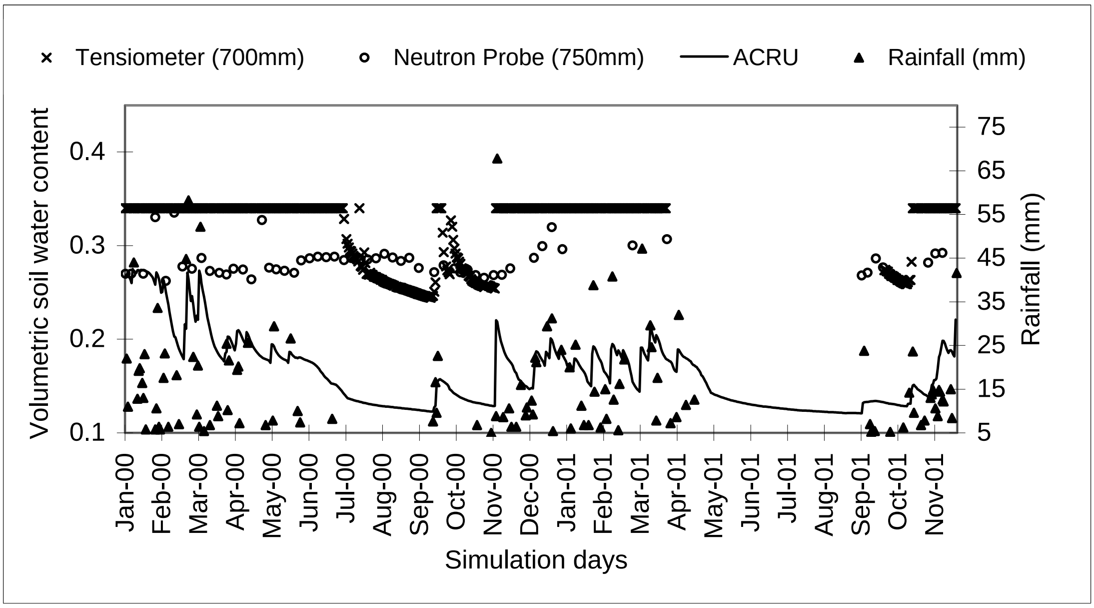

Figure 4.37. Comparison of *ACRU* model predicted B-horizon soil water content, and tensiometer and neutron probe measured soil water content for nest LC08 at Weatherley Hillslope 1 for the 700 mm soil depth.

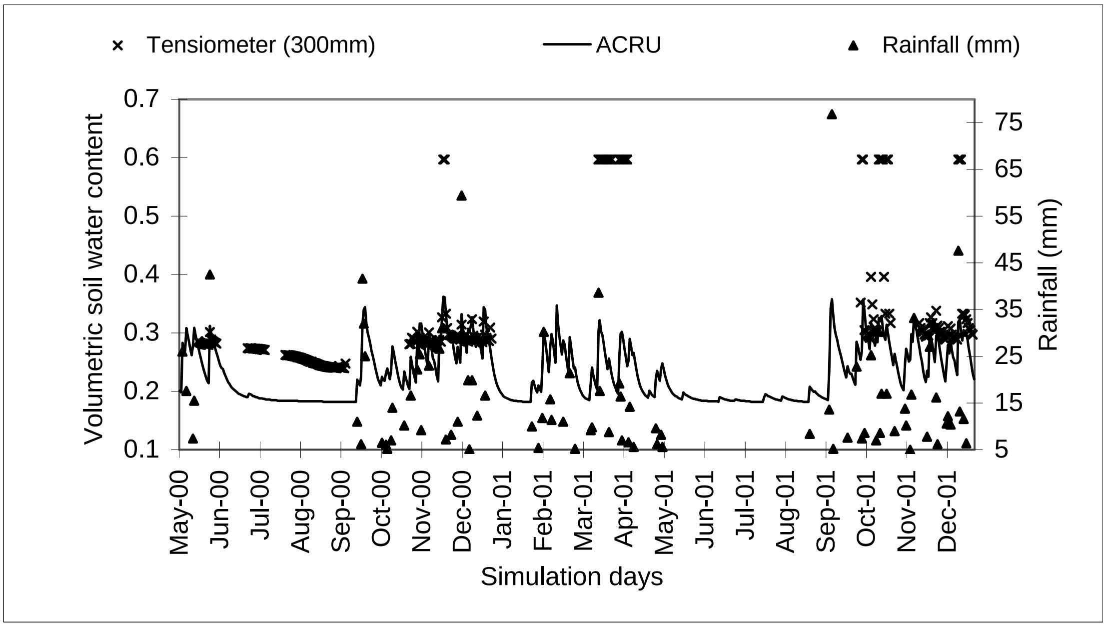

Figure 4.38. Comparison of *ACRU* model predicted and measured tensiometer soil water content for nest SG04 at Zululand Hillslope 2 for the 300 mm soil depth.

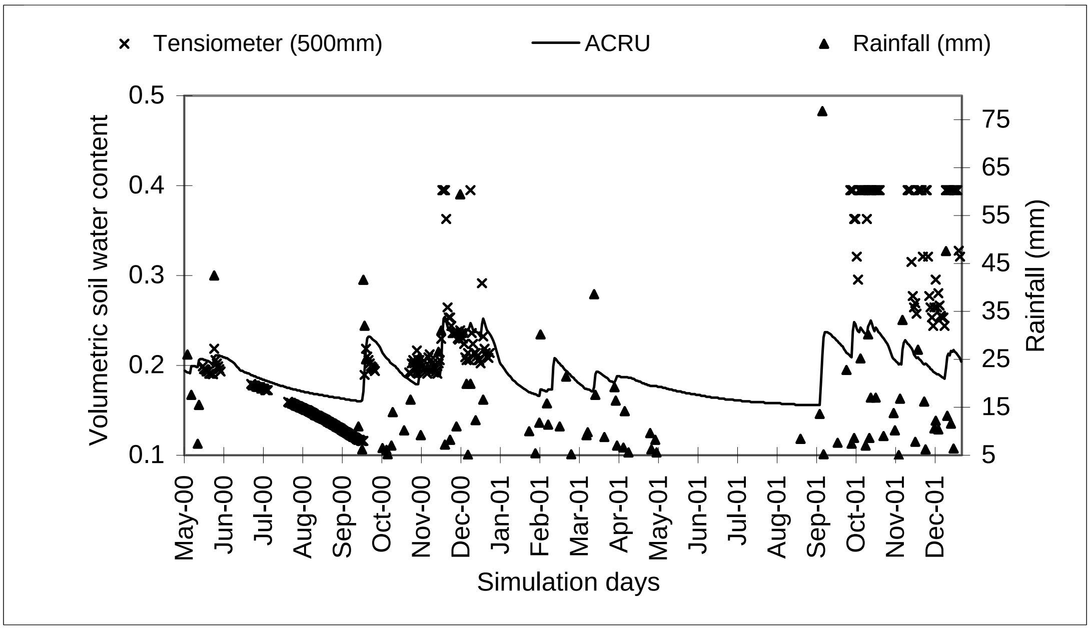

Figure 4.39. Comparison of *ACRU* model predicted and measured tensiometer soil water content for nest SG04 at Zululand Hillslope 2 for the 500 mm soil depth.

4.1.3.3 RUNOFF

The topological based *ACRU* model, configured in the distributed mode, with upslope contributions to the soil profile in the riparian zone, provided a reasonable prediction of the runoff observed at the downstream weir as can be seen in the daily simulations from January 1999 to December 2001 for the Weatherley catchment in Figures 4.40 to 4.42.

The maximum daily flows recorded were generally larger than those predicted by the *ACRU* model, despite the model allowing 95% of the rainfall event storm flow to manifest on the day of the storm. This was evident in peak events in February 1999 (Figure 4.40), February and March 2000 (Figure 4.41) and February 2001 (Figure 4.42). It was also clear that the predicted discharge recedes much faster than that observed as was clearly seen on 3 March 2000, (Figure 4.43), where a predicted maximum daily flow of 27.5 mm was followed by a discharge of some 2 mm. While the measured peak flow (33.5 mm) was reasonably predicted, the subsequent day's observed flow was 8.1 mm, which was greater than the predicted flow of 2.2 mm. Similarly, on 1 March 2000, the predicted flow reduced to 1.8 mm after a minor rain event, whereas the observed flow continued accumulating to 7.7 mm (Figure 4.43). This could be due to the *ACRU* model's inability to predict the retarded through flow, accumulating in the lower parts of the slope after events. Nevertheless the final base flows some four days after an event were successfully predicted, indicating that the evapotranspiration losses are faithfully represented in the model.

The *ACRU* model predictions at the H-flume of the W17 catchment in Zululand followed the trend of recorded runoff as is illustrated in Figure 4.44. However, the rapid responses recorded were not adequately simulated. Attempts to increase the variation between peak flow and baseflow, by increasing the percentage of rapid discharge from each event in the simulated flows, resulted in a poor representation of the sustained flows observed between rainfall events. This was evidence of the inability of the model to represent the rapid initial response, but sustained seepage from flow accumulations at the toe of hillslopes, observed in small catchments.

Clearly the *ACRU* model is designed for use in catchments far larger than those simulated in this study, but there was equally a lesson to be learned from these observed responses. Configuring the *ACRU* model in a terraced system appears to improve the simulation of sustained low flows post-event. Nevertheless, some improvements could be made by incorporating dominant features of sources and response times of hillslope mechanisms into the model.

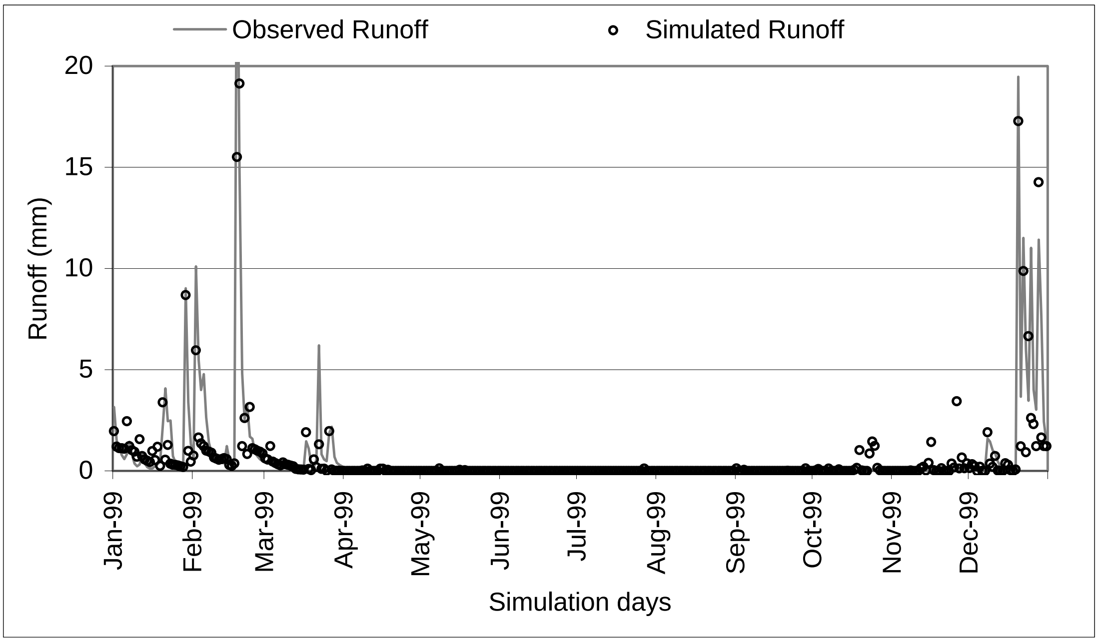

Figure 4.40. Comparison of *ACRU* model predicted and measured daily runoff at the lower weir, Weatherley, 1999.

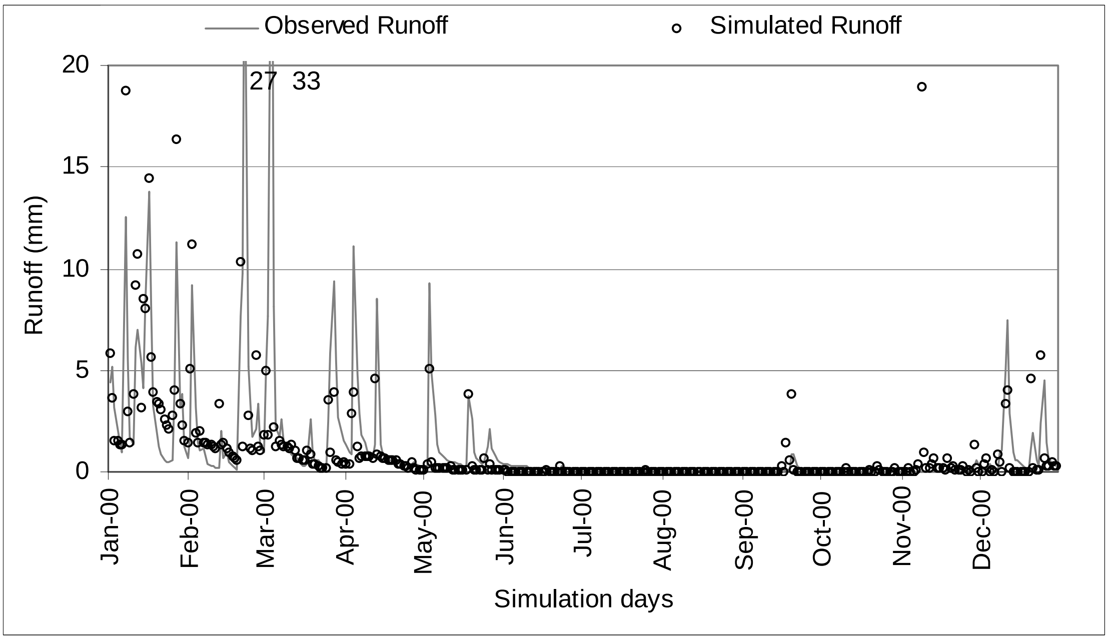

Figure 4.41. Comparison of *ACRU* model predicted and measured daily runoff at the lower weir, Weatherley, 2000.
* The values in the graphs are off-scale peak heights.

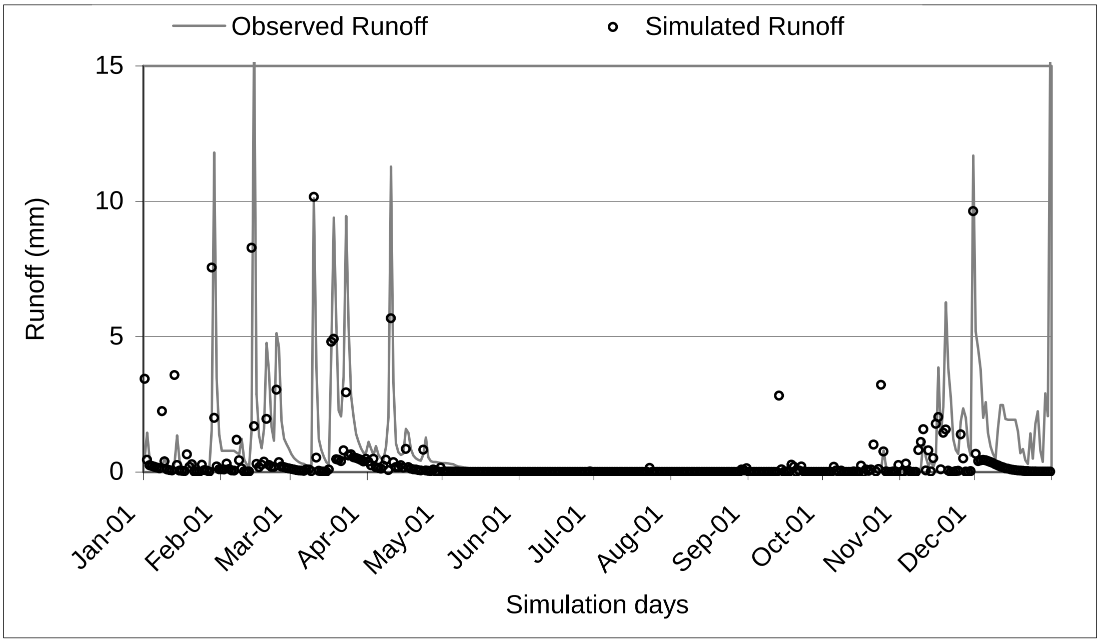

Figure 4.42. Comparison of *ACRU* model predicted and measured daily runoff at the lower weir, Weatherley, 2001.

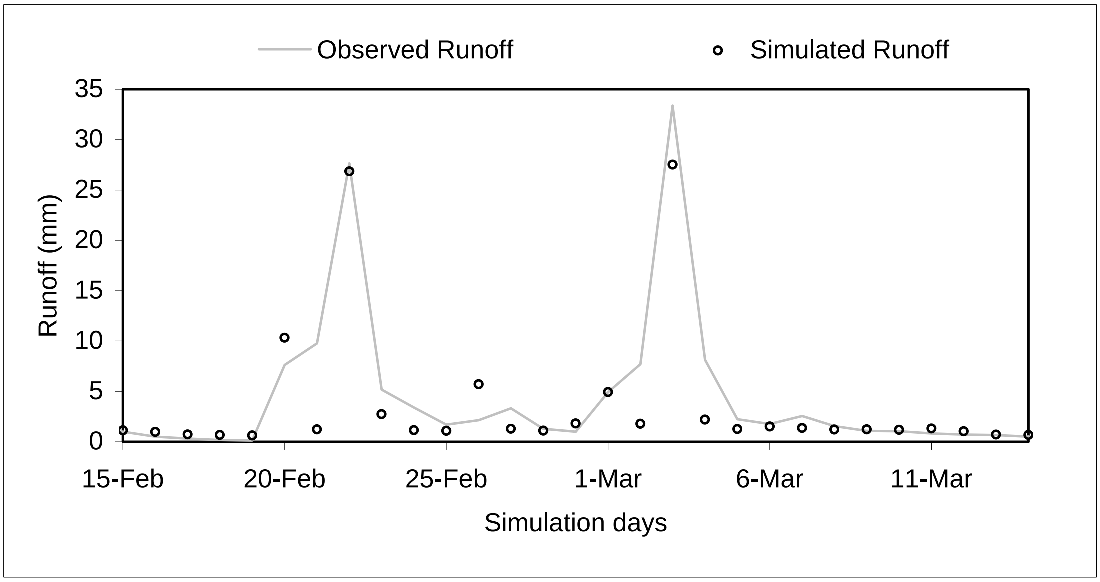

Figure 4.43. Comparison of *ACRU* model predicted and measured daily runoff at the lower weir, Weatherley, 15 February - 15 March 2000.

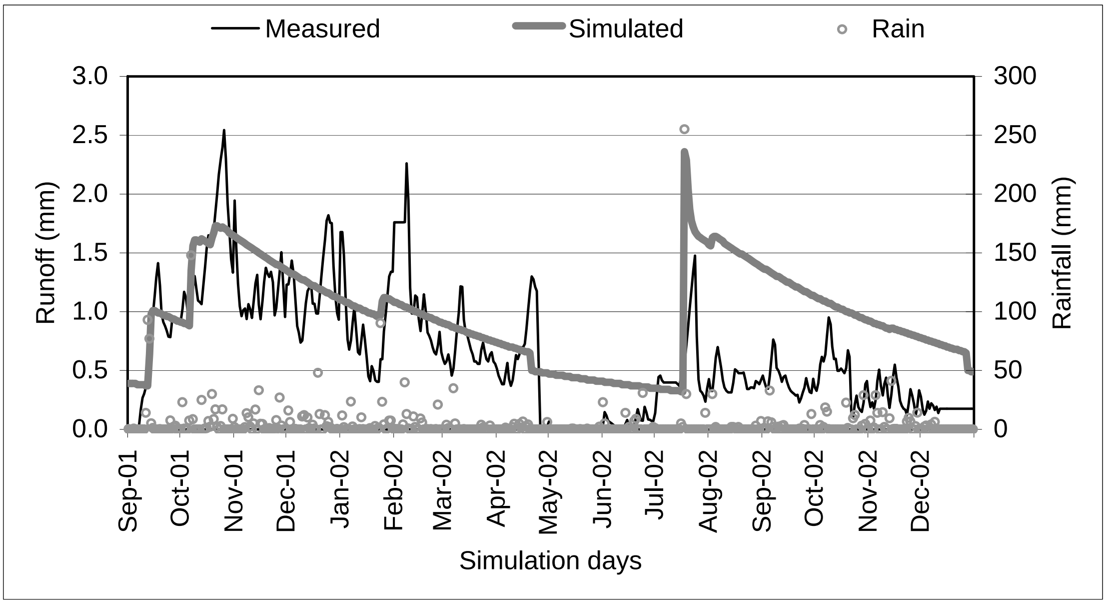

Figure 4.44. Comparison of *ACRU* model predicted and measured runoff at the H-flume in W17 catchment, Zululand.

4.2 SEDIMENT YIELD

Sediment yield measurements possess the advantage of providing a spatially integrated assessment of erosion rates in the upstream catchment area. Information on sediment yield at the outlet of a catchment can provide a useful perspective on the rate of erosion and soil loss in the catchment upstream. In principle, measurements of sediment yield at a single point at the catchment outlet can provide information on average rates of erosion within the catchment, whereas a large number of plot or similar measurements might be required in order to derive an equivalent average (Walling, 1994).

4.2.1 Typical Erosion Processes

There are several aspects that must be recognized in interpreting sediment yield measured at the outlet of a catchment. The first relates to the processes of sediment delivery or conveyance interposed between on-site erosion and downstream sediment yield. Only a fraction, and often a rather small fraction of the sediment eroded within a catchment reaches the basin outlet and is represented in the sediment yield. Deposition and temporary or permanent storage may occur on the hillslopes, particularly where gradients decline downslope at the base of a hillslope, in swales, on the floodplain, and in the channel itself. The second issue relates to the temporal discontinuity that may be involved in sediment delivery. Sediment eroded at one location may be stored temporarily and subsequently remobilised several times before reaching the drainage basin outlet. A third aspect stems from the fact that the sediment transported by a river represents material derived from a variety of sources in addition to upland erosion. These sources include channel and gully erosion and mass movements reaching the channel network.

The measurements of sediment made at the catchment outlet during this project refer to the sediment derived from runoff related concentrations of suspended solids. The bedload component was not included since it does not move relatively fast as it is stored and released by depressions and reservoirs within the river reach. It is difficult to identify a particular bedload sample with a hydrological process responding to a specific storm event, and elaborate devices are usually required to sample bedload. Consequently this component of sediment yield was not considered in this project and no effort has been made to estimate the bedload component. Sediment yields have also not been determined from weir survey data which will include both bedload and suspended load. However, this survey will necessarily lack the temporal resolution of weir sediment monitoring data aimed primarily at providing estimates of long-term sediment yields which did not fall within the scope of this project and available financial resources. The automatic ISCO samplers used were programmed to collect samples at predetermined increments of discharge which were obtained from a fixed inlet and not collected isokinetically. However, to date, there is no entirely satisfactory and generally applicable instrumentation for monitoring sediment.

At the field and small catchment scale, daily and event based sediment yield is expressed in terms of kg sediment delivered from a hillslope or small catchment. Since the area of the catchments / hillslopes differ, sediment yield is expressed as kg/ha in section 4.2 and in Chapter 5. For simulation over longer periods, such as the scenario predictions in Chapter 6, sediment yield at the field and catchment scale is preferably expressed as t/ha.a (International Soil Science Society, 1996).

4.2.1.1 WEATHERLEY RESEARCH CATCHMENT

At the Weatherley research catchment the topography is simple, but has a complex soil and soil erodibility pattern. A marsh exists along the entire reach of the stream and ranges in width from 100 to 400 m. Deposition and temporary or permanent storage of sediment may occur at this area on the hillslopes, causing low sediment delivery to the channel system. The catchment was under pristine grassland condition which served as a case study for background erosion values.

The channels at the upper reaches were under good grass cover with high root mass that favoured deposition in the channels, while at the lower reaches of the stream the channel is open and with little vegetation to cause backwater effects for potential deposition. Classical gullies also occur in the catchment from which sediment might have been delivered to the stream system. However, the selected models were not developed to simulate the classical gullies and their processes.

4.2.1.2 ZULULAND RESEARCH CATCHMENT

The Zululand research catchment is characterised by highly erosive rainfall events and steep topography. However, the very high infiltration rates and very low erodibilities of the soils cause very low erosion rates and consequently low sediment yield. No classical gullies occur in the catchment. Very dense vegetation with high root mass occupies the channels, causing channel erosion to be very low and deposition potential to be very high. A relatively new phenomenon in the catchment is that riparian areas are drained and cultivated for vegetable gardens and growing amadumbe. Since the riparian areas are those most susceptible to erosion in the Zululand catchment landscape it is expected that sediment yields will increase.

4.2.2 WEPP model

Verification of the sediment yield component of the WEPP model was conducted against daily sediment load values derived from runoff related concentrations of suspended solids for the Weatherley research catchment at the lower weir, and for the Zululand research catchment at the H-flume.

The sediment yield predicted by the WEPP model was compared with the daily sampled suspended sediment load at the lower weir of the Weatherley research catchment for the period January 2001 to September 2002 (Figure 4.45). The WEPP model predicted sediment yield for only a few rainfall events which coincided mostly with the big rainfall and runoff events. Although some predicted daily sediment yield was in close agreement with the measured sediment load, the variability in predicted sediment yield was high compared to the measured sediment load. No sediment yield was predicted for several days during the wet seasons although measured daily sediment load was higher than 0.3 kg/ha.day. On the other hand, daily sediment yield was over-predicted for certain rainfall events in the order of 5 to 12 times the recorded suspended sediment load (see values indicated in Figure 4.45). The profound effect that the WEPP model considers only infiltration excess overland flow and not partial area response or interflow on runoff

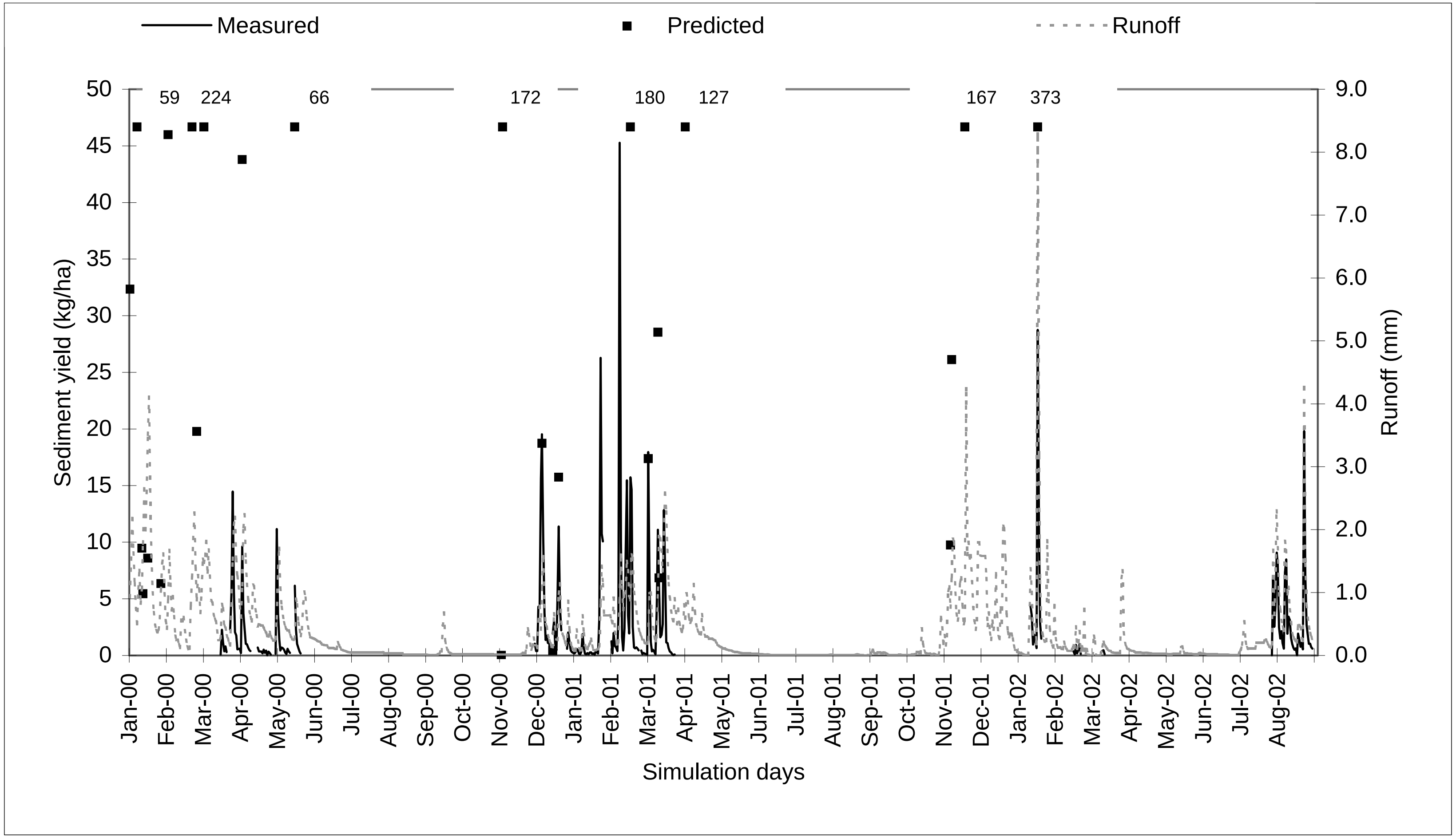

Figure 4.45. Comparison of WEPP model predicted sediment yield and measured suspended sediment load for the lower weir at the Weatherley catchment for the period January 2000 to September 2002.
* The values in the graphs are off-scale peak heights.

predictions (as discussed in section 4.1.2.2) was reflected in the sediment yield predictions. This was to be expected since the hydrological component of the WEPP model is the primary input to the erosion and sediment yield component by providing the erosion and sediment yield component with the duration of rainfall excess, rainfall intensity during the period of rainfall excess, the runoff volume and the peak discharge rate (Stone et al., 1995).

The predicted sediment yield and measured sediment load was summed on a monthly basis and is shown in Table 4.3 for months with a continuous record of sampled suspended sediment. The correlation between predicted sediment yield and measured monthly totals of suspended sediment was relatively poor (R^2 of 0.5059). Studies have shown variations in measured erosion data to be high, with the many unknown factors and interactions which occur in nature causing a high level of uncertainty in erosion predictions in general.

Table 4.3. The WEPP predicted sediment yield and measured suspended sediment totalled on a monthly basis for months with a continuous record of sampled suspended sediment for the Weatherley catchment

MONTH	PREDICTED SEDIMENT (kg/ha)	SAMPLED SEDIMENT (kg/ha)
April 2000	43.78	24.27
May 2000	66.15	30.81
December 2000	34.89	95.02
February 2001	197.87	133.22
March 2001	52.76	81.39
TOTAL	395.46	364.72

The sediment yield predicted by the WEPP model was compared with the suspended sediment load measured at the H-flume installed at the Zululand research catchment for the period January 2002 to April 2002 (Figure 4.46). The WEPP model predicted sediment yield for only two rainfall events which corresponded with the two major runoff events. For the first event, sediment yield was only a fifth of the measured sediment load, whereas the predicted sediment for the second event was almost double that measured. Except for these two events, no sediment yield was predicted which was in contradiction with the measured sediment load. Measured daily suspended sediment load varied mostly around 1.27 kg/ha.day with a minimum value of 0.25 kg/ha.day for the recording period. The effect of the limitation that the WEPP model considers only infiltration excess overland flow on runoff was reflected in the sediment yield predictions. When the total amounts of predicted sediment yield (28.89 kg/ha) and sampled suspended sediment load (221.83 kg) were compared for the recording period, the WEPP model under-predicted sediment yield by a factor of 7. This illustrated the effect of the limitation in the WEPP model by not considering partial area response or interflow on sediment yield predictions at the Zululand research catchment.

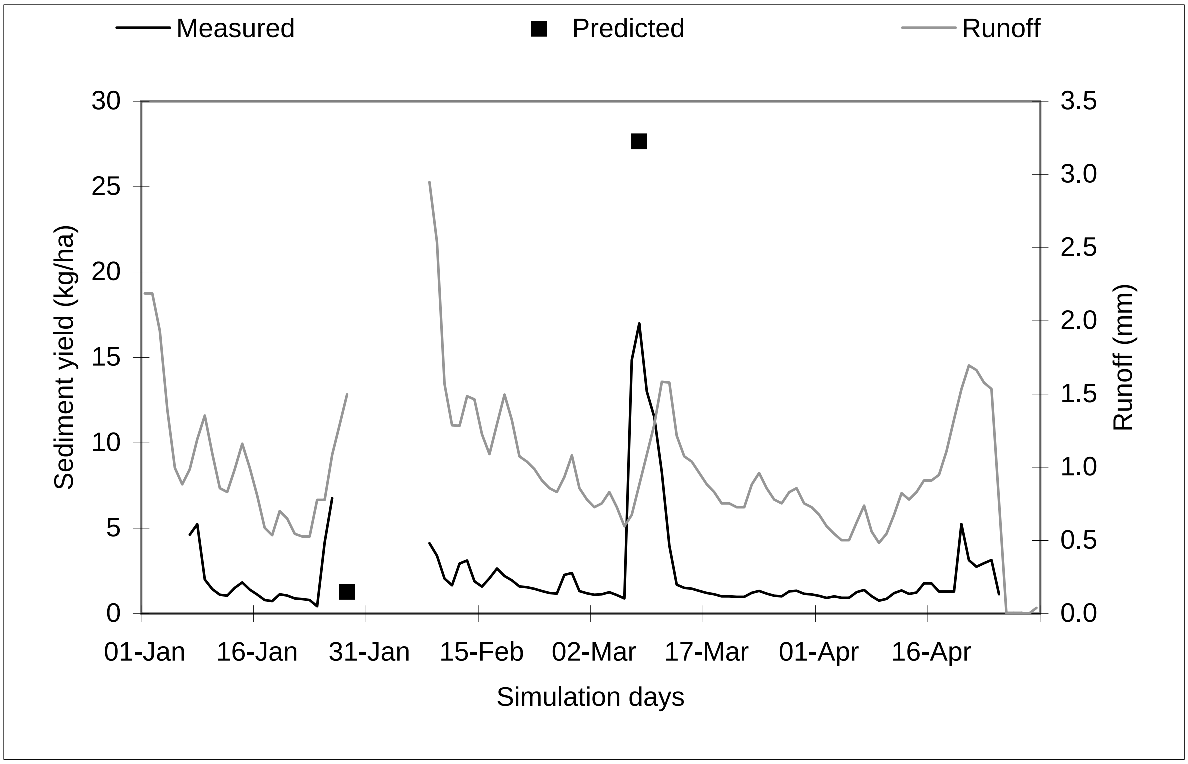

Figure 4.46. Comparison of WEPP model predicted sediment yield and measured suspended sediment load for the H-flume at the Zululand catchment for the period January 2002 to April 2002.

4.2.3 *ACRU* model

The *ACRU* model has over-predicted the daily sediment yield in the Weatherley catchment (Figure 4.47). These over-predictions may be exacerbated by the fact that there were no measurements made over some of the apparently high daily sampled suspended sediment events. The initial simulations were performed with a cover factor of 0.02, representing the average conditions of the veld in the catchment. However, this parameter was reduced to 0.011, indicative of a good grass cover with at least 25% ground cover, as was the case on the lower slopes. This has produced some reasonable predicted sediment yields as shown in the detailed period January to April 2001 (Figure 4.48). These were typical of the smaller sampled sediment loads, which were reasonably predicted. Unfortunately the highest predicted daily sediment yield of some 130 kg/ha in early 2000 has no corresponding measured estimates. Since the extreme events were responsible for the bulk of the long-term sediment yield, it is imperative that some of these larger events be observed.

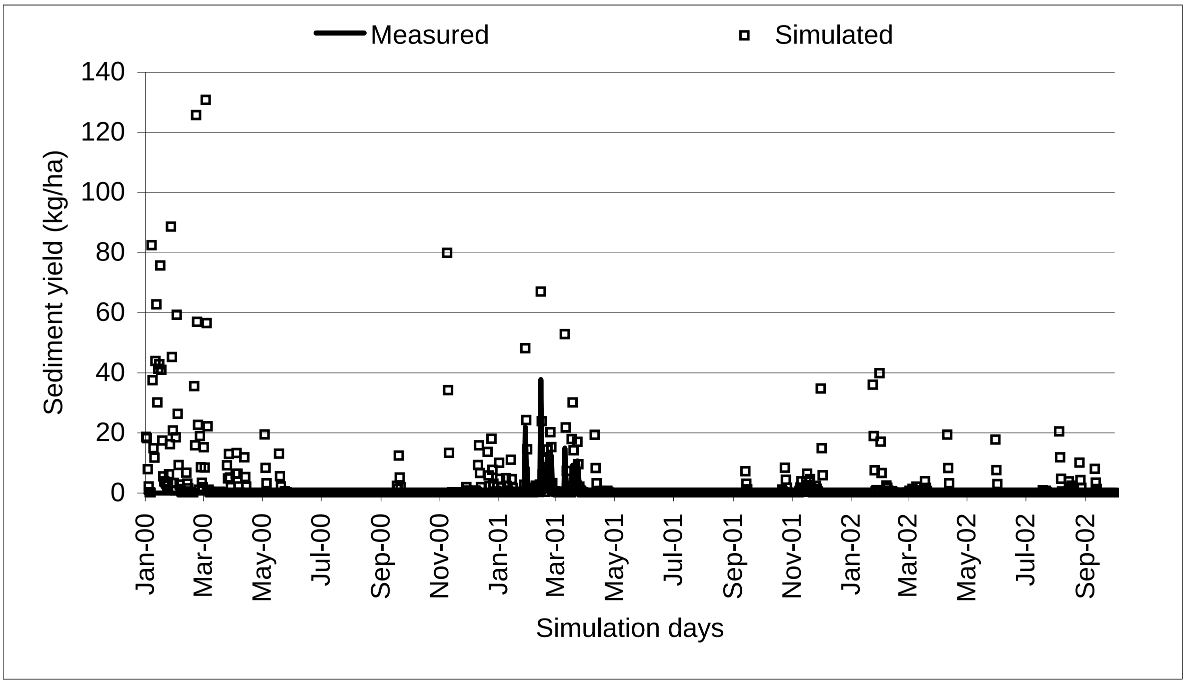

Figure 4.47. Comparison of *ACRU* model predicted sediment yield and measured suspended sediment load at the lower weir, Weatherley, January 2000-October 2002.

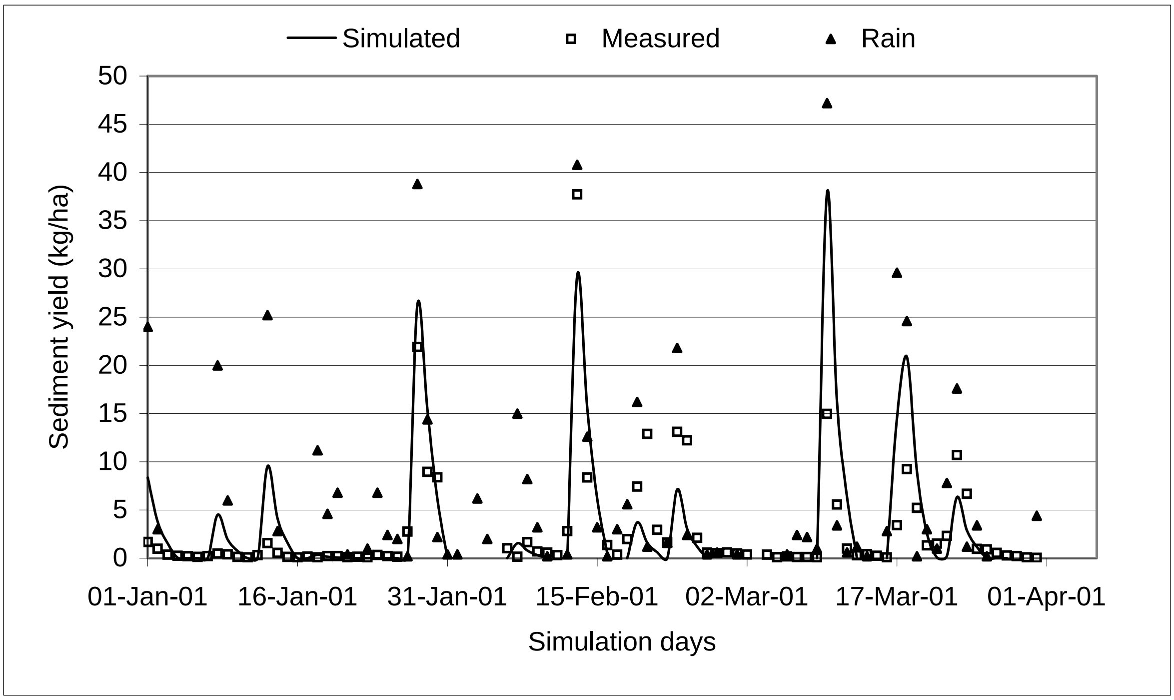

Figure 4.48. Comparison of *ACRU* model predicted sediment yield and measured suspended sediment load at the lower weir, Weatherley, January 2001-April 2001.

A comparison of predicted sediment yield and measured sediment load for those days in which both measured and predicted yields were available, reveals that the predicted sediment yields were evenly spread about the 1:1 line of equal predicted yield and observed load (Figure 4.49). However, the variability was high. The maximum predicted daily sediment yield from this set of values was some 38 kg/ha.day, which was more than double the sediment load of 13 kg/ha.day estimated from suspended sediment measurements. The maximum daily sediment load derived from a measured event, 39 kg/ha.day, was 26% greater than the 29 kg/ha.day predicted sediment yield. This variability can be attributed to the lack of detail of prevalent cover conditions, inability of the model to capture the effects of events of different intensity and to the variability in the predicted hydrology, which drives the erosion and sediment transport.

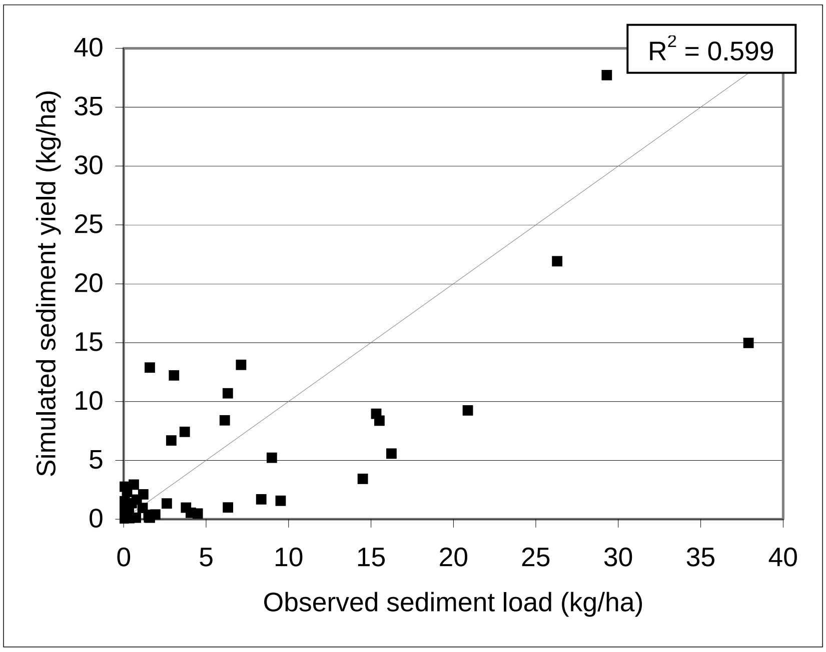

Figure 4.49. Scatter plot of *ACRU* model predicted daily sediment yield and measured daily sediment load at the lower weir, Weatherley, January 2000 - December 2002.

The cumulative sediment yield over the months during which there was a continuous record of sampled suspended sediment reveals a total of 453 kg/ha predicted against 367 kg/ha measured. This indicates an over-prediction of sediment yield, but, since the comparison does not include sampled suspended sediment for the extreme events of early 2000, this should not be taken as conclusive. A comparison of the monthly predicted sediment yield and measured sediment load presented in Table 4.4 shows that the total sediment yield for February 2001 was lower than that estimated from sampled sediments. The remaining four months in this set were over-predicted. This supports the notion that the *ACRU* model predicts long-term sediment yields adequately, but fails to reproduce observed daily sediment yield consistently.

Table 4.4. The *ACRU* predicted sediment yield and measured suspended sediment totalled on a monthly basis for months with a continuous record of sampled suspended sediment for the Weatherley catchment

MONTH	PREDICTED SEDIMENT (kg/ha)	SAMPLED SEDIMENT (kg/ha)
April 2000	57.53	24.27
May 2000	63.77	30.81
December 2000	104.67	95.02
February 2001	85.73	133.22
March 2001	141.80	81.39
TOTAL	453.47	364.72

The predicted sediment yields in the Zululand catchment at the H-flume were significantly lower than the measured daily suspended sediment load (Figure 4.50). However, the sediment yield was naturally low in this well vegetated subcatchment. The maximum measured daily sediment load was some 4 kg/ha, while that predicted was 0.5 t/ha. The failure of the model to reproduce these sediment yields reflected its inability to predict the smaller sediment yield events. On a catchment of this size, the intensity of the rainfall event is significant in determining the resulting sediment yield. On a daily time step, as simulated in the *ACRU* model, this resulted in a smaller predicted discharge and peak flow as was illustrated in Figure 4.44. The resulting predicted energy for erosion and sediment transport is thus lower than the prevailing condition.

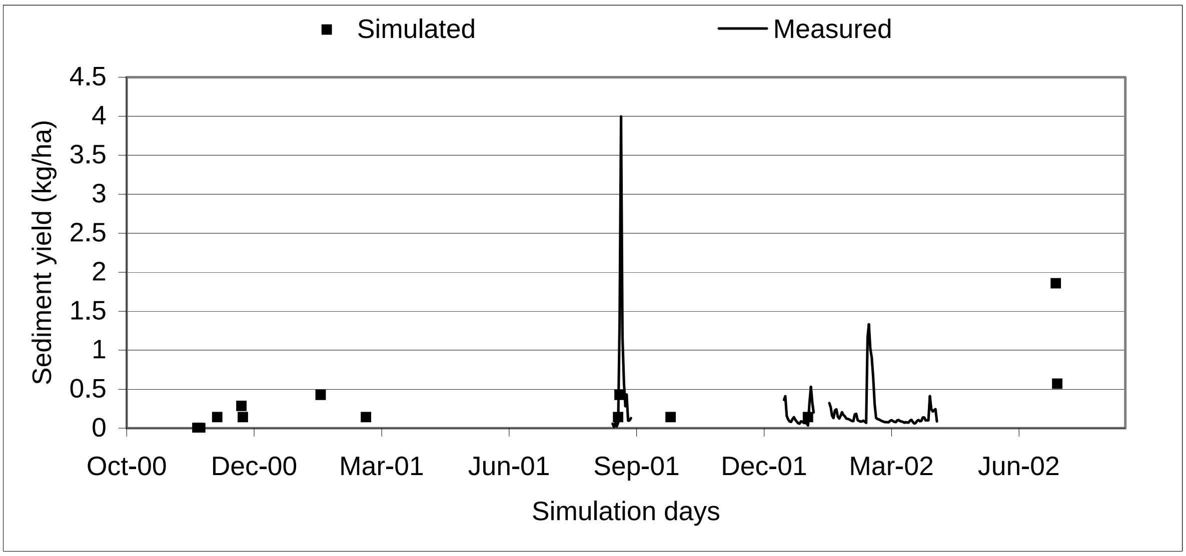

Figure 4.50. Comparison of *ACRU* model predicted and estimated daily sediment loads at the H-flume, Zululand, October 2000-June 2002. (Measurements started in September 2001).

Caution should therefore be exercised when using the *ACRU* model on small catchments where variation in rainfall intensity dominates the sediment delivery process. In addition, the source of surface water discharge needs to adequately represented in the model at this scale.

CHAPTER 5
PARAMETERISATION EFFECTS

Data with a high spatial and temporal resolution were used to prepare the model input files for the model verification discussed in the previous chapter. These included *inter alia* 1-minute time step recorded rainfall (for WEPP model), 10 X 10 m (0.01 ha) Digital Elevation Models and detailed soil maps (30 and 90/100 m grid observation points). However, this level of detailed data exists only for a limited number of research catchments / areas and the model user would most often be faced with coarser scale data. Furthermore, due to the decreased time in data preparation and computer run-time for lower levels of discretization (by spatial / temporal lumping of data) of modelling units, users are most often tempted to choose a coarse level of discretization. Consequently, it was important to verify the performance of the models where input data files were prepared from various scales of spatial and temporal resolution of input data being proposed in the third objective of this study. An verification of a model's response to the spatial and temporal resolution of input data can yield a great deal of insight into the nature of the model. Also, to the degree that the model accurately represents the physical system which it simulates, sensitivity analysis can provide insight into the factors which influence the response of the physical system. Several sensitivity analyses were conducted on model input parameters of the WEPP model and *ACRU* model to identify those parameters that are the most important to estimate accurately. Since previous studies discussed the parameter sensitivity analysis and uncertainty propagation of the WEPP model (e.g. Nearing, Deer-Ascough and Laflen, 1990; Baffaut, Nearing, Ascough and Liu, 1997) and the *ACRU* model (e.g. Schulze, 1995b), similar studies were not repeated in this project given that the parameters to which the models are sensitive are known. The focus of this chapter was rather on the impact that the level of discretization has on the prediction results.

5.1 RAINFALL FREQUENCY

Time series data on precipitation are the input data that drive the hydrological components of sediment yield models, and consequently the models will be sensitive to rainfall data as a key model parameter. The *ACRU* model uses daily rainfall data to drive the hydrological model for the sediment yield component, whereas the WEPP model uses both rainfall amount and storm intensities of breakpoint rainfall data as model inputs to drive the hydrological, erosion and sediment yield components of the model. For the *ACRU* model, 1-minute recorded rainfall data were totalled on a daily basis before the model menubuilder files were prepared. The effect of rainfall frequency on the *ACRU* model was not evaluated, because the *ACRU* model could not run on rainfall data other than daily rainfall.

5.1.1 WEPP model

Sensitivity analyses were performed by Nearing et al. (1990) to determine the sensitivity of the WEPP model hillslope version to soil, plant and residue, slope profile and hydrological parameters. They concluded that the WEPP model was extremely sensitive to both the hydrological inputs of rainfall intensity and runoff rate. Intensity was particularly important for hillslopes and overland flow elements (modelling units along the hillslopes that across their width are relatively homogeneous in terms of soil and land management) with low slope gradients and short slopes, i.e. where interrill detachment was important. Runoff rates were important on all ranges of slope lengths and gradients. The results show the major importance of good hydrological estimates for the WEPP model in order to produce reasonably accurate erosion rates.

The BreakPoint Climate Data Generator (BPCDG) program (Zeleke, Winter and Flanagan, 1999) was used to create the climate input file for the WEPP model. The precipitation file of the BPCDG program required information on the rainfall storm pattern, which included information on the amount of rainfall, intensity and beginning and end times for each of the storm intensity slope breaks. The intensity slope breaks were identified manually from plots of cumulative rainfall amount (y-axis) and time (x-axis) for each rainfall event for the 1-minute recorded rainfall data. The rainfall amount and beginning and the end times for each slope break were then determined. In order to analyse the effect of the temporal resolution of the rainfall record, the 1-minute recorded data were totalled on the basis of 15- and 60-minute time steps. The intensity slope breaks and information on the storm pattern were then determined as discussed above for the 1-minute recorded rainfall data.

The effects of 1-, 15- and 60-minute time step rainfall data on predicted sediment yield from Hillslopes 1, 2a and 3 at the Weatherley catchment were compared for the years 1998 to 2001 and are illustrated in Figures 5.1, 5.2 and 5.3 respectively. The amount of predicted events that produced sediment yield at the hillslopes differed considerably between the 1-, 15- and 60-minute time steps. For the 1-minute time step, 30 events were predicted, whereas for the 60-minute time step no event was predicted at any of the hillslopes. Only three events were predicted at Hillslopes 1 and 2a, and five at Hillslope 3 for the 15-minute time increment. Although the magnitude of the predicted sediment yield matched that of the predicted runoff for these events, predicted runoff was much higher at two events than the predicted sediment yield. Both these events occurred during February. Maximum values for the leaf area index and above-ground live biomass were predicted for February (see Figure 4.9). The good soil surface cover protected the soil from erosion through protecting the soil from direct raindrop impacts and by decreasing the peak runoff ratio owing to the higher Mannings roughness coefficients. Figure 5.4 demonstrates the effect of 1-, 15- and 60-minute time step rainfall data on predicted sediment yield at the lower weir of the Weatherley research catchment.

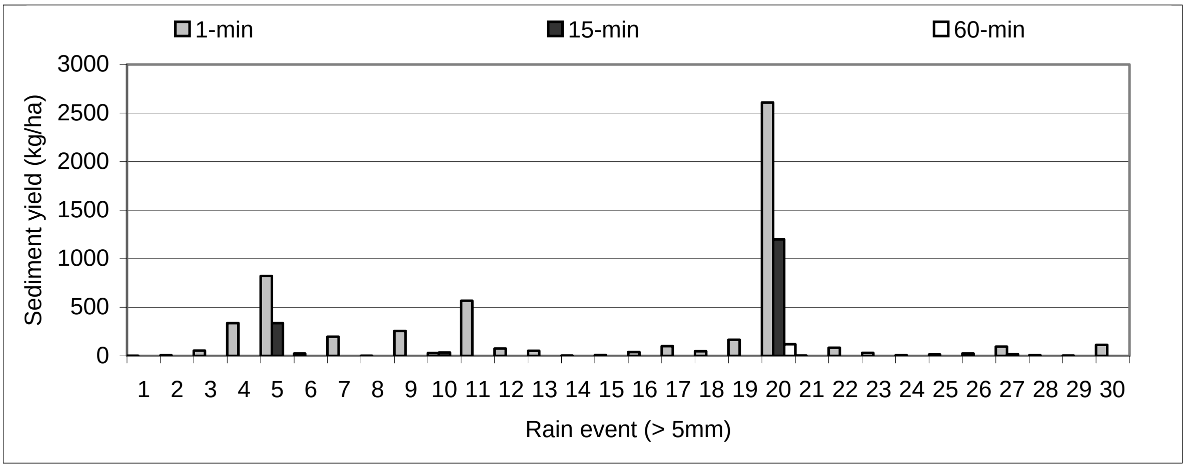

Figure 5.1. Comparison of the WEPP model predicted sediment yield for Weatherley Hillslope 1 between 1-, 15- and 60-minute time step rainfall data for the period 1998 to 2001.

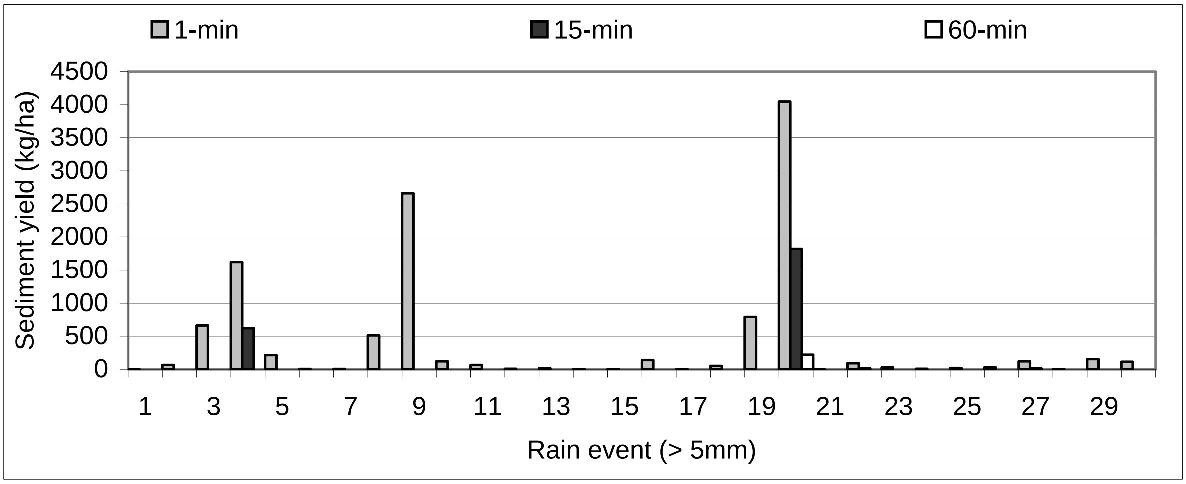

Figure 5.2. Comparison of the WEPP model predicted sediment yield for Weatherley Hillslope 2a between 1-, 15- and 60-minute time step rainfall data for the period 1998-2001.

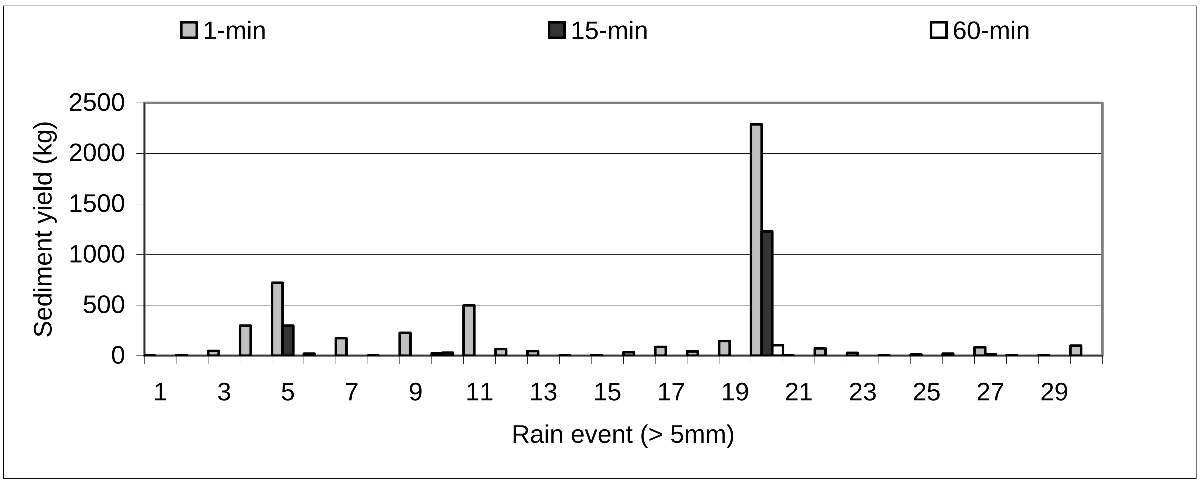

Figure 5.3. Comparison of the WEPP model predicted sediment yield for Weatherley Hillslope 3 between 1-, 15- and 60-minute time step rainfall data for the period 1998 to 2001.

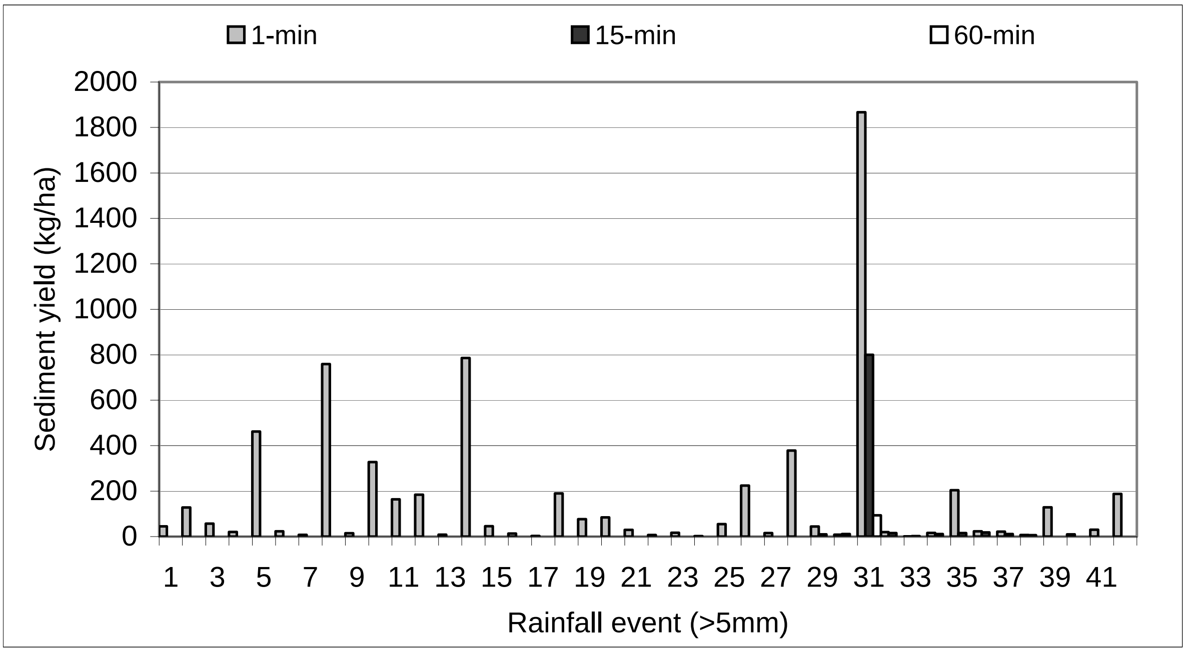

Figure 5.4. Comparison of the WEPP model predicted sediment yield at the lower weir of Weatherley between 1-, 15- and 60-minute time step rainfall data for the period 1998 to 2001.

The considerable under-prediction of sediment yield at the hillslopes when 15- and 60-minute time step rainfall data were used as a substitute to the 1-minute rainfall data was reflected in the predicted sediment yield at the lower weir of the Weatherley catchment. Sediment yield was predicted for only seven and two events with the 15- and 60-minute time step rainfall data respectively, compared with the 41 events when 1-minute time step rainfall data was used. In the three cases where considerable runoff was predicted but only small amounts of sediment yield, the good soil surface cover during February 2000 and 2001 protected the soil from erosion as discussed above. The predicted sediment yield that was simulated from the 1-minute rainfall record was in close agreement with the measured suspended sediment load, except for events 29 and 35 (Figure 5.4). It is evident that the predicted sediment yield from the 15-minute rainfall data was in closer agreement with the measured suspended sediment load than the predicted sediment yield when the 1-minute recorded data were used. This suggests that the WEPP model could over-predict sediment yield in certain cases when 1-minute time step rainfall data were used.

The effects of 1-, 15- and 60-minute rainfall time steps on predicted sediment yield at Hillslopes 1 and 2 at the Zululand catchment were compared for the year 2001 and are illustrated in Figures 5.5 and 5.6.

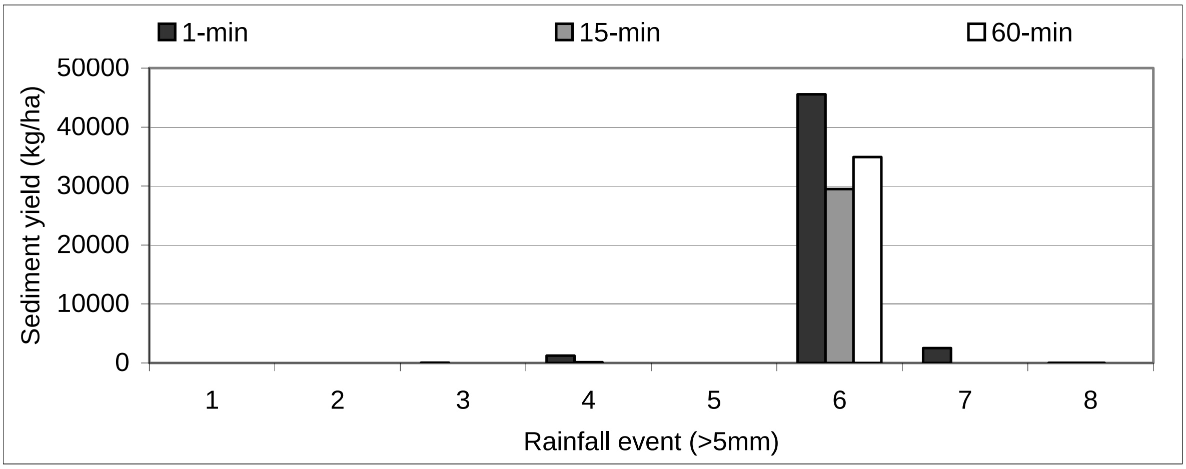

Figure 5.5. Comparison of WEPP model predicted sediment yield at the Zululand Hillslope 1 between 1-, 15- and 60-minute time step rainfall data for the period 2001.

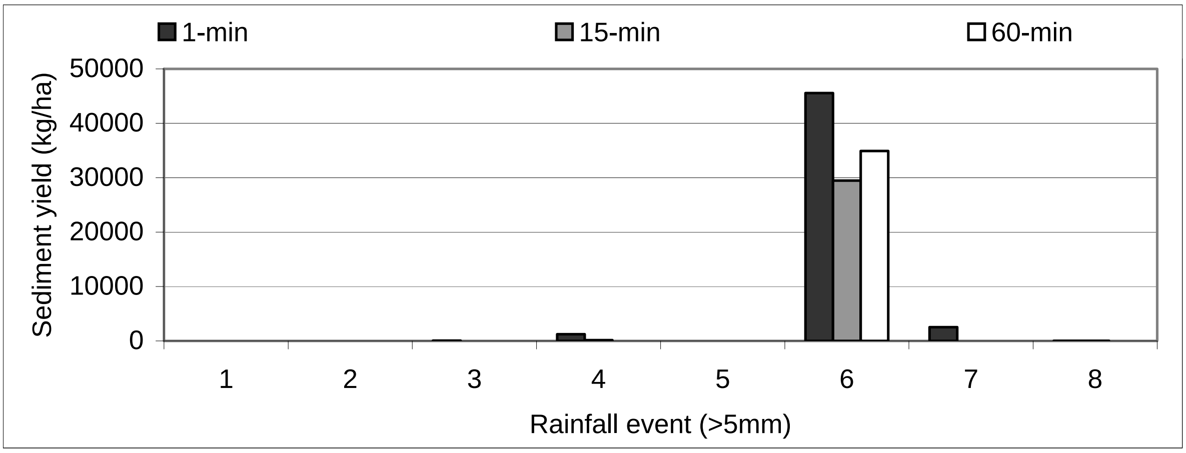

Figure 5.6. Comparison of WEPP model predicted sediment yield at the Zululand Hillslope 2 between 1-, 15- and 60-minute time step rainfall data for the period 2001.

The amount of predicted events that produced sediment yield at the hillslopes differed considerably between the recorded 1-minute time step and both the 15- and 60-minute time steps. For the 1-minute time step, ten and eight events were predicted for Hillslopes 1 and 2 respectively, whereas for the 15- and 60-minute time steps only two events were predicted. The sediment yield predicted for the latter two events were in the same order of magnitude as for that predicted for the two events for the 1-minute time step, due to the large rainfall events (92 and 148 mm) which took place on both those days. In contrast with the eight events in which the WEPP model predicted sediment delivered at the end of Hillslope 2, the WEPP model predicted sediment yield for only two events at the H-flume when 1-minute time step rainfall data were used. When 15- and 60-minute time step rainfall data were used, the WEPP model predicted sediment yield at the H-flume for only the day with 148 mm rainfall. The sediment yield predicted at the H-flume was comparable when 1-, 15- and 60-minute time step rainfall data were used to prepare the rainfall data file.

The results of the effect of the time resolution of the rainfall data record indicated that the WEPP model was extremely sensitive to the temporal resolution of the rainfall data record because this model is very sensitive to storm intensity in addition to rainfall amount. When the time step in rainfall data was increased from 1 to 15 minutes, storm intensity almost always decreased, which had a profound effect on the interaction between the infiltration capacity and rainfall flux simulated by the WEPP model. When storm intensity was calculated from 60-minute time step rainfall data, the intensity was so low that the WEPP model did not predict any runoff and sediment yield, except for extreme rainfall events as indicated at the Zululand research catchment. The rainfall amount and storm intensity interaction played an important role in the simulations of the WEPP model in that infiltration excess overland flow could only be generated when the storm intensity exceeded the infiltration capacity. Secondly, it is also important in transforming the time intensity distribution of rainfall excess (after ponding) into a time intensity distribution of runoff to simulate sediment delivery during peak runoff amounts. These results confirmed the conclusion made in Chapter 4 that the application of the WEPP model is restricted to areas where infiltration excess overland flow occurs. Since the WEPP model could only predict runoff and sediment yield for breakpoint rainfall data prepared from 1-minute time step recording periods, the application of the WEPP model is restricted to areas where these very detailed rainfall records exist, which are normally limited to research projects with some focus on storm intensities. Even so, both the Department of Water Affairs and Forestry and the South African Weather Service had rain gauges that could measure to 1-minute time step resolution, but that data was normally discarded after it had been converted to hourly averages (Basson, 2003; Personal communication). It is expected that 1-minute rainfall data would most probably be collected for the area where the intention is to apply the WEPP model, which has the drawback of too short a period of recorded rainfall for erosion and sediment yield studies.

5.1.2 *ACRU* model

The *ACRU* model is a daily time step simulation model. Therefore no other time steps were attempted. Nevertheless, sub-daily time interval fluxes were observed in both catchments, particularly those in the Weatherley catchment from the near surface macropore zone. In order to cater for this rapid response, the *ACRU* model simulations were set up to release 95% of the stormflow generated by a rainfall event within the day of the event. This was exceptionally high for this particular process, but the catchment is small, flow paths are relatively short and flow rates were rapid in the saturated state.

5.2 TOPOGRAPHY AND SOIL

5.2.1 WEPP model

The first two important questions a user faces when trying to model a catchment are: “What channels should be represented in the model?” and “How many hillslope profiles should be used to characterise an area?” The process of identifying the channels and hillslopes which represent the catchment components is called catchment discretization. The spatial variability and the complexity of patterns in soil, topography and land management do not only affect the layout of the channels and hillslopes, but also the amount of overland flow elements (areas along a hillslope with relatively homogenous soil and land management). The WEPP model allows the user to characterise the slope profile (slope lengths and steepness) with up to ten relatively homogeneous slope units along the hillslope. However, the level of discretization greatly influences the data requirement and the required computer time, increasing them according to the number of hillslopes and channels used. Furthermore, the wide range of conditions that the WEPP model can represent requires a large number of parameters to characterise the various hillslopes and channels. For large catchments, the representation of all channels and hillslopes adds to the cost of data preparation and required computer time and may not increase accuracy.

The Zululand catchment is spatially highly heterogeneous in terms of topography and land use. This was ideal to verify the incorporation of spatial discretization by models. Unlike Zululand, the topography of Weatherley is simple, but has a complex soil pattern. For the watershed version of the WEPP model, it is important to know the impact which the level of discretization has on the results. It is important to evaluate the sensitivity of the results to the amount of detail in the data and to estimate the level of discretization which is appropriate.

For the verification study the Weatherley and Zululand research catchments were characterised according to the slope, the soil units and land management. This had led to numerous hillslopes which were further divided into several overland flow elements (OFEs) to take account of the spatial variability along the stream system and the hillslopes. A lot of time was spent in the preparation of the input data for each of the OFEs for the various hillslopes and channels (indicated as distributed OFEs in the following figures) from the acquired spatially distributed data. In order to evaluate the effect of various levels of spatial representivety, the OFEs along a hillslope were first lumped together by means of weighted averages to give two OFEs per hillslope, one that represents the crests and midslopes and another that represents the footslopes and valley bottoms (indicated as lumped OFEs in the following figures). The second level by generalising the spatial representivety was to calculate one weighted average value for the hillslope (indicated as weighted average in the following figures). These generalisations take account of the effect of spatial representivety along the hillslope. In order to take account of the effect of spatial representivety along the stream system across the hillslopes, the catchment was discretizised by lumping the hillslopes as illustrated in Figure 5.7.

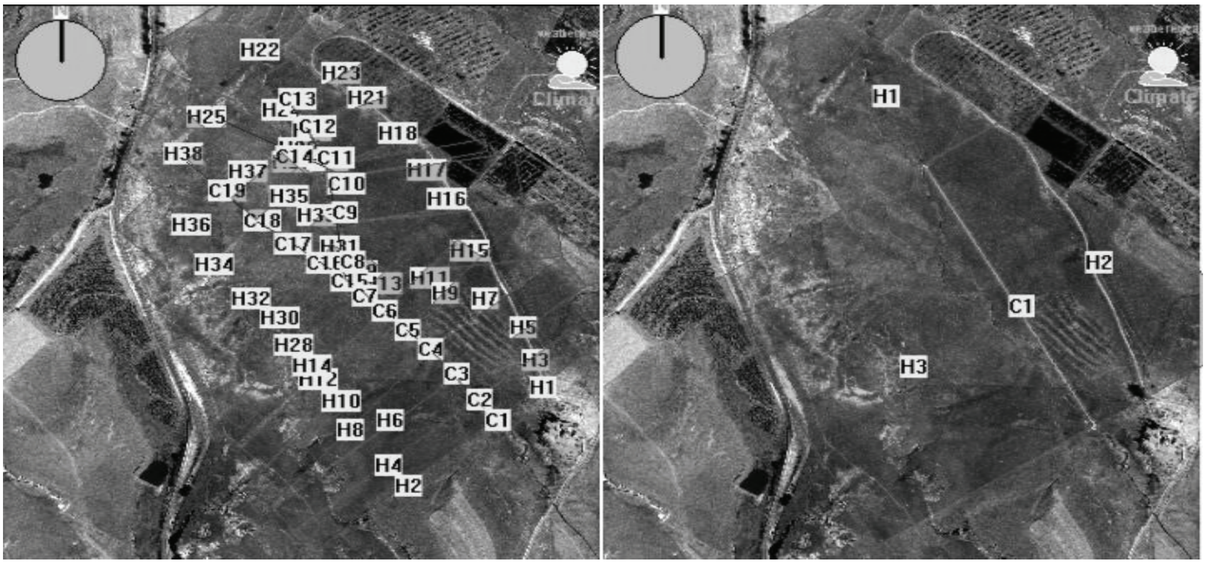

Figure 5.7. Discretization of the Weatherley catchment; on the left is a high level of discretization (indicated as distributed in Figure 5.11) and on the right is the catchment discretizised into three hillslopes and one channel which is an example of a low level of discretization (indicated as catchment discretization in the Figure 5.11).

The effects of different levels of spatial representation of slope and soil profile along the selected hillslopes at the Weatherley catchment are shown in Figures 5.8 to 5.10. Generally, a trend towards a decrease in sediment delivery at the end of Hillslopes 1 and 3 was observed as the level of spatial representation along the hillslopes increased. However, at Hillslope 2a no difference in the sediment delivery was found between the levels of spatial representation. This could be ascribed to relatively similar slope profiles along the hillslope and the absence of the marsh area where deposition and temporary storage may occur. The predicted sediment delivery values at the end of Hillslopes 1 and 3 were relatively similar, but differed from that predicted from the distributed OFEs scenario. This indicated that the WEPP model was able to take account of the variability in micro-topography for deposition and temporal storage and possibly of soil hydraulic conductivity along the hillslope catena. However, a larger variation between the different levels of spatial representation was expected due to the rather complex and spatially variable hillslope flow mechanisms and water fluxes along the hillslope catena described in section 4.1.1.1. This confirms the conclusion made in Chapter 4 that the WEPP model was unable to properly take account of the effect by not considering partial area response or interflow on sediment yield predictions. Figure 5.11 illustrates the catchment discretization effect.

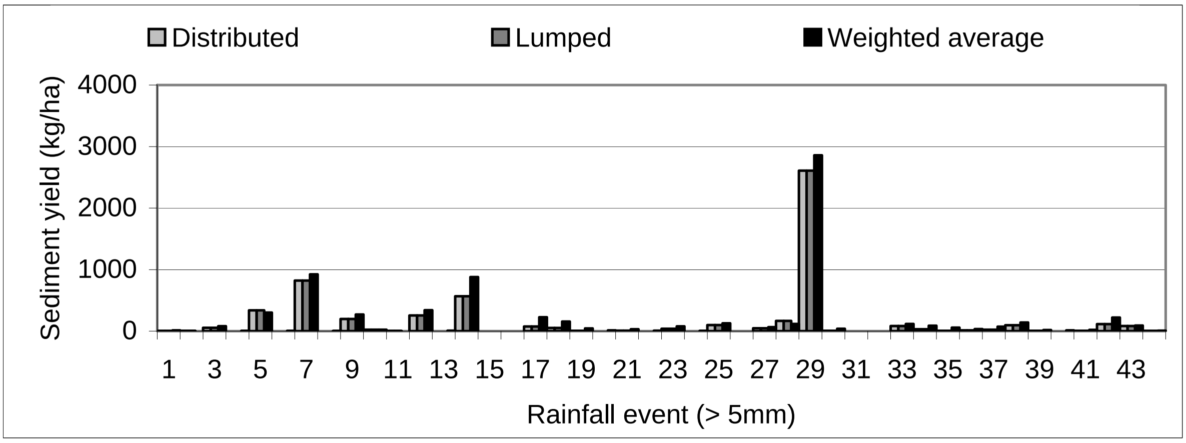

Figure 5.8. Effect of various levels of spatial representation of the soil and topography at Hillslope 1 of the Weatherley catchment.

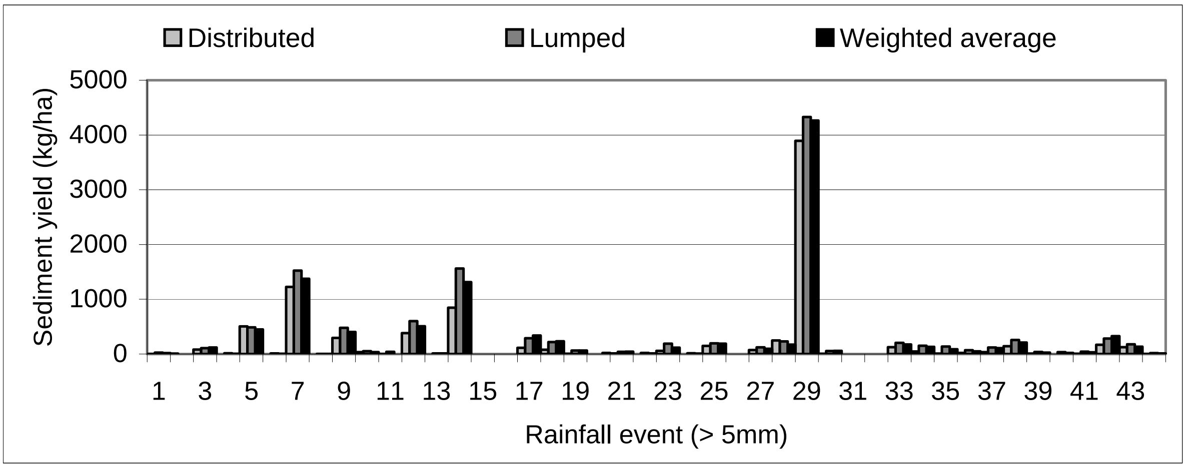

Figure 5.9. Effect of various levels of spatial representation of the soil and topography at Hillslope 2a of the Weatherley catchment.

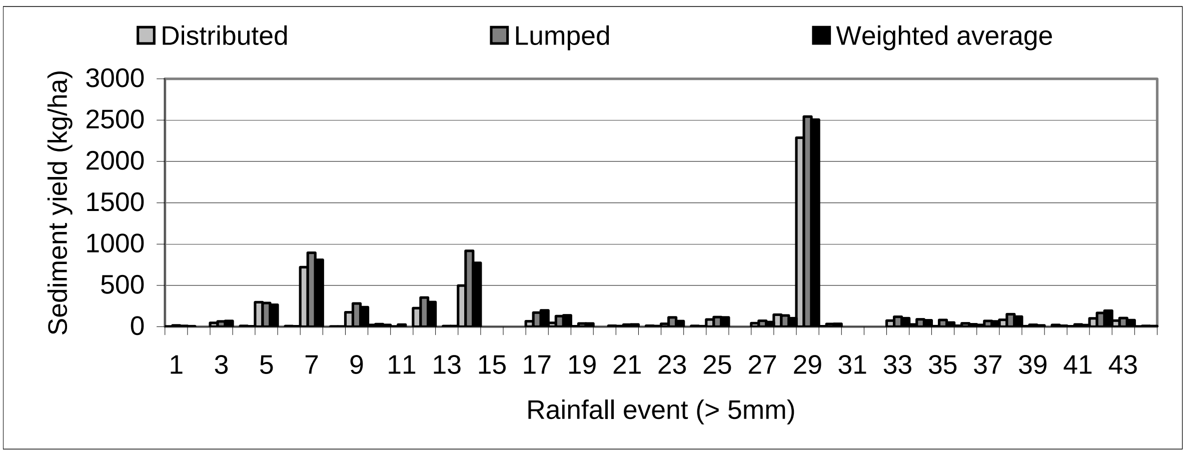

Figure 5.10. Effect of various levels of spatial representation of the soil and topography at Hillslope 3 of the Weatherley catchment.

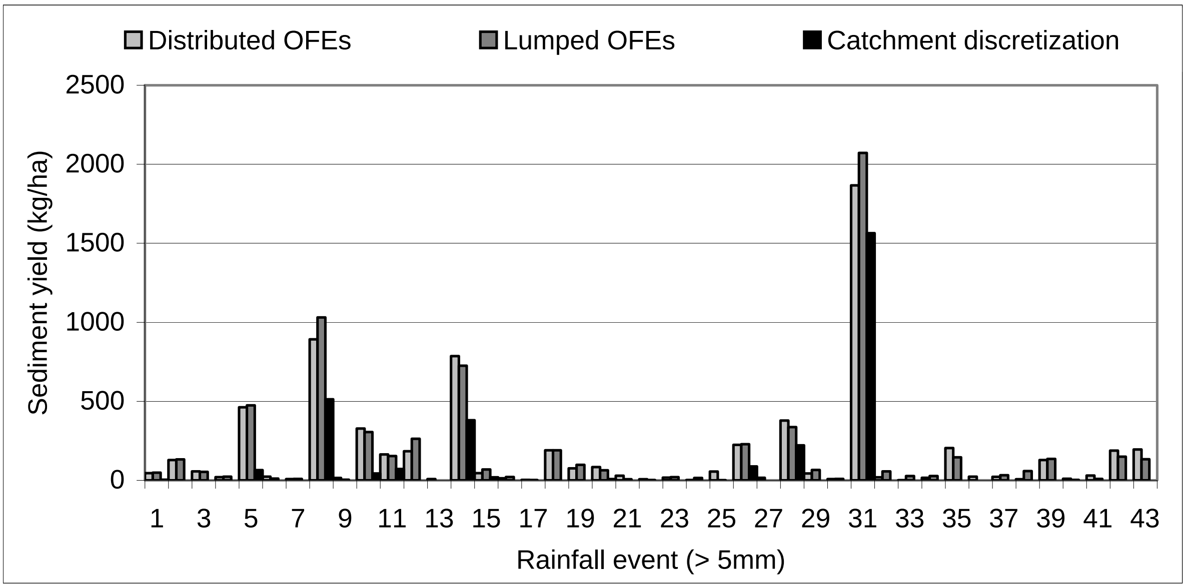

Figure 5.11. Effect of various levels of spatial representation of the soil and topography for the Weatherley catchment.

The sediment yield values predicted at the lower weir of the Weatherley catchment on the basis of distributed OFEs were most often in close agreement with the predicted sediment yield from the lumped OFEs. However, the predicted sediment yield was much higher than when the catchment was discretizised into three hillslopes and one channel (see Figure 5.7). This was in contradiction to what was expected as the spatial variability in soil, slope and land management were much higher along the hillslope catena than between the hillslopes. The large increase in predicted sediment yield with the increase in the number of channel elements was not expected; sediment yield was predicted at only 11 events with the low level of catchment discretization compared to the 43 events with the high level of catchment discretization. The same effect was found in a study on the sensitivity of the WEPP model to catchment discretization by Baffaut et al. (1997). They explained the results by the way the WEPP model simulates channel runoff. For each channel element, the excess rain is calculated as a function of the rain characteristics, the soil characteristics and the moisture condition. The runoff volumes from upstream elements are then added. Recession infiltration (infiltration losses after rainfall stops) is then calculated as a function of time of equilibrium of the channel element, the runoff volume and the rainfall duration. As runoff losses were calculated for channel elements in the upstream part of the catchment, the time of equilibrium was smaller, causing a decrease in calculated recession infiltration losses. For this reason the runoff volumes, and consequently the peak flow discharge rates and sediment yield, increased as the channel was divided in smaller segments.

5.2.2 *ACRU* model

Catchments can be subdivided into convenient response units or zones for input into the *ACRU* model. This was especially significant with the topological advances introduced into the model in this version. A cascading terrace subdivision of the Weatherley catchment has been implemented in this study, based primarily on the dominant processes in the soil profile and soil/bedrock interface as described in Chapter 4. These interleading response units channel subsurface water from the upper parts of the slope into the A-horizon of the lower, flatter slopes. The upper slopes allowed rapid ingress of rainfall into the profile, but also rapidly conducted this to the A-horizon of the lower slopes. Sediment transport in overland flow was assumed only in the lower slopes near riparian confluent zones. Data collected at runoff plots throughout the Weatherley catchment reveal that surface runoff was limited in the upper slopes. The simulation of this "distributed" configuration of response units was contrasted against a simulation in which the whole catchment was taken as a single "lumped" unit. The results of this comparison are shown in Figures 5.12 and 5.13. Clearly the sediment yield from the lumped, full catchment was larger than from the distributed zones, which yields sediments only from a single response unit adjacent to the riparian zone. Moisture accumulation from upslope, however, contributed to the antecedent conditions in the lower zone and allowed for larger flows and erosive energy on these lower slopes. In the sequence of predicted sediment yield from January to April 2001, illustrated in Figure 5.12, the sediment yield from the lumped catchment was significantly greater than that from the distributed network of subcatchments. This is because the whole of the catchment was deemed to be producing sediments in the lumped case, whereas, in the distributed example, only the near stream zones contribute sediment. It is interesting to note, however, that the lumped sediment yields were not always proportionally higher than the distributed yields (Figure 5.13).

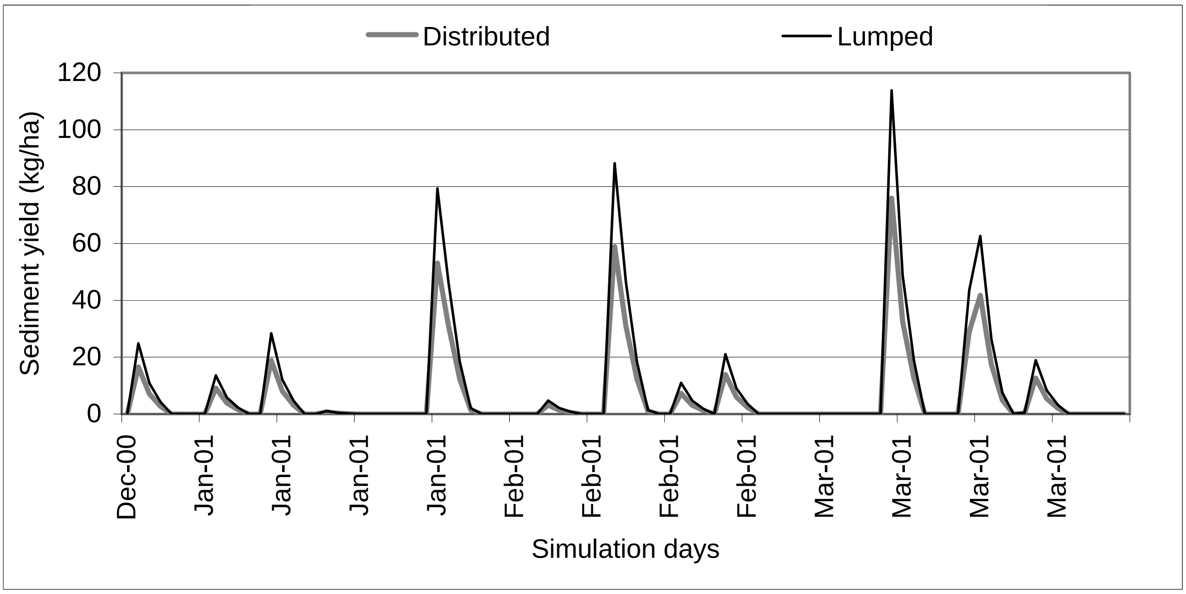

Figure 5.12. *ACRU* model predicted sediment yield in the Weatherley research catchment using a single lumped catchment and a cascading terrace system of distributed response units (January to April 2001).

On average, the lumped sediment yields were some 1.3 times as high as the yields from the distributed system. There is a maximum envelope confining the lumped loads to some 1.5 times those of the distributed simulation (Figure 5.13), this probably being the limit of sediment production where hydrological conditions in both lumped and distributed cases were clearly similar. However, there were significant events during which the load from the distributed network exceeds the lumped condition, as evidenced by the values below the 1:1 line in Figure 5.13. These simulated events were produced during wet antecedent conditions in the lower slopes, contributing to increased flow and peak discharges in this zone and resulting in higher erosion and sediment-carrying energy.

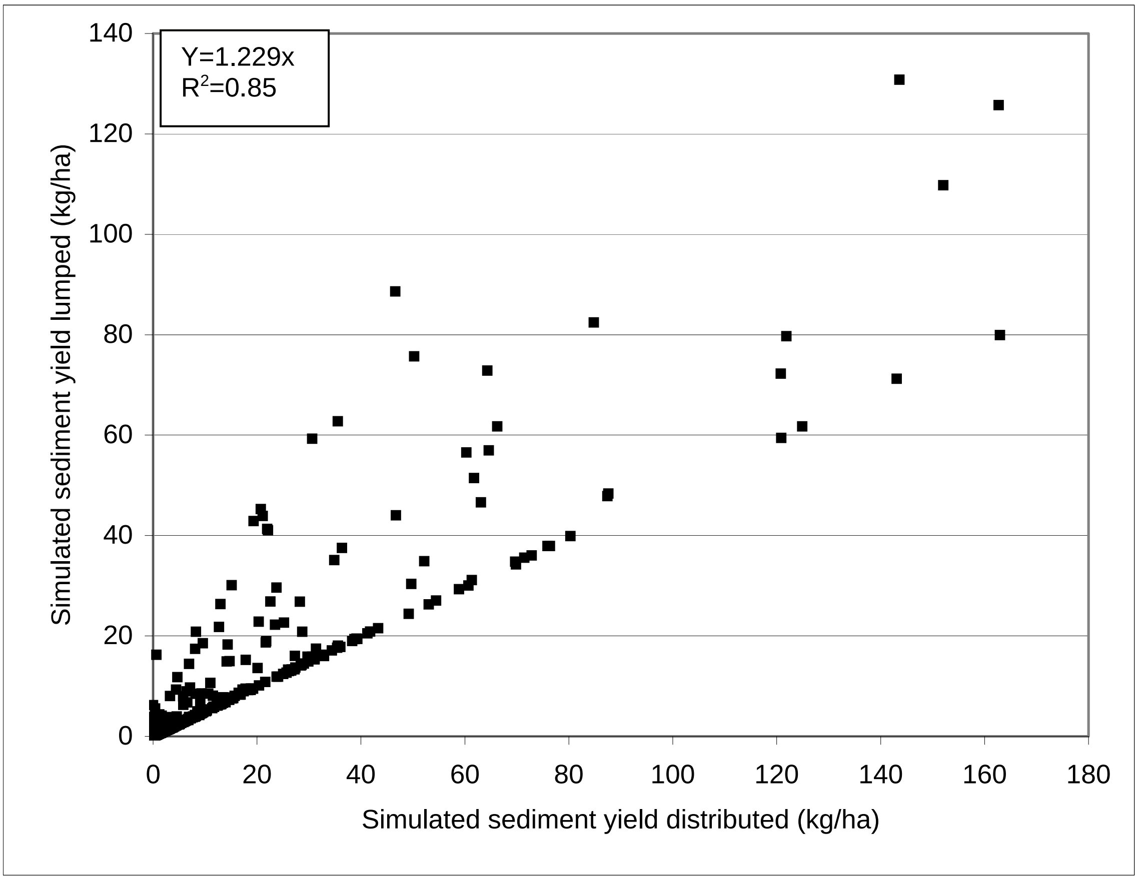

Figure 5.13. Comparison of the distributed and lumped catchment simulations at Weatherley, (1998-2002), showing the data regression (dotted) and 1:1 (solid) lines.

CHAPTER 6
SIMULATION OF SCENARIOS

In the previous two chapters on model verification and parameterisation effects, the performance of the selected models was verified in terms of the processes prevailing in the selected catchments and in terms of the temporal and spatial representation of the catchment characteristics. The focus of this chapter, and the second objective of the study, was to get some indication of the ability of the selected models to predict sediment yield for typical South African agricultural practices by assessing the impacts through land management scenario predictions for the land uses occurring at the research areas. The predicted values of the scenario predictions were relative (i.e. they were not absolute) and that they could only be used to compare different options.

It is expensive and time consuming to monitor the impact of various land use and management practices on erosion and sediment delivery from farm land in a range of ecosystems and climatic conditions. The objective of developing prediction tools, such as the selected models, was to supply decision makers involved in soil and water conservation, as well as environmental planning and assessment, with a tool to assess the impact of land management practices and conservation planning on soil loss and sediment yield. Sediment yield predictions (in which we have some degree of confidence) on the impact of the current land management practices, background and potential erosion rates and the ranking of alternative management practices, could be a powerful tool for conservation and water resource planning. Therefore, it is important that the models should be able to predict the supply of sediment from farmland under various agricultural practices and erosion control technologies.

6.1 EXTREME RAINFALL EVENTS

Extreme rainfall events have a major impact on erosion and sediment yield and are a key driver in the production and delivery of sediment yield. A single extreme rainfall event can produce more sediment than a number of small to moderate rainfall events during the year. One of the major advantages of conceptual and process models over the empirical models is that sediment yield can be predicted for a single storm / rain day, whereas empirical models give long-term annual rates (Morgan, 1995). The effect of an extreme rainfall event in relation to long-term annual rainfall was examined.

The 5-year period (1998 to 2002) of 1-minute rainfall time series data recorded during the project was too short to identify the extreme events. Professor Smithers from the School of Bioresources Environmental Hydrology at the University of Natal was consulted on the short duration rainfall data that were used during a Water Research Commission project on “Development and evaluation of techniques for estimating short duration design rainfall in South Africa” as input in the models. Two stations (Table 6.1) were selected from which the data were used to identify the extreme rainfall events and as model input data. Permission was granted by the two organisations who recorded the rainfall data, namely the South African Weather Services (SAWS) and the South African Sugar Association (SASA), to use the corrected short duration rainfall data provided by Smithers.

Table 6.1. Site characteristics of the stations used in identifying the extreme events (after Smithers and Schulze, 2000)

ORGANISATION	LOCATION	STATION	YEARS RECORD	LATITUDE	LONGITUDE	MAP
SAWS	Kokstad	0180722	21	30º32'00"	29º25'00"	1304
SASA	Mtunzini	Samtz	14	28º56'00"	31º42'00"	1338

The highest two daily rainfall amounts out of the 21 and 14 years of available records for Kokstad and Mtunzini stations, respectively, were selected to analyse the effect of large storm events on predicted sediment yield. The rainfall events selected for the Kokstad gauge are approximately the 5-year return interval event (75 mm) and the 20-year event (96 mm), while those for the Mtunzini gauge are approximately the 5-year event (129 mm) and the 20-year event (236 mm). Table 6.2 summarises the daily rainfall amounts for selected return intervals for the Kokstad and Mtunzini rain gauges.

Table 6.2. Daily rainfall extremes (mm) for selected return intervals (years)

RETURN INTERVAL	2	5	10	20	50
Kokstad	52	71	85	101	124
Mtunzini	90	137	176	221	292

The option in the WEPP model to run in a single storm mode was invoked to predict the contribution of extreme rainfall events to sediment yield in relation to average predicted annual sediment yield. The information that was required by the WEPP model to run in a single storm mode was the storm amount, duration, maximum intensity and percentage of storm duration to peak. The effect of storm amount and duration on sediment yield from an extreme event relative to the average predicted annual sediment yield is summarised in Figure 6.1. A default value of 20% was used for the percentage of storm duration to peak. The selected extreme events comprised several showers of higher and lower rainfall intensities during the day which could not be dealt with in the single storm mode of the WEPP model.

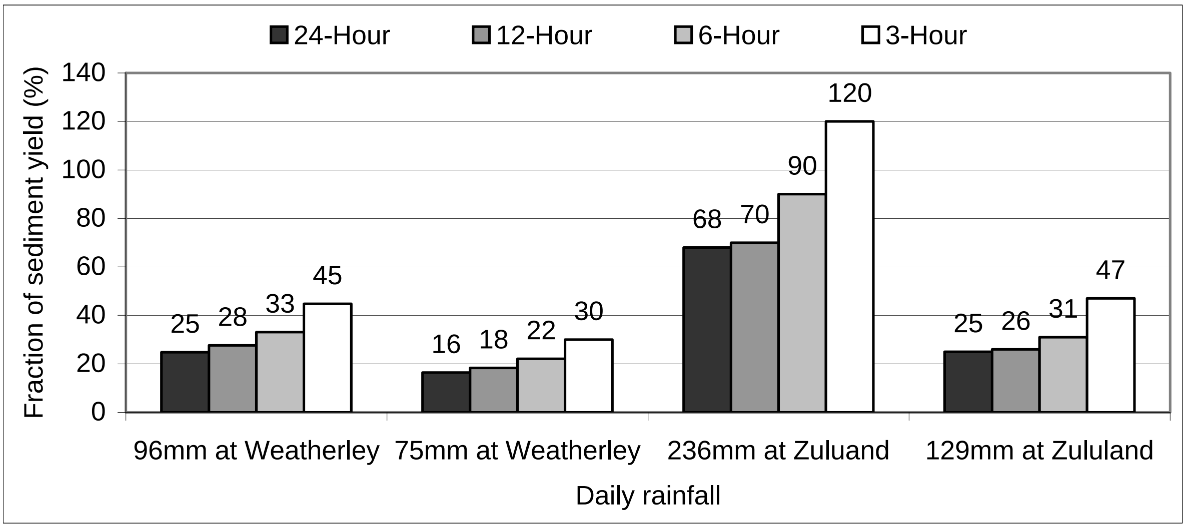

Figure 6.1. Effect of storm amount and duration on the predicted sediment yield during an extreme event relative to the average annual sediment yield predicted for the period 1998 to 2002 for the Weatherley and Zululand catchments.

The predicted effect of storm duration was relatively similar for the 24 and 12-hour storm durations for the selected extreme events, whereas the effect was almost twice as much for the 3-hour storm duration compared to the 24 and 12-hour storms. The effect of storm amount was relatively similar for the 5-year (75 mm) and 20-year (96 mm) return intervals at Weatherley catchment, whereas at Zululand catchment the fraction of sediment yield for the 20-year (236 mm) return interval was more than twice that for the 5-year (129 mm) return interval.

The fraction of sediment yield from an event of 96.1 mm compared with the average predicted annual sediment yield for the period 1998 to 2002 at the lower weir of the Weatherley catchment was 30% (most of the rain fell in 9 hours). At the H-flume of the Zululand research catchment, the predicted sediment yield from an extreme event of 236.4 mm was 57% of the average predicted annual sediment yield for the period 1998 to 2002. Most of the rain fell in 14 hours. The predicted sediment yield from the 128.8 mm rain event where most of the rain fell in 9 hours was 29% of the average predicted annual sediment yield.

The *ACRU* model predicted the sediment yield of an extreme rainfall event on 18 January 2000 (96 mm) and on 7 July 2000 (75 mm) for the lower weir at the Weatherley catchment. The first event represented 48% of the average annual sediment yield predicted for the period of 1998 to 2002 whereas the second event represented 20%.

6.2 LAND MANAGEMENT PRACTICES

6.2.1 WEPP model

The WEPP model is a powerful prediction tool in simulating various farming systems and agricultural practices. Prediction results were visually presented along a hillslope or in catchments through the Windows interface (Figure 6.2). Detailed simulation could easily be done through default files on specific management practices such as burning, grazing, tillage operations, etc. (Figure 6.3). The extensive agricultural operational and tillage implement databases make the WEPP model a very powerful tool in the assessment of various agricultural practices and in conservation planning (National Soil Erosion Research Laboratory, 1999; 2002).

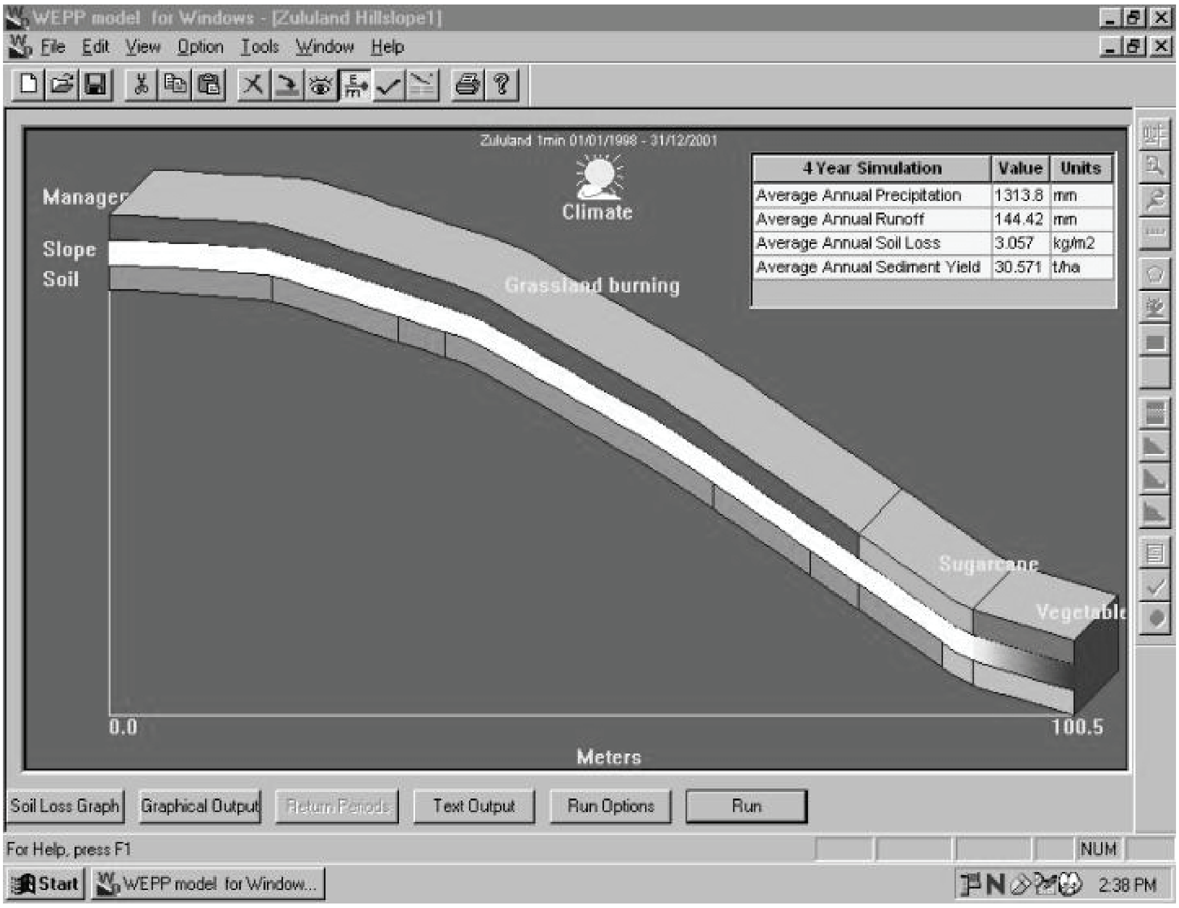

Figure 6.2. Presentation of soil loss and deposition (layer in centre) and sediment yield at the end of the hillslope for the Zululand research catchment.

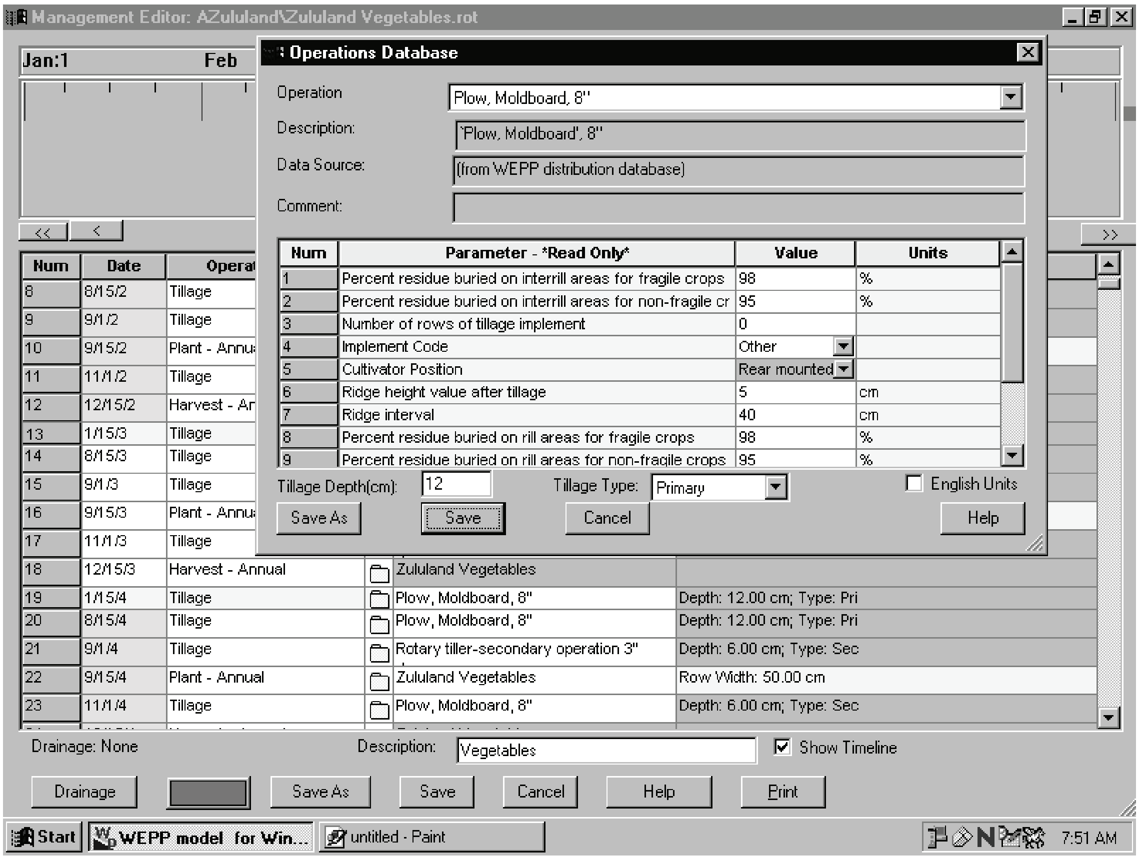

Figure 6.3. Tillage operational database of the land management input file.

The impact of farming systems on sediment yield at the end of a hillslope at the Kokstad research station, the lower weir at the Weatherley catchment and the H-flume at the Zululand catchment in relation to the background values (pristine conditions) is illustrated in Figure 6.4. The predicted sediment yields at all three research sites for rangeland conditions were comparable with the background values, while sediment yields from maize crop production systems were several orders of magnitude higher than the background values.

Predicted sediment yields for the current land use at Weatherley and Kokstad research sites were comparable with the background values since both sites were under veld: the Weatherley catchment was in pristine condition while Kokstad was under grazing. The higher predicted sediment yield values of the current land use at Zululand catchment compared to background values were due to the vegetable gardens at the footslopes and the sugarcane fields.

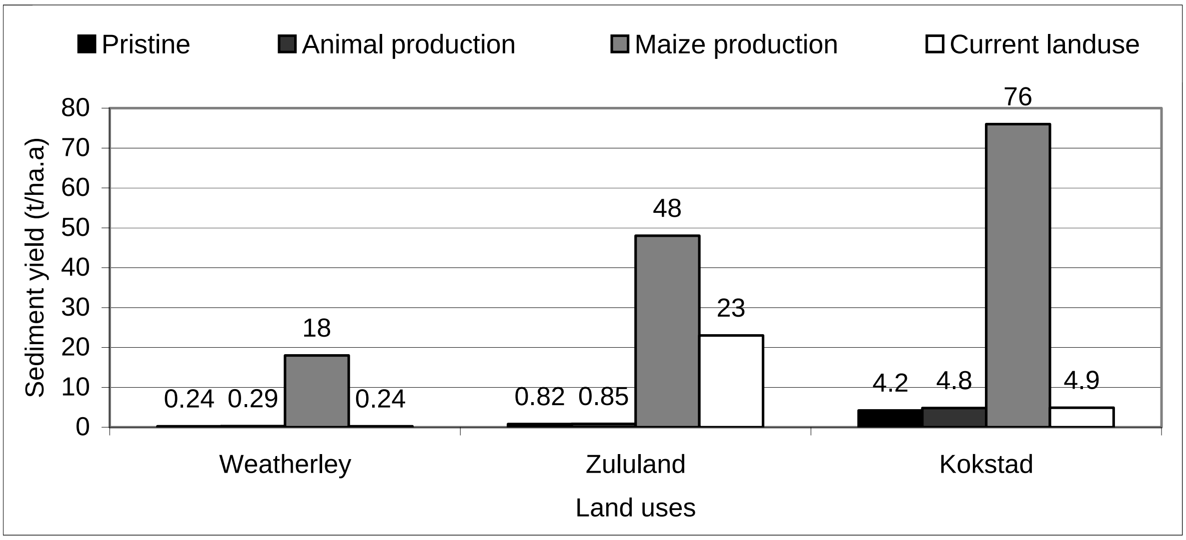

Figure 6.4. WEPP model predicted sediment yield for selected farming systems.

The low sediment yield values for pristine conditions and animal production predicted by the WEPP model at Weatherley were due to the large marsh area around the stream systems which serves as a depositional area at the footslopes for the eroded sediment from the steep midslopes, while at Zululand catchment they were due to the very low erodibility (i.e. high stability) of the soils. The higher predicted sediment yield at Kokstad research site compared to Weatherley and Zululand catchments was contributable to the good delivery of eroded sediment at the bottom of the hillslope which has no footslopes or valley bottoms that could serve as temporal depositional areas.

It appears from these initial estimates that the sediment yield predicted by the WEPP model for cultivated land was high considering commonly used values for soil loss tolerance of 5-12 t/ha.a based on soil renewal rates for shallow to deep soils. Sediment yield may have been an important consideration in arriving at the value of 11 t/ha.a which has been widely accepted as a maximum allowable rate of erosion (International Soil Science Society, 1996). Furthermore, questionnaires from the World Overview of Conservation Approaches and Technologies (WOCAT) conducted in South Africa reveal that soil loss values exceeding about 50 t/ha.a were high for South African conditions (Food and Agricultural Organisation, 2003). Sediment yield is only a fraction of soil loss, yet it comprises about 90% of soil loss for such small catchments as in this study (Morgan, 1995).

A further analysis of the impact of various veld management practices was done through predictions of sediment yield made with the WEPP model. Estimation of grazing capacities and veld management norms for a grazing system for the three research sites was done according to procedures described in a handbook for agricultural advisors in KwaZulu-Natal by Smith (1998). The estimated grazing capacities for Weatherley and Kokstad sites (Dry Highland Sourveld) were 2.78 ha/AU, while for Zululand (Moist Coast Highland Ngongoni Veld) it was 1.8 ha/AU. The herbage consumption was 2500 kg/AU.a. Annual rainfall for Weatherley and Kokstad was taken as 750mm and for Zululand as 1150mm, with 80% of the total rainfall occurring during the growing season. Herbage yield for an average veld condition was taken as 3 kg DM per mm of rain during growing season, and 50% utilization of veld was assumed. Three scenarios of grazing systems were simulated at three stocking rates, namely 5, 2 and 1 ha/AU. The veld management practices for the three grazing system scenarios were:

1. A rotation system where the period of stay was 10 days and the period of absence was 20 days.
   The veld was grazed from the beginning of October to the end of April.
   Burning dates were 1 September each year.
2. No rotational system, thus the veld had no rest periods.
   The veld was grazed from the beginning of October to the end of April.
   Burning dates were 1 September each year.
3. No rotational system, thus the veld had no rest periods.
   The veld was grazed throughout the year.
   Burning dates were 1 September each year.

The impact of various stocking rates and veld management systems on sediment yield was predicted for the Weatherley, Zululand and Kokstad research sites for the years 1998-2002 and is illustrated in Figure 6.5. The predicted sediment yields between scenarios 2 and 3 were of the same values, and are therefore presented as No-control, while scenario 1 is presented as Rotation.

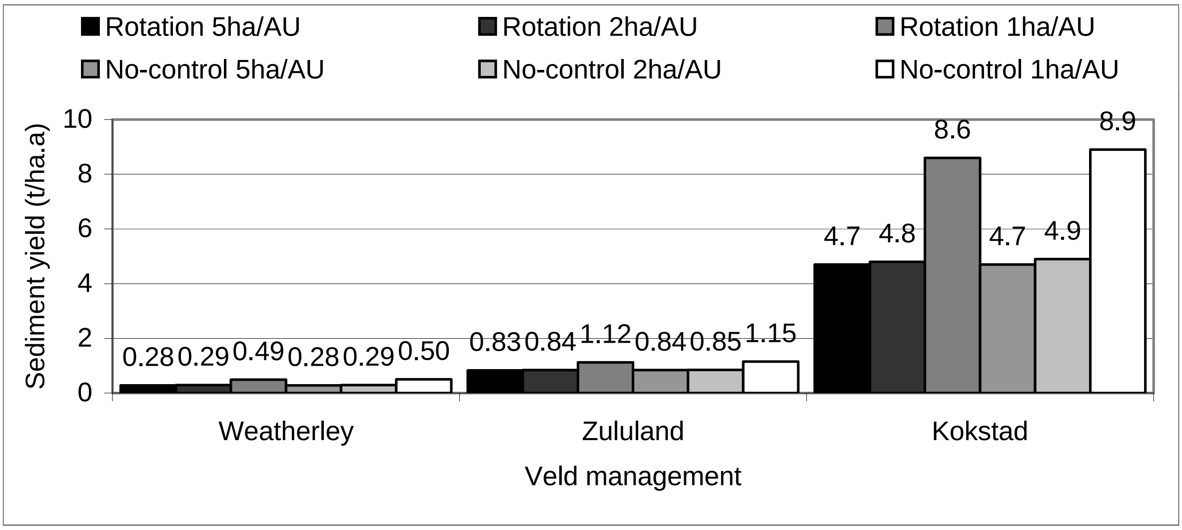

Figure 6.5. WEPP model predicted sediment yield for selected veld management practices.

In general, very low sediment yield values were predicted at Weatherley and Zululand catchments due to the large marsh area around the stream systems at Weatherley and the very low soil erodibility at Zululand. These effects were discussed in a previous paragraph. The predicted impact of stocking rates on sediment yield was similar for the 2 and 5 ha/AU at all three research sites, but differed from the 1 ha/AU stocking rate which was almost twice as high as the lower stocking rates. This indicated that the WEPP model predicted higher sediment yield values for cases where the stocking rates were higher than the recommended rates.

Contrary to what was expected, the WEPP model predicted similar sediment yield values for the Rotation and No-control scenarios at all three research sites. This indicated that the WEPP model was not able to simulate the impact of grazing rest periods; especially the expected higher sediment yields for scenario 3 than for scenario 1.

The WEPP model also did not predict different sediment yield values for various burning dates (data not shown). The predicted sediment yield did not differ if burning occurred in the winter, early spring, late spring, summer or autumn. The predicted sediment yield was similar for two burnings during the year (early spring and summer) compared to only one burning during early spring. Therefore, the WEPP model was not sensitive to the impact of wrong burning dates or accidental veld fires on sediment yield at the three research sites.

The impact of various cultivation practices on sediment yield was predicted with the WEPP model. Mr. John Veidge of the farm High Field, 10km from Maclear, was consulted on the cultivation and agronomic practices for a maize production system. He has converted from a conventional tillage practice to minimum tillage. The cultivation and agronomic practices for the following tillage practices for a maize production system are described:

1. Conventional-till

During the fourth week of August, the land was ploughed with a 14” mouldboard plough to a depth of 15cm. A secondary tillage operation was performed in the first week of October with a 20” one-way disc before planting. Herbicide was applied during planting time in the second week of October. Two secondary tillage operations followed after planting with 3X9” multiple sweeps during the second week of November and December. Harvesting occurred at the end of July, where after grazing of maize stubble occurred during July and August. All these operations could be simulated with the WEPP model, except for the grazing between harvesting and ploughing.

2. Minimum-till

In the first week of October, the land was ripped with a five-tooth ripper to a depth of 2m. This primary cultivation operation was followed up with a one-way 20” disc as a secondary tillage, immediately prior to planting and herbicide application. No further secondary tillage operations occurred. Harvesting occurred at the end of July, where after grazing of maize stubble occurred during July and August. All these operations could be simulated with the WEPP model, except for the grazing between harvesting and ploughing.

3. No-till

During the first week of October, planting and herbicide application occurred. Harvesting occurred at the end of July, where after grazing of maize stubble occurred during July and August. All these operations could be simulated with the WEPP model, except for the grazing between harvesting and ploughing.

4. Conventional-till with filter strips

The practice was the same as for conventional-till, except that 5m-wide vegetative filter strips on the farmer's field were established.

5. Conventional-till with a buffer strip

The practice was the same as for conventional-till, except that a 50m-wide vegetative buffer strips adjacent to the riparian area were established. This conservation measure is also called riparian buffers.

The impact of various tillage practices and biological erosion control measures on sediment yield was predicted for the Weatherley, Zululand and Kokstad research sites for the years 1998-2002 and is illustrated in Figure 6.6.

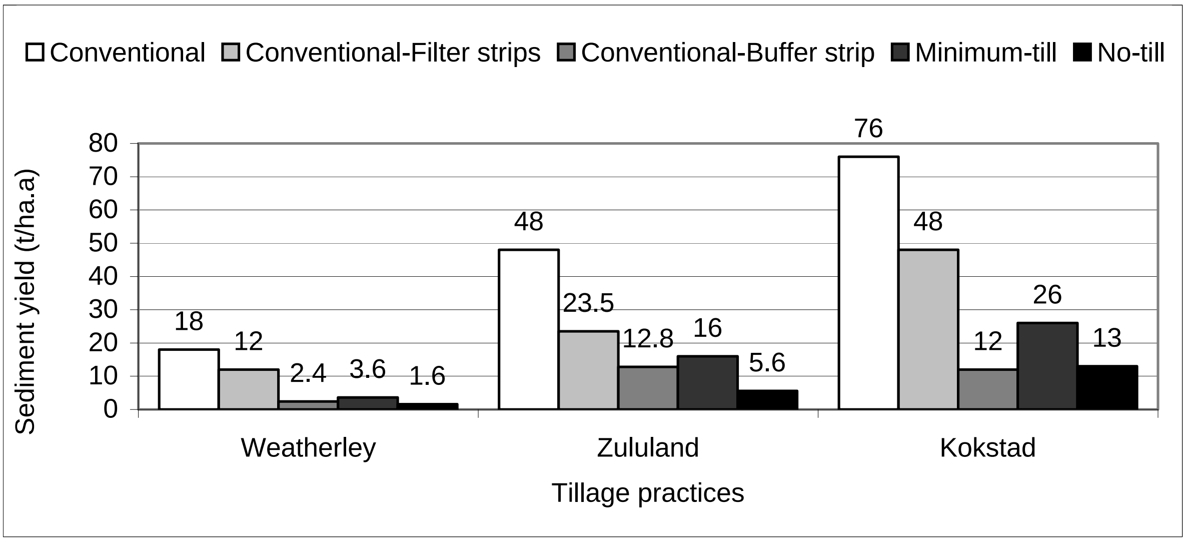

Figure 6.6. WEPP model predicted sediment yield for selected tillage practices and biological erosion control measures.

In general, the predicted sediment yield for arable land at Weatherley catchment was the lowest, followed by Zululand catchment, while it was the highest at the Kokstad hillslope. This was due to the large marsh area around the stream systems at Weatherley and the very low soil erodibility at Zululand as discussed in a previous paragraph. The differences in predicted sediment yield between the tillage practices (Figure 6.6) were much higher than for veld management (Figure 6.5).

The effect of predicted impact of tillage practices on sediment yield was similar at all three research sites: conventional-till > conventional-till with vegetative filter strips > minimum-till > no-till > conventional-till with a riparian buffer strip. The predicted sediment yields for minimum- and no-till were 20-34% and 9-17%, respectively, of that of the conventional-till cropping system. Predicted sediment yield for the minimum-till cropping system was about 2-3 times higher than for the no-till cropping systems. The application of biological erosion control measures as part of the conventional-till cropping system, such as vegetative filter strips and riparian buffer strip, significantly reduces the predicted sediment yield. The predicted sediment yields for conventional-till with vegetative filter strips and conventional-till with a riparian buffer strip were 49-63% and 13-27%, respectively, of that of the conventional-till cropping system without any erosion control measures. Although the implementation of a riparian buffer zone has the largest reduction in predicted sediment yield, the riparian buffer zone only prevented the eroded sediment from entering the stream system and did not eliminate erosion on the hillslope.

The capability of the WEPP model for conservation planning was illustrated on a hillslope at the Zululand catchment. The hillslope displayed in Figure 6.2 was used as an example to predict the impact of intensification of agricultural land use on sediment yield delivered at the end of the hillslope. The following sequence of land use intensification was predicted:

1. The entire hillslope was under grassland which was in a pristine condition.
2. The entire hillslope was under grassland for grazing purposes.
3. The crest, and upper and middle midslopes were under grassland for grazing, the lower midslope was under sugarcane production and the footslope was cultivated for vegetable gardens. This is the current land use on the hillslope as displayed in Figure 6.2.
4. The crest and midslopes were under sugarcane production and the footslope was cultivated for vegetable gardens.
5. Scenario 4 with erosion control measures. The upper part of the footslope was cultivated for vegetable gardens, while the lower part of the footslope was planted with grasses to serve as a riparian buffer zone. The surface roughness of the primary cultivation with a mouldboard plough was also maintained (no smoothing of surfaces after primary cultivation) at the vegetable gardens.

Veld management for grazing purposes includes a stocking rate of 2 ha/AU, grazing period of mid-October to the end of April, and burning in mid-August. The sugarcane was harvested in mid-August. The primary cultivation operation at the vegetable gardens was with a mouldboard plough, followed by seedbed preparation and weed control (both using hand labour) during the growing season. Vegetables were planted in mid-September and harvested from mid-December, where after land was left until the primary cultivation operation. Information on these land management and crop production practices was collected from the local people in the catchment during field works. The predicted impact of agricultural land use intensification on sediment yield for the years 1998-2002 is illustrated in Figure 6.7.

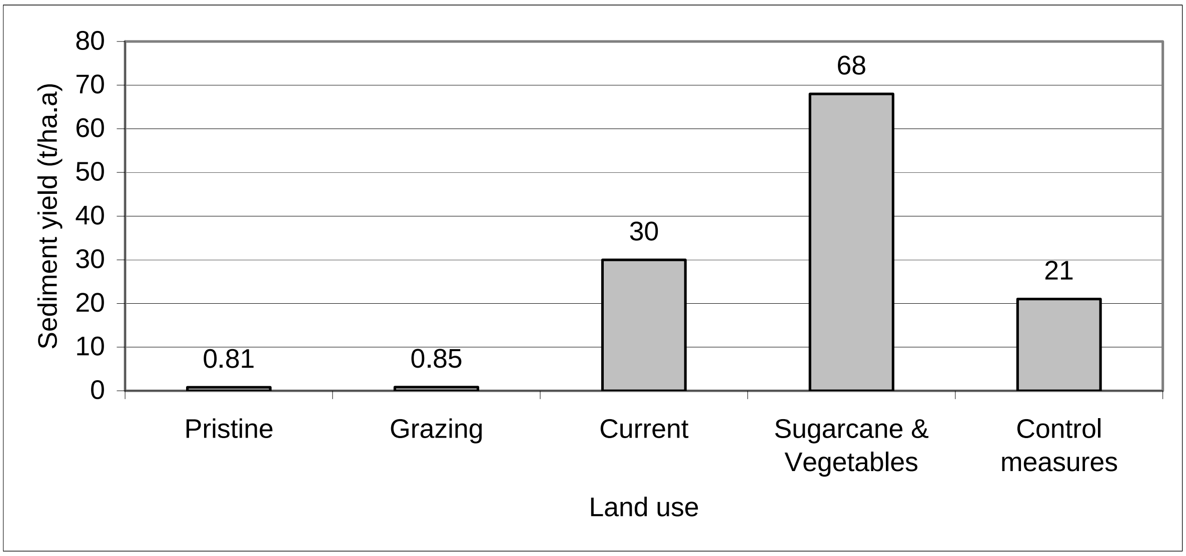

Figure 6.7. WEPP model predicted sediment yield for agricultural land use intensification.

As was expected, the impact on eroded sediment delivered at the end of the hillslope increased as the land on the hillslope was utilised more intensively. The predicted sediment yield increased significantly when the lower midslope was put under sugarcane production and the footslope was cultivated for vegetables gardens (current land use); an increase of 35 times in sediment yield was predicted compared to where the entire hillslope was utilised for grazing. The predicted sediment yield increased 2.25 times further when the grassland at the crest and upper and middle midslopes of the current land use was converted to sugarcane. The implementation of erosion control measures as discussed under point 5 has led to a considerable decrease in predicted sediment yield which was even lower than the current land use. This demonstrated the impact of erosion control measures on the reduction in the delivery of eroded sediment to the stream at the end of the hillslope, especially when the measures are focused at the lower part of the hillslope, namely at the footslope and lower midslopes.

The preceding discussion on scenario predictions showed the power of the WEPP model as a decision-making tool to assess the impact of agricultural land uses, the intensification of land use, farming systems and agricultural management practices (veld management, tillage practices and erosion control measures) and conservation planning on soil loss and sediment yield for hillslopes and field-size catchments.

6.2.2 *ACRU* model

The sediment yield simulations with the *ACRU* model are driven both by the hydrology and the sediment transport characteristics. Average annual sediment loads were simulated for the five-year period, 1998 to 2002, using different land use conditions. Predictions were made for pristine veld conditions, veld in burnt condition, veld under grazing, veld under grazing with burning, minimum tillage, and conventional tillage (Figure 6.8). It was assumed that the whole of the contributing area was under each of these land uses in turn.

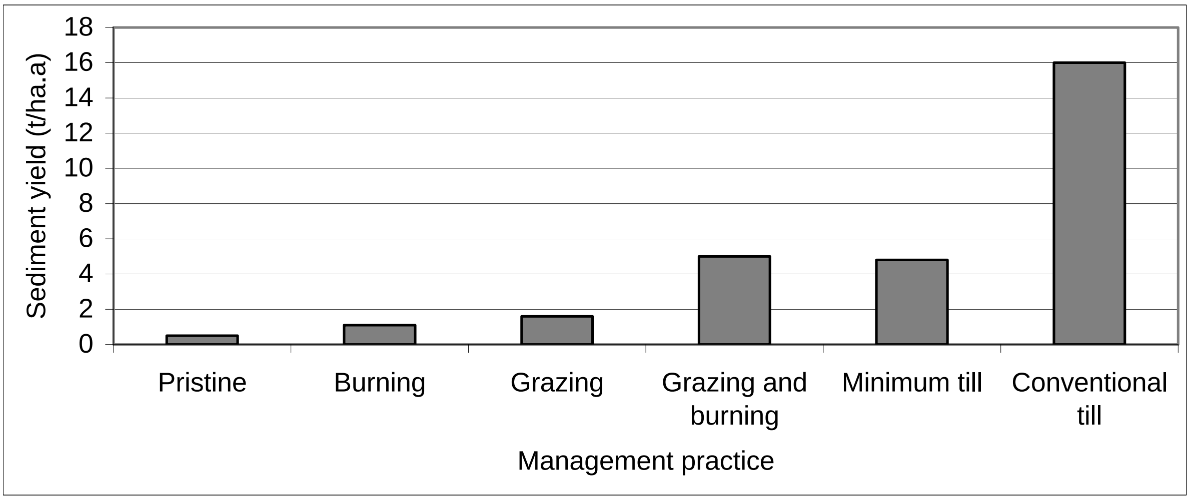

Figure 6.8. *ACRU* model predicted sediment yield from the Weatherley catchment for selected farming practices.

For the pristine conditions, default values for the vegetation characteristics of crop coefficient, fraction of root depth in the A-horizon, leaf area index and interception loss were assumed for veld in good condition. These parameters affect the runoff quantity and peak flow and thus contribute to the energy available for erosion and sediment transport in the MUSLE equation. The cover protection factor was set at 0.011 for veld in good condition. This represents a minimum canopy cover of 25% with a grass-derived ground cover of at least 85%, or alternatively, a maximum grass canopy of 75% with a ground cover of 80%. It is thus most dependent on the ground cover. The sediment yield from these pristine conditions is some 5 t/ha.a (Figure 6.6), which is not considered severe.

The veld under burnt conditions was simulated by assuming veld in fair condition vegetation characteristics and assuming reduced initial abstraction from the rainfall events. The cover protection factor was increased (i.e. less protection) to 0.02. This resulted in an annual average sediment yield of some 1.1 t/ha.a. This is less than the effective sediment yield from a burnt forest area of some 5 t/ha.a observed in the Natal midlands (V1h020) by Scott (1994). The veld under grazing was simulated by assuming the veld in fair condition default in the *ACRU* model, together with a cover factor ranging from 0.02 to 0.011 during the year. The resulting sediment yield from these conditions was some 1.6 t/ha.a. The superposition of burning and grazing, assuming veld in poor condition, together with reduced rainfall initial abstraction and a cover factor of 0.02, resulted in an annual sediment yield of some 5 t/ha.a. The minimum tillage land use was simulated assuming a maize crop as is grown in the Mgeni region of KwaZulu-Natal, with a cover factor of 0.03 (50% mulch, 60% canopy, first year after planting and compacted seedbed). This practice yielded some 4.8 t/ha.a which is less than the 10 t/ha.a average tolerable soil loss for cultivated land in South Africa, reported by Scott (1994). The conventional-till scenario, however, with 20% mulch and 70% cover, yields some 16 t/ha.a, which exceeds the reported tolerable limit.

These results demonstrate the versatility of the *ACRU* model to simulate a wide variety of sediment production land uses. The exercise highlights the care with which the hydrological and sediment yield parameters must be derived, prior to running the model.

It is emphasized that the simulated values were relative (i.e. they were not absolute) and that they could only be used to compare different options.

CHAPTER 7
MODEL DISCUSSION

Models are being developed to better understand the complex erosion processes that occur on agricultural catchments, but they are of necessity simplifications of reality. It is generally recognized that a good model should satisfy the requirements of reliability, universal applicability, easy use with a minimum of data, comprehensiveness in terms of the factors and erosion processes included, and the ability to take into account changes in land use and conservation practice. It should simulate the erosion system in a reasonably realistic way and also give plausible results for extreme conditions. The success of any model must be judged by how well it meets its objectives or requirements (Morgan, 1995).

7.1 MODEL PURPOSE

Understanding the purpose of a model is important in using the model. The objectives of the modelling exercise influence factors such as the scale at which a model needs to operate and the levels of detail and accuracy required (Morgan, 1995).

The focus of this project was on verifying selected sediment yield models in predicting the impact of farming practices on headwater catchment streams, riparian areas and wetlands at the small catchment scale (<10 km^2). Detailed modelling at the hillslope to small catchment scale follows an initial screening / priority setting phase which involves prediction of sediment yield at the large catchment scale from limited data to identify homogeneous erosion units, problem areas and problematic land uses and management practices upon which to focus (Kirkby, 1998). Models selected for detailed modelling at the hillslope to small catchment scale need to predict with greater accuracy than the models applied at the large catchment scale because they are used for evaluating the severity of erosion and sediment delivery under different management systems and may be intended as design tools for the selection of conservation practices (Morgan, 1995).

The WEPP model is a process-oriented model, based on modern hydrological and erosion science, and designed for routine assessment of soil erosion by organisations involved in soil and water conservation and environmental planning and assessment. The model has the capabilities of predicting spatial and temporal distribution of erosion and sedimentation along hillslopes and in field-sized catchments over time (Nearing et al., 1989). A research version of the *ACRU* model applied in this study simulated the spatial distribution of water and sediment generation, particularly in terms of the topography of hillslopes, to predict the resultant stream sediment load.

7.2 CONCEPTUALISATION OF PROCESSES

7.2.1 Sediment yield

The *ACRU* model is an example of a conceptual sediment yield model since the sediment yield module is based on the Modified Universal Soil Loss Equation (MUSLE), where the erosive and transport energies are derived from the product of peak stormflow and runoff volume for daily rainfall events. Although the hydrological component of sediment yield models based on the MUSLE technology may be process based, these types of models are conceptual since they predict sediment yield by using the most important factors that affect it (hydrology, soil erodibility, slope length and slope gradient, vegetation management and erosion-control practices), and are based on spatially lumped forms of water and sediment continuity equations and sediment routing. The focus of the conceptual models has been to predict sediment yields, primarily using the concept of the unit hydrograph (Nearing, Lane and Lopes, 1994).

Theoretically, the WEPP model simulates the erosion processes more accurately than the *ACRU* model. The WEPP model is an example of a process model which simulates the erosion and sediment yield processes in a distributed way by applying the fundamental erosion processes of interrill erosion (principally detachment by raindrop impact and lateral transport by thin flow), rill and concentrated flow erosion (detachment by flow), sediment transport by flow, deposition by flow, deposition in impoundments, and concentrated flow hydraulics. The WEPP model incorporates the continuity equation for sediment routing along the hillslope and through the catchment, which is a statement of the conservation of matter as it moves through space over time and is based on the fundamental concept that sediment yield is assumed to be limited by either the sediment made available by detachment or by transport capacity. WEPP also estimates the sediment characteristics, such as specific gravity and particle composition (% sand, % silt, % clay and % organic matter), and sediment enrichment (Flanagan et al., 1995). Since the WEPP model simulates the erosion processes and the behaviour of sediment movement more accurately, it should provide more reliable results and should be the preferred model to be used for management alternatives, especially for ungauged catchments.

Neither model was designed to take account of headcut erosion, sloughing of gully sidewalls, subsurface / pipe erosion or the effects of seepage on erosion in concentrated flow channels, because they lack a sidewall failure mechanism component. These processes could occur in small catchments such as those used in this study, which could severely under-predict erosion and sediment yield when the classical gullies are active. Some classical gullies occurred in the Weatherley catchment, but they might not have been very active during the period of this study. In a literature review study by van Zyl (2004), where fifteen models were theoretically evaluated for their suitability to predict sediment yield for South African conditions, only two models were capable of simulating headcut, gully sidewall and pipe erosion in addition to erosion-related overland flow (interrill erosion) and concentrated flow (rill and ephemeral channel erosion). This is obviously a severe limitation if models simulating sediment yield from only overland and concentrated flow, such as the WEPP model and *ACRU* model, are to be used to plan soil conservation programmes in catchments where gullies are the dominant source of sediment. Several studies have shown that most of the sediment yield models were unsuccessful in predicting sediment yield in catchments where gullies are the dominant source of sediment (Armstrong and Mackenzie, 1995).

7.2.2 Spatial distribution of erosion

The combination of a non-uniform spatially distributed vegetation, irregular terrain and complex pedological patterns along a hillslope results in a situation whereby the hydrological response to rainfall events at the small catchment scale may be spatially non-uniform, with overland flow occurring in localised areas. Even though sediment yield is expressed as a ratio of mass per total catchment area, sediment can originate from localised areas in a catchment where saturation excess and interflow are the dominant overland flow generation mechanisms. Identifying the spatial mosaic pattern of contrasting hydrological response units, and hence the spatial connectivity of runoff producing areas, is of great importance in identifying those areas vulnerable to erosion and sediment delivery. Initial soil moisture, connectivity between hydrological source areas and the development of continuous hydrological pathways are critical in determining sediment delivery from hillslopes to the channel system. Surface runoff from source areas which are spatially isolated and upslope of the channel will be re-absorbed by the surrounding drier areas which act as sinks for overland flow and transported sediment (Walter, Walter, Brooks, Steenhuis, Boll and Weiler, 2000; Fitzjohn, Ternan and Williams, 1998).

The WEPP model considers mainly infiltration excess overland flow (rain intensity is larger than the rain infiltration into the soil). The WEPP model does not explicitly consider partial area overland flow conditions which occur as a result of saturation overland flow (a rising water table prevents further rain infiltration at the saturated surface soil) and interflow (exfiltration of water at a downslope position after having infiltrated upslope and flowed laterally within the soil profile) (Stone et al., 1995; Savabi and Williams, 1995). Conversely, the research version of the *ACRU* model used in this study included several features to account for more detailed hillslope hydrological processes affecting partial area overland flow conditions.

Generation of surface runoff by processes other than infiltration excess overland flow means the distribution of surface erosion features will depend upon factors other than infiltration capacity. Sediment yield models that ignore soil saturation encountered at the foot of a hillslope and interflow may well fail to predict important erosional and sedimentation features within a catchment. The generation of additional volumes of overland flow due to the influence of saturation excess and interflow causes erosion and sediment delivery to be localised at hydrologically sensitive areas, which are most often in close proximity of streams such at the footslopes and valley bottoms (Burt, 1998; van Zyl, 2004).

It was shown at the Weatherley catchment that the advancements in the research version of the *ACRU* model provided an accurate prediction of the observed runoff and most likely of localised erosion and sediment delivery at hydrologically sensitive areas. The application of the WEPP model will be limited to soils in South Africa where the hydrology is dominated by infiltration excess overland flow; i.e. shallow soils or soils with gradual hydraulic transitions between soil horizons which occur on flat slopes.

Models that run on a daily time step, such as the research version of *ACRU*, will fail to predict the burst effect of high intensity rain storms where even a relatively small to moderate event with a high storm intensity could cause erosion and delivery of sediment to the stream system.

7.3 MODEL APPLICATION

The application of the selected models provides major advantages over several existing erosion prediction technologies. The most notable advantage includes capabilities for estimating spatial and temporal distributions of sediment yield and sediment delivery from hillslopes, entire farming fields and small catchments on a daily, monthly or average annual basis. This has the benefit of analyzing the impact of farming practices on sediment yield throughout the season according to the discharge volume or rainfall and the type of land use and management practices (harvest, fallow, cultivation, etc). The WEPP model also calculates sediment particle characteristics.

The Windows user-interface programs and databases, such as a crop parameter and a tillage implement database, made the WEPP model a very powerful tool in presenting the predicted impacts of various land management practice scenarios. However, the WEPP model is too demanding in data requirements, most of which were not readily available, to be widely applicable in South Africa. Rainfall data with high temporal resolution is essential to run the WEPP model and the WEPP model was extremely sensitive to the rainfall input file since surface runoff, erosion and sediment delivery are simulated from both rainfall amount and storm intensity. The high recording frequency of rainfall time series data needed and the time-consuming process in preparing the rainfall input data for the WEPP model severely limit its application in South Africa. It was also impossible to take advantage of the CLIGEN model, which is the climate generation method used in the WEPP model for the continuous modelling option, due to unavailability of sufficient climate data.

In contrast to the WEPP model, the components used in the *ACRU* model have been extensively researched for Southern African conditions. The *ACRU* model requires a minimum of data to represent the catchment hydrology and sediment yield and has the advantage, in South Africa, that the model builders can be directly consulted. In addition, much of the data gathering for these models has been incorporated in predefined data sets for various regions and climate, vegetation and soil types. These data sets aid the user in selecting proper inputs and increase the ease of input selection. Furthermore, the soil, vegetation, slope and management erosion-related parameters are derived from the RUSLE model, which is a well established and documented model with an extensive database.

Although the WEPP model is superior to the research version of the *ACRU* model applied in this study in the extent to which the models could predict various land management scenarios and the visual presentation of spatial and temporal distribution of erosion and sedimentation along hillslopes and in field-sized catchments, the application of the *ACRU* model is likely to be more successful in predicting sediment yield for South African conditions since the WEPP model needs more detailed input data that are mostly not readily available in South Africa. This is especially true for rainfall and plant management data.

CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Model verification

The WEPP model conceptualises the erosion processes, the factors affecting them, and the behaviour of sediment movement along hillslopes and through the catchment more accurately than the *ACRU* model*,* since the WEPP model is based on modern hydrological and erosion science. However, the WEPP model considers mainly infiltration excess overland flow (where rain intensity is larger than the rain infiltration into the soil) and does not explicitly consider partial area overland flow conditions which occur as a result of saturation excess overland flow (when a rising water table prevents further rain infiltration at the saturated surface soil) or interflow (where infiltrated water exfiltrates at a downslope position after having flowed laterally within the soil profile). The WEPP model accurately predicted the soil water content at the upper part of the hillslopes (crest and midslope) where the effect of saturation excess and interflow were negligible, but was unable to accurately predict the soil water content at the lower part of the hillslopes (lower midslope and footslope) due to the dominance of saturation excess overland flow and interflow. Therefore, the WEPP model was unable to satisfactorily predict runoff and sediment yield at the Weatherley and Zululand catchment outlets because it does not explicitly consider partial area overland flow conditions.

The sediment yield module of the *ACRU* model is based on the Modified Universal Soil Loss Equation (MUSLE) technology where sediment yield is predicted on a lumped conceptualisation of water and sediment continuity equations and sediment routing by using the most important factors that affect sediment yield. The conceptualisation of the erosion processes, the behaviour of sediment movement along hillslopes and through the catchment, and the factors affecting the erosion processes of the *ACRU* model*,* are inferior to the process-based erosion model WEPP. Conversely, the research version of the *ACRU* model applied in this study included several features to account for more detailed hillslope hydrological processes affecting partial area overland flow conditions. The research version of the *ACRU* model did not predict the soil water content at the upper part of the hillslopes (crest and midslope) with the same accuracy as the WEPP model since this version of the *ACRU* model runs on a daily time step which failed to predict the burst effect of high intensity rain storms whereby even a relatively small to moderate event with a high storm intensity could cause erosion and delivery of sediment to the stream system. Nevertheless, it was shown at the Weatherley catchment that the advancements in the research version of the *ACRU* model to account for more detailed hillslope hydrological processes affecting partial area overland flow conditions provided a more accurate prediction of runoff and sediment yield predictions, compared with water and sediment discharge measured at the catchment outlets, than predicted by the WEPP model.

The results from this study on model verification clearly demonstrate the importance that sediment yield models applied at the hillslope and small catchment scale should take account of the specific hillslope flow path mechanisms that occur in a small catchment. For reliable sediment yield predictions at the small catchment scale, it is expected that the application of sediment yield models that consider mainly infiltration excess overland flow, which occurs most often on shallow soils or on flat terrain with soils with gradual hydraulic transition between soil horizons, would have limited application in South Africa. In the eastern parts of South Africa where water erosion is one of the major land degradation mechanisms under a higher rainfall, e.g. Mpumulanga, the eastern Free State, KwaZulu-Natal and the Eastern Cape, the terrain is usually steep and the hydraulic transition between soil horizons is often abrupt. It is to be expected that this would give rise to partial area overland flow conditions which will most often occur at areas close to the stream system (lower midslopes, footslopes and valley bottoms) as a result of saturation excess overland flow and/or interflow.

Neither models were designed to take account of headcut erosion, sloughing of gully sidewalls, subsurface / pipe erosion or the effects of seepage on erosion in concentrated flow channels, because they lack a sidewall failure and piping mechanism component. These processes could occur in small catchments such as those used in this study, which the selected model could severely under-predict erosion and sediment yield when the gullies are active. This is obviously a severe limitation if the WEPP model and *ACRU* model are to be applied to plan soil conservation and water quality programmes in catchments where gullies are the dominant source of sediment.

Parameterisation effects

Rainfall data with high temporal resolution is essential to run the WEPP model, and the WEPP model was extremely sensitive to the rainfall input file since surface runoff, erosion and sediment delivery are simulated from both rainfall amount and storm intensity. The high recording frequency of rainfall time series data needed and the time-consuming process in preparing the rainfall input data for the WEPP model severely limit its application in South Africa mainly to research projects with some focus on storm intensities. The *ACRU* model is a daily time step simulation model; therefore no other time steps were attempted.

Data collected at runoff plots throughout the Weatherley catchment reveal that surface runoff is limited in the upper slopes. Most of the runoff generation in the Weatherley and Zululand catchments occurs at the foot of the slopes that give rise to partial area overland flow rather than catchment-scale overland flow conditions. It is to be expected that catchment discretization (the process of identifying subcatchments, channels and hillslopes which represent the catchment components) would affect sediment yield predictions.

For the WEPP model, the effects of catchment discretization were analysed through the amount of hillslopes and channels in the catchment, and the amount of overland flow elements (OFE) along hillslopes. An OFE is an area on the hillslope with relatively homogeneous soil and land management. The sediment yield predicted on the basis of spatial representivity of soil, slope and land management along a hillslope through 8-10 OFEs along a hillslope was comparable with the predicted sediment yield where spatial representivity of soil, slope and land management along a hillslope were lumped into one OFE. On the other hand, the sediment yield predicted for a high level of catchment discretization (38 hillslopes connected to 19 channels) was much higher than for a low level of discretization (3 hillslopes connected to 1 channel). This was in contradiction to what was expected as the spatial variability in soil, slope and land management was much higher along the hillslope catena than between the hillslopes. The WEPP model was unsuccessful in taking into account the effect of spatial representivity of soil, slope and land management along the hillslope catena since the WEPP model does not explicitly consider hillslope processes which give rise to partial area overland flow conditions. The fact that the WEPP model was insensitive to the effect of spatial discretization along hillslopes confirms the importance that sediment yield models applied at the small catchment scale should take account of the specific hillslope flow path mechanisms which occur in such a catchment.

The effects of catchment discretization were analysed for the research version of the *ACRU* model by simulating the catchment as a distributed configuration of response units in contrast to when the whole catchment is taken as a single lumped unit. The predicted sediment yield from the lumped, full catchment was higher than from the distributed zones, which yield sediment only from a single response unit adjacent to the riparian zone. This was because the whole of the catchment was deemed to be producing sediment in the lumped case, whereas, in the distributed example, only the near stream zones contributed sediment. The advantage of sediment yield models simulating the catchments as a distributed configuration of response units over models in which the whole catchment is taken as a single lumped unit was illustrated in that the predicted sediment yield in the former case was closer to measured sediment load than in the latter case. The simulation of the catchments as a distributed configuration of response units would be important at the small catchment scale for catchments where partial area overland flow conditions exist.

Simulation of scenarios

Extreme events have a major impact on erosion and sediment yield and are a key driver in the production and delivery of sediment yield. One of the major advantages of the WEPP model is that single storm events could be simulated in addition to the continuous simulation mode. Simulation of extreme events with a 20-year return interval at the Weatherley and Zululand catchments indicated that up to 30 and 60%, respectively, of the long-term average annual sediment yield could be delivered from hillslopes and small catchments in a single event. For the same event at Weatherley, the research version of the *ACRU* model applied in this study predicted that 50% of the long-term average annual sediment yield was delivered during the extreme event.

The focus of sediment yield predictions at the small catchment scale is to evaluate the severity of erosion under different management systems and may be intended as design tools for the selection of conservation practices. The WEPP model is a powerful prediction tool in simulating various farming systems and agricultural practice scenarios, because prediction results were visually presented along a hillslope or in a catchment through the Windows interface, and the various agricultural practice scenarios could easily be simulated in great detail through the use of default files from the extensive agricultural operational (e.g. burning, grazing, planting, harvesting, herbicide application, etc.) and tillage implement databases. The impact of various land management practice scenarios was simulated by the research version of the *ACRU* model from default values for the vegetation characteristics of crop coefficient, fraction of root depth in the A-horizon, leaf area index and interception loss from the agrohydrological model component, and by adjusting the canopy and ground-cover factors of the sediment yield model component. It is emphasized that the simulated values were relative (i.e. they were not absolute) and that they could only be used to compare different options.

Both the WEPP model and the research version of the *ACRU* model predicted a small increase in sediment yield when land in a pristine condition (natural erosion) was utilised for animal production, but a dramatic increase was predicted when rangeland was converted to arable land. It was predicted that the utilization of land for grazing purposes produced acceptable erosion rates which were less than the soil loss tolerance value. Predicted erosion rates were also in the range of the soil loss tolerance value when no- and minimum tillage practices were applied during a maize cropping system, but it was predicted that a maize cropping system under conventional cultivation practices produced unacceptably high erosion rates which exceed the soil loss tolerance value. The WEPP model predicted that the use of vegetative erosion control measures (vegetative filter strips and riparian buffer zones) was as effective as conservation cultivation methods (no- and minimum tillage) in decreasing sediment delivery to the stream systems from agricultural land under conventional cultivation. The impact of the various land management scenarios was compared on a relative basis since the comparisons were based on predicted sediment yield values and not on absolute values based on measured field data.

The WEPP model is superior to the research version of the *ACRU* model in the extent to which the models predict various land management scenarios, and the visual presentation of spatial and temporal distribution of erosion and sedimentation along hillslopes and in catchments. However, the application of the research version of the *ACRU* model is likely to be more successful in predicting sediment yield for South African conditions since the WEPP model needs more detailed input data that are mostly not readily available in South Africa. This is especially true for rainfall and plant management data.

8.2 RECOMMENDATIONS

The following future research needs were identified from this study:

1. Integration of the biophysical environment with the land user's socio-economic environment

A follow-up study on the integration of the impact of agricultural practices on the biophysical environment with the land user's socio-economic environment through participatory research is of prime importance. The selection of good agricultural practices and/or conservation measures, identified through scenario predictions demonstrated in this study, should be matched with *inter alia* the compatibility with existing farming practices, economic viability, farmer aspirations in producing site/area-specific erosion control measures. An ideal opportunity was identified during the information day at the Zululand catchment for such a project which could give valuable insights on the integration of LandCare and Integrated Catchment Management principles.

2. Classification of slope characteristics and soil forms in terms of hillslope flow path mechanisms

A study is needed to develop a classification scheme for linking slope characteristics and soil forms with the various hillslope flow path mechanisms. This study should include hillslopes occurring over a range of climatic, terrain and soil patterns (Land types), for instance along a transect extending across Mpumulanga – Gauteng - North West provinces and Mpumulanga – eastern Free State – KwaZulu-Natal – Eastern Cape provinces. Close collaborative research between soil scientists and hydrologists would be needed. The identification of the dominant flow path mechanism(s) along a hillslope with this classification scheme would greatly improve the predictive capability of sediment delivery and sediment-bound chemical constituents from agricultural land to the stream systems of small to large catchments.

3. Verification of gully erosion models

Model suites / systems need to be verified which take account of overland and concentrated flow erosion and gully erosion in catchments where gullies are the dominant source of sediment. Most of the sediment yield models do not simulate gully erosion which would be a severe limitation if these models are to be used to plan erosion control measures in catchments where gullies are the dominant source of sediment.

4. Remote sensing

The possibilities that low-level remote sensing hold for cost-effectively acquiring geo-referenced land-based data should be explored. The possibilities related to erosion include detailed land management images (up to 0.3m if required), a bare soil index, leaf area indexes for canopy covers, detailed Digital Elevation Models, and the mapping of gullies.

REFERENCES

AGUS, F., GINTINGS, A.N., KURNIA, U., ABDURACHMAN, A. AND VAN DER POEL, P., 1998. Soil erosion research in Indonesia: Past experiences and future direction. In: F.W.T. Penning de Vries, F. Agus AND J. Kerr (eds.). Soil erosion at multiple scales: Principles and methods for assessing causes and impacts, pp. 317-342. CABI Publishing, Wallingford.

ALBERTS, E.E., NEARING, M.A., WELTZ, M.A., RISSE, L.M., PIERSON, F.B., ZHANG, X.C, LAFLEN, J.M. AND SIMANTON, J.R., 1995. Soil component. In: NSERL (eds.). USDA – Water Erosion Prediction Project (WEPP), Technical Documentation, pp. 1.1 – 1.12. NSERL Report No 10, NSERL, USDA-ARS, West Lafayette, IN, USA.

ARMSTRONG, J. AND MACKENZIE, D., 1994. Catchment scale erosion prediction for land management planning. *Aust. J. Soil Water Cons.* 8(2), 29-40.

ARNOLD, J.G., WELTZ, M.A., ALBERTS, E.E. AND FLANAGAN, D.C., 1995. Plant growth component. In: NSERL (eds.). USDA – Water Erosion Prediction Project (WEPP), Technical Documentation, pp. 1.1 – 1.12. NSERL Report No 10, NSERL, USDA-ARS, West Lafayette, IN, USA.

ASCOUGH II, J.C., BAFFAUT, C., NEARING, M.A. AND FLANAGAN, D.C., 1995. Watershed model channel hydrology and erosion processes. In: NSERL (eds.). USDA – Water Erosion Prediction Project (WEPP), Technical Documentation, pp. 1.1 – 1.12. NSERL Report No 10, NSERL, USDA-ARS, West Lafayette, IN, USA.

BAFFAUT, C., NEARING, M.A., ASCOUGH, J.C. AND LUI, B., 1997. The WEPP watershed model:II. Sensitivity analyses and discretization on small watersheds. *Trans. ASAE* 49(4), 935-943.

BEASLEY, D.B., HUGGINS, L.F. AND MONKE, E.J., 1980. ANSWERS: A model for watershed planning. *Trans. ASAE* 23, 938-944.

BEVIN K.J., LAMB, R., QUINN, P.F., ROMANOWICZ, R. AND FREER, J., 1995. TOPMODEL. In: Computer Models of Watershed Hydrology (ed: V. Singh), 627-668. Water Resources Publications, Littleton, CO.

BRICQUET, J.P. AND CLAUDE, J., 1998. Latest developments in the design of hydrological studies of watersheds. In: F.W.T. Penning de Vries, F. Agus AND J. Kerr (eds.). Soil erosion at multiple scales: Principles and methods for assessing causes and impacts, pp. 317-342. CABI Publishing, Wallingford.

BURT, T.P., 1998. Infiltartion for soil erosion models: Some temporal and spatial complications. In: J. Boardman and D. Favis-Mortlock (eds.). Modelling soil erosion by water, Series I: Global environmental change, pp. 35-41. Springer-Verlag, Berlin.

CIESIOLKA, C.A.A. AND ROSE, C.W., 1998. The measurement of soil erosion. In: F.W.T. Penning de Vries, F. Agus AND J. Kerr (eds.). Soil erosion at multiple scales: Principles and methods for assessing causes and impacts, pp. 287-302. CABI Publishing, Wallingford.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY, 1996. The philosophy and practice of integrated catchment management: implications for water resource management in South Africa. Water Research Commission, Pretoria. WRC Report No. TT81/96.

DICKINSON, A. AND COLLINS, R., 1998. Predicting erosion and sediment yield at catchment scale. In: F.W.T. Penning de Vries, F. Agus AND J. Kerr (eds.). Soil erosion at multiple scales: Principles and methods for assessing causes and impacts, pp. 317-342. CABI Publishing, Wallingford.

ELLIOT, B., WARD, A., LANE, L.J. AND LAFLEN, J.M., 1989. An overview of WEPP: Water Erosion Prediction Project. Paper presented at the Southern African Regional Commission for Conservation and Utilisation of Soil, 16th regular meeting of the subcommittee for Land-use Planning and Erosion Control (LUPEC). Mbabane, Swaziland, 12-14 September 1989.

ELWELL, H.A., 1978. Modelling soil losses in southern Africa. *J. Agric. Eng.* 23, 117-127.

ESPREY, L.J., 1997. Hillslope experiments in the North Eastern Cape to measure and model subsurface flow processes. Unpublished M.Sc dissertation. Department of Agricultural Engineering, University of Natal.

FITZJOHN, C., TERNAN, J.L. AND WILLIAMS, A.G., 1998. Soil moisture variability in a semi-arid gully catchment: Implications for runoff and erosion control. *Catena* 32, 55-70.

FLANAGAN, D.C. AND NEARING, M.A., 2000. Sediment particle sorting on hillslope profiles in the WEPP model. *Trans. ASAE* 43, 573-583.

FLANAGAN, D.C. AND NEARING, M.A., 1995. Abstract. In: NSERL (eds.). USDA – Water Erosion Prediction Project (WEPP), Technical Documentation. NSERL Report No 10, NSERL, USDA-ARS, West Lafayette, IN, USA.

FLANAGAN, D.C., ASCOUGH, J.C., NEARING, M.A. AND LAFLEN, J.M., 1995. Overview of the WEPP Erosion Prediction Model. In: NSERL (eds.). USDA – Water Erosion Prediction Project (WEPP), Technical Documentation, pp. 1.1 – 1.12. NSERL Report No 10, NSERL, USDA-ARS, West Lafayette, IN, USA.

FOSTER, G.R., FLANAGAN, D.C., NEARING, M.A., LANE, L.J., RISSE L.M. AND FINKNER, S.C., 1995. Hillslope erosion component. In: NSERL (eds.). USDA – Water Erosion Prediction Project (WEPP), Technical Documentation, pp. 1.1 – 1.12. NSERL Report No 10, NSERL, USDA-ARS, West Lafayette, IN, USA.

FOOD AND AGRICULTURAL ORGANISATION, 2003. World Overview of Conservation Approaches and Technologies: Land and Water Digital Media Series.

HICKSON, R. AND LORENTZ, S.A., 1999. Identifying Dominant Hydrological Processes on Molteno Formations of the North Eastern Cape Province. Ninth South African Hydrology Symposium, University of the Western Cape, November, 1999. pp 10.

HOWE B.J. AND LORENTZ S.A., 1995. Modelling sediment yield in the Mzinduzi basin using contributing area techniques. Proc. 7th South African National Hydrology Symposium. IWR Grahamstown.

INTERNATIONAL SOIL SCIENCE SOCIETY, 1996. Terminology for soil erosion and conservation. Grafisch Service Centrum, Wageningen.

JAKEMAN, A.J., GREEN, T.R., ZHANG, L., BEAVIS, S.G., EVANS, J.P., DIETRICH, C.R. AND BARNES, B., 1998. Modelling catchment erosion, sediment and nutrient transport in large basins. In: F.W.T. Penning de Vries, F. Agus AND J. Kerr (eds.). Soil erosion at multiple scales: Principles and methods for assessing causes and impacts, pp. 317-342. CABI Publishing, Wallingford.

KELBE, B., MULDER, G.J., BODENSTEIN, B., HATTINGH, D. AND VERWEY, A., 1992. An investigation of the Hydrological response to Third World settlements in the Periurban areas of Kwazulu Natal. Water Research Commission, Pretoria. WRC Report No. 233/1/92.

KELBE, B., SNYMAN, N. AND MULDER, G., 1996. Modelling Aspects of Hydrological Processes and Water Quality characteristics in the Zululand Coastal Region. Water Research Commission – Draft Report.

KIRKBY, M., 1998. Evaluation of plot runoff and erosion forecasts using the CSEP and MEDRUSH models. In: J. Boardman and D. Favis-Mortlock (eds.). Modelling soil erosion by water, Series I: Global environmental change, pp. 35-41. Springer-Verlag, Berlin.

KNISEL, W.G., 1980. CREAMS: a field scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Report 26.

LANE, L.J., RENARD, K.G., FOSTER, G.R. AND LAFLEN, J.M., 1992. Development and application of modern soil erosion prediction technology – The USDA experience. *Aust. J. Soil Res.* 30, 893-912.

LINACRE, E.T., 1977. A simple formula for estimating evaporation rates in various climates, using temperature data alone. *Agricultural Meteorology* 18, 409-424.

LORENTZ, S.A. AND SCHULZE, R.E., 1995. Sediment yield. In: Schulze, R.E. (ed.). Hydrology and Agrohydrology: A text to accompany the *ACRU* 3.00 Agrohydrological Modelling System. Water Research Commission, Pretoria TT69/95. pp AT23-1 to AT23-15.

LORENTZ, S.A., RIENKS, S., JETTEN, V., DE ROO, A., KELBE, B. AND SNYMAN, N., 1997. Runoff and Sediment Modelling Data for Experimental Catchments in Zululand, South Africa. University of Natal Report.

LORENTZ, S.A. AND ESPREY, L.J., 1998. Baseline hillslope study prior to afforestation in the Umzimvubu headwaters of the North East Cape Province, South Africa. In: Kovar, K., Tappeiner, U., Peters, N.E. and Craig, R.C. (eds.) Hydrology, Water Resources and Ecology in Headwaters (Proceedings of the Headwater '98 Conference held at Meran/Merano, Italy, April 1998) IAHS Publ. No. 248:267-273.

LORENTZ, S.A. AND HICKSON, R., 2001. Applying Hillslope Hydrology Observations to Catchment Modelling in Molteno Formations. Paper presented at Tenth South African National Hydrology Symposium: 26-28 September, 2001.

LORENTZ, S., PRETORIUS, J., THORNTON-DIBBS, S. AND GOBA, P., 2003. Hydrological Systems Modelling Research Programme: Hydrological Processes. Phase II: Quantification of Hillslope, Riparian and Wetland Processes. WRC Report No. K5/1061. Water Research Commission, Pretoria. (in Press).

MCDONNELL, J. J., FREER, J., HOOPER, R., KENDALL, C., BURNS, D., BEVANS, K. AND PETERS, J., 1996. New method developed for studying flow in hillslopes. *EOS, Transactions, AGU* 77(47), 471-472.

MCGLYNN, B.L., MCDONNELL, J.J. KENDALL, C. AND HOOPER, R.P. 2001. The effects of catchment scale and landscape organization on streamflow generation processes. AGU Chapman Conference on State-of-the-Art in Hillslope Hydrology. Sunriver, OR, Oct 8-12, 2001. Abstracts. p38.

MEIN, R.G. AND LARSON, C.L., 1973. Modelling infiltration during a steady rain. *Water Resources Research* 9(2):384-394.

MORGAN, R.P.C., 1995. Modelling soil erosion. In: R. Morgan (ed.). Soil erosion and conservation. 2nd ed. Longman Group Ltd., London.

MORGAN, R.P.C., QUINTON, J.N. AND RICKSON, R.J., 1994. Modelling methodology for soil erosion assessment and soil conservation design: the EUROSEM approach. Outlook in Agriculture 23, 5-9.

MULDER, G.J., 1984. Die invloed van infiltrasie op stormwaterafloop in die opvanggebied van die Ntuzerivier (Zoeloelandse kusstrook). Water Research Commission, Pretoria. WRC report no. 66/4/84.

MULDER, G.J. AND KELBE, B., 1992. An investigation of the Hydrological response to Third World settlements in the Periurban areas of Kwazulu Natal. Water Research Commission, Pretoria. WRC Report No. 233/2/92.

NATIONAL SOIL EROSION RESEARCH LABORATORY, 1999. WEPP model version 1999.5. [Web] http://topsoil.nserl.purdue.edu/nserlweb/weppmain.htm. [Date of access 21/05/1999].

NATIONAL SOIL EROSION RESEARCH LABORATORY, 2002. WEPP model version 2002.7. [Web] http://topsoil.nserl.purdue.edu/nserlweb/weppmain.htm. [Date of access 30/07/2002].

NEARING, M.A., DEER-ASCOUGH, L. AND LAFLEN, J.M., 1990. Sensitivity analysis of the WEPP hillslope profile erosion model. *Trans ASAE*, 33(3), 839-849.

NEARING, M.A., FOSTER, G.R., LANE, L.J. AND FINKNER, S.C., 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. *Trans. ASAE* 32, 1587-1593.

NEARING, M.A., LANE, L.J. AND LOPES, V.L., 1994. Modelling soil erosion. In: R. Lal (ed.). Soil erosion research methods. St. Lucie Press, Delray Beach, Florida.

NEARING, M.A. AND NICKS, A.D., 1998. Evaluation of the Water Erosion Prediction Project (WEPP) model for hillslopes. In: J. Boardman and D. Favis-Mortlock (eds.). Modelling soil erosion by water, Series I: Global environmental change, pp. 43-53. Springer-Verlag, Berlin.

PENMAN, H.L., 1963. Vegetation and Hydrology. Tech. Com. No. 53, Commonwealth Bureau of Soils, Harpenden, England.

POESEN, J.W.A., VANDAELE, K. AND WESEMAEL, B., 1998. Gully erosion: Importance and model applications. In: J. Boardman and D. Favis-Mortlock (eds.). Modelling soil erosion by water, Series I: Global environmental change, pp. 285-312. Springer-Verlag, Berlin.

PRETORIUS, D.J., 1998. The development of land degradation monitoring and auditing techniques with the aid of remote sensing and GIS. Report prepared by the ARC-Institute for Soil, Climate and Water, Pretoria, South Africa for the National Department of Agriculture – Directorate Agricultural Resource Concervation. Report no. GW/A/96/33.

RENARD, K.G., FOSTER, G.R., WEESIES, G.A., MCCOOL, D.K, AND YODER, D.C., COORDINATORS. 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Soil Loss Equation (RUSLE). U.S. Dept. of Agriculture, Agric. Handbook No. 703, 404 pp.

RITCHIE, J.T., 1972. A model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research* 8(5):1204-1213.

ROBERTS, V.G., HENSLEY, M., SMITH-BAILLIE, A.L. AND PATERSON, D.G., 1996. Detailed Soil Survey of the Weatherley Catchment. Institute of Soil, Climate and Water, Pretoria. ISCW report no. GW/A/96/33.

ROSE, C.W., WILLIAMS, J.R., SANDERS, G.C. AND BARRY, D.A., 1983. A methametical model of soil erosion and deposition process. I. Theory for a plane element. *Soil Sci. Soc. Amer. J.* 47, 991-995.

RUTHERFURD, I., HAIRSINE, P. AND WALKER, M., 1996. Stream management in Australia – A review of the 1st National Stream Management Conference, 1996. *Aust. J. Soil Cons.* 9(4), 27-33.

SAVABI, M.R. AND WILLIAMS, J.R., 1995. Water Balance and Percolation. In: NSERL (eds.). USDA Water Erosion Prediction Project (WEPP), Technical Documentation, pp. 5.1 – 5.14. NSERL Report No 10, NSERL, USDA-ARS, West Lafayette, IN, USA.

SAVABI, M.R., SKAGGS, R.W. AND ONSTAD, C.A., 1995. Subsurface Hydrology. In: NSERL (eds.). USDA – Water Erosion Prediction Project (WEPP), Technical Documentation, pp. 6.1 – 6.14. NSERL Report No 10, NSERL, USDA-ARS, West Lafayette, IN, USA.

SCHULZE, R.E., 1995a. Hydrology and Agrohydrology: A text to accompany the *ACRU* 3.00 Agrohydrological Modelling System. Water Research Commission, Pretoria TT69/95. pp AT23-1 to AT23-15.

SCHULZE, R.E., 1995b. Sensitivity of *ACRU* model output to input. In: Schulze, R.E. (ed.). Hydrology and Agrohydrology: A text to accompany the *ACRU* 3.00 Agrohydrological Modelling System. Water Research Commission, Pretoria TT69/95. pp AT23-1 to AT23-15.

SCHULZE, R.E., 1995c. Streamflow. In: Schulze, R.E. (ed.). Hydrology and Agrohydrology: A text to accompany the *ACRU* 3.00 Agrohydrological Modelling System. Water Research Commission, Pretoria TT69/95. pp AT23-1 to AT23-15.

SCOTT, D. F. 1994. The hydrological effects of fire in South African catchments. PhD thesis. Department of Agricultural Engineering, University of Natal, Pietermaritzburg. South Africa.

SMITH (1998). Handbook for agricultural advisors in KwaZulu-Natal. KwaZulu-Natal Department of Agriculture.

SMITHERS JC AND SCHULZE RE, 1995. Data and information input required to operate the *ACRU* model. In: Schulze, R.E. (ed.). Hydrology and Agrohydrology: A text to accompany the *ACRU* 3.00 Agrohydrological Modelling System. Water Research Commission, Pretoria TT69/95. pp AM2-1 to AM2-12.

SMITHERS JC AND SCHULZE RE, 2000. Development and evaluation of techniques for estimating short duration design rainfall in South Africa. Water Research Commission, Pretoria. WRC Report No. 681/1/00.

STONE, J.J., LANE, L.J., SHIRLEY, E.D. AND HERNANDEZ, M., 1995. Hillslope Surface Hydrology. In: NSERL (eds.). USDA – Water Erosion Prediction Project (WEPP), Technical Documentation, pp. 4.1 – 4.20. NSERL Report No 10, NSERL, USDA-ARS, West Lafayette, IN, USA.

UHLENBROOK, S. AND LEIBUNDGUT, CH., 2002. Process-oriented catchment modeling and multiple-response validation. *Hydrol. Process*. 16:423-440.

VALENTIN, C., 1998. Towards an improved predictive capability for soil erosion under global change. In: J. Boardman and D. Favis-Mortlock (eds.). Modelling soil erosion by water, Series I: Global environmental change, pp. 7-29. Springer-Verlag, Berlin.

VAN ZYL, A.J., 2004. Modelling non-point source pollution in agriculture from field to catchment scale: a scoping study – sediments and metal pollution and related activities. Institute of Soil, Climate and Water, Pretoria. ISCW report no. GW/A/04/08.

VERSTER, E., 1992. Production of the sediment yield delivery potential map for southern Africa. Report to the Water Research Commission by Sigma Beta, WRC report no. 297/2/92.

WALLING, D.E., 1994. Measuring sediment yield from river basins. In: R. Lal (ed.). Soil erosion research methods. Soil and Water Conservation Society and St Lucie Press, Delray Beach, Florida, USA.

WALTER, M.T., WALTER, M.F., BROOKS, E.S., STEENHUIS, T.S., BOLL, J. AND WEILER, K., 2000. Hydrologically sensitive area: Variable source area hydrology implications for water quality risk assessment. *J. Soil Water Cons.* 55(3), 277-284.

WILCOX, B.P. AND SIMANTON, J.R., 1998. Predicting runoff in semiarid woodlands: Evaluation of the WEPP model. In: J. Boardman and D. Favis-Mortlock (eds.). Modelling soil erosion by water, Series I: Global environmental change, pp. 131-140. Springer-Verlag, Berlin.

WILLIAMS, J.R., 1975. Sediment-yield prediction with Universal Equation using runoff energy factor. In: Present and prospective technology for predicting sediment yields and sources, pp. 244-251. USDA publication no. ARS-540.

WILLIAMS, J.R. AND BRENDT, H.D., 1977. Sediment yield based on watershed hydrology. *Trans. ASAE* 20, 1100-1104.

WISCHMEIER, W.H. AND SMITH, D.D., 1965. Predicting raifall-erosion losses from cropland east of Rocky Mountains. Agricultural Handbook, no. 282. USDA, Washington DC.

WISCHMEIER, W.H., JOHNSON, C.B. AND CROSS, B.V., 1971. A soil erodibility nomograph for farmland and construction sites. Journal of Soil and Water Conservation, 28, 189-193.

YALIN, M.S., 1963. An expression of bed-load transportation. Journal of Hydraulic Division, American Society of Civil Engineers 98: 221-250.

ZELEKE, G., WINTER, T., AND FLANAGAN, D., 1999. BPCDG: Breakpoint Climate Data Generator for WEPP using observed standard weather data sets. Extracted from [http://toppsoil.nserl.purdue.edu/weppmain/wepp.html] on 10 August 2000.

APPENDIX 1

PREPARATION OF CLIMATE AND RAINFALL INPUT DATA FOR WEPP MODEL

1 PREPARATION OF CLIMATE DATA

The BreakPoint Climate Data Generator (BPCDG) program (see section 3.3) was used to prepare the weather data file (*.cli) for the WEPP model. The BPCDG program requires four input files that were created by a text editor from existing databases:

- Station information (*st.dat)
- Rainfall (storm) pattern (*pl.csv)
- Temperature and wind (*cs.csv)
- Radiation and dew point temperature and wind tables (*cl.dat)

Table 1.1 summarises the climatic data required by the BPCDG program.

Table 1.1. Climatic data required by the BPCDG program to prepare the weather data file for the WEPP model

STATION INFORMATION	RAINFALL (Breakpoint values)	OTHER CLIMATIC VARIABLES (Daily values)
Name Elevation Latitude Longitude Years of observed data	Beginning and ending times Rainfall amount Rain intensity	Maximum temperature Minimum temperature Dew point temperature Wind velocity at 8 and 18 hours* Wind direction at 8 and 18 hours* Radiation

* Only qualitative values

The School of Bioresources Engineering and Environmental Hydrology (SBEEH), University of Natal, supplied rainfall data for Weatherley (1998-2002), Kokstad (2000-2002) and Zululand (2000-2001), while the Department of Hydrology, University of Zululand (UZ-DH), supplied rainfall data for the Zululand catchment (W1H017) for 1998 and 1999. Rainfall was monitored at the weir of Zululand's catchment by using autographic chart recorders. UZ-DH digitised the autographic charts so that all the rainfall data were in the same format to be prepared for the rainfall input file of the BPCDG program. The digital 1-minute recorded rainfall data were converted into the data required by the rainfall input file of the BPCDG program by applying the developed programs discussed in section 3.3.

The station information, temperature, wind and radiation data for Weatherley and Kokstad were downloaded from the National Agromet Databank at the ARC-ISCW. The specific data that were downloaded for 1998 and 2002 included:

- Maximum temperature (MxT)
- Minimum temperature (MnT)
- Wind speed
- Wind direction
- Radiation
- Relative humidity (RH)

The downloaded data on wind speed and direction were converted through written algorithms to wind speed and direction classes and codes as required by the BPCDG program (Table 1.2).

Table 1.2. The conversion of information on wind speed and direction to wind speed and direction classes and codes as required by the BPCDG program

WIND VELOCITY (ms^{-1}) CONVERSION TABLE		WIND DIRECTION (º) CONVERSION TABLE	
0.0	n (none)	0	(n) north
1.5	w (weak)	22.5	(nne) north north-east
3.0	m (moderate)	45	(ne) north east
6.5	s (strong)	67.5	(ene) east north-east
8.0	v (very strong)	90	(e) east
		112.5	(ese) east north-east
		135	(se) south east
		157.5	(sse) south south-east
		180	(s) south
		202.5	(ssw) south south-west
		225	(sw) south west
		247.5	(wsw) west south-west
		270	(w) west
		292.5	(wnw) west north-west
		315	(nw) north west
		337.5	(nnw) north north-west

As dew point temperature was not monitored, it was derived from relative humidity and temperature as follows:

1. Obtain the saturation vapour pressure (Es):

   Es=6.11*10.0*(7.5*Tc/(237.7+Tc))

2. Use the saturation vapour pressure and the relative humidity to compute the actual vapour pressure (E) of the air:

   E=(RH*Es)/100

3. Dew point temperature (Td) is calculated as:

   Td=(-430.22+237.7*ln(E))/(-ln(E)+19.08)

When relative humidity was not available it was derived as follows:

1. Obtain the saturation vapour pressure (Es) from dry bulb temperature (Tdry):

   Es=0.611exp (17.27*Tdry/(Tdry+237.3))

2. Use the saturation vapour pressure and the wet bulb temperature (Twet) to compute the actual vapour pressure (E) of the air:

   E=0.611exp(17.27*Twet/(Twet+237.3))-0.0008*100*(Tdry-Twet)

3. Dew point temperature (Td) is calculated as:

   Td = Tdry*(1-ln(E/ES)/19.65)

The radiation for Zululand was calculated from the sunshine duration at Heatonville and Mtunzini (South African Sugar Association (SASA)) as follows:

1. Compute the inverse relative distance Earth-Sun:

d_r = 1+0.033cos*(0.0172*DOY)

2. Solar declination:

δ = 0.409*sin(0.0172DOY-1.39)

3. Sunset hour angle:

ω_s =arcos(-tanφ*tan δ)

4. Extraterrestrial radiation:

Ra=37.6* d_r *(ω_s*sinφ*sin δ+cosφ*cos δ*sin ω_s)

5. Maximum sunshine duration:

N=7.64* ω_s

6. Radiation:

Rs=(0.24+0.49*n/N)*Ra

where DOY is the day of the year, n is sunshine duration and φ is the latitude in Radians.

For both Weatherley and Zululand the radiation (MJ m^{-2} day^{-1}) was converted to Langleys as required by the BPCDG program. This was done by multiplying radiation by 100/4.184 or 23.90.

During the five-year period between 1998 and 2002 almost one year's data from Weatherley were missing, with the exception of radiation where approximately two year's data were missing. Data from stations close to Weatherley station were considered to patch the missing data. These stations include Somerton, Wildebees, Tree Fern Pool and Funeray (Table 1.3).

Table 1.3. Weather stations used to patch Weatherley station

NUMBER	LAT	LON	ALT (m)	NAME	INSTITUTION
30087	-31.1196	28.1279	1289	Wildebees	NECF
30148	-31.0401	28.1419	1174	Tree Fern Pool	NECF
21865	-31.0936	28.2311	1289	Somerton	ARC-ISCW
30193	-31.1000	28.3330	1325	Weatherley	NECF
30149	-31.3883	28.0833	1550	Funeray	ARC-ISCW

*NECF: North-East Cape Forestry

Long-term mean 10-daily maximum and minimum temperature values were derived from long-term mean temperature surfaces created by ARC-ISCW and a relationship between the stations was determined by plotting these points (Figures 1.1 and 1.2). These figures illustrate that Somerton and Weatherley's long-term mean maximum and minimum temperature 10-daily values are very similar, followed by Wildebees. Thus, Somerton data was mainly used to patch the missing data at Weatherley. When the other stations were used, a factor was added for the difference between the stations. This factor was the difference between the long-term mean 10-daily values for the two stations. For the few days that were still missing, averages were used in which the 1997 data was also included (this was only necessary for 1 day, except for radiation). Because of the fact that 50% of the radiation data were missing, monthly averages for radiation were used rather then daily values in the *cl.dat input files.

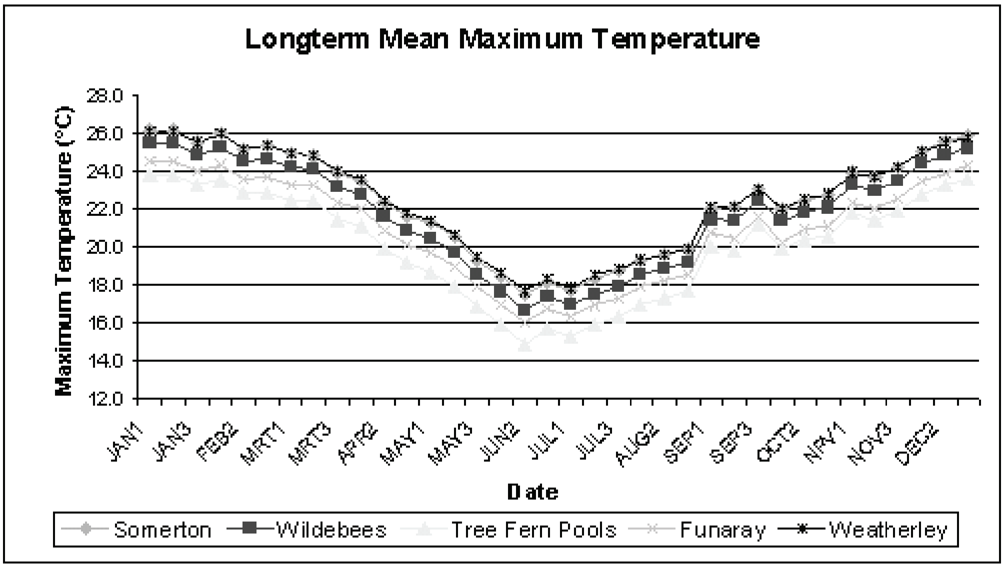

Figure 1.1. Ten-daily long-term mean maximum temperatures.

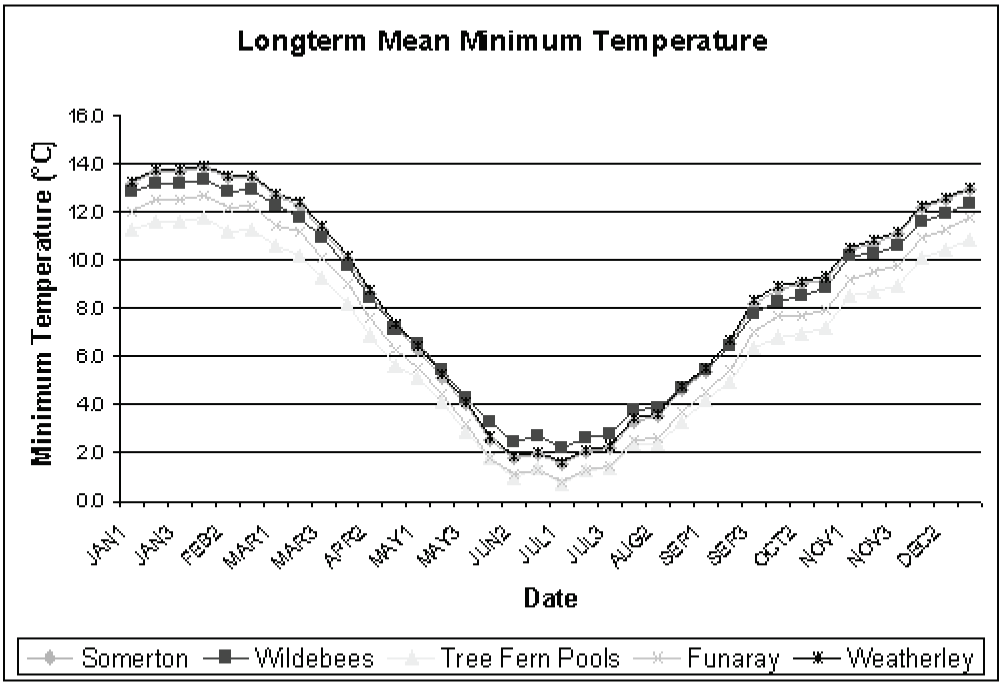

Figure 1.2. Ten-daily long-term mean minimum temperatures.

No climate data were available for Zululand. Instead three stations close to the Zululand station were used to create data for the period 1998 to 2002. These stations include Heatonville and Mtunzini (both SASA stations) and Mtunzini (an ARC-ISCW station) (Table 1.4). Again, long-term mean 10-daily Tx and Tn values were derived from long-term mean temperature surfaces and a relationship between the stations was determined by plotting these points (Figures 1.3 and 1.4). For all these stations, factors were calculated to incorporate the difference between the stations. The station in best agreement with Zululand was used in each case.

Table 1.4. Weather stations used to patch Zululand station

NUMBER	LAT	LON	ALT	NAME	INSTITUTION
	-28.8333	31.7550	260	Zululand	
460	-28.7167	31.8000	200	Heatonville	SASA
0011	-28.9330	31.7000	36	Mtunzini (SASEX)	SASA
30281	-28.9500	31.7000	38	Mtunzini (ARC-ISCW)	ARC-ISCW

Kokstad's weather data was reasonably complete. Only 9 days of temperature data needed patching for which Beginsel and Fort Donald (ARC-ISCW stations) were used. Unfortunately the Kokstad station did not have wind, dew point temperature and radiation data. Fort Donald's wind data was used and Matatiele's (a South African Weather Service (SAWS) station) sunshine hours (to calculate radiation) and relative humidity (to calculate dew point temperature) (Table 1.5).

Table 1.5. Weather stations used to patch Kokstad station

NUMBER	LAT	LON	ALT	NAME	INSTITUTION
12890	-30.5167	29.4167	1372	Kokstad-Agr	ARC-ISCW
19711	-30.2833	29.0667	1463	Beginsel	ARC-ISCW
30439	-30.68	29.55	1259	Fort Donald	ARC-ISCW
02075310	-30.35	28.8	1490	Matatiele	SAWS

Once the four input files were successfully prepared for the BPCDG program, the program was run to identify any data errors and to see if more than 50 breakpoints occurred in a day. If the run was successful, an output file was produced in the correct format for the WEPP model. The output files of the BPCDG program were then imported into the WEPP model.

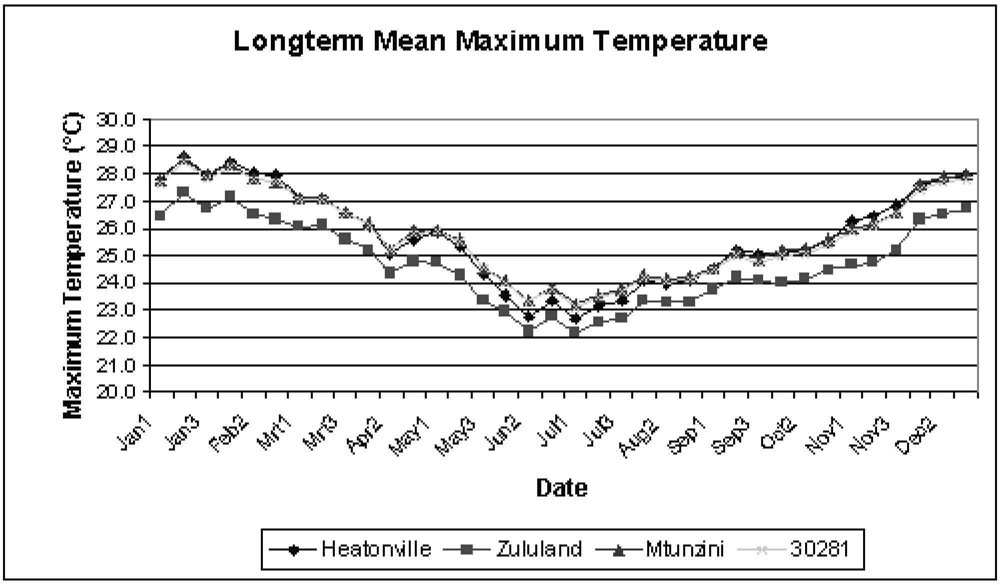

Figure 1.3. Ten-daily long-term mean maximum temperatures for the Zululand Patch.

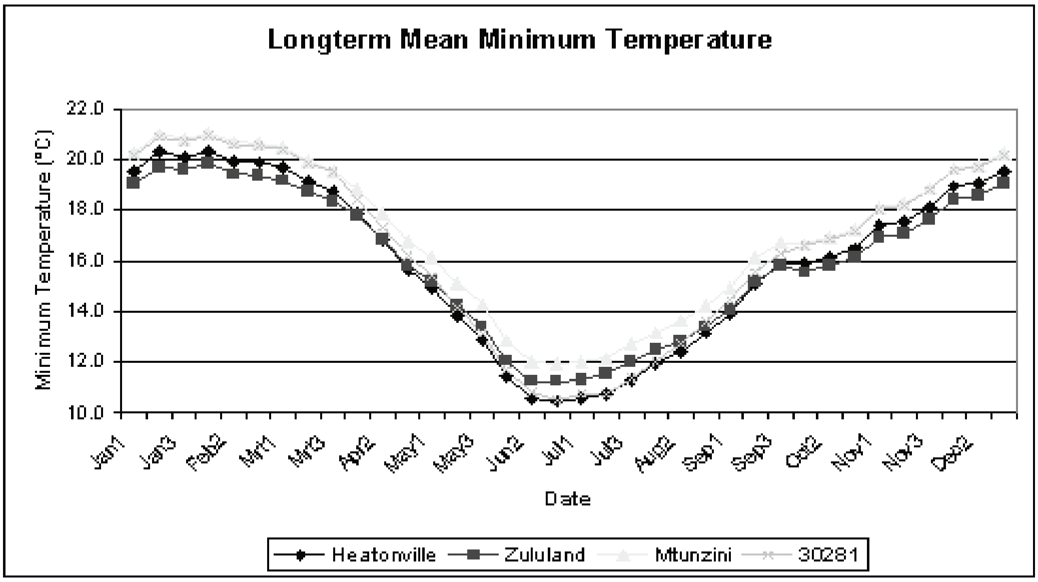

Figure 1.4. Ten-daily long-term mean minimum temperatures for the Zululand Patch.

2 BREAKPOINT CLIMATE DATA GENERATOR (BPCDG) PROGRAM

2.1 Methodology

Simulated climate for the WEPP model simulations is normally generated using the CLIGEN program, which is a computer program run separately from the WEPP model. However, the CLIGEN program itself requires specially formatted monthly statistical weather data as input, which are not readily available in many countries, including South Africa (see Chapter 3 for work done on the CLIGEN program). It was anticipated in the project proposal that a program should be developed to substitute the CLIGEN program in order to prepare the WEPP model climate input files from climatic data collected at the three study sites. During the WEPP model training workshop a stand-alone program, the BreakPoint Climate Data Generator (BPCDG) program (Zeleke, Winter and Flanagan, 1999), was obtained to create breakpoint climate data for the WEPP model from standard rain gauge data and other daily weather data sets of any meteorological station.

The BPCDG program was designed to use actual measured storm data rather than storm data generated by using different probability functions. The BPCDG program has the following advantages:

- It allows direct use of observed storm and other daily standard climate data sets;
- It is easy to apply, and the input files required can be created with any text editor;
- It doesn't confront the user with various statistical procedures for preparing input data sets;
- The input data can be found in any standard climate station and there is no need for special climate stations, such as the 15-minute precipitation recording stations in the US; and
- It creates intermediate files to help users identify errors and to allow for easy checking of their data sets (Zeleke et al., 1999).

The first file of the BPCDG program requires information on the rainfall storm pattern, such as amount of rainfall, and beginning and end times of the storm intensity slope breaks. The BPCDG program was developed to prepare the rainfall storm file from autographic rainfall record charts (Zeleke, October 2000, personal communication). However, rainfall data was collected by automatic weather stations (minute intervals) at the three study sites. The National Soil Erosion Research Laboratory (NSERL) of the United States Department of Agriculture - Agricultural Research Services (USDA-ARS), which is the developer of the WEPP model and WEPP model supported programs such as the BPCDG program, was approached on the availability of a program that has some code that can identify similar rainfall intensities from the rainfall data collected (minute intervals) by an automatic weather station (Flanagan, October 2000, personal communication). Personnel at NSERL were not aware of such a program or coding. After further consultation on the possibilities of preparing the rainstorm file of the BPCDG program from rainfall data collected by an automatic weather station, the only viable option was to plot cumulative rainfall amount (y-axis) against time (x-axis) for each rainfall event. Since intensity is a slope, i.e. rainfall amount / time interval, it is very easy to identify the intensity slope breaks and to calculate the amount, and beginning and end times for each slope break.

As this option is very time consuming, it was decided to write a program that identifies "periods of equal intensity" and determines the amount of rain, beginning and end times, and rain intensity for each “period of equal intensity”. However, the simple algorithms identifying periods of equal intensity were not as accurate as was desired since the change in intensity in a period of equal intensity is often larger than between these periods. Therefore, considerable programming was required. Two programs were written with different approaches:

1. Making a cumulative plot of rainfall amount against time and then searching for changes in slope (Figure 2.1). Factors such as the "window of time" and the sensitivity of slope to define a "change" in slope were important.
2. Determining breakpoints without calculating intensity, but by determining breakpoints from the time increments for each 0.2 mm rain (Figure 2.2).

SBEEH wrote the first program and ARC-ISCW the second program.

2.2 Results

The rainfall file of the BPCDG program (Zeleke et al., 1999) requires information about the amount of rain, beginning and end times, and rain intensity for each “period of equal intensity” (breakpoint rainfall) for a specific rainfall event (see section 3.3). Two programs were therefore written that identify periods of equal rain intensity.

According to the developers of the BPCDG program, the procedure to be followed for obtaining information for the rainstorm file of the BPCDG program is to plot cumulative rainfall (y-axis) against cumulative time (x-axis) for each rainfall event. The breakpoint rainfall is determined from intensity slope breaks (Zeleke, October 2000, personal communication). Figure 2.3 illustrates the breakpoints of a rainfall event at Weatherley. The first program (Figure 2.1) is based on the above-mentioned procedure by searching for changes in the slope pattern in the cumulative rain vs. time plot.

The second program determines breakpoint rainfall without calculating intensity, but from the time increment for each 0.2 mm of rain (Figure 2.2.). Figure 2.4 illustrates how the second program determines the intensity slope breaks for the same rain event as in Figure 2.3. The second program first identifies all the time increments of rain amounts exceeding 0.2 mm. These time increments are converted to increments of 0.2 mm rain amounts. The difference between each 0.2 mm rain time increment and the average time increment of the storm is calculated (time inc-avg time inc). The intensity slope breaks are identified when the line of time inc–avg time inc intersects zero on the y-axis (Figure 2.4).

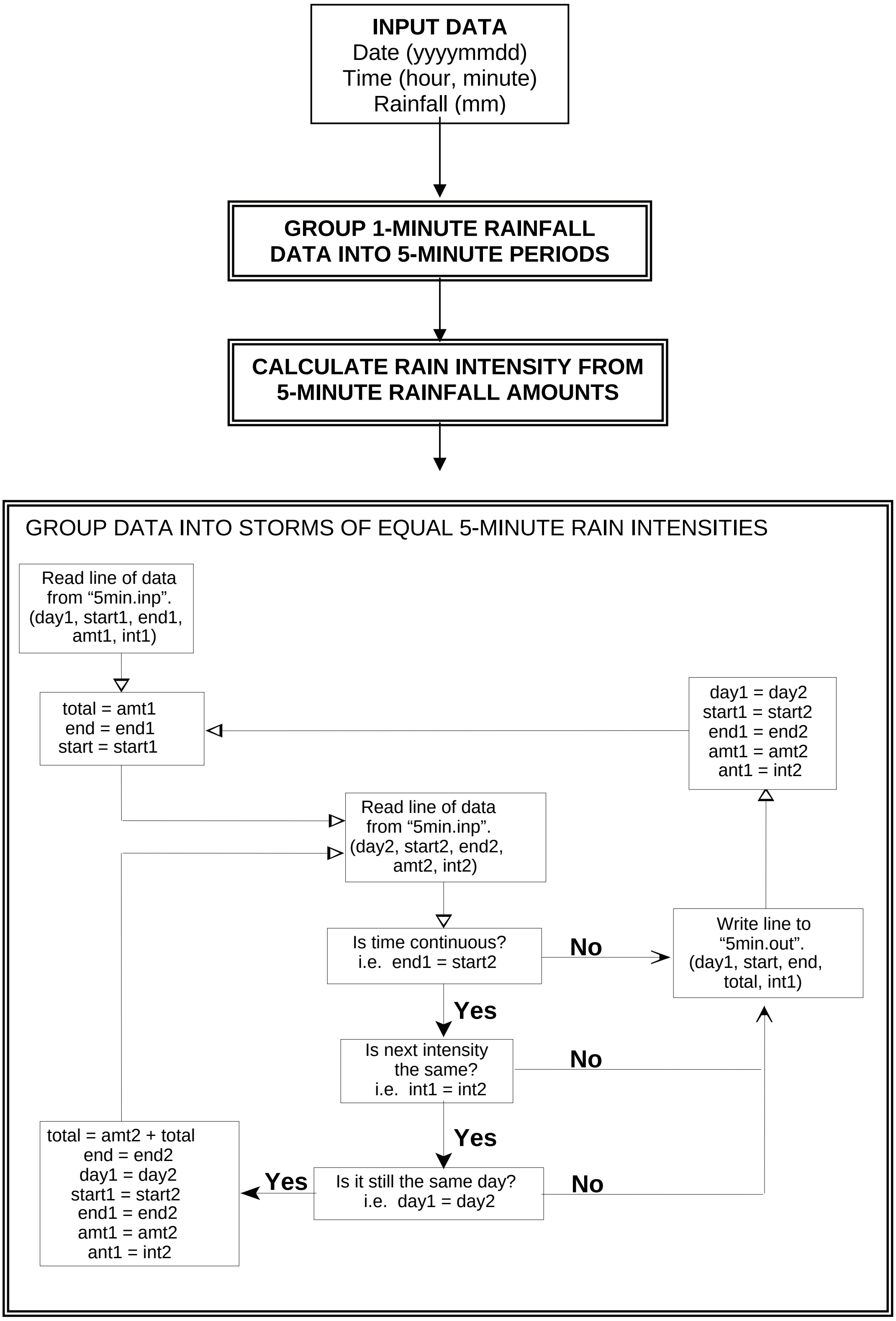

Figure 2.1. Determining breakpoints of rain intensity from calculated 5-minute rain intensity data.

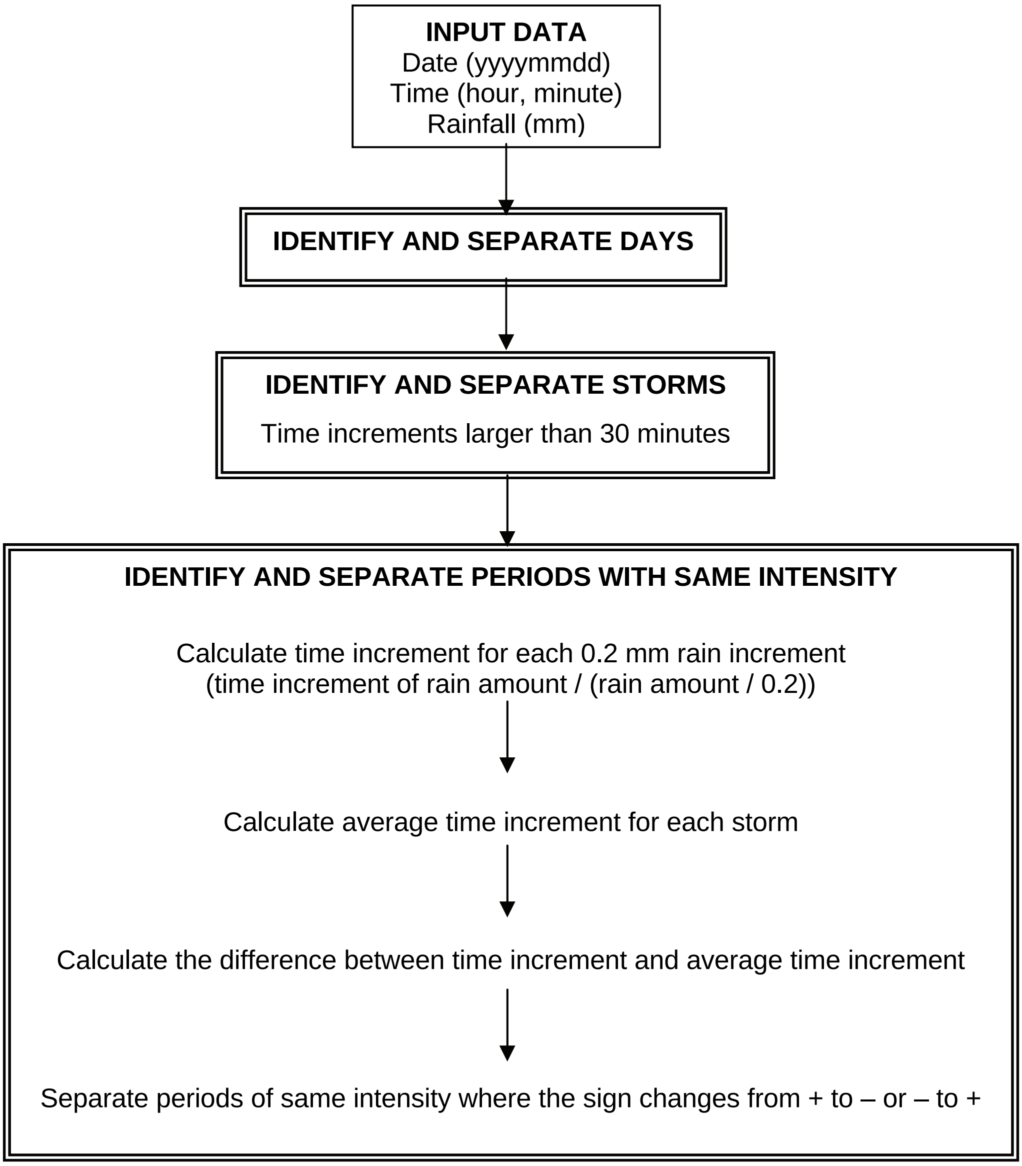

Figure 2.2. Determining breakpoints of same rain intensity without calculating rain intensity.

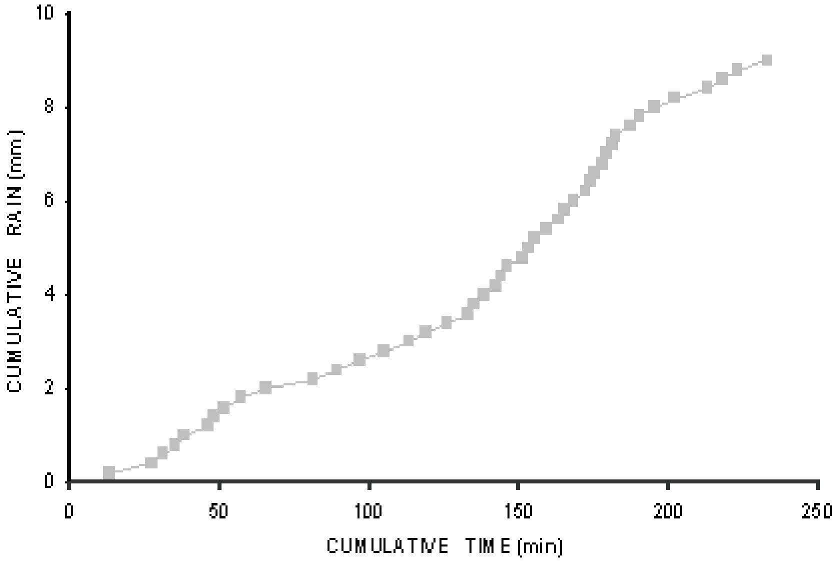

Figure 2.3. Intensity slope breaks of a rain event at Weatherley.

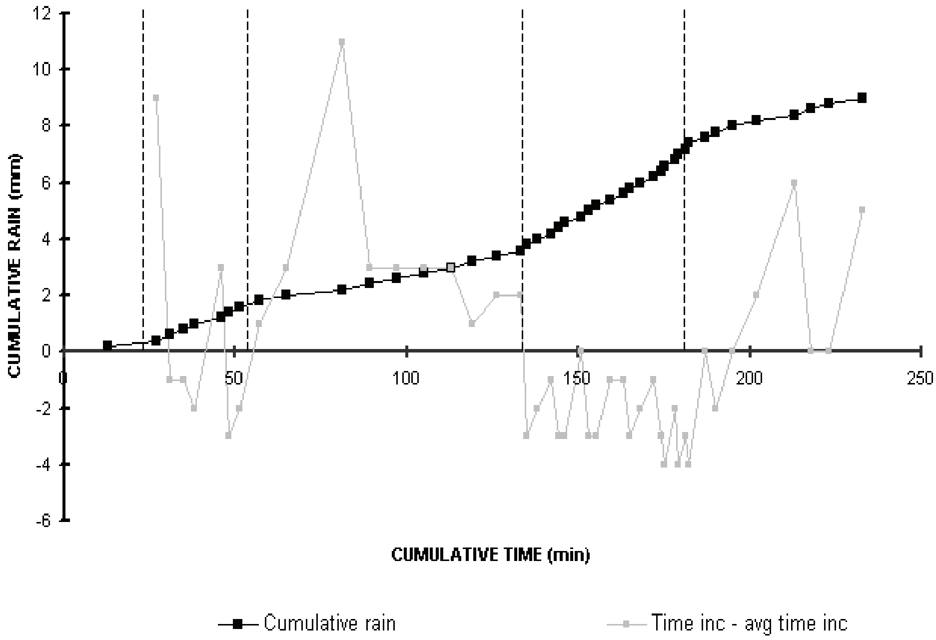

Figure 2.4. Identification of intensity slope breaks from time increment for each 0.2 mm rain.

The performance of the two programs was investigated by means of eight rainfall events where the shape of the cumulative rain vs. time plot curves varies considerably. The amount of breakpoints predicted by the two programs is summarised in Table 2.1.

Table 2.1. Comparison of the amount of breakpoints predicted by the suggested manual procedure and the two programs

Event	Manual procedure as suggested by BPCDG developers	Program based on the time increments of 0.2 mm rain	Program based on the changes in intensity slope		
			From 15-minute periods	From 10-minute periods	From 5-minute periods
1	5	5	9	16	18
2	2	2	6	6	7
3	8	4	6	7	12
4	4	4	9	10	17
5	3	3	8	9	11
6	2	2	2	2	3
7	8	7	8	9	15
8	4	6	4	5	8
Total	36	33	52	64	91

For most of the events, results from the second program, which is based on time increments of 0.2 mm precipitation for identifying slope breaks, resembled those obtained from the manual procedure suggested by the BPCDG program developers. The total amount of breakpoints predicted for all eight events is almost identical to that of the manual procedure. However, the program under-predicts for event 3 due to a smooth curve and high rain intensities during the event. The first program, which is based on changes in the intensity slope, over-predicts the amount of breakpoints compared to the suggested manual procedure, especially for the predictions made from 10 and 5-minute periods. However, predictions derived from 15-minute periods are more accurate than the second method for a third of the events.

The programs calculated the rainfall intensities for each of the identified breakpoints. The minimum, average and maximum rainfall intensities during each event are compared in Tables 2.2, 2.3 and 2.4. In general, the rainfall intensities calculated by the manual procedure, the second program and the first program with 15-minute periods are similar. The first program using 10 and 5-minute periods over-predicts the average and maximum rainfall intensities compared to the suggested manual procedure.

It is therefore concluded that the first program using data from 5 and 10-minute periods should not be used to identify the breakpoints or to calculate rainfall intensities for the breakpoints. To identify the breakpoints and to calculate the rainfall intensities for the breakpoints manually, as suggested by the BPCDG program developers, is not a simple task. Apart from the time and expense involved, data accuracy must be controlled, which is a problem for such huge data sets. It was not possible within the scope of this project to refine the programming of the second program to correct the under-prediction of breakpoints in certain storms. The breakpoints were thus identified manually.

Table 2.2. Comparison of the *minimum* rainfall intensities for each event as calculated by the programs

	Event								
	1	2	3	4	5	6	7	8	Avg
Manual procedure as suggested by BPCDG developers	0.9	1.0	0.7	0.2	1.0	12.0	1.0	12.0	3.6
Program based on the time increments of 0.2 mm rain	0.9	1.0	1.3	0.2	1.1	13.5	1.0	6.0	3.1
Program based on the changes in intensity slope: 15-minute periods	2.4	2.4	2.4	2.4	2.4	7.2	2.4	2.4	3.0
Program based on the changes in intensity slope: 10-minute periods	2.4	2.4	2.4	2.4	2.4	14.4	2.4	9.6	4.8
Program based on the changes in intensity slope: 5-minute periods	2.4	2.4	2.4	2.4	2.4	7.2	2.4	2.4	3.0

Table 2.3. Comparison of the *average* rainfall intensities for each event as calculated by the programs

	Event								
	1	2	3	4	5	6	7	8	Avg
Manual procedure as suggested by BPCDG developers	2.2	2.1	19.0	3.6	2.9	18.0	4.0	12.4	8.0
Program based on the time increments of 0.2 mm rain	2.2	2.05	14.5	3.6	2.9	18.8	3.6	10.5	7.3
Program based on the changes in intensity slope: 15-minute periods	3.3	2.7	16.2	4.4	3.7	11.2	4.2	16.2	7.7
Program based on the changes in intensity slope: 10-minute periods	5.3	4.4	27.4	7.7	5.6	16.8	7.2	31.2	13.2
Program based on the changes in intensity slope: 5-minute periods	8.0	4.8	32.4	9.3	6.6	16.8	9.0	39.0	15.7

Table 2.4. Comparison of the *maximum* rainfall intensities for each event as calculated by the programs

	Event								
	1	2	3	4	5	6	7	8	Avg
Manual procedure as suggested by BPCDG developers	4.1	3.1	51.4	6.0	6.6	24.0	10.0	13.0	14.8
Program based on the time increments of 0.2 mm rain	4.3	3.1	37.8	6.0	6.6	24.0	7.4	18.0	13.4
Program based on the changes in intensity slope: 15-minute periods	9.6	4.8	52.8	7.2	7.2	14.4	9.6	33.6	17.4
Program based on the changes in intensity slope: 10-minute periods	9.6	9.6	101	12.0	14.4	19.2	16.8	55.2	29.7
Program based on the changes in intensity slope: 5-minute periods	14.4	9.6	98.4	19.2	19.2	26.4	21.6	81.6	36.3

3 CREATION OF THE CLIGEN WEATHER STATION STATISTIC INPUT FILE (*.PAR) FOR USE IN THE WEPP MODEL

An attempt was made to produce simulated climate for the WEPP model using the CLIGEN program, which is a computer program run separately from the WEPP model. The specially formatted monthly statistical weather data needed as input in the CLIGEN program are:

1. Precipitation depth (inches) per day, which included mean, skew coefficient and standard deviation.
2. Probability of a wet day followed by a wet day.
3. Probability of a wet day followed by a dry day.
4. Mean maximum and minimum daily air temperature.
5. Standard deviation for daily maximum and minimum temperatures.
6. Mean daily solar radiation and standard deviation.
7. Mean maximum daily 30-minute liquid precipitation intensity.
8. Mean daily dew point temperature.
9. Cumulative distribution of computed time to peak rainfall intensity values.
10. Percentage of time of wind from each of the 16 wind directions.
11. Average, standard deviation and skew coefficient of each of the 16 wind directions.
12. Percentage of time there are calm conditions.

For the first three input data, rainfall data for Kokstad was available for 21 years and was used in the calculations. To compute the skew coefficient, a normal distribution was assumed using 0.1, 0.02 and 0.01 increments ranging from –4 to 4. Only 5 years of data was available to compute inputs 3 to 6 and 8.

Wind data was only available for 1 year and computing the wind inputs (10 to 12), values would not be representative of the area's climate and could thus not be used. Although it is possible to use a USA station with similar climate wind input, the selection of a suitable site turned out to be problematic. The site needed to be on the east coast of the USA (where synoptic flow would be similar to that on the east coast of South Africa) and have similar latitude (30°40'48") and elevation (1259 m). Since the Kokstad station is situated relatively close to the coast, interaction with the ocean plays a significant role in the wind directions prevailing at the station. Thus distance to the ocean also needs to be considered. A station that satisfied all these criteria could not be found. Having to choose another station would mean that the wind would not be well represented.

An even greater challenge was raised for inputs 7 and 9. Converting this data into a format that could be used would be very time consuming. Since it would take in the order of 2 months to prepare the data it was consequently decided not to continue with the preparation of the CLIGEN program input files.

APPENDIX 2
CONSULTATION ON SUGGESTED PLANT PARAMETER VALUES FOR THE WEPP MODEL

	INSTITUTION	CONSULTATION
Dr Tony Palmer	ARC – Range and Forage Institute	- Suggested plant parameter values for year to year modelling conditions for Weatherley catchment - List of names to contact for information on specific parameters
Dr Herman Fouche	ARC – Range and Forage Institute	- Suggested plant parameter values for year to year modelling conditions for Weatherley catchment - List of names to contact for information on specific parameters - Suggested a sensitivity analysis to rate plant parameters according to impact on model outputs - Suggested to start first with parameters for which the model outputs are sensitive
Ms Sheila Elliot	KwaZulu-Natal Department of Agriculture	- Suggested plant parameter values for year to year modelling conditions for Kokstad research site and Zululand catchment - Parameterisation of collected data at Kokstad experimental site into the specific WEPP model parameters - List of names to contact for information on specific parameters - Information on the grazing and burning operations at Kokstad experimental site
Mr Francois Olivier	SASEX	- Suggested sugar cane plant parameter values for year to year modelling conditions for the Zululand catchment - Kc values of sugarcane of water usage for sugarcane
Dr Dennis Flanagan	USDA – Agricultural Research Service: National Soil Erosion Research Laboratory	- How to develop the WEPP model plant growth parameters for new situations
Dr Jim Frankenberger	USDA – Agricultural Research Service: National Soil Erosion Research Laboratory	- Solutions to overcome model defects in the May 1999 version of the Windows Interface for the WEPP model - Provided a website address to download the latest April 2001 version of the Windows Interface for the WEPP model
Dr John Laflen	USDA – Agricultural Research Service: National Soil Erosion Research Laboratory	- Suggested plant parameter values for year to year modelling conditions Importing the created rangeland data and management files of the May 1999 version into the rangeland data and management directory of the April 2001 version - Clarification of incorrect plant growth simulations

PERSON	INSTITUTION	CONSULTATION
Mr Alan Short	KwaZulu-Natal Department of Agriculture	- Percentage dry matter of living matter - Start and end of growing season at Kokstad - Start of senescence - Above-ground biomass for encampments at Kokstad - Change of canopy cover at Kokstad - Grazing periods at Kokstad trials - Burning dates at Kokstad trials - Stocking rates at Kokstad trials
Mr P Bester	National Botanical Institute	- Start of growing season for grass at Weatherley - When grass reach peak canopy cover - Start of senescence - Burning times
Mr Hugo le Roux	NECF	- Burning dates at Weatherley
Dr Colin Everson	CSIR Environmentek	- Leaf area index
Mr Phillip Frost	ARC – Institute for Soil, Climate and Water	- Ten daily NVDI (Normalised Difference Vegetation Index) values for the study areas to assess periods of plant growth initiation and senescence

APPENDIX 3
REPORT ON CAPACITY BUILDING

Capacity building, with reference to the previously disadvantaged, that was carried out during this project was related to: 1) Involvement of students from previously disadvantaged communities in project research activities; 2) Interaction between researchers and land users by transversing the study catchment with the farmers as guides and by means of participatory rural appraisal; and 3) transfer of practical knowledge gained during the project to the community involved in the catchment.

1 INVOLVEMENT OF STUDENTS FROM PREVIOUSLY DISADVANTAGED COMMUNITIES

Students from previously disadvantaged communities were involved in project activities such as field survey, data collection and data analysis, and learning and use of various computer programs.

1.1 Student from the Professional Development Programme of the ARC

The Agricultural Research Council funded a student at ARC-ISCW through the Professional Development Programme aimed at young graduates from disadvantaged backgrounds. Mr Peter M. Lentsoane, a student from the University of the North, registered for a Masters degree in Soil Science at the University of Pretoria. Permission was given by the Water Research Commission to use data collected during this project for his thesis. However, in the end he decided to base his thesis on a Landcare project entitled "The evaluation of erosion models as indicators for the monitoring and assessment of soil erosion in Landcare". Nevertheless, the knowledge he gained on the influence of topographical, soil, land management, plant and stream channel characteristics on erosion, and the assembling and description of such data as model inputs during fieldwork trips undertaken for this project were invaluable in carrying out the research for his M.Sc. Agric thesis. Mr Lentsoane is shown in Photos 1 to 6 when he joined the project team during field trips.

Photo 1. Mr Lentsoane at the upper weir at the Weatherley research catchment.

Photo 2. Mr Lentsoane (second from right) at the Kokstad research trial.

Photo 3. Mr Lentsoane recording some information on grassland parameters at Zululand.

Photo 4. Mr Lentsoane taking some samples from sugarcane at Zululand catchment.

Photo 5. Mr Lentsoane joining the project team during field trips.

Photo 6. Mr Lentsoane enjoying the sea at the chalets where the project team stayed during the field trips at the Zululand research catchment

1.2 Students from the University of Zululand

With the soil survey at the Zululand research catchment, students from the University of Zululand were trained in-field on how to identify, describe and classify the soil horizons. The students were also shown how to map the various soil units.

2 INTERACTION BETWEEN RESEARCHERS AND LAND USERS

During the execution of the project, researchers interacted with the land users in two ways. Firstly by transversing the study catchments with farmers as guides, which helped the researchers in understanding indigenous wisdom relating to land and water issues. Secondly, interaction occurred by means of participatory rural appraisal (PRA) techniques. PRA helps to better perceive management and survival strategies. It thus gave the researchers a better understanding and appreciation of the rural situation.

2.1 Informing the community at Zululand of intended work

As the farming system practised at the Zululand research catchment is community-based, several attempts were made to inform the community on research in the catchment. These attempts included a rapid rural appraisal conducted with farmers in the catchment by an agricultural development consultant, by informing the Amakhosi of KwaMkhwanazi and Mzimela Tribal Authorities on the research, and by using agricultural extension services to communicate with the farmers. The letter written by Mr Walter Sibiya on behalf of the project team to inform the Mzimela Tribal Authority of the intended work is attached.

2.2 Farming systems analyses

Capacity building activities were aimed at identifying and describing farming systems in the study area by means of an informal (unstructured) survey. Ongoye catchment was identified as the study area and the community in the vicinity was targeted. The survey was done by Mr Sthembiso Bulose of iSineke Developments (Appendix 4).

The objectives of the survey were the following:

- Collection of information on their farming systems;
- Identification of different management practices, specifically those with a conservation approach;
- Identification of soil degradation problems (e.g. erosion) that influence farming productivity (from a farmer perspective);
- Identification of leader farmers (in terms of soil conservation) for further interviewing.

The survey was organised in such a way that the interviewer exercised minimum control over the responses and allowed the respondents to direct the course of the interview. Even though the interviewer was guided by the topics outlined below, the interview was formulated to stimulate an informal discussion. Only farmers around the catchment were targeted for the research study. Consequently ten farmers were randomly selected and interviewed.

The local extension officer at the Felixton Mill and Estates of Tongaat-Hulett, Mr Walter Sibiya, was also consulted and involved in liaising. Mr Sibiya was also involved, together with the University of Zululand, in the WOCAT questionnaires, which were aimed at collecting and analysing information on soil and water conservation technologies and approaches.

The topics that were covered in the study included:

- Description of farming systems
- Farming system activities
- Conservation measures
- Farming system inputs
- Farming system outputs
- Farmers

Some of the major conclusions of the survey were the following:

- That sugarcane production, together with timber production, are the main small-scale cash cropping systems, and are supplemented by subsistence crops.
- That the crops are grown in a mixed cropping system, particularly inter-cropping sugarcane with vegetables. Sugarcane is the main crop in all combinations.
- That family labour is mainly used, with occasional employment of casual labour for selected production activities.
- That fertiliser is used to maximise yields.
- That hand hoes are used, particularly during weeding.
- That soil conservation practices are limited.

2.3 Interaction with community during field work

The community was often involved during fieldwork at the Zululand research catchment. From the first visit to the catchment, the local youth regularly followed the project team during field data collection. During these times, discussions with the youth were initiated on the type of soils and plants, whilst good land husbandry and the conservation of good water quality were emphasised. The workings of the equipment used were also shown to them, and they were allowed to make some test measurements.

Assistance during several field trips was needed from the locals at the Zululand catchment. Four persons, namely Emmanuael, Thabani, Mbhekeni and Bhekumusa Dindi, were compensated when they helped with various tasks. These included the construction and installation of the tensiometers (no photos), digging of soil profile pits (Photo 7), the determination of the soil hydraulic properties (Photo 8) and the installation of the runoff plots.

With the collection of sediment load samples, it was realized that the dense riparian vegetation near the weir caused deposition of sediment during small and moderate rainstorms. It was therefore decided to construct an additional monitoring point upstream of the dense riparian vegetation. This weir is a small structure with an H-flume, sump, ISCO-sampler and an encoder and logger (Photo 9). Several contractors were approached to build the wing walls, foundation and ISCO sampler housing for the H-flume. Mr Alford Dindi, who lives within the catchment, was contracted to do the building (Photo 10). He did an excellent job which he can be, and indeed is, very proud of!

Photo 7. Locals helped in digging soil profile pits.

Photo 8. Locals helped with the determination of soil hydraulic properties per soil horizon.

Photo 9. H-Flume of which the wing walls, foundation and ISCO housing were built.

Photo 10. Mr Alford Dindi seated in the middle of the community leaders.

3 TRANSFER OF PRACTICAL KNOWLEDGE TO THE COMMUNITY IN THE CATCHMENT

An Information Day was held on 8 July 2002, which preceded the penultimate meeting of the Steering Committee the following day, to report back to the community on the project in the Zululand catchment by transferring practical knowledge learned in the project to the community and community leaders involved in the catchment.

Ms Ginty Kelbe and a student of the University of Zululand saved the day by helping with the arrangements. The cooking team (ladies only) was already well organized and started cooking early in the day (Photo 11). There was concern when the people did not arrive for the meeting's scheduled start at 10:00, but it eventually began at 12:20. The programme was as follows:

1. Opening with a prayer (Parson).
2. Welcoming (Induna Msameli).
3. Importance of sustainable practices (Mr Walter Sibia).
4. Aerial photo map so that community can mark their homesteads on it (just to break the ice).
5. Report back to the community on the project (Mr Albert van Zyl).
6. Demonstration of the runoff plots (Mr Mike Kidson).
7. Soil profiles (Albert).
8. Erosion practices (Albert).
9. Expression of thanks (Student from University of Zululand).

The student from the University of Zululand was the Chairman of the meeting (Photo 12).


Photo 11a and b. Pap, samp, vegetables and meat for the main meal cooked at the Information Day.

The meeting was held in the open air under beautiful trees that provided welcoming shade on a hot and dry day. The meeting was opened with a prayer by the local parson; whereafter the "up and doing" Induna Msameli (Photo 12) did the welcoming. Mr Walter Sibiya from the extension services discussed enthusiastically some sustainable land management practices and the importance thereof (Photo 13). In order to break the ice, each head of a homestead had to identify its location on the aerial photo produced by the Institute (Photos 14-15). The excited group was then informed about the project results, erosion and the importance of sustainable land use. Mr Mike Kidson from the Institute for Soil, Climate and Water then illustrated what had been said by means of a practical demonstration of the effect of ground cover on erosion with the runoff plots. The group really enjoyed Mike's story-telling approach and was amazed at the difference in runoff and sediment. Equally astonishing was the amount of water applied to the soil with ground cover before any runoff or leaching occurred: ten times more than the bare soil would not be an exaggeration!

Photo 12. A student from University of Zululand was the Chairman of the meeting.

Photo 13. Mr Walter Sibiya talked on the importance of sustainable land management. Ms Ginty Kelbe is to his right and Induna Msameli is on the far right in the white shirt.

Photo 14. The head of each homestead identified the location and marked it with its name.

Photo 15. Induna Msameli had to help at certain stages. The marked homesteads on the digital multispectral images were given to him.

The whole group, including Induna Msameli, the community, extension officers and students from the University of Zululand, was taken to land under grassland, sugarcane and vegetable gardens where visual signs of land degradation like erosion at each site were discussed. It was unbelievable to what extent the people “drank in” the information and asked questions. Active discussions were also held on why land degradation and erosion occurred and what management practices it would be better to follow, such as correct burning times, ridge tillage methods for increased soil surface roughness and the use of mulches. There were excellent examples of land degradation gradients at the grassland and vegetable garden, which were used to explain the transition from good to poor vegetation and soil conditions and the consequences thereof.

Two soil profiles were visited with widely differing characteristics. The group showed a keen interest in them and what the differences in soil characteristics mean. The use and crop suitability of the soils were also discussed. One lady confirmed that the water quality of her sugarcane from the poorly drained soils is too high when told that the soil is too wet for sugarcane and the well-drained soil form is in fact excellent for sugarcane production. The conservation of the riparian vegetation and soils was again stressed to ensure good water quality.

After the closure of the meeting, the community enjoyed their food and the party lasted until dusk. In conclusion, the enthusiasm of the community and their need for information was overwhelming.

Tongaat-Hulett Sugar Limited

Registration No. 65/00565/06

Felixton Mill & Estates
Private Bag X02
Felixton 3875
KwaZulu-Natal, South Africa
Telephone: (0351) 7915000
Fax: (0351) 91864
http://www.huletts.co.za.

02 July 1999

Mzimela Tribal Authority
P O Box 1084
Esikhawini
3887

Attention: Nkosi M B Mzimela

UDABA: ABACWANINGI ABASEBENZENZELANA NE-UNIZUL

Ezinsukwini ezimbalwa ezedlule, ngike ngahajelwa abacwaningi (Researchers) ababevela kwi-Agricultural Research Council, base bebeka udaba lokucwaninga ngamanzi nenhlabathi, okuthintene nabalimi bendawo yakho. Ngesikhathi befika kimi ngabe sengibatshela ukuthi kufanele amakhosi ezindawo akwazi abakwenzayo, ngokunjalo nemvelaphi yabo.

Lesike isicelo nokwazisa inkosi yesizwe, ukuthi I-university ekhona endaweni, inohlelo lokucwaninga isebenzelana ne-Agricultural Research Council enzinze ePitoli. Njengoba sengishilo basithintile nathi bezolimo bakamoba ukuba sazi ngokwenzekayo selekele uma ie kunesidingo.

Lolucwaningo luthinta ukongiwa komhlabathi namanzi, izinto eziyifa laphakade labantwana besizwe. Ngaleyondlela bazobonana namalunga omphakathi wesizwe sakho, olimayo.

Loluhlelo lucwaninga ikakhulukazi luqaphela ukuthiteka kwemimfula nemithombo, abatshali bezilimo abayisebenzisayo, okuze kundale ukuba eminye ivaleke.

Besinga thokoza uma inkosi noMkhandlu bebamukela laba bacwaningi, basizwe ekulondolozeni imishini yabo yokucwaninga. Empeleni bazoshiya imishini yabo endaweni ukuze ithathe imininingwane, ekugcineni nemiphumela itholwe.

NjengoMeluleki wendawo ngibe sengibacela ukuthi imiphumela yocwaningo, ifinyelele kubantu bendawo, okusetshenzwe nabo, futhi imibiko ifike njalo ngesikhathi ucwaningo luqhubeka.

Bheka incazelo yalomsebenzi, nabantu abathintekayo abayingxenye kaHulumeni.
Ngiyethemba isicelo sethu somukeleka eMkhandlwini.

Obhalile.

W M SIBIYA
AREA MANAGER: FELIXTON SOUTH

Tongaat-Hulett Sugar Limited

Registration No. 65/00565/06

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Private Bag X02
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21 July 1999

I.S.C.W
Private Bag X79
Pretoria
0001

Attention: Mnr A J Van Zyl

Dear Sir

RE: ARC UNIVERSITY OF ZULULAND

Please note that Amakhosi of KwaMkhwanazi and Mzimela Tribal Authorities, have been informed about your team. One of them has responded, saying that he wants to see your team before they start to operate in his area. See copies of the letters.

Thank you.

Yours faithfully

WALTER SIBIYA
AREA MANAGER SOUTH OF FELIXTON

APPENDIX 4
FARMING SYSTEMS ANALYSIS
iSineke Developments

1 INTRODUCTION
1.1 Background

This research study was aimed at identifying and describing farming systems in the study area by means of an informal (unstructured) survey. Ongoye catchment was identified as the study area and the community in the vicinity was targeted.

1.2 Objectives

- Collection of information on their farming systems.
- Identification of different management practices, specifically those with a conservation approach.
- Identification of soil degradation problems (e.g erosion) that influence farming productivity (from a farmer perspective).
- Identification of leader farmers (in terms of soil conservation) for further interviewing.

2 METHODOLOGY

The research was organised in such a way that the interviewer exercised minimum control over the responses and allowed the respondents to direct the course of the interview. Even though the interviewer was guided by the topics outlined below, the interview was formulated to stimulate an informal discussion. Only farmers around the catchment were targeted for the research study. Consequently 10 farmers were randomly selected and interviewed. The topics that were covered in the study included:

- Description of farming systems
- Farming system activities
- Conservation measures
- Farming system inputs
- Farming system outputs
- Farmers

3 PRESENT LAND USE AND NATURAL RESOURCES

The catchment area is predominantly used for small-scale sugarcane farming, communal grazing, minimally for other crop production, as well as for residential purposes. The area falls under a coastal regional climate and has an average rainfall of between 1200 mm and 1500 mm per annum. The soils are deep and are reported to be productive. One of the important features of the area is the noticeably good cover of Kikuyu grass that transects large parts of the landscape. There is also a small stream that runs across the catchment.

4 RESULTS AND DISCUSSION

4.1 Demographics of Farmers

The gender of the selected farmers was balanced as 5 women and 5 men were interviewed. Although it was not possible to obtain information about the farmers' exact ages, they indicated that their ages were above 45 years. General discussions with the community members indicated that there is a very low level of employment in the area and few employment opportunities; as such, the most important source of income was reported to be farming. Most of the farmers did not have any other alternative income sources. Some farmers are solely dependent on the farming income for sustenance of their livelihoods. Eight out of the 10 farmers interviewed indicated that they were unable to read or write. The literacy level in the area was reported to be generally low. The level of literacy of the sample farmers seems to match the levels of literacy reported for most rural areas in South Africa.

4.2 Farming activities

4.2.1 CROP ENTERPRISES

The most important crop enterprises are:

- Cash Crops
- Food Crops
- Cash-Food crops

4.2.1.1 Cash Crops

There are two important cash crops that are grown in the area *viz* sugarcane and timber. Sugarcane takes precedence over timber because of the relatively short period of realisation of returns. Timber returns take a considerably long period of time and it is therefore not extensively grown such that it is not regarded as a priority cash crop by the farmers.

All the farmers interviewed indicated that they are involved in small-scale sugarcane farming. Sugarcane farming was observably the predominant farming enterprise in the catchment area, and as such the focus of the discussion was mostly on its production.

A mutually beneficial relationship has been organised with Huletts Felixton Mill and the farmers operate through the Sugar Association. Huletts initiated the arrangement so as to assist the local farmers not only to increase their income, but also to provide them with a relatively stable income base. The arrangement is such that for the duration of the contract the farmers are supplied with fertilizer and inputs at low cost, and the farmers in return take the produce to the Sugar Association for marketing. This means that they are not only guaranteed a market for their sugarcane but an income as well. Further, the arrangement provides for a local farmer who transports the harvest from the farmers to a collection point where a truck from Huletts collects the harvest. The farmers therefore have the added advantage of an organised transport system for their produce.

Each farmer utilises the piece of land under his or her ownership. There are no farmers that share plots for sugarcane growing. The farmers reported that they have been growing sugarcane for periods ranging between 3 to 18 years. Some farmers indicated that they plant sugarcane between May and June, while others indicated that they plant it between August to November. Those that planted between August and November indicated that they did so in order to utilise the warmth of the soil during these months, since sugarcane requires warm soil during planting. The growing period for sugarcane is approximately one year. Most farmers reported that they harvest the sugarcane crop one year after the planting date - during the exact month that they planted it.

The sugarcane crop is weeded twice in each growing season and this occurs when the cane plants are about 0.25 m high and when they are waist high (approximately 1m). Very few farmers indicated that they weed three times in any one season.

Although family labour is mostly used for this enterprise, occasionally local casual labour is employed particularly during weeding and harvesting periods.

Farmers also indicated that they use inputs such as fertilizer to improve the potential production and that the only implements used are hoes particularly during weeding.

The information made available by the local extension office indicated that each of the farmers have an average farm size of approximately 2 ha. From this 2 ha piece of land, each farmer is able to generate a net income of approximately R2000.00 per annum.

There are also well established timber plantations belonging to farmers that are operated through a joint venture between Sappi and the sample farmers. None of the farmers indicated any considerable commitment to timber production though. They indicated that it takes a long period to harvest and obtain an income. However, they have recently identified a way of obtaining some short-term returns from timber production although the returns are minimal. A local market has been identified where the farmers sell the pulp from the trees to the local community for purposes of building huts and for fencing.

4.2.1.2 Food Crops

There are a small number of farmers who are involved with food crop growing at a subsistence level. Only three of the interviewed farmers indicated that they are involved in small-scale maize farming and for subsistence purposes only, although they sell it occasionally. In fact only one farmer indicated that he sells the surplus maize to the local community. They further reported that they plant maize only to maintain a traditional practice. Other crops that are cultivated for subsistence include vegetables such as onions, potato, spinach and cabbage. These vegetables are inter-cropped or used in a rotation system. Although inter-cropping is also practised as a traditional production method, the farmers reported that they practise it because they believe that in that manner they realise a reasonably high production levels from the crops. It was further observed that in some farms maize was inter-cropped with beans.

4.2.1.3 Cash-Food Crops

Fruits are commonly grown for both cash and food purposes. Fruits that are grown include Bananas, Avocado, Pears, Paw paw, Guava and Oranges. Most fruit trees are grown for wind-break purposes but some fruits are sold to the local community particularly if there is surplus.

4.2.2 ANIMAL ENTERPRISES

The sampled farmers also rear animals. It was, however, indicated that this farming activity has decreased in the last five years as farmers have tended to increase the land under sugarcane cultivation. Of the 10 farmers that were interviewed, only 5 rear cattle and goats. Of the latter 5 farmers, only 1 farmer had more than 5 animals. Between the 10 farmers, they own 14 cattle and 18 goats. Farmers indicated that their animals drink water from the stream at a point next to the weir. However, although the sample farmers kept few animals, visual observation and general discussions indicated that there are farmers who own a lot more animals than were reported.

The farmers in the area use a communal grazing system. There is a piece of land that has been allocated to the community by the chief for grazing purposes which was initially demarcated in a grazing camp system. However, from discussions, it became apparent that the fence has been removed and the grazing camp is now an open field. This has created friction amongst the farmers as the animals trespass on the neighbouring sugarcane plantations.

4.3 Farming System Analysis

4.3.1 CROPPING SYSTEM

The cropping system in the area consists predominantly of rainfed sugarcane plantations. The dominance of sugarcane is evidenced from the fact that all farmers cultivate sugarcane. Approximately 80% of the farmers in the sample cultivate sugarcane only. The other 20% cultivate sugarcane as well as other crops such as vegetables. Maize-sugarcane rotations are also a common practice in the area. Farmers maximise land use intensity by planting these multiple combinations of crops, and sugarcane is commonly the main crop in any of the crop combinations. The crops that are grown in combination include maize, beans, potato, onions, cabbage and spinach. Fruit trees were also observed on some farms to constitute part of such crop combinations.

4.3.2 ANIMAL PRODUCTION SYSTEM

Animals are kept as part of the broader farming system in the area. The practised animal production system is only restricted to rearing of beef cattle and goats. Few farmers from the sample keep animals, and when they do, they are kept particularly for various traditional reasons other than to provide an income. In recent years, there has been a marked shift in agricultural land use with regard to animal production such that present land use is skewing towards sugarcane production. The shift in production objectives to sugarcane farming is said to have been facilitated by the secured market for sugarcane and the relatively high income associated with sugarcane farming in the area. This is an important shift, considering that traditionally, the numbers of animals reared and particularly the number of animals kept by households were important determinants of status and wealth in rural KwaZulu areas. This shows that demonstrable high returns from sugarcane farming have facilitated the changing household production decisions and objectives to a predominantly cropping system that provides returns in a reasonably short period of time.

Livestock is grazed in the allocated grazing camp in an open and random grazing system. There are no attempts to adopt an organised grazing system for the area that may promote maintenance of the vigour of palatable species. This present grazing system has the potential of encouraging land degradation.

4.4 Soil Conservation System

During the interviews, the farmers indicated that they do not practise any conservation measures. However, during informal discussions and through visual observation, it became apparent that the farmers do in fact practise conservation but not as a deliberate act of good farming practice. They indicated that over the years, they have been taught to always leave crop residues in the field particularly after harvest. This is said to improve the soil moisture retention by the soil. However, this is done more as a routine, rather than through an inherent understanding of the importance and purpose of such practices. Farmers also indicated that the residues provide compost.

In addition, strip cropping is practised by farmers as a conservation measure although it was not explicitly expressed as such by the farmers themselves during the interviews. However, through visual observation, it was evident that the local farmers use strip cropping as a method of conserving soil and water. The farmers indicated that strip cropping, depending on the crop in the strip, reduces runoff velocity and traps sediments.

None of the farmers indicated the use of cover crops. However, the area has a good cover of Kikuyu grass which is known to minimize soil erosion as it holds the soil structure together through its deep rooting system. The vegetative cover provided by this grass therefore contributes considerably to protection against raindrop impact and runoff.

Further, the area under discussion is gently sloping. There were no signs of visible land degradation through soil erosion in the entire project area. On such near level areas, many tillage systems provide the desired conditions and effectively conserve the soil and water resources. As slope increases, the choices become more limited. A conservation tillage system that maintains surface residues is best suited for water erosion control on sloping soils when other supporting practices are not used (FAO, 1987). The farmers in the area leave crop residues and practise strip cropping, which probably contribute to the fact that there was no soil degradation problem that was identified that influences farming productivity. This relatively favourable topography of the area also contributes to the reasons why the farmers do not practise major conservation measures like contours and terraces.

5 CONCLUSION

As can be expected of farming systems in most rural areas of Kwazulu-Natal, the farming activities in the project area are multiple. It can be concluded from the preceding discussion that the farming system in the catchment seems to be characterised by:

- A predominantly small-scale cash cropping system through sugarcane growing and timber production which is supplemented by subsistence crops.
- The crops are grown in a mixed cropping system, particularly inter-cropping sugarcane with vegetables. Sugarcane is the main crop in all combinations.
- To a lesser extent crop rotation and minimum tillage are practised.
- Relatively small-scale animal production, reared in a communal grazing system.
- Predominant utilisation of family labour with occasional employment of casual labour for selected production activities.
- Use of fertilizer to maximise yields.

- The use of hoes particularly during weeding. Hoes are the only implements used.
- The practice of soil conservation measures.
- No observable soil and land degradation through water erosion because of the subconscious conservation measures practised such as strip cropping, burying crop residue and a good soil cover by Kikuyu grass.
- A relatively level topography that renders the area less susceptible to soil erosion.

6 CONCLUDING REMARKS

It is known that success of studies that centre around the community depend entirely on the involvement of the community in the project. In order for the project to achieve the intended objective of capacity building, there is a need to foster ownership of the process by the community from the beginning. Thus, it may be important to rigorously seek local knowledge for the research project. The envisaged placement of monitoring equipment should be done and negotiated with the community in order to foster such ownership. This is important, as the community will then protect the equipment from being damaged.

The research team members need to observe community values which should be catered for in the project setup. Meetings should rather be arranged with the local extension office that is responsible for area, which will in turn inform the local traditional leaders.