MODELLING THE IMPACTS OF LAND COVER AND LAND MANAGEMENT PRACTICES ON STREAM FLOW REDUCTION

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Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

1 BACKGROUND AND MOTIVATION

Land use can exert strong influences on water resources in terms of quantity and quality. For these reasons there is a need to accurately estimate the impacts of land use on streamflow. These impacts form an important focus in South Africa's National Water Act (Act No. 36 of 1998), which includes provision for certain land uses to be declared as a Stream Flow Reduction Activity (SFRA). Thus far, forestry has been declared a SFRA, while other land uses may also be declared so in future (Department of Water Affairs and Forestry, 1999).

Given the large number of possible land uses and site conditions prevailing in South Africa, the impacts of land use on streamflow cannot be deduced solely from the limited measurements that are available, but should be supplemented with estimates from conceptual-physical hydrological simulation models which have been developed and tested using observed hydrological data. A number of catchment studies investigating the impacts of forestry on streamflow have been conducted in South Africa. These studies have facilitated the verification and enhancement of hydrological models under forested catchments. In contrast there are almost no controlled catchment scale land use experiments involving agricultural (non-forestry) land uses (Kruger *et al*., 2000). However, there are studies that have been conducted at smaller scales, such as at runoff plot scale. These small-scale data may still be applied, with appropriate care, in verification studies of hydrological models, thus enabling the potential improvement of these models and their estimates of streamflow in agricultural catchments.

In this study, land use is considered to comprise of both land cover, i.e. crops, and the land management practices applied to those crops. These management practices impact the runoff from cropped areas and may exert more influence on the water balance than the crop itself. Examples of management practices that may reduce runoff include tillage, contouring, terracing, water harvesting and strip cropping. Such practices need to be assessed as potential SFRAs (DWAF, 1999) and have not been considered in previous studies (e.g. Kruger *et al*., 2000).

2 OBJECTIVES

Given the above background to land use impacts on streamflow in South Africa, the objectives of this project were defined as follows:

- the acquisition and collation of historical measured field data that focuses on land use related hydrological processes;
- the synthesis of the above field data in terms of land use impacts on hydrological response; and
- the enhancement of suitable modelling tools through application of the data in model verification studies at various sites.

The first objective was considered a vital aspect of the project given that many good quality field data have been collected in the past in South Africa. These data sets have often not been utilised to their full potential and, furthermore, are at risk of being misplaced or discarded as time progresses, research emphasis changes and the researchers involved retire. These historical data sets still have great value in current research, especially given the high costs of conducting field measurements. Use of observed data in model development is vital to ensure continued relevance of the model predictions.

As the background context of this study related to streamflow reduction activities, the focus of the project was on non-irrigated conditions.

3 METHODOLOGY

Given the importance of both land cover and land management on hydrological responses, the methodology used to achieve the above objectives was as follows:

- **The identification of key land use/s for consideration in the study:** A decision was made to focus on two crops, *viz*. maize and wheat, subjected to different forms of tillage practice, namely conventional tillage (CvT), conservation tillage (CsT) and no till (NT).
- **The acquisition and collation of historical observed field data that are relevant to assessing the hydrological impacts of the selected land management practice (tillage):** Data from runoff plots subjected to the above tillage practices were obtained from the University of the Free State (UFS), the Directorate of Engineering and Soil Conservation (DESC) and the South African Rainfall Simulator Programme (SARSP).
- **The synthesis of the observed field data (from runoff plots) in terms of land use impacts on hydrological responses:** To limit the scope of the study, the synthesis was restricted to maize plots at the Cedara site (the DESC study) and wheat monocrop plots at the Bloemfontein site (the UFS study), where attention was focussed on the seasonal trends in runoff between the different tillage practices. In the case of the SARSP data, analysis was directed at seeking trends in initial abstractions across multiple sites. It was hoped that this analysis could be used to improve the modelling of this component of the runoff process.
- **The configuration and application of a hydrological model, *ACRU*, at selected sites:** The *ACRU* model (Schulze, 1995) was applied to simulate the impacts of tillage on runoff at the Cedara and Bloemfontein sites.
- **The verification of *ACRU* output against the observed site data:** The *ACRU* simulations of hydrological response were verified not in terms of absolute runoff values, but rather in terms of the relative sequences and orders of magnitude of runoff responses generated under the different tillage practices considered.
- **The enhancement of *ACRU*'s land use modelling capabilities based on the results of the site modelling:** These enhancements were to be achieved through improved model algorithms, modelling strategies and model input values.
- **The enhancement of baseline land cover modelling in *ACRU*:** This research was aimed at improving the estimation of hydrological land cover input parameters for modelling baseline land cover (represented by the Acocks' Veld Types).

The final aspect of the project methodology was implemented to address inconsistencies identified by Gush *et al*. (2002) in the land cover input parameters for the Acocks' Veld Types. While this aspect of the project was not linked with the rest of the methodology outlined above, it was deemed by the project steering committee to fit within the objectives of this project, as it related to enhancing the ability of the *ACRU* model to assess land use impacts on hydrological responses.

Numerous historical studies representing a broad spectrum of land use related data were reviewed before the decision was made to direct the focus of this project on the hydrological impacts of crops under different forms of tillage. The decision to focus on tillage as a land management practice was made because of the widespread nature of this practice. There is also a growing trend towards conservation and no till practices which have many environmental and agronomic benefits, but which may result in a reduction of runoff. To date, there has been little research into modelling the effects of tillage for use with the *ACRU* model.

In this study the term "runoff" refers to surface runoff in the context of runoff plots, and "quickflow" in the context of simulation results. Quickflow, as simulated by *ACRU*, comprises of runoff that would leave the catchment (in the context of catchment modelling) on the same day as the rainfall event. While these quantities are not identical, it was considered justifiable to regard simulated quickflow as representative of observed surface runoff (from a runoff plot), as the goal in modelling tillage practices in this study was not to simulate absolute runoff values, but rather the relative sequences and orders of magnitude of runoff from different practices.

The *ACRU* model is a conceptual-physical model which is structured to be sensitive to the influence of land cover and its management on hydrological responses, and is thus well suited as a tool for implementing certain aspects of the National Water Act. While it is possible to represent a number of different land covers in the model, the hydrological responses of which have been verified against experimental data, land management impacts are less well represented and verified. Land management may, in many cases, be more influential on hydrological responses than land cover *per se*.

4 SCALE CONSIDERATIONS

In the context of the National Water Act, the "water use" of land uses is measured in terms of their impacts on streamflow in a water course. However, with the exception of commercial forestry and a single set of sugarcane catchments, there is no catchment-scale experimental data available for use in model verification studies. Thus, information for these studies is limited to data collected from runoff plots. It is inevitable that hydrological responses at plot scales are influenced by localised factors, and will be more marked and exhibit greater variability than catchment responses. Furthermore, the design and small size of runoff plots implies that the measured responses are not likely to reflect subsurface movement of water.

The high variability of runoff responses at runoff plot scale and the methods of data collection limit their usefulness for verification of hydrological models such as the *ACRU* model. Thus, the focus in this project is on identifying and simulating processes that may operate at scales larger than the scale of the observation and which will appear as trends in the data, and ignoring processes occurring at scales smaller than the observation which may appear as "noise". Small-scale runoff plot studies may reveal greater detail about hydrological mechanisms, but generalisations are more likely to be identifiable at broader scales (Jewitt and Görgens, 2000). The modelling conducted in this project is thus initiated within the context of a sacrifice of detail in order to reveal broader scale spatial and temporal hydrological patterns. As explained above, it is necessary to consider the impacts of agricultural land use in the water course, i.e. at the catchment outlet. In this study, the *ACRU* model is used a tool which effectively upscales runoff plot scale information to a catchment level response. However, given the complications described above, verification of the *ACRU* model will focus on ensuring that relative hydrological responses under different tillage practices are represented at seasonal scale.

5 SYNTHESIS OF MEASURED RUNOFF PLOT DATA

The synthesis was performed on measured data from runoff plots under maize at Cedara (DESC study) and a wheat monocrop at Bloemfontein (UFS study). Attention was focussed on the seasonal trends in runoff between the different tillage practices. In the case of the SARSP, analysis was directed at seeking trends in initial abstractions across multiple sites.

5.1 Directorate of Engineering and Soil Conservation Data Set

The DESC runoff plot data were collected during a project titled "Erosion Studies using Natural Runoff Plots" (DESC Facet No. N5711/38/1/1), which was conducted over the period from 1983 to 1999. The motivation for the project originated from concerns about the loss of soil from arable land in KwaZulu-Natal.

The methodology employed in the project involved setting up a number of runoff plots at 8 sites in KwaZulu-Natal. No till, conservation tillage and conventional tillage practices were applied in the experiment. At most sites a bare fallow (BF) control runoff plot was maintained. Runoff plots were planted to a variety of crops. Soil and water losses resulting from natural rainfall were measured at all runoff plots. Rainfall records were kept at all sites and measurements of soil and crop characteristics were carried out at various intervals. Before the DESC data could be used it was necessary to sort and collate the hardcopy and electronic data, as they had become disorganised over time.

The runoff observed for all considered events on the Cedara site maize plots (where the CvT treatment was represented by a spring plough practice) was summed for each season and is plotted in Figure 1. The seasonal values of runoff were also accumulated over the period of simulation and plotted as cumulative plots.

Figure 1 indicates that the responses of the various treatments was generally in the order: BF, CvT, CsT, NT (decreasing). The order of responses corresponded to the amount of mulch cover on the various plot treatments, i.e. a greater mulch cover led to less runoff.

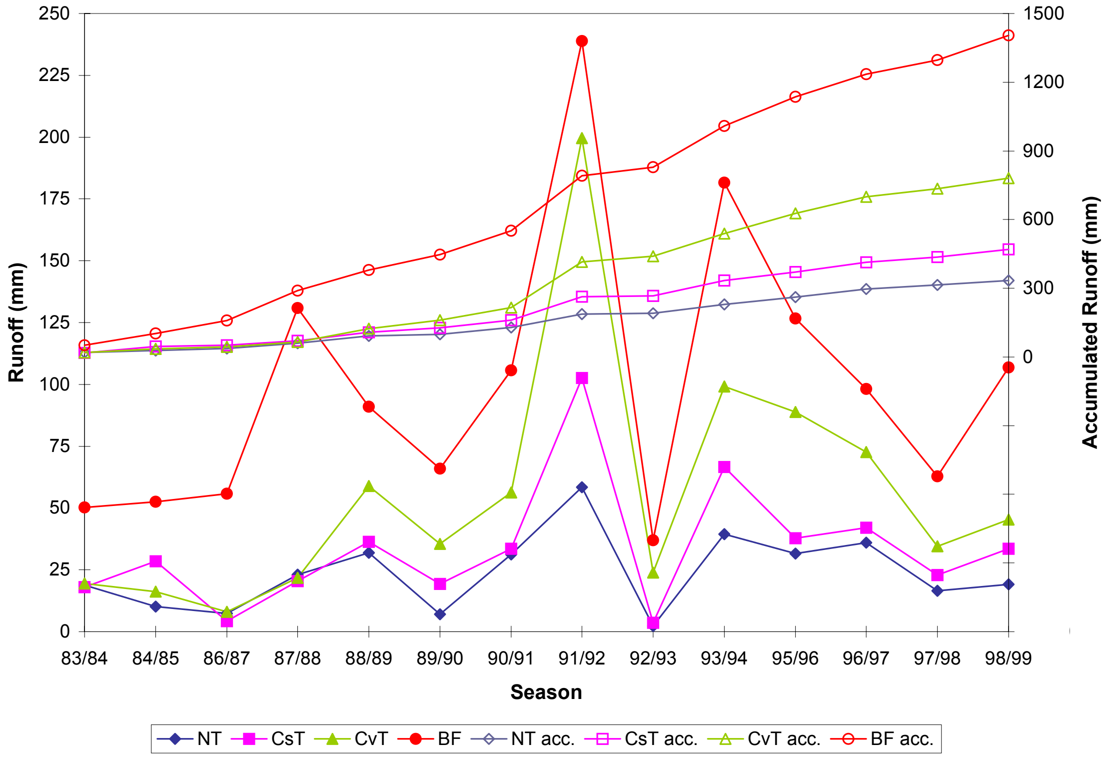

Figure 1 Observed seasonal and accumulated runoff for maize under various tillage practices at Cedara

5.2 University of the Free State Data Set

The UFS runoff plot data were collected during a WRC project titled "Opgaring en Benutting van Reënwater in Grond vir die Stabilisering van Plantproduksie in Halfdroë Gebiede" (Bennie *et al.*, 1994), which was conducted over the period from 1988 to 1993. The project arose out of a need to stabilise crop production in semi-arid regions, especially in dry years, through the development of sustainable dryland farming systems.

In the UFS project an intensive study of the soil water balance under different crop management and tillage practices was carried out at four sites in the Free State Province, including a site at Bloemfontein. A combination of three tillage practices and six crop management practices was investigated, giving rise to a matrix of 18 treatments. The tillage practices comprised of no till, conservation tillage and conventional tillage. The crop management practices consisted of winter and summer monocrops, three combinations of winter/summer crop rotations and a practice where a crop (winter or summer) was planted depending on the level of plant available soil water at planting time. These crop practices were compared with reference conditions represented by pasture, climax veld and subclimax veld.

Measurements were made of the water balance and of soil and crop characteristics. These included runoff measurements, which were made on plots under natural and simulated rainfall conditions. These measurements were used in assessing the effect of the crop and tillage practices on the water balance and on crop production. The electronic database developed in the project required reformatting into a more contemporary format before it could be used in this study.

For the natural rainfall wheat monocrop runoff plots at Bloemfontein, runoff was summed for each season, including the fallow seasons, and is plotted in Figure 2. Cumulative plots of the data also appear in the graph. Figure 2 indicates that the responses of the various treatments was generally in the order: NT, CsT, CvT (decreasing runoff). Bennie *et al*. (1994) concluded that the amount of mulch cover on the NT and CsT treatments was ineffective in reducing runoff relative to CvT, and that runoff was dependent more on the degree of soil disturbance, which improved the infiltrability of the soil.

5.3 South African Rainfall Simulator Programme Data Set

The SARSP (McPhee *et al*., 1983) was initiated in 1980 under the auspices of the Division of Agricultural Engineering. It involved performing rainfall simulator tests at about 97 sites in the country, where these sites were mostly situated in wheat lands in the Western Cape Province, maize lands in the KwaZulu-Natal and North West Provinces and in pineapple lands in the Eastern Cape Province. The runoff plot variables measured in the Programme allowed for the quantification of initial abstractions (I_a) before stormflow commencement, where these abstractions consist of interception, infiltration and depression storage. The analysis of the SARSP data in the current study was aimed at finding relationships to predict the abstractions directly as a physical quantity in millimetres, rather than by way of a coefficient, which has traditionally been the method adopted.

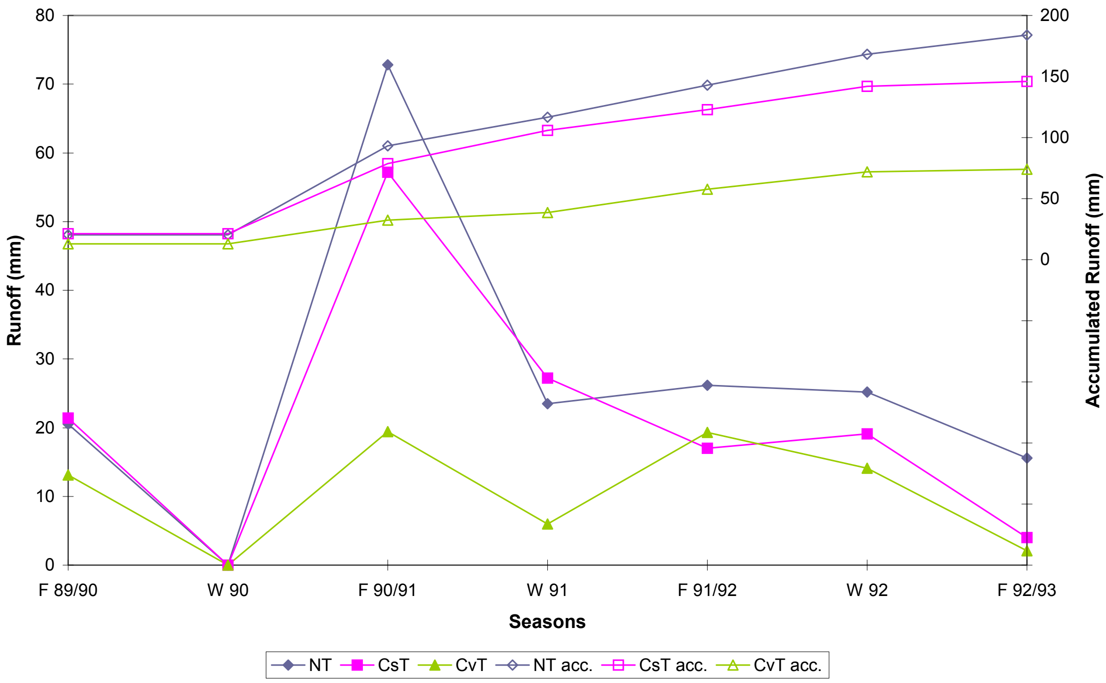

Figure 2 Observed seasonal and accumulated runoff for the wheat monocrop practice under various tillage systems at Bloemfontein

The motivation for launching the SARSP originated from similar concerns to those in the DESC project, i.e. the large losses of soil from arable land in South Africa. Various mulch, crop and tillage conditions were represented in the runoff plots at the various sites. At most sites a reference condition was represented, where this plot consisted of bare soil tilled in a standard manner. Two one-hour simulated storms separated by a 24-hour period were applied to the runoff plots at an intensity of approximately 63mm/h. The first storm represented dry conditions while the second storm represented wet conditions. Before each rainfall simulator test, soil information relating to structure, texture, organic matter and permeability were collected.

In analysing the SARSP data for trends in I_a, the relationships between I_a and several influencing factors were investigated. These included application intensity, slope, total cover and soil organic matter content. The data for the first and second storms were plotted separately owing to the strong influence that antecedent moisture had on the results. The graphs plotted indicated no useful trends between I_a and application intensity, slope, total cover, and organic matter, whether for the first or second storm. To assess if soil type was a strongly influencing factor, additional sets of graphs were plotted (I_a versus application intensity, slope and total cover), where only single soil types were represented in each graph. Only weak trends were found in some of these graphs.

McPhee *et al*. (1983) concluded that soil loss was affected by many factors other than those prevailing at the sites on the day of testing. These factors included crop and tillage history, rainfall regime and antecedent soil moisture, and would have also affected runoff. The large number of sites and the different times of the year over which tests were performed would have further contributed to the high variability in runoff and soil loss results. For the purpose of finding generalised relationships to predict I_a, the data set would have been more useful if fewer sites had been used, and more extensive tests of the factors effecting hydrological response, performed.

The original intent of analysing the SARSP data set was to improve the modelling of I_a in the *ACRU* model, through identifying potential predictive relationships in the runoff plot data. As no suitable relationships could be found in the data set, this approach was not pursued further.

6 REPRESENTATION OF TILLAGE IN THE *ACRU* MODEL

Hydrological processes that are implicated in tillage include interception, infiltration, evaporation, surface detention, soil moisture retention, redistribution and drainage and transpiration. Each form of tillage influences these processes to a greater or lesser degree and should be represented in the modelling approach. The influences of factors at the site of interest also determine how hydrological processes respond to tillage. Examples of such factors include the nature of the rainfall, the slope and the type of soil at the site.

In the modelling approach adopted the following tillage influences were represented:

- **Suppression of evaporation by a mulch cover.** This was represented in the model by the implementation of a new algorithm relating the suppression of maximum soil water evaporation to the percentage of mulch cover present.

- **Influence of mulch cover and surface roughness on infiltration and depression storage.** This influence was represented in the model through selection of appropriate values of the coefficient of initial abstraction (COIAM). This parameter, along with the soil water content of the topsoil at porosity (PO1) and depth of soil effective in stormflow generation (SMDDEP), is used in quantifying the initial abstractions of rainfall into the soil that occur before runoff commences. An intuitive approach to systematically estimating the *ACRU* COIAM parameter for different tillage (mulch cover, surface roughness) and site conditions was developed. The generic approach was developed with the intention of it being applicable under varying conditions and not just at the sites where the approach was developed.
- **Effect of plough action on soil moisture storage within the depth of soil effective in stormflow generation.** The soil disturbance caused by a plough, especially in conventional tillage, has the potential to increase the porosity of the topsoil. This has the effect of increasing the moisture storage capacity of the soil, which in turn affects the ability of the soil to infiltrate water and generate stormflow. Typical values of top- and subsoil porosity tabulated in the *ACRU* Theory Manual (Schulze, 1995) for different soil textural classes for freshly tilled and end of season conditions were used to represent the influence of tillage on soil porosity. Rules for determining values of the SMDDEP parameter, which take into account the depth of tillage, were developed.

7 MODELLING THE IMPACTS OF TILLAGE ON RUNOFF

The *ACRU* model is a catchment model and could not be applied directly to simulate the runoff from a runoff plot. Instead, the model was applied on hypothetical 1km^2 area catchments having similar climate, soil and land use properties to the runoff plots at Cedara and Bloemfontein. Owing to the differences in scale between plots and catchments, the aim of the modelling exercise was to replicate at catchment scale the relative runoff responses of the different tillage treatments observed on the runoff plots.

7.1 Cedara Runoff Simulations

The runoff from the DESC maize crops under different tillage practices (NT, CsT, CvT) and the bare fallow condition was simulated for the seasons from 1983/84 to 1998/99. During the course of the simulations that were performed to refine the tillage modelling approach, the following were noted:

- The runoff reducing effects of mulch cover (e.g. increased infiltration opportunity, crust prevention, organic matter enhancement) influenced the response of the NT and CsT treatments at Cedara to a greater degree than that initially represented in the modelling approach.
- The soil profile description at Cedara, which was carried out before commencement of the experiment, noted the frequent occurrence of macropores in the soil. These macropores, which would have been derived from soil organisms, roots etc., would have been maintained under NT and would have facilitated rapid infiltration and movement of water through the soil.
- Given that the experiment was conducted over 17 seasons, it is possible that a plough pan could have formed under the CvT treatment if no preventative action

was taken. To confirm the presence of a pan the soil profile would have had to be examined during the course of the experiment. For the purposes of this study it was assumed that a plough pan did form

Given the above, the following modifications of the initial modelling approach were proposed:

- The value of COIAM for all months of the year was set to 0.35 for the NT treatment to account for increased infiltration opportunity afforded by the mulch.
- The interception of rainfall by the maize crop on the NT treatment was increased to account for interception by the mulch (VEGINT variable).
- In an attempt to account for macropore flow under the NT treatment, the variable controlling the vertical drainage of water from the A to B horizon under saturated conditions (ABRESP), was increased from the default value of 0.4 (for a Hutton Doveton soil) to a value of 1.0.
- To account for the influence of a plough pan on the CvT plot, SMDDEP was reduced from the general site value of 0.30m (estimated according to standard procedures) to the depth of tillage (0.25m). A further change was made by reducing the ABRESP parameter from the default value of 0.4 to 0.1 to simulate the inhibited vertical drainage resulting from the presence of a plough pan.

It was assumed that the mulch and macropore effects in the CsT system would have been less influential than for NT. Therefore the interception was increased to a lesser degree than NT. The value of ABRESP was increased from 0.4 to 0.7 for CsT.

The runoff simulated for all considered events was summed for each season and plotted in Figure 3. The seasonal values of runoff were accumulated over the period of simulation and plotted as cumulative plots in Figure 3.

For the BF treatment simulation (Figure 3), runoff was distinctly higher than the other treatments, as was observed on the runoff plots (Figure 1). The sequence of CvT, CsT and NT runoff responses was generally correctly simulated. In the observed runoff data (Figure 1) the differences between the CvT treatment and the other cropped treatments was often larger than that simulated (e.g. 1991/92 season), while the differences between the CsT and NT treatments were mostly of a similar order of magnitude for simulated and observed (exceptions being the 1991/92 and 1993/94 seasons). The cumulative plots verify that over the period considered, as a whole, the differences between the cropped treatments were not well simulated, with the simulated differences being too small relative to the observed differences.

For all treatments the seasonal variation in simulated runoff shows the following differences in trends when compared to the observed (Figure 1) runoff:

- the simulated runoff in 1983/84 is higher than that simulated in 1984/85, while the observed runoff shows little difference; and
- the simulated runoff in 1995/96 is higher than that in 1993/94, while the observed runoff shows the opposite trend (no events were considered in 1994/95).

The reasons for the consistent over-simulation of runoff of the different tillage treatments in the 1983/84 and 1995/96 seasons relative to the 1984/85 and 1993/94

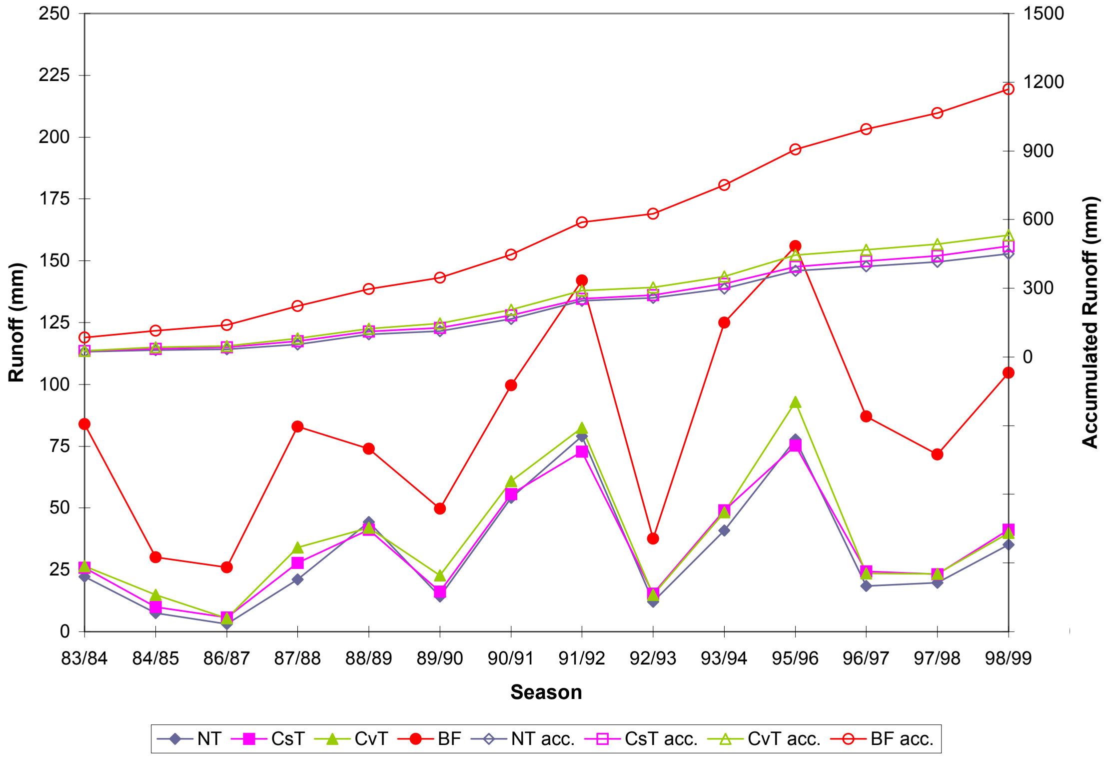

Figure 3 Simulated seasonal and accumulated runoff for maize under various tillage practices at Cedara

seasons, respectively, are not clear. The observed response in 1983/84 may be atypical due to this season being one of the first to be monitored, thus the need for a "settling down" period to observe a more typical response. The 1983/84 and 1995/96 seasons may also have been over-simulated due to a systematic error in the measurement of runoff. Alternatively, there may have been some variation in the management of the runoff plots that was not accounted for during those seasons.

7.2 Bloemfontein Runoff Simulations

The runoff from wheat monoculture crops under different tillage practices (NT, CsT, CvT) at Bloemfontein was simulated for the seasons from 1989/90 to 1992/93. The same mulch effects initially represented in the Cedara simulations were used to represent the tillage treatments at Bloemfontein, these being suppression of soil water evaporation and infiltration effects represented in the COIAM parameter. No mention was made by Bennie *et al*. (1994) of a plough pan forming under CvT or of the frequent occurrence of natural macropores under NT. The relatively short period of the experiment may not have allowed time for a plough pan to develop. Runoff was concluded to decrease with the amount of soil disturbance caused by tillage, further suggesting that no plough pan was present under CvT.

The simulated seasonal runoff for the different tillage practices (wheat monoculture plots) at Bloemfontein is plotted in Figure 4. The seasonal values of runoff were accumulated over the period of simulation and plotted as cumulative plots in Figure 4. The sequence of runoff for the various treatments was generally correctly simulated (see Figure 2), with the W91 and F91/92 seasons being exceptions. In

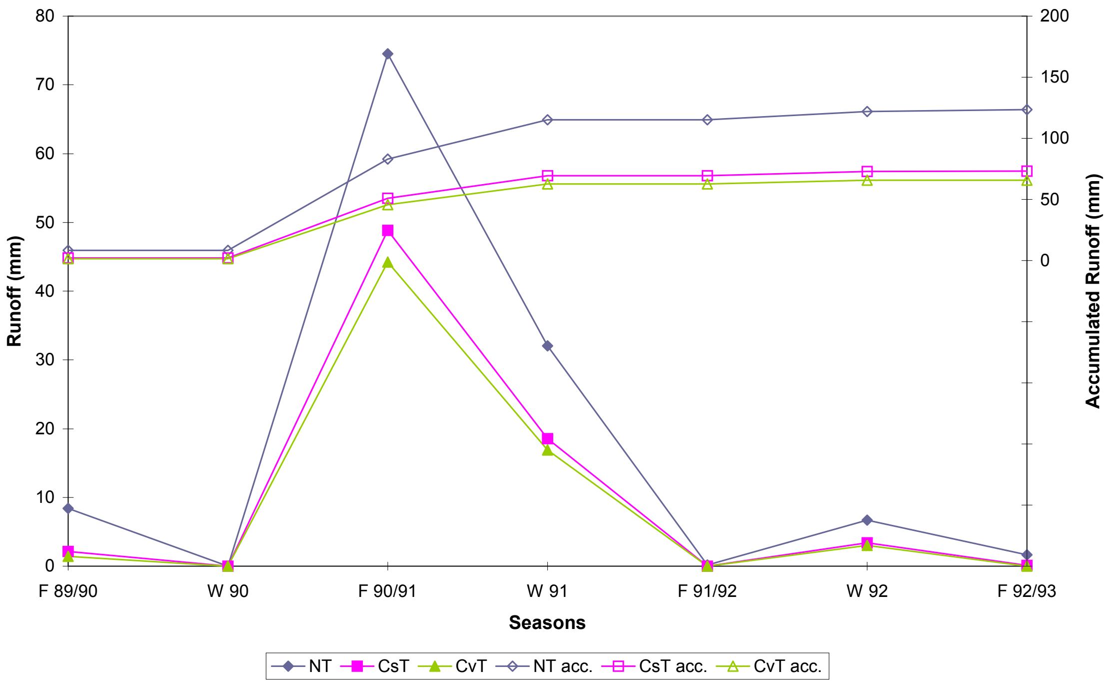

Figure 4 **Simulated seasonal and accumulated runoff for the wheat monocrop practice under various tillage systems at Bloemfontein**

most seasons, the relative simulated differences between the CsT and CvT treatments were, once again, smaller than the observed differences. In particular, the small differences in the F90/91 and W91 seasons represented an over-simulation of the CvT treatment relative to that of CsT. The cumulative plots verify that over the simulation period as a whole the modelled differences between the CsT and CvT treatments were not well simulated, with the CvT treatment being over-simulated and the CsT under-simulated relative to the observed data. It is believed that the sandy nature of the soil at the Bloemfontein site led it to becoming compacted under NT and resulted in higher runoff than the conventionally tilled runoff plot.

8 IMPROVEMENTS TO THE MODELLING OF BASELINE LAND COVER

When assessing the impacts of different land uses on streamflow, it is necessary to have a baseline against which these land uses can be compared. Several options for a baseline land cover are available in South Africa, the Acocks' Veld Types being one example of a land cover that has become accepted as a baseline. In the study of Gush *et al*. (2002), where streamflow reductions resulting from commercial afforestation were estimated, inconsistencies in the approach used to estimate the *ACRU* hydrological input parameters for the Acocks' Veld Types were identified. At the request of the WRC an improved approach to estimating the input parameters was developed within this project.

To ensure consistency in the estimation of *ACRU* input parameters, the hydrological attributes of the Veld Types were related to biomass. Biomass curves were developed for each Veld Type based on the premise that biomass is dependent on energy and moisture, as expressed in the following variables:

- moisture growing season (MGS)
- heat units (base 10°C)
- mean annual rainfall (MAP)
- rainfall concentration
- frost duration.

Climatic data contained in the Quaternary Catchments (QC) and gridded databases of the School of Bioresources Engineering and Environmental Hydrology (BEEH) were used in the calculation of the above variables. From the generated biomass curves the required hydrological land cover parameters were derived, namely, crop coefficients (CAY), rainfall interception per rainday (VEGINT), fraction of roots in the topsoil (ROOTA) and percentage surface cover (PCSUCO).

The use of climatic drivers of plant growth in deriving land cover input parameters ensured consistency and transparency in the development of these parameters. The revised model input parameters, combined with the new algorithm to account for soil water evaporation suppression by mulch cover (discussed earlier), signify improvements to the modelling of Acocks' Veld Types, and thus baseline land cover, for application in comparative hydrological studies.

9 CONCLUSIONS

The three runoff plot data sets acquired in this project were processed into a form that makes them readily available for future use. In the case of the DESC data, the work conducted in collating the data set has been of significant benefit in ensuring its future usefulness. In the synthesis of the data sets, focus was directed on aspects of interest to the modelling of tillage in the *ACRU* model. Further analyses in other areas of interest may be performed in future.

The approach adopted to modelling tillage in the project correctly predicted the seasonal sequence of runoff responses of the different tillage practices at Cedara and Bloemfontein for most seasons. The relative orders of magnitude of runoff responses of the different practices were less well represented, with the simulated responses being closer in value than the observed. The tillage modelling approach requires further testing and refining. This needs to be directed at hydrological responses other than runoff, and for a greater range of site conditions including, for example, different climates and soils.

The representation of rainfall intensity in the infiltration/runoff processes of *ACRU* should be pursued further, as should the estimation of rainfall intensities in the absence of suitable measured data. The identification of relationships in suitable observed infiltration/runoff data sets that could be used to predict initial abstractions in *ACRU* directly, rather than from a coefficient, should also be pursued further.

Although this study has focused on the hydrological impacts of tillage as a land management practice, the modifications introduced to the *ACRU* model in the project could, in many cases, be applicable to other land use types. Thus the ability of the model to simulate a wider range of land use impacts on hydrological responses has potentially have been improved.

The research conducted in this project has improved the representation of different tillage practices in *ACRU*. However, the influence of these practices on streamflow may only be simulated with relatively low confidence at this time. A variety of reasons exist for this, including the following:

- The ability of the model to simulate the impacts of different tillage practices at catchment scales is still uncertain, as suitable observed data at such scales are not available. Problems arise when scaling results from runoff plots to catchments.
- The differences which were simulated between the various tillage practices in this study need to be verified against observations of other aspects of hydrological response, e.g. evaporation, changes in soil moisture, crop yield, groundwater recharge and base/low flows.
- The representation of tillage practices in the model needs to be verified at other locations having different climates, soils and slopes to those at Cedara and Bloemfontein.

This project has focussed on surface runoff processes and has not considered impacts on low flows. The lack of relevant observed data against which low flow simulations involving agricultural land uses can be compared, presents difficulties. It is likely that impacts on base/low flows would have to be considered indirectly via a general assessment of the water balance.

As the impacts of tillage on catchment streamflow (both stormflow and baseflow) can only be simulated with low confidence (see above), any current application of *ACRU* that might suggest certain tillage practices reduce streamflows would not constitute sufficient evidence for these practices to be considered as streamflow reduction activities. Such deductions cannot be made from observations either, as no suitable measurements are available as yet. If reduced tillage practices such as no till were found to reduce streamflow, these reductions would have to be weighed up against the many potential environmental and agronomic benefits that may be derived from these practices.

The new approach developed to estimate *ACRU* land cover input parameters for the Acocks' Veld Types, based on climatic drivers of plant growth, has ensured consistency and transparency in estimates of these parameters. This represents an important improvement, particularly as Acocks' Veld Types become accepted as a baseline land cover in assessing streamflow reduction activities. Ideally, the input parameters and simulated hydrological response of the Veld Types should be assessed against observed data.

It is suggested that the implementation of SFRAs in the National Water Act needs some careful conceptual re-consideration. This statement is made in view of the dynamic nature of land cover and land management that characterises agricultural land uses. Difficulties may arise in assessing the impacts of these land uses on streamflow at the catchment outlet, since a mixed signal may be evident as a consequence of lags in the hydrological system, where impacts on streamflows not only reflect the current land use, but also recent past land uses. The dynamic nature of short rotation agricultural land uses also implies that the control of these land uses would be very difficult if they were to be declared as streamflow reduction activities.

The crops planted and the management practices applied are constantly changing, both spatially and temporally, and would be difficult to monitor over large areas. It may be more appropriate to assess hydrological impacts in terms of changes in total evaporation, although such an approach also poses challenges due to high temporal and spatial variability in soil moisture, the major limiting factor to total evaporation in South African conditions.

10 EXTENT TO WHICH PROJECT OBJECTIVES WERE MET

- **The acquisition and collation of historical measured field data focussing on land use related hydrological processes.** After considering a number of possible data sets in this objective, three runoff plot data sets were acquired which reflected runoff responses under various crops and tillage practices. The data sets were collated into a form that facilitated other aspects of this project and which will also ensure their usefulness in future research.
- **The synthesis of the above field data in terms of land use impacts on hydrological responses.** This objective was achieved by way of analyses of the data that were directed at aspects of interest in the modelling of hydrological impacts of tillage in *ACRU*. Further analyses in other areas of interest may be performed in future.
- **The enhancement of suitable modelling tools through application of the data in model verification studies at various sites.** This objective was achieved through the enhancement of the *ACRU* model, where a more systematic approach to representing the influence of tillage in the model was developed and verified against measured runoff plot data from the DESC and UFS studies. The approach requires further testing and refining, where hydrological responses other than runoff are considered, and where a greater range of site conditions are represented, e.g. under different climates and soils. The impact of tillage on catchment streamflow can only be simulated with low confidence at present.

11 RECOMMENDATIONS FOR FUTURE RESEARCH

- In the absence of rainfall intensity measurements, methods of estimating indices of spatial and temporal patterns of rainfall intensity from daily rainfall records, should be developed for use with hydrological models to improve the modelling of runoff responses. Rainfall intensity is an important determinant in hydrological response from land uses such as tilled agricultural fields, and should be represented in some manner in the infiltration/runoff process, as was attempted in this study.
- The tillage modelling approach adopted in this study needs to be tested and refined further in terms of hydrological responses other than runoff, e.g. soil loss. The approach also needs to be tested under a greater range of site conditions including different soils, slopes and climates.
- The simulation of initial abstractions in the *ACRU* model might be improved if predictive relationships could be found to directly predict I_a as a physical quantity in millimetres, rather than by way of a coefficient. This would depend on the availability of suitable runoff plot data sets (involving rainfall simulators).
- The modelling of tillage impacts on base/low flows has not been tested against observed data in this study. The lack of suitable observed data implies that the

impacts would have to be assessed indirectly via a general assessment of the water balance.

- The modelling of tillage impacts on water quality should be investigated, as this study has only considered impacts on water quantity. The potentially beneficial impacts of reduced tillage on water quality might outweigh any negative impacts that these practices have on water quantity.
- The land use related input parameters estimated for the Acocks' Veld Types in this study, and the resulting simulated hydrological responses, should be assessed against observed data.
- It is suggested that the implementation of SFRAs in the National Water Act needs some careful conceptual re-consideration. This statement is made in light of the dynamic nature of land cover and land management that characterises agricultural (non-forestry) land uses. As discussed previously, difficulties may arise in assessing the impacts of these land uses on streamflows at a catchment outlet. Furthermore, if these land uses were to be declared as SFRAs they would be difficult to regulate given their highly variable spatial and temporal nature. It may be more appropriate to assess hydrological impacts in terms of changes in total evaporation, although such an approach also poses challenges.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF DEFINITIONS AND ABBREVIATIONS

ABRESP*	**fraction of "saturated" soil water to be redistributed daily from the topsoil into the subsoil when the topsoil is above its drained upper limit**
BEEH	**School of Bioresources Engineering and Environmental Hydrology**
Baseflow	**consists of water from previous rainfall events that has percolated through the soil horizons into the intermediate and groundwater zones and then contributes as a delayed flow to the streams within a (sub)catchment**
BF	**bare fallow**
BFRESP*	**fraction of "saturated" soil water to be redistributed daily from the subsoil into the intermediate/groundwater store when the subsoil is above its drained upper limit**
c	**regression coefficient in the SCS Stormflow Model**
CAY*	**crop coefficient**
COIAM*	**coefficient of initial abstraction**
CsT	**conservation tillage**
CvT	**conventional tillage**
DESC	**Directorate of Engineering and Soil Conservation**
DWAF	**Department of Water Affairs and Forestry**
E	**total evaporation, comprising of transpiration and evaporation from the soil (mm)**
E_m	**maximum evaporation, i.e. potential total evaporation (mm)**
$\bar{f}$	**average infiltration rate (mm/h)**
I	**application intensity (mm/h)**
I_a	**initial abstractions, i.e. the amount of rainfall abstracted before stormflow commences, where this comprises of interception, infiltration and depression storage (mm)**
MAP	**mean annual precipitation (mm)**
MGS	**moisture growing season i.e. the period when, on average, there is enough water in the soil for sustained plant growth to take place**
NT	**no till**
PCSUCO*	**percentage surface cover**
PO1*	**soil water content at saturation for the topsoil** ($m.m^{-1}$)
PO2*	**soil water content at saturation for the subsoil** ($m.m^{-1}$)
P_g	**gross daily precipitation as defined in the SCS Stormflow Model (mm)**
$\bar{q}$	**average runoff rate (mm/h)**
Q	**stormflow depth in the SCS Stormflow Model (mm)**
QC	**Quaternary Catchment**
QFRESP*	**stormflow response fraction for the catchment/subcatchment, i.e. the fraction of the total stormflow that will run off from the catchment/subcatchment on the same day as the rainfall event**
Quickflow	**component of stormflow leaving the catchment on the same day as the causative rainfall event**

ROOTA*	**fraction of roots in the topsoil that are effective in transpiration**
ROOTB*	**fraction of roots in the subsoil that are effective in transpiration**
RR_o	**random roughness immediately after a tillage operation (mm)**
RR_p	**random roughness after a certain amount of cumulative rainfall since a previous tillage operation (mm)**
Runoff	**surface runoff in the context of observed runoff plot data and quickflow in the context of simulation results**
S	**potential maximum retention in the SCS Stormflow Model (mm)**
SARSP	**South African Rainfall Simulator Programme**
SCS	**Soil Conservation Service of the United States Department of Agriculture**
SFRA	**Stream Flow Reduction Activity**
SMDDEP*	**Critical depth of soil effective in stormflow generation (m)**
Stormflow	**the water which is generated on or near the surface of a (sub)catchment from a rainfall event, to contribute to flow in the streams within that (sub)catchment**
Streamflow	**consists of stormflow and baseflow**
t	**time to runoff commencement (h)**
TAM	**total available moisture in the soil accessible to plants**
UFS	**University of the Free State**
USLE	**Universal Soil Loss Equation**
VEGINT*	**interception loss per rainday by vegetation (mm)**
WRC	**Water Research Commission**

*** denotes *ACRU* variables**

1 INTRODUCTION

1.1 Background and Objectives

The demand for water in South Africa is steadily increasing, while the supply is generally limited and very variable. This has led to increasing competition for water amongst various users in the country. Land use can exert strong influences on water resources in terms of quantity and quality, thus there is a need to accurately estimate the impacts of land use on streamflow. These impacts form an important focus in South Africa's National Water Act (Act No. 36 of 1998), which includes provision for certain land uses to be declared as a Stream Flow Reduction Activity (SFRA).

A streamflow reduction activity is defined as
"… any activity (including the cultivation of any particular crop or other vegetation) … [that] … is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly" (National Water Act Section 36(2)).

The National Water Act (NWA) identifies a number of types of water use, including SFRAs, as a means to administering the future allocation of water amongst different users. SFRAs are regulated by a licensing system which will have implications in terms of the charging of water levies. Thus far, forestry has been declared a SFRA, while other land uses may also be declared so in future (Department of Water Affairs and Forestry, 1999).

It is important to note that the definition of SFRAs considers a change in the streamflow in a water course. The hydrological response of a catchment is dependent not only on land use, but also on other factors including climate, soils and topography. In discussions regarding the water balance of forested sites, it has been suggested that over a period of ten years or more, that a streamflow reduction can be equated to the change in total evaporation (E) for the area under consideration, provided land management practices are not varied over this period (Gush *et al*., 2002). However, in the case of agricultural crops, the management of the area under consideration is likely to be dynamic and is unlikely to remain static over a long period. Thus, simply equating streamflow reduction to changes in E may not be valid. Hydrological modelling tools that can integrate the major relevant factors to simulate the impact on catchment streamflow, are thus required. The need to accurately estimate land use impacts on catchment streamflow is important as, in a South African context, this is the scale at which water resources are managed. Given the large number of possible land uses and locations, these impacts cannot be deduced solely from limited available measurements, but should be supplemented with estimates from conceptual-physical hydrological simulation models which have been developed and tested using observed hydrological data.

A number of catchment studies investigating the impacts of forestry on streamflow have been conducted in South Africa. These studies have facilitated the verification and enhancement of hydrological models under forested catchments. In contrast there are almost no controlled catchment scale land use experiments in South Africa involving agricultural (non-forestry) land uses (Kruger *et al*., 2000). However, there are studies which have been conducted at smaller scales, such as at runoff plot scale. These small-scale data may still be applied, with appropriate care, in verification studies of hydrological models, thus enabling the potential improvement of these models and their estimates of streamflow in agricultural catchments.

For the purposes of this report, land use is comprised of both land cover, i.e. crops, and the land management practices applied to those crops. These management practices impact the runoff from cropped areas. Examples of management practices that may reduce runoff include tillage, contour banking, terracing, water harvesting and strip cropping. Such practices need to assessed as potential SFRAs (DWAF, 1999) and have not been considered in previous studies (e.g. Kruger *et al*., 2000). It has been suggested that management practices applied to a crop may exert more influence on the water balance and runoff, than the crop itself.

Given the above background to land use impacts on streamflow in South Africa, the objectives of this project were defined as follows:

- the acquisition and collation of historical measured field data that focuses on land use related hydrological processes;
- the synthesis of the above field data in terms of land use impacts on hydrological response; and
- the enhancement of suitable modelling tools through application of the data in model verification studies at various sites.

The first objective was considered a vital aspect of the project given that many good quality field data have been collected in the past in South Africa. These data sets have often not been utilised to their full potential and, furthermore, are at risk of being misplaced or discarded as time progresses, research emphasis changes and the researchers involved retire. These historical data sets still have great value in current research, especially given the high costs of conducting field measurements. Use of observed data in model development is vital to ensure continued relevance of the model predictions.

As the background context of the study related to streamflow reduction activities, the focus of the project was on non-irrigated conditions. Irrigation is not considered as a SFRA in the NWA, but is controlled under other sections of the Act.

1.2 Outline of Methodology

Given the importance of both land cover and land management on hydrological responses, the methodology employed to achieve the above objectives was as follows:

- **The identification of key land use/s for consideration in the study:** A decision was made to focus on two crops, *viz*. maize and wheat, subjected to different forms of tillage practice, namely conventional tillage (CvT), conservation tillage (CsT) and no till (NT).
- **The acquisition and collation of historical observed field data that are relevant to assessing the hydrological impacts of the selected land management practice (tillage):** Data from runoff plots subjected to the above

tillage practices were obtained from the University of the Free State (UFS), the Directorate of Engineering and Soil Conservation (DESC) and the South African Rainfall Simulator Project (SARSP). The UFS study included four sites with runoff plots, the DESC study approximately eight sites and the SARSP approximately 97 sites. A wide variety of crops were represented in these studies including maize, wheat, dry beans, soya beans, sunflowers, tobacco, sorghum and pineapples. Bare fallow conditions were also represented.

- **The synthesis of the observed field data (from runoff plots) in terms of land use impacts on hydrological responses:** The synthesis was restricted to maize plots at the Cedara site (the DESC study) and wheat monocrop plots at the Bloemfontein site (the UFS study), where attention was focussed on the seasonal trends in runoff between the different tillage practices. In the case of the SARSP data, analysis was directed at seeking trends in initial abstractions across multiple sites and the associated conditions at these sites.
- **The configuration and application of a hydrological model, *ACRU*, at selected sites:** The *ACRU* model (Schulze, 1995) was applied to simulate the impacts of tillage on runoff at the Cedara and Bloemfontein sites.
- **The verification of *ACRU* output against the observed site data:** The *ACRU* simulations of hydrological response were verified not in terms of absolute runoff values, but rather in terms of the relative sequences and orders of magnitude of runoff responses generated under the different tillage practices considered.
- **The enhancement of *ACRU*'s land use modelling capabilities based on the results of the site modelling:** These enhancements were to be achieved through improved model algorithms, modelling strategies and model input values.
- **The enhancement of baseline land cover modelling in *ACRU*:** This research was aimed at improving the estimation of hydrological land cover input parameters for modelling baseline land cover (represented by the Acocks' Veld Types).

The final aspect of the project methodology was implemented to address inconsistencies in the land cover input parameters for the Acocks' Veld Types. These inconsistencies were detected in the WRC/DWAF funded forestry SFRA project of Gush *et al*. (2002), and were addressed within this project at the request of the WRC. While this aspect of the study was not linked with the rest of the methodology outlined above, it was deemed to fit within the objectives of the project as it related to enhancing the ability of the *ACRU* model to assess land use impacts on hydrological responses. The research is presented in a separate chapter of the report (Chapter 6).

Numerous historical studies were reviewed before the decision was made to direct the focus of this project on the hydrological impacts of crops under different forms of tillage. The data collected in the reviewed studies represent a broad spectrum of land use related data that could potentially have been used in a South African study on modelling land cover and land management impacts on hydrological response under non-irrigated conditions. A list of references to these studies is presented in Appendix A The data collected in the studies included, *inter alia*, measurements of climate, total evaporation, soil and crop characteristics, infiltration and runoff. The researchers involved in some of the studies were interviewed to help ascertain the suitability of the collected data sets for use in this project.

The decision to focus on tillage as a land management practice in this project was made because of the widespread nature of this practice. At present, conservation till and no till are practiced on a relatively small scale in the country: In KwaZulu-Natal province, an estimated 10000ha of land is under no till (Russell, 2002; pers. comm.). In the Free State and North West Provinces, approximately 1.5 million hectares of land is under stubble mulch tillage (a form of CsT) to control wind erosion on sandy soils (Bennie, 2003; pers. comm.). In the Western Cape Province approximately 90000ha of land is under CsT, while an estimated 40000ha is under NT (Agenbag, 2003; pers. comm.). However, there is a growing trend towards conservation and no till practices as alternatives to conventional tillage. Reduced till practices have a number of potential benefits for farmers, for example, lower machinery and associated fuel costs, which is likely to accelerate the trend towards these practices. Reduced tillage may, however, result in a reduction of runoff. To date, there has been little research into modelling the effects of tillage on runoff for use with the *ACRU* model.

The runoff plots from the DESC, UFS and SARSP studies provide important sources of runoff plot data in South Africa. The impact of tillage on runoff was systematically represented in the DESC and UFS studies. Although the runoff plots are small (e.g. 5.5m^2 in the UFS study), it is believed that they can still be a valuable source of information in verifying process representations within catchment hydrological models. This is especially so in the absence of controlled catchment-scale land use experimental data.

The synthesis of runoff plot data and application of these data in model verification studies was restricted to the Cedara maize and Bloemfontein wheat monoculture plots to limit the scope of the analyses. These sites also represented the best managed experiments, being close to where the relevant researchers were based. In the case of the Cedara site, the maize plots had the longest record of measurements available, while at the Bloemfontein site, the wheat monocrop was the simplest to analyse. The SARSP data was specifically analysed for trends in initial abstractions of water before runoff commenced, in an attempt to improve the modelling of this component of the runoff process.

In this study the term “runoff” will refer to surface runoff in the context of runoff plots, and “quickflow” in the context of simulation results. Quickflow, as simulated by the *ACRU* model, comprises of runoff which would leave the catchment (in the context of catchment modelling) on the same day as the rainfall event. It is likely to include surface runoff, but not exclusively so, as some areas will be characterised by rapid interflow that also leaves the catchment on the same day. Quickflow is that component of flow simulated by *ACRU* that best represents the runoff observed from a runoff plot. It is considered justifiable to regard simulated quickflow as representative of observed surface runoff from a runoff plot, as the goal in modelling tillage practices in this study is not to simulate absolute runoff values, but rather the relative sequences and orders of magnitude of runoff from different practices. These sequences and orders of magnitude should be similar whether one considers quickflow or surface runoff.

The *ACRU* model is well suited as a water resources management tool for implementing certain aspects of the National Water Act. It is a conceptual-physical model which is structured to be sensitive to the influence of land cover and its management on hydrological responses, and is thus suited to investigating what-if scenarios for planning purposes. It has been extensively verified both locally and internationally (Schulze and Smithers, 2002). While it is possible to represent a number of different land covers in the model, the hydrological responses of which have been verified against experimental data, land management impacts are less well represented and verified. Land management may, in many cases, be more influential on hydrological responses than land cover *per se*.

1.3 Scale Considerations

Complex scaling issues limit the direct verification of a catchment scale model against data which have been observed at plot or small field scale. Calder (1998) has identified various "limits" to E in various climates of the world (Table 1.1). Calder (1998) suggests that the physics of the evaporation process is well known and that equations representing the process for different land uses are widely used and applied across a range of spatial scales. In temperate regions of the world, where these equations were developed, and where radiation may be major limit to E, it is accepted these equations may be valid and may be applicable across a range of spatial scales. However, Calder (1998) classifies South Africa as "Dry Tropical", and suggests that the limits to E are considered to be mainly soil moisture availability and crop characteristics. If it is accepted that soil moisture is the major limitation to E under typical South African conditions, then in order to simulate E, soil moisture should be measured or estimated. This complicates the simulation approach considerably. Soil moisture is dependent on a wide variety of factors, including soil type and management practices, which may affect infiltration into, and runoff and evaporation from, the soil. All of these factors may be highly variable, both spatially and temporally. Soil types are naturally variable, while agricultural management such as tillage practices, crop planting dates or erosion control structures may be different from year to year and from field to field.

Table 1.1 Principal limits and controls on evaporation for different land uses in different climates (after Calder, 1998)

Principal Limits on Evaporation		
Temperate Climate		
Land use	Dry	Wet
Tall crop	Physiology Soil moisture	Advection
Short crop	Soil moisture Radiation	Radiation Physiology
Tropical Climate		
Land use	Dry	Wet
Tall Crop	Soil moisture Tree size	Rain drop size Physiology
Short crop	Soil moisture	Radiation

Streamflow at the outlet of a catchment provides a measurable integrator of the highly variable land use related hydrological processes that operate within that catchment. However, with the exception of commercial forestry and a single set of sugarcane catchments, experimental data in this regard do not exist in South Africa. Furthermore, as stated above, a review of available international literature suggests that catchment-scale experiments which consider hydrological implications of short rotation agricultural crops as opposed to longer term land use change are extremely rare (Blackie *et al*., 1979). Thus, information in this regard is limited to data collected from runoff plots, ranging from 5 – 70 m^2 in size. It is inevitable that hydrological responses at plot scales are influenced by localised factors, and will be more marked and exhibit greater variability than catchment responses. Furthermore, the design and small size of runoff plots implies that the measured responses are not likely to reflect subsurface movement of water. Indeed, the small size of runoff plots implies that measurements are more a reflection of infiltration responses, than runoff response. Typically, measurements from runoff plots are event-based rather than continuous. Thus, a continuous water balance cannot be resolved.

Figure 1.1 indicates that studies conducted at a coarse time scale at fine spatial scales have a low predictive capacity. Fine temporal scale studies conducted at coarse spatial scales may appear to have high predictive capacity, however, they may be only "pseudopredictions", as the time resolution of the natural dynamics of the system under consideration are longer than the study period. This relationship between spatial resolution and predictability has also been analysed by Costanza and Maxwell (1993). They found that while increasing scale provides more descriptive information about the aggregate patterns in the data, it also increases the difficulty of accurately modelling those patterns. Allied to this, Wiens (1989) and Levin (1992) both concluded that fine-scale studies may reveal greater detail about biophysical mechanisms, but that generalisations are more likely to be identifiable at broader scales. In other words, processes operating at scales larger than the scale of the observation extent appear as trends in the data, processes occurring at scales smaller than the scale of observation appear as noise.

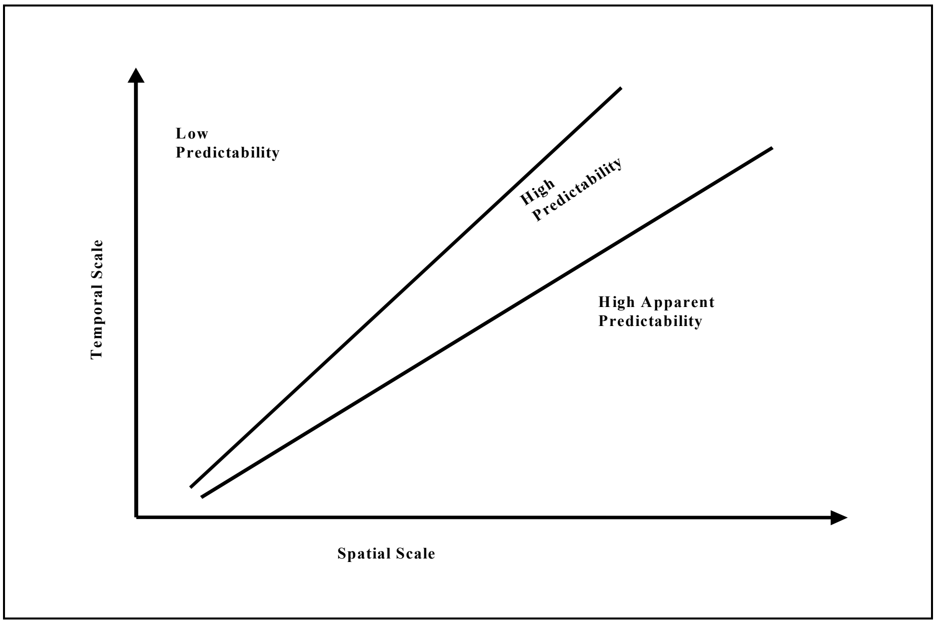

Figure 1.1 The effects of scale on predictability (after Wiens, 1989)

Many researchers have noted that local interactions are more pronounced at smaller than at larger scales (Wiens, 1989; Blöschl and Sivapalan, 1995). Often, they avoid the confusing picture presented by local interactions by focussing on processes and phenomena which involve broad spatial scales. These appear to be changing at rates which require long time scales to observe and model (Meentemeyer, 1989; Blöschl and Sivapalan, 1995; Jewitt and Görgens, 2000). This is a basic technique of scientific enquiry (Levin, 1992), i.e. by changing the scale of prediction, it is possible to move from apparently unpredictable, unrepeatable individual cases to collections of cases whose behaviour is regular enough to allow generalisations to be made. In the context of this study, it must be recognised that small-scale studies may reveal greater detail about hydrological mechanisms, but that generalisations are more likely to be identifiable at broader scales (Jewitt and Görgens, 2000). Levin (1992) believes that the key to understanding how information is transferred across scales is to determine what information is preserved and what information is lost as one moves from one scale to another. Attempts to understand this have included the development of scaling rules (or laws), the use of hierarchies to reflect the range of scales being dealt with and the selection of units that are representative of and characteristic of a larger unit. It is always preferable to scale up from fine resolution data to coarse scales, than vice versa, as the loss of resolution can be monitored and evaluated.

The high variability of runoff responses at runoff plot scale and the methods of data collection limit their usefulness for verification of hydrological models such as the *ACRU* model. Thus, the focus in this project is on identifying and simulating processes that may operate at scales larger than the scale of the observation, and which will appear as trends in the data, and ignoring processes occurring at scales smaller than the observation which may appear as "noise". In this way, the modelling exercise described in Chapter 5 is initiated within the context of a sacrifice of detail in order to reveal broader scale spatial and temporal hydrological patterns. As explained above, it is necessary to consider the impacts of agricultural land use in the water course, i.e. at the catchment outlet. In this study, the *ACRU* model is used as a tool which effectively upscales runoff plot scale information to a catchment level response. However, given the complications described above, verification of the *ACRU* model will focus on ensuring that relative hydrological responses under different tillage practices are represented at a seasonal time scale.

In Chapter 2 of this report the synthesis of measured data (from runoff plot studies) obtained for use in the project is presented. In Chapter 3, an abbreviated background theory to the *ACRU* model is given. This is followed in Chapter 4 by a description of how tillage is represented in *ACRU* in this study. In Chapter 5 the modelling of tillage impacts on runoff response at Cedara and Bloemfontein is presented. In Chapter 6, improvements to the modelling of baseline land cover are presented. General discussion and recommendations for future research are presented in Chapters 7 and 8 respectively.

2 SYNTHESIS OF MEASURED RUNOFF PLOT DATA

The synthesis of measured runoff plot data from the DESC, UFS and SARSP studies is presented in separate sections of this chapter, with each section including subsections detailing the objectives and methodology of the particular study, a description of the data set collected and an analysis of trends in the data. In the case of the DESC and UFS studies an additional subsection is included to describe the work that was required to prepare the data before trends could be analysed.

2.1 Directorate of Engineering and Soil Conservation Data Set

The DESC runoff plot data were collected during a project titled “Erosion Studies using Natural Runoff Plots” (DESC Facet No. N5711/38/1/1), which was conducted over the period from 1983 to 1999. The project was led throughout most of its duration by Mr WB Russell, who was assisted by Mr M Gibbs. At the time of writing this report the results of the project had yet to be formally written up owing to staffing constraints. Details regarding the project were obtained from annual project progress reports, notebooks and from discussions with Mr Russell.

2.1.1 Objectives and methodology of the original study

The objectives of the study were as follows:

- to determine the Universal Soil Loss Equation (USLE) erodibility indices (K factors) of six agronomically important soils in KwaZulu-Natal; and
- to determine the conservation value of various tillage practices on arable land (these practices ranging from conventional tillage to no till).

The motivation for setting these objectives originated from concerns about the loss of soil from arable land in KwaZulu-Natal. The quantification of the effects of tillage on erosion was considered important in addressing this problem. The need to obtain local input data for application in the USLE was also considered important as this information was to be used to improve guidelines for the design of contour banks as an erosion control measure.

The methodology employed to achieve these objectives involved setting up a number of runoff plots during the course of the project at 8 sites in KwaZulu-Natal (Figure 2.1). At most sites a bare fallow (BF) control runoff plot was maintained to allow for the determination of USLE K factors. The K factor is defined as the rate of soil loss per rainfall erosion index unit, as measured on a standard USLE plot, which is kept continuously in a bare fallow condition and where tillage is performed up- and downslope (Renard *et al*., 1991). Runoff plots under various tillage practices were also set up, these plots being planted to a variety of crops. Soil and water losses resulting from natural rainfall events were measured at all runoff plots. Rainfall records were kept at all sites and measurements of soil and crop characteristics were carried out at various intervals to enable the calculation of the USLE crop cover and management factors.

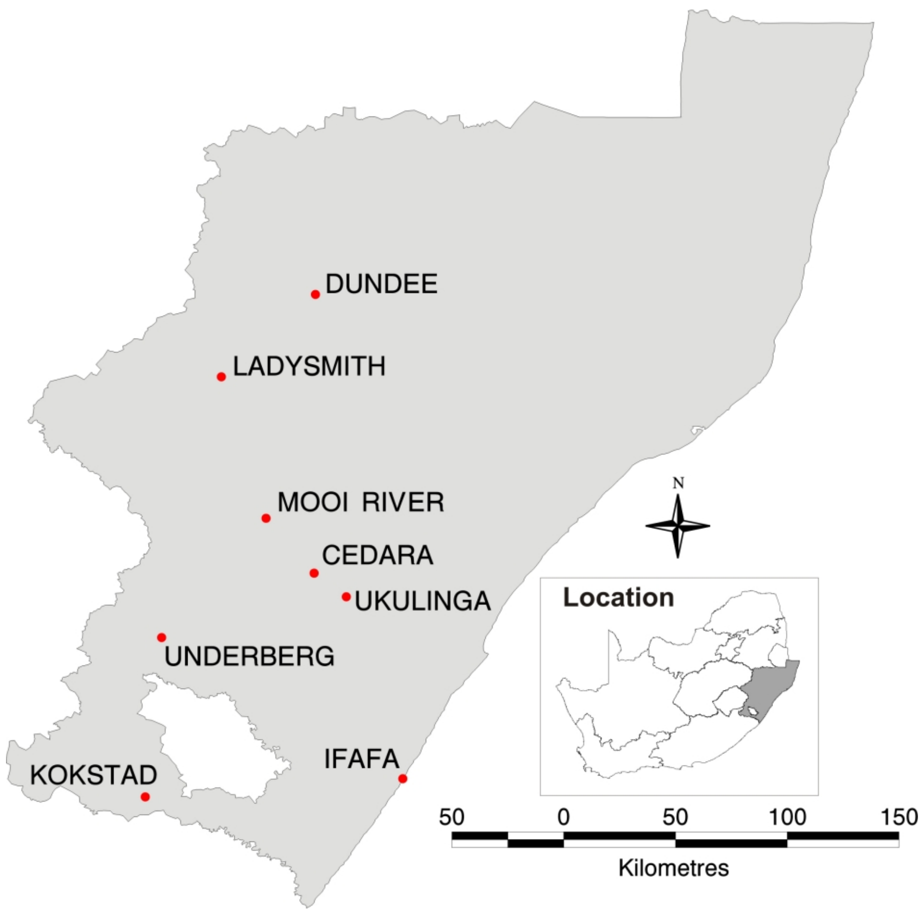

Figure 2.1 Locations of the DESC runoff plot sites in KwaZulu-Natal

The runoff plots were, as far as possible, set up to conform to the standard USLE specifications, these being 22.1 x 3 metres and on slopes of 9%. Duplicate plots were set up for each treatment. The plots were bordered on three sides by metal shuttering dug into the soil surface in order to exclude extraneous runoff. The lower end of the plot was bordered by a concrete sill and gutter. A pipe then led the water and sediment to measurement tanks. Runoff was calculated by measuring the depth of water in the tank(s) and multiplying by the area. The amount of sediment was calculated by analysing the sediment concentration in water samples, taken after thorough mixing of water in the tank.

2.1.2 Sorting and collating of data

Before the DESC data could be used it was necessary to sort and collate the dataset as it had become disorganised over time. This task had not been performed by DESC owing to staff shortages resulting from the untimely death of Mr Gibbs. An agreement was reached whereby the research team would re-organise the data on behalf of DESC, in exchange for the use of the data. A large amount of data were collected over the 17 years that the project spanned, and this resulted in a significant amount of time being expended on the task of sorting and collating the data (approximately 2-3 months). This effort was justified as the task of collating measured field data fell within the brief of the project. The DESC data set is also considered to be a valuable one given the current high costs of field work. It is thus a valuable source of information for hydrological process studies in South Africa.

The dataset existed in hardcopy and electronic form. The hardcopy data were first sorted according to site and then according to the following data types:

- rainfall
- soil loss/runoff
- soil, crop or other data.

The first two data types were then separated into raw and processed data. Any extra copies of the data were discarded for the sake of manageability and storage space.

The electronic data generally consisted of the processed data referred to above, and were sorted into the same data types. A logical directory structure and file naming system was introduced to facilitate ease of use of the dataset. If multiple copies of a data file existed the most up-to-date file was kept and the remaining files deleted. The data were initially stored on several hundred 3½" disks and were consolidated to fit onto one compact disc.

2.1.3 Description of the data set

To provide an overview of the DESC data set, general information pertaining to the various runoff plots that were set up during the course of the DESC project is given in Table 2.1. The locations of the plots (sites) are indicated in the table, along with the crops planted, the tillage practices applied and the seasons in which runoff and soil loss measurements were made.

The Cedara site plots had the biggest range of crop and tillage treatments. The maize plots were monitored throughout the experiment and were foundational to the project. They were well maintained by project staff stationed at the DESC offices at Cedara. It is for these reasons that the maize plots were selected for analysis in the runoff modelling described in Chapter 5. Further details regarding the Cedara maize plots are provided in the following paragraphs.

The treatments applied to the maize and bare fallow plots are outlined in Table 2.2. The exact slopes of the individual runoff plots were not consistently reported in the data set. The range of slopes reported was from 6.9 to 9.95%. In the 1995/96 to 1997/98 seasons cultivation was performed up and down the slope in contrast to the other seasons where cultivation took place along the contour. The maize crop was generally planted at the beginning of November each year and was harvested in June. After emergence the plant population was reduced to 45000 plants per hectare.

Table 2.1 General information pertaining to the DESC runoff plots

*use of runoff plots uncertain

Site and Crops	Tillage Practice	Monitored Seasons															
		83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	98/99
Cedara																	
maize	CvT, CsT, NT	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
soyabean	CvT							×	×	×	×	×	×	×	×	×	×
dry bean	CvT							×		×	×	×	×	×	×	×	
sunflower	CvT							×		×	×	×	×		×	×	
tobacco	CvT							×	×	×	×	×					
bare fallow		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Dundee																	
maize	CvT, CsT								×	×	×	×	×	×	×	×	
soyabean	CvT								×	×	×	×	×	×	×	×	
tobacco	CvT								×	×	×	×					
bare fallow		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Mooi River																	
maize	CvT										×	×	×	×	×	×	
tobacco	CvT										×	×					
bare fallow											×	×	×	×	×	×	×
Kokstad																	
veld												×					
Ladysmith																	
bare fallow		×	?*	×	?*	×	×	×	×								
Underberg																	
pinus patula										×	×	×	×				
Ifafa																	
banana	CvT, NT												×	×	×		×
Ukulinga																	
bare fallow		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×

Table 2.2 Treatments applied to the maize and bare fallow runoff plots at Cedara

Plot No.	Tillage Type	Treatment
1	NT	**Direct drilling:** Using a no-till planter, seed was drilled directly into the ground after the previous season's crop residue had been chopped into 300mm lengths. No other tillage operations were carried out. Weed control was carried out chemically. On average, mulch cover was 80% at planting and declined at a rate of 18% per month during the season.
2	CsT	**Chisel ploughing/stubble mulch till:** After harvest, half of the residue from the previous crop was removed to simulate winter grazing of the stalks. The remaining stalks were chopped into 300mm lengths and the soil ploughed in August to a depth of 150mm using a chisel plough with duckfoot sweeps. A tined-harrow operation was carried out shortly before planting for weed control. On average, mulch cover was 35% at planting and declined at a rate of 8% per month during the season.
3	CvT	**Mouldboard ploughing in spring:** The spring plough plots were disc harrowed to chop up the stalks in August, mouldboard ploughed in late September/early October after the first rains to a depth of 250 mm, and then disced again just before planting. As with the chisel plough plots, half of the stalks were removed to simulate grazing. The rest of the stalks were ploughed into the soil. On average, mulch cover was 3% at planting.
4	CvT	**Mouldboard ploughing in autumn:** At physiological maturity in late March the entire maize crop was removed to simulate a silage making operation. Mouldboard ploughing followed immediately and left the soil surface rough and cloddy through winter. Disc-harrowing was carried out just before planting in spring. On average, mulch cover was 1.5% at planting.
5	BF	**Control:** In order to eliminate any effect of changing cover through the season, and in order to derive soil erodibility indices, these plots were cultivated downhill using a rotovator and kept clean and fallow throughout the experiment. Any rilling was smoothed out as soon as possible after the rainfall event which caused it.

The variables that were measured on the runoff plots, the frequency with which they were measured and the period of monitoring are listed in Table 2.3. The period of monitoring is approximate in some cases owing to uncertainty as to whether the whole record had been accounted for. In a number of cases data were missing or were not recorded within the tabulated monitoring periods.

Table 2.3 Variables measured on the maize and bare fallow runoff plots at Cedara

Variable	Measurement Frequency	Monitoring Period*
runoff	per event	1983/84 – 1998/99
soil loss	per event	1983/84 – 1998/99
rainfall	continuous	1983/84 – 1998/99
organic matter	seasonal	1983/84 – 1993/94
organic carbon	seasonal	1983/84 – 1993/94
mulch cover**	± 10 per season	1983/84 – 1993/94
canopy cover**	± 10 per season	1983/84 – 1993/94
crop yield**	seasonal	1983/84 – 1998/99
fertilizer loss**	per event	1983/84 – 1989/90
soil moisture	seasonal	1985/86 – 1992/93

* approximate
** not applicable to bare fallow runoff plot

Rainfall was initially measured using an autographic rain gauge located at the runoff plots. Later in the experiment this gauge was replaced with an electronically monitored tipping bucket rain gauge. Processed data from these gauges were not readily available in electronic form. It was noted that when runoff, soil loss and rainfall were tabulated in the DESC data set, the rainfall figures were derived from the nearby Cedara Meteorological Station (Station No. 0239482A), as opposed to the gauge erected at the runoff plots.

A soil profile description was carried out at the beginning of the project. This description classified the soil as a Hutton Doveton (MacVicar *et al.*, 1977). A second profile description in the 1990/91 season re-classified the soil as an Inanda clay (SCWG, 1991). The soil depth was reported to be 2m.

2.1.4 Trends in runoff from the Cedara maize plots

In the analysis of trends in runoff on the Cedara maize plots, attention is focussed at the seasonal time scale, as this is the scale at which responses were to be modelled in the project, as explained in Chapter 1. In the DESC study, runoff observations were made as soon as possible after a significant runoff producing event, usually the day after an event. Smaller events between these observations may have resulted in some runoff being generated, which would then have been reflected in the observations. For some events, it was unclear from the observed record as to whether individual plots were missing data, did not generate any runoff or were not measured in terms of runoff response because, for example, they were harvested prior to the other plots. Thus in the analysis of observed runoff trends a decision was made to only consider events where runoff data were generated for all plots. This may imply that only larger events are considered. The runoff observed for all considered events was summed for each season and plotted in Figure 2.2. To limit the number of treatments in the analysis of observed (this chapter) and simulated (Chapter 5) runoff responses at Cedara, the autumn plough CvT treatment was not considered in this study (maize cultivated for silage). Therefore all references to CvT at Cedara refer to the spring plough maize crop (maize cultivated for grain).

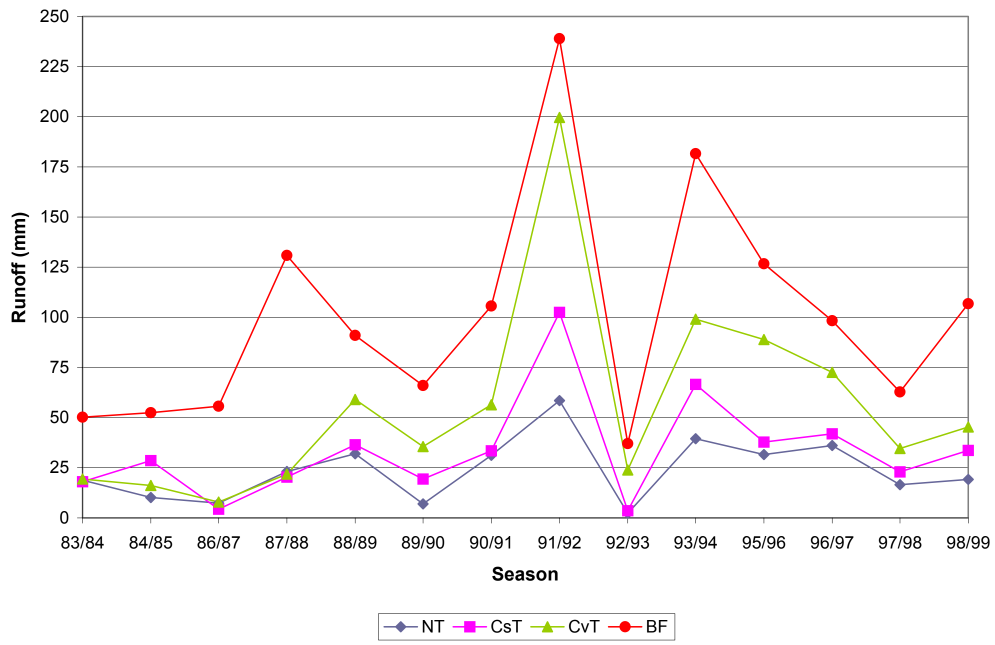

Figure 2.2 Observed seasonal runoff for maize under various tillage practices at Cedara

Figure 2.2 indicates that the responses of the various treatments is generally in the order: BF, CvT, Cst, NT (decreasing). The order of responses corresponds to the amount of mulch cover on the various plot treatments, i.e. a greater mulch cover leads to less runoff.

2.1.5 Rainfall erosivity project

During the course of the DESC runoff plot project, another related project was initiated. This project was entitled “Study of the Rainfall Erosivity Pattern of the Natal Region” (DESC Facet No. N5711/38/1/4). The objectives of the project were to develop an improved map of rainfall erosivity for KwaZulu-Natal, which could then be applied in the USLE for quantifying soil loss and for designing soil conservation structures. It was believed that a more accurate assessment of rainfall erosivity over the province was vital for calculations of soil loss to be useful, given that rainfall energy is an important driver in the erosion process.

The methodology proposed for the project was to:

- identify all known recording rain gauges in the province (operated by various organisations);
- negotiate to obtain the rainfall data from these organisations;
- extend the existing network of gauges to cover all important agronomic areas which have a high erosion potential; and
- prepare an updated rainfall erosivity map from the acquired data every five years.

The data from some 50 stations were acquired during the project, including data from the sites used in the runoff plot project. The data sets from both projects were originally stored together, and it was thus necessary to sort and collate both sets of data before the runoff plot project data could be used in this modelling study. The rainfall data from those sites that were not related to the runoff plot project were separated out and stored separately. These data included both raw and processed data. The data remain a valuable source of information for rainfall-related studies. They were used in the WRC project entitled “Regionalisation of Rainfall Statistics for Design Flood Estimation” (Project No. K5/1060) completed in 2002.

2.2 University of the Free State Data Set

The UFS runoff plot data were collected during a WRC project titled “Opgaring en Benutting van Reënwater in Grond vir die Stabilisering van Plantproduksie in Halfdroë Gebiede” (Bennie *et al*., 1994). The project was conducted over the period from 1988 to 1993 by the Department of Soil Science at the UFS under the leadership of Prof ATP Bennie.

2.2.1 Objectives and methodology of the original study

The UFS project arose out of a need to stabilise crop production in semi-arid regions, especially in dry years, through the development of sustainable dryland farming systems. The use of irrigation to stabilise crop production was considered to be increasingly less viable, given the increasing scarcity of water and the rising costs of establishing and operating irrigation systems.

The objectives of the study were as follows:

- the determination of the impact of different crop management and tillage practices on the soil water balance, where practices that are effective in the accumulation of water in the root zone form the focus;
- the determination of the efficiency of use of stored soil water in the above practices;
- the determination of the economic implications of the different practices; and
- the development of guidelines for maximising accumulation of rain water in soil, and the efficient use of this water in dryland crop production in semi-arid regions.

To achieve the objectives of the project an intensive study of the soil water balance under different crop management and tillage practices was carried out at four sites in the Free State Province. These sites were at Bloemfontein, Petrusburg, Hoopstad and Tweespruit (Figure 2.3). A combination of three tillage practices and six crop management practices was investigated, giving rise to a matrix of 18 treatments. The tillage practices comprised of no till, conservation tillage and conventional tillage. The crop management practices consisted of:

- *Practice 1*: A winter monocrop (wheat) which relied primarily on stored soil water as the sites were located in a summer rainfall region.
- *Practices 2–4*: A winter and summer crop rotation where one winter crop and one summer crop was grown every 3 years. Three combinations of this practice

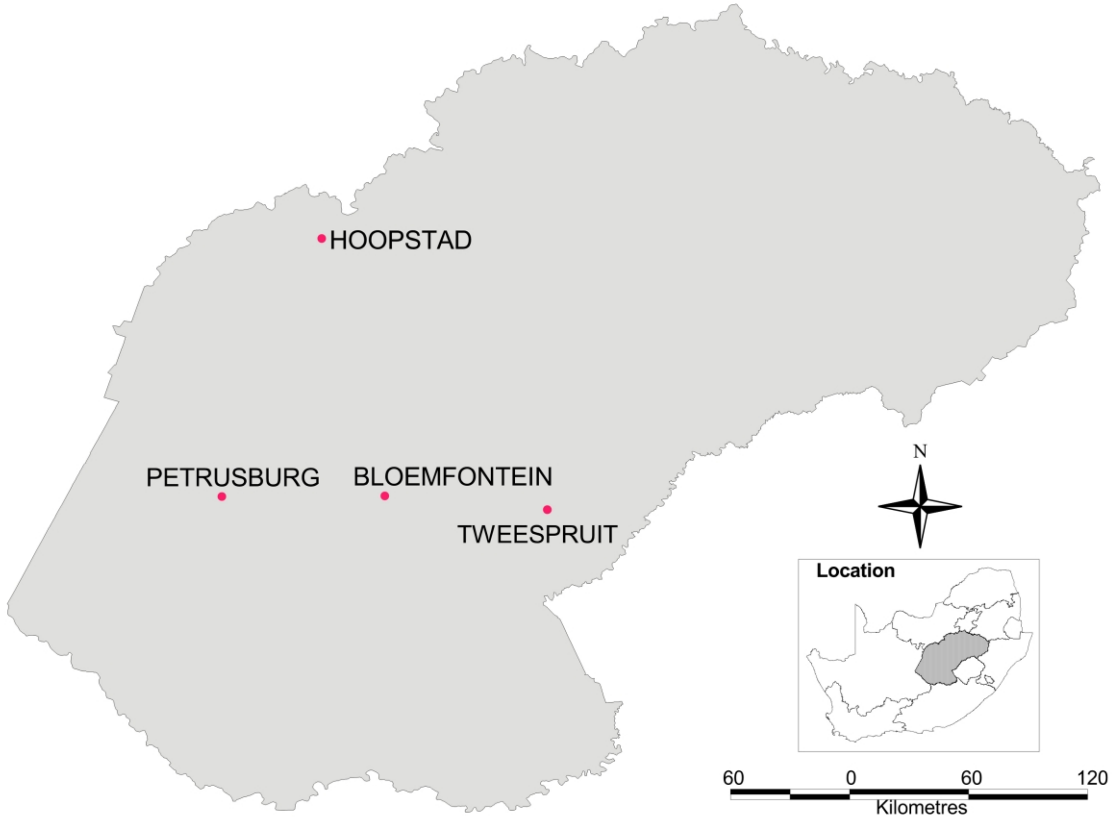

Figure 2.3 Locations of the UFS runoff plot sites in the Free State

with different lengths of time for soil water accumulation between crops, was implemented.

- *Practice 5*: A summer monocrop (maize, sorghum or sunflower) which grew during the wet season.
- *Practice 6*: A system where a crop (winter or summer) was planted whenever the plant available soil water exceeded 120mm in the potential root zone at planting time.

These crop practices were compared with reference conditions represented by pasture, climax veld and subclimax veld.

Measurements were made of the water balance and of soil and crop characteristics. These included runoff measurements, which were made on plots under natural and simulated rainfall conditions. These measurements were used in assessing the effect of the crop and tillage practices on the water balance and on crop production. The efficiency of water use of the various practices was then determined and expressed in economic terms. To develop guidelines for practical application of the research findings, the UFS project team decided that the results should be incorporated into a computer model, which could then be applied under a variety of climates, soils, crops and management practices. Progress was made in developing algorithms to calculate various components of the water balance. At the time the project report was written the study was reputed to be the most comprehensive quantification of the soil water balance under semi-arid conditions in South Africa.

2.2.2 Sorting and collating of data

A large amount of data was collected during the course of the UFS project and was stored in a well managed electronic database. A copy of the database was obtained from Prof Bennie during a visit to Bloemfontein. The approximately 600 data files were then converted from an outdated spreadsheet format to Microsoft Excel format. The files were initially stored on multiple 3½" disks and were consolidated to fit onto one compact disc with an appropriate directory structure to distinguish files representing different sites and tillage practices. Crop practices were denoted in the file names. Spreadsheet macros were then written to extract and condense the data relevant to this project into a form that would be suitable for verification studies with the *ACRU* model.

2.2.3 Description of the data set

To provide an overview of the UFS data set, Figure 2.4 shows the growth seasons of the different crops planted during the study for the various crop management practices and sites. The periods over which the veld and pasture reference conditions were monitored are also shown. The coloured blocks representing the growth seasons of the various crops are drawn in monthly increments. The exact calendar days of transition between cropped and fallow periods are indicated by numbers inside the blocks. For each crop, records were kept of the cultivar planted, the planting density, the plant population (except at Bloemfontein) and the fertilizer applied.

Each of the crop management practices shown in Figure 2.4 was implemented under NT, CsT and CvT tillage systems (as discussed previously). The management of the various tillage systems is outlined in Table 2.4.

Records were kept of the machinery used in the various tillage operations at the different sites, along with the operating costs incurred.

Soil profile descriptions were carried out at the four sites. The soils were classified as follows (SCWG, 1991):

Bloemfontein - Bainsvlei Amalia (Bv3200)
Petrusburg - Hutton Ventersdorp (Hu3200)
Hoopstad - Clovelly Mooilaagte (Cv3200)
Tweespruit - Westleigh Mareetsane (We2000).

Soil texture analyses were carried out at 300mm intervals to a depth of 3000mm (2400mm at Tweespruit). The slopes of the sites were 1.3% (Bloemfontein), 2.8% (Petrusburg), 0.5% (Hoopstad) and 1.9% (Tweespruit).

Details of the soil water balance and crop components that were measured at the various sites are presented in Table 2.5. In addition to the 2 weekly measurements of rainfall indicated in Table 2.5, rainfall was also measured on a continuous basis with tipping bucket raingauges at each site. However, the data derived from these gauges were of poor quality and were not utilised (Bennie, 2001; pers. comm.).

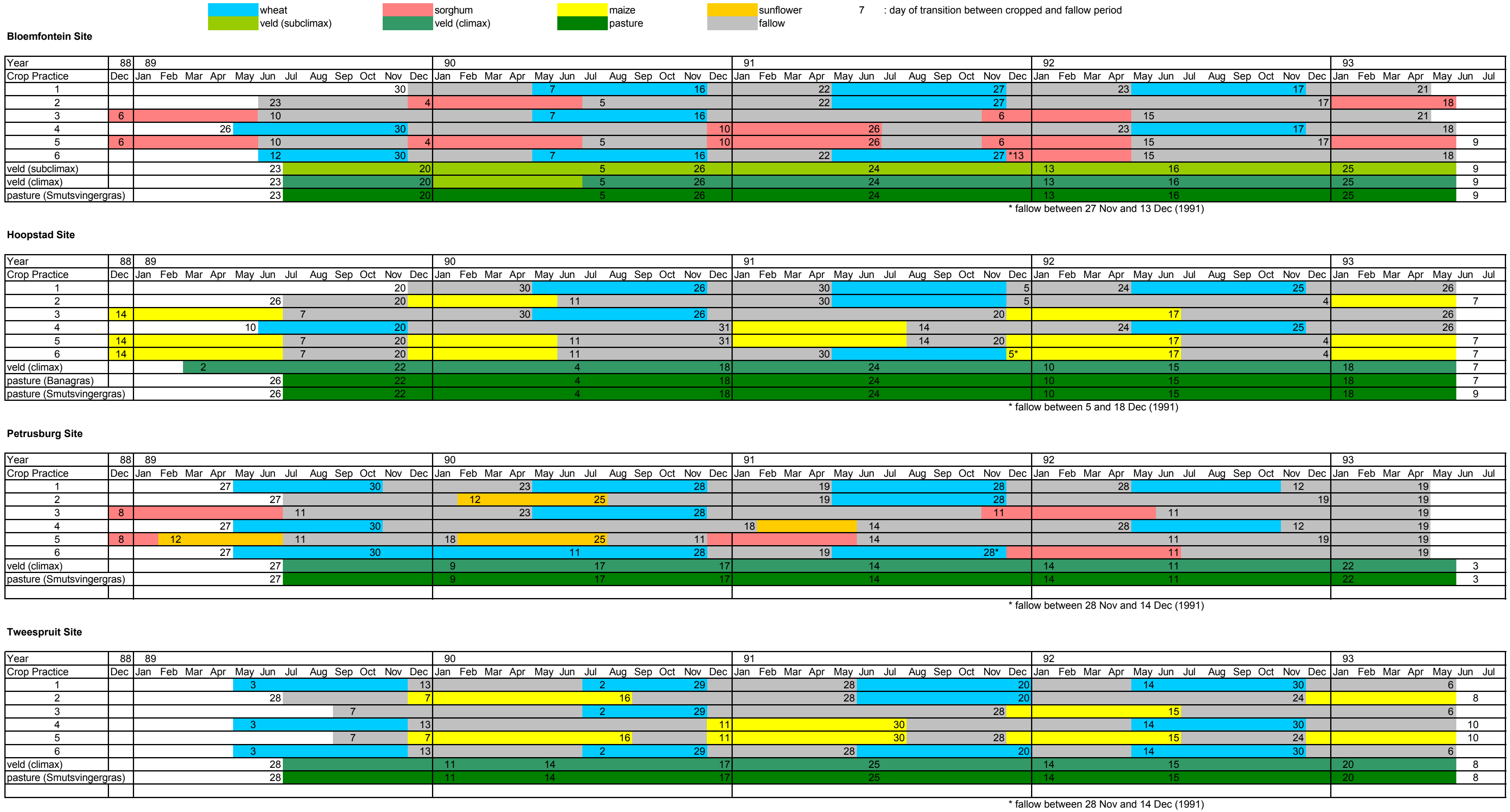

Figure 2.4 Growth seasons of crops planted in the UFS study

Table 2.4 Management of tillage practices in the UFS study

Tillage Type	Management
NT	Soil only disturbed during planting and fertilization which were carried out with a pneumatic planter. Weed control was carried out by chemical means via a spray boom mounted on a vehicle.
CsT	After harvest, the stalks of the crop were cut off from the roots using a chisel plough with sweeps (blade plough at Hoopstad), and then left on the surface to form a mulch. At Bloemfontein and Petrusburg, the same implement was used for weed control and final seedbed preparation, while at Tweespruit a tiller with sweeps was used. At Hoopstad, a rod weeder and blade plough was used for weed control. Before planting, the rows of tractor tracks were ripped to a depth of 650mm, after which a rod weeder was used for seedbed preparation.
CvT	Directly after harvest the crop residue and weeds were incorporated into the soil to a depth of 150mm using a tandem disc. During February/March the fields to be planted to winter crops were mouldboard ploughed, while those to be planted to summer crops were ploughed with the same implement in October/November. The soil was only ploughed when the soil moisture was such that stable clods would be produced. At all sites weed control and seedbed preparation were carried out using the same implements used in the CsT practice.

To characterise the soil water balance further, deep percolation was estimated using a relationship dependent on soil moisture, while total evaporation, being the remaining variable to be quantified in the water balance, was estimated as the balance of the other components.

Table 2.5 Soil water balance and crop variables measured in the UFS study

Variable	Measurement Frequency
rainfall	2 weekly
runoff (under natural rainfall)*	2 weekly (cropped), monthly (fallow)
field soil moisture (neutron probe)	2 weekly (cropped), monthly (fallow)
crop characteristics	
total above ground biomass	seasonal
crop yield	seasonal
leaf area index	5 times/season (different growth stages)
root development	5 times/season (different growth stages)

The runoff measurements under natural rainfall indicated in Table 2.5 were only made at the Bloemfontein and Tweespruit sites, as runoff seldom occurred at the Hoopstad and Petrusburg sites. The runoff plots were designed so that two rows of the summer crops could fit into the plots across their width. At Bloemfontein the plots were 2.7m wide and 2.04m long, while at Tweespruit they were 1.8m wide and 2.78m long. The sides of the plots were made of galvanised sheeting that was driven

100mm into the ground and that extended 200mm above the surface. A pipe of 100mm diameter led the runoff water at the lower end of the plot into a 210 litre drum that was sealed to prevent evaporative losses. The amount of runoff after rainfall was determined by pumping the water out of the drum.

In a separate set of measurements, the infiltration/runoff characteristics induced by the different tillage practices were measured at all the sites under conditions of simulated rainfall. The measurements were taken on 1m^2 plots during fallow periods in crop practices 2 to 4. The plots were demarcated by a hollow steel frame of dimensions 1m by 1m, that was driven 100mm into the ground. Runoff from the plots was measured at regular five minute intervals by way of a pipe that led the runoff water from the lowest point of the plot to a container underground. A rainfall simulator based on those of Meyer and Harmon (1979) and Claassens and Van der Watt (1993) was used to apply rainfall at a certain intensity on the soil when in a dry state (directly after harvest), and then 24 hours later when in a wet state (at the same intensity). At the start of the second storm the soil moisture content was assumed to be at drained upper limit. Storms of three different intensities were simulated for both wet and dry conditions. The procedure was repeated after each stage of tillage outlined in Table 2.4 for the various tillage systems.

The following variables were measured for each storm in the rainfall simulator experiment:

- application rate
- surface cover
- bulk density
- initial soil water content
- sorptivity
- time to runoff commencement
- time to final infiltration rate and
- final infiltration rate.

In a further exercise, the evaporation of water from the soil was measured at the various sites for different tillage practices. The objective of these measurements was to assess if differences in mulch cover and topsoil porosity, as induced by different tillage practices, result in differences in evaporation from the soil, leading to possible increases in soil moisture storage and improved crop yields under certain practices. The responses of three variations of CvT, and two variations of CsT, were compared with a single NT system. The variations in the systems were designed to represent different degrees of soil disturbance. Micro-lysimeters were used to measure evaporation from the soil. In one experiment, lysimeters were wet to drained upper limit and then allowed to dry out, while in another experiment the lysimeters were wet up and then periodically exposed to artificial rainfall. The lysimeters were weighed at intervals ranging from several hours to several days, depending on whether they had been recently exposed to rainfall. Measurements were carried out for a total period of approximately 60 days.

The Bloemfontein site was well maintained by project staff at the UFS. The wheat monocrop (crop practice 1) at this site had consistent plant and harvest months throughout the experiment, which would make it simple to represent in the *ACRU* model. It is for these reasons that the wheat monocrop runoff plots at Bloemfontein (incorporating NT, CsT and CvT under natural rainfall) were selected for analysis in the runoff modelling in Chapter 5. In the following section the runoff data collected from these plots are analysed for trends.

2.2.4 Trends in runoff from the Bloemfontein wheat monocrop plots

For reasons discussed previously, attention was focussed at the seasonal time scale in analysing runoff trends on the UFS plots. Runoff was summed for each season, including the fallow seasons, and plotted in Figure 2.5. The naming convention adopted to identify seasons was as follows:

- fallow seasons, which spanned two calendar years (summer period), were prefixed with an F and followed by the years concerned e.g. F89/90; and
- wheat seasons, which fell over winter during a single calendar year, were prefixed with a W and followed by the year concerned e.g. W90.

Figure 2.5 indicates that the responses of the various treatments is generally in the order: NT, CsT, CvT (decreasing runoff). Bennie *et al*. (1994) concluded that the amount of mulch cover on the NT and CsT treatments was ineffective in reducing runoff relative to CvT, and that runoff was dependent more on the degree of soil disturbance, which improved the infiltrability of the soil. On average, the amount of mulch cover on the treatments at the beginning of a season was 52%, 18% and 3% for the NT, CsT and CvT treatments respectively. These averages were based on mulch cover data collected taken during the representation of different rainfall

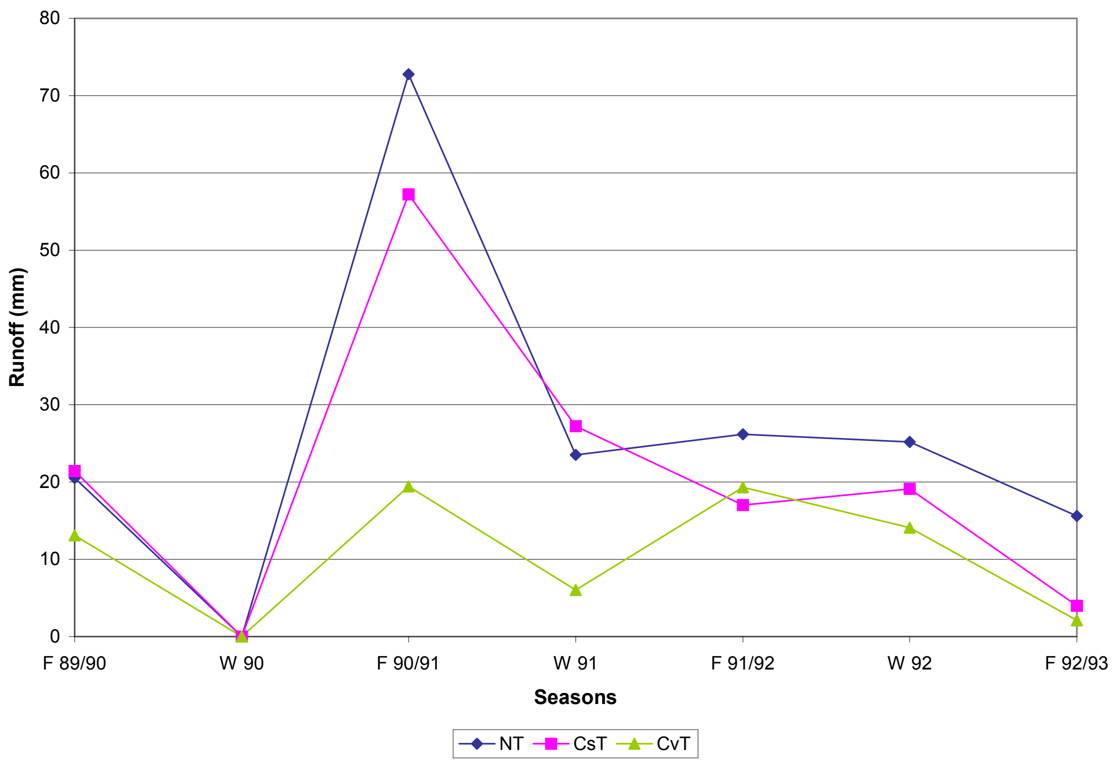

Figure 2.5 Observed seasonal runoff for the wheat monocrop practice under various tillage systems at Bloemfontein

application intensities in the rainfall simulator measurements at Bloemfontein (Bennie *et al*., 1994).

The results of the rainfall simulator experiment revealed that application intensity, with the exception of the lowest intensity applied (60mm/h), had more influence on infiltration/runoff characteristics than the tillage practices. This was ascribed to the very high intensities that were applied (up to 192mm/h). It is believed that rainfall intensities of these magnitudes will occur very seldom, and thus the trends in runoff observed under the simulated rainfall will not be considered further in this study.

2.3 South African Rainfall Simulator Programme Data Set

The SARSP (McPhee *et al*., 1983) was initiated in 1980 under the auspices of the Division of Agricultural Engineering. It provided the stimulus for launching the DESC project (Section 2.1). The SARSP involved performing rainfall simulator tests in numerous areas around the country. The runoff plot variables measured in the Programme allowed for the quantification of initial abstractions before stormflow commencement, where these abstractions consist of losses due to interception, initial infiltration and depression storage. In this section, an analysis of the SARSP data was performed with the aim of improving the simulation of initial abstractions in the *ACRU* model. The traditional approach to representing initial abstractions in the model (by way of a coefficient) is described in Chapter 3. Schulze (1995) suggested that this approach might be improved if relationships could be identified that allow for initial abstractions to be predicted directly as a physical quantity in millimetres, rather than by way of a coefficient. The ability to quantify initial abstractions from the SARSP data, and the large number of sites in the experiment, led to the hypothesis that a suitable generalised relationship to predict initial abstractions might be found.

2.3.1 Objectives and methodology of the original study

The objectives of the SARSP were to:

- assess the extent of soil and runoff losses from arable land under varying levels of mulch and crop cover;
- indicate areas of high erosion potential in the country; and
- generate local input data for use in a soil loss equation.

The motivation for launching the SARSP originated from similar concerns to those discussed in Section 2.1 (DESC project), namely the large losses of soil from arable land in South Africa. Prevention of soil loss was seen to be an integral part of conserving agricultural resources for optimal production. It was believed that soil conservation techniques involving the use of soil loss equations, which have been developed in other countries, could be applied in South Africa using local input data.

Experiments involving measurement of runoff from plots under natural rainfall were considered to be time consuming, and generally only allowed for the collection of a limited number of variables. The use of rainfall simulators to apply simulated rainfall to runoff plots was seen as a method of confirming the results from natural rainfall experiments. Simulated rainfall experiments also had the advantage of allowing for the collection of a much wider range of soil loss related variables under controlled conditions (McPhee *et al*., 1983).

A portable rainfall simulator was used in the experiments. This allowed the project team to travel around the country to many different sites to measure soil and runoff losses. The rainfall simulator used was a rotating-boom type simulator similar to the one developed by Swanson (1965). The nozzles used were developed by Meyer and McCune (1958) to approximate the drop size distribution of natural rainfall in the Eastern USA. The drop size distribution and terminal velocity of the drops upon reaching the ground combined to give a rainfall energy which was approximately 75% of that of natural rainfall, leading the researchers involved to conclude that the simulated rainfall could be used as an approximation of natural rainfall conditions.

Four runoff plots representing different mulch and crop conditions were prepared in the soil below the rainfall simulator at each site. In most cases one of these plots represented a reference condition, where this plot consisted of bare soil tilled in a standard manner. Corrugated iron sheeting was used to form the borders of the plots to prevent water moving into and leaving from the plots. At the lowest end of the plots a sill plate was inserted into the soil to prevent subsurface flow and to provide a surface for placing a collection chute for capturing runoff water. The plot dimensions were 10.67m by 1.8m, except in the case of pineapple plots where the width of the plot corresponded to the ridge spacing of 1.3m.

Two one-hour simulated storms separated by a 24-hour period were applied to the runoff plots at an intensity of approximately 63mm/h. The first storm represented dry conditions while the second storm represented conditions at drained upper limit. Water samples were taken at regular intervals during the tests to assess sediment concentration and then combined with runoff hydrographs to give total soil loss.

Before each rainfall simulator test, soil samples were taken to provide information relating to soil texture, organic matter, soil structure and permeability, which then enabled predictions of soil erodibility to be made from the nomograph of Wischmeier *et al*. (1971). The predicted erodibility was then compared with measured erodibility, where this is defined as the soil loss per unit of rainfall erosivity from a standard bare reference plot of 9% slope and 22.13m slope length. As the reference plots in the SARSP did not conform to these size and slope specifications, the measured soil loss had to be adjusted accordingly before determining erodibility.

2.3.2 Description of the data set

In McPhee *et al*. (1983), data were tabulated for 178 runoff plots representing different site and treatment combinations. A description of the different treatments and the associated number of runoff plots appears in Table 2.6.

The majority of these runoff plots did not have crops growing in them at the time measurements were taken. The runoff plots were set up at about 97 sites, and were mostly situated in wheat lands in the Western Cape Province, maize lands in the KwaZulu-Natal and North West Provinces and in pineapple lands in the Eastern Cape Province. The reference treatments described in Table 2.6 are the closest representation of conventional tillage, as defined previously in this report, while the mulched treatments best represent conservation tillage. The plots having high levels of mulch would begin to represent NT from a mulch perspective, but not from a soil disturbance perspective. The undisturbed mulch and canopy treatments provide the best representation of NT. Mulched conditions in the SARSP were mostly represented by placing residues on the soil surface by hand. However, this is not a good representation of mulched conditions under normal CsT and NT conditions, as the mulch would not have had time to "bond" with the soil surface (over several seasons), and would thus have been far less effective than mulch attained through normal CsT and NT practices (Russell, 2002; pers. comm.).

Table 2.6 Description of runoff plot treatments in the SARSP study

Treatment	Description	Approximate Number of Runoff Plots
Reference	Bare soil plot tilled up and down the slope with tillage implements normally used in the area to create a suitable tilth and seedbed for a specific crop	89
Mulched*	Tilled in the same manner as reference plots. Surface mulch placed by hand on the soil to represent different levels of surface cover	40
Undisturbed mulch	No tillage action applied to the soil prior to simulated storm	2
Undisturbed canopy	Crop growing in undisturbed soil	5
Undisturbed veld	Not explained	1
Seedbed: ridge & furrow	Bare seedbed prepared by a tine implement leaving ridges and furrows	3
Ridged	Ridged lands for pineapple production having a bare soil surface	36
Ridged (minimum till)	Ridged land for pineapple production where a pineapple residue mulch is left on the soil surface	2
	Total	178

* In 3 cases mulch was not applied by hand, but derived from a mulch till practice

The variables that were measured on the runoff plots included the following:

- slope
- cover (surface or canopy)
- stone mulch cover
- soil texture and organic matter content (reference plots)
- application intensity (measured for first and second storms)
- runoff (")
- soil loss (")
- time to runoff commencement (").

Canopy cover was measured in cases where a crop was growing in the soil at the time of measurement. Application intensity was tabulated because, although an attempt was made to keep the intensity as close to 63mm/h as possible, in practice there was a fairly large range in intensities observed (36mm/h).

The following information relating to the runoff plots was also noted in McPhee *et al*. (1983):

- soil type
- crop history
- plot treatment
- type of cover (surface or canopy)
- soil structure code (as defined in Wischmeier *et al*. (1971) for reference plots)
- soil permeability code (").

The data collected during the runoff plot measurements enabled the calculation of initial abstraction amounts and average infiltration rates for both first and second storms, where:

$$I_a = I * t$$

where I_a = initial abstractions (mm)
I = application intensity (mm/h)
t = time to runoff commencement (h)

$$\bar{f} = I - \bar{q}$$

where $\bar{f}$ = average infiltration rate (mm/h)
$\bar{q}$ = average runoff rate (mm/h).

As the length of a simulated storm was one hour, the average runoff rate was simply equal to the depth of runoff (in mm) recorded during that hour.

2.3.3 Trends in initial abstractions

In analysing the SARSP data for trends in I_a, the relationships between I_a and several influencing factors were investigated. These included application intensity, slope, total cover and soil organic matter content. Total cover in this context consisted of the total of the surface mulch cover, the canopy cover and the stone mulch cover (where appropriate). Organic matter was only tabulated in McPhee *et al*. (1983) for the reference plots, as this variable was used in predicting soil erodibility for comparison with measured erodibility. Graphs plotted of I_a versus application intensity, slope and total cover are given in Figures 2.6, 2.7 and 2.8, respectively, but excluding the data from the ridged pineapple lands. These data were excluded as the ridging practice employed was quite different to the tillage practiced on other plots in the Programme, and would have complicated the interpretation of results. The data from reference plots (non-ridged) in the pineapple lands were, however, still considered in the analysis. The data for the first and second storms were plotted separately owing to the strong influence that antecedent moisture had on the results.

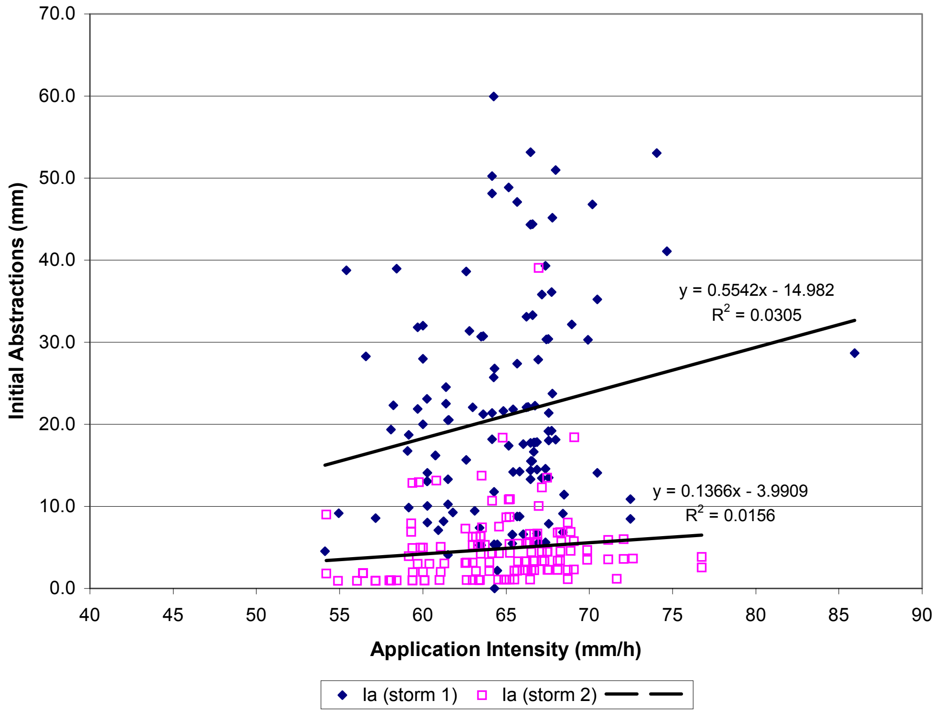

Figure 2.6 Plot of I_a versus application intensity based on runoff plot data from the SARSP

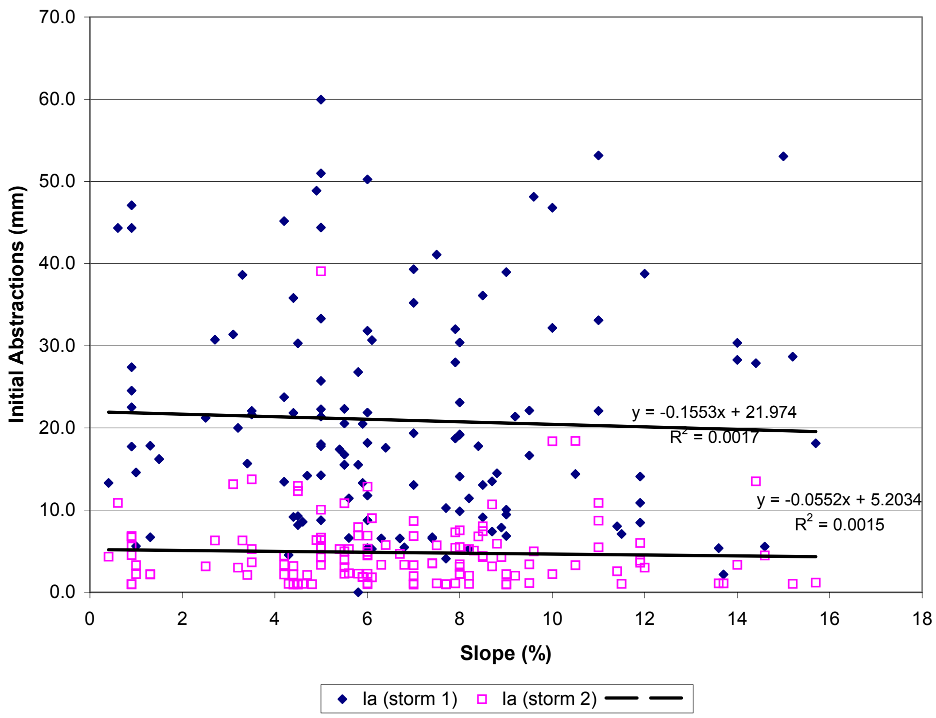

Figure 2.7 Plot of I_a versus slope based on runoff plot data from the SARSP

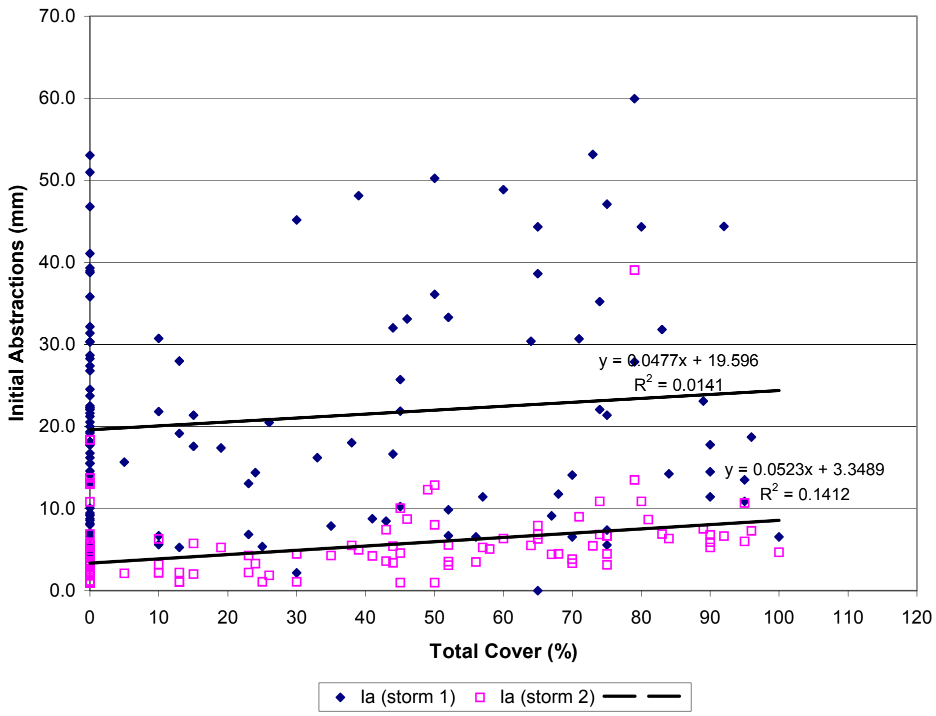

Figure 2.8 Plot of I_a versus total cover based on runoff plot data from the SARSP

The graphs indicate no trends between I_a and application intensity, slope or total cover, whether for the first or second storm. The lack of a trend in Figure 2.8 implies that plotting mulch practices separately would not yield a trend. A marked distinction between first and second storm data points was evident in all graphs. For field conditions at drained upper limit (second storm), the I_a amount observed was under 20mm in almost all cases.

To assess if soil type was a strongly influencing factor, additional sets of graphs were plotted (I_a versus application intensity, slope and total cover), where only single soil types were represented in each graph. Weak trends were found for some soils, while other soils yielded no trends. The presence of trends, or lack thereof, was not consistent for particular soil types when considering different variables and storms. Owing to this inconsistency, the limited number of soils represented and the desire to find generalised relationships, these sets of graphs are not presented in this report.

Figure 2.9 is a plot of I_a versus organic matter for all reference plots. A weak trend exists for the first storm while for the second storm there is no trend.

McPhee *et al*. (1983) concluded that soil loss was affected by many factors other than those prevailing at the sites on the day of testing. These factors included crop and tillage history, rainfall regime and antecedent soil moisture. These factors would have also affected runoff. The large number of sites and the different times of the year over which tests were performed would have further contributed to the high variability in runoff and soil loss results. This variability poses a problem when attempting to identify trends in the hydrological response of the runoff plots. For the

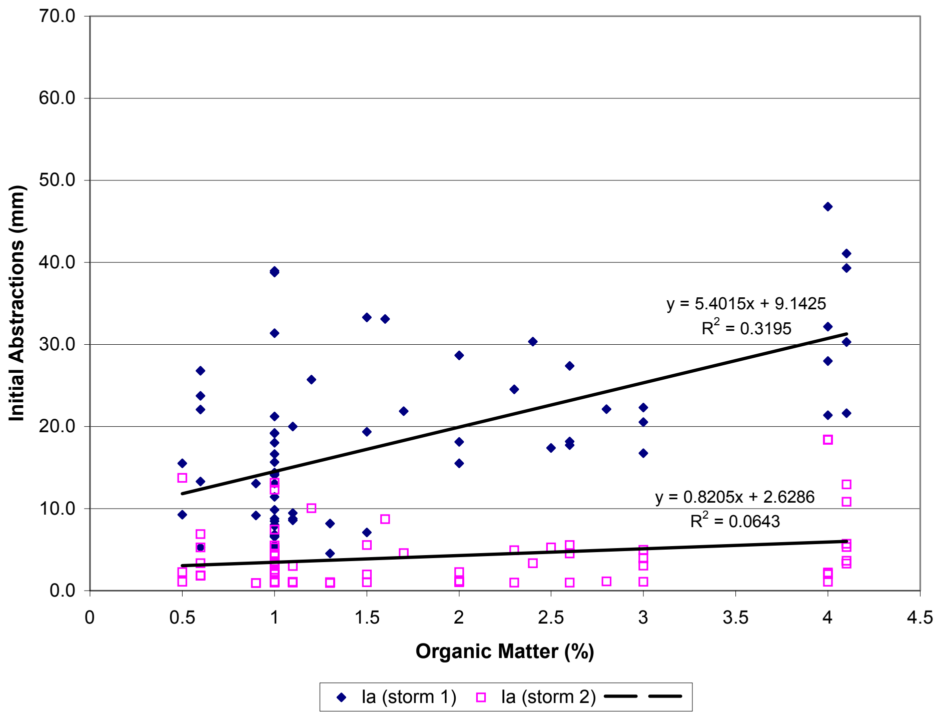

Figure 2.9 Plot of I_a versus organic matter based on runoff plot data from the SARSP

purpose of finding generalised relationships to predict I_a, the data set would have been more useful had fewer sites been used, and more extensive tests been performed of the factors effecting hydrological response. For example, at a particular site, a range of application intensities, slope (if present), cover, organic matter and soil moisture content could have been tested. The clear distinction between first and second storm results indicates that testing a range in soil moisture content may, in particular, have yielded useful results.

The original intent of analysing the SARSP data set was to improve the modelling of I_a in the *ACRU* model, through identifying potential predictive relationships in the runoff plot data. As no suitable relationships could be found in the data set, this approach could not be pursued further. A refinement of the traditional approach to modelling I_a was implemented therefore, and is discussed in Chapter 4.

In this chapter various observed data sets from different studies have been examined and synthesised. The DESC and UFS data sets will be used in the effort to improve the simulation of land use impacts on runoff (Chapter 4). In the following chapter, a condensed background to the *ACRU* model is given. This theory is given to better facilitate understanding of the modelling approach adopted in Chapter 4.

3 BACKGROUND TO THE *ACRU* MODEL

ACRU is a daily time step, conceptual-physical and multipurpose agrohydrological model, with the capability to simulate numerous variables of interest (e.g. daily streamflow, seasonal crop yields), either at a specific location, or for a catchment. The model revolves around multi-layer soil water budgeting, and is structured to be hydrologically sensitive to catchment land uses and management strategies, and changes thereof (Schulze, 1995).

In this chapter, a brief overview of the model input and output is first presented. The processes that are represented in the model are then discussed. Particular reference is made to the runoff generating mechanisms, as these processes are a key focus in this project. For a more comprehensive description of the model and its applications the reader is referred to the model documentation (Schulze, 1995; Smithers and Schulze 1995, Schulze and Smithers, 2002).

3.1 Overview of Model Input and Output

The *ACRU* model requires ***INPUT*** of known, or measurable, or derivable, factors including data/information on:

- *climate* (e.g. daily rainfall, maximum and minimum temperature, reference potential evaporation)
- *soils* (e.g. horizon thicknesses, soil water retention at critical soil water contents, saturated drainage rates)
- *land uses* (e.g. crop types, levels of management, planting dates, growth rates, above-and-below-ground vegetation attributes at different growth stages)
- *soil water budgeting* (e.g. onset of plant stress, degrees of stress, capillary movement)
- *runoff producing mechanisms* (e.g. stormflow generation, baseflow rates, impervious areas)

and, where appropriate, information on:

- *irrigation practices* (e.g. crop type, above-and-below-ground attributes at different growth stages, modes of scheduling and their controls, source of water, application efficiencies) and, where relevant, information on
- *dams* (e.g. inflows, full supply capacities, surface areas, evaporation rates, releases, abstractions and inter-basin transfers) or
- *other abstractions* (e.g. domestic, livestock by amount, season and source of water).

This information is ***TRANSFORMED*** in the model by considering:

- the climate, soil, vegetative, hydrological and management *subsystems*
- how they *interact* with one another
- what *thresholds* are required for responses to take place
- how the various responses are *lagged* at different rates and
- whether there are *feedforwards* and *feedbacks* which allow the system to respond in a positive or reverse direction.

The model then produces ***OUTPUT*** of the unmeasured variable to be assessed, such as:

- *streamflow* (e.g. from different parts of the catchment, including stormflow and baseflow on a daily basis and low flow which can be accumulated)
- *crop yield* (e.g. per season, annum or growth cycle; dryland or irrigated; and where relevant, with economic analysis)
- *irrigation water requirements* (gross or net requirements; associated crop yields; deep percolation and stormflow from irrigated areas ; water use efficiencies under different modes of scheduling water for irrigation; analysis of incremental benefit of applying irrigation vs dryland farming)
- *peak discharge*
- *sediment yield* (event-by-event for the pertinent hydrological, soil, slope, plant cover and management conditions) or
- *total evaporation* (comprising of transpiration and soil water evaporation at both potential and actual rates).

All of the above may be output with a risk analysis (e.g. month-by-month and annual statistics under median conditions and for, say, driest and wettest years in 10 or 20 years; flow variability or extreme value analysis).

3.2 Processes Represented in the Model

The *ACRU* model revolves around multi-layer soil water budgeting as depicted in Figure 3.1. That rainfall and/or irrigation application not abstracted as interception or as stormflow (either rapid response or delayed), first enters through the surface layer and "resides" in the topsoil horizon. When that is "filled" to beyond its drained upper limit (field capacity) the "excess" water percolates into the subsoil horizon(s) as saturated drainage at a rate (represented by a parameter known as ABRESP) dependent on respective horizon soil textural characteristics, wetness and other drainage related properties. Should the soil water content of the bottom subsoil horizon of the plant root zone exceed the drained upper limit, saturated vertical drainage/recharge (controlled by a parameter known as BFRESP) into the intermediate and eventually groundwater stores occurs, from which baseflow may be generated at an exponential decay rate dependent on geological/aquifer characteristics and the groundwater store. Unsaturated soil water redistribution, both upwards and downwards, also occurs, but at a rate considerably slower than the water movement under saturated conditions, and is dependent, *inter alia*, on the relative wetnesses of adjacent soil horizons in the root zone.

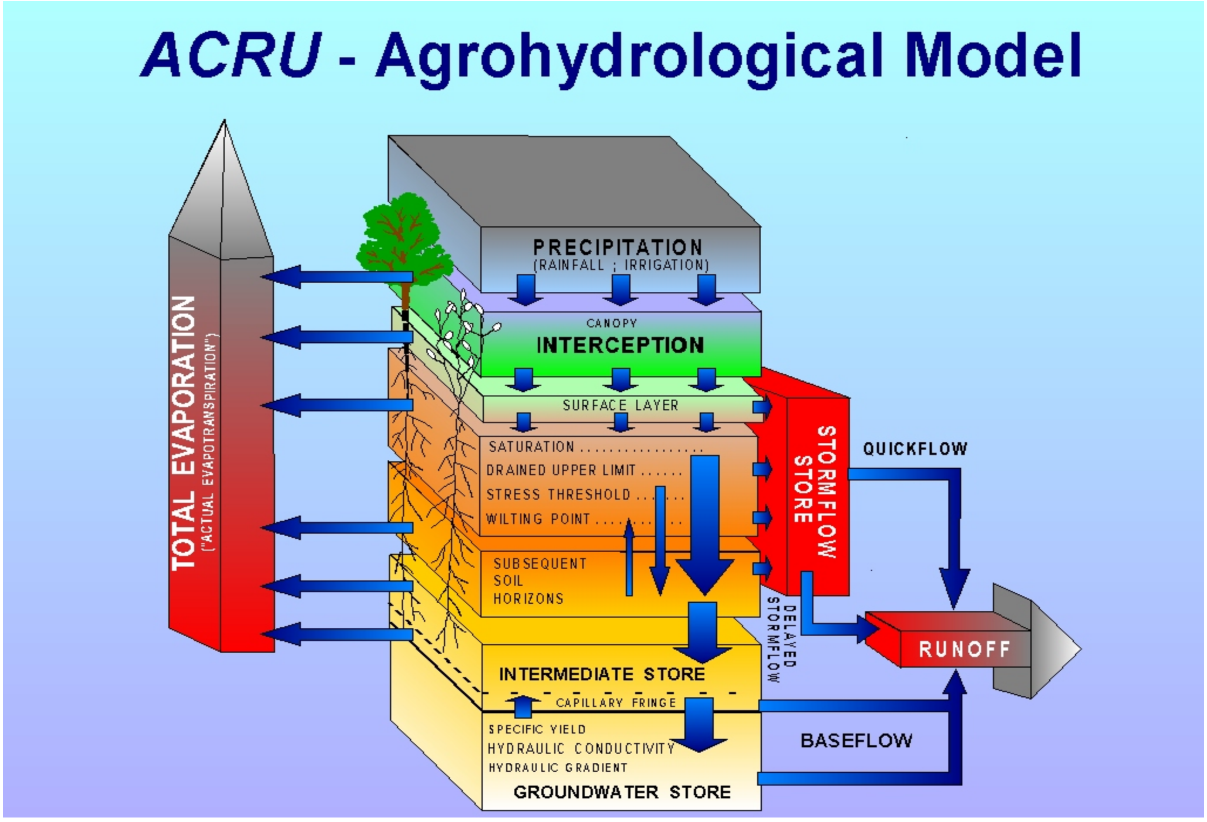

Figure 3.1 Structure of the *ACRU* model (Schulze, 1995)

Evaporation takes place from water previously intercepted by the crop's or vegetation's canopy, as well as simultaneously from the various soil horizons, in which case it is either split into separate components of soil water evaporation (from the topsoil horizon only) and plant transpiration (from all horizons in the root zone), or combined, as total evaporation. Evaporative demand on the plant is estimated, *inter alia*, according to atmospheric demand (through a reference potential evaporation) and the plant's stage of growth. The roots absorb soil water in proportion to the distributions of root mass density within the respective horizons (represented by variables ROOTA and ROOTB), except when conditions of low soil water content prevail, in which case the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

It is vital in land use and crop yield modelling to determine at which point in the depletion of the plant available water reservoir plant stress actually sets in, since stress implies a soil water extraction below optimum, the necessity to irrigate (if irrigation is applied) and also implies a reduction in crop yield. In modelling terms, this problem may be expressed as the critical soil water content at which total evaporation, E (formerly termed "actual evapotranspiration"), is reduced to below the vegetation's maximum evaporation, E_m (formerly termed "potential evapotranspiration"). E equals E_m until a certain fraction of maximum (profile) available soil water to the plant, TAM, is exhausted. Research shows that the critical soil water fraction at which stress commences varies according to atmospheric demand and the critical leaf water potential of the respective vegetation, the latter being an index of the resilience of the vegetation to stress situations. The implications of stress setting in at such different levels of soil water content are significant in terms of total crop evaporation, crop production modelling and irrigation scheduling.

The generation of stormflow in *ACRU* is simulated using a modified SCS (United States Department of Agriculture, 1985) approach which is based on the premise that, after initial abstractions (through interception, depression storage and infiltration before runoff commences), the runoff produced is a function of the magnitude of the rainfall and the soil water deficit from a critical response depth of the soil. In equation form stormflow is calculated as follows:

$$Q = \frac{(P_g - I_a)^2}{P_g - I_a + S} \text{ for } P_g > I_a$$

where Q = stormflow depth (mm)
P_g = gross daily precipitation amount (mm)
I_a = initial abstractions (mm) before stormflow commences, consisting mainly of interception, infiltration and depression storages
S = potential maximum retention (mm), which is equated to a soil water deficit.

In order to eliminate the necessity of estimating both I_a and S, I_a may be expressed in terms of S by the empirical relationship

$$I_a = cS$$

where c = regression coefficient, in this context commonly referred to as the coefficient of initial abstraction.

The stormflow equation thus becomes

$$Q = \frac{(P_g - cS)^2}{P_g + S(1 - c)}$$

In the model software, c is represented by the parameter COIAM (Coefficient of initial abstraction), for which a value must be input for each month of the year. It is dependent on vegetation, site and management characteristics. The default value of the coefficient suggested in Schulze (1995) is 0.2. The coefficient can increase to (say) 0.3 or 0.4 immediately after ploughing when surface roughness is high, or under forested conditions, and reduce to (say) 0.05 or 0.15 under conditions of soil compaction or in peri-urban situations. Schulze *et al*. (1984) related the coefficient to physiographic factors (catchment area, slope, stream order, drainage density) and climatic factors (rainfall amount, intensity, duration and antecedent soil water status) with multivariate equations. These gave regionally improved estimates of stormflow but no universally applicable equation for COIAM was found. Schulze (1995) alluded to relating initial abstraction *amounts* (rather than a *coefficient* of S) to vegetation and rainfall intensity variables as a future approach in the *ACRU* model. In the previous chapter, an attempt was made to develop relationships to predict initial abstraction amounts for tilled conditions based on runoff plot data from the SARSP.

The soil water deficit antecedent to a rainfall event (S) is simulated by *ACRU*'s multi-layer soil water budgeting routines on a daily basis. It is taken as the difference between water retention at porosity and the actual soil water content just prior to the rainfall event. The deficit is calculated over the depth of soil that is critical (effective) in generating stormflow, represented in the model by the variable SMDDEP. SMDDEP has been found to depend, *inter alia*, on the dominant runoff-producing mechanism. This depth is therefore (generally) shallow in more arid areas characterised by eutrophic (i.e. poorly leached and drained) soils and high intensity storms which would produce predominantly surface runoff, and is generally deeper in high rainfall areas with dystrophic (highly leached, well-drained) soils where interflow and "push-through" runoff generating mechanisms predominate. Based on experience with *ACRU* simulations, Schulze (1995) suggested a matrix of SMDDEP values for different climatic, vegetation and soils characteristics, as depicted in Figure 3.2.

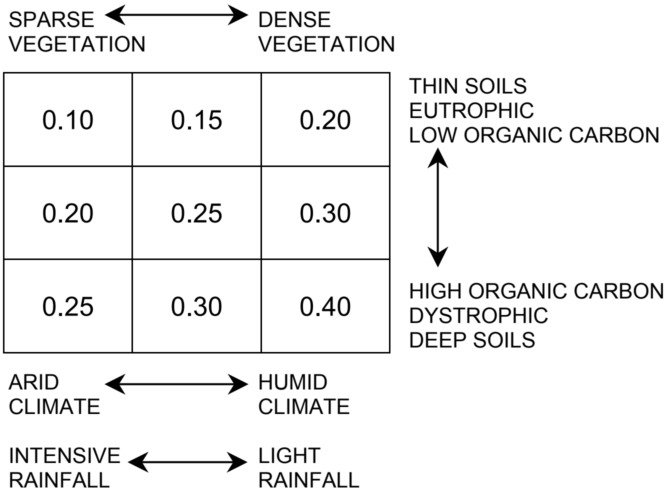

Figure 3.2 Suggested values of the critical stormflow response depth (SMDDEP) according to climatic, vegetation and soils characteristics (Schulze, 1995)

Not all the stormflow generated by a rainfall event is same-day response at a catchment's outlet; stormflow is therefore split into quickflow (i.e. same-day response) and delayed stormflow (Figure 3.1), with the "lag" (which may be conceptualised as a surrogate for simulating interflow) dependent, *inter alia*, on soil properties, catchment size and the drainage density. Soils with a high interflow potential would respond rapidly, as would small and/or steep and/or urbanised catchments when compared with relatively larger ones and/or catchments with gentler gradients or dense land cover, where infiltrability is high and lateral flow occurs more slowly. The stormflow response fraction (QFRESP) is used in the model to specify the amount of stormflow that will run off a catchment on the same day as the rainfall event. The remaining stormflow is “retained” to the next day when the same fraction of the remaining stormflow is discharged into the channel. The QFRESP parameter, which acts as a decay function, only controls the timing of stormflow over one or several days and not the total amount of stormflow, which is calculated initially at the time of the causative rainfall event.

By virtue of their size and design, the runoff measured from a runoff plot is likely to comprise only of surface runoff. Quickflow, as simulated by the *ACRU* model, comprises of runoff that leaves the catchment on the same day as the rainfall event. It is likely to include surface runoff, but not exclusively so, as some areas will be characterised by rapid interflow that also leaves the catchment on the same day. Quickflow is the component of flow simulated by *ACRU* that best represents the runoff observed from a runoff plot. Therefore, as alluded to in the introduction to this report, the term “runoff” in this study will refer to surface runoff in the context of runoff plots, and quickflow in the context of simulation results. It is considered justifiable to regard simulated quickflow as representative of observed surface runoff from a runoff plot, as the goal in modelling tillage practices in this study is not to simulate absolute runoff values, but rather the relative sequences and orders of magnitude of runoff from different practices. These sequences and orders of magnitude should be the same whether one considers quickflow or surface runoff.

In this chapter, some background theory to the *ACRU* model has been provided. In the following chapter the modelling of runoff plot data from the DESC and UFS projects will be presented.

4 REPRESENTATION OF TILLAGE IN THE *ACRU* MODEL

In attempting to model the impact of tillage on runoff, it is necessary to consider how tillage affects relevant hydrological processes. This chapter begins by considering these effects. Following this, the approach to represent tillage in the *ACRU* model is presented.

4.1 Influence of Tillage on Hydrological Processes

The typical operations carried out during CvT, CsT and NT systems will be discussed before considering the influence of tillage on hydrological processes.

Typically, CvT systems involve an aggressive working of the soil resulting in complete inversion of the soil clods, such as that produced by a mouldboard plough. Plant residues remaining on the soil surface (after any grazing) are cut up and incorporated into the soil. With CsT systems, the primary tillage implement is usually a chisel plough, which cuts into the soil, resulting in only partial inversion of the clods. This results in some surface residues being left on the surface. The grooves cut by the chisel plough can improve infiltration into the soil. Both CvT and CsT systems will usually require the seedbed to be brought to a finer condition, typically with the use of a harrow implement. Under NT systems, the only (minimal) disturbance of the soil occurs during planting, which is usually carried out with the use of a pneumatic drill planter. Weed and pest control under NT (and sometimes CsT) systems, is carried out by chemical means to avoid disturbance of the soil.

A generalised table of the soil properties affected by tillage and the hydrological processes implicated, is presented below (Table 4.1).

Table 4.1 Generalised table of the soil properties affected by tillage and the implicated hydrological processes

Soil Properties Affected by Tillage	Hydrological Processes Implicated
mulch cover and organic matter content	interception infiltration evaporation
surface roughness and crusting	infiltration surface detention evaporation
pore characteristics and structure	moisture retention redistribution and drainage transpiration
impeding layers (plough pan)	drainage infiltration

Under a NT system, mulch cover, and thus organic matter content near the surface, will be high. This results in increased interception and a tendency to improve infiltration. Evaporation from the soil surface is suppressed by the mulch cover. The mulch cover protects the soil surface from raindrop impact and crusting, thus further improving infiltration. As there is no plough action, the surface of the soil is not made rough, as is the case with CvT systems. The pore characteristics and soil structure are preserved by a NT system. An impeding layer in the form of a plough pan, is not created under a NT system.

Under a CvT system, surface residues are either removed or incorporated into the soil, thus eliminating any mulch cover. This results in reduced interception and increased evaporation relative to NT. Initially during a season, the greater surface roughness from ploughing will improve infiltration and surface detention. However, the lack of a protective mulch cover can make the soil vulnerable to crusting later in the season. The initially rough surface also increases evaporation relative to NT. The aggressive plough action used in CvT systems causes significant changes in the pore characteristics and structure of the soil. Total porosity and thus retention of water and transpiration are generally increased, while structure and pore continuity are disrupted, resulting in changes in redistribution and drainage patterns. Macropores derived from roots and soil organisms are affected in particular, which reduces the number of pathways for rapid water movement. The action of ploughing in CvT systems frequently results in the formation of plough pans, which restricts the vertical movement of water, thus forcing water to move laterally.

Relative to CvT and NT, CsT systems represent an intermediate level of soil disturbance. This is reflected in the degree to which soil properties (especially mulch cover) and associated hydrological processes are impacted. This may imply that prediction of runoff impacts under CsT systems is more difficult, as it is uncertain whether the system will respond more like CvT or NT.

The influence of factors at the site of interest also determines how hydrological processes respond to tillage of the soil. These factors include the nature of the rainfall that occurs at the site, i.e. the intensity and amount of the rainfall. The slope of the site and type of soil being tilled are also important For example, if rainfall intensity at a site is high, then crusting is more likely under CvT conditions (no protective mulch) than at sites with low intensity. The likelihood of crusting would also be higher on certain soils (those with high silt and very fine sand content) than others (Russell. 2002; pers. comm.). Crusting leads to lowered infiltration and thus higher amounts of runoff. This runoff would be greater on sites with steep slopes, than those with gentle slopes.

When investigating the impacts of tillage on hydrological processes, it is also important to consider that these processes form part of a system. A change in one part of the system will influence another part. This can complicate prediction of the impacts of tillage on runoff. For example, the increased surface roughness of a soil under CvT systems initially results in improved infiltration, however, the incorporation of residues during ploughing makes the soil vulnerable to crusting later in the season, thus reducing infiltration.

4.2 Development of an Approach to Represent Tillage in *ACRU*

In representing tillage practices in the *ACRU* model, emphasis was initially focussed on mulch cover, surface roughness and porosity. The following influences were represented:

- mulch cover impacts on evaporation and infiltration;
- surface roughness impacts on infiltration and depression storage; and
- plough action impacts on soil porosity.

These influences were represented by implementing new algorithms in the model and by selecting appropriate inputs to the model, as outlined below:

4.2.1 Suppression of evaporation by mulch cover

A new algorithm was implemented that allows for maximum (wet condition) soil water evaporation (i.e. non-transpiration component of total evaporation) to be suppressed by a surface cover (e.g. mulch, litter layer, stone/rock). The algorithm assumes that there is a linear relationship between surface cover and maximum soil water evaporation, such that complete cover still allows 20% of evaporation to occur. The relationship is presented in graphical form in Figure 4.1 where a maximum soil water evaporation amount of 8mm for a certain day has been suppressed for varying levels of surface (mulch) cover.

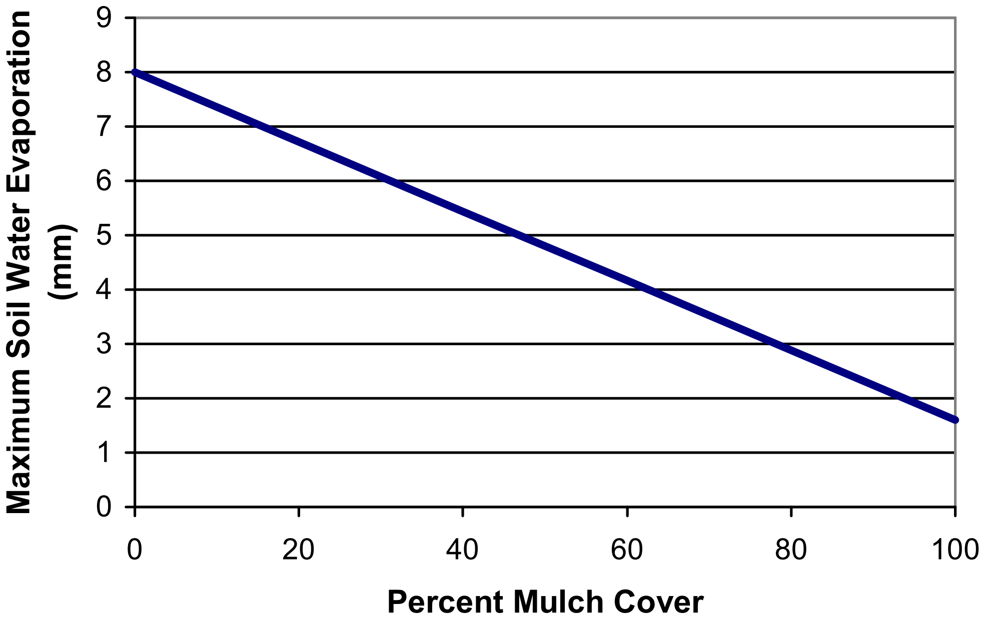

Figure 4.1 Suppression of a maximum soil water evaporation amount of 8mm by a mulch for varying percentages of cover

In equation form the relationship may be written as:

$$POSOEV_s = POSOEV_i - (0.8*(PCSUCO/100)*POSOEV_i)$$

where $POSOEV_s$ = suppressed maximum soil water evaporation (mm)
$POSOEV_i$ = initial maximum soil water evaporation (mm) and
PCSUCO = percentage surface cover.

Percentages of mulch cover (PCSUCO) are input to the model in the form of 12 monthly averages. The soil water evaporation suppression relationship is applied on a daily basis, with the amount of mulch for any particular day being assumed to be equal to the average of the month in question. Once the suppressed maximum soil water evaporation for a day has been calculated, the actual soil water evaporation is determined by accounting for the wetness of the soil.

4.2.2 Influence of mulch cover and surface roughness on infiltration and depression storage

The influence of mulch cover and surface roughness on infiltration and depression storage was represented in the model through selection of appropriate values of the coefficient of initial abstraction (COIAM). This parameter, along with the soil water content of the topsoil at porosity (PO1), i.e. saturation, and depth of soil effective in stormflow generation (SMDDEP), is used in quantifying the initial abstractions of rainfall into the soil that occur before runoff commences (see Chapter 3). When comparing the influence of different tillage practices on hydrological response at a site, certain characteristics of the site will also influence the relative response of the practices. The slope and rainfall intensity at a site will influence the degree to which mulch cover and surface roughness affect infiltration and depression storage. These site factors were included in the selection of COIAM values. The COIAM values were determined by referring to the matrix of values in Figure 4.2.

		Sparse Mulch (0-20%)				Dense Mulch (>80%)		
	Category	1	2	3	4	5	Category	
Smooth (0-8mm)	1	0.10	0.15	0.20	0.25	0.32	1	Steep (>12%)
Surface	2	0.15	0.16	0.22	0.27	0.34	2	Slope
	3	0.20	0.22	0.23	0.29	0.36	3	
Rough	4	0.25	0.27	0.29	0.31	0.38	4	Gentle
Surface (>32mm)	5	0.32	0.34	0.36	0.38	0.40	5	Slope (0-3%)
	Category	1	2	3	4	5	Category	
		(>120mm/h) Intense Rainfall				(0-30mm/h) Light Rainfall		

Figure 4.2 Suggested values of COIAM according to mulch cover, slope, rainfall intensity and surface roughness

The matrix of values was developed by first identifying the range of COIAM values typically used in *ACRU* applications (Schulze, 1995). The values range from 0.10 to 0.40. The four factors considered in selecting COIAM values were then each associated with one side of the matrix, such that moving from left to right across the matrix or from top to bottom of the matrix represented an increase in COIAM, in accordance with changes in the various factors. The factors were represented in the matrix in categorical form, as indicated in Table 4.2 (random roughness was used as an index of surface roughness). The COIAM values were represented systematically throughout the matrix so that a value of COIAM could be determined for any combination of categories of mulch cover, slope, rainfall intensity and surface roughness. Twelve values of the COIAM parameter are required for input to the *ACRU* model, these values representing each month of the year. Thus typical categories of rainfall intensity, slope (invariant), surface roughness and mulch cover, representing each month of the year, must be determined.

Table 4.2 Categories of mulch cover, slope, rainfall intensity and random roughness used in determining values of COIAM

Category	Rainfall Intensity (mm/h)	Slope (%)	Random Roughness (mm)	Mulch Cover (%)
1	> 120	> 12	0 – 8	0 – 20
2	90 – 120	9 – 12	8 – 16	20 – 40
3	60 – 90	6 – 9	16 – 24	40 – 60
4	30 – 60	3 – 6	24 – 32	60 – 80
5	0 – 30	0 – 3	> 32	> 80

Random roughness (RR) describes the random variations in elevation of the soil surface (microrelief), as measured with a relief meter. It is specifically defined as the standard error of individual elevations after the effect of oriented roughness (from tillage) has been removed (Zobeck and Onstad, 1987). As the effect of tillage in orientating the soil surface in particular direction/s in not taken into account, RR reflects the overall (orientation independent) roughness of the soil surface after tillage. The influence of slope is also removed in the calculation of the roughness index. Zobeck and Onstad (1987) proposed a model for predicting changes in RR as a result of successive tillage operations and the accumulation of rainfall during a season:

$$RR_p = RR_o * 0.89e^{-0.026P}$$

where RR_p = random roughness after P cm of cumulative rainfall since the previous tillage operation (mm) and
RR_o = random roughness immediately after a tillage operation (mm).

The model was applied in this study to determine typical RR for each month of the year, taking into account the tillage operations and average monthly rainfalls at the sites.

4.2.3 Effect of plough action on soil moisture storage within the depth of soil effective in stormflow generation

The soil disturbance caused by a plough, especially in conventional tillage, has the potential to increase the porosity of the topsoil. This has the effect of increasing the moisture storage capacity of the soil, which in turn affects the ability of the soil to infiltrate water. A wet soil tends to infiltrate less water than a dry soil, leading to higher runoff amounts. The degree to which tillage affects topsoil porosity depends on the implement used and the type of soil concerned. In the *ACRU* Theory Manual (Schulze, 1995), typical values of top- and subsoil porosity have been tabulated for different soil textural classes (Table 4.3). For topsoils, values have also been provided for freshly tilled and end of season conditions. These were applied in the modelling of tillage in this research.

The moisture of a soil only influences infiltration and runoff to a certain critical depth of soil, which in *ACRU* is represented by the variable SMDDEP (see Chapter 3). In most applications of *ACRU* this variable is estimated by referring to the matrix in Figure 3.2, similar to the one proposed for estimating COIAM in this research. The estimates provided in the SMDDEP matrix represent a general starting value for the site of interest. A single value of the variable representing all months of the year, is input to the model. In distinguishing between different tillage types, adjustments to SMDDEP were recommended in the following cases:

- Where tillage was deeper than the table-derived value: The disturbance of the soil below the general site SMDDEP is likely to induce soil moisture changes in this depth of soil, thus necessitating an increase to the value of SMDDEP.
- Where a tillage implement resulted in the formation of a plough pan at a depth shallower than the general SMDDEP for the site: A plough pan inhibits vertical drainage, thus limiting the depth of soil effective in stormflow generation. This results in increased runoff.

Having discussed the approach to representing tillage in the *ACRU* model in this chapter, the following chapter details the simulations of runoff at the Cedara and Bloemfontein sites.

Table 4.3 Typical values of soil hydrological input parameters for different textural classes (after Rawls *et al.*, 1982; Schulze *et al.*, 1987; Buitendag, 1990; Everett, 1990)

Soil Texture Number	Soil Texture Class	Horizon	Typical Percentages of				Bulk Density (Mg/m^3)	Total Porosity (m^3/m^3)	Effective Porosity (m^3/m^3)	Saturated Hydraulic Conductivity (mm/h)	Redistribution Fraction (/day)
			Clay	Silt	Sand	Organic Carbon					
1	CLAY	Topsoil (untilled) Topsoil (tilled) Subsoil	50	37	13	0.38	1.22 1.20 1.37	.470 .549* .538^ .482	- .536 .470	0.6	.25
2	LOAM	Topsoil (untilled) Topsoil (tilled) Subsoil	18	25	57	0.52	1.26 1.09 1.42	.512 .589* .524^ .480	- .512 .464	13	.50
3	SAND	Topsoil (untilled) Topsoil (tilled) Subsoil	3	4	93	0.71	1.32 1.17 1.50	.446 .559* .503^ .440	- .452 .430	210	.80
4	LOAMY SAND	Topsoil (untilled) Topsoil (tilled) Subsoil	7	7	86	0.61	1.31 1.16 1.51	.452 .562* .505^ .477	- .457 .432	61	.70
5	SANDY LOAM	Topsoil (untilled) Topsoil (tilled) Subsoil	10	15	75	0.71	1.26 1.11 1.46	.486 .582* .524^ .466	- .505 .448	26	.65
6	SILTY LOAM	Topsoil (untilled) Topsoil (tilled) Subsoil	18	55	27	0.58	1.13 1.01 1.34	.530 .619* .575^ .500	- .527 .495	6.8	.45
7	SANDY CLAY LOAM	Topsoil (untilled) Topsoil (tilled) Subsoil	27	8	65	0.19	1.35 1.25 1.58	.435 .523* .500^ .405	- .486 .393	4.3	.50
8	CLAY LOAM	Topsoil (untilled) Topsoil (tilled) Subsoil	32	22	46	0.10	1.22 1.12 1.41	.474 .576* .541^ .456	- .497 .451	2.3	.40
9	SILTY CLAY LOAM	Topsoil (untilled) Topsoil (tilled) Subsoil	33	46	21	0.13	1.25 1.21 1.40	.489 .544* .528^ .473	- .509 .469	1.5	.35
10	SANDY CLAY	Topsoil (untilled) Topsoil (tilled) Subsoil	40	5	55	0.38	1.35 1.25 1.53	.393 .529* .492^ .428	- .430 .423	1.2	.40
11	SILTY CLAY	Topsoil (untilled) Topsoil (tilled) Subsoil	50	37	13	0.38	1.23 1.20 1.38	.476 .547* .536^ .480	- .531 .476	0.9	.35

* Freshly tilled ^ End of season value

5 MODELLING THE IMPACTS OF TILLAGE ON RUNOFF

The modelling of runoff at the Cedara and Bloemfontein sites is presented in this chapter. A series of simulations was performed in the study during which the modelling approach presented in Chapter 4 was refined.

As discussed in the introduction of this report, the *ACRU* model is a catchment model and could not be applied directly to simulate the runoff from a runoff plot. Instead, the model was applied on hypothetical 1km^2 area catchments having similar climate, soil and land use properties to the runoff plots at Cedara and Bloemfontein. Owing to the differences in scale between plots and catchments, the aim of the modelling exercise was to replicate at catchment scale the relative runoff responses of the different tillage treatments observed on the runoff plots.

5.1 Cedara Runoff Simulations

The runoff from the DESC maize crops under different tillage practices (NT, CsT, CvT:spring plough) and the bare fallow condition (see Chapter 2.1) was simulated for the seasons from 1983/1984 to 1998/1999. A "warm-up" period from the beginning of 1980 to the start of monitoring was also included to initialise the soil water budget of the model. The preparation of general inputs to the model (i.e. those not specific to tillage) is first summarised in this section. Various simulation runs, corresponding to refinements of the modelling approach, were performed before reaching a final result. The final run is presented in Section 5.1.2 of this chapter, while the full set of runs is presented in Appendix B. The inputs applied in these runs that are specific to tillage are presented with the simulation results.

5.1.1 General input preparation

Climate: The daily rainfall record for the period of simulation was obtained from the Cedara meteorological station, which was situated within 500m of the runoff plots. Daily maximum and minimum temperatures were also obtained from this station for input to the model. As the station was close to the runoff plots, no adjustment of the data was considered necessary.

Soils: The soil type and depth was obtained from the soil profile description, while the texture, limits of plant available water (permanent wilting point and drained upper limit) and vertical drainage variables (ABRESP and BFRESP) were derived from clay distribution models and other default information contained in the *ACRU* User Manual (Smithers and Schulze, 1995). No soil sample analyses were available to estimate the latter variables.

Land cover: The option in the model to calculate crop coefficients based on thermal time (driven by daily maximum and minimum temperatures as described in Schulze, 1995) was selected for the maize crops. The amount of interception per rainday and the fraction of roots in the topsoil were derived from standard tabulated values in the *ACRU* software, but modified to represent the longer than normal growing season. For the bare fallow condition crop coefficients were set to 0.2 to simulate evaporation from the soil surface.

Total evaporation: The option in the model to simulate transpiration and evaporation from the soil as separate entities was selected. This option is required in order to model the effect of a mulch.

Streamflow: QFRESP is a catchment modelling variable which represents the fraction of stormflow that will run off a catchment on the same day as the rainfall event. As all runoff will cease from a runoff plot on the same day as the rainfall event, this variable was set to 1.0. It would be undesirable when verifying catchment simulations against the runoff plot observations to have stormflow continuing on days subsequent to the rainfall event.

5.1.2 Simulations

During the course of the simulations that were performed to refine the tillage modelling approach (Appendix B), the following were noted:

- The runoff reducing effects of mulch cover (e.g. increased infiltration opportunity, crust prevention, organic matter enhancement) influenced the response of the NT and CsT treatments at Cedara to a greater degree than that initially represented in the modelling approach.
- The soil profile description at Cedara, which was carried out before commencement of the experiment, noted the frequent occurrence of macropores in the soil. These macropores, which would have been derived from soil organisms (especially earthworms), roots etc., would have been maintained under NT and would have facilitated rapid infiltration and movement of water through the soil.
- Given that the experiment was conducted over 17 seasons it is possible that a plough pan could have formed under the CvT treatment if no preventative action was taken. It has been speculated that the high clay content of the soil would not have provided favourable conditions for pan formation (Russell, 2002; pers. comm.). However, to confirm the presence or absence of a pan the soil profile would have had to be examined during the course of the experiment. For the purposes of this study it was assumed that a plough pan did form.

Given the above, the following modifications of the initial modelling approach were proposed:

- The value of COIAM for all months of the year was set to 0.35 for the NT treatment to account for increased infiltration opportunity afforded by the mulch.
- The interception of rainfall by the maize crop on the NT treatment was increased to account for interception by the mulch (VEGINT variable)
- In an attempt to account for macropore flow under the NT treatment, the variable controlling the vertical drainage of water from the A to B horizon under saturated conditions (ABRESP), was increased from the default value of 0.4 (for a Hutton Doveton soil) to a value of 1.0.
- To account for the influence of a plough pan on the CvT plot, SMDDEP was reduced from the general site value of 0.30m (according to Figure 3.2) to the depth of tillage (0.25m according to Table 2.2). A further change was made by

reducing the ABRESP parameter from the default value of 0.4 to 0.1 to simulate the inhibited vertical drainage resulting from the presence of a plough pan.

It was assumed that the mulch and macropore effects in the CsT system would have been less influential than for NT. Therefore, the interception was increased to a lesser degree than NT. The value of ABRESP was increased from 0.4 to 0.7 for CsT. The full set of values of tillage related variables used in the final simulation run at Cedara is presented in Tables 5.1 and 5.2.

Table 5.1 PCSUCO, COIAM and VEGINT values used in final Cedara simulation run for maize

Variable	Trea-tment	Monthly Inputs											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PCSUCO (%)	NT	39.0	23.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	73.0	57.0
	CsT	13.0	5.0	5.0	5.0	5.0	5.0	5.0	35.0	35.0	35.0	31.0	22.0
	CvT	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	BF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COIAM	NT	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CsT	0.19	0.19	0.19	0.22	0.22	0.22	0.22	0.26	0.26	0.23	0.23	0.22
	CvT	0.19	0.19	0.19	0.22	0.22	0.22	0.22	0.23	0.26	0.23	0.21	0.21
	BF	0.19	0.19	0.19	0.22	0.22	0.22	0.22	0.22	0.22	0.19	0.21	0.19
VEGINT (mm)	NT	1.60	1.50	1.40	1.30	1.10	1.00	0.90	0.80	0.70	0.60	0.60	1.00
	CsT	1.55	1.45	1.35	1.25	1.05	0.80	0.65	0.55	0.50	0.50	0.55	0.95
	CvT	1.50	1.40	1.30	1.20	0.50	0.50	0.50	0.50	0.50	0.00	0.50	0.90
	BF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 5.2 SMDDEP, PO1 and ABRESP values used in final Cedara simulation run for maize

Treatment	SMDDEP (m)	PO1 (m/m)	ABRESP
NT	0.30	0.393	1.0
CsT	0.30	0.450	0.7
CvT	0.25	0.510	0.1
BF	0.30	0.400	0.1

For PCSUCO, the average values of mulch cover for each month of the year were derived from the measurements of mulch that were made each season (Table 2.2).

For the CsT, CvT and BF treatments, values of COIAM were determined according to the approach described in Section 4.2.2, i.e. the monthly values of COIAM were obtained from Figure 4.2 for the appropriate categories of mulch cover, slope, rainfall intensity and surface roughness. The appropriate categories of the determining variables are tabulated in Table 5.3. The values of PCSUCO were used to determine the categories of mulch cover. The slopes of the runoff plots were very similar and all fell within Category 3. Rainfall intensity was assumed to fall within Category 4 during the summer months and Category 5 during winter months. The categories of surface roughness were determined by applying the random roughness equation of Zobeck and Onstad (1987), as described in Section 4.2.2.

Table 5.3 Categories of variables used in determining COIAM values for the final simulation run at Cedara

Month	Rainfall Intensity	Slope	Random Roughness				Mulch Cover			
			NT	CsT	CvT	BF	NT	CsT	CvT	BF
Jan	4	3	1	1	1	1	2	1	1	1
Feb	4	3	1	1	1	1	2	1	1	1
Mar	4	3	1	1	1	1	1	1	1	1
Apr	5	3	1	1	1	1	1	1	1	1
May	5	3	1	1	1	1	1	1	1	1
Jun	5	3	1	1	1	1	1	1	1	1
Jul	5	3	1	1	1	1	1	1	1	1
Aug	5	3	1	3	2	1	1	2	1	1
Sep	5	3	1	3	4	1	1	2	1	1
Oct	4	3	1	2	3	1	1	2	1	1
Nov	4	3	1	2	2	2	4	2	1	1
Dec	4	3	1	1	2	1	3	2	1	1

The standard values of VEGINT described in Section 5.1.1 (modified for the crop cycle practiced at Cedara) were assumed to be representative of the CvT treatment. These values were increased for the CsT and NT treatments, as discussed above.

The *ACRU* model only allows for a single topsoil porosity value to be entered into the model (PO1 variable). This variable was estimated for the CvT treatment by averaging the freshly tilled and end of season default values contained in Table 4.3 for the relevant soil type (sandy clay). For the NT treatment the untilled value of topsoil porosity was used. As CsT causes less disturbance of the soil than CvT, an average of the NT and CvT porosity values was used. For the BF treatment a porosity value that was slightly higher than untilled conditions was used, as this plot was kept bare through shallow action of a rotovator. The default porosity value tabulated in Table 4.3 for the subsoil was used for all treatments (PO2 = 0.428m/m).

After running the *ACRU* model, the daily simulated runoff was accumulated over the intervals between runoff plot observations. These observations were made as soon as possible after a significant runoff producing event, usually the day after an event. In some smaller events runoff was simulated by the model but was not observed on the runoff plots. In these instances simulated runoff was still included in the accumulation. As discussed in Chapter 2.1, it was unclear for some events in the observed runoff record as to whether plots were missing data, did not generate any runoff or were not measured in terms of runoff response. Thus a decision was made to only consider events where runoff was recorded on all plots. This may imply that only larger events are considered. The runoff simulated for all considered events was summed for each season and plotted in Figure 5.1. The seasonal values of runoff were accumulated over the period of simulation and plotted as cumulative plots in Figure 5.1. For ease of reference, the corresponding graph for observed data which was presented in Figure 2.2 is presented again in Figure 5.2. The data are also presented in the form of cumulative plots in this graph.

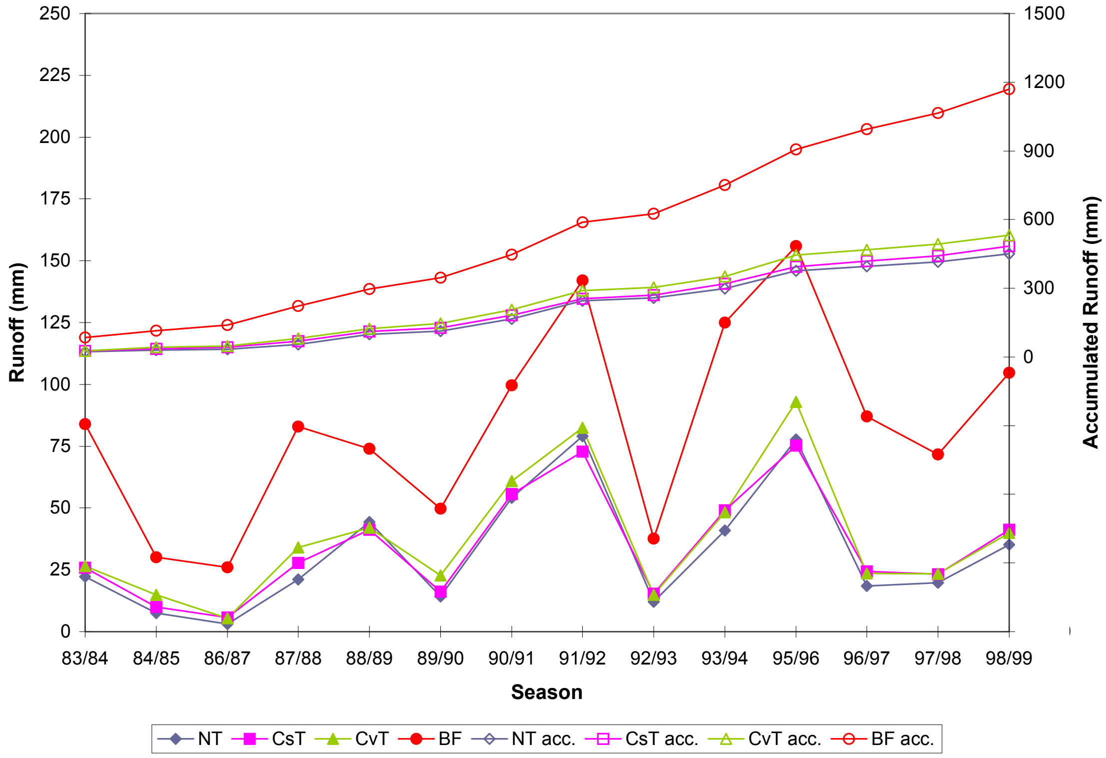

Figure 5.1 Simulated seasonal and accumulated runoff for maize under various tillage practices at Cedara

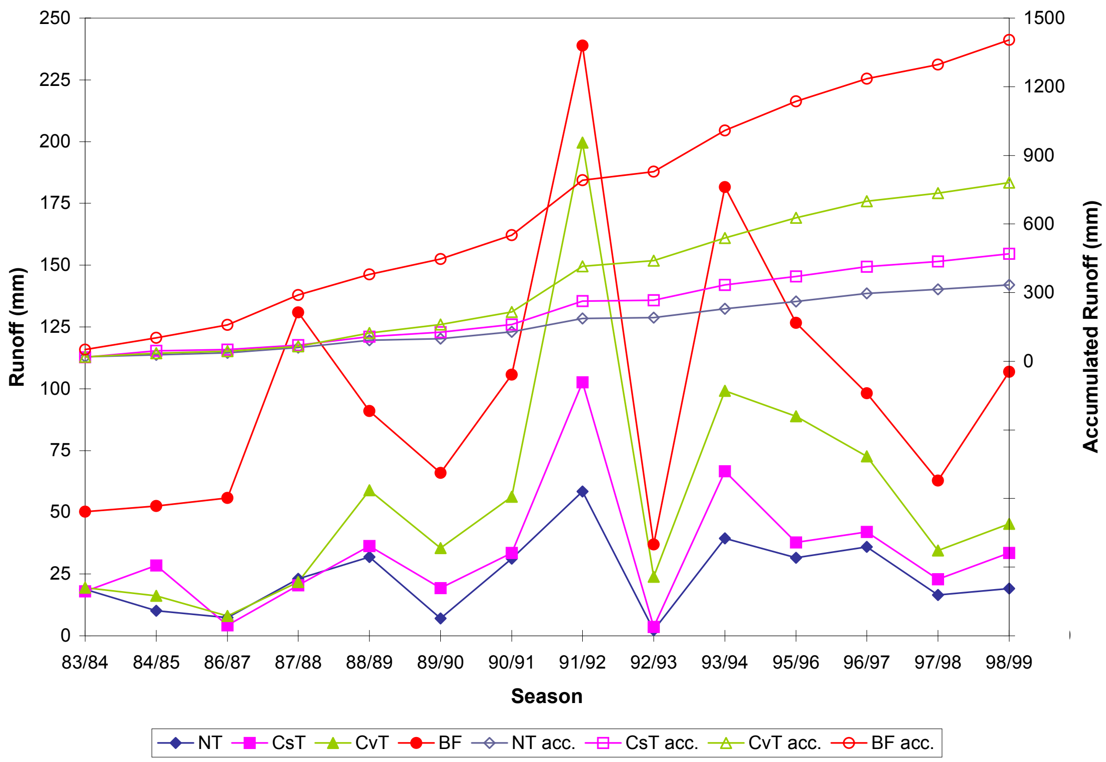

Figure 5.2 Observed seasonal and accumulated runoff for maize under various tillage practices at Cedara

For the BF treatment simulation (Figure 5.1), runoff was distinctly higher than the other treatments, as was observed on the runoff plots. The sequence of CvT, CsT and NT runoff responses was generally correctly simulated. In the observed runoff data (Figure 5.2) the differences between the CvT treatment and the other cropped treatments was often larger than that simulated (e.g. 1991/92 season), while the differences between the CsT and NT treatments were mostly of a similar order of magnitude for simulated and observed (exceptions being the 1991/92 and 1993/94 seasons). The cumulative plots verify that over the period considered, as a whole, the differences between the cropped treatments were not well simulated, with the simulated differences being too small relative to the observed differences.

For all treatments the seasonal variation in simulated runoff (Figure 5.1) shows the following differences in trends when compared to the observed (Figure 5.2) runoff:

- the simulated runoff in 1983/84 was higher than that simulated in 1984/85, while the observed runoff shows little difference; and
- the simulated runoff in 1995/96 was higher than that in 1993/94, while the observed runoff shows the opposite trend (no events were considered in 1994/95).

5.2 Bloemfontein Runoff Simulations

The runoff from wheat monoculture crops under different tillage practices (NT, CsT, CvT) was simulated for the seasons from 1989/1990 to 1992/1993. A “warm-up” period from the beginning of 1988 to the start of monitoring was also included to initialise the water budget of the model. The preparation of general inputs to the model (i.e. those not specific to tillage) is first summarised in this section. The simulation of runoff from the various treatments is then presented in a subsequent section, along with the inputs applied in the model that are specific to tillage.

5.2.1 General input preparation

Climate: For reasons discussed in Chapter 2.2, the daily rainfall record for application in the *ACRU* simulations was not obtained from measurements at the runoff plot site, but rather from a nearby South African Weather Services raingauge (0261183W) located at 29°03’S 26°07’E. A study of a topographical map indicated that the rainfall recorded at this station is likely to give a reasonable representation of rainfall at the runoff plot site. A record of daily maximum and minimum temperatures for application in modelling at the site was derived from surrounding meteorological stations using a spatial temperature estimation technique developed by Schulze, as reported in Lumsden *et al*. (1999).

Soils: The soil type, depth, texture and limits of plant available water (permanent wilting point and drained upper limit) were extracted from information provided in Bennie *et al*. (1994), while values of the vertical drainage variables (ABRESP and BFRESP) were obtained from the *ACRU* User Manual (Smithers and Schulze, 1995) for the relevant soil type.

Land cover: The crop coefficients, amount of interception per rainday and the fraction of roots in the topsoil for wheat in the Free State were derived from standard tabulated values in the *ACRU* software modified to represent the growing season adopted at the Bloemfontein site.

Total evaporation: The option in the model to simulate transpiration and evaporation from the soil as separate entities was selected. This option is required in order to model the effect of a mulch.

Streamflow: The QFRESP variable was set to a value of 1.0 for the same reasons discussed in the Cedara site simulations.

5.2.2 Simulations

The same mulch effects initially represented in the Cedara simulations were used to represent the tillage treatments at Bloemfontein, these being suppression of evaporation from the soil and infiltration effects represented in COIAM (determined from Figure 4.2). No mention was made by Bennie *et al*. (1994) of a plough pan forming under CvT, or of the frequent occurrence of natural macropores under NT. The relatively short period of the experiment would probably not have allowed time for a plough pan to develop. Runoff was concluded to decrease with the amount of soil disturbance caused by tillage, further suggesting that no plough pan was present under CvT.

Measurements of mulch cover were available at the beginning of the season for the various tillage practices. To estimate mulch cover for the rest of the season for input to the model (PCSUCO), it was assumed that the drier, semi-arid climate in Bloemfontein would result in mulch decaying at half the rate observed at Cedara. The resulting values of PCSUCO are tabulated in Table 5.4.

Monthly values of COIAM were obtained from Figure 4.2 for the appropriate categories of mulch cover, slope, rainfall intensity and surface roughness. The values of COIAM selected are also tabulated in Table 5.4.

Table 5.4 Values of PCSUCO and COIAM used in Bloemfontein simulations

Variable	Trea-tment	Monthly Inputs											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PCSUCO (%)	NT	43.0	34.0	25.0	16.0	7.0	5.0	5.0	5.0	5.0	5.0	5.0	52.0
	CsT	14.0	10.0	6.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	18.0
	CvT	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
COIAM	NT	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.22	0.22	0.23
	CsT	0.25	0.25	0.27	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.27
	CvT	0.27	0.27	0.27	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.31

In determining COIAM, the values of PCSUCO were used to determine the appropriate categories of mulch cover. The slope of the runoff plots was 1.3% (Category 5). Rainfall intensity was assumed to fall within Category 3 during the summer months and Category 4 during winter months. The categories of surface roughness were determined by applying the random roughness equation of Zobeck and Onstad (1987). The categories of the variables used to determine COIAM are tabulated in Table 5.5.

Table 5.5 Categories of variables used in determining COIAM in Bloemfontein simulations

Month	Rainfall Intensity	Slope	Random Roughness			Mulch Cover		
			NT	CsT	CvT	NT	CsT	CvT
Jan	3	5	1	2	3	3	1	1
Feb	3	5	1	2	3	2	1	1
Mar	3	5	1	3	3	2	1	1
Apr	4	5	1	2	2	1	1	1
May	4	5	1	2	2	1	1	1
Jun	4	5	1	2	2	1	1	1
Jul	4	5	1	2	2	1	1	1
Aug	4	5	1	2	2	1	1	1
Sep	4	5	1	2	2	1	1	1
Oct	3	5	1	2	2	1	1	1
Nov	3	5	1	2	2	1	1	1
Dec	3	5	1	3	4	3	1	1

As there was no mention of plough pan formation in Bennie *et al*. (1994), and as the depths of tillage were not deeper than the general value of SMDDEP estimated for the Bloemfontein site (from Figure 3.2), SMDDEP was set to the general site value for all tillage treatments (0.25m).

Values of top- and subsoil porosity (PO1 and PO2) were estimated using the same assumptions as those adopted at Cedara. The values derived for the loamy sand at Bloemfontein appear in Table 5.6.

Table 5.6 Estimated top- and subsoil porosity values for the Bloemfontein site

Soil Horizon	Porosity (m/m)		
	NT	CsT	CvT
Topsoil	0.452	0.519	0.533
Subsoil	0.477	0.477	0.477

After running the *ACRU* model the daily simulated runoff was accumulated over the intervals between runoff plot observations. The runoff for these intervals was then summed for each season and plotted in Figure 5.3. The seasonal values of runoff were then further accumulated over the period of simulation and plotted as cumulative plots in Figure 5.3. For ease of reference, the corresponding graph for observed data which was presented in Figure 2.5 is presented again in Figure 5.4. The observed data are also presented in the form of cumulative plots in this graph. For the simulated runoff, seasons were defined in the same manner as the observed data, where distinction was made between cropped and fallow periods. The naming of seasons followed the convention adopted in the observed runoff graphs, as described in Chapter 2.2.

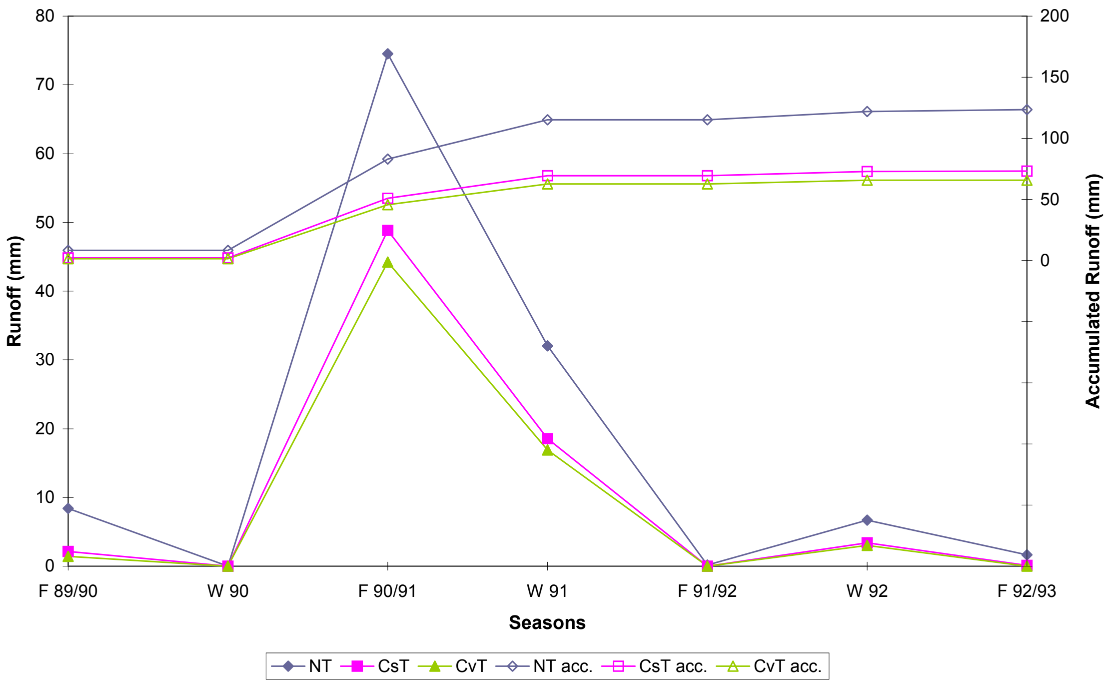

Figure 5.3 Simulated seasonal and accumulated runoff for the wheat monocrop practice under various tillage systems at Bloemfontein

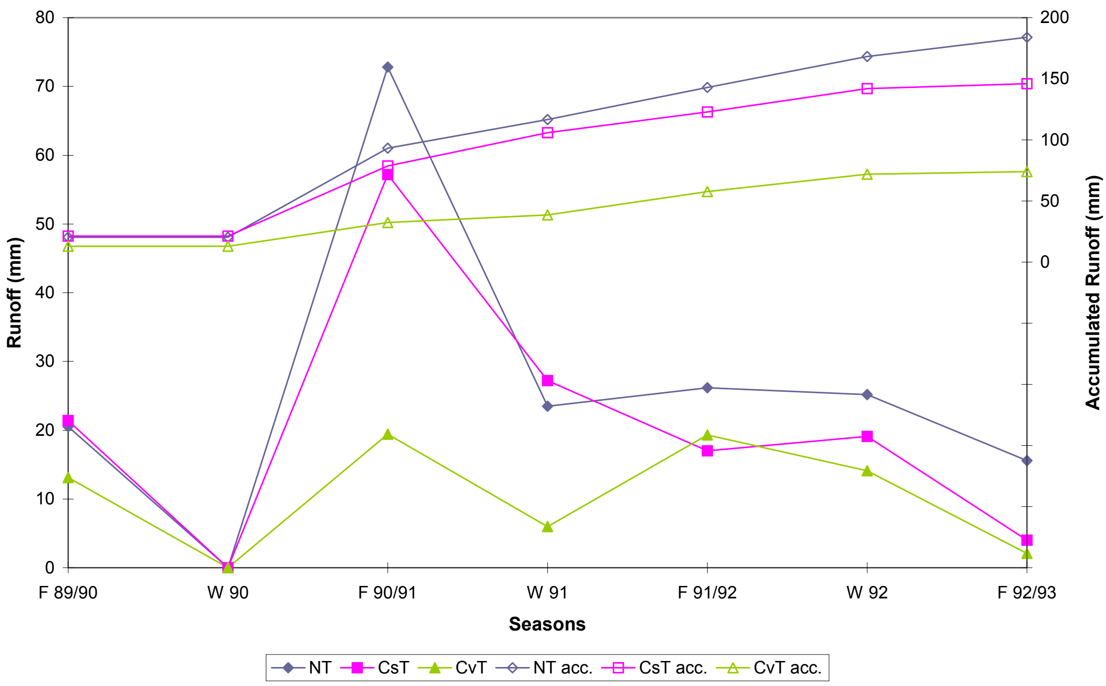

Figure 5.4 Observed seasonal and accumulated runoff for the wheat monocrop practice under various tillage systems at Bloemfontein

The sequence of runoff for the various treatments is generally correctly simulated, with the W91 and F91/92 seasons being exceptions. In most seasons, the relative simulated differences between the CsT and CvT treatments are smaller than the observed differences. In particular, the small differences in the F90/91 and W91 seasons represent an over-simulation of the CvT treatment relative to that of CsT. The cumulative plots verify that over the simulation period, as a whole, the modelled differences between the CsT and CvT treatments were not well simulated, with the CvT treatment being over-simulated and the CsT under-simulated relative to the observed data.

Examination of the rainfall record used in the simulations revealed that the failure of the model to simulate runoff in the F91/92 season may be due to this record having more dispersed rainfall events during this season than those actually experienced at the runoff plot site. However, this is difficult to verify with only accumulated rainfall at the site being available.

5.3 Discussion

Runoff in the 1983/84 and 1995/96 seasons was consistently over-simulated for the Cedara tillage treatments relative to the 1984/85 and 1993/94 seasons, respectively. The reasons for this are not clear. The observed response in 1983/84 may be atypical as a result of this season being one of the first to be monitored, thus the need for a “settling down“ period to observe a more typical response. The land on which the runoff plots were laid out was not cultivated for at least 10 years prior to commencement of the experiment, and would thus have had relatively high organic matter levels. This might explain why the observed runoff response was lower than that simulated (Russell, 2002; pers. comm.). Runoff from the 1983/84 and 1995/96 seasons may also have been over-simulated due to a systematic error in the measurement of runoff. Alternatively, the over-simulation may be due to a variation in the management of the runoff plots that was not accounted for during those seasons. Although the downhill cultivation of the runoff plots during the 1995/96 to 1997/98 seasons was not represented in the model, the over-simulation of runoff in the 1995/96 season is not consistent with such an omission, which would be likely to cause an under-simulation rather than an over-simulation. It is understood that winter lupins were planted on the plots subsequent to the retirement of Mr Russell in September 1995 (Russell, 2002; pers. comm.), however, no details of this could be found in the DESC data set.

In the Bloemfontein runoff experiments it is likely that the NT system resulted in greater runoff than that from the CvT treatment because of surface crusting problems developing in the NT treatment, which had low random roughness and insufficient mulch cover (Bennie, 2003; pers. comm.). Soils with a clay content of less than 20% in the tilled layer are very vulnerable to compaction (Berry, 2001). Berry (2001) suggests that soils with a clay content of between 1 and 8% in the tilled layer will require tillage to break up compacted layers after one season of no-till under dryland grain crops. As the soil at the Bloemfontein site had a clay content of 8% in the top 300mm, it is conceivable that this soil could have become compacted under NT which would have further contributed to this treatment having higher runoff than the conventionally tilled runoff plot. Measurements of bulk density during the observation of infiltration/runoff characteristics at Bloemfontein (soil in a dry condition before application of simulated rainfall), appear to verify that compaction under NT did occur. In the runoff simulations, the CvT treatment was assigned a higher soil porosity relative to the NT treatment. This indirectly simulates a higher state of compaction under NT versus CvT treatments. The basic level at which mulch cover effects were represented in the Bloemfontein simulations is justified because of the relatively low levels of mulch cover observed at the site.

The different sequences of response of the various tillage practices at the Cedara and Bloemfontein sites implies that a NT system will not always result in less runoff than a CvT system. In the case of the Bloemfontein site, NT yielded the most runoff as a result of surface crusting, soil compaction and relatively low mulch cover. This highlights the importance of considering site characteristics (e.g. soils, climate, vegetation) when predicting the impact of different tillage practices on runoff response. While reduced tillage systems are usually implemented with the partial objective of reducing surface runoff and associated soil loss, they may also be implemented to control wind erosion, where reductions in runoff relative to CvT systems may not occur.

Based on the experience gained in modelling tillage at Cedara and Bloemfontein, it is hypothesised that, in general, the response of a NT system relative to a CvT system depends on the balance of the effects caused by increased mulch cover and the lack of plough action. The effects of increased mulch cover include increased infiltration opportunity, crust prevention and organic matter enhancement, while lack of plough action results in lower porosity and, therefore, less moisture storage capacity, as well as the possibility of compaction problems. The response of a CvT system can be influenced by a plough pan if present. In a NT system, any naturally occurring macropores (derived, for example, from soil organisms or roots) that are present, are preserved. These pores can be very effective in maintaining good rates of water infiltration into the soil. The increased porosity of a CvT system resulting from the creation of artificial macropores during ploughing is temporary, as consolidation of the soil takes place during the season. The response of any tillage system is also very dependent on site characteristics such as rainfall properties, slope and soil type.

The response of a CsT system relative to that of NT and CvT is difficult to predict, as it represents an intermediate level of plough action and mulch cover development. It is uncertain as to whether such a system will behave more like NT or CvT.

In this chapter the modelling of tillage impacts on runoff has been investigated. In the next chapter improvements to the modelling of baseline land cover will described. The hydrological response of a baseline land cover is an important consideration when investigating the responses of different land uses.

6 IMPROVEMENTS TO THE MODELLING OF BASELINE LAND COVER

When assessing the impacts of different land uses on streamflow, it is necessary to have some baseline against which these land uses can be compared. For example, the water use of SFRAs are compared to a baseline water use. Several options for a baseline land cover are available in South Africa, each of these having advantages and disadvantages in their application as a baseline, for example,

- veld in a specified hydrological condition e.g. good, fair or poor condition corresponding to a cover of >75%, 50-75% and <50%, respectively (as defined in Schulze *et al*., 1993),
- actual land use in a specified baseline year e.g. 1996, the year of the CSIR's National Land Cover information, or
- a land cover representing "natural" vegetation e.g. Acocks' (1988) Veld Types.

The Veld Types of Acocks' were mapped on the basis of botanical composition and practical utilisation, and were defined to be units of vegetation whose range of variation is small enough to permit the same farming potential throughout the unit. In total 70 Veld Types were identified and mapped in the country.

The Acocks' Veld Types have been used in previous comparative hydrological studies as a baseline (Schulze *et al*., 1996; Schulze *et al*. 1999; Gush *et al*., 2002). The study of Gush *et al*. (2002) was an important WRC/DWAF funded research project to estimate streamflow reductions resulting from commercial afforestation in South Africa, with a view to the future application of this information in water use authorization and allocation processes in the country. During the course of the study inconsistencies were identified in the approach used to estimate the *ACRU* hydrological input parameters for the Acocks' Veld Types. At the request of the WRC an improved approach to estimating the input parameters was developed within this project, and is reported in this chapter.

6.1 New Approach to Estimating *ACRU* Input Parameters for Acocks' Veld Types

To ensure consistency in the estimation of *ACRU* input parameters, the hydrological attributes of the Veld Types were related to biomass. Biomass curves were developed for each Veld Type based on the premise that biomass is dependent on energy and moisture, as expressed in the following variables:

- moisture growing season (MGS)
- heat units (base 10°C)
- mean annual rainfall (MAP)
- rainfall concentration and
- frost duration.

Climatic data contained in the Quaternary Catchments (QC) and gridded databases of the School of Bioresources Engineering and Environmental Hydrology (BEEH) were used in the calculation of the above variables.

Moisture growing season is the period when, on average, there is enough water in the soil for sustained plant growth to take place. For sustained plant growth to occur, consideration is given to whether precipitation exceeds some lower threshold of plant evaporative losses. A simple water budgeting approach applied by the FAO (1978) was adapted to determine the average MGS for each Acocks' Veld Type.

Rainfall concentration gives an indication of whether rainfall is distributed throughout the year or whether it is concentrated around a particular time/s of the year.

The distribution of MGS, heat units and frost duration throughout the year as well as the associated MAP and rainfall concentration, as determined from climatic data in the BEEH QC database, is presented in Figure 6.1 for the first 34 Veld Types and in Appendix C for the full set of 70 Veld Types. The MGS is presented in different shades of green for the 10th, 50th and 90th percentile conditions. The median condition was used in the generation of biomass curves.

From the generated biomass curves the required hydrological land cover parameters were derived, namely, crop coefficients (CAY), rainfall interception per rainday (VEGINT), fraction of roots in the topsoil (ROOTA) and percentage surface cover (PCSUCO). The parameters for the first 18 Veld Types are presented in Table 6.1 while the parameters for the full set of Veld Types is presented in Appendix D. Further detail regarding the generation of the biomass curves and the derivation of the required land cover parameters is given in Schulze (2003).

6.2 Discussion

The Acocks' Veld Types have become an accepted baseline land cover in South Africa. The use of climatic drivers of plant growth in deriving land cover input parameters has ensured consistency and transparency in the development of these parameters. The approach to estimating input parameters was presented to members of the National Botanical Institute who were supportive of the methodology employed. The revised model input parameters, combined with the new algorithm to account for soil water evaporation suppression by mulch cover (Section 4.2.1), serve to improve the modelling of Acocks' Veld Types, and thus baseline land cover, for application in comparative hydrological studies.

Moisture Growing Season (days) : Lowest 10% Median Highest 10%
Frost Duration (only if > 10 days) :
Heat Units (base 10ºC) per month : 201

Number	Acocks' Veld Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	FROST (days) / MGS (days)	MAP (mm)	CONC %
	COASTAL TROPICAL FOREST TYPES															
1	Coastal Forest and Thornveld	428	392	412	338	278	201	200	231	270	313	340	405	256	929	37
2	Alexandria Forest	361	336	341	272	223	153	141	162	188	229	267	324	277	666	9
3	Pondoland Coastal Plateau Sourveld	366	337	352	285	239	171	169	197	221	253	276	336	269	1235	39
4	Knysna Forest	341	314	305	230	163	93	76	96	130	186	243	307	32 / 316	864	6
5	Ngongoni Veld - Zululand	349	322	330	257	195	120	122	164	203	239	266	327	10 / 236	901	46
6	Zululand Thornveld	434	388	406	329	264	177	184	236	285	327	353	414	205	790	47
7	Eastern Province Thornveld	350	326	329	257	206	126	119	153	180	219	252	315	10 / 237	683	28
	INLAND TROPICAL FOREST TYPES															
8	North-Eastern Mountain Sourveld	330	291	296	230	158	74	79	135	200	256	278	316	26 / 194	991	59
9	Lowveld Sour Bushveld	431	384	394	312	234	146	150	212	281	341	365	415	192	862	59
	TROPICAL BUSH AND SAVANNA TYPES (BUSHVELD)															
10	Lowveld	474	424	442	359	282	194	320	257	317	369	393	454	177	692	53
11	Arid Lowveld	487	433	446	366	285	191	195	257	324	386	419	470	114	533	63
12	Springbok Flats Turf Thornveld	419	367	367	272	175	78	81	160	260	340	362	400	46 / 136	556	63
13	Other Turf Thornveld	473	407	403	288	171	60	60	160	290	397	419	451	68 / 116	565	64
14	Arid Sweet Thornveld	478	417	420	321	216	111	112	197	305	395	426	460	25 / 48	418	68
15	Mopani Veld	504	442	460	380	298	201	205	265	332	406	441	487	103	421	68
16	Kalahari Thornveld	477	416	389	258	138	21	20	99	207	322	383	464	89 / 25	313	65
17	Kalahari Thornveld invaded by Karoo	453	384	347	209	93	0	0	54	154	274	342	422	110 / 9	321	60
18	Mixed Bushveld	433	378	380	284	184	83	85	167	270	353	378	415	42 / 132	524	65
19	Sourish Mixed Bushveld	417	360	350	248	141	41	42	126	233	329	359	398	63 / 142	591	63
20	Sour Bushveld	384	332	330	240	143	45	43	124	228	305	338	367	60 / 145	630	65
21	False Thornveld of Eastern Cape	361	332	322	231	157	69	62	110	158	211	258	327	50 / 60	521	30
22	Invasion of Grassveld by Acacia Karoo	329	291	270	167	81	0	0	49.6	113	175	227	296	114 / 95	523	45
23	Valley Bushveld	372	342	343	264	203	116	113	153	192	239	278	343	23 / 221	629	35
24	Noorsveld	423	384	366	255	178	83	71	121	180	251	314	388	54 / 0	262	31
25	Succulent Mountain Scrub	392	354	333	224	135	42	31	76	137	214	281	357	84 / 0	306	20
26	Karroid Broken Veld	392	353	327	212	118	26	14	57	123	209	279	355	94 / 110	203	32
27	Central Upper Karoo	374	328	291	155	48	0	0	0	78	177	252	335	138 / 20	231	49
28	Western Mountain Scrub	388	365	343	215	119	14	0	39	108	202	278	349	109 / 11	210	42
29	Arid Karoo	422	381	355	224	115	12	1.6	54	138	237	311	383	105 / 23	141	54
30	Central Lower Karoo	394	351	324	206	110	20	8	56	126	212	281	358	101	208	37
31	Succulent Karoo	403	375	364	272	192	107	78	110	164	242	309	366	37 / 48	140	53
32	Orange River Broken Veld	465	406	380	251	138	30	23	87	180	291	360	431	87 / 4	180	63
33	Namaqualand Broken Veld	403	378	367	261	163	72	54	88	158	242	309	364	52 / 40	122	58
34	Strandveld	360	337	338	272	197	123	95	116	153	226	284	326	3 / 112	184	56

Figure 6.1 Climatic drivers used to develop biomass curves for selected Acocks' Veld Types

Table 6.1 *ACRU* land cover input parameters for selected Acocks' Veld Types

CAY : WATER USE (CROP) COEFFICIENT
VEGINT : INTERCEPTION (mm) per RAINDAY
COIAM : COEFFICIENT OF INTIAL ABSTRACTIONS (INFILTRABILITY)
ROOTA : ROOT FRACTION IN TOPSOIL

	ACOCKS' VELD TYPE	%SUR-FACE COVER	VARIA-BLE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
			COASTAL TROPICAL FOREST TYPES													
1	Coastal Forest and Thornveld	100.00	CAY	0.85	0.85	0.85	0.85	0.75	0.65	0.65	0.75	0.85	0.85	0.85	0.85	0.80
			VEGINT	3.10	3.10	3.10	3.10	2.50	2.00	2.00	2.50	3.10	3.10	3.10	3.10	2.82
			ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
2	Alexandria Forest	100.00	CAY	0.60	0.85	0.85	0.85	0.75	0.75	0.70	0.70	0.70	0.65	0.60	0.60	0.72
			VEGINT	2.00	2.50	2.50	2.50	2.00	2.00	1.90	1.90	1.90	1.90	1.90	1.90	2.08
			ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
3	Pondoland Coastal Plateau Sourveld	91.20	CAY	0.80	0.80	0.80	0.70	0.60	0.55	0.50	0.60	0.70	0.75	0.75	0.80	0.70
			VEGINT	2.50	2.50	2.50	2.30	2.00	2.00	2.00	2.00	2.20	2.30	2.40	2.50	2.27
			ROOTA	0.80	0.80	0.80	0.80	0.85	0.90	0.90	0.85	0.80	0.80	0.80	0.80	0.83
			COIAM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25	0.28
4	Knysna Forest	100.00	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.80	0.85	0.85	0.85	0.85	0.85	0.85
			VEGINT	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
			ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
5	Ngongoni Veld - Zululand	73.40	CAY	0.70	0.70	0.70	0.65	0.55	0.50	0.50	0.55	0.60	0.65	0.65	0.70	0.62
			VEGINT	1.40	1.40	1.40	1.40	1.30	1.20	1.20	1.30	1.40	1.40	1.40	1.40	1.35
			ROOTA	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.90	0.90	0.90	0.90	0.92
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
6	Zululand Thornveld	91.20	CAY	0.80	0.80	0.80	0.70	0.65	0.50	0.50	0.60	0.75	0.80	0.80	0.80	0.71
			VEGINT	2.40	2.40	2.40	2.10	1.80	1.80	1.80	1.80	2.20	2.40	2.40	2.40	2.16
			ROOTA	0.80	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.80	0.80	0.80	0.80	0.83
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
7	Eastern Province Thornveld	82.30	CAY	0.75	0.75	0.75	0.65	0.50	0.40	0.40	0.40	0.60	0.70	0.75	0.75	0.62
			VEGINT	1.60	1.60	1.60	1.50	1.40	1.30	1.30	1.40	1.60	1.60	1.60	1.60	1.51
			ROOTA	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.85	0.82	0.80	0.80	0.80	0.84
			COIAM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.28
			INLAND TROPICAL FOREST TYPES													
8	North-Eastern Mountain Sourveld	82.30	CAY	0.75	0.75	0.75	0.60	0.50	0.25	0.25	0.25	0.50	0.70	0.70	0.75	0.56
			VEGINT	2.60	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.60	2.60	2.60	2.37
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.87	0.80	0.80	0.80	0.87
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
9	Lowveld Sour Bushveld	82.30	CAY	0.75	0.75	0.75	0.70	0.65	0.60	0.55	0.55	0.60	0.75	0.75	0.75	0.68
			VEGINT	2.50	2.50	2.50	2.40	2.20	2.00	2.00	2.20	2.40	2.50	2.50	2.50	2.35
			ROOTA	0.80	0.80	0.80	0.85	0.85	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
			TROPICAL BUSH AND SAVANNA TYPES (BUSHVELD)													
10	Lowveld	91.20	CAY	0.80	0.80	0.80	0.65	0.55	0.40	0.40	0.40	0.60	0.75	0.75	0.80	0.64
			VEGINT	2.50	2.50	2.50	2.10	1.90	1.90	1.90	1.90	2.10	2.50	2.50	2.50	2.23
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
11	Arid Lowveld	91.20	CAY	0.80	0.75	0.60	0.50	0.45	0.40	0.40	0.40	0.40	0.50	0.75	0.80	0.56
			VEGINT	2.10	2.10	2.10	2.00	1.90	1.80	1.80	1.80	1.90	2.00	2.10	2.10	1.98
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
12	Springbok Flats Turf Thornveld	82.30	CAY	0.70	0.70	0.60	0.50	0.45	0.30	0.20	0.20	0.40	0.50	0.70	0.75	0.50
			VEGINT	2.30	2.30	2.30	2.00	1.80	1.70	1.60	1.70	1.80	2.00	2.30	2.30	2.01
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.90	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
13	Other Turf Thornveld	82.30	CAY	0.75	0.70	0.60	0.50	0.45	0.20	0.20	0.20	0.40	0.50	0.60	0.70	0.48
			VEGINT	2.30	2.30	2.30	2.00	1.80	1.70	1.60	1.70	1.80	2.00	2.30	2.30	2.01
			ROOTA	0.80	0.80	0.80	0.85	0.85	1.00	1.00	1.00	0.90	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
14	Arid Sweet Thornveld	82.30	CAY	0.75	0.60	0.50	0.45	0.35	0.30	0.20	0.20	0.40	0.55	0.65	0.75	0.48
			VEGINT	1.60	1.60	1.60	1.50	1.30	1.20	1.10	1.10	1.20	1.40	1.60	1.60	1.40
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.95	1.00	1.00	0.95	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
15	Mopani Veld	82.30	CAY	0.75	0.55	0.50	0.40	0.40	0.40	0.40	0.40	0.40	0.50	0.60	0.75	0.50
			VEGINT	1.80	1.60	1.50	1.50	1.50	1.40	1.30	1.30	1.30	1.50	1.70	1.80	1.52
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
16	Kalahari Thornveld	82.30	CAY	0.65	0.75	0.70	0.60	0.45	0.20	0.20	0.20	0.40	0.50	0.55	0.65	0.49
			VEGINT	1.10	1.10	1.10	1.10	1.00	0.90	0.80	0.80	0.80	0.90	1.00	1.10	0.98
			ROOTA	0.80	0.80	0.80	0.87	0.93	1.00	1.00	1.00	0.90	0.88	0.85	0.80	0.89
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
17	Kalahari Thornveld invaded by Karoo	64.50	CAY	0.60	0.65	0.60	0.45	0.30	0.20	0.20	0.20	0.20	0.40	0.50	0.60	0.41
			VEGINT	1.50	1.60	1.60	1.50	1.30	1.10	1.10	1.10	1.20	1.30	1.40	1.50	1.35
			ROOTA	0.80	0.80	0.80	0.87	0.93	1.00	1.00	1.00	1.00	0.95	0.90	0.80	0.90
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
18	Mixed Bushveld	82.30	CAY	0.75	0.75	0.65	0.55	0.40	0.20	0.20	0.30	0.55	0.60	0.75	0.75	0.54
			VEGINT	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.40	2.40	2.60	2.60	2.33
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25

7 GENERAL DISCUSSION

In this study, the impacts on runoff of land cover in the form of maize and wheat crops, and land management, in the form of different tillage practices, have been investigated. Observed runoff plot data were obtained from three studies conducted in South Africa. These data were synthesised and then used to attempt to improve the modelling of land use by the *ACRU* model. By virtue of the nature of runoff plot data, the study focussed on surface and near-surface runoff processes. The research was carried out in a context of increasing competition for water amongst different users in South Africa, and the need to accurately estimate the impacts of land use on streamflow, particularly in light of the declaration of SFRAs, and the associated implications for water use licensing and charging of water levies.

An important objective of this study was the acquisition and collation of historical measured field data that focuses on land use related hydrological processes. This objective was considered important because, although many good quality field data have been collected in the past in South Africa, these data sets have often not been utilised to their full potential, and, furthermore, are at risk of being misplaced or discarded as time progresses and research emphasis changes. It is believed that such data still have great value in research, especially given the high costs of conducting field measurements. In the project a decision was made to focus on runoff plot data where the hydrological impacts of crops under different forms of tillage were investigated.

Three runoff plot data sets were acquired in this regard. The acquisition and collation of the Directorate of Engineering and Soil Conservation runoff plot data set is considered to be particularly significant in terms of the factors motivating the data acquisition and collation objective of the project. The DESC study has yet to be formally reported and has no staff actively working with the data set. The original technician responsible for the study is now retired, but may be contracted to complete a final report (Armour, 2002). The electronic and hardcopy data collected required considerable effort and time before they could be used in analyses for this report. The work conducted in this project has been of significant benefit in ensuring the future usefulness of this data set.

The project by Bennie *et al*. (1994) was well reported. However, many of the data collected, in particular runoff and soil moisture data, were not published in the report *per se*, and were only available directly from Prof Bennie in a outdated spreadsheet format on multiple 3½" disks. The conversion of these data files to a contemporary spreadsheet format (Microsoft Excel) and consolidation onto one compact disc, make them more readily available to other users. The data were also processed into a form better suited for use in model verification studies.

The South African Rainfall Simulator Programme data set has now been formatted into a contemporary electronic spreadsheet format (Microsoft Excel) and is more readily available for further analyses and use. The project has served to revive the use of this data set, which was collected some 20 years ago.

The three data sets acquired in this project have been synthesised, with analyses being performed on aspects of interest to the modelling of tillage practices with the *ACRU* model. The data sets are available for further analyses to be conducted in other areas of interest.

The approach adopted to modelling tillage in the project focussed on representing the influences of mulch cover, surface roughness and plough action on processes such as interception, infiltration, depression storage, evaporation, soil moisture storage and vertical drainage. In modelling the impacts of tillage on initial abstractions, an intuitive approach to systematically estimate the *ACRU* initial abstraction parameter (COIAM) for different tillage and site conditions was developed. This parameter, along with the parameter for the critical depth of soil for stormflow generation (SMDDEP), is important in the *ACRU* model to simulate the infiltration/runoff process, and is influenced by a number of factors. The generic approach was developed with the intention of it being applicable under varying conditions and not just at the sites where the approach was developed.

The approach used to model tillage correctly predicted the seasonal sequence of runoff responses of the different tillage practices at Cedara and Bloemfontein for most seasons. The relative orders of magnitude of runoff responses of the different practices were less well represented, with the simulated differences in runoff between the practices being smaller than those observed. The approach to modelling tillage thus requires further research to improve the results. The improvements in simulation results that were obtained during the course of the project and the lessons learned still represent progress in the modelling of tillage with the *ACRU* model.

The different sequences of response of the various tillage practices at the Cedara and Bloemfontein sites implies that a NT system will not always result in less runoff than a CvT system. In the case of the Bloemfontein site, NT yielded the most runoff as a result of surface crusting, soil compaction and relatively low mulch cover. This highlights the importance of considering site characteristics (e.g. soils, climate, vegetation) when predicting the impact of different tillage practices on runoff response. While reduced tillage systems are usually implemented with the partial objective of reducing surface runoff and associated soil loss, they may also be implemented to control wind erosion, where reductions in runoff relative to CvT systems may not occur.

Based on the experience gained in modelling tillage at Cedara and Bloemfontein, it is hypothesised that, in general, the response of a NT system relative to a CvT system depends on the balance of the effects caused by increased mulch cover and the lack of plough action. The effects of increased mulch cover include increased infiltration opportunity, crust prevention and organic matter enhancement, while lack of plough action results in lower porosity and, therefore, less moisture storage capacity, as well as the possibility of compaction problems. The response of a CvT system can be influenced by a plough pan if present. In a NT system, any naturally occurring macropores (derived, for example, from soil organisms or roots) that are present, are preserved. These pores can be very effective in maintaining good rates of water infiltration into the soil. The increased porosity of a CvT system resulting from the creation of artificial macropores during ploughing is temporary, as consolidation of the soil takes place during the season. The response of any tillage system is also very dependent on site characteristics such as rainfall properties, slope and soil type.

For future applications of *ACRU*, a summary of general recommendations for determining values of relevant input variables under tilled conditions in South Africa, is presented in Table 7.1. It is emphasized that these recommendations represent a starting point in modelling different forms of tillage with the *ACRU* model, and that further research (see above and below) is required to improve the representation of tillage in the *ACRU* model and the resulting simulations that are obtained.

Table 7.1 Summary of general recommendations for determining values of relevant *ACRU* input variables under tilled conditions in South Africa

Variable	Source of Information	Comments
PCSUCO	Literature / available data	If appropriate, Cedara (Table 5.1) and Bloemfontein (Table 5.4) values may be used to represent maize in more humid areas and winter wheat in more arid areas, respectively.
COIAM	Figure 4.2	Use PCSUCO values to represent mulch cover in the COIAM matrix. Use the random roughness equation of Zobeck and Onstad (1987), or an alternative, to represent surface roughness. If in a more humid area (e.g. Cedara) set all NT values to 0.35.
PO1	Table 4.3	For NT: use untilled topsoil porosity value. For CvT: use average of freshly tilled and end of season topsoil porosity values. For CsT: use average of NT and CvT topsoil porosity values.
SMDDEP	Figure 3.2 (general SMDDEP value for site)	If depth of till > $SMDDEP_{site}$, set SMDDEP = depth of till. If depth of till < $SMDDEP_{sitet}$ and plough pan present, set SMDDEP = depth of till. Else set SMDDEP = $SMDDEP_{site}$
ABRESP	Smithers & Schulze (1995)	If a plough pan is present decrease value to 0.1. If naturally occurring macropores are frequent (e.g. from earthworms, root channels), increase value to 0.7 for CsT and 1 for NT.
VEGINT	*ACRU* software	Default values represent CvT mulch conditions. For more humid areas (e.g. Cedara), increase default values to represent CsT and NT mulch conditions.

One of the site factors that was considered in the approach to modelling I_a in this study, was rainfall intensity. Monthly categories of this variable were used in the selection of COIAM values. In practice, the estimation of monthly categories of rainfall intensity in a catchment would pose difficulties owing to lack of suitable data. Methods of estimating rainfall intensity in the absence of suitable measured data, and the representation of this variable in infiltration/runoff processes needs to be pursued further, as it is an important determinant in hydrological response, particularly at smaller scales.

Although an attempt to identify relationships in the SARSP data to directly predict initial abstractions as a physical quantity in millimetres gave inconclusive results, this approach is still believed to be worth pursuing, provided suitable observed data sets can be found (e.g. from the USA). In order for predictive relationships to be established, these data sets should focus on fewer sites than those of the SARSP, but contain a greater range in test conditions at each site, e.g. mulch cover, antecedent soil moisture and rainfall application intensity. This would result in less variability in the data as a result of differences between sites, thus allowing for the possibility of developing usable predictive relationships. The approach to modelling I_a adopted in this project tends to represent influencing factors in a linear manner, whereas predictive relationships based on observed data might represent these factors in a more realistic non-linear manner.

When considering the hydrological impacts of tillage at a field scale, it is not only the type of practice (e.g. NT, CsT, CvT) which is important, but also the manner in which it is implemented. For example, the operations performed and the timing of the operations, which implements are used, the susceptibility of the soils to develop plough pans, the frequency with which these plough pans are broken up, and the depth and cover of mulch typically left on the soil surface after tillage. At a catchment scale, these aspects of management, as well as the types of crops and areas planted, are likely to be highly variable over time and space. The *ACRU* model is able to represent annual changes in land cover and land management by way of the dynamic land use option (Schulze, 1995). Spatial variations in land use can be accommodated to some extent by delineating the catchment into smaller more homogeneous subcatchments. However, in a practical context, spatial variations in land use would still exist, and a generalised representation of land use in the subcatchments would need to be developed from available information. For large-scale catchments this would constitute a major task, and the decision to represent management practices such as tillage should take this into account.

It should be noted that although this study has focused on the hydrological impacts of tillage as a land management practice, the modifications introduced to the *ACRU* model in the project could, in many cases, be applicable to other land use types. Thus the ability of the model to simulate a wider range of land use impacts on hydrological response has potentially been improved. For example; initial abstractions are an important component of the runoff generation process regardless of the management practice. A further example is the suppression of soil water evaporation due to a mulch cover, which can occur in almost any vegetative land use.

As the *ACRU* model has been widely verified in previous studies (Schulze, 1995), it may be used to simulate the impacts on catchment streamflow of maize, wheat and a variety of other crops (e.g. sorghum, sunflower), as well as combinations of these crops. The research conducted in this project has improved the representation of tillage practices in such crop impact assessments. However, the influence of different tillage practices on streamflow may only be simulated with relatively low confidence at this time. A variety of reasons exist for this, including the following:

- The ability of the model to simulate the impacts of different tillage practices at catchment scales is still uncertain as suitable observed data at such scales are not available. Problems arise when scaling results from runoff plots to catchments, as has been discussed in this report.
- The differences which were simulated between the various tillage practices in this study need to be verified against observations of other aspects of hydrological response, e.g. evaporation, changes in soil moisture, crop yield, groundwater recharge and base/low flows. Such an investigation may help to explain the small differences in simulated runoff response found in the study.
- The representation of tillage practices in the model ideally needs to be verified in other locations having different climates, soils and slopes to those at Cedara and Bloemfontein.

This project has focussed on surface runoff processes and has not considered the impacts on base/low flows. The impacts of tillage on these flows may be difficult to predict and may depend on factors such as climate and soil type. For instance, a no till practice which causes an increase in infiltration and soil moisture may result in increased groundwater recharge and thus baseflow. Alternatively, the increase in infiltration and soil moisture may result in increased transpiration and a negligible impact on baseflow. The lack of relevant observed data against which base/low flow simulations involving agricultural land uses can be compared presents difficulties (i.e. data from controlled catchment scale experiments are not available). It is likely that the impacts on base/low flows would have to be considered indirectly via a general assessment of the water balance.

As the impacts of tillage on catchment streamflow (both stormflow and baseflow) can only be simulated with low confidence (see above), any current application of *ACRU* that might suggest certain tillage practices reduce streamflow would not constitute sufficient evidence for these practices to be considered as streamflow reduction activities. Such deductions cannot be made from observations either, as no suitable measurements are available as yet. If reduced tillage practices such as no till were found to reduce streamflow, these reductions would have to be weighed up against the many benefits that may be derived from these practices. This implies that SFRA policy may have to become more flexible to accommodate the potential benefits of these (and other) agricultural practices. Examples of the potential benefits of no till include reduced soil loss and improved stream water quality. This study has only considered the impacts of tillage on water quantity, and has not considered impacts on water quality, an important consideration in the management of water resources. From an agronomic perspective, benefits such as higher crop yields (resulting from wetter soil moisture), reduced input costs (resulting from fuel savings) and thus greater overall profitability can potentially be attained under no till.

The new approach developed to estimate *ACRU* land cover input parameters for the Acocks' Veld Types, based on climatic drivers of plant growth, has ensured consistency and transparency in estimates of these parameters. This represents an important improvement, particularly as Acocks' Veld Types become accepted as a baseline land cover in assessing streamflow reduction activities. Consistency and transparency are required in the determination of SFRAs and associated licensing procedures (DWAF, 1999). Ideally, the input parameters and simulated hydrological response of the Veld Types should be assessed against observed data. The data currently being collected in the WRC funded project entitled "Improving the Basis for Predicting Evapotranspiration from Dry-land Crops and Veld Types in South African Hydrological Models" (Project No. K5/1219), should facilitate some assessments in this regard.

This study has considered the impacts of short rotation (seasonal) agricultural crops and associated management practices on runoff responses. In this context, it is suggested that the concept of streamflow reduction activities needs to be re-considered, as difficulties arise when assessing such a land use in terms of this concept of "water use", when "water use" is determined at the catchment outlet. The difficulties arise from the dynamic changes in land cover and land management which characterise agricultural land use. These changes imply that a mixed signal will be evident in the resulting impacts on streamflow as a consequence of lags in the hydrological system, where impacts on streamflow not only reflect the current land use, but also recent past land uses. In terms of longer rotation land uses, such as forestry, this phenomenon is less pronounced, particularly if management practices are consistent. The dynamic nature of short rotation agricultural land uses also implies that the control of these land uses would be very difficult if they were to be declared as streamflow reduction activities. The crops planted and the management practices applied are constantly changing, both spatially and temporally, and would be difficult to monitor over large areas.

In recent international literature, researchers have distinguished between movement of water in the hydrological cycle when in vapour form, as opposed to liquid form, where these are termed "green" water and "blue" water respectively (Falkenmark *et al*., 1999; FAO, 2000). The land use in a catchment partitions rainfall between water vapour flows to the atmosphere as evaporation and transpiration (green water), and flow of water to rivers and groundwater (blue water). The difficulties discussed above in assessing the impacts of crops and associated management practices on streamflow (blue water), including low flows, imply that it is perhaps more appropriate to assess impacts on total evaporation losses (green water), particularly as these form a larger component of the water balance. However, as discussed in the introduction to this report, the estimation of evaporative losses from crops is complicated by high spatial and temporal variability in soil moisture, which is the major limiting factor to total evaporation losses in South African conditions. The assessment and control of crop and associated management impacts on water resources therefore remains a difficult issue to address for legislators, managers and researchers.

8 RECOMMENDATIONS FOR FUTURE RESEARCH

A summary of recommendations emanating from this study is presented below:

- In the absence of rainfall intensity measurements, methods of estimating indices of spatial and temporal patterns of rainfall intensity from daily rainfall records, should be developed for use in hydrological models to improve the modelling of runoff responses. Rainfall intensity is an important determinant in hydrological response from land uses such as tilled agricultural fields, and should be represented in some manner in the infiltration/runoff process, as was attempted in this study.
- The tillage modelling approach adopted in this study needs to be tested and refined further in terms of hydrological responses other than runoff, e.g. soil loss. The approach also needs to be tested under a greater range of site conditions including different soils, slopes, and climates.
- It is believed that the simulation of initial abstractions in the *ACRU* model might be improved if predictive relationships could be developed to directly predict I_a as a physical quantity in millimetres, rather than by way of a coefficient. This would depend on the availability of suitable runoff plot data sets involving rainfall simulators, as discussed in Chapter 7.
- The modelling of the impacts of tillage on base/low flows has not been verified against observed data in this study. The lack of suitable observed data implies that the impacts would have to be assessed indirectly via a general assessment of the water balance.
- The modelling of tillage impacts on water quality should be investigated as this study has only considered impacts on water quantity. The potentially beneficial impacts of reduced tillage on water quality might outweigh any negative impacts that these practices have on water quantity.
- The land use related input parameters estimated for the Acocks' Veld Types in this study, and the resulting simulated hydrological responses, should be assessed against observed data. The data currently being collected in another WRC funded project (Project No. K5/1219) will partially facilitate these assessments.
- It is suggested that the implementation of SFRAs in the National Water Act needs some careful conceptual re-consideration. This is in view of the dynamic nature of land cover and land management which characterises typical agricultural (non-forestry) land uses. As discussed in Chapter 7, difficulties may arise in assessing the hydrological impacts of these land uses in terms of impacts on streamflow. Furthermore, if these land uses were to be declared as SFRAs they would be difficult to regulate given their highly variable (spatial and temporal) nature. It may be more appropriate to assess hydrological impacts in terms of changes in total evaporation through the concepts of water use efficiency and "green water" ("more crop per drop"), although such an approach also presents challenges and may not be entirely satisfactory.

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APPENDIX B SIMULATIONS PERFORMED AT THE CEDARA SITE IN THE REFINEMENT OF THE TILLAGE MODELLING APPROACH

The series of simulations which was performed in the refinement of the tillage modelling approach at Cedara was as follows:

Run A

In Run A, the values assigned to tillage related variables were as follows:

For PCSUCO, the average values of mulch cover for each month of the year were derived from the measurements of mulch that were made each season. The values input to the model are tabulated in Table A1.

Monthly values of COIAM were obtained from Figure 4.2 for the appropriate categories of mulch cover, slope, rainfall intensity and surface roughness. The values of COIAM selected are tabulated in Table A1, while the appropriate categories of the determining variables are tabulated in Table A2.

Table A1 Values of PCSUCO and COIAM used in Run A

Variable	Trea-tment	Monthly Inputs											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PCSUCO (%)	NT	39.0	23.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	73.0	57.0
	CsT	13.0	5.0	5.0	5.0	5.0	5.0	5.0	35.0	35.0	35.0	31.0	22.0
	CvT	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	BF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COIAM	NT	0.22	0.22	0.19	0.22	0.22	0.22	0.22	0.22	0.22	0.19	0.27	0.25
	CsT	0.19	0.19	0.19	0.22	0.22	0.22	0.22	0.26	0.26	0.23	0.23	0.22
	CvT	0.19	0.19	0.19	0.22	0.22	0.22	0.22	0.23	0.26	0.23	0.21	0.21
	BF	0.19	0.19	0.19	0.22	0.22	0.22	0.22	0.22	0.22	0.19	0.21	0.19

Table A2 Categories of variables used in determining COIAM in Run A

Month	Rainfall Intensity	Slope	Random Roughness				Mulch Cover			
			NT	CsT	CvT	BF	NT	CsT	CvT	BF
Jan	4	3	1	1	1	1	2	1	1	1
Feb	4	3	1	1	1	1	2	1	1	1
Mar	4	3	1	1	1	1	1	1	1	1
Apr	5	3	1	1	1	1	1	1	1	1
May	5	3	1	1	1	1	1	1	1	1
Jun	5	3	1	1	1	1	1	1	1	1
Jul	5	3	1	1	1	1	1	1	1	1
Aug	5	3	1	3	2	1	1	2	1	1
Sep	5	3	1	3	4	1	1	2	1	1
Oct	4	3	1	2	3	1	1	2	1	1
Nov	4	3	1	2	2	2	4	2	1	1
Dec	4	3	1	1	2	1	3	2	1	1

In determining COIAM, the values of PCSUCO were used to determine the appropriate categories of mulch cover. The slopes of the runoff plots were very similar and all fell within Category 3. Rainfall intensity was assumed to fall within Category 4 during the summer months and Category 5 during winter months. The categories of surface roughness were determined by applying the random roughness equation of Zobeck and Onstad (1987).

A general value of SMDDEP was estimated for the Cedara site by referring to Figure 3.2 (value = 0.3m). The depths of ploughing at the runoff plots were 0.15m for CsT and 0.25m for CvT (Table 2.2). In the annual reports on the runoff plot experiments no mention was made of the formation of a plough pan. Therefore, since no plough pans were noted in the reports, and the depth of ploughing was not greater 0.3m, the general value of SMDDEP estimated for Cedara was used in Run A (0.3m).

The *ACRU* model only allows for a single topsoil porosity value to be entered into the model (PO1 variable). This variable was estimated for the CvT treatment by averaging the freshly tilled and end of season default values contained in Table 4.3 for a sandy clay soil (value = 0.510m/m). For the NT treatment the untilled value of topsoil porosity was used (0.393m/m). As CsT causes less disturbance of the soil than CvT, an average of the NT and CvT porosity values was used (0.450m/m). For the BF treatment a porosity value that was slightly higher than untilled conditions was used (0.400m/m), as this treatment was kept bare through shallow action of a rotovator. The default porosity value tabulated in Table 4.3 for the subsoil (sandy clay soil) was used for all treatments (PO2 = 0.428m/m).

After running the *ACRU* model the daily simulated runoff was accumulated over the intervals between runoff plot observations. These observations were made as soon as possible after a significant runoff producing event, usually the day after an event. In some smaller events runoff was simulated by the model but was not observed on the runoff plots. In these instances simulated runoff was still included in the accumulation. As discussed in Chapter 2.1 it was unclear for some events in the observed runoff record as to whether plots were missing data, did not generate any runoff or were not measured in terms of runoff response. Thus a decision was made to only consider events where runoff was recorded on all plots. This may imply that only larger events are considered. The runoff simulated for all considered events was summed for each season and plotted in Figure A1. The corresponding graph for observed data was presented in Chapter 2 (Figure 2.2)

The BF treatment was simulated as having the highest runoff, as was observed on the runoff plots. However, with respect to the cropped treatments, the NT treatment was simulated as having the highest runoff, and CvT the lowest, which was the opposite of what was observed on the runoff plots.

It is suspected that the differences in simulated runoff between the various cropped treatments is due to the influence of the PO1 variable. A large PO1 value, as used in the CvT simulation, results in a low runoff as the soil has a greater capacity to absorb and store water. The converse applies in the case of the NT simulation.

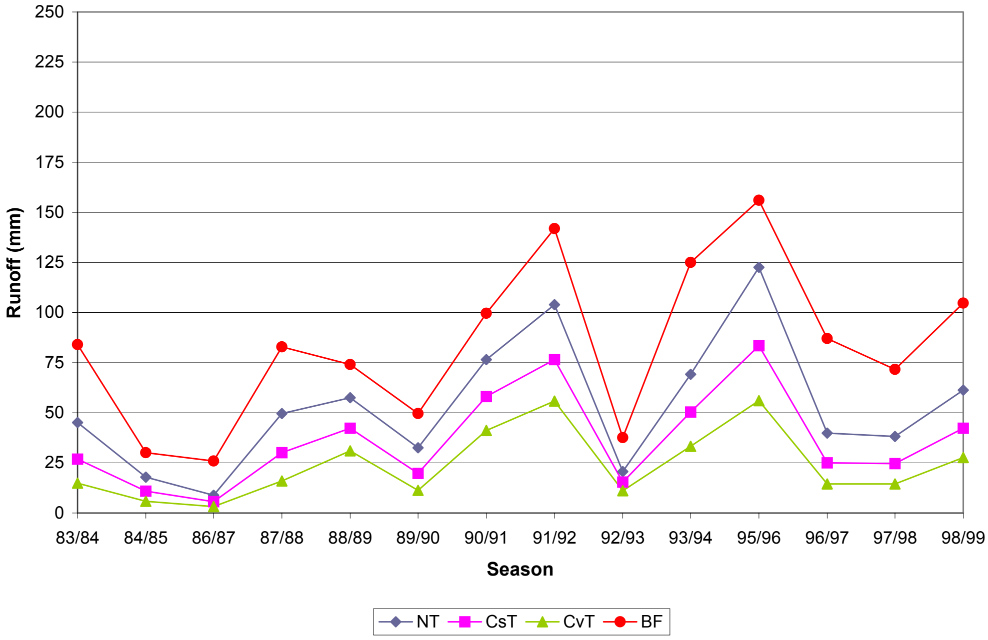

Figure A1 Simulated seasonal runoff for maize under various tillage practices at Cedara: Run A

<u>Run B</u>

To verify that the PO1 variable predominantly influences the simulated differences between the tillage treatments in Run A, simulations were performed where all treatments (including BF) were assigned the NT PO1 value. All other variables were maintained at the same values. The new set of simulations is presented in Figure B1. As expected, the differences between the cropped treatments were found to be very small. The runoff for the BF treatment was still distinctly higher than the cropped treatments. This can be ascribed to the low total evaporation and zero interception on this treatment, which would maintain higher soil moisture levels and thus runoff amounts.

<u>Run C</u>

It is suggested that the runoff reducing effects of mulch cover (e.g. increased infiltration opportunity, crust prevention, organic matter enhancement) influenced the response of the NT treatment at Cedara to a greater degree than that represented in the modelling approach thus far. Furthermore, the soil profile description at Cedara, which was carried out before commencement of the experiment, noted the frequent occurrence of macropores in the soil. These macropores, which would have been derived from soil organisms, roots etc., would have been maintained under NT and would have facilitated rapid infiltration and movement of water through the soil.

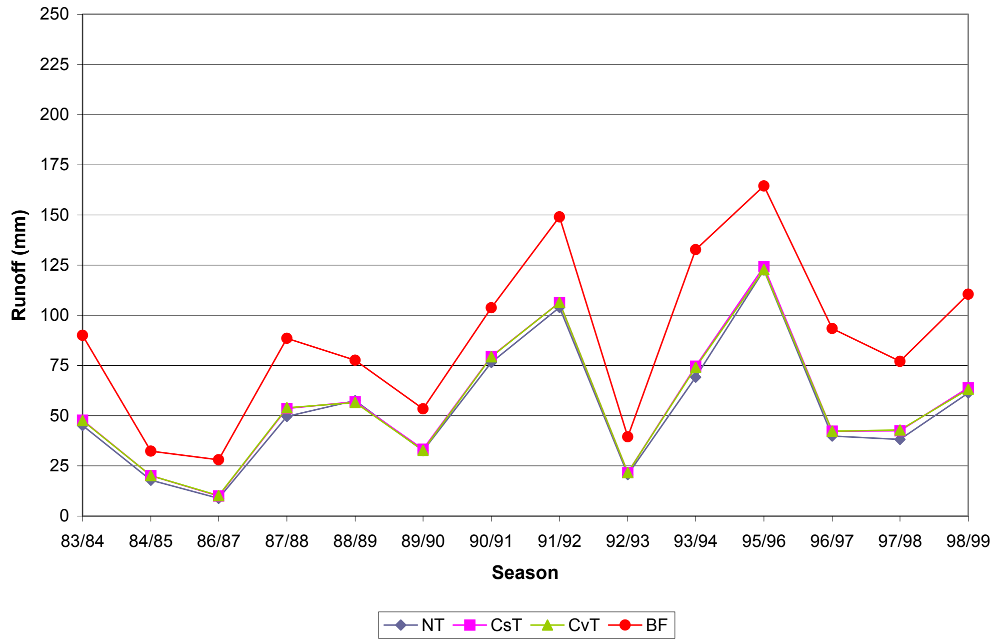

Figure B1 Simulated seasonal runoff for maize under various tillage practices at Cedara: Run B

To enhance the representation of mulch cover and to account for the influence of naturally occurring macropores, the following changes were introduced:

- the value of COIAM for all months of the year was set to 0.35 for the NT treatment to account for increased infiltration opportunity afforded by the mulch;
- the interception of rainfall by the maize crop on the NT treatment was increased to account for interception by the mulch (VEGINT variable); and
- In an attempt to account for macropore flow, the variable controlling the vertical drainage of water from the A to B horizon under saturated conditions (ABRESP), was increased from the default value of 0.4 to 1.0.

It was assumed that the mulch and macropore effects in the CsT system would have been less influential than for NT. Therefore the interception was increased to a lesser degree than NT. The value of ABRESP was increased from 0.4 to 0.7. COIAM was maintained at previous values. The values of VEGINT used for all treatments are shown in Table C1. The resulting simulations are plotted in Figure C1.

Table C1 Values of VEGINT used in Run C

Variable	Trea-tment	Monthly Inputs											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
VEGINT (mm)	NT	1.60	1.50	1.40	1.30	1.10	1.00	0.90	0.80	0.70	0.60	0.60	1.00
	CsT	1.55	1.45	1.35	1.25	1.05	0.80	0.65	0.55	0.50	0.50	0.55	0.95
	CvT	1.50	1.40	1.30	1.20	0.50	0.50	0.50	0.50	0.50	0.00	0.50	0.90
	BF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

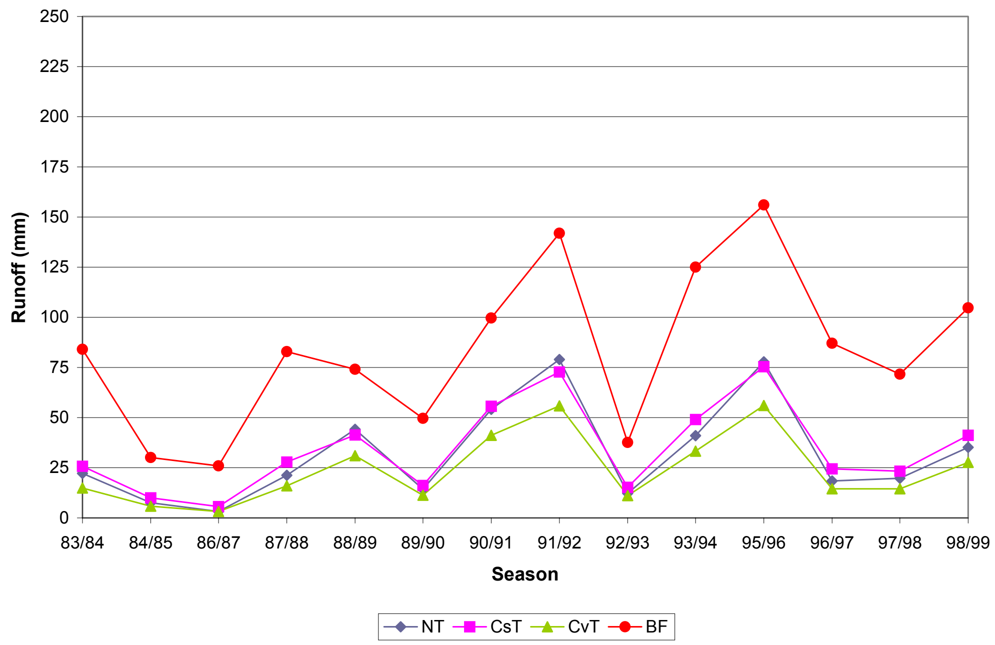

Figure C1 Simulated seasonal runoff for maize under various tillage practices at Cedara: Run C

Figure C1 shows that the increased emphasis on mulch and macropore effects generally results in the correct simulated sequence of CsT and NT runoff. The differences between the treatments are small. In the observed runoff data (Figure 2.2) the differences are also mostly small, exceptions being the 91/92 and 93/94 seasons. The simulated CvT runoff was still not in the correct sequence relative to the other treatments as it yielded the lowest runoff of the cropped treatments, while observations indicated that it was the highest.

Run D

It is suspected that a plough pan may have formed on the CvT runoff plot. Given that the experiment was conducted over 17 seasons, it is possible that a pan may have formed if no preventative action was taken. It has been speculated that the high clay content of the soil would not have provided favourable conditions for pan formation (Russell, 2002; pers. comm.). However, to confirm the presence or absence of a pan the soil profile would have had to be examined during the course of the experiment. For the purposes of this study it was assumed that a plough pan did form.

To account for the influence of a plough pan on the CvT plot, SMDDEP was reduced from the general site value (0.30m) to the depth of tillage (0.25m). A further change was made by reducing the ABRESP parameter from the default value of 0.4 to 0.1. This simulates the inhibited vertical drainage resulting from the presence of a plough pan. The results of these input refinements are shown in Figure D1.

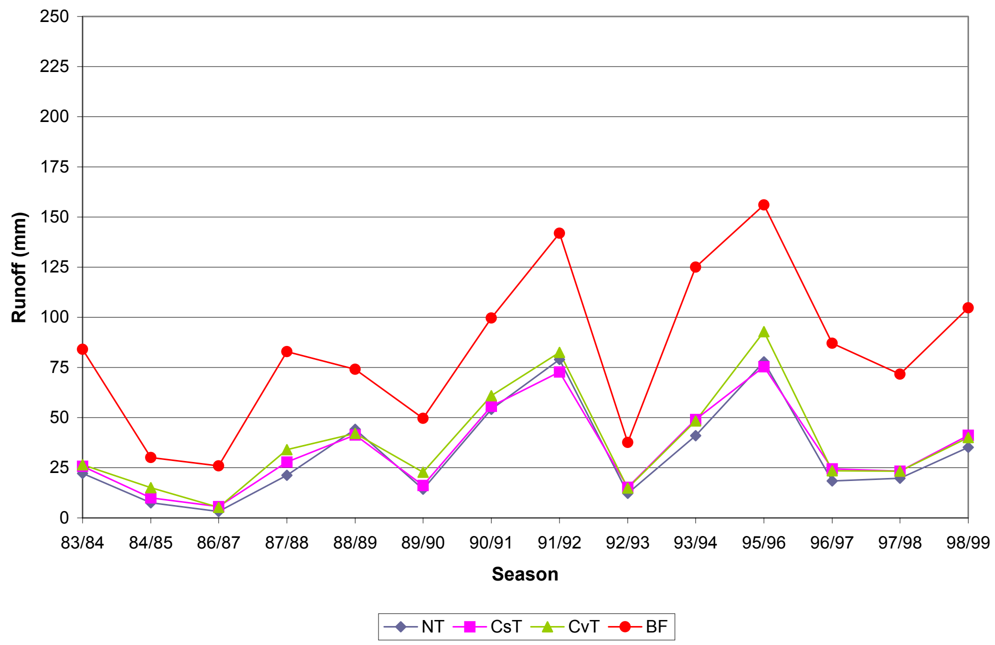

Figure D1 Simulated seasonal runoff for maize under various tillage practices at Cedara: Run D

The simulation of a plough pan increases CvT runoff such that it is greater than CsT runoff, thus ensuring the correct simulated sequence of runoff between the various cropped tillage treatments, relative to the observed. The simulated differences between the CvT and CsT treatments were smaller than those observed on the runoff plots. In certain seasons the CvT observed runoff data yields a much more peaked response relative to the other treatments than that represented in the model (e.g. 91/92 season).

APPENDIX C CLIMATIC DRIVERS USED TO DEVELOP BIOMASS CURVES FOR THE ACOCKS' VELD TYPES

Moisture Growing Season (days) : Lowest 10% Median Highest 10%
Frost Duration (only if > 10 days) :
Heat Units (base 10ºC) per month : 201

Number	Acocks' Veld Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	FROST (days)	MGS (days)	MAP (mm)	CONC %
	COASTAL TROPICAL FOREST TYPES																
1	Coastal Forest and Thornveld	428	392	412	338	278	201	200	231	270	313	340	405		256	929	37
2	Alexandria Forest	361	336	341	272	223	153	141	162	188	229	267	324		277	666	9
3	Pondoland Coastal Plateau Sourveld	366	337	352	285	239	171	169	197	221	253	276	336		269	1235	39
4	Knysna Forest	341	314	305	230	163	93	76	96	130	186	243	307	32	316	864	6
5	Ngongoni Veld - Zululand	349	322	330	257	195	120	122	164	203	239	266	327	10	236	901	46
6	Zululand Thornveld	434	388	406	329	264	177	184	236	285	327	353	414		205	790	47
7	Eastern Province Thornveld	350	326	329	257	206	126	119	153	180	219	252	315	10	237	683	28
	INLAND TROPICAL FOREST TYPES																
8	North-Eastern Mountain Sourveld	330	291	296	230	158	74	79	135	200	256	278	316	26	194	991	59
9	Lowveld Sour Bushveld	431	384	394	312	234	146	150	212	281	341	365	415		192	862	59
	TROPICAL BUSH AND SAVANNA TYPES (BUSHVELD)																
10	Lowveld	474	424	442	359	282	194	320	257	317	369	393	454		177	692	53
11	Arid Lowveld	487	433	446	366	285	191	195	257	324	386	419	470		114	533	63
12	Springbok Flats Turf Thornveld	419	367	367	272	175	78	81	160	260	340	362	400	46	136	556	63
13	Other Turf Thornveld	473	407	403	288	171	60	60	160	290	397	419	451	68	116	565	64
14	Arid Sweet Thornveld	478	417	420	321	216	111	112	197	305	395	426	460	25	48	418	68
15	Mopani Veld	504	442	460	380	298	201	205	265	332	406	441	487		103	421	68
16	Kalahari Thornveld	477	416	389	258	138	21	20	99	207	322	383	464	89	25	313	65
17	Kalahari Thornveld invaded by Karoo	453	384	347	209	93	0	0	54	154	274	342	422	110	9	321	60
18	Mixed Bushveld	433	378	380	284	184	83	85	167	270	353	378	415	42	132	524	65
19	Sourish Mixed Bushveld	417	360	350	248	141	41	42	126	233	329	359	398	63	142	591	63
20	Sour Bushveld	384	332	330	240	143	45	43	124	228	305	338	367	60	145	630	65
21	False Thornveld of Eastern Cape	361	332	322	231	157	69	62	110	158	211	258	327	50	60	521	30
22	Invasion of Grassveld by Acacia Karoo	329	291	270	167	81	0	0	49.6	113	175	227	296	114	95	523	45
23	Valley Bushveld	372	342	343	264	203	116	113	153	192	239	278	343	23	221	629	35
24	Noorsveld	423	384	366	255	178	83	71	121	180	251	314	388	54	0	262	31
25	Succulent Mountain Scrub	392	354	333	224	135	42	31	76	137	214	281	357	84	0	306	20
26	Karroid Broken Veld	392	353	327	212	118	26	14	57	123	209	279	355	94	110	203	32
27	Central Upper Karoo	374	328	291	155	48	0	0	0	78	177	252	335	138	20	231	49
28	Western Mountain Scrub	388	365	343	215	119	14	0	39	108	202	278	349	109	11	210	42
29	Arid Karoo	422	381	355	224	115	12	1.6	54	138	237	311	383	105	23	141	54
30	Central Lower Karoo	394	351	324	206	110	20	8	56	126	212	281	358	101		208	37
31	Succulent Karoo	403	375	364	272	192	107	78	110	164	242	309	366	37	48	140	53
32	Orange River Broken Veld	465	406	380	251	138	30	23	87	180	291	360	431	87	4	180	63
33	Namaqualand Broken Veld	403	378	367	261	163	72	54	88	158	242	309	364	52	40	122	58
34	Strandveld	360	337	338	272	197	123	95	116	153	226	284	326	3	112	184	56

APPENDIX C   Continued

Moisture Growing Season (days) : Lowest 10% Median Highest 10%
Frost Duration (only if > 10 days) :
Heat Units (base 10ºC) per month : 201

Number	Acocks' Veld Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	FROST (days)	MGS (days)	MAP (mm)	CONC %
	FALSE KAROO TYPES																
35	False Arid Karoo	426	367	333	200	91	0	0	48	140	245	314	394	117	6	239	55
36	False Upper Karoo	386	326	291	161	51	0	0	17	111	208	272	350	128	25	355	49
37	False Karroid Broken Veld	371	332	312	201	110	23	14	67	135	208	264	336	89	18	362	35
38	False Central Lower Karoo	392	353	332	224	133	44	34	82	152	228	287	361	80	11	323	33
39	False Succulent Karoo	400	372	352	230	119		8	50	129	219	294	360	95	11	99	47
40	False Orange River Broken Veld	457	389	357	222	112	3	0	71	168	281	348	426	101	7	297	59
41	Pan Turf Veld invaded by Karoo	426	363	333	207	96	0	0	67	171	276	332	400	105	9	405	58
42	Karroid Merxmuellera Mountain Veld replaced by Karoo	329	290	254	128	26	0	0	0	69	150	215	291	151	12	316	36
43	Mountain Renosterveld	352	321	288	164	67	0	0	0	65	155	237	312	121	51	308	34
	TEMPERATE AND TRANSITIONAL FOREST AND SCRUB TYPES																
44	Highland Sourveld and Döhne Sourveld	296	265	254	164	84	3	2	59	126	174	209	270	96	216	815	50
45	Natal Mist Belt Ngongoni Veld	316	290	291	216	144	63	68	118	171	212	239	299	42	230	920	50
46	Coastal Rhenosterveld	358	333	324	242	163	95	67	85	123	200	263	322	14	138	434	34
47	Coastal Macchia	338	312	309	239	163	104	78	88	122	189	245	304	10	142	430	36
	PURE GRASSVELD TYPES																
48	Cymbopogon-Themeda Veld	335	281	257	143	34	0	0	17	120	203	246	307	123	171	629	54
49	Transitional Cymbopogon Themeda Veld	358	301	276	159	47	0	0	25	134	225	269	330	122	102	546	54
50	Dry Cymbopogon-Themeda Veld	395	336	313	197	84	0	0	60	173	268	311	371	111	107	506	57
51	Pan Turf Veld	414	351	322	201	90	0	0	60	167	268	320	386	107	26	436	58
52	Themeda Veld or Turf Highveld	302	2602	250	150	48	0	0	39	144	217	240	284	111	173	662	59
53	Patchy Highveld to Cymbopogon-Themeda Veld Transition	316	270	256	150	45	0	0	34	140	217	246	295	116	170	639	57
54	Turf Highveld to Highland Sourveld Veld Transition	281	239	229	138	43	0	0	34	131	189	215	262	115	184	697	59
55	Bankenveld to Turf Highveld Transition	310	267	256	155	54	0	0	42	150	226	249	291	110	170	675	59
56	Highland Sourveld to Cymbopogen-Themeda Veld Transition	293	249	229	125	22	0	0	9	107	175	210	267	128	197	716	54
57	North-Eastern Sandy Highveld	267	230	223	140	51	0	0	45	135	188	209	251	91	192	769	59
58	Themeda-Festuca Alpine Veld	166	136	101	9	0	0	0	0	0	47	83	135	209	216	728	50
59	Stormberg Plateau Sweetvelt	290	241	200	84	0	0	0	0	45	126	179	253	158	108	539	43
60	Karroid Merxmuellera Mountain Veld	316	274	239	117	14	0	0	0	63	143	203	279	153	17	413	40
	FALSE GRASSVELD TYPES																
61	Bankenveld	337	293	281	182	78	0	0	64	176	256	278	321	96	167	658	60
62	Bankenveld to Sour Sandveld Transition	319	277	278	192	105	20	25	98	182	234	258	305	76	206	848	58
63	Piet Retief Sourveld	317	280	284	204	124	41	47	115	189	237	258	305	57	213	918	57
64	Northen Tall Grassveld	371	325	336	252	177	90	98	160	227	274	300	355	31	210	839	54
65	Southern Tall Grassveld	333	297	293	206	124	41	43	105	174	225	257	313	74	200	812	56
66	Natal Sour Sandveld	347	305	309	221	136	50	56	122	198	247	276	332	69	191	746	58
67	Pietersburg Plateau False Grassveld	355	308	307	230	143	50	50	118	206	281	309	341	55	122	477	64
68	Eastern Province Grassveld	357	326	309	218	138	53	42	93	144	202	252	322	78	12	388	28
69	Macchia	319	302	284	195	113	35	14	36	83	160	228	284	63	149	625	50
70	False Macchia	330	304	295	206	127	45	31	62	110	175	230	293	75	218	532	12

APPENDIX D *ACRU* LAND COVER INPUT PARAMETERS FOR THE ACOCKS' VELD TYPES

CAY : WATER USE (CROP) COEFFICIENT
VEGINT : INTERCEPTION (mm) per RAINDAY
COIAM : COEFFICIENT OF INTIAL ABSTRACTIONS (INFILTRABILITY)
ROOTA : ROOT FRACTION IN TOPSOIL

	ACOCKS' VELD TYPE	%SUR-FACE COVER	VARIA-BLE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
			COASTAL TROPICAL FOREST TYPES													
1	Coastal Forest and Thornveld	100.00	CAY	0.85	0.85	0.85	0.85	0.75	0.65	0.65	0.75	0.85	0.85	0.85	0.85	0.80
			VEGINT	3.10	3.10	3.10	3.10	2.50	2.00	2.00	2.50	3.10	3.10	3.10	3.10	2.82
			ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
2	Alexandria Forest	100.00	CAY	0.60	0.85	0.85	0.85	0.75	0.75	0.70	0.70	0.70	0.65	0.60	0.60	0.72
			VEGINT	2.00	2.50	2.50	2.50	2.00	2.00	1.90	1.90	1.90	1.90	1.90	1.90	2.08
			ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
3	Pondoland Coastal Plateau Sourveld	91.20	CAY	0.80	0.80	0.80	0.70	0.60	0.55	0.50	0.60	0.70	0.75	0.75	0.80	0.70
			VEGINT	2.50	2.50	2.50	2.30	2.00	2.00	2.00	2.00	2.20	2.30	2.40	2.50	2.27
			ROOTA	0.80	0.80	0.80	0.80	0.85	0.90	0.90	0.85	0.80	0.80	0.80	0.80	0.83
			COIAM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25	0.28
4	Knysna Forest	100.00	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.80	0.85	0.85	0.85	0.85	0.85	0.85
			VEGINT	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
			ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
5	Ngongoni Veld - Zululand	73.40	CAY	0.70	0.70	0.70	0.65	0.55	0.50	0.50	0.55	0.60	0.65	0.65	0.70	0.62
			VEGINT	1.40	1.40	1.40	1.40	1.30	1.20	1.20	1.30	1.40	1.40	1.40	1.40	1.35
			ROOTA	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.90	0.90	0.90	0.90	0.92
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
6	Zululand Thornveld	91.20	CAY	0.80	0.80	0.80	0.70	0.65	0.50	0.50	0.60	0.75	0.80	0.80	0.80	0.71
			VEGINT	2.40	2.40	2.40	2.10	1.80	1.80	1.80	1.80	2.20	2.40	2.40	2.40	2.16
			ROOTA	0.80	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.80	0.80	0.80	0.80	0.83
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
7	Eastern Province Thornveld	82.30	CAY	0.75	0.75	0.75	0.65	0.50	0.40	0.40	0.40	0.60	0.70	0.75	0.75	0.62
			VEGINT	1.60	1.60	1.60	1.50	1.40	1.30	1.30	1.40	1.60	1.60	1.60	1.60	1.51
			ROOTA	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.85	0.82	0.80	0.80	0.80	0.84
			COIAM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.28
			INLAND TROPICAL FOREST TYPES													
8	North-Eastern Mountain Sourveld	82.30	CAY	0.75	0.75	0.75	0.60	0.50	0.25	0.25	0.25	0.50	0.70	0.70	0.75	0.56
			VEGINT	2.60	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.60	2.60	2.60	2.37
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.87	0.80	0.80	0.80	0.87
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
9	Lowveld Sour Bushveld	82.30	CAY	0.75	0.75	0.75	0.70	0.65	0.60	0.55	0.55	0.60	0.75	0.75	0.75	0.68
			VEGINT	2.50	2.50	2.50	2.40	2.20	2.00	2.00	2.20	2.40	2.50	2.50	2.50	2.35
			ROOTA	0.80	0.80	0.80	0.85	0.85	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
			TROPICAL BUSH AND SAVANNA TYPES (BUSHVELD)													
10	Lowveld	91.20	CAY	0.80	0.80	0.80	0.65	0.55	0.40	0.40	0.40	0.60	0.75	0.75	0.80	0.64
			VEGINT	2.50	2.50	2.50	2.10	1.90	1.90	1.90	1.90	2.10	2.50	2.50	2.50	2.23
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
11	Arid Lowveld	91.20	CAY	0.80	0.75	0.60	0.50	0.45	0.40	0.40	0.40	0.40	0.50	0.75	0.80	0.56
			VEGINT	2.10	2.10	2.10	2.00	1.90	1.80	1.80	1.80	1.90	2.00	2.10	2.10	1.98
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
12	Springbok Flats Turf Thornveld	82.30	CAY	0.70	0.70	0.60	0.50	0.45	0.30	0.20	0.20	0.40	0.50	0.70	0.75	0.50
			VEGINT	2.30	2.30	2.30	2.00	1.80	1.70	1.60	1.70	1.80	2.00	2.30	2.30	2.01
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.90	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
13	Other Turf Thornveld	82.30	CAY	0.75	0.70	0.60	0.50	0.45	0.20	0.20	0.20	0.40	0.50	0.60	0.70	0.48
			VEGINT	2.30	2.30	2.30	2.00	1.80	1.70	1.60	1.70	1.80	2.00	2.30	2.30	2.01
			ROOTA	0.80	0.80	0.80	0.85	0.85	1.00	1.00	1.00	0.90	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
14	Arid Sweet Thornveld	82.30	CAY	0.75	0.60	0.50	0.45	0.35	0.30	0.20	0.20	0.40	0.55	0.65	0.75	0.48
			VEGINT	1.60	1.60	1.60	1.50	1.30	1.20	1.10	1.10	1.20	1.40	1.60	1.60	1.40
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.95	1.00	1.00	0.95	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
15	Mopani Veld	82.30	CAY	0.75	0.55	0.50	0.40	0.40	0.40	0.40	0.40	0.40	0.50	0.60	0.75	0.50
			VEGINT	1.80	1.60	1.50	1.50	1.50	1.40	1.30	1.30	1.30	1.50	1.70	1.80	1.52
			ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80	0.84
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
16	Kalahari Thornveld	82.30	CAY	0.65	0.75	0.70	0.60	0.45	0.20	0.20	0.20	0.40	0.50	0.55	0.65	0.49
			VEGINT	1.10	1.10	1.10	1.10	1.00	0.90	0.80	0.80	0.80	0.90	1.00	1.10	0.98
			ROOTA	0.80	0.80	0.80	0.87	0.93	1.00	1.00	1.00	0.90	0.88	0.85	0.80	0.89
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
17	Kalahari Thornveld invaded by Karoo	64.50	CAY	0.60	0.65	0.60	0.45	0.30	0.20	0.20	0.20	0.20	0.40	0.50	0.60	0.41
			VEGINT	1.50	1.60	1.60	1.50	1.30	1.10	1.10	1.10	1.20	1.30	1.40	1.50	1.35
			ROOTA	0.80	0.80	0.80	0.87	0.93	1.00	1.00	1.00	1.00	0.95	0.90	0.80	0.90
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
18	Mixed Bushveld	82.30	CAY	0.75	0.75	0.65	0.55	0.40	0.20	0.20	0.30	0.55	0.60	0.75	0.75	0.54
			VEGINT	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.40	2.40	2.60	2.60	2.33
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25

APPENDIX D Continued

CAY : WATER USE (CROP) COEFFICIENT
COIAM : COEFFICIENT OF INTIAL ABSTRACTIONS (INFILTRABILITY)
VEGINT : INTERCEPTION (mm) per RAINDAY
ROOTA : ROOT FRACTION IN TOPSOIL

	ACOCKS' VELD TYPE	%SUR-FACE COVER	VARIA-BLE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
19	Sourish Mixed Bushveld	82.30	CAY	0.75	0.75	0.75	0.60	0.45	0.20	0.20	0.20	0.55	0.70	0.75	0.75	0.55
			VEGINT	2.70	2.70	2.60	2.20	2.00	2.00	2.00	2.00	2.20	2.50	2.70	2.70	2.36
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.90	0.85	0.80	0.80	0.80	0.86
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
20	Sour Bushveld	82.30	CAY	0.75	0.75	0.75	0.60	0.45	0.20	0.20	0.20	0.55	0.70	0.75	0.75	0.55
			VEGINT	2.70	2.70	2.60	2.20	2.00	2.00	2.00	2.00	2.20	2.50	2.70	2.70	2.36
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.90	0.85	0.80	0.80	0.80	0.86
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.15	0.24
21	False Thornveld of Eastern Cape	82.30	CAY	0.75	0.75	0.75	0.50	0.40	0.35	0.30	0.30	0.40	0.45	0.50	0.55	0.50
			VEGINT	1.70	1.70	1.70	1.60	1.40	1.30	1.30	1.30	1.30	1.40	1.40	1.50	1.47
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.85	0.80	0.89
			COIAM	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.27
22	Invasion of Grassveld by Acacia Karoo	64.50	CAY	0.63	0.65	0.65	0.55	0.40	0.20	0.20	0.20	0.20	0.40	0.50	0.60	0.43
			VEGINT	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.00	1.00	1.00	1.10	1.20	1.08
			ROOTA	0.80	0.80	0.80	0.90	0.90	1.00	1.00	1.00	1.00	0.90	0.85	0.80	0.90
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
23	Valley Bushveld	82.30	CAY	0.75	0.75	0.75	0.65	0.55	0.20	0.20	0.40	0.60	0.75	0.75	0.75	0.59
			VEGINT	2.50	2.50	2.50	2.20	2.00	2.00	1.90	1.90	2.20	2.50	2.50	2.50	2.27
			ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.95	0.90	0.80	0.80	0.80	0.87
			COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.20	0.26
24	Noorsveld	20.00	CAY	0.40	0.40	0.40	0.40	0.35	0.25	0.20	0.25	0.35	0.40	0.40	0.40	0.35
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
			ROOTA	0.80	0.80	0.80	0.80	0.87	0.93	1.00	1.00	0.95	0.90	0.80	0.80	0.87
			COIAM	0.15	0.15	0.15	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.15	0.24
25	Succulent Mountain Scrub	20.00	CAY	0.40	0.40	0.40	0.35	0.30	0.30	0.30	0.30	0.30	0.40	0.40	0.40	0.35
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
26	Karroid Broken Veld	37.80	CAY	0.30	0.30	0.40	0.50	0.50	0.40	0.35	0.35	0.40	0.30	0.30	0.30	0.37
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25	0.28
27	Central Upper Karoo	37.80	CAY	0.50	0.50	0.50	0.40	0.30	0.20	0.20	0.20	0.20	0.30	0.40	0.50	0.35
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	1.00	0.90	0.80	0.80	0.90
			COIAM	0.15	0.15	0.15	0.15	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.24
28	Western Mountain Scrub	20.00	CAY	0.30	0.30	0.30	0.30	0.40	0.40	0.40	0.35	0.30	0.30	0.30	0.30	0.33
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
			ROOTA	0.80	0.80	0.80	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.80	0.80	0.89
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
29	Arid Karoo	10.00	CAY	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			VEGINT	0.20	0.20	0.20	0.20	0.25	0.30	0.25	0.20	0.20	0.20	0.20	0.20	0.22
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.26
30	Central Lower Karoo	15.00	CAY	0.30	0.30	0.35	0.35	0.30	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.28
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.80	1.00	1.00	1.00	1.00	0.95	0.80	0.80	0.88
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
31	Succulent Karoo	20.00	CAY	0.30	0.30	0.30	0.30	0.30	0.40	0.40	0.35	0.30	0.30	0.30	0.30	0.32
			VEGINT	0.20	0.20	0.20	0.25	0.35	0.40	0.35	0.30	0.20	0.20	0.20	0.20	0.25
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	0.95	0.90	0.90	0.90	0.90	0.93
			COIAM	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.28
32	Orange River Broken Veld	10.00	CAY	0.25	0.30	0.30	0.25	0.25	0.20	0.20	0.20	0.25	0.30	0.30	0.30	0.26
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.80	0.80	0.88
			COIAM	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.28
33	Namaqualand Broken Veld	15.00	CAY	0.25	0.25	0.25	0.30	0.35	0.35	0.35	0.30	0.25	0.25	0.25	0.25	0.28
			VEGINT	0.20	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.20	0.20	0.20	0.20	0.23
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
34	Strandveld	20.00	CAY	0.30	0.30	0.30	0.30	0.40	0.40	0.40	0.40	0.35	0.30	0.30	0.30	0.34
			VEGINT	0.50	0.50	0.50	0.50	0.60	0.60	0.60	0.50	0.50	0.50	0.50	0.50	0.53
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
				FALSE KAROO TYPES												
35	False Arid Karoo	20.00	CAY	0.30	0.40	0.40	0.30	0.25	0.20	0.20	0.20	0.25	0.30	0.30	0.30	0.28
			VEGINT	0.40	0.40	0.40	0.40	0.40	0.30	0.30	0.30	0.30	0.30	0.40	0.40	0.36
			ROOTA	0.80	0.80	0.80	0.80	0.95	1.00	1.00	1.00	0.95	0.80	0.80	0.80	0.88
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
36	False Upper Karoo	37.80	CAY	0.45	0.50	0.50	0.40	0.25	0.20	0.20	0.20	0.25	0.30	0.35	0.40	0.33
			VEGINT	0.70	0.70	0.70	0.70	0.60	0.60	0.50	0.50	0.40	0.40	0.50	0.60	0.58
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.95	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.24

APPENDIX D Continued

CAY : WATER USE (CROP) COEFFICIENT
VEGINT : INTERCEPTION (mm) per RAINDAY
COIAM : COEFFICIENT OF INTIAL ABSTRACTIONS (INFILTRABILITY)
ROOTA : ROOT FRACTION IN TOPSOIL

	ACOCKS' VELD TYPE	%SUR-FACE COVER	VARIA-BLE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
37	False Karroid Broken Veld	37.80	CAY	0.45	0.50	0.50	0.40	0.25	0.20	0.20	0.20	0.25	0.30	0.35	0.40	0.33
			VEGINT	0.70	0.70	0.70	0.70	0.60	0.60	0.50	0.50	0.40	0.40	0.50	0.60	0.58
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.95	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.24
38	False Central Lower Karoo	37.80	CAY	0.45	0.50	0.50	0.40	0.25	0.20	0.20	0.20	0.25	0.30	0.35	0.40	0.33
			VEGINT	0.70	0.70	0.70	0.70	0.60	0.60	0.50	0.50	0.40	0.40	0.50	0.60	0.58
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.95	0.90	0.80	0.80	0.88
			COIAM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.24
39	False Succulent Karoo	10.00	CAY	0.30	0.30	0.30	0.30	0.30	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.28
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
40	False Orange River Broken Veld	10.00	CAY	0.30	0.30	0.30	0.30	0.30	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.28
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
41	Pan Turf Veld invaded by Karoo	10.00	CAY	0.30	0.30	0.30	0.30	0.30	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.28
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
42	Karroid Merxmuellera Mountain Veld replaced by Karoo	37.80	CAY	0.30	0.50	0.50	0.40	0.20	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30
			VEGINT	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
			ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	1.00	0.90	0.80	0.80	0.90
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
43	Mountain Renosterveld	37.80	CAY	0.30	0.30	0.30	0.30	0.50	0.40	0.30	0.30	0.30	0.30	0.30	0.30	0.33
			VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.87
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	TEMPERATE AND TRANSITIONAL FOREST AND SCRUB TYPES															
44	Highland Sourveld and Döhne Sourveld	73.40	CAY	0.70	0.70	0.70	0.50	0.30	0.20	0.20	0.20	0.50	0.65	0.70	0.70	0.50
			VEGINT	1.60	1.60	1.60	1.40	1.20	1.00	1.00	1.00	1.30	1.60	1.60	1.60	1.38
			ROOTA	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
45	Natal Mist Belt Ngongoni Veld	73.40	CAY	0.70	0.70	0.70	0.50	0.35	0.25	0.20	0.20	0.55	0.70	0.70	0.70	0.52
			VEGINT	1.50	1.50	1.50	1.30	1.10	1.10	1.10	1.10	1.40	1.50	1.50	1.50	1.34
			ROOTA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
46	Coastal Rhenosterveld	37.80	CAY	0.40	0.40	0.40	0.45	0.50	0.50	0.50	0.50	0.50	0.45	0.40	0.40	0.45
			VEGINT	0.80	0.80	0.80	1.00	1.20	1.20	1.20	1.20	1.00	0.80	0.80	0.80	0.97
			ROOTA	0.95	0.95	0.95	0.90	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.93
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
47	Coastal Macchia	55.60	CAY	0.35	0.40	0.42	0.50	0.60	0.60	0.60	0.60	0.55	0.50	0.40	0.35	0.49
			VEGINT	0.80	0.80	0.80	0.80	1.00	1.00	1.00	1.00	1.00	0.90	0.80	0.80	0.89
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PURE GRASSVELD TYPES															
48	Cymbopogon-Themeda Veld	64.50	CAY	0.65	0.65	0.65	0.55	0.40	0.20	0.20	0.20	0.40	0.50	0.65	0.65	0.48
			VEGINT	1.20	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.00	1.10	1.20	1.20	1.12
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
49	Transitional Cymbopogon Themeda Veld	64.50	CAY	0.65	0.65	0.65	0.50	0.25	0.20	0.20	0.20	0.30	0.45	0.50	0.60	0.43
			VEGINT	1.10	1.10	1.10	1.10	0.90	0.80	0.80	0.80	0.90	1.00	1.10	1.10	0.98
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
50	Dry Cymbopogon-Themeda Veld	64.50	CAY	0.60	0.65	0.65	0.50	0.30	0.20	0.20	0.20	0.30	0.40	0.50	0.55	0.42
			VEGINT	1.00	1.00	1.00	0.90	0.90	0.90	0.80	0.80	0.80	0.90	1.00	1.00	0.92
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
51	Pan Turf Veld	64.50	CAY	0.58	0.65	0.60	0.50	0.35	0.20	0.20	0.20	0.30	0.40	0.50	0.55	0.42
			VEGINT	1.10	1.10	1.10	1.10	1.00	0.90	0.80	0.80	0.80	0.90	1.00	1.10	0.98
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
52	Themeda Veld or Turf Highveld	64.50	CAY	0.65	0.65	0.65	0.50	0.40	0.20	0.20	0.20	0.35	0.55	0.65	0.65	0.47
			VEGINT	1.20	1.20	1.20	1.10	1.00	0.90	0.90	0.90	1.10	1.20	1.20	1.20	1.09
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
53	Patchy Highveld to Cymbopogon-Themeda Veld Transition	64.50	CAY	0.65	0.65	0.65	0.50	0.40	0.20	0.20	0.20	0.35	0.55	0.65	0.65	0.47
			VEGINT	1.20	1.20	1.20	1.10	1.00	0.90	0.90	0.90	1.10	1.20	1.20	1.20	1.09
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
54	Turf Highveld to Highland Sourveld Veld Transition	55.60	CAY	0.60	0.60	0.60	0.52	0.40	0.20	0.20	0.20	0.35	0.50	0.60	0.60	0.45
			VEGINT	1.30	1.30	1.30	1.20	1.00	0.90	0.90	0.90	1.10	1.20	1.30	1.30	1.14
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25

APPENDIX D Continued

CAY : WATER USE (CROP) COEFFICIENT
VEGINT : INTERCEPTION (mm) per RAINDAY
COIAM : COEFFICIENT OF INTIAL ABSTRACTIONS (INFILTRABILITY)
ROOTA : ROOT FRACTION IN TOPSOIL

	ACOCKS' VELD TYPE	%SUR-FACE COVER	VARIA-BLE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
55	Bankenveld to Turf Highveld Transition	64.50	CAY	0.65	0.65	0.65	0.50	0.35	0.20	0.20	0.20	0.35	0.55	0.65	0.65	0.47
			VEGINT	1.20	1.20	1.20	1.20	1.00	0.90	0.90	0.90	1.10	1.20	1.20	1.20	1.10
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
56	Highland Sourveld to Cymbopogen-Themeda Veld Transition	59.16	CAY	0.62	0.62	0.62	0.50	0.30	0.20	0.20	0.20	0.25	0.50	0.62	0.62	0.44
			VEGINT	1.10	1.10	1.10	1.10	1.00	0.90	0.90	0.90	1.00	1.10	1.10	1.10	1.03
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
57	North-Eastern Sandy Highveld	59.16	CAY	0.62	0.62	0.60	0.50	0.35	0.20	0.20	0.20	0.35	0.50	0.62	0.62	0.45
			VEGINT	1.30	1.30	1.30	1.20	1.00	1.00	1.00	1.10	1.20	1.30	1.30	1.30	1.19
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
58	Themeda-Festuca Alpine Veld	37.80	CAY	0.50	0.50	0.45	0.35	0.20	0.20	0.20	0.20	0.30	0.35	0.45	0.50	0.35
			VEGINT	1.30	1.30	1.30	1.10	0.90	0.90	0.90	0.90	1.10	1.20	1.30	1.30	1.13
			ROOTA	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.95
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
59	Stormberg Plateau Sweetvelt	55.60	CAY	0.60	0.60	0.60	0.55	0.40	0.20	0.20	0.20	0.20	0.35	0.45	0.55	0.41
			VEGINT	1.30	1.30	1.30	1.20	1.10	1.00	0.90	0.90	0.90	1.00	1.10	1.20	1.10
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.94
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
60	Karroid Merxmuellera Mountain Veld	55.60	CAY	0.40	0.60	0.60	0.40	0.20	0.20	0.20	0.20	0.20	0.30	0.30	0.35	0.33
			VEGINT	0.60	0.60	0.60	0.60	0.50	0.40	0.40	0.40	0.40	0.40	0.50	0.50	0.49
			ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	1.00	0.95	0.90	0.80	0.91
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
			FALSE GRASSVELD TYPES													
61	Bankenveld	64.50	CAY	0.65	0.65	0.65	0.50	0.35	0.20	0.20	0.20	0.25	0.50	0.65	0.65	0.45
			VEGINT	1.30	1.30	1.30	1.30	1.10	1.00	1.00	1.00	1.10	1.20	1.30	1.30	1.18
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
62	Bankenveld to Sour Sandveld Transition	73.40	CAY	0.70	0.70	0.70	0.50	0.40	0.20	0.20	0.20	0.50	0.60	0.65	0.70	0.50
			VEGINT	1.20	1.20	1.20	1.20	1.10	1.00	1.00	1.00	1.10	1.20	1.20	1.20	1.13
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
63	Piet Retief Sourveld	73.40	CAY	0.70	0.70	0.70	0.55	0.45	0.20	0.20	0.20	0.50	0.60	0.70	0.70	0.52
			VEGINT	1.30	1.30	1.30	1.30	1.10	1.00	1.00	1.00	1.20	1.30	1.30	1.30	1.20
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
64	Northen Tall Grassveld	82.30	CAY	0.75	0.75	0.75	0.50	0.40	0.30	0.20	0.20	0.55	0.70	0.75	0.75	0.55
			VEGINT	1.70	1.70	1.70	1.60	1.50	1.40	1.40	1.50	1.60	1.70	1.70	1.70	1.60
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
65	Southern Tall Grassveld	82.30	CAY	0.75	0.75	0.75	0.50	0.40	0.20	0.20	0.20	0.55	0.70	0.75	0.75	0.54
			VEGINT	1.60	1.60	1.60	1.60	1.50	1.40	1.40	1.40	1.50	1.60	1.60	1.60	1.53
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
66	Natal Sour Sandveld	82.30	CAY	0.75	0.75	0.70	0.50	0.35	0.20	0.20	0.20	0.50	0.65	0.70	0.75	0.52
			VEGINT	1.80	1.80	1.80	1.80	1.60	1.40	1.40	1.40	1.50	1.70	1.80	1.80	1.65
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15	0.25
67	Pietersburg Plateau False Grassveld	64.50	CAY	0.65	0.65	0.50	0.40	0.35	0.20	0.20	0.30	0.50	0.55	0.65	0.65	0.47
			VEGINT	1.00	1.00	1.00	0.90	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.92
			ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.95	0.90	0.90	0.94
			COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15	0.25
68	Eastern Province Grassveld	55.60	CAY	0.50	0.60	0.50	0.40	0.30	0.20	0.20	0.20	0.30	0.40	0.50	0.50	0.38
			VEGINT	1.20	1.20	1.20	1.10	1.00	0.90	0.90	0.90	1.00	1.10	1.20	1.20	1.08
			ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90	0.93
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
69	Macchia	55.60	CAY	0.45	0.45	0.50	0.60	0.60	0.60	0.60	0.60	0.60	0.55	0.50	0.45	0.54
			VEGINT	1.00	1.00	1.10	1.20	1.20	1.20	1.20	1.20	1.10	1.10	1.00	1.00	1.11
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
70	False Macchia	55.60	CAY	0.45	0.45	0.50	0.60	0.60	0.60	0.60	0.60	0.60	0.55	0.50	0.45	0.54
			VEGINT	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.80	0.80	0.80	0.86
			ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30

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Development of the building block methodology for instream flow assessments and supporting research on the effects of different magnitude flows on riverine ecosystems

RE Tharma and JM King

South African rivers mirror the world-wide trend in their deteriorating condition. This is largely due to general catchment degradation and increasing manipulation of flow regimes to provide water for the ever-increasing population. One of the ways in which this is being addressed is through the emerging science of environmental flow assessment. The flow regimes recommended by this process are designed to contain or mitigate the impacts of such water resource developments. The cost of poorly functioning rivers is high, with much of the cost being borne by those least able to withstand them - the rural poor.

This report is the definitive work on the building block methodology (BBM), a process developed to assess flow requirements of rivers. It also covers the considerable amount of research done by the team to complement the development of the BBM. The principal aim of the research programme was to improve understanding of the relationships between the magnitude, duration, timing and frequency of different categories of flow and the structure and functioning of riverine ecosystems. Such aspects as base flows, specifically dry-season low flows, freshes and floods are covered with specific research investigating topics such as sediment transport, the effect of base flows on macro-invertebrate assemblages and triggers for fish breeding.

Report Number: 576/1/98 **ISBN: 1 86845 503 3**

Estimation of streamflow reductions resulting from commercial afforestation in South Africa

MB Gush • DF Scott • GPW Jewitt • RE Schulze • TG Lumsden • LA Hallowes • AHM Görgens

The main objective of this project was to verify the *ACRU* model on available streamflow data from experimental or research afforested catchments and thereafter to apply the model to all regions with economically viable afforestation potential. The goal of the project was to produce regional look-up tables providing quaternary catchment scale streamflow reduction estimates, acceptable to a wide group of stakeholders.

This project essentially comprised two simulation phases: the verification phase and the extrapolation phase. Although the one was a planned progression from the other, some fundamental differences existed between the two simulation phases, primarily in connection with the level of detail of input data. These differences were unavoidable, but it is, nevertheless, important not to infer too much accuracy in the extrapolation phase that was not in the verification phase.

The *ACRU* model was verified with acceptable success on the same experimental data sets that were used to produce the CSIR curves. Weaknesses in the model that emerged during the verification phase were difficulties in accounting for the full storage capacity of the soil profile and the year-to-year carry over of water storage or usage. Therefore, amounts of water used in evaporation appeared to be limited by current rainfall.

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