HYDROLOGICAL COMPLEXITIES IN ASSIGNING RAINFED SUGARCANE A "STREAM FLOW REDUCTION ACTIVITY"

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Abstract

The influence of land use on hydrological responses has long been a subject of study in South Africa. Impacts of land use on runoff have recently received a new focus with the enactment of the National Water Act of 1998, which includes the concept of levying land uses that are so-called "Stream Flow Reduction Activities" (SFRAs). This paper assesses the hydrological complexities which abound when setting out to declare a land use, in this case sugarcane, a SFRA from a scientific point of view. Using only the simplest of hydrological indices, *viz*. Median Annual Streamflow (MAS), results show that when the *ACRU* agrohydrological model is used at the level of Quaternary Catchments in the sugarcane belt of South Africa, no simple rainfall : runoff relationships exist. MAS is, furthermore, found to be highly dependent on soil depth. When reductions of MAS by sugarcane are evaluated against a baseline land cover, in this case Acocks' Veld Types, results again show complex spatial variations across the sugarcane belt. The paper concludes that from a scientific perspective it is very difficult to find simple solutions to declare a land use a SFRA.

Keywords: sugarcane, streamflow reduction, simulation, *ACRU* model

Land use and hydrological responses in South Africa :

Historical perspective

The influence of land use on hydrological responses has long been appreciated in South Africa. First mooted in the 1930s, and put into operation in the late 1940s, for example, were a number of paired experimental catchments under the auspices of the erstwhile SA Forest Research Institute, to assess the impacts of commercial afforestation on natural catchment streamflow regimes in the winter (Jonkershoek) and summer (Cathedral Peak) rainfall regions of South Africa. Similar afforestation experiments were later set up in many parts of South Africa. Results were essentially conclusive : trees "used" more water than the natural vegetation they replaced by varying amounts depending on climate, species and degree of afforestation (Bosch, 1982). Consequently, the Afforestation Permit System, whereby licences for further afforestation were either issued or not, dependent upon influences on regional hydrology, was instituted in 1972.

Amongst the South African engineering hydrological fraternity the strong influences of land use were being stressed nearly 40 years ago already by Reich's (1962) promotion of the event based SCS technique for design hydrograph generation - a technique which emphasized safe hydrological design, by consideration not only of different agricultural land covers, but more specifically by accounting for effects of mechanical and conservation practices of land use management on hydrological responses. This resulted in a series of user manuals on the SCS hydrograph generation technique for South African conditions (Schulze and Arnold, 1979; Schmidt and Schulze, 1988; Schulze *et al*., 1993), each highlighting land use influences on hydrology.

The land use related concepts imbedded in the event based SCS methodology, although substantially modified and refined over time, subsequently found their way into continuous, daily time step multi-purpose hydrological simulation models such as CREAMS (Knisel, 1980) and *ACRU* (Schulze, 1995), whose focus was, *inter alia*, the ability to simulate differences between hydrological responses of a range of agricultural practices.

On an experimental basis, the quest in South Africa to evaluate and understand impacts of land use management practices on components of the hydrological cycle, continued in the 1980s and 1990s by way of extensive plot scale simulator studies on runoff and soil loss conducted by the then Division of Agricultural Engineering, as well as soil water extraction studies by neutron probe and later micro-meteorological methods on different land uses, but primarily on commercial tree plantations (e.g. Jewitt and Schulze, 1991; Moerdyk and Schulze, 1991; Summerton, 1996).

Also in the 1980s, the SA Sugar Association's Experiment Station, SASEX, initiated a cluster of four small experimental catchments at La Mercy to assess the influences of different management practices on runoff and sediment yield from sugarcane plantations (Platford, 1983; Haywood and Schulze, 1991). It is from these catchment studies that Smithers, Mathews and Schulze (1996) derived representative values of critical variables for use in the *ACRU* model when simulating the hydrology from sugarcane plantations under different management scenarios in South Africa.

A vast South African hydrological literature bears testimony to the significance and concern of potential land use influences on hydrology. Thus, an entire symposium was devoted to land use issues in hydrology in 1981 already (Maaren, 1981), while the annual conference proceedings of the SA Sugar Technologists' Association and the biennial proceedings of the National Hydrology Symposia as well as journals such as *Water SA* and *Agricultural Engineering in SA* collectively contain scores of papers on the subject. Additionally, under the senior author's supervision alone, 3 PhD and 20 masters theses have been completed on aspects of hydrological impacts of land use - many of them experiment based or model based with field verifications.

Land use and hydrological responses in South Africa : The present situation

The entire issue of land use influences on hydrological responses has recently become entrenched in South African law with the passing of the National Water Act (NWA) of 1998. In this Act a major focus is on so-called "Stream Flow Reducing Activities" (SFRA's), whereby designated rainfed land use activities are to be regulated by licence and forms of taxation which are related, *inter alia*, to the water use by the respective land uses. At the present time (March 2000) afforestation has been singled out for licensing purposes in the Act, but potential streamflow reduction activities of other agricultural land uses, *inter alia* sugarcane, are currently being assessed.

The Act is prompting major dryland agricultural land use sectors such as the commercial timber, sugarcane, maize or livestock industries to ask, for example,

- how much water they utilise in producing their commodities
- whether the water is being used efficiently in terms of Rand produced per m^3 of water or mm of rainfall, or in regard to tons produced per mm of water used
- how their water use compares with that of other, or regionally competing, crops

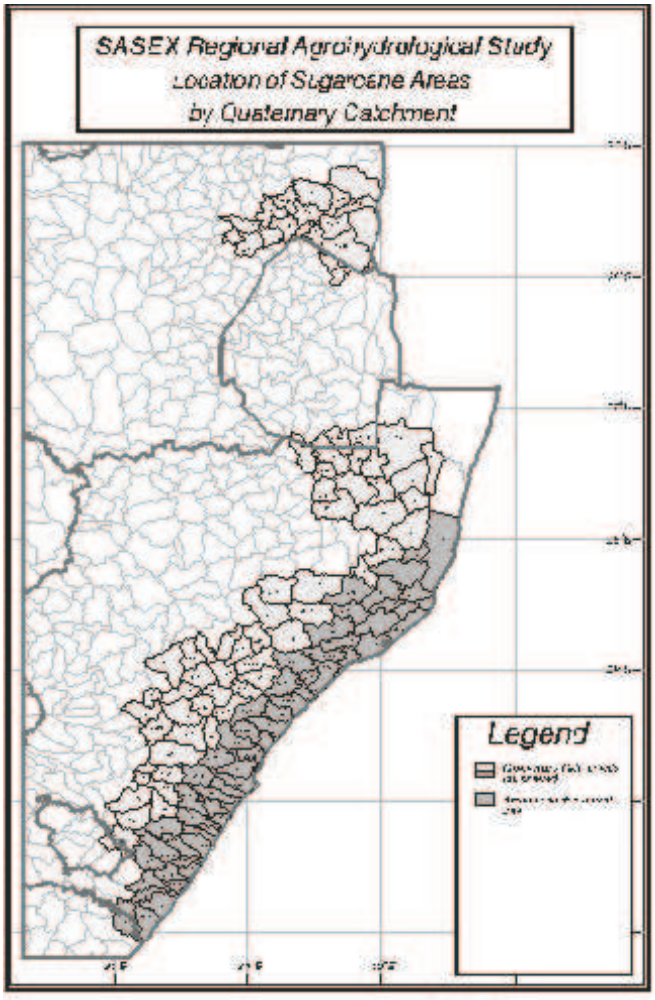

Figure 1 . Location of sugarcane areas in South Africa by Quaternary Catchment

- how water utilisation of the crop/commodity varies from region to region within South Africa, i.e. where are the optimum and marginal production regions with respect to water usage and
- whether there are regions where, in accordance with concepts imbedded in the NWA, certain crops or management practices should be encouraged or discouraged.

Objectives of this study

In the light of the above background, SASEX requested the School of Bioresources Engineering and Environmental Hydrology (BEEH) of the University of Natal to undertake a regional simulation analysis within the sugarcane production areas of South Africa (Figure 1), with the overall objective of assessing what the regional water use patterns and hydrological impacts of sugarcane would be (e.g. can generalizations be made? do hydrological responses follow simple patterns? or are there regional complexities hitherto not appreciated?), should sugarcane be declared a "streamflow reduction activity".

This regional study was undertaken

- at a spatial resolution of Quaternary Catchments (QCs) as delineated by the Department of Water Affaires and Forestry (DWAF)
- for two specified soil conditions representing total available moisture capacities (TAM) of 60 and 150 mm receptively (i.e. shallow and deep soils)
- with the baseline land cover for the comparative hydrology being specified as Acocks'
- (1988) Land Types and
- using the physical-conceptual, daily time step and multipurpose *ACRU* agrohydrological modelling system.

The paper first describes the necessity of selecting a baseline land cover against which to assess hydrological responses of a specific land use such as sugarcane, followed by a summary of the *ACRU* model and its input requirements, then evaluates regional patterns of streamflows and streamflow reductions resulting from rainfed sugarcane, before drawing conclusions on the complexities of declaring sugarcane a "Stream Flow Reduction Activity".

What constitutes a baseline land cover for hydrological comparisons?

The Necessity for a Baseline Land Cover, and Options Considered

When assessing "Stream Flow Reduction Activities" in light of the National Water Act, a pertinent question is "Assessing, against what?" A baseline land cover is thus required against which to compare SFRAs of any land use under scrutiny.

Several options for selecting a baseline land cover are available, for example, using

- veld in a specified hydrological condition, e.g. in good, fair or poor conditions, as defined in Schulze *et al.* (1993), as the baseline

- however, not all current lands under sugarcane were converted from veld in, say, fair hydrological condition, and

- veld in fair condition in coastal areas has different hydrological response attributes to that in the inland which experiences frost and, hence, senesces; or using

- actual land cover or land use in a specified year as the baseline, e.g.

  - 1972, when the Afforestation Permit System was introduced or

  - 1996 , the baseline year of the CSIR's National Land Cover information

  - but, land cover in a specified year would depend largely on regional development levels at that specific point in time, which may be highly irregular for historical, political, economical or social reasons ; or using

- a land cover representing "natural" vegetation, or a land cover in pristine or near pristine condition

  - however, no perfect natural vegetation classification exists which is entirely compatible with hydrological requirements.

Of these three options, however, the last named was considered potentially the most objective. The classification selected to represent "natural" conditions was Acocks' (1988) Veld Types, which had been used previously as a baseline in comparative hydrological studies in the Pongola (Schulze *et al*., 1996) and the Mgeni catchments (Kienzle, Lorentz and Schulze, 1997).

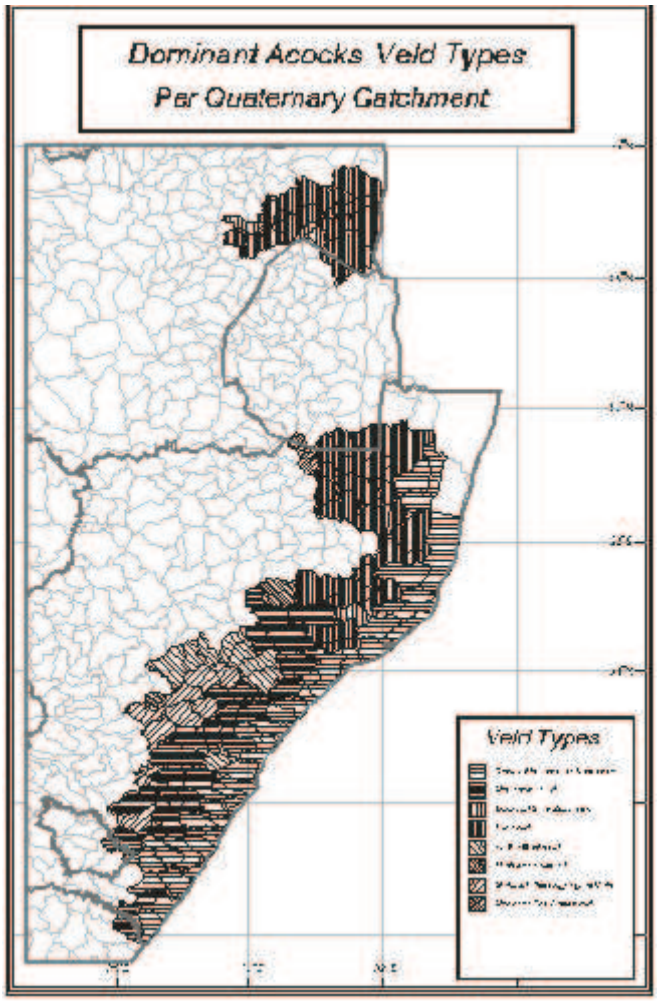

Figure 2. Dominant Acocks' Veld Types per Quaternary Catchment in the designated sugarcane belt.

Approach Adopted

A GIS coverage of Acock's Veld Types was overlaid over the 127 QCs in Figure 1 making up the sugarcane production areas and for each QC the dominant Acocks' Veld Type (i.e. the one with the largest proportion in the QC) was assumed to represent the baseline land cover of that QC. From Figure 2 it may be seen that eight Veld Types were identified in the sugarcane belt. Their hydrological attributes are discussed in the following section.

The *Acru* Model

Concepts of the ACRU *Model*

ACRU is a daily time step, physical-conceptual and multi-purpose model (Figure 3) with options to output, *inter alia*, daily values of streamflow, peak discharge, recharge to groundwater, reservoir status, irrigation water supply and demand, as well as seasonal crop yields, at a specific location or for a catchment. The model revolves around multi-layer soil water budgeting

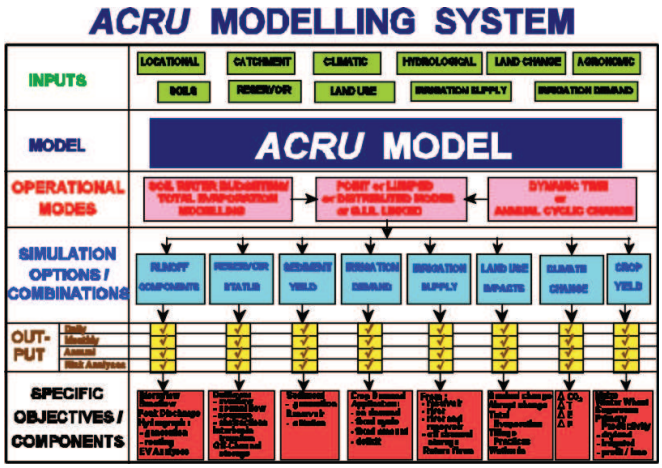

Figure 3. *ACRU* : Concepts of the modelling system (Schulze, 1995).

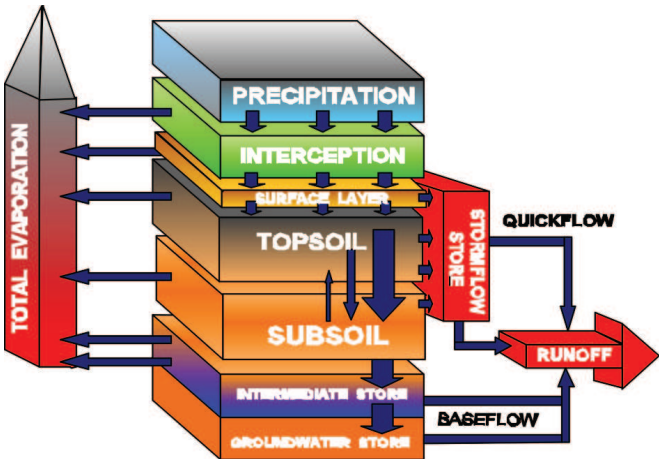

Figure 4. *ACRU* : Model structure (Schulze, 1995).

(Figure 4) and is structured to be hydrologically sensitive to catchment land uses and management strategies and changes thereof.

General Structure of ACRU

Multi-layer soil water budgeting by partitioning and redistribution of soil water is depicted in Figure 4. 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 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 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.

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, 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.

The generation of stormflow in *ACRU* 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. The soil water deficit antecedent to a rainfall event is simulated by *ACRU*'s multi_layer soil water budgeting routines on a daily basis. The critical response depth 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. 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 4), 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.

Acru Model Input

Location

The sugarcane production areas for this study were delimited by SASEX and are represented by the 127 Quaternary Catchments shown in Figure 1 as two consolidated regions. The area excludes sugarcane producing regions of Swaziland. This delimitation incorporates the present cane growing regions of South Africa as well as potential areas, and is based on rainfall and temperature criteria for dryland production (Schulze, 1997), with obvious consideration having been given to proximity to existing sugar mills. For *ACRU* simulations the QCs were treated as hydrologically independent (unlinked) catchments.

Daily Rainfall

Hydrological responses, in nature and also in a daily model such as *ACRU*, are highly sensitive to rainfall input. To account for the regional, seasonal and daily diversity of rainfall, rainfall stations with long duration and quality controlled daily data in and immediately adjacent to the study area were extracted from the rainfall database housed in the Computing Centre for Water Research (CCWR). For each station, daily records for the concurrent 45 year period from 1950 to 1994 were used. Where individual periods of rainfall data were missing, these values were estimated from surrounding stations by an inverse distance square weighting technique, developed by Meier (1997).

Potential Evaporation

For this study the Linacre (1991) daily equation for potential evaporation, E_r was selected as the reference because it uses daily maximum and minimum temperatures together with latitude and altitude to estimate simplified mass transfer and energy budget components of evaporation, mimicking those of the much more complex Penman equation. For the wind function in the Linacre equation a standard default value of 1.6 $m.s^{-1}$ was used for the entire study area. Output from the Linacre equation was verified against recorded A-pan data and, where necessary, regional adjustments were made (Schulze *et al*., 1999).

Soils

All simulations in this study were repeated twice assuming soils of total available moisture capacity (*TAM*) equivalent to 60 mm and 150 mm, i.e. for relatively shallow and deep soils. *TAM* was assumed in this study to be the water held in a soil between its drained upper limit (*DUL*) and its lower limit, or permanent wilting point (*PWP*). To obtain these values of *TAM*, a sandy clay loam with a *PWP* of 0.160 $m.m^{-1}$ and a *DUL* of 0.260 $m.m^{-1}$ for both the topsoil and subsoil horizons was assumed. The soil's water retention at saturation (*PO*) was set at 0.435 $m.m^{-1}$, but this *PO* value was increased to 0.470 $m.m^{-1}$ for the topsoil in simulations of sugarcane responses, because of bulk density changes in the topsoil associated with tillage practices (Schulze, 1995).

The thickness of the topsoil for both of the *TAM* specifications was set at 0.3 m, while the subsoil thickness was then varied between 0.3 m for a *TAM* of 60 mm and 1.2 m for a *TAM* of 150 mm. The soils were assumed not to have shrink-swell properties and saturated soil water redistribution was set to take place at 0.5 of "excess" water (> *DUL*) per day for both soil horizons.

Land Cover : General

Land cover and land use affect hydrological responses through canopy and litter interception, infiltration of rainfall into the soil and the rates of evaporation and transpiration of soil water out of soil. Land cover/use input into *ACRU* therefore includes

- an interception loss value, which can change from month to month during a plant's annual growth cycle, to account for the estimated interception of rainfall by the plant's canopy on a rainday,
- a monthly water use (or "crop") coefficient (converted internally in the model to daily values by Fourier Analysis), which reflects the ratio of water use by vegetation under conditions of freely available soil water to the evaporation from a reference potential evaporation, in this study the Linacre (1991) equation regionally adjusted to A-pan equivalent values, and

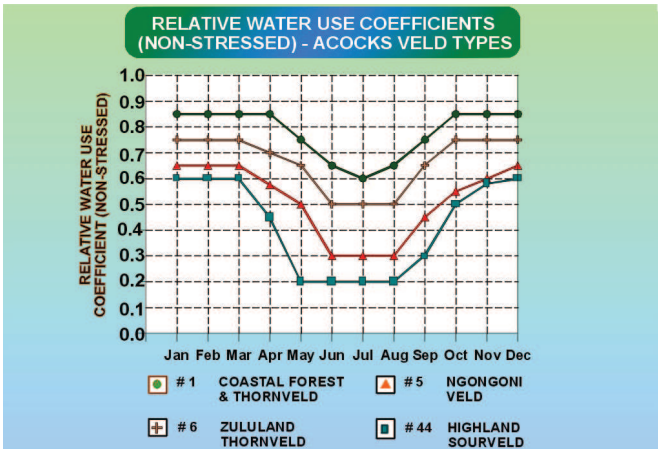

Figure 5. Water use coefficients for different Acocks' Veld Types in the sugarcane belt.

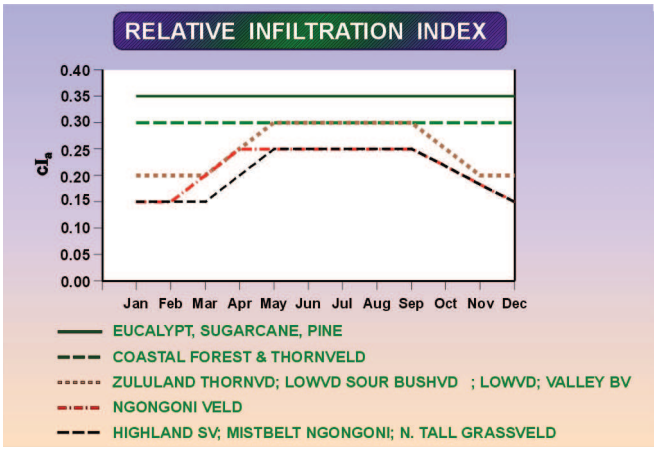

Figure 6. Differences in the coefficients of initial abstractions (cI_a), an index of infiltration, between baseline and competing land uses.

- the fraction of plant roots that are active in extracting soil moisture from the topsoil horizon in a given month, this fraction being linked to root growth patterns during a year and periods of senescence brought on, for example, by lack of soil moisture or by frost.

A further variable which can change seasonally is the coefficient of the initial abstraction (cI_a) which accounts for vegetation, soil surface and climate influences on stormflow generation. In *ACRU* this coefficient takes cognisance of surface roughness (e.g. after ploughing) and initial infiltration before stormflow commences. Higher values of cI_a under sugarcane plantations, for example, reflect enhanced infiltration rates while lower values on veld in summer months reflect higher rainfall intensities (and consequent low initial infiltration amounts).

Input Values of Land Cover and Land Use Attributes

The hydrological attribute values for the Acocks' Veld Types as well as for sugarcane are given in Table 1. Source of information for sugarcane was the WRC report on "Impacts of Sugarcane Production and Changing Land Use on Catchment Hydrology" by Schmidt, Smithers, Schulze and Mathews (1998), while for Acocks' Veld Types values were obtained from Schulze and Hohls (1993) and Schulze (1995;1999).

Certain features appearing in Table 1 require commenting on. These include

- the significant differences between the water use coefficients of different Acocks' Veld Types, depicted diagrammatically in Figure 5 , which highlight the necessity of using different natural vegetation attributes in different climate regions when undertaking SFRA assessments;
- similarly, the inter-vegetation and intra-seasonal ranges of the coefficient of initial abstraction (Figure 6), which may be viewed as an infiltration index;
- the distinction between attributes of veld in the frost-free coastal zone (shown in Figure 1) and the interior, where frost causes senescence of grassland; and
- sugarcane attributes assuming "whole farm" operations, with cane at various stages of maturity resulting in averaged intra-season values of cane which is assumed to be burnt at harvest and with a mix of 50% conventional and 50% minimum tillage plus contours (Schmidt *et al.*, 1998).

Runoff : General

In daily runoff determinations the *ACRU* model distinguishes between stormflow generation and baseflow generation. Stormflow from a rainfall event depends on

- the *magnitude* of the rainfall (hence daily rainfall input) ,
- the *initial abstractions* (I_a) before runoff commences (i.e. interception, surface depression storage and infiltration - hence inputs on soil properties and seasonally varying evaporative demand, plus a coefficient of initial abstraction, cI_a , which also accounts for seasonal rainfall intensity patterns),

Table 1. Month-by-month input variables for baseline land cover categories and land uses.

Land Cover/ Land Use	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Acocks # 1 Coastal Forest and Thornveld	Water Use Coefficient	.85	.85	.85	.85	.75	.65	.60	.65	.75	.85	.85	.85
	Interception (mm) per Rainday	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Fraction of Roots in Topsoil	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75
	Coefficient of I_a	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30
Acocks # 5 Ngongoni Veld	Water Use Coefficient	.65	.65	.65	.55	.50	.30	.30	.30	.45	.55	.60	.65
	Interception (mm) per Rainday	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	Fraction of Roots in Topsoil	.90	.90	.90	.94	.97	1.0	1.0	1.0	.97	.94	.90	.90
	Coefficient of I_a	.15	.15	.20	.25	.25	.25	.25	.25	.25	.20	.20	.15
Acocks # 6 Zululand Thornveld	Water Use Coefficient	.75	.75	.75	.70	.65	.50	.50	.50	.65	.75	.75	.75
	Interception (mm) per Rainday	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Fraction of Roots in Topsoil	.80	.80	.80	.80	.90	.90	.90	.90	.80	.80	.80	.80
	Coefficient of I_a	.20	..20	.20	.25	.30	.30	.30	.30	.30	.25	.20	.20
Acocks # 9 Lowveld Sour Bushveld	Water Use Coefficient	.75	.75	.75	.70	.65	.60	.55	.60	.65	.70	.75	.75
	Interception (mm) per Rainday	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
	Fraction of Roots in Topsoil	.80	.80	.80	.80	.90	.90	.90	.90	.80	.80	.80	.80
	Coefficient of I_a	.20	.20	.25	.30	.30	.30	.30	.30	.30	.25	.20	.20
Acocks # 10 Lowveld	Water Use Coefficient	.75	.75	.75	.65	.55	.40	.40	.40	.60	.75	.75	.75
	Interception (mm) per Rainday	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
	Fraction of Roots in Topsoil	.80	.80	.80	.80	.90	.90	.90	.90	.80	.80	.80	.80
	Coefficient of I_a	.20	.20	.25	.30	.30	.30	.30	.30	.30	.25	.20	.20
Acocks # 23 Valley Bushveld (Northern Variation)	Water Use Coefficient	.78	.78	.78	.65	.55	.40	.40	.40	.60	.72	.78	.78
	Interception (mm) per Rainday	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Fraction of Roots in Topsoil	.75	.75	.75	.85	.90	.90	.90	.90	.80	.75	.75	.75
	Coefficient of I_a	.20	.20	.25	.30	.30	.30	.30	.30	.30	.25	.20	.20
Acocks # 44 Highland Sourveld	Water Use Coefficient	.60	.60	.60	.45	.20	.20	.20	.20	.30	.50	.60	.60
	Interception (mm) per Rainday	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Fraction of Roots in Topsoil	.90	.90	.90	.95	1.0	1.0	1.0	1.0	1.0	.95	.90	.90
	Coefficient of I_a	.15	.15	.15	.20	.25	.25	.25	.25	.25	.20	.20	.15
Acocks # 45 Natal Mistbelt Ngongoni Veld	Water Use Coefficient	.63	.63	.63	.50	.35	.25	.25	.25	.40	.53	.63	.63
	Interception (mm) per Rainday	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
	Fraction of Roots in Topsoil	.90	.90	.90	.94	1.0	1.0	1.0	1.0	1.0	.94	.90	.90
	Coefficient of I_a	.15	.15	.15	.20	.25	.25	.25	.25	.25	.20	.20	.15
Acocks # 64 Northern Tall Grassveld	Water Use Coefficient	.75	.75	.75	.50	.30	.30	.30	.30	.55	.70	.75	.75
	Interception (mm) per Rainday	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Fraction of Roots in Topsoil	.90	.90	.90	.95	1.0	1.0	1.0	1.0	.95	.90	.90	.90
	Coefficient of I_a	.15	.15	.15	.20	.25	.25	.25	.25	.25	.20	.20	.15
Sugarcane	Water Use Coefficient	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80
	Interception (mm) per Rainday	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Fraction of Roots in Topsoil	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80
	Coefficient of I_a	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30

- the *wetness of the catchment* (hence the daily multi-soil layer water budget to calculate antecedent condition prior to a rainfall event) and
- a *critical soil depth* (D_{sc}) which is considered in stormflow generation procedures (and which is dependent on vegetation, soil and rainfall characteristics).
- The stormflow generated from the catchment's hillslope after a given rainfall event does not all reach the stream on the same day that the rain fell, because part of it is a delayed lateral flow. A delay factor (F_{sr}) has therefore been incorporated in *ACRU* (dependent on catchment slope, area, soil and vegetation characteristics).
- The rain which falls on the permanently wet riparian zone (i.e. adjunct impervious areas) is considered to contribute to same-day and direct stormflow.

The baseflow contribution

- derives from accumulated soil water which has *percolated* out of the base of the subsoil horizon (hence the importance of soil depth and the saturated redistribution fraction) into a baseflow store, from which
- baseflow amounts are released into the stream at an exponential rate (F_{bfi})

Runoff Attributes Used in Simulations

Values of cI_a have been given in Table 1 for different baseline Veld Types and for sugarcane. These account also for seasonal rainfall intensity characteristics. Values of D_{sc} were input as the thickness of the topsoil horizon for all land covers/uses except for sugarcane, where from previous verification studies (Schmidt *et al.,* 1998*)* a value of 0.35 m was used. For the stormflow delay factor F_{sr} , a value of 0.3 was used for all QCs. Adjunct and disjunct impervious areas were assumed to be absent for these simulations of comparative hydrology. Finally for the baseflow decay rate, F_{bfi} , a regional value of 0.009 (i.e. 0.9% per day) was used in all simulations.

In this comparative study soil water evaporation and plant transpiration were considered as an entity of "evapotranspiration", and not split into its components. Plant water stress was assumed to occur at a typical 0.4 of *TAM* for sugarcane, as well as for Acocks' Veld Types.

Results

Can the Potential Streamflow Reduction Activity of Sugarcane be Expressed by Simple Regional Curves ?

Before the first detailed regional results are even shown, it is evident from the aforegoing sections that the methodology to set up the *ACRU* model implies some specialist modelling. Since, for a given land use such as sugarcane, the *ACRU* model's biomass attributes as well as the soil input variables for all QCs remain at fixed values, and only the climate changes from QC to QC, this begs the questions whether in the sugarcane belt the rainfall : runoff relationship, and hence potential SFRAs, cannot be expressed by a simple regional curve in order to simplify decisions.

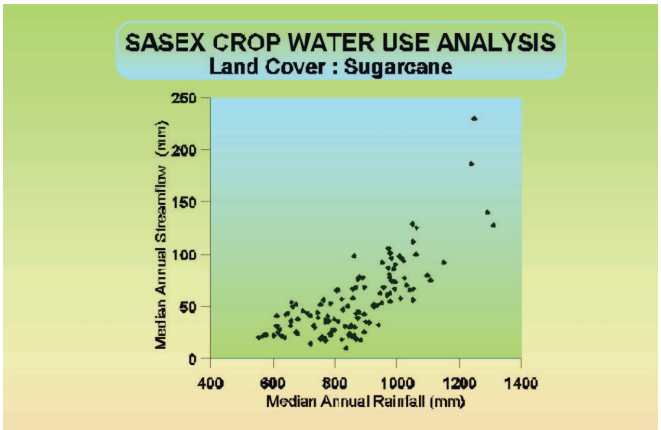

Figure 7. Scatterplot of the median annual streamflow to rainfall relationship for sugarcane grown on deep soils in 127 Quaternary Catchments.

To test this hypothesis, a runoff : rainfall scatter plot from the 127 QC results was produced for median annual conditions. Figure 7 illustrates very clearly that no such simple relationship exists and that for a given median annual rainfall a resultant runoff can vary markedly within the sugarcane production belt. In an attempt to reduce the scatter, plots were produced of only those QCs in areas with, say, a 13 month harvest cycle or a 16 or a 21 month cycle, but the plots did not improve.

One has to therefore conclude at the outset that no simple crop, or region specific, answers to questions around SFRAs will be available.

Annual Streamflows Generated from Sugarcane under Median Hydrological Conditions

For this hydrological study the median annual, rather than the mean, was selected as the simplest index of available water resources under different land use and soil conditions. The median is the statistically expected value at the 50th percentile, i.e. as many years will have higher streamflows than the median, as will have lower streamflows. In streamflow studies the means of annual flow are very often distorted (skewed) by a few exceptional events and are thus not considered as valuable as medians in overall water resources assessments. It should also be noted that in this report the terms "runoff" and "streamflow" are used interchangeably, in both cases implying the total runoff from a QC, made up of the sum of stormflows and baseflows. In descriptions which follow, "deep" soils imply those with a Total Available Moisture of 150 mm, while "shallow" soils are assumed to have a *TAM* = 60 mm.

Figures 8 - 10 highlight the following:

- They confirm the high and curvilinearly amplified dependence of streamflow on rainfall for sugarcane, which was already illustrated in Figure 7. For both deep and shallow soil conditions significant regional differences in median annual streamflows are evident, ranging from < 10 mm to > 180 mm.
- On deep soils (*TAM* = 150 mm) considerably less streamflow is generated than on the shallow soils (*TAM* = 60 mm), where the soil profile can be filled more rapidly and primarily more baseflow is produced (Figures 8 and 9). The response

differences are not uniform, however, with streamflows from shallow soils increasing relative to decreases in rainfall, while in absolute terms the difference is considerably higher along the coast and elsewhere with higher rainfall (*cf.* Figure 10).

Streamflow Reductions Between Baseline Land Cover and Sugarcane under Median Conditions

A major focus of the National Water Act of 1998 is on so-called "Stream Flow Reduction Activities" (SFRAs) by land uses, with the premise that declared land uses should be levied in some way relative to the water they utilized and the streamflow they reduce. Since SFRAs have to be established against a baseline land cover, it stands to reason that certain land uses will generate less, and others more, than the baseline land cover which, for purposes of this comparative hydrology is the dominant Acocks Veld Type for a given Quaternary Catchment. The dependence of a streamflow reduction (or enhancement) on the baseline land cover cannot be overstressed.

Streamflow reduction by a land use can be expressed in two ways, *viz*.

- as an *absolute* change, expressed as the difference, in mm or in m^3 , between the streamflows from the baseline cover (Q_{BL}) and the land use under consideration (Q_{LU}), i.e. Q_{BL} - Q_{LU}, or
- as a *relative* change , expressed as the percentage streamflow reduction in relation to that of the baseline land cover, i.e. $100(Q_{BL} - Q_{LU})/Q_{BL}$.

With reference to Figures 11 and 12 the following may be interpreted with respect to unit streamflow changes (i.e. on a hectare to hectare basis) emanating from sugarcane replacing the baseline land cover:

- The absolute streamflow reduction for sugarcane is generally less than 25 mm along the coast, but more than 60 mm in the inland cane growing areas, with the transition between responses on the coast and the inland being very abrupt (Figure 11).
- In relative terms this translates to a streamflow reduction of < 20% along the coast and up to 40 - 60% inland (Figure 12); however, regional patterns are complex.

Conclusions

This study of median annual hydrological responses from sugarcane in South Africa has shown clearly that runoff cannot be reduced to simple regional generalisations or simple curves of runoff: rainfall relationships. Rather, responses have been shown to be highly location specific, often with distinct north vs south coast contrasts, and with further variation be-

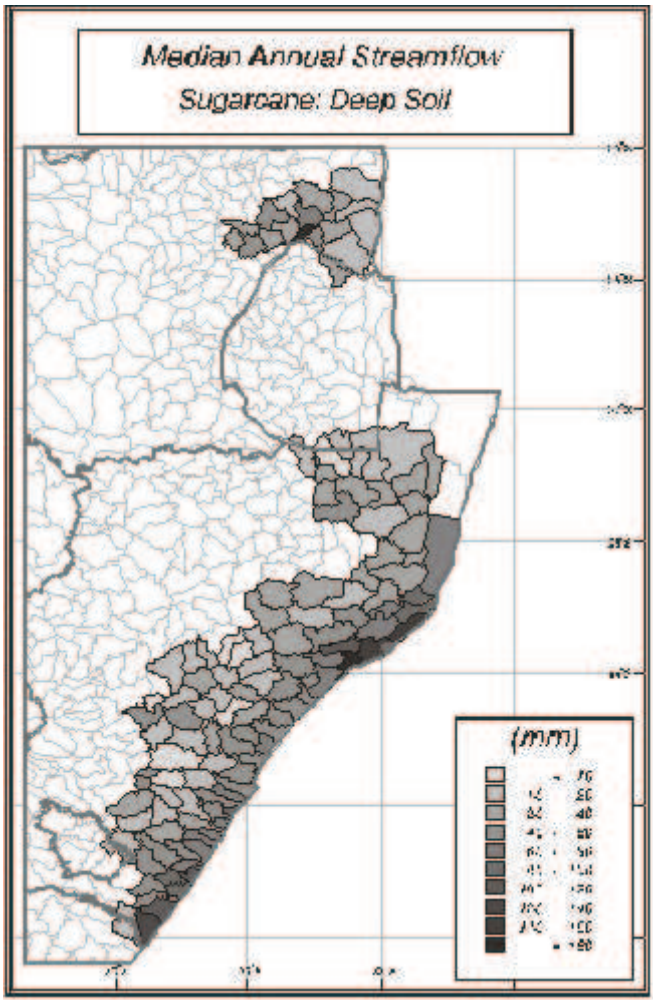

Figure 8. Median annual streamflows (mm) from sugarcane grown on deep soils.

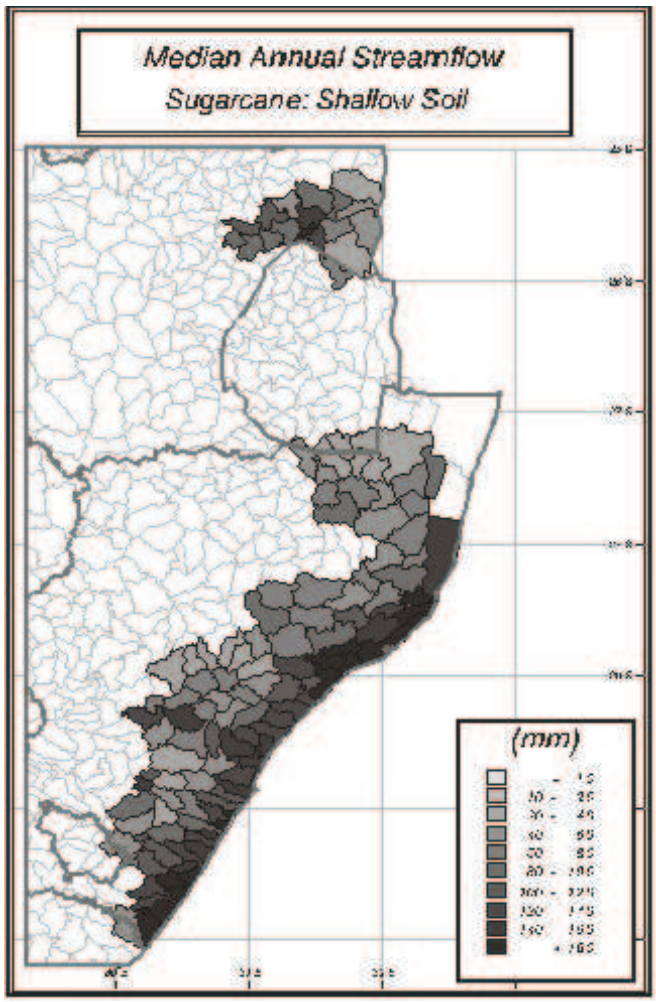

Figure 9. Median annual streamflows (mm) from sugarcane grown on shallow soils.

tween the coastal and interior regions. Furtherore, soils have a marked influence on runoff responses.

The results illustrate that the so-called "Stream Flow Reduction Activities" concept enshrined in the National Water Act of 1998, even at the coarsest level of annual responses and assuming uniformity of climate and soil within Quaternary Catchments are, hydrologically, a complex issue which does not become any simpler when, for example,

- differences in hydrological responses between wet years or dry years, or
- monthly time scales, or
- differences in hydrological responses within individual QCs, or
- different management practices within a single land use such as sugarcane are considered.

Had month-by-month analyses from the daily hydrological model been presented, more complexities would have shown up, also between the stormflow and baseflow components of runoff. Equally, had the spatial analysis considered smaller units than the Quaternary Catchment, even more geographic variability would have been exposed. The matter of spatial resolution is illustrated very clearly in Figure 13. The map shows the coefficient of variation of mean annual precipitation, MAP, plotted at a resolution of 1 minute of degree latitude/longitude within QCs to generally be around 20-30% and in places as high as 40%. The above arguments further confirm the notion that hydrological responses are highly complex over space and time and that they need to be assessed with the use of daily soil water budget models such as *ACRU* rather than with coarse, calibrated monthly tools from which no scientifically justifiable extrapolations can be made.

This evaluation therefore concludes that should any levies be placed on sugarcane as a "Stream Flow Reduction Activity", that these either have to be researched in depth to account for

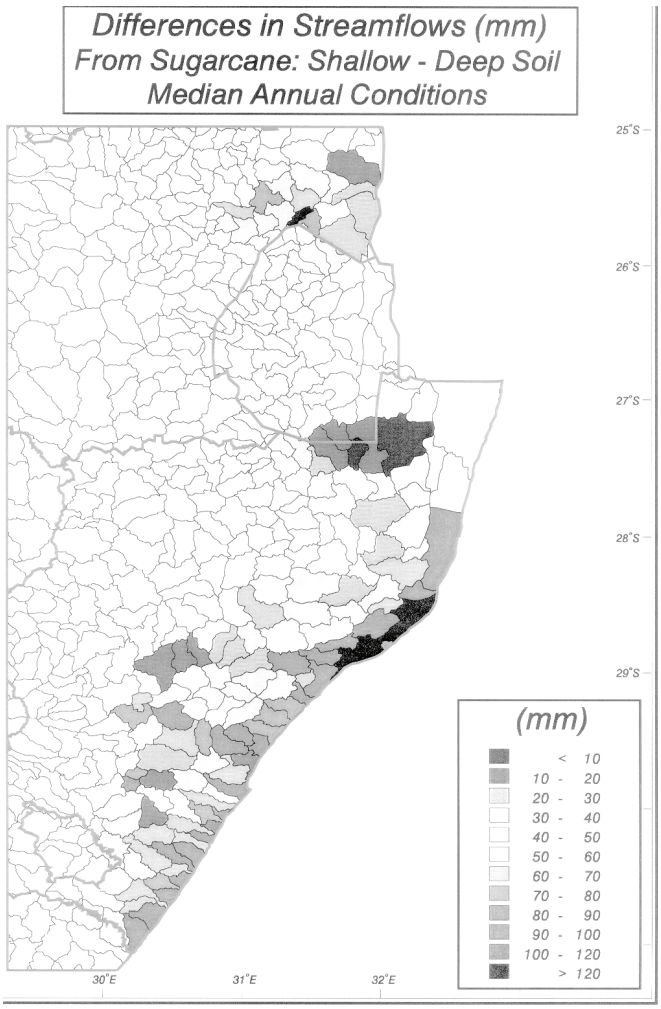

Figure 10. Differences in median annual streamflows (mm) between sugarcane grown on shallow and deep soils.

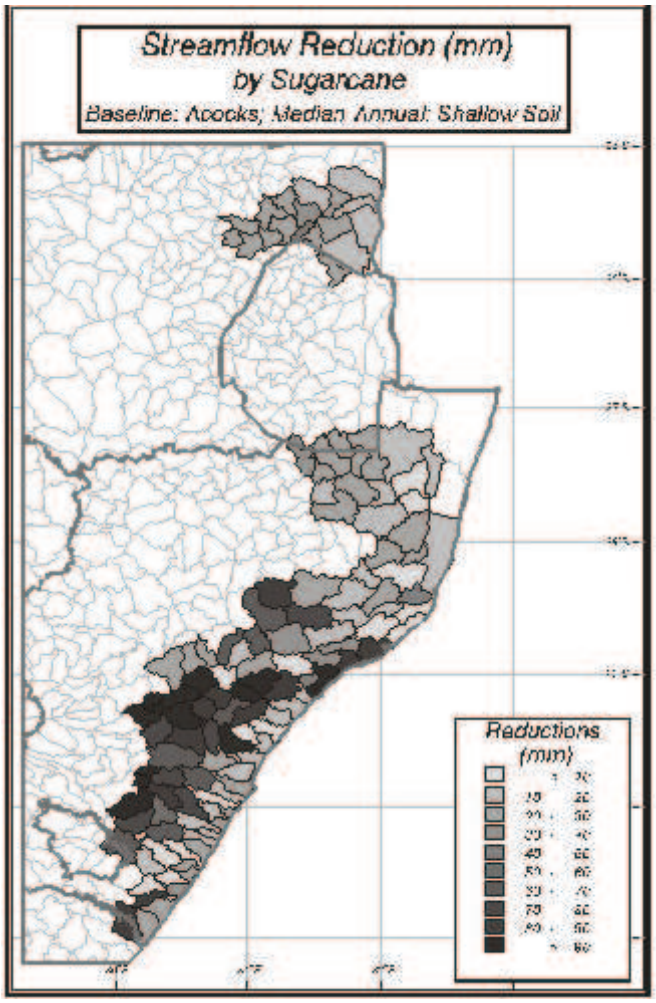

Figure 11. Streamflow reduction (mm) by sugarcane under median conditions on a shallow soil (*TAM* = 60 mm).

the regional diversity which exists in hydrological responses and levels of management or, alternatively, has to be left at so simple a level as not to evoke scientific controversy and exposure to known inconsistences.

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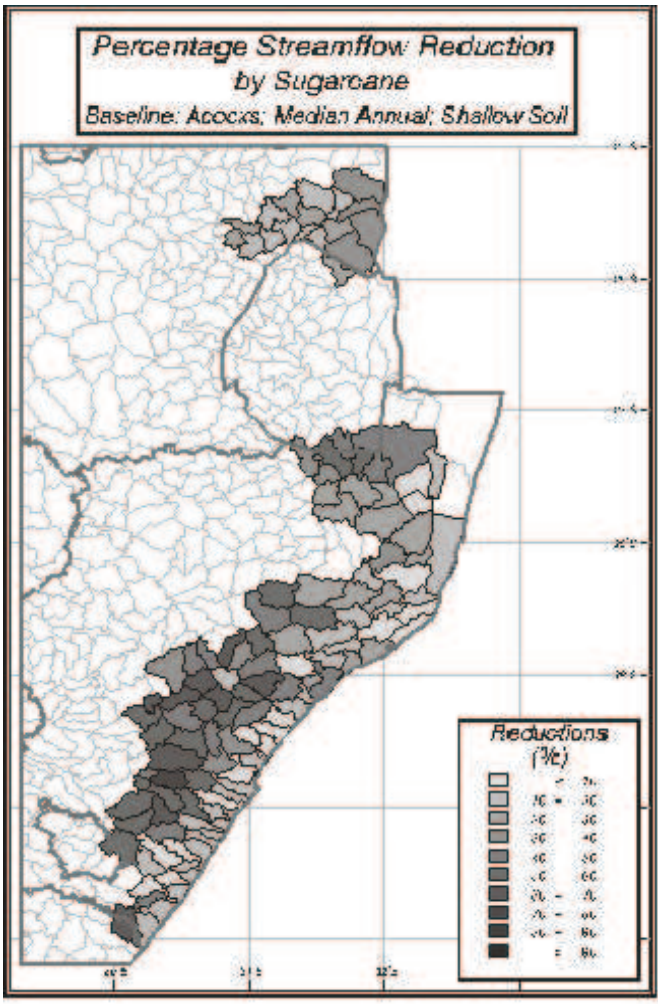

Figure 12. Percentage streamflow reduction by sugarcane under median conditions on a shallow soil (TAM = 60mm).

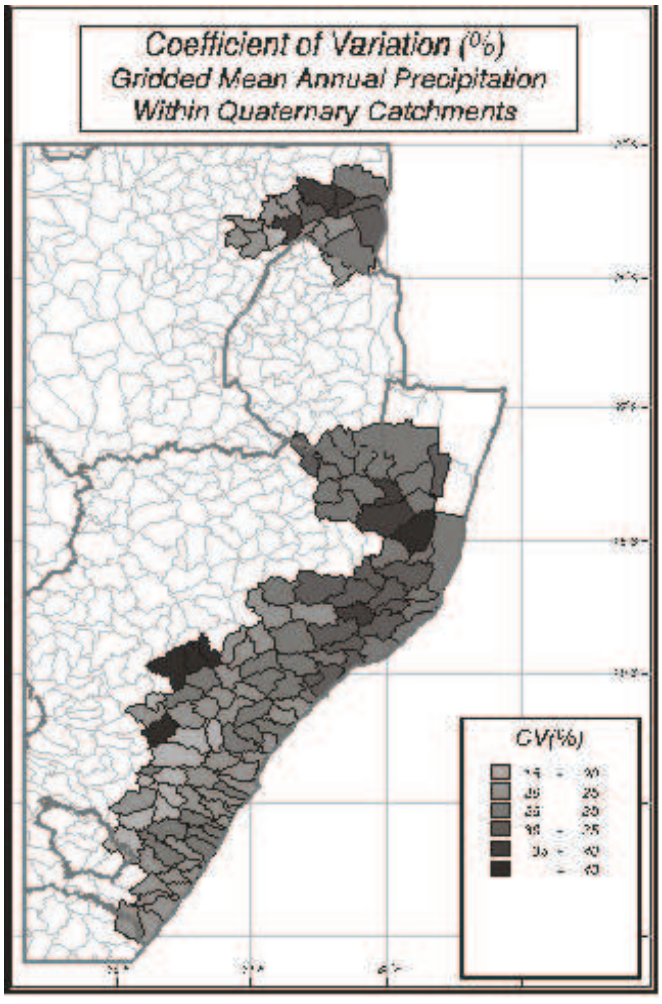

Figure 13. Coefficient of variation (%) of gridded mean annual precipitation within quaternary catchments.

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