Modelling Impacts of Dryland Sugarcane on Streamflows in a Water Stressed Catchment in KwaZulu-Natal

C.E Talanda[1], M. Horan[2], R. Schulze[2], N Lecler[3], T. Nditwani[4]

[1]WRP Consulting Engineers, Pretoria, South Africa
[2] University of KwaZulu-Natal, Pietermaritzburg, South Africa
[3] South African Sugarcane Research Institute, Mount Edgecombe, South Africa and Honorary Associate Professor, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, South Africa
[4]The Department of Water Affairs and Forestry, South Africa

Abstract

Recent studies have indicated that water allocated to users in the Mhlathuze River catchment exceeds the available yield of the system. As a result, a detailed Water Availability Assessment Study in the catchment has been initiated by the Department of Water Affairs and Forestry (DWAF). The study should assist the DWAF's process of Water Allocation Reform (WAR) and Compulsory Licensing, which aims to ensure that the available water resources are reconciled, allocated and managed in a fair and equitable manner.

Sugarcane is produced in the Mhlathuze catchment in both its dryland and irrigated forms. The *ACRU* agrohydrological model was used to conduct an objective and quantitative investigation into the potential impact of dryland sugarcane on streamflows in the Mhlatuze catchment. The streamflows/water balances associated with sugarcane and the relevant baseline land cover represented by Acocks' vegetation types were simulated and then compared for specific soil and climatic conditions occurring in the Mhlatuze catchment. The results showed that the impact of sugarcane on streamflows varied considerably, depending predominantly on the baseline land cover it would have replaced. Details of the assumptions made in the study, the model configuration and results obtained from the analyses are presented in this paper.

Keywords: *Sugarcane, Streamflow Reduction Activity (SFRA), ACRU model*

1 Introduction

Recent studies have indicated that water allocated to users in the Mhlathuze River catchment (Figure 1.1) exceeds the available yield of the system. In contrast, however, the actual water use (mainly of the irrigation sector) is significantly less than the allocations and these constantly remained lower than the system yield over time. This anomaly between allocation and actual water use and the competition for additional water from the existing developed water resources has also become a significant risk to further economic development in the area. Equity requirements also require more water to be made available. As a result, the Mhlathuze River catchment has been identified as one of the priority catchments for the implementation of WAR and Compulsory Licensing, to reconcile the water resource allocations in a fair and equitable manner. A detailed Water Availability Assessment Study in the catchment has been commissioned by DWAF. A product of the study is to develop water availability assessment methodologies (including mathematical models) that can be used for decision support as part of WAR and Compulsory Licensing.

The Mhlathuze River system supplies water to the urban, domestic, industrial, and mining sectors situated around Richard's Bay and Empangeni on the north coast of KwaZulu-Natal, as well as to the agricultural sector, irrigating mainly sugarcane and citrus. The W12 Tertiary Catchment encompasses the Mhlathuze River catchment along with several smaller coastal catchments (Figure 1.1). The main regulating storage in the catchment is the Goedetrou Dam, which is located in the upper reaches of the catchment (Figure 1.1). The W11 and W13 Tertiary Catchments include the Amatikulu and the Mlalazi River catchments respectively (Figure 1.1). This area is predominantly agricultural in nature. Both irrigated and dryland sugarcane are produced in these catchments and a significant amount of commercial afforestation is also present.

Commercial production forestry is currently the only Streamflow Reduction Activity (SFRA) declared in terms of the National Water Act (NWA). Studies commissioned by the DWAF to identify additional SFRAs have concluded that these should only include dryland crops. A set of criteria has been defined to assist in indicating which other agricultural land uses could be declared as SFRAs. Use of these criteria has identified both dryland sugarcane and plantation bamboo to be potential SFRA candidates. The sugar industry has strongly opposed the criteria used, arguing that the use of potential evapotranspiration rather than actual evapotranspiration as a filter for selecting potential SFRAs is both scientifically flawed (Bezuidenhoud, et al., 2006) and a contradiction to Section 36 of the NWA. The forestry sector however favour that other water users be included. The key reason for the declaration of water-using activities as SFRAs is the need for appropriate control over the use of water resources, preventing an uncontrolled diminution of the resource, and allowing a re-allocation of water either for equity or to meet the human and/or environmental Reserve should this be necessary (DWAF, 2005).

The objective of this study was to establish time series of streamflow reductions (SFRs) at Quaternary Catchment scale, resulting from dryland sugarcane in the Mhlathuze, Amatikulu and Mlalazi catchments on the KwaZulu-Natal north coast. The methodology used for the SFR estimation for commercial afforestation in South Africa (Gush *et al.*, 2002) was adopted for the study. The *ACRU* agrohydrological model (Schulze, 1995 and updates) was used for the investigation.

2 Method and Assumptions

Sugarcane has a 12 month growing cycle in the three catchments and the cane was assumed to be a ratoon (rather than a plant) crop. The simulation was carried out in each Quaternary Catchment (QC) for four dates designating the beginning of a growth cycle, *viz.* May, July, September, and November.

Two scenarios were simulated using the *ACRU* model. For Scenario 1 it was assumed that the entire catchments were covered with dryland sugarcane and while for Scenario 2, Acocks' (1988) Veld Types, representing baseline (i.e. reference) land covers were assumed to cover the catchments (cf. Figure 1.1). The SFRs were estimated by subtracting the total flows from Scenario 1 from those of Scenario 2.

In order to perform the simulations for the dryland sugarcane scenario, the crop coefficients of sugarcane needed to be determined, as discussed below.

2.1 Crop Coefficients

The crop coefficients vary between the different Quaternaries and for the different dates designating the beginnings of a growth cycle, and hence the daily crop coefficients were calculated for each of the cycles for each Quaternary, as opposed to using the frequently applied all-year-round averaged *ACRU* sugarcane crop coefficients of 0.8. The following equations were used for the calculations of daily crop coefficients (Hughes, 1992):

$$K_c = 0.297 + (1.32 \times 10^{-6} \times GD_a^2) - (6.83 \times 10^{-10} \times GD_a^3) - K_{red} \quad (1)$$

$$K_{red} = 0.05 + (1.32 \times 10^{-6} \times GD_r^2) - (6.83 \times 10^{-10} \times GD_r^3) \quad (2)$$

where:

K_c	=	daily sugarcane crop coefficient
K_{red}	=	crop coefficient reduction factor
GD_a	=	accumulated degree days since beginning of the growth cycle (°C day)
GDr	=	accumulated degree days since initiation of ripening (°C day) and before deterioration of the crop commences
Degree day	=	$((T_{max}+T_{min})/2)$ - 12 (°C day)
T_{max}	=	daily maximum temperature (°C)
T_{min}	=	daily minimum temperature (°C)

with the following limits:

K_c	≤	1 for plant crop
	≤	0.96 for first ratoon crop
	≤	0.92 for second and subsequent ratoons
	≤	0.50 during ripening
GD_a	≤	1300.

Daily climatic information (T_{max}, T_{min}, rainfall) for the 50 year period 1950 – 1999 for each of the Quaternaries making up the catchments was extracted from databases developed in the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal (BEEH) by Lynch (2004) and Schulze and Maharaj (2004). The daily maximum and minimum temperatures were used to determine the daily crop coefficients for each Quaternary and for each of the growth cycles commencing in different months. For this study an assumption was made that the crop did not reach the deterioration stage after ripening and hence the crop coefficient reduction factor (K_{red}) did not play a role, i.e. $K_{red} = 0$. If any deterioration would take place, the water use would be slightly overestimated in the simulation. A full canopy crop coefficient limit of 0.92 (second and subsequent ratoons) was assumed. The median monthly values for K_c, used in subsequent calculations (cf Section 2.2) were then determined.

2.2 Additional ACRU Model Input Variables

The following *ACRU* model input variables were derived for each month of the year for the simulation of streamflows from dryland sugarcane:

- Fraction of effective root distribution in the topsoil horizon (ROOTA)
- Interception loss (mm/rainday) by vegetation (VEGINT)
- Percentage of surface cover/litter/mulch (PCSUCO)

All three these variables are functions of the median monthly crop coefficients and were determined by the linear relationships illustrated in Figure 2.1.

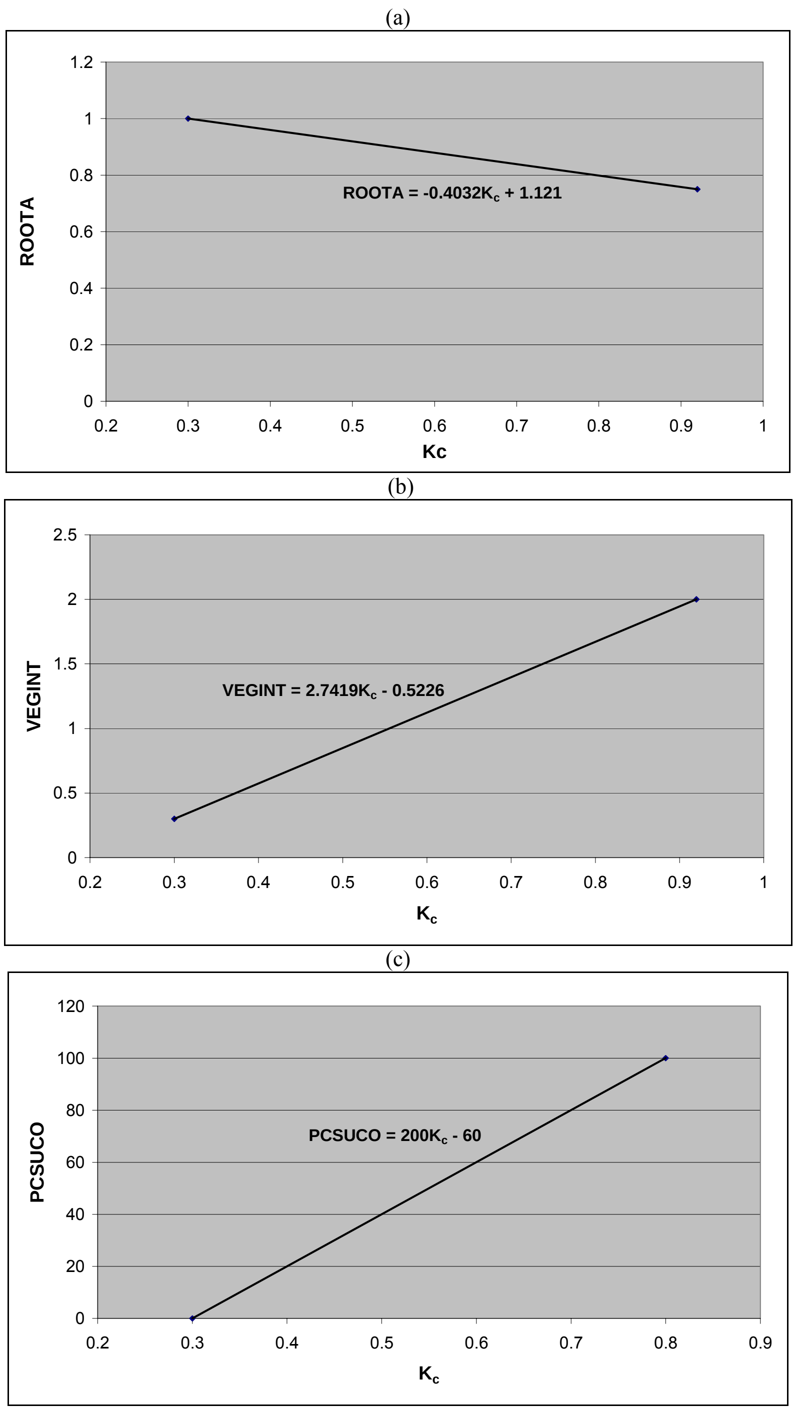

Figure 2.1. Linear relationships between (a) ROOTA and K_c, (b) VEGINT and K_c and (c) PCSUCO and K_c

The soil was assumed to be a deep sandy clay loam with thicknesses of 0.3 m and 0.6 m respectively for the top- and subsoil horizons. Any potential differences in actual transpiration amounts would be greater for a deep soil compared to a shallow soil. The *ACRU* variables used for simulating streamflows from dryland sugarcane are given in Table 2.1 below.

Table 2.1. Input variables to the *ACRU* model for simulations of streamflows from dryland sugarcane

Variable	Description	Value/Source
CORPPT	Rainfall adjustment factors to give a more representative catchment/subcatchment rainfall from station data	BEEH databases
Tmax/Tmin/A-pan	Mean monthly climatically data	BEEH databases
EQPET	Method used to derive reference potential evaporation (E_r) where daily A-pan equivalent evaporation is the reference	102 (monthly totals of daily A-pan equivalent evaporation)
ALBEDO	Reflection coefficient of incoming shortwave radiation fluxes	0.07 (default value)
DEPAHO	Thickness of topsoil horizon (m)	0.30 m
DEPBHO	Thickness of subsoil horizon (m)	0.60 m
WP	Soil water content ($m.m^{-1}$) at permanent wilting point	0.159 (for both horizons - *ACRU* Manual)
FC	Soil water content ($m.m^{-1}$) at drained upper limit	0.254 (for both horizons - *ACRU* Manual)
PO	Soil water content ($m.m^{-1}$) at saturation (i.e. porosity)	0.402 (for both horizons- *ACRU* Manual)
ABRESP	Fraction of saturated soil water to be redistributed daily from the topsoil to the subsoil	0.5 (value for SaClLm – *ACRU* Manual)
BFRESP	Fraction of saturated soil water to be redistributed from the subsoil to the intermediate/groundwater store	0.5 (value for SaClLm – *ACRU* Manual)
CAY	Monthly average of daily crop coefficients	Per planting date (Equation 1 and 2)
VEGINT	Interception loss ($mm.rainday^{-1}$) by vegetation	Linear f(CAY) (Figure 2.1 (b))
ROOTA	Fraction of effective root distribution in the topsoil horizon	Linear f(CAY) (Figure 2.1 (a))
EFRDEP	Effective rooting depth (m), defaulted to combined thicknesses of the topsoil horizon + subsoil horizon	0.9 (bothhorizons)
EVTR	Option for estimating total evaporation as an entity or by soil water evaporation (E_s) and plant transpiration (E_t) computed separately	2 (soil water evaporation and transpiration computed separately)
CONST	Fraction of the plant available water of a soil horizon at which total evaporation is assumed to drop below the maximum evaporation during the drying of the soil	0.4 (*ACRU* Manual)
QFRESP	Stormflow response fraction for the catchment/subcatchment	0.21 (Gush *et al*., 2002)
SMDDEP	Effective critical depth of the soil from which stormflow generation takes place	0.0 (equivalent to the topsoil horizon soil thickness)
ADJIMP	Fraction of the catchment occupied by Impervious areas that are adjacent to the water course	0.0 (assumption)
DISIMP	Fraction of the catchment occupied by Impervious areas that are not adjacent to the water course	0.0 (assumption)
COIAM	Coefficient of initial abstraction	0.35 (*ACRU* Manual)
PCSUCO	Percentage surface cover (mulch, litter etc.)	-100 (linear f(K_c)) ≤0.8) (Figure 2.1(c))
COLON	Percentage of root colonization in the subsoil horizon	100% (to be comparable to that of baseline land cover)

The Acocks Veld Types occur in the different Quaternaries as listed below and illustrated in Figure 1.1:

W11A = Ngongoni veld
W11B = Coastal forest and thornveld
W11C = Coastal forest and thornveld
W12A = Ngongoni veld

W12B = Ngongoni veld
W12C = Zululand thornveld
W12D = Lowveld
W12E = Lowveld
W12F = Coastal forest and thornveld
W12G = Zululand thornveld
W12H = Coastal forest and thornveld
W12J = Coastal forest and thornveld
W13A = Coastal forest and thornveld
W13B = Coastal forest and thornveld

Identical soils and climate related input variables were used in simulations for each Quaternary Catchment for the two scenarios. The Acocks-related variables were obtained from Schulze (2004).

3 Results

The calculated median monthly crop coefficients for the different Quaternaries for the four selected beginnings of growth cycles are shown in Tables 3.1 - 3.4.

Table 3.1. Median monthly dryland sugarcane K_c values for the beginning of a growth cycle in May

QUAT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
W11A	0.92	0.92	0.92	0.92	0.31	0.36	0.43	0.50	0.64	0.81	0.92	0.92
W11B	0.92	0.92	0.92	0.92	0.32	0.40	0.50	0.62	0.79	0.92	0.92	0.92
W11C	0.92	0.92	0.92	0.92	0.32	0.41	0.52	0.64	0.82	0.92	0.92	0.92
W12A	0.92	0.92	0.92	0.92	0.30	0.31	0.32	0.33	0.39	0.49	0.64	0.82
W12B	0.92	0.92	0.92	0.92	0.31	0.35	0.41	0.48	0.61	0.78	0.92	0.92
W12C	0.92	0.92	0.92	0.92	0.31	0.35	0.40	0.46	0.60	0.76	0.92	0.92
W12D	0.92	0.92	0.92	0.92	0.31	0.35	0.40	0.46	0.60	0.76	0.92	0.92
W12E	0.92	0.92	0.92	0.92	0.32	0.40	0.51	0.63	0.81	0.92	0.92	0.92
W12F	0.92	0.92	0.92	0.92	0.32	0.42	0.54	0.67	0.85	0.92	0.92	0.92
W12G	0.92	0.92	0.92	0.92	0.32	0.39	0.49	0.60	0.79	0.92	0.92	0.92
W12H	0.92	0.92	0.92	0.92	0.32	0.41	0.53	0.66	0.85	0.92	0.92	0.92
W12J	0.92	0.92	0.92	0.92	0.32	0.42	0.55	0.69	0.86	0.92	0.92	0.92
W13A	0.92	0.92	0.92	0.92	0.32	0.39	0.49	0.60	0.76	0.92	0.92	0.92
W13B	0.92	0.92	0.92	0.92	0.32	0.41	0.54	0.67	0.84	0.92	0.92	0.92

Table 3.2. Median monthly dryland sugarcane K_c values for the beginning of a growth cycle in July

QUAT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
W11A	0.92	0.92	0.92	0.92	0.92	0.92	0.30	0.33	0.42	0.57	0.76	0.92
W11B	0.92	0.92	0.92	0.92	0.92	0.92	0.30	0.35	0.48	0.68	0.89	0.92
W11C	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.36	0.49	0.69	0.91	0.92
W12A	0.90	0.92	0.92	0.92	0.92	0.92	0.30	0.30	0.33	0.40	0.53	0.72
W12B	0.92	0.92	0.92	0.92	0.92	0.92	0.30	0.32	0.41	0.56	0.75	0.92
W12C	0.92	0.92	0.92	0.92	0.92	0.92	0.30	0.32	0.40	0.55	0.74	0.92
W12D	0.92	0.92	0.92	0.92	0.92	0.92	0.30	0.35	0.48	0.69	0.91	0.92
W12E	0.92	0.92	0.92	0.92	0.92	0.92	0.30	0.36	0.50	0.70	0.92	0.92
W12F	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.37	0.51	0.72	0.92	0.92
W12G	0.92	0.92	0.92	0.92	0.92	0.92	0.30	0.35	0.49	0.71	0.92	0.92
W12H	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.36	0.52	0.74	0.92	0.92
W12J	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.37	0.52	0.73	0.92	0.92
W13A	0.92	0.92	0.92	0.92	0.92	0.92	0.30	0.35	0.47	0.65	0.86	0.92
W13B	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.36	0.50	0.70	0.91	0.92

Table 3.3. Median monthly dryland sugarcane K_c values for the beginning of a growth cycle in September

QUAT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
W11A	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.40	0.57	0.80
W11B	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.43	0.65	0.91
W11C	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.43	0.66	0.92
W12A	0.83	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.30	0.35	0.46	0.64
W12B	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.40	0.56	0.80
W12C	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.40	0.56	0.80
W12D	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.44	0.67	0.92
W12E	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.44	0.67	0.92
W12F	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.44	0.68	0.92
W12G	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.45	0.69	0.92
W12H	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.46	0.71	0.92
W12J	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.45	0.68	0.92
W13A	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.42	0.62	0.87
W13B	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.43	0.65	0.91

Table 3.4. Median monthly dryland sugarcane K_c values for the beginning of a growth cycle in November

QUAT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
W11A	0.72	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.47
W11B	0.80	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.52
W11C	0.81	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.33	0.53
W12A	0.59	0.82	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.31	0.41
W12B	0.71	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.47
W12C	0.71	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.47
W12D	0.82	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.33	0.53
W12E	0.82	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.33	0.53
W12F	0.83	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.33	0.54
W12G	0.84	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.33	0.55
W12H	0.86	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.33	0.56
W12J	0.84	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.33	0.54
W13A	0.78	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.51
W13B	0.81	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.32	0.53

The SFRs (i.e. reductions in total flows, mm) due to dryland sugarcane were calculated for 50 years of daily climate input data for each Quaternary Catchment as follows:

$$\frac{(Acocks - Sugar_{May}) + (Acocks - Sugar_{Jul}) + (Acocks - Sugar_{Sep}) + (Acocks - Sugar_{Nov})}{4} \qquad (3)$$

The daily streamflow values were then summed into 50 annual values from which the median annual value was selected to represent the SFR for each Quaternary. The median annual total flows obtained for baseline land cover (Acocks), sugarcane for the different beginnings of growth cycles and the SFRs (all in mm) for each Quaternary are given in Table 3.5.

Table 3.5. Median annual total streamflows and median annual SFRs (mm) due to dryland sugarcane

	W11A	W11B	W11C	W12A	W12B	W12C	W12D	W12E	W12F	W12G	W12H	W12J	W13A	W13B
Acocks	147.9	113.1	146.0	108.2	104.1	75.1	112.7	212.5	252.5	109.8	144.1	267.7	161.0	318.5
Sugar May	127.4	124.4	157.8	103.5	88.0	67.7	97.6	190.0	254.5	103.1	149.9	274.1	170.1	330.1
Sugar July	130.7	128.4	157.7	103.1	82.3	72.1	98.1	192.8	264.5	102.8	154.6	279.1	171.4	339.2
Sugar Sept	127.9	121.6	157.0	100.4	79.2	73.2	96.8	197.2	268.4	105.4	156.1	277.2	171.0	340.5
Sugar Nov	131.1	123.3	163.0	100.4	83.1	71.1	94.6	197.7	256.4	105.3	156.0	283.3	178.7	346.4
SFR	**17.9**	**-8.0**	**-9.2**	**10.1**	**15.0**	**3.0**	**6.0**	**13.4**	**-8.9**	**3.44**	**-8.0**	**-3.4**	**-9.4**	**-12.5**

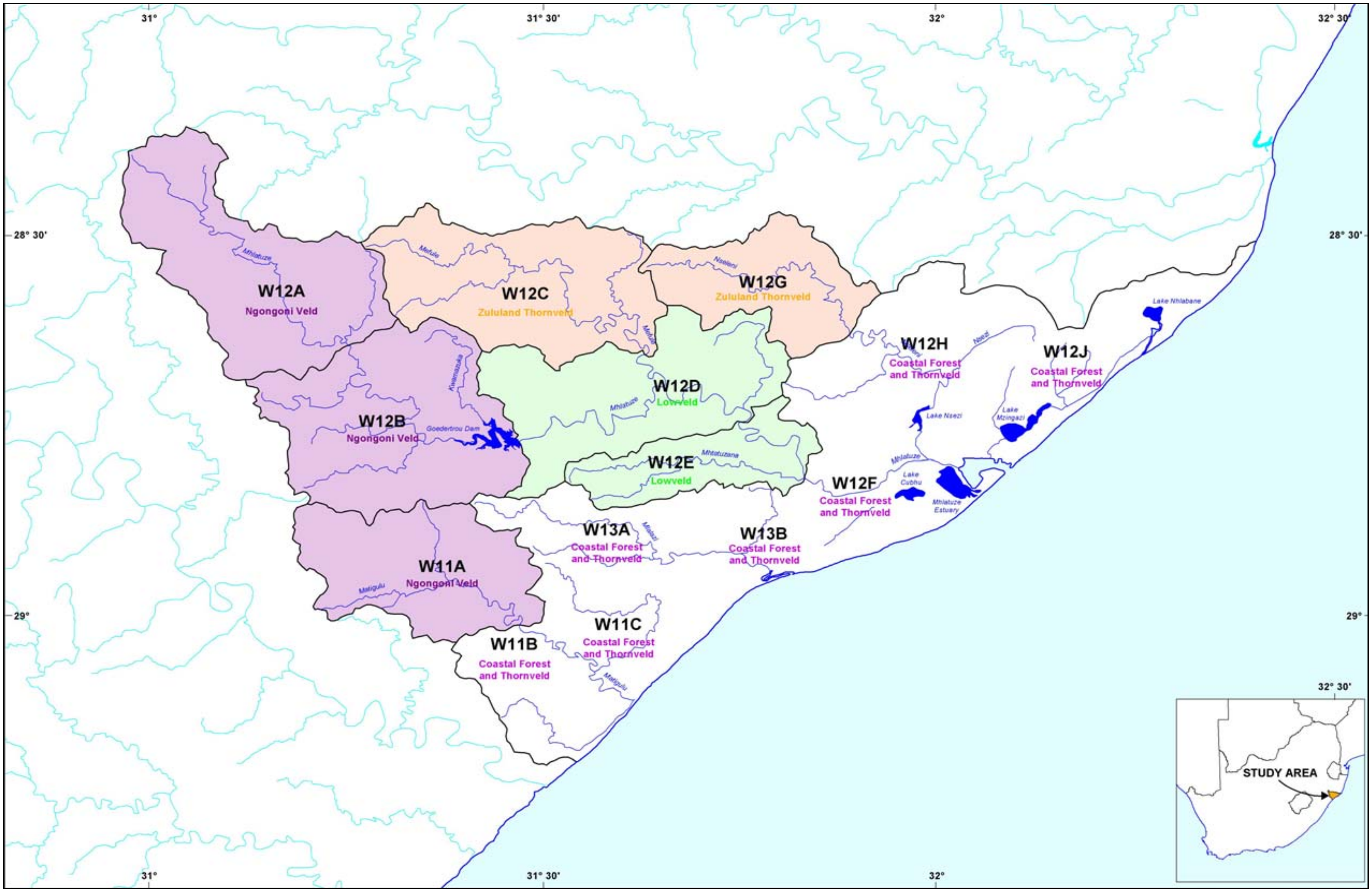

Figure 1.1. Quaternary Catchments making up the study area, with Acocks' (1988) baseline land cover types superimposed

4. Discussion of Results

Based on the results in Table 3.5 it may be seen that negative SFR values (i.e. increases in median annual streamflows due to conversion of baseline land cover to sugarcane) were simulated for approximately 50% of the Quaternaries. Negative SFRs are found mainly at the coastal Quaternaries where Coastal Forest and Thornveld occurred as the baseline Acocks land cover, as opposed to Ngongoni Veld and Lowveld, where positive streamflow reductions occurred (cf. Figure 1.1).

The reason for this is that high biomass Coastal Forest and Thornveld vegetation is a larger water user, and, hence, has a greater impact on the hydrological resources than the remaining baseline vegetation types. For assessing water availability in catchments such as the Mhlathuze, Amatikulu and Mlalazi . a conservative approach would be to assume that the annual flows remain unchanged for those Quaternary Catchments where an increase in annual flow due to dryland sugarcane was simulated. The process of including dryland sugarcane under the SFRA Water Use Licensing System is, however, far more complex than shown by only the above analysis and a more comprehensive study would be required to address the issues of, for example, regional variability, temporal variability (e.g. wet vs. dry years) and applying spatial resolutions finer than Quaternaries. It is also important that the actual area in a catchment covered by a SFRA be taken into account when assessing the hydrological impact of an SFRA, as the magnitude of the impact will largely depend on this.

It must be noted that the streamflow results obtained could not be verified with actual measured results; as such data does not exist. The algorithms used in the model, for example, to relate canopy development to thermal time, and sugarcane evapotranspiration to a reference evaporation estimate, are however based on well researched experiments and observations.

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