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Atlas of water use and yield of biofuel crops in suitable growing areas (Volume 3)

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WATER RESEARCH COMMISSION

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Report to the
WATER RESEARCH COMMISSION

by

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This report (**Volume 3**) is part of a three-volume series. **Volume 1** is a synthesis report which focuses on the key findings of the project. **Volume 2** provides more detail regarding the field work as well as the mapping and modelling components of the project. **Volume 3** represents the biofuels atlas and assessment utility.

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EXECUTIVE SUMMARY

BACKGROUND AND MOTIVATION

South Africa is following the international trend of liquid biofuel production, as noted in the South African Biofuels Industrial Strategy of 2007. This strategy highlighted the benefits of biofuel production in terms of alleviating poverty in rural areas, promoting rural economic development and stimulating agricultural production. A 2% blend of biofuels in the national liquid fuel supply, equivalent to an annual production of approximately 400 million litres of biofuel, was proposed by the former Department of Minerals and Energy. To ensure sustainable biofuel production, South Africa plans to grow feedstock on currently under-utilised arable land and preferably under rainfed conditions.

In 2006, the task team that developed the biofuels strategy urged the government to determine the impacts of biofuel feedstock production on both water quality and water quantity. The Water Research Commission (WRC) responded to this request and funded a two-year (2007-2009) scoping study on the water use of biofuel feedstocks. The main aims of the scoping study were to 1) identify suitable feedstock for the production of biofuel, 2) map areas climatically suited to feedstock cultivation, 3) determine the available knowledge on feedstock water use, 4) model the water requirements of selected feedstock, and 5) identify existing knowledge gaps.

The scoping study report concluded that both sugarcane and sweet sorghum show potential to use more water than the natural vegetation they may replace, whilst other crops (e.g. sugarbeet, canola, soybean & sunflower) do not. However, the scoping study highlighted that for the emerging feedstocks (e.g. sugarbeet & sweet sorghum), parameter values were gleaned from the international literature. The literature also provided conflicting water use figures for certain feedstocks (in particular sweet sorghum) and that knowledge is surprisingly limited for certain crops (e.g. canola). The scoping study recommended a need to better understand the water use and yield of biofuel feedstocks. In addition, a more detailed mapping approach was required to identify feedstock growth areas that considered additional site factors (not just rainfall and temperature). Based on these recommendations, the WRC initiated and funded a six-year (i.e. more comprehensive) follow-up study.

This six-year solicited project began in April 2009 and was led by the University of KwaZulu-Natal, in close collaboration with the CSIR (Natural Resources & Environment) and the University of Pretoria (Department of Plant Production & Soil Science). The aims of the follow-up study were broadly similar to those of the scoping study, except for the need to estimate crop yield and biofuel yield.

PROJECT OBJECTIVE AND AIMS

The overall objective of this project was to determine the water use of selected biofuel feedstocks deemed suitable for bioethanol and biodiesel production in selected high and low potential bio-climatic regions of South Africa. The specific aims of the project were as follows:

AIM 1 - To specify and prioritise currently grown and potential alternative first and second generation crops and cropping systems including both annual and perennial crops/trees with attention to, amongst others:

- Crops and crop rotations for food and forage production,
- Crops and crop rotations for biofuel production,
- Multiple use systems e.g. food, fodder and fuel crop combinations,
- Monoculture high density crop production systems,
- Tree feedstocks in plantations, agro-forestry or alley cropping systems, and
- Cellulosic feedstocks.

AIM 2 - To review and characterise crop parameters, water use and yield (biomass, biofuel and by-products) of crops based on existing knowledge or estimation thereof by applying existing tools with reference to those prioritised in South Africa and those which have potential as alternative biofuel crops as identified above.

AIM 3 - To identify and describe bio-climatic regions suitable for these priority crop/tree systems for biofuel production with reference to, amongst others:

- Rainfall average and variability,
- Surface and underground water resources,
- Temperature average and extremes,
- Soil properties,
- Known pests and diseases, and
- Topography.

AIM 4 - To determine crop parameters and model water use of specific crops/trees for biofuel that have potential but insufficient knowledge exists in South Africa to promote effective production.

AIM 5 - To determine the biofuel yield potential of crops in the respective bio-climatic regions under rainfed and/or irrigated conditions.

AIM 6 - To estimate or quantify the water use efficiency of these crops with reference to, amongst others, the following parameters:

- Biomass yield per m^3 water over the full productive cycle, and
- Biofuel yield per m^3 water over the full productive cycle.

AIM 7 - To assess the impact of land use changes on the water balance, within selected key catchments of the specified bio-climatic regions and at appropriate scales, with introduction of crops suitable for biofuel production.

AIM 8 - To develop a user-friendly, map-based software utility for the planning and management of biofuels in South Africa, drawing on findings from the specific aims listed above.

AIM 9 - To provide training opportunities for one post doctorate, two full-time PhD and five full-time MSc students. The principal researcher was also encouraged to obtain a PhD degree (part-time).

METHODOLOGY

With reference to **AIM 1** (to specify and prioritise feedstocks), the project was largely governed by the revised national biofuels industrial strategy, which was published by the former Department of Minerals and Energy in 2007. This strategy recommended two bioethanol feedstocks (i.e. sugarcane & sugarbeet) and three biodiesel feedstocks (i.e. soybean, canola & sunflower) for biofuel production. An inaugural symposium and workshop was held on 10th and 11th February 2010 respectively. One of the main objectives of the workshop was to identify key feedstocks for further investigation by the project team. Two feedstocks, namely sugarbeet and sweet sorghum, were highlighted for field-based research. These two crops were also recommended for further investigation in the biofuels scoping study report published in November 2009. From 2011 onwards, two potential biofuel manufacturers (i.e. Mabele Fuels & Arengo 316) expressed interest in grain sorghum. At a biofuels technical meeting held on 17th July 2012, the decision was made to measure the water use and yield of grain sorghum. Thus, the final list of prioritised crops was sugarcane, sugarbeet, sweet sorghum, grain sorghum, soybean and canola. Sunflower was not included and was replaced with grain sorghum, as agreed to at the reference group meeting on 23rd July 2014.

With reference to **AIM 2** (to evaluate and characterise feedstocks), information pertaining to, *inter alia*, crop parameters, water use and yield of the prioritised crops was gleaned from the field-based research as well as a thorough review of available literature (refer to Volume 2). The task highlighted the lack of information available for emerging feedstocks such as sugarbeet and sweet sorghum. Furthermore, surprisingly little information is also known about canola production in South Africa, which was unexpected.

AIM 3 is referred to as the mapping component of the project, with the modelling component involving **AIM 4** (water use modelling) and **AIM 5** (crop yield modelling). In order to derive parameters for certain feedstocks, field-based research was conducted at a number of research farms. The output from the modelling component of this project largely addressed **AIM 6** (estimation of water use efficiency) and **AIM 7** (hydrological impact of feedstock cultivation). In order to meet **AIM 8**, a software program called the Biofuels Assessment Utility was developed. Lastly, a number of students from the University of KwaZulu-Natal and the University of Pretoria worked on the project over its six-year time span (**AIM 9**). The methodology developed for each of these project components is summarised next.

Field work

Based on recommendations from the scoping study and the inaugural workshop, initial field work focused on the emerging feedstocks, in particular sugarbeet and sweet sorghum. Thus, field trials were established in the 2010/11 season to measure the water use and yield under optimal (i.e. no stressed) conditions of a) sweet sorghum at the Ukulinga (University of KwaZulu-Natal) and Hatfield (University of Pretoria) research farms, and b) sugarbeet (Ukulinga only).

The trials were repeated in 2011/12 to obtain two seasons of water use and yield data. In 2012/13, a third sugarbeet trial was undertaken at Ukulinga as well as research on grain sorghum (at Ukulinga and Hatfield). In the final season (2013/14), the grain sorghum trial at

Ukulinga was repeated and cost over R134 100, thus highlighting the expense of field work. Water use and yield data for soybean and yellow maize was derived by another WRC-funded project (No. K5/2066). A summary of the crop coefficients used to parameterise a hydrological model is provided in this report. The model was then used to assess the hydrological impact on downstream water availability that may result from biofuel feedstock cultivation.

Model selection

In this study, the *ACRU* agrohydrological modelling system was selected and used to estimate the water use of selected biofuel feedstocks. This daily time-step, process-based model was used to simulate runoff response for different land covers, as the sum of both storm flow and base flow. The *ACRU* model was selected to ensure compatibility with previous studies. Furthermore, the simulated runoff response from different land covers has been widely verified against observed runoff from different catchments.

In order to estimate the yield of each prioritised feedstock, the *AQUACROP* model was used. This model, developed by the FAO based in Rome (Italy), was selected because of its sensitivity to water stress. *AQUACROP* has already been parameterised for a number of biofuel feedstocks, including sugarcane, sugarbeet, grain sorghum, soybean and sunflower. In addition, a plug-in version exists which facilitates multiple (i.e. iterative) runs for estimating regional crop yield.

AQUACROP is ideally suited to assessing the impact of water availability on crop production for both irrigated and rainfed agriculture. Daily transpiration is multiplied by a water productivity parameter (which differentiates C_3 from C_4 plants) in order to calculate biomass production, which is then accumulated over the growing season. Crop yield is calculated as the product of accumulated biomass and the harvest index. Finally, nutrient deficiencies and salinity effects are simulated indirectly by moderating canopy cover development over the season, and by reducing, *inter alia*, crop transpiration.

Quinary sub-catchments

For operational decision making, the former Department of Water Affairs delineated South Africa into 22 primary drainage basins, each of which has been sub-divided into interlinked secondary, tertiary and quaternary (i.e. 4^{th} level) catchments. In total, 1 946 quaternary level catchments make up the contiguous area of southern Africa (i.e. RSA, Lesotho & Swaziland). Each quaternary has been assigned a single rainfall driver station deemed representative of the entire catchment area.

However, considerable physiographic heterogeneity exists within many of the quaternaries. For this reason, each catchment has been further sub-divided into three sub-catchments, according to altitude criteria. The upper, middle and lower quinaries of unequal area (but of similar topography) were sub-delineated according to "natural breaks"' in altitude by applying the Jenks optimisation procedure. This resulted in 5 838 quinary sub-catchments deemed to be more homogeneous than the quaternary catchments, in terms of their altitudinal range. In this study, the quinary sub-catchment (and not the quaternary catchment) was selected as the modelling and mapping unit. The quinary sub-catchments soils database contains soils information derived from land types developed by the former Soils and Irrigation Institute. The land types identified in each quinary were area weighted in order to derive one set of soils attributes (e.g. soil water retention parameters and soil depth) deemed to be presentative of the entire sub-catchment.

All model simulations were performed using the quinary sub-catchment climate database. This database contains 50 years (1950 to 1999) of daily climate data (rainfall, maximum temperature, minimum temperature & reference evaporation) deemed representative of each hydrological sub-catchment. The same rainfall station selected to drive each quaternary catchment was used to represent each of the three quinary sub-catchments. However, monthly adjustment factors were derived for each quinary and then applied to the daily rainfall record obtained from each quaternary rainfall driver station. In this way, a unique 50-year daily rainfall record was created for each of the 5 838 quinaries. The multiplicative adjustment factors were derived by first calculating spatial averages of all the one arc minute gridded median monthly rainfall values located within each quinary sub-catchment boundary. The ratio of these spatially averaged monthly rainfall totals to the driver station's median monthly rainfalls was then calculated to arrive at the 12 monthly adjustment factors.

A representative grid point location was chosen for each quinary sub-catchment. This was done by first calculating the mean altitude of each quinary from a 200 m Digital Elevation Model. Grid points located within a sub-catchment boundary at an altitude similar to the sub-catchment mean were then identified. From these, the grid point closest to the sub-catchment centroid was then selected to represent the quinary.

For each selected grid point, an algorithm was used to derive daily maximum and minimum temperature data from the two nearest temperature stations. A monthly lapse rate adjustment was applied to account for altitude differences between the nearest temperature stations and the altitude of the selected grid point. Daily data from each temperature station was weighted according to distance (i.e. from the grid point to each station). Daily temperature data generated for the selected grid point was then used to estimate solar radiation and relative humidity. From this, daily estimates of reference evaporation (Penman-Monteith or FAO56 equivalent) were derived assuming a default wind speed of 1.6 m s^{-1}.

Since *ACRU* uses the A-pan evaporimeter as its reference, FAO56-based reference evaporation was adjusted to A-pan equivalent evaporation using a monthly multiplicative factor which ranged from 1.17 to 1.37 (i.e. A-pan evaporation exceeds FAO56 evaporation by 17 to 37%). This adjustment was derived from the reciprocal of a pan factor, which was calculated for a green fetch of 200 m and an average daily wind speed was 1.6 m s^{-1}. The pan factor varied monthly according to mean monthly relative humidity estimates.

Revised climate database

In this study, the daily temperature dataset deemed representative of each quinary centroid was revised. The algorithm used to select two representative temperature stations for each grid point was modified. The improved algorithm considered both the distance and altitude difference between the neighbouring temperature stations. This modification allowed for the selection of stations slightly further away, but required a smaller altitude adjustment of temperature. The weighting factor was corrected to assign more influence to the "best" (but not necessarily the closest) station. Daily reference (FAO56) evaporation estimates were then calculated from the revised temperatures values. In addition, a different technique was used to calculate monthly adjustment factors to derive unscreened A-pan equivalent evaporation from FAO56-based reference evaporation. The technique was based on a modified version of the so-called "*PENPAN*" equation, which recently has been successfully applied in Australia to estimate A-pan equivalent evaporation. The adjustments suggest that A-pan equivalent evaporation exceeds FAO56 evaporation by a factor ranging from 17 to 51% for southern Africa. Hence, the revised quinary sub-catchment climate database contains improved temperature and evaporation estimates.

Water use modelling

The same methodology that has been established (and accepted) in South Africa to determine the potential impact of a land use change from natural vegetation on downstream water availability, was used in this study. In essence, the *ACRU* hydrological model was parameterised for natural vegetation and used to determine long-term mean annual runoff response for baseline (i.e. historical) conditions (MAR_{base}). The Acocks Veld Type map is used to represent natural vegetation or pristine conditions.

The *ACRU* model was then parameterised for each prioritised feedstock and used to estimate the runoff response for a 100% land cover change (MAR_{crop}). Model parameter values were gleaned from 1) field work undertaken as part of this study, and 2) an extensive review of available literature.

Hydrological impacts of land use change

The relative reduction in annual runoff (MAR_{redn}) that may result from the intended land use change was calculated as (MAR_{base} - MAR_{crop})/MAR_{base}, which was expressed as a percentage change. Positive MAR_{redn} values suggest that the intended land use change may result in less water being available to downstream users. An annual reduction of 10% or more was considered significant and used to identify feedstocks that may need to be declared as Stream Flow Reduction Activities or SFRAs.

Of more concern is the impact of land use change on stream flow during the low flow period. The start of the driest three-month period (or driest quartile) was determined using the monthly stream flow estimates produced by *ACRU* for the baseline (i.e. natural vegetation). This reduction in monthly runoff over driest quartile was then determined and expressed as a percentage relative to the baseline. If this percentage exceeded 25%, the land use change may also be considered a considered a SFRA.

Biofuels assessment utility

A PC-based software utility was developed to 1) disseminate stream flow output from the *ACRU* model, and 2) assess the impact on a land use change to feedstock cultivation on downstream water availability. This utility will mainly be used by the Department of Water and Sanitation to assess a feedstock's stream flow reduction potential in any quinary sub-catchment.

Crop yield modelling

Previous work on national yield modelling involved the use of simple empirically-based yield models, which could not account for, *inter alia*, the so-called "CO_2 fertilisation effect". For example, the yield models developed by Barry Smith utilise monthly rainfall and temperature data to derive crop yield estimates. In this study, a unique approach was adopted which involved the use of a more complex, deterministic-based model to simulate crop yield at the national scale.

Due to the conservative nature of most of *AQUACROP*'s parameters, the model requires the "fine-tuning" of only a few parameters in order to provide realistic estimates of crop yield. For this project, the model was well calibrated for both sugarcane and sugarbeet, in order to better represent local growing conditions. Similarly, research conducted as part of another WRC Project (K5/2066) assisted with the calibration of soybean and yellow maize. For grain sorghum, the default crop parameter file was mainly used. Where possible, the calibrated model was validated using datasets for other locations that were not used in the calibration process.

The use of *AQUACROP* to derive estimates of crop yield at the national level involved linking the model to the quinary sub-catchment climate and soils database. Over 5 000 lines of computer code were written to facilitate and automate this process. Typical planting dates for each feedstock were obtained from a literature review. The model was used to estimate yield for each prioritised feedstock (some with two different planting dates) across all 5 838 quinary sub-catchments. This meant the model was run for areas not suited to crop growth (i.e. too cold and/or too dry), which caused *AQUACROP* to "crash". The automation process was specifically designed to re-start the model run if such an event occurred.

A variety of maps were produced from output simulated by *AQUACROP* at the quinary sub-catchment scale for three bioethanol crops (sugarcane, sugarbeet & grain sorghum) and two biodiesel crops (canola & soybean). These maps included the mean and median seasonal yield as well as the inter-seasonal variation in yield. Similar maps were produced for crop water use efficiency. Other maps which show the number of years of simulated yield data and the risk of crop failure were also produced. Yield and water use efficiency derived using *AQUACROP* was then compared to that derived using the Soil Water Balance (*SWB*) model for certain quinaries located in the Western Cape.

Biofuel yield potential

The theoretical biofuel yield was estimated from the sugar, starch and seed oil content of feedstocks studied in the field. However, the stoichiometric yield of bioethanol or biodiesel is also dependent on the crop yield. To simply this calculation, the biofuel yield was also estimated from the product of the crop yield and the extraction rate. A table of biofuel extraction rates for selected feedstocks is presented in this report.

Land suitability mapping

For the biofuels scoping study, a literature review was undertaken to glean climate criteria for optimum crop growth. A geographic information system was then used to map areas climatically suited to optimum feedstock cultivation. This was achieved by applying the climatic thresholds to spatial datasets of rainfall and temperature. These spatial datasets were obtained from the South African Atlas of Climatology and Agrohydrology.

In this study, the literature review was expanded to include new reference material not used in the scoping study to glean growth criteria for each crop. In addition, three additional site criteria were considered for mapping. For example, relative humidity was incorporated as an index of disease incidence. Soil depth and slope were used to eliminate shallow soils and steep slopes, which are not deemed suitable for crop production. Each site factor was weighted accordingly to indicate its overall influence on crop survival, with rainfall deemed twice as important as temperature and slope (and four times more important than relative humidity and soil depth).

A number of improvements were made to the mapping approach used in the scoping study. For example, a unique method was used to consider the timing of monthly rainfall across the growing season. The water use coefficient was used to determine in which month the crop's water requirement peaks. Similarly, more weighting was assigned to relative humidity criteria in the months where disease outbreak is more probable. The mapping approach also considered existing land use and land cover, in order to eliminate "no-go" crop cultivation areas (i.e. urban areas, water bodies and areas formally protected for their high biodiversity value).

RESULTS AND DISCUSSION

From the field work component of this project, the following information was generated for selected bioethanol feedstocks:

- Water use over the growing season, defined as accumulated total evaporation (i.e. actual evapotranspiration) measured under stress-free growing conditions.
- Final crop yield and sugar content of sugarbeet and sweet sorghum.
- Final crop yield and starch content of grain sorghum.
- Theoretical bioethanol yield derived from crop yield and sugar/starch content.
- Water use efficiency, defined as crop yield per unit water use.
- Biofuel use efficiency, or the theoretical biofuel yield per unit water use.

From WRC Project No. K5/2066, the above information was included for soybean and yellow maize. Using the available information, this list of feedstocks was ranked in terms of water use efficiency and biofuel use efficiency. The results show that sugarbeet is most water use efficient in terms of producing "more crop per drop", whilst grain sorghum is least efficient. However, in terms of biofuel use efficiency, yellow maize is the most efficient at producing more biofuel per unit of water consumed by the crop, with soybean regarded as the least efficient.

The primary outputs generated from the modelling of water use, and thus available for each of the 5 838 quinary sub-catchments, include the following:

- Estimates of daily, monthly and annual stream flow response from natural vegetation.
- Estimates of daily, monthly and annual stream flow response from a land cover of selected biofuel feedstocks.
- Maps highlighting quinaries in which a reduction in mean annual runoff of 10% or more may occur for selected feedstocks.
- Maps highlighting quinaries where a 25% or larger reduction in monthly runoff may occur during the low flow period.
- The shift in low flow period that may result from a land cover change from natural vegetation to the intended feedstock.

Based on *ACRU*'s simulated runoff output, canola is least likely to cause a significant (i.e. ≥ 10%) reduction in water available to downstream users, whereas sugarcane exhibits the highest SFR potential (i.e. highest crop water use). Few quinaries were flagged where a significant (i.e. ≥ 25%) reduction in monthly runoff accumulated over the low flow period may occur. However, all feedstock crops have the potential to shift the start of the low flow quartile (i.e. driest three months of the year), when compared to that for natural vegetated conditions. Hence, the reduction in flow flows may be exacerbated by this shift in "seasonality".

From the crop yield modelling, the following information is available for each of the 5 838 quinary sub-catchments for rainfed conditions:

- seasonal estimates of yield and water use efficiency for selected feedstocks,
- long term attainable yield and water use efficiency (mean and median),
- inter-seasonal variation in crop yield and water use efficiency,
- risk of crop failure, defined as the probability of a seasonal yield of zero dry tons per hectare,
- number of seasons of simulated yield and water use efficiency data, and
- length of the growing season.

The maps show that sugarcane is most water use efficient when produced along the coastal areas of KwaZulu-Natal and the Eastern Cape. Similarly, canola is most water use efficient when grown in the Western Cape region. Using the average crop yield estimate for a particular quinary, the biofuel yield potential can be determined using representative extraction rates. The results indicate that bioethanol feedstocks require much less arable land than biodiesel feedstocks to produce 1 000 m^3 of biofuel.

Land suitability maps were produced for sugarcane, sugarbeet, grain sorghum, soybean and canola. For certain feedstocks, the areas highlighted as highly suitable for crop production do not necessarily correspond to quinary sub-catchments exhibiting high crop yields. The results show a significant (i.e. ≈50%) reduction in the area considered suitable for soybean production when compared to the map published in the scoping study report. The cultivation of sugarbeet planted in winter will likely require supplemental irrigation. The canola map does not identify suitable production areas in the Free State, where cultivation is possible under rainfed conditions during the winter months.

INTERPRETATION OF RESULTS

With regard to assessing the stream flow reduction potential of a particular feedstock, the mean and not median runoff statistic should be used. In terms of quantifying the long-term attainable yield for a particular location, the median statistic is recommended and not the mean.

Although WUE is highly influenced by environmental factors that affect crop growth (e.g. cultivar choice, planting date, plant density etc.), the metric shows potential for highlighting optimum *vs*. sub-optimum growing areas. However, if used as a standalone metric, it can be easily misinterpreted. Hence, it is recommended that WUE is considered in relation to the expected yield for a particular location.

CONCLUSIONS

It is important to note that research priorities changed over the project's duration due to, *inter alia*, policy amendments and new developments pertaining to South Africa's biofuels industry. For example, field work and modelling efforts shifted focus to grain sorghum, which was not considered a prioritised feedstock at the outset of the project. Nevertheless, the project contributed to the generation of new knowledge as follows:

- Monthly crop coefficients were derived for prioritised feedstocks that are deemed representative of local conditions.
- These crop coefficients were used to improve estimates of the hydrological impact of feedstock production on downstream water availability.
- The crop coefficients were also used to determine the optimum distribution of monthly rainfall over the growing season.
- A land use change to feedstock cultivation may cause a possible shift in the low flow period, which was highlighted as another potential impact on downstream water users.
- The land suitability maps provide more realistic estimates of the total land area deemed suitable for feedstock cultivation.
- The use of a deterministic-type crop model to derive estimates of attainable yield and water use efficiency at a national scale represents a major contribution to the existing knowledge base on agricultural production potential.
- Thus, the mapping and crop yield modelling approaches developed for this project are considered unique and innovative.

Using a hydrological simulation model, the potential impact on catchment water resources of large scale land use change to feedstock cultivation was assessed. In addition, a crop water productivity model was used to provide estimates of attainable yield for selected feedstock crops at the national scale. Water use efficiency (WUE = yield per unit of crop water use) was then calculated for each hydrological sub-catchment across the country. It is envisaged that the project outcomes will benefit end-users in the following manner:

- The Department of Water and Sanitation will utilise the large database of monthly and annual runoff simulations to assess the stream flow reduction potential of selected feedstocks in any quinary sub-catchment.
- The biofuel manufacturers will utilise the land suitability and crop yield maps to identify and target areas where feedstock should be cultivated.

- Agricultural extension officers will also find the crop yield maps useful for advising emerging farmers on which crop is best suited to their location.
- The Department of Energy could utilise the information to revise the country's biofuel production potential.
- WUE estimates for each biofuel feedstock may assist land use planners in striving towards the most beneficial use of available water resources.

Crop water use is incorporated into most standards that have been developed to measure agriculture sustainability. However, various metrics are used to assess this. In general, water use in agriculture usually means the total volume of rain water consumed by the crop (i.e. green water component of the "water footprint" concept), or the volume of surface water or ground water applied as irrigation (i.e. blue water component).

The results from this study highlight the diverse range in feedstocks when ranked according to their biofuel yield potential per unit land area (i.e. "land footprint") or per unit water use (i.e. "water footprint"). The output from this comprehensive six-year study has confirmed that water availability and not land availability, will limit South Africa's biofuel production potential. The environmental impact of biofuel feedstock production depends on the mix of feedstocks used to meet the volume targets set by the mandatory blending rates.

RECOMMENDATIONS FOR FUTURE RESEARCH

Owing to the high cost of field experimentation, the study of emerging crops, where best agronomic practices aren't well established, is not recommended. The variability in seasonal estimates of water use efficiency derived from measurements for both sugarbeet and sweet sorghum highlight this point.

The threshold of 25% currently used to assess a significant reduction in monthly runoff over the low flow period may be too high and needs to be re-assessed. The shift in low flow period is cause for concern and should be factored into the assessment of a feedstock's potential to be declared a stream flow reduction activity.

Considerable effort is required to develop a land suitability map for a particular feedstock. Output (in particular yield and WUE) from the crop modelling component should be used as input for the mapping approach in order to improve the assessment of land suitability.

Canola was incorrectly identified as a feedstock where sufficient knowledge exists for modelling feedstock water use and yield. It is recommended that the water use and yield of canola is measured in the field to improve the current lack of knowledge pertaining to this crop. Furthermore, canola's land suitability map should be revised by modifying the rainfall thresholds in an attempt to identify suitable growing areas in the eastern parts of the Free State.

It is recommended that the stream flow database required by the biofuels assessment utility is distributed to end-users on DVDs. However, updates should be distributed via the internet using SAEON's data portal.

It is envisaged that a number of end-users will request output in a GIS-compatible format. To facilitate such requests, it is recommended that such data are made available for download via the internet from SAEON's data portal.

It is envisaged that the recommendations for future work which emanated from this project, will guide a follow-up study that was initiated and funded by the WRC. This five-year project (No. K5/2491 titled "Water use of strategic biofuel crops") began in April 2015 and will terminate in March 2020.

EXTENT TO WHICH OBJECTIVES WERE MET

The project was required to specify and prioritise currently grown and potential alternative first and second generation crops (**AIM 1**). In this study, no research effort was focused towards 2nd generation feedstocks. Although Napier grass was initially flagged as a potential second generation feedstock, it would be prohibited for use in biofuel production if draft regulations pertaining to alien invasive plants are promulgated. With reference to **AIM 2** (i.e. to evaluate and characterise feedstocks), information pertaining to, *inter alia*, crop parameters, water use and yield of the prioritised crops was gleaned from the field-based research as well as a thorough review of the available literature.

The terms of reference of this project required the estimation of water use of feedstocks suitable for bioethanol and biodiesel production in selected high and low potential bio-climatic regions of South Africa. For example, **AIM 7** required the impact of land use change on the water balance of selected key catchments to be assessed. In this study, feedstock water use was modelled for all regions across South Africa. The approach taken to run the models for all quinaries and not a subset of quinaries where the crop may grow (i.e. based on the land suitability map) provides the following advantages:

- The national yield maps can be used to validate and improve the land suitability maps, especially since the latter maps differentiate low from high potential production areas.
- It avoids the scenario where additional model runs may be required in the future to generate data for "missing" quinaries, which were not highlighted as suitable growing areas for a particular feedstock.

Two simulation models were used to provide estimates of crop water use (**AIM 4**) and yield (**AIM 5**) at the national scale, for multiple feedstocks and planting dates. The time and effort required to complete this computationally complex task meant that the following specific aims were not met:

- The biofuel yield potential of crops in the respective bio-climatic regions (**AIM 5**) was not mapped.
- Similarly, the biofuel yield per unit of water used over the full productive cycle (**AIM 6**) was not mapped.
- The modelling was undertaken for rainfed conditions and thus, no work was conducted for irrigated crops (**AIM 5**).

With reference to **AIM 6**, water use efficiency was defined as the utilisable crop yield (and not the biomass yield) per unit of water utilised over the full productive cycle. With reference to **AIM 3**, the availability of groundwater resources was considered in the mapping approach to identify suitable crop production areas.

Regarding **AIM 8**, a map-based software utility originally developed in 2009 to assess the stream flow reduction potential of commercial afforestation (called the SFRA Assessment Utility), was modified to meet the needs of this project. Significant improvements were made to the utility, with additional functionality added.

AIM 9 refers to capacity building which is discussed further in the section that follows. In summary, the project did not meet the envisaged target of graduating five MSc and two PhD students.

CAPACITY BUILDING AND TECHNOLOGY TRANSFER

Finally, at the outset of this project, it was envisaged that two full-time PhD and five full-time MSc students would obtain their degrees through this project. To date, only two MSc students have graduated. However, two part-time students (one MSc and a PhD) are currently in the process of finalising their write-ups.

Over the six-year project duration, numerous presentations were given to both local and international audiences. The project benefitted from the knowledge gained at the Bioenergy Australia conference in 2011. In addition, the project gained exposure at the World Biofuels Markets conference at Rotterdam in 2013.

A poster was presented at SANCIAHS in 2012 and a paper at SANCIAHS in 2014. A paper was also presented at the World Soybean Research Conference in 2013 and at the SASTA Congress in 2014. Presentations were also given at the WRC research symposiums in 2011, 2013 and 2015.

Two symposiums and workshops were also organised as part of the project. The inaugural symposium and workshop took place in February 2010, with a follow-up symposium and workshop held in January 2013. The latter resulted in two popular articles which appeared in the Farmers Weekly and Landbou Weekblad magazines in February and March 2013 respectively. A popular article was published in the Water Wheel in the March/April 2014 edition as well as an online article on Engineering News in May 2014. The project was also mentioned in an article published in the Mercury newspaper on 27th March 2014. Finally, a paper emanating from the project on the water use efficiency of sweet sorghum was published in Water SA in January 2016.

DATA AND TOOLS

The project has generated over 1 000 gigabytes (Gb) of compressed model output pertaining to the national water use and crop yield simulations. In addition, high frequency measurements of air temperature used to estimate crop water use via the surface renewal method was also generated. The biofuels assessment utility will be used to disseminate a large database (i.e. ≈43.3 Gb) of daily stream flow simulations for natural vegetation as well as selected feedstocks. All raw and processed data is stored and archived on a fileserver located in the ICS Server Room on the main campus of the University of KwaZulu-Natal in

Pietermaritzburg. All project-related data and information was backed up to an external hard drive to be stored for the next five years. Contact person: Richard Kunz (kunzr@ukzn.ac.za).

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LIST OF ABBREVIATIONS

ACCI	African Centre for Crop Improvement
ACRU	Agricultural Catchments Research Institute
AgMIP	Agricultural Model Intercomparison and Improvement Project
AET	Actual EvapoTranspiration
APAN	USWB Class A evaporimeter
ARC	Agricultural Research Council
ARDA	Agrarian Research and Development Agency
ASCE	American Society of Civil Engineers
AWS	Automatic Weather Station
B5	5% biodiesel blend
BEEH	Bioresources Engineering and Environmental Hydrology (former)
CEC	Crop Estimates Committee
CARA	Conservation of Agricultural Resources Act
CGI	Crop Grains Institute or the ARC
CN	Curve Number
CNW	CaNola Winter
CO_2/CO2	Carbon Dioxide concentration
COMPETE	Competence Platform on Energy Crop and Agroforestry Systems for Arid and Semi-arid Ecosystems
cpl	cents per litre
CRBD	Completely Randomised Block Design
CSIR	Council for Scientific and Industrial Research
CSV	Comma Separated Values
CWRR	Centre for Water Resources Research
DAFF	Department of Agriculture, Forestry and Fisheries
DAP	Days After Planting
DDGS	Distiller's Dried Grains and Solubles
DoA	Department of Agriculture (former)
DoE	Department of Energy
DEAT	Department of Environmental Affairs and Tourism
DRDLR	Department of Rural Development and Land Reform
DME	Department of Minerals and Energy (former)
DST	Department of Science and Technology
DUL	Drained Upper Limit
DWA	Department of Water Affairs (former)
DWAF	Department of Water Affairs and Forestry (former)
DWS	Department of Water and Sanitation
E2	2% bioethanol blend
E3	3% bioethanol blend
E8	8% bioethanol blend
E10	10% bioethanol blend
EMA	Expectation Maximisation Algorithm
ESRI	Environmental Systems Research Institute
ET	EvapoTranspiration

EVS	Early Vegetative Stage
EWRI	Environmental and Water Resources Institute
FAO	Food and Agriculture Organisation of the United Nations
FAO56	Food and Agriculture Organisation, Paper No. 56
FAOSTAT	FAO STATistics
GAIN	Global Agricultural Information Network
GDD	Growing Degree Day
GDP	Gross Domestic Product
FC	Field Capacity
GTZ	German Technical Cooperation
FDR	Frequency Domain Reflectometry
GIS	Geographic Information System
GRS	GRain Sorghum
HI	Harvest Index
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
INTSORMIL	INTernational SORghum and MILlet Collaborative Research Support Program
IDC	Industrial Development Corporation
IoA	Index of Agreement
ISCW	Institute for Soil, Climate and Water
LAI	Leaf Area Index
LFR	Low Flow Runoff
LVS	Late Vegetative Stage
MAE	Mean Absolute Error
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff (or stream flow)
MdAR	Median Annual Runoff (or stream flow)
masl	metres above sea level
MAT	Mean Annual Temperature
NLC	National Land Cover
NDA	National Department of Agriculture
NPAES	National Protected Area Expansion Strategy
NWA	National Water Act
OEM	Original Equipment Manufacturer
PAR	Photosynthetically Active Radiation
PAW	Plant Available Water
PENPAN	Penman-type equation to estimate A-pan equivalent evaporation
PWP	Permanent Wilting Point
RCBD	Randomised Complete Block Design
REW	Readily Evaporable Water
RISKMAN	Risk Manager
RMSE	Root Mean Square Error
RUE	Radiation Use Efficiency
SAAMIIP	Southern Africa Agricultural Model Intercomparison and Improvement Project

SACU	Southern African Customs Union
SADC	South African Development Community
SAEON	South African Environmental Observation Network
SANBI	South African National Biodiversity Institute
SANCID	South African National Committee on Irrigation and Drainage
SAPIA	South African Petroleum Industry Association
SAS	Statistical Analysis System (Institute)
SASA	South African Sugar Association
SASRI	South African Sugarcane Research Institute
SAT	Semi-Arid Tropics
SBS	SugarBeet Summer
SBW	SugarBeet Winter
SCA	SugarCAne
SCWG	Soil Classification Working Group
SFR	Stream Flow Reduction
SFRA	Stream Flow Reduction Activity
SIRI	Soil and Irrigation Research Institute (former)
SLA	Specific Leaf Area
SLS	Surface Layer Scintillometry
SMRI	Sugar Milling Research Institute
SPH	Stems Per Hectare
SSH	Sweet Sorghum Hatfield
SSU	Sweet Sorghum Ukulinga
SNF	SuNFlower
SWB	Soil Water Balance
SYB	SoYBean
TAW	Total Available Water
TC	ThermoCouple
TDR	Time Domain Reflectometry
TFS	Total Fermentable Sugars
TPO	Total POrosity
UKZN	University of KwaZulu-Natal
UP	University of Pretoria
USA	United States of America
USDA	United States Department of Agriculture
USDoE	United States Department of Energy
USGS	United States Geological Survey
USWB	United States Weather Bureau
VEGMAP	National Vegetation Map of South Africa Project
VPD	Vapour Pressure Deficit
WAS	Water Administration System
WBGU	German Advisory Council on Global Change
WGS	World Geodetic System
WP	Water Productivity
WRC	Water Research Commission
WUE	Water Use Efficiency

LIST OF SYMBOLS

Roman Symbols (lowercase)

a	constant in *PENPAN* equation (2.4)
a	amplitude used in calculation of sensible heat H
c	velocity of the electromagnetic signal in free space (m s^{-1})
c_p	specific heat capacity of air (J kg^{-1} $^oC^{-1}$)
c_s	specific heat capacity of soil (J kg^{-1} $^oC^{-1}$)
c_{ds}	specific heat capacity of dry soil (J kg^{-1} $^oC^{-1}$)
c_w	specific heat capacity of water (J kg^{-1} $^oC^{-1}$)
d	root depth (cm)
e_a	actual vapour pressure (kPa)
e_s	saturated vapour pressure (kPa)
e_s - e_a	vapour pressure deficit (kPa)
k	thermal diffusivity of the wood (cm^2 s^{-1})
l_{ij}	length of the soil material between ports i and j (cm)
p	depletion fraction
r^2	coefficient of determination
r_s	surface resistance (s m^{-1})
u	daily averaged wind speed at height 2 m (m s^{-1})
u_2	daily averaged wind speed at height 2 m (m s^{-1})
u_*	wind friction velocity (m s^{-1})
v_1	increases in temperature of downstream probe (ºC)
v_2	increases in temperature of upstream probe (ºC)
w'	fluctuation from the mean of the vertical wind speed (m s^{-1})
x	distance between the heater and either temperature probe (cm)
z	measurement height of sonic anemometer (m)
z	elevation in masl

Roman Symbols (uppercase)

A	altitude (degrees decimal; always positive)
A	total cross-sectional area of the column (cm^2)
ALTF	altitude factor (m)
C	cloudiness (oktas)
D	Index of Agreement
D	vapour pressure deficit (kPa)
D	drainage (mm)
DSTF	distance factor (minutes of a degree)
E	total evaporation (mm day^{-1})
E_a	aerodynamic term of Penman-type equation (mm $month^{-1}$)
E_p	unscreened A-pan equivalent evaporation using *PENPAN* method (mm $month^{-1}$)
E_{pp}	screened A-pan equivalent evaporation (mm $month^{-1}$)
E_m	maximum evaporation (mm day^{-1})
E_r	reference evaporation (mm day^{-1})

E_{sm}	maximum soil water evaporation (mm)
E_{tm}	maximum crop transpiration (mm)
ET	actual evapotranspiration (mm) accumulated over growing season
ET_a	actual evapotranspiration (mm day^{-1})
ET_c	crop evapotranspiration (mm day^{-1})
ET_m	maximum evapotranspiration (mm day^{-1})
ET_o	reference crop (grass) evaporation using FAO56 method (mm day^{-1})
ET_p	potential evapotranspiration (mm day^{-1})
ET_r	reference crop (alfalfa) evaporation using ASCE-EWRI method (mm day^{-1})
F	term used to calculate H
FE	fermentation efficiency (%)
FI_{PAR}	fraction of photosynthetically active radiation intercepted by the canopy
FD	fetch distance (m)
G	soil heat flux density (MJ m^{-2} day^{-1})
G_{plate}	energy flux measured using the soil heat flux plates (MJ m^{-2} day^{-1})
G_{store}	energy flux stored in soil above heat flux plates (MJ m^{-2} day^{-1})
GDD	growing degree days (day ºC)
H	Linacre's augmentation radiation term
H	sensible heat flux (W m^{-2})
H_{i}	total hydraulic head at port i (cm)
H_{j}	total hydraulic head at port j (cm)
I	irrigation (mm)
K_a	apparent dielectric constant
K_c	crop coefficient (or water use coefficient)
$K_{c\ end}$	end-season crop coefficient
$K_{c\ ini}$	initial-season crop coefficient
$K_{c\ mid}$	mid-season crop coefficient
K_{cb}	basal crop coefficient
K_p	pan coefficient (or pan factor)
Ks_{ij}	saturated hydraulic conductivity of the soil between port i and j (cm s^{-1})
L	waveguide or probe length (m)
L_{dev}	length of the crop development stage (fraction)
L_{end}	length of the end-season stage (fraction)
L_{ini}	length of the initial-season stage (fraction)
L_{mid}	length of the mid-season stage (fraction)
L_a	apparent probe length (m)
M_s	dry mass of soil core (g)
MAE	mean absolute error (%)
MAR	mean annual runoff (mm day^{-1} or mm month^{-1})
MAR_{base}	mean annual runoff from the baseline land cover (mm day^{-1} or mm month^{-1})
MAR_{crop}	mean annual runoff from the crop surface (mm day^{-1} or mm month^{-1})
MAR_{org}	mean annual runoff determined using original quinary climate database (mm day^{-1} or mm month^{-1})
MAR_{rev}	mean annual runoff determined using revised quinary climate database (mm day^{-1} or mm month^{-1})
$MdAR$	median annual runoff (mm day^{-1} or mm month^{-1})
N	number of observations or measurements

P	atmospheric pressure (kPa)
P	precipitation (mm)
P	term used to calculate H
PAW	plant available water (m m^{-1} or vol %)
Q	volumetric outflow rate (cm^{3} s^{-1})
R	runoff (mm)
R^2	coefficient of determination
R_a	extra-terrestrial solar radiation (MJ m^{-2} day^{-1})
R_{max}	total seasonal rainfall threshold (mm), above which the crop dies
R_{min}	total seasonal rainfall threshold (mm), below which the crop dies
R_{np}	net energy available to an A-pan (W m^{-2})
R_{nr}	net energy available to a short grass surface (W m^{-2})
R_{ns}	net solar radiation (MJ m^{-2} day^{-1})
R_s	incoming solar radiation (MJ m^{-2} day^{-1})
R_{so}	clear-sky solar radiation (MJ m^{-2} day^{-1})
R_n	net radiation (MJ m^{-2} day^{-1})
R_{nl}	net longwave radiation (MJ m^{-2} day^{-1})
$RANK$	temperature station ranking (fraction)
RH_{ave}	mean monthly relative humidity (%)
RH_{max}	daily maximum relative humidity (%)
RH_{min}	daily minimum relative humidity (%)
RMSE	root mean square error
RMSEs	systematic RMSE
RMSEu	unsystematic RMSE
S	soil water storage (mm)
T	daily air temperature (°C)
T_{ave}	average air temperature (°C)
T_{bse}	crop base temperature (°C), i.e. lower threshold temperature when crop development ceases
T_{upp}	upper threshold temperature when crop development ceases (°C)
T_a'	fluctuation of air temperature from the mean (°C)
T_s	soil temperature (°C)
T_c	crop transpiration (mm day^{-1})
T_d	daily dew point temperature (°C)
T_{dew}	monthly dew point temperature (°C)
T_{max}	daily maximum air temperature (°C)
T_{min}	daily minimum air temperature (°C)
T_*	temperature scale of turbulence (°C)
V_h	heat pulse velocity (cm hr^{-1})
V_s	volume of each soil core (cm^{3})
WUE_{obs}	observed waster use efficiency (kg m^{-3})
WUE_{sim}	simulated waster use efficiency (kg m^{-3})
Y	root fraction
Y	crop yield (dry kg ha^{-1})
Y_a	actual crop yield (dry kg ha^{-1})
Y_m	maximum crop yield (dry kg ha^{-1})

Greek Symbols

α	correction or weighting factor
α	albedo of evaporating surface (fraction)
α_s	albedo of surface surrounding the A-pan (fraction)
Δ	slope of the vapour pressure curve (kPa °C^{-1})
γ	psychrometric "constant" (kPa °C^{-1})
λ	latent heat of vapourisation (MJ kg^{-1} or MJ kg^{-1})
λ	inverse of the slope of the logarithmic tension-moisture curve
λE	latent energy flux λE (W m^{-2} or J s^{-1} m^{-2})
Φ	porosity of the soil (fraction)
ρ_a	density of air (kg m^{-3})
ρ_b	bulk density of the soil (kg m^{-3})
ρ_s	bulk density of the soil (kg m^{-3})
ρ_w	density of water (kg m^{-3})
τ	inverse ramp frequency used in calculation of sensible heat H
θ_{DUL}	soil water content at the drained upper limit (m m^{-1} or vol %)
θ_{PWP}	soil water content at the permanent wilting point (m m^{-1} or vol %)
θ_{TPO}	soil water content at total porosity, i.e. saturation (m m^{-1} or vol %)
θ_v	volumetric soil water content (m^3 m^{-3})

***ACRU* parameters and variables**

CAY	monthly crop coefficient (K_c)
CELRUN	stream flow generated from the sub-catchment, including the contribution from all upstream sub-catchments (mm day^{-1} or mm month^{-1})
COFRU	base flow recession constant (set to 0.009)
COIAM	coefficient of initial abstraction
COLON	monthly fraction of root colonisation of the B-horizon
CONST	fraction of plant available water at which total evaporation is assumed to drop below maximum evaporation (i.e. the onset of plant water stress)
CORPPT	monthly precipitation adjustment factors (e.g. to account for differences in monthly rainfall between the selected driver station and spatially averaged estimates for the sub-catchment)
CORPAN	monthly APAN adjustment factors (e.g. to adjust Penman-Monteith evaporation estimates to APAN equivalent evaporation)
EFRDEP	effective soil depth for colonisation by plant roots
EVTR	determines whether transpiration and soil water evaporation are calculated as separate components (*EVTR*=2) or combined (*EVTR*=1)
IRUN	determines if base flow contributes to stream flow
PCSUCO	monthly fractions (expressed as a %) of the soil surface covered by crop residue
ROOTA	monthly fraction of roots in the A-horizon
RUNCO	base flow store (mm)
SIMSQ	stream flow generated from the sub-catchment (mm day^{-1} or mm month^{-1})
SMDDEP	effective soil depth (in m) from which storm flow generation takes place (set to topsoil depth)
QFRESP	storm flow response fraction for the catchment (set to 0.30)

VEGINT	monthly interception loss (mm rainday^{-1})

AQUACROP parameters and variables

B	biomass production (kg m^{-2})
BIO	above-ground biomass produced (t ha^{-1})
CC_o	initial canopy cover at emergence (%)
CC_{pot}	potential canopy cover under non-limited growing conditions (%)
CC_x	maximum canopy cover reached (%)
CN	curve number
CFA	number of crop failures
CO2	monthly ambient CO_2 concentration (ppm)
CYC	length of crop cycle from germination to peak yield (days)
DRA	amount of water drained out of the soil profile (mm)
E	soil water evaporation (mm)
ETC	total amount of water evapotranspired from the crop (mm)
ETR	monthly reference evaporation (mm)
D_r	root zone depletion (mm)
GDD	growing degree days accumulated for month (°C day)
GRO	length of growing season (days)
HI	harvest index
HI_o	reference harvest index
HID	harvest index (%)
INF	amount of water infiltrated into the soil profile (mm)
IRR	amount of water applied as irrigation (mm)
K_s	stress coefficient
K_y	yield response factor
K_{SAT}	saturated hydraulic conductivity (mm h^{-1} or mm d^{-1})
PGDP	Provincial Growth and Development Plan
PMS	potential maximum storage (mm)
RAI	monthly rainfall (mm)
REW	readily evaporable water (mm)
RUN	amount of water lost to surface runoff (mm)
SEA	total number of seasons simulated by the model
SOI	amount of water evaporated from the soil surface (mm)
StExp	level of water stress that reduces leaf expansion (%)
Tn	daily minimum air temperature (ºC)
Tr	transpiration (mm)
TRA	amount of water transpired from the crop surface (mm)
Tx	daily maximum air temperature (ºC)
UPF	amount of water moved upward by capillary rise (mm)
W_r	equivalent water depth (m)
WP	water productivity parameter (kg m^{-2} mm^{-1})
*WP**	normalised water productivity (kg m^{-2})
WPM	water use efficiency at maturity (kg m^{-3})
WPY	water use efficiency when yield peaks (kg m^{-3})
YLD	dry crop yield (t ha^{-1})

Z_{eff}	effective rooting depth (m)
Z_{min}	minimum rooting depth (m)
Z_{max}	maximum rooting depth (m)

SWB parameters and variables

CDM	canopy dry matter yield (kg m^{-2} or t ha^{-1})
DM	dry matter production (g m^{-2})
DWR	dry matter water ratio (Pa)
E_c	radiation conversion efficiency (MJ^{-1})
FI or FI_s	fraction of intercepted solar radiation
H_c	mean maximum plant height during the period of calculation (m)
$K_{c\ max}$	maximum crop coefficient value following rain or irrigation
K_s	canopy radiation extinction coefficient for solar radiation
HDM	harvestable dry matter yield (kg m^{-2} or t ha^{-1})
LAI	leaf area index (m^2 m^{-2})
PT	potential transpiration (mm)
LDM	leaf dry matter yield (kg m^{-2})
R_s	daily total solar radiation (MJ m^{-2})
SDM	stem dry matter yield (kg m^{-2})
SLA	specific leaf area (m^2 m^{-2})
TDM	total dry matter yield (kg m^{-2} or t ha^{-1})
VPD	vapour pressure deficit (Pa)

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1 INTRODUCTION

1.1 Background and Rationale

South Africa is following the international trend of liquid biofuel production, as noted in the South African Biofuels Industrial Strategy of 2007 (DME, 2007a). This strategy highlighted the benefits of biofuel production in terms of alleviating poverty in rural areas, promoting rural economic development and stimulating agricultural production. A 2% blend of biofuels in the national liquid fuel supply, equivalent to an annual production of approximately 400 million litres of biofuel, was proposed by the former Department of Minerals and Energy (DME, 2007a). The strategy aimed to replace 240 million litres of petrol with bioethanol made from sugarcane and sugarbeet (Mbohwa and Myaka, 2011), as well as the production of 160 million litres of biodiesel from sunflower, canola and soybean. To ensure sustainable biofuel production, South Africa plans to grow feedstock on currently under-utilised arable land and preferably under rainfed conditions.

In 2006, the task team that developed the biofuels strategy urged the government to determine the impacts of biofuel feedstock production on both water quality and water quantity (DME, 2006a). The Water Research Commission (WRC) responded to this request and funded a two-year (2007-2009) scoping study on the water use of biofuel feedstocks. The study was conducted by the former School of Bioresources Engineering and Environmental Hydrology (BEEH), based at the University of KwaZulu-Natal (UKZN) in Pietermaritzburg. The main aims of the scoping study were to 1) identify suitable feedstock for the production of biofuel, 2) map areas climatically suited to feedstock cultivation, 3) determine the available knowledge on feedstock water use, 4) model the water requirements of selected feedstock, and 5) identify existing knowledge gaps around feedstocks.

In November 2009, the WRC published the scoping study report on the water use of potential biofuel feedstocks (Jewitt *et al*., 2009a). The report identified 20 crops which may be utilised for biofuel production in South Africa. The water use of selected feedstocks was then simulated using the *ACRU* hydrological model developed by Schulze (1995). Of these, two feedstocks (sweet sorghum and sugarcane) may have the potential to use substantially more water than the reference natural vegetation. However, the scoping study highlighted that for the emerging feedstocks (e.g. sugarbeet & sweet sorghum), parameter values were gleaned from the international literature. The literature also provided conflicting water use figures for certain feedstocks (in particular sweet sorghum) and that knowledge is surprisingly limited for certain crops (e.g. canola). The scoping study recommended a need to better understand the water use and yield of biofuel feedstocks. In addition, a more detailed mapping approach was required to identify feedstock growth areas that considered additional site factors, i.e. not just rainfall and temperature feedstocks (Jewitt *et al*. 2009a). Based on these recommendations, the WRC initiated and funded a six-year (i.e. more comprehensive) follow-up study (WRC, 2010).

In November 2008, the WRC initiated and funded a second, more detailed project entitled: “Water use of cropping systems adapted to bio-climatic regions in South Africa and suitable for biofuel production”. The funding totalled R7.4 million and the project commenced in April 2009, with termination in March 2015. This six-year solicited project was awarded to the Centre for Water Resources Research (CWRR; previously called BEEH) at UKZN, who partnered with the University of Pretoria (UP) and the Council for Scientific and Industrial Research (CSIR). The aims of this follow-up study were broadly similar to those of the scoping study, except for the need to estimate crop yield and biofuel yield.

1.2 Project Objective and Aims

The overall objective of this project was to determine the water use of selected biofuel feedstocks deemed suitable for bioethanol and biodiesel production in selected high and low potential bio-climatic regions of South Africa. The specific aims of the project were as follows:

AIM 1 - To specify and prioritise currently grown and potential alternative first and second generation crops and cropping systems including both annual and perennial crops/trees with attention to, amongst others:

- Crops and crop rotations for food and forage production,
- Crops and crop rotations for biofuel production,
- Multiple use systems e.g. food, fodder and fuel crop combinations,
- Monoculture high density crop production systems,
- Tree feedstocks in plantations, agro-forestry or alley cropping systems, and
- Cellulosic feedstocks.

AIM 2 - To review and characterise crop parameters, water use and yield (biomass, biofuel and by-products) of crops based on existing knowledge or estimation thereof by applying existing tools with reference to those prioritised in South Africa and those which have potential as alternative biofuel crops as identified above.

AIM 3 - To identify and describe bio-climatic regions suitable for these priority crop/tree systems for biofuel production with reference to, amongst others:

- Rainfall average and variability,
- Surface and underground water resources,
- Temperature average and extremes,
- Soil properties,
- Known pests and diseases, and
- Topography.

AIM 4 - To determine crop parameters and model water use of specific crops/trees for biofuel that have potential but insufficient knowledge exists in South Africa to promote effective production.

AIM 5 - To determine the biofuel yield potential of crops in the respective bio-climatic regions under rainfed and/or irrigated conditions.

AIM 6 - To estimate or quantify the water use efficiency of these crops with reference to, amongst others, the following parameters:

- Biomass yield per m^3 water over the full productive cycle, and
- Biofuel yield per m^3 water over the full productive cycle.

AIM 7 - To assess the impact of land use changes on the water balance, within selected key catchments of the specified bio-climatic regions and at appropriate scales, with introduction of crops suitable for biofuel production.

AIM 8 - To develop a user-friendly, map-based software utility for the planning and management of biofuels in South Africa, drawing on findings from the specific aims listed above.

AIM 9 - To provide training opportunities for one post doctorate, two full-time PhD and five full-time MSc students. The principal researcher was also encouraged to obtain a PhD degree (part-time).

1.3 Approach

With reference to **AIM 1** (to specify and prioritise feedstocks), the project was largely governed by the revised national biofuels industrial strategy (DME, 2007a). This strategy recommended two bioethanol feedstocks (i.e. sugarcane & sugarbeet) and three biodiesel feedstocks (i.e. soybean, canola & sunflower) for biofuel production. The final list of prioritised feedstocks considered in this study was also influenced by the recommendations in the biofuels scoping study report (Jewitt *et al.*, 2009a). In addition, an inaugural symposium and workshop was held on 10th and 11th February 2010 respectively. One of the main objectives of the workshop was to identify key feedstocks for further investigation by the project team. Finally, a biofuels technical meeting was held on 17th July 2012 to discuss whether grain sorghum should be included in the list of prioritised feedstocks.

With reference to **AIM 2** (to evaluate and characterise feedstocks), information pertaining to, *inter alia*, crop parameters, water use and yield of the prioritised crops was gleaned from the field-based research as well as a thorough review of available literature (refer to **Volume 2**). **AIM 3** is referred to as the mapping component of the project, with the modelling component involving **AIM 4** (water use modelling) and **AIM 5** (crop yield modelling). In order to derive parameters for certain feedstocks, field-based research was conducted at a number of research farms. The output from the modelling component of this project largely addressed **AIM 6** (estimation of water use efficiency) and **AIM 7** (hydrological impact of feedstock cultivation). In order to meet **AIM 8**, a software program called the Biofuels Assessment Utility was developed. Lastly, a number of students from the University of KwaZulu-Natal and the University of Pretoria worked on the project over its six-year time span (**AIM 9**).

1.4 Structure of Report

Over the six-year project, a total of 21 deliverables were produced for the WRC which addressed the various project aims. These deliverables were combined into three final reports. It is important to note that the majority of the research pertaining to crop yield and water use efficiency (WUE) modelling was conducted in 2015 and thus, was not previously reported.

Volume 1 is a synthesis report which contains the key findings of the project. Hence, this volume is intended for a wider audience, including decision-makers. **Volume 2** represents the technical report which provides the necessary detail regarding the field-based research, as well as the methodology used for the mapping and modelling components. Hence, this volume is intended for those (i.e. scientists) requiring more detail on the methodology. **Volume 3** (this document) represents the biofuel atlas and assessment utility. It provides the output (as maps, tables, tools etc.) from the modelling and mapping work.

Volume 1 is essentially a summarised version of **Volume 2**. Thus, the chapter headings are identical in each document, which allows the reader to easily find and peruse the detailed methodology given in **Volume 2**. In **Volume 1**, each chapter contains a synthesised description of the methodology (c.f. sub-section "**Approach**"), which should suffice for the reader that doesn't require the necessary detail (which is included in **Volume 2**).

Chapter 2 provides a summarised description of the datasets used for derive the maps. The mapping (i.e. land suitability) component of the study is presented in **Chapter 5**, with the water use and yield modelling component provided in **Chapter 3** and **Chapter 4** respectively. The biofuels assessment utility is described in **Chapter 6** and the user manual given in **APPENDIX J**. Finally, the main conclusions drawn from the study are listed in **Chapter 8** of **Volume 1**.

2 SPATIAL AND TEMPORAL DATABASES

In order to map areas optimally and sub-optimally suited to the growth of selected biofuel feedstocks as well as quantifying the water use impacts of feedstock production, various spatial and temporal databases were acquired or developed. In addition, spatial datasets required to run the selected yield model were also developed. This section describes where relevant spatial information was sourced from as well as how the data were used in the land suitability evaluation.

2.1 Introduction

In order to derive land suitability maps for biofuel feedstock production, five important spatial datasets were collected from different sources. These include monthly rainfall totals, monthly means of daily temperature and relative humidity as well as soil depth and slope. The updated South African Atlas of Climatology and Agrohydrology (Schulze, 2007) provided a valuable source of climatic, edaphic and topographic information. The gridded databases of monthly rainfall, temperature, and relative humidity were of particular importance to this study. Each of these datasets is described next in more detail.

2.2 Rainfall

2.2.1 Description

Gridded datasets showing the spatial variation in monthly rainfall totals were required to derive seasonal rainfall (i.e. monthly rainfall accumulated over the growing season). In South Africa, two projects funded by the Water Research Commission (WRC) have provided spatial estimates of monthly rainfall that were derived from rain gauge (i.e. point) measurements. These two projects are briefly described next. However, data developed by Lynch (2004) was used in this study.

The first project was titled "*Mapping of Mean Annual Precipitation and Other Rainfall Statistics over Southern Africa*" (Dent *et al*., 1989), which was superseded by the second project in 2004. The latter project was titled "*Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*" and the report was finalised in December 2004 (Lynch, 2004).

The Lynch (2004) study developed rainfall databases containing daily and monthly data collected from rainfall recording stations located in the SADC (South African Development Community) region. The SADC region includes South Africa, Namibia, Zimbabwe and Mozambique. Different in-filling algorithms were used to patch missing rainfall data and produce a continuous daily rainfall dataset. These included Inverse Distance Weighting, the Expectation Maximisation Algorithm, the Median Ratio Method and a Monthly Infilling Technique (Lynch, 2004). Spatial estimates of monthly and annual rainfall were derived from the points using a spatial interpolation technique (i.e. geographically weighted regression). Site factors including latitude, longitude, altitude and slope were used to interpolate monthly rainfall for each minute of a degree arc (Lynch, 2004).

2.2.2 Source

The gridded rainfall databases of mean monthly rainfall totals are freely available for download from SAEON's data portal (http://data.saeon.ac.za/). To assist with data downloads, it is recommended the user sets the "Custodian:" search field to the following: BioEngineering and Environmental Hydrology, UKZN

2.3 Temperature

2.3.1 Description

Gridded datasets showing the spatial variation in monthly maximum, minimum and average temperatures were derived by Schulze and Maharaj (2007a) in a project also funded by the WRC. Schulze and Maharaj (2004) developed a database of 51 years (1950-2000) of observed daily minimum and maximum temperature for approximately 970 temperature recording stations in South Africa. The observed temperature data were quality controlled, with missing values in-filled to produce a continuous daily record. Missing temperature records were in-filled because modelling cannot be undertaken without a continuous dataset. For each minute of a degree arc, two recording stations were selected (from different quadrants). The selection was based on minimising the distance from, and the altitude between, the grid point and each temperature station. Point estimates of daily temperature were then derived by adjusting for the altitude difference between the grid point and the two recording stations, using regionally and seasonally determined lapse rates. This process was then repeated for each of the 437 039 grid points across southern Africa, to produce an extensive database (≈160 Gb in size) of 51 years of estimated daily minimum and maximum temperatures (Schulze and Maharaj, 2007a).

2.3.2 Source

The gridded rainfall databases of mean monthly rainfall totals are freely available for download from SAEON's data portal (http://data.saeon.ac.za/). To assist with data downloads, it is recommended the user sets the "Custodian:" search field to the following: BioEngineering and Environmental Hydrology, UKZN

2.4 Relative Humidity

2.4.1 Description

According to Schulze *et al*. (2007a), uncorrected actual vapour pressure is predictable month-by-month in South Africa, using predominantly geographical factors and regression equations for each month. Saturated vapour pressure is a function of air temperature and thus varies daily and within the day. Hence, RH_{min} and RH_{max} can also vary from day to day (Schulze, 2007). Daily estimates of RH_{min}, RH_{max} and RH_{ave} (averaged) were derived for every minute of a degree arc, using the daily temperature dataset described above.

2.4.2 Source

The gridded rainfall databases of mean monthly rainfall totals are freely available for download from SAEON's data portal (http://data.saeon.ac.za/). To assist with data downloads, it is recommended the user sets the "Custodian:" search field to the following: BioEngineering and Environmental Hydrology, UKZN

2.5 Soil Depth

2.5.1 Description

The Land Type soils database at a 1:250,000 scale, developed by the former Soil and Irrigation Research Institute (SIRI, 1987 and updates), represents the most detailed soils information currently available for South Africa. For the purpose of mapping, the depth of the A- and B-horizons was extracted for all soil series in South Africa and the values were then summed to provide total soil depth (Schulze and Horan, 2007b). According to Schulze and Horan (2007b), the B-horizon is the "moisture storage" horizon and largely determines plant water availability. This reflects the underlying geology and shows a greater range of depth than the topsoil (Schulze and Horan, 2007b).

2.5.2 Source

This dataset is available on DVD as part of the 2007 version of the South African Atlas of Climatology and Agrohydrology (Schulze, 2007). The reader is requested to contact the WRC (orders@wrc.org.za) for a copy of this DVD.

2.6 Saturated Hydraulic Conductivity

2.6.1 Description

The soil's hydraulic conductivity determines the rate of water delivery to the evaporation zone (typically the top 10 cm of the soil profile), which limits the evaporation rate of soil water. The *AQUACROP* model requires the saturated hydraulic conductivity (K_{SAT} in mm d^{-1}), which is not available in the quinary sub-catchment soils database and hence was estimated for this project using a pedotransfer function developed by Saxton and Rawls (2006). The reader is referred to **Section 6.5.2.1** of **Volume 2** for more information on the derivation of this parameter.

2.6.2 Source

This dataset was generated specifically for this study.

2.7 Slope

2.7.1 Description

According to Schulze and Horan (2007a), altitude for South Africa was initially mapped at a spatial resolution of one-minute arc. The gridded altitude values were derived from various sources, with altitudes initially collated from 1:250 000 topographic sheets during the Dent *et* *al*. (1989) study of spatial rainfall. These initial values were then modified and corrected with the 200 m Digital Elevation Model (DEM) obtained from the Surveyor General's office (Schulze and Horan, 2007a). Since then, the 200 m DEM was superseded by the SRTM 90-m DEM.

2.7.2 Source

For more information, regarding the 90-m DEM for South Africa, the reader is referred to http://dds.cr.usgs.gov/srtm/. The slope dataset was derived as part of a WRC-funded project by Weepener *et al*. (2011). The reader is requested to contact the WRC (orders@wrc.org.za) for this dataset.

2.8 Land Use/Cover

2.8.1 Description

The National Land Cover (NLC) project of 2000 (NLC2000) was published in 2005 and superseded the first national land cover dataset of 1994 (NLC1994) published in 1996. Due to the rather outdated information on land use, there is high demand for improved information at the national scale. Since 2000, some Provinces (e.g. KwaZulu-Natal, North West, Gauteng, Mpumalanga & Northern Cape) and certain municipalities (nine in the Western Cape) have already produced finer scale land cover and/or land use data products.

SANBI undertook a project in 2009 to join the best available land cover datasets together and produce an updated layer called NLC2009. If no updated land cover information is available for a region, the project made use of NLC2000 as the base layer. This was the case for the Limpopo, Free State and Eastern Cape Provinces. The merging of spatial information from different sources (or custodians) is complex. The goal was to ensure spatial compatibility and thematic comparability amongst the different land cover datasets. Updated information was also obtained from other custodians and included:

- cultivated areas (ARC),
- informal settlements (ESKOM),
- commercial plantations (DWA),
- indigenous forests (DWA), and
- dams (DWA).

All updated raster and vector (i.e. polygon) datasets were re-projected to meters (Albers Conical Equal Area; datum & spheroid as WGS1984). Raster datasets were resampled (using a majority filtering) to a spatial resolution of 30 by 30 m where needed. Resampling was performed. Vector data were converted to raster (cell size of 30 x 30 m). All datasets were clipped using official provincial boundaries obtained from the Demarcation Board[1] to prevent problems from cross-boundary overlap.

Due to the different spatial scales of the datasets and mapping classes used, a standardised classification scheme was developed that was common to all datasets and applicable for the proposed utilisation of the final product. The final classification scheme was reduced to

[1] http://www.demarcation.org.za/pages/default_new.html

seven classes in total as presented in **Figure 1**. Unfortunately, the boundaries of protected areas were not included in the NLC2009 database.

“Plantations” refers to commercial forestry areas. The “urban (built-up)” areas include cities, rural clusters, formal residential, informal residential, commercial, industrial and smallholdings. “Water bodies” include lakes, dams and wetlands of South Africa. “Natural” areas include indigenous forest, woodland, bushland, shrubland, herbland, Fynbos as well as bare rock and soil. “Cultivation” includes commercial and subsistence farmland, whether dryland or irrigated, as well as sugarcane.

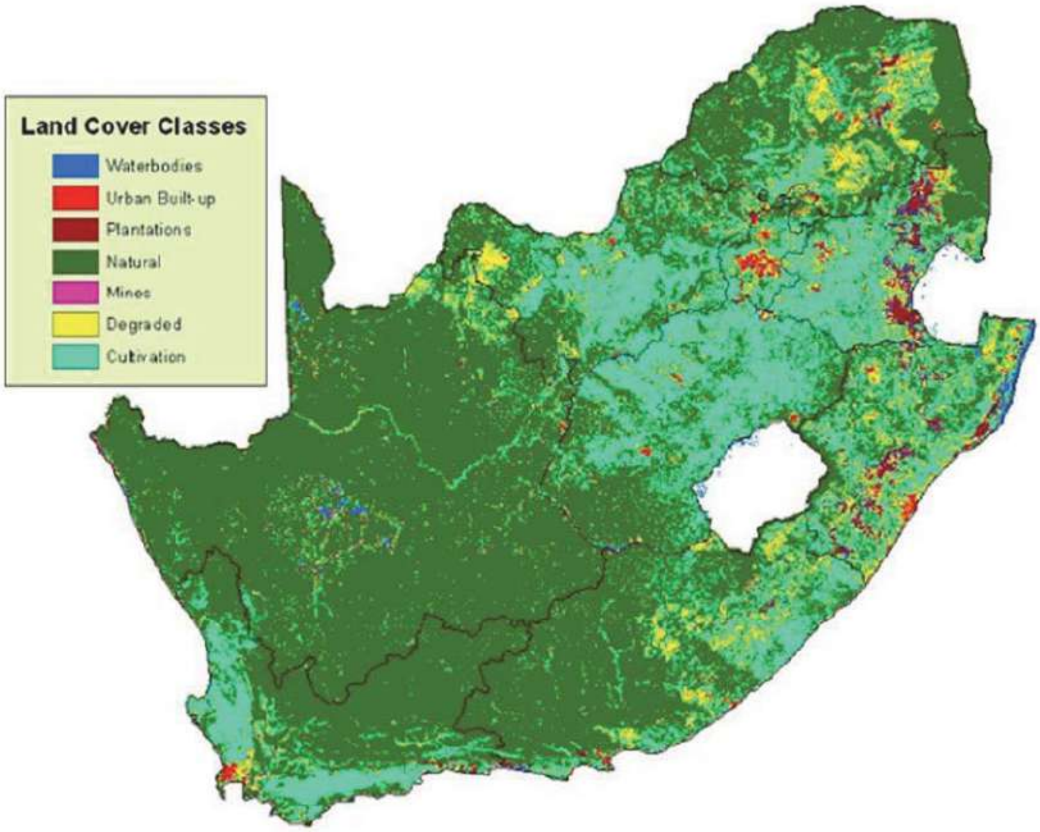


Figure 1 Updated national land cover of 2009 showing seven classes (Source: SANBI website[2])

2.8.2 Source

The South African National Biodiversity Institute (SANBI) distributes their biodiversity information to end-users via their Biodiversity-GIS website (http://bgis.sanbi.org/).

2.9 Protected Areas

2.9.1 Description

The formal protected areas (**Figure 2**) include land-based and marine protected areas that are recognised in terms of the Protected Areas Act. Protected areas are defined in the 2008

[2] http://bgis.sanbi.org/landcover/project.asp

National Protected Area Expansion Strategy (NPAES) as areas of land or sea that are formally protected by law and managed mainly for biodiversity conservation. These are:

- special nature reserves,
- national parks,
- nature reserves (including provincial nature reserves),
- protected environments,
- natural world heritage sites (not cultural world heritage sites),
- marine protected areas,
- specially protected forest areas,
- mountain catchment areas, and
- local authority protected areas.

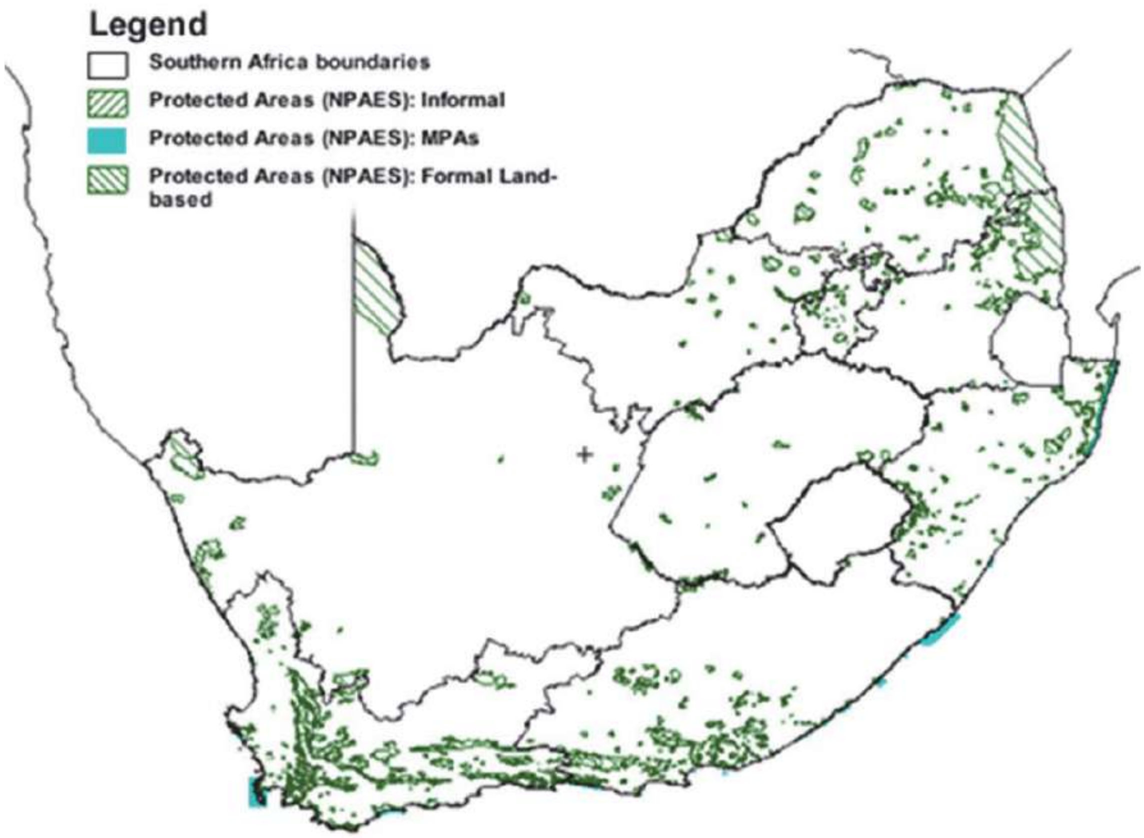


Figure 2 Formal protected areas as part of the National Protected Areas Expansion Strategy (Source: SANBI website[3])

It does not include informal conservation areas (e.g. conservancies) or non-natural areas within protected environments. Conservation areas are areas of land not formally protected by law but informally protected by the current owners and users and managed at least partly for biodiversity conservation. Because there is no long-term security associated with conservation areas, they are not considered a strong form of protection. Conservation areas are not a major focus of the NPAES and are therefore not included in the formal protected area layer.

[3] http://bgis.sanbi.org/protectedareas/protectedAreas.asp

2.9.2 Source

The South African National Biodiversity Institute (SANBI) distributes their biodiversity information to end-users via their Biodiversity-GIS website (http://bgis.sanbi.org/).

2.10 Quinary Sub-catchment Boundaries

2.10.1 Description

Quinary sub-catchments are topographically based sub-divisions of the national quaternary catchments, originally delineated by the former Department of Water Affairs. Each fourth level quaternary catchment was sub-delineated into three fifth level quinary catchments according to altitude criteria. The upper, middle and lower quinaries of unequal area (but of similar topography) were sub-delineated according to "natural breaks" in altitude by applying the Jenks' optimisation procedures (**Figure 3**), which is available within the ArcGIS software suite. This resulted in 5 838 quinary catchments deemed to be more homogeneous than the quaternaries in terms of their altitudinal range.

Figure 3 Sub-delineation of quaternary catchments from altitude (left) into three quinaries by natural breaks (middle) with flow paths of water (right) (Schulze *et al*., 2011)

The rainfall station selected to represent the parent quaternary catchment was again selected to represent all three quinary catchments (located within the quaternary). Owing to a lack of reliable station data in certain areas, a particular rainfall station could "drive" the hydrology of more than one quaternary catchment (and hence multiple quinary catchments). A total of 1 240 rainfall "driver" stations were used to provide daily rainfall for each of the 5 838 quinaries.

For each quinary, monthly rainfall adjustment factors were applied to the driver station's record in order to generate daily rainfall data deemed more representative of that quinary. These monthly adjustment factors were determined by comparing the driver station's mean monthly rainfall totals to the spatial average of all mean monthly rainfall grid cells (derived by Lynch, 2004) located within each quinary.

A representative temperature "station" for each quinary was selected from the temperature database derived by Schulze and Maharaj (2004) as follows. The 200 m digital elevation model was used to calculate the spatially averaged altitude for each quinary. Grid cells with mean altitudes similar to those of the quinary means, and located as close as possible to the quinary centroid (and preferably located within the quinary boundary), were then selected to represent each of the 5 838 quinaries. An exponential decay function using the altitude difference (between the catchment mean and grid cell) and distance (between the quinary centroid and grid cell) was developed to automate the selection process.

2.10.2 Source

This dataset is available on request from UKZN (contact Mark Horan; horan@ukzn.ac.za).

2.11 Revised Quinary Sub-catchment Database

2.11.1 Description

The quinary sub-catchment climate database was revised, based on a number of improvements which are summarised as follows:

- A new algorithm was used to select two representative temperature stations for each quinary's centroid location.

- Revised estimates of daily maximum and minimum temperature were then derived for each quinary.

- Incoming solar radiation (R_s) estimates were limited to the range $0.3 \cdot R_{so} < R_s < 1.0 \cdot R_{so}$, where R_{so} represents clear sky radiation.

- Incoming solar radiation (R_s) estimates were also limited to the range $0.23 \cdot R_a < R_s < 0.77 \cdot R_a$, where R_a represents extra-terrestrial radiation.

- The default wind speed used for the estimation of reference evaporation was 2.0 m s^{-1} (and not 1.6 m s^{-1} as in previous studies).

- Finally, revised estimates of FAO56-based reference crop evaporation were derived for all 5 838 quinaries.

The above-mentioned adjustments to estimated R_s values (i.e. $R_s > 0.3 \cdot R_{so}$ & $R_s > 0.23 \cdot R_a$) ensured that $R_s/R_{so} > 0.30$, thus preventing the calculation of negative net outgoing longwave radiation. Hence, these checks improved the estimates of net radiation used by the FAO56 method. A total of 1 414 579 daily instances affecting the majority of quinaries were finally corrected. These corrections also prevented negative values of net outgoing longwave radiation. The reader is referred to **Section 6.5.1** of **Volume 2** of a detailed description of this dataset.

2.11.2 Source

This dataset was specifically generated for this study and is not yet considered part of the public domain.

2.12 Summary

Table 1 summarises the various data sources used for land suitability mapping. For additional information pertaining to each data set, the reader is referred to the reference provided in the table. The sub-section that follows describes the methodology used in this study to evaluate the suitability of land to grow biofuel feedstocks.

Table 1 Sources of climatic (rainfall, temperature & relative humidity), edaphic (soil depth) and topographic (slope) data used in this study

Datasets	Description	[1]Source	Reference
Rainfall	Monthly rainfall totals	CWRR	Lynch (2004)
Temperature	Means of daily maximum, minimum & average temperature	CWRR	Schulze and Maharaj (2007a)
Relative humidity	Means of daily average & minimum relative humidity	CWRR	Schulze *et al*. (2007a)
Slope	Digital elevation model	ARC	Weepener *et al*. (2011)
Soil depth	Depth of topsoil and subsoil horizons	CWRR	Schulze (2007)
Land use	Land use in South Africa	SANBI	Bhengu *et al*. (2008)
Protected Areas	Formal and informal protected areas in South Africa	SANBI	Bradshaw (2010)

[1] Note: Centre for Water Resources Research (CWRR)
Agricultural Research Council (ARC)
South African National Biodiversity Institute (SANBI)

3 HYDROLOGICAL IMPACTS OF FEEDSTOCK PRODUCTION

This chapter addresses the following two project aims, *viz*.:

- To determine crop parameters and model water use of specific crops/trees for biofuel that have potential but insufficient knowledge exists in South Africa to promote effective production.

- To assess the impact of land use change on the water balance of selected key catchments deemed suitable for biofuel feedstock cultivation.

In this chapter, the approach adopted in South Africa to assess feedstock water use as a possible stream flow reduction activity is given.

3.1 Introduction

Section 36 of the National Water Act (NWA) declares land that is used for commercial afforestation to be a Stream Flow Reduction Activity (SFRA), and also makes provision for other activities (i.e. land uses) to be so declared if this should prove justified. This would be on the basis of such an activity being "likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly". Thus "water use" is defined as the difference in runoff generated by the feedstock under consideration and that generated under natural conditions. This builds on the definition accepted for commercial forestry, i.e. the water used by afforestation is the reduction in stream flow compared with the stream flow that would have occurred from natural vegetation. Thus, in order to determine the hydrological impact of land use change to feedstock production, it is necessary to first define the baseline vegetation against which the water use comparisons are made.

3.2 Hydrological Baseline

3.2.1 Background

"Water use" in the context of SFRA assessments is defined as the difference in mean annual stream flow (MAR) resulting from a change in land use from the baseline (i.e. natural vegetation) to the cultivation of biofuel feedstock (or crop). This difference (MAR_{base} - MAR_{crop}) is then expressed as a percentage of the baseline stream flow (MAR_{base}). The definition of a SFRA in the NWA provides ambiguity in at least two aspects. The first of these concerns the use of the word "significantly" and the various interpretations thereof and the other concerns the consideration of the impact on the Reserve. If the impact exceeds 10%, the proposed land use change may be declared as an SFRA (Jewitt *et al*., 2009b). However, Scott and Smith (1997) highlighted the fact that stream flow reductions during low flow periods may be proportionately greater than for total annual flows.

3.2.2 Methodology

It is virtually impossible to measure crop water use under all the possible combinations of climate, soils and management conditions in South Africa. Hence, it is necessary to use a model which can accurately simulate water use of crops across all conditions. The *ACRU* model (Schulze, 1995) was selected to assess the hydrological impacts of land use changes to feedstock production on downstream water availability. *ACRU* is primarily a catchment-scale, daily time-step rainfall-runoff model. The model operates as a process-based, multi-soil layer water budget which is sensitive to land management and land use changes. *ACRU* is a physical-conceptual model with various outputs which have been widely verified against observations in many countries and conditions.

The approach followed was similar to that used in previous studies and is as follows:

- The revised quinary sub-catchment database, together with the *ACRU* agrohydrological model (Schulze, 1995), was used to simulate the runoff response from a land cover of natural vegetation.

- The monthly rainfall adjustment factors developed for the original quinary sub-catchment database were used in this study.

- The monthly adjustments were applied to the observed daily rainfall record obtained from the rainfall driver station in order to improve the representativeness of rainfall at the sub-catchment scale.

- Solar radiation was estimated from temperature using the technique described by Chapman (2004) and Schulze and Chapman (2007).

- Daily estimates of reference evapotranspiration for each quinary were derived using the Penman-Monteith (FAO56) method. A new wind speed of 2.0 m s^{-1} was assumed.

- A new approach was developed to calculate pan coefficients which involved a comparison of FAO56-based reference evaporation, with APAN equivalent evaporation estimated using a modified *PENPAN* equation.

- The new pan coefficients (or pan factors) indicate that the difference between FAO56 and APAN reference evaporation is larger than previously thought.

- New monthly adjustment factors were applied to the Penman-Monteith reference evaporation estimates to ensure that the *ACRU* model was driven by APAN equivalent evaporation and not reference crop evaporation.

- Where possible, certain parameters and variables were “tweaked” to reflect the current understanding of crop water use.

- *ACRU* input parameters and variables for Acocks Veld Types were obtained from the COMPOVEG database maintained by the CWRR.

- Model parameters representing Acocks were characterised in accordance with guidelines from the National Botanical Institute.

- Further explanation on the derivation of these values for the 70 baseline land cover types was provided by Schulze (2004) and Schulze (2008). If the dominant land cover is grassland, the model parameterisation represents the average state of grassland in a particular quinary sub-catchment.

- The *ACRU* model was then used to simulate mean monthly and annual runoff response for baseline conditions (MAR_{base}), i.e. the runoff produced from a land cover of natural vegetation.

- The *ACRU* model was run at the national scale for all 5 838 quinaries, regardless of whether the feedstock could be successfully grown in the quinary.

The main reason for running the model for all quinaries was to avoid the scenario where, if a land suitability map for a particular feedstock is updated or refined, additional model runs may then be required for quinaries not previously highlighted as being suitable for the production of that feedstock.

3.2.3 Results and discussion

Figure 4 represents the mean annual runoff (MAR; based on the *ACRU* output variable *SIMSQ*) produced from a land cover of natural vegetation using the revised quinary sub-catchment climate database (i.e. MAR_{base}). The map highlights the low runoff response from the western parts of the country due to the low and erratic rainfall experienced in this region.

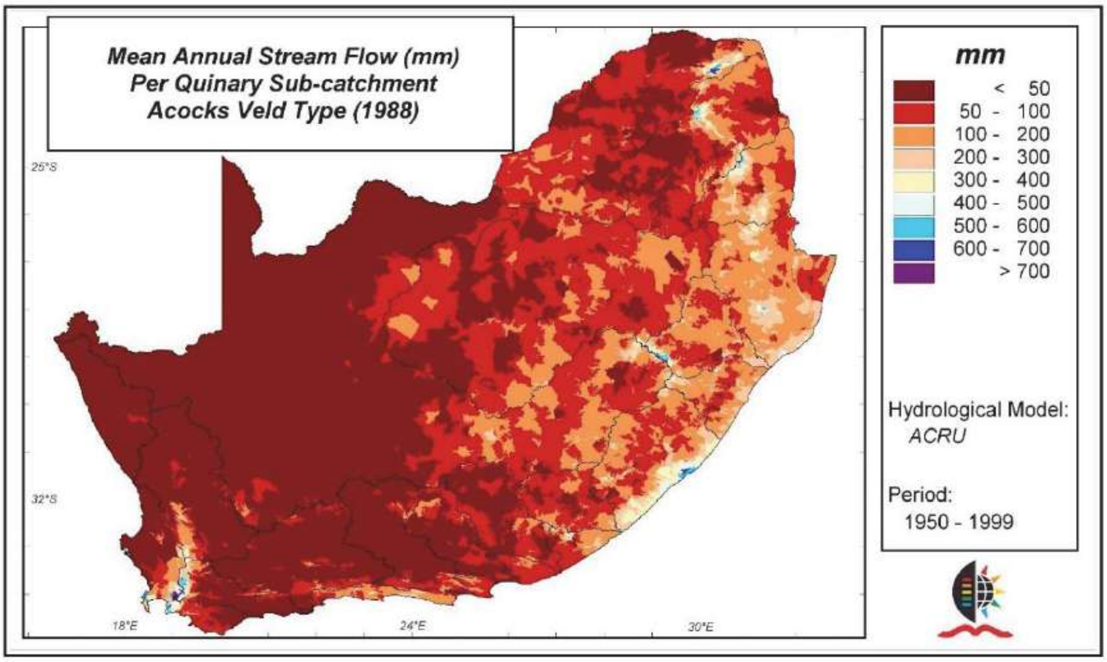


Figure 4 Mean annual stream flow simulated for each quinary sub-catchment for a land cover of natural vegetation using the revised quinary sub-catchment climate database

The mean and median statistic converge (i.e. approximate one another) when there are no outliers (or extreme values, both high and low). This is better understood by considering the ratio of median to mean annual runoff (i.e. *MdAR/MAR*) for baseline conditions (i.e. natural vegetation cover). This ratio is below one (i.e. median < mean, due mainly to flood events) for the majority (5 730 of 5 838) quinaries. The ratio approximates unity (i.e. median within 1% of the mean) for only 83 quinaries. For the remaining 25 quinaries, the ratio is above 1 (i.e. median > mean, due mainly to drought events). The histogram of this ratio is given in **Figure 5** and shows that values range from 0.5 to 1.0 for the majority (89%) of quinary sub-catchments.

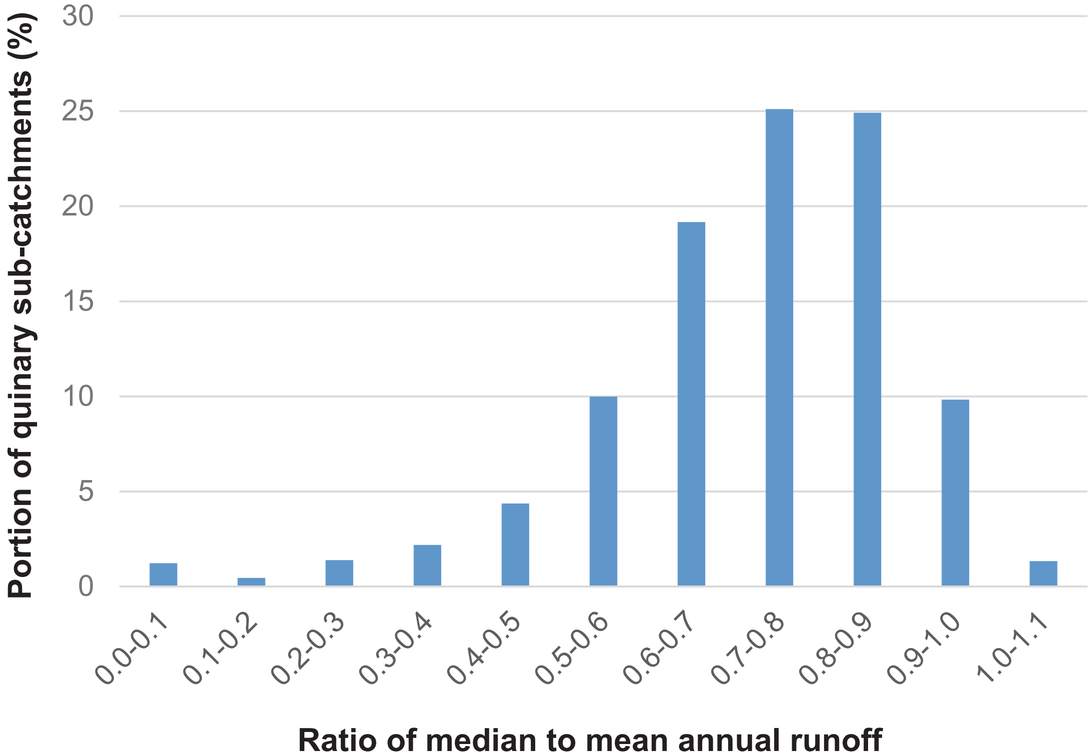


Figure 5 Histogram of the median annual runoff to mean annual runoff ratio across all 5 838 quinaries

The spatial distribution of the median to mean annul runoff ratio is shown in **Figure 6**. In the wetter regions of the country, the mean and median annual runoffs are similar, whereas they differ substantially in the lower rainfall areas. The map highlights “sensitive” sub-catchments where the mean and median statistic differ substantially (i.e. mean is “skewed” by highly variable runoff caused by low rainfall events). The next step involved assessing the hydrological impact of feedstock production using both the mean and median statistics.

It is evident that, compared to the original quinary climate database (Schulze *et al*., 2011), the revised A-pan equivalent evaporation estimates are higher, which results in less stream flow being simulated.

The “enhanced” A-pan evaporation resulted in a reduction in simulated MAR for 5 622 of the 5 838 quinaries. On average, the reduction is 12.09 mm of MAR, with a range of 0.00 to 171.64 mm. However, more runoff was simulated for 216 quinaries, with the average being 21.25 mm (range 0.03 to 144.83 mm).

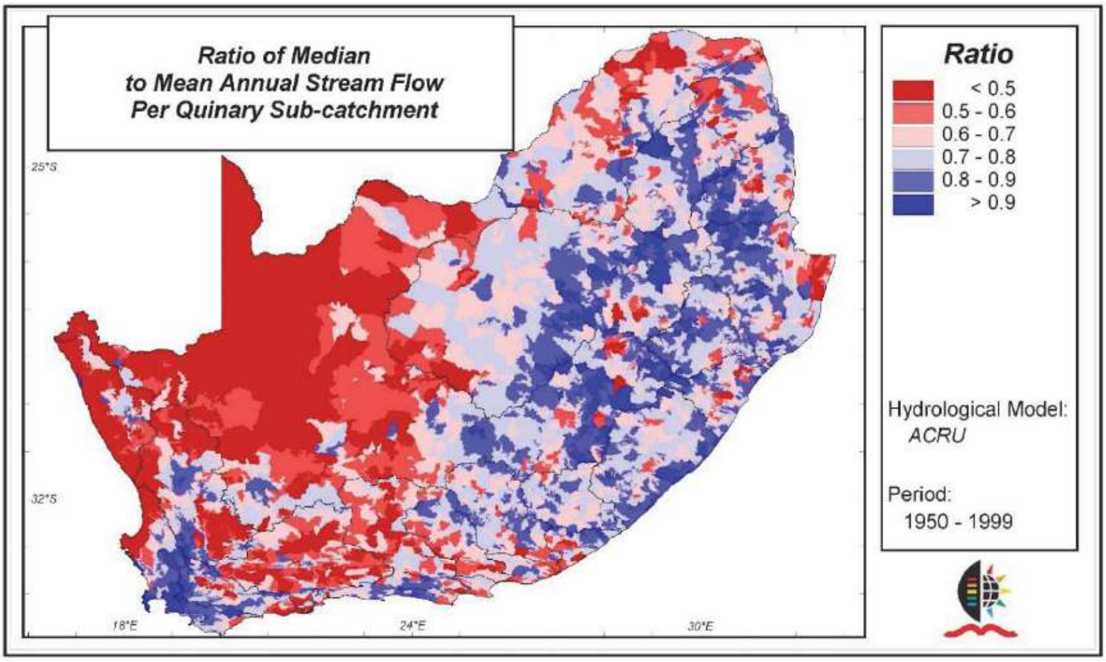


Figure 6 The ratio of median to mean annual runoff for the baseline

For the majority of quinaries, the highest and lowest monthly runoff is generated predominately in February and August respectively. This highlights the fact that most of the quinaries occur within the summer rainfall region of southern Africa. The same trends were observed for monthly stream flows generated using the original quinary climate database. Hence, the revised database of enhanced evaporation did not alter the monthly distribution of simulated runoff. The difference in February's and August's monthly runoff obtained from both climate databases is below 10 mm for the majority of quinary sub-catchments.

3.3 Feedstock Water Use

3.3.1 Background

Land cover and land use affect hydrological responses through canopy and litter interception, infiltration of rainfall into the soil and the rates of soil water evaporation and transpiration from the vegetation layer. The sensitivity analysis undertaken by Angus (1989) showed that stream flow output is sensitive to changes in crop coefficients. For this reason, considerable effort was spent on deriving crop coefficient values for selected feedstocks from field-based observations. This addressed a recommendation from the biofuels scoping study (Jewitt *et al*., 2009a) for better knowledge of crop water use, especially the emerging crops such as sugarbeet and sweet sorghum.

3.3.2 Methodology

The *ACRU* model was run at a national scale to estimate the runoff response from a land cover of biofuel feedstock. The model was run for three bioethanol feedstocks and two biodiesel feedstocks, some with two typical planting dates as shown in **Table 2**.

Table 2 Feedstock planting dates assumed for the simulation of runoff response using the *ACRU* model

Feedstock	Planting date
Sugarcane - averaged	ratoon
Sugarbeet - summer	1st September
Sugarbeet - winter	1st June
Sweet sorghum - inland	1st December
Sweet sorghum - interior	1st December
Grain sorghum	1st November
Soybean	1st November
Canola - winter	1st April

The approach followed for each feedstock was similar to that used for the simulation of baseline runoff, except for the following:

- Typical planting dates were selected for each feedstock that was modelled.

- For sugarcane, crop coefficient values available for each of the three production areas (Inland, South Coast & North Coast) were averaged to produce one set of monthly values deemed representative of all sugarcane growing areas.

- Two national runs for sugarbeet were also undertaken to represent a summer and winter planting. In Cradock (Eastern Cape), sugarbeet will likely be grown in winter (i.e. May-June planting), whilst farmers in other areas may decide to plant sugarbeet in summer (as a rotational crop).

- For sweet sorghum, the crop coefficients (K_c) obtained at the Ukulinga and Hatfield research farms differ significantly. Thus, two national runs were undertaken to emphasise the impact of management practice on crop coefficients as well as the importance of using locally determined K_c values and the *ACRU* model's sensitivity to this input.

- Hatfield-based crop coefficients are representative of growing conditions in the **interior** or a higher planting density, whilst Ukulinga-based values better represent growing conditions **inland** of coastal areas or a lower planting density.

- The crop coefficients for grain sorghum were averaged for two growing seasons based on estimates derived at Ukulinga.

- The crop coefficients for soybean were estimated under dryland conditions and not irrigated (i.e. no water stress) conditions as prescribed by Allen *et al*. (1998).

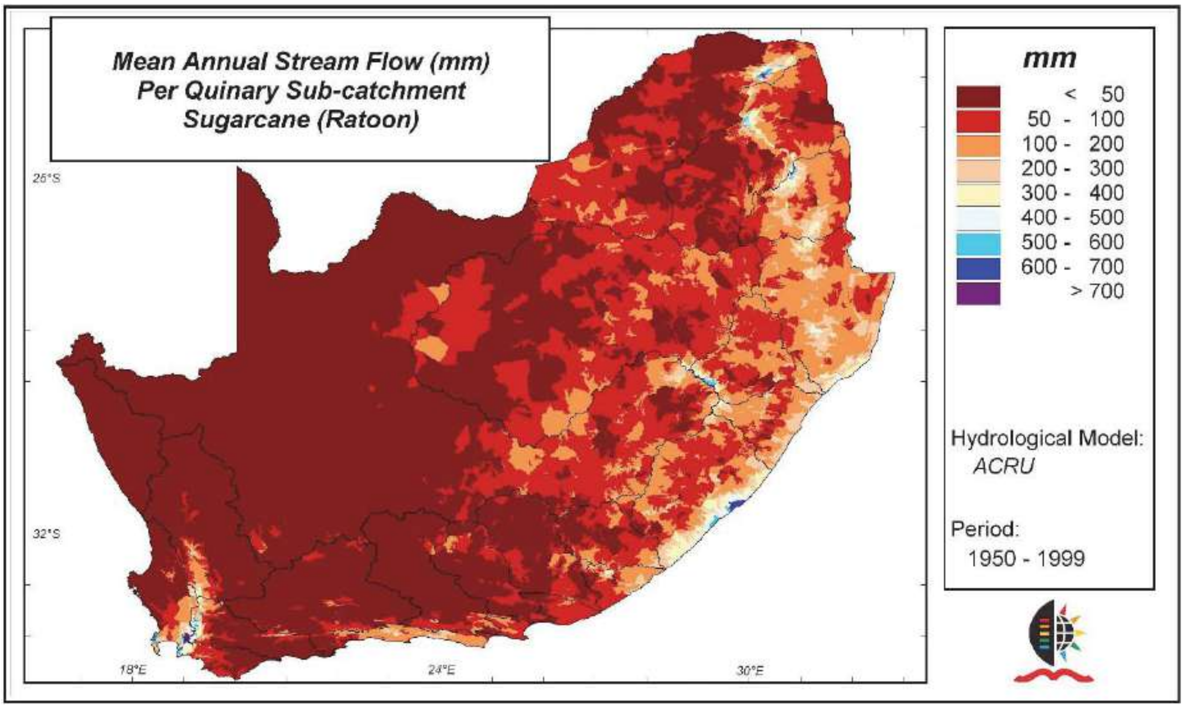
- Since all crop coefficients derived from field-based research used FAO56 as the evaporation, they were adjusted to APAN equivalent values using the pan coefficients calculated with the *PENPAN* equation.

- For annual crops, a monthly crop coefficient of 0.35 was used to represent fallow conditions. This value was decreased to 0.25 in the case of sweet sorghum grown in the interior (Hatfield) and for sunflower.

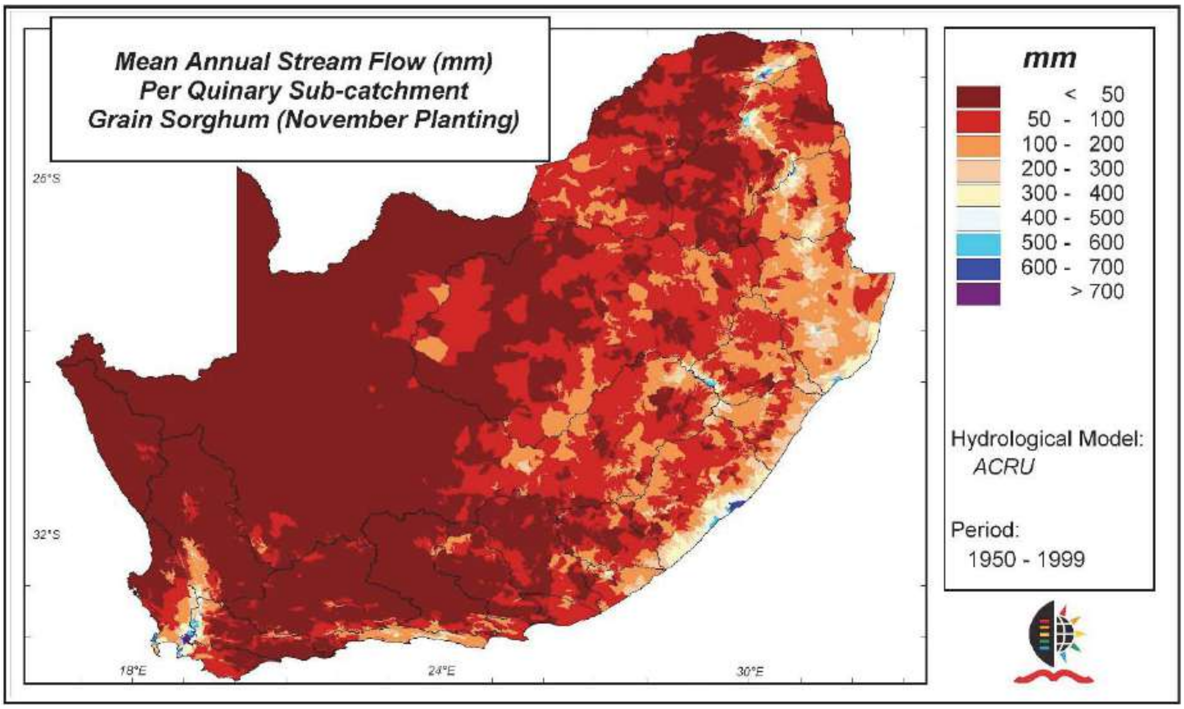
- The model was re-run for a 100% land cover change to a particular crop (i.e. biofuel feedstock), in order to simulate mean annual runoff from the crop surface (MAR_{crop}).

3.3.3 Results and discussion

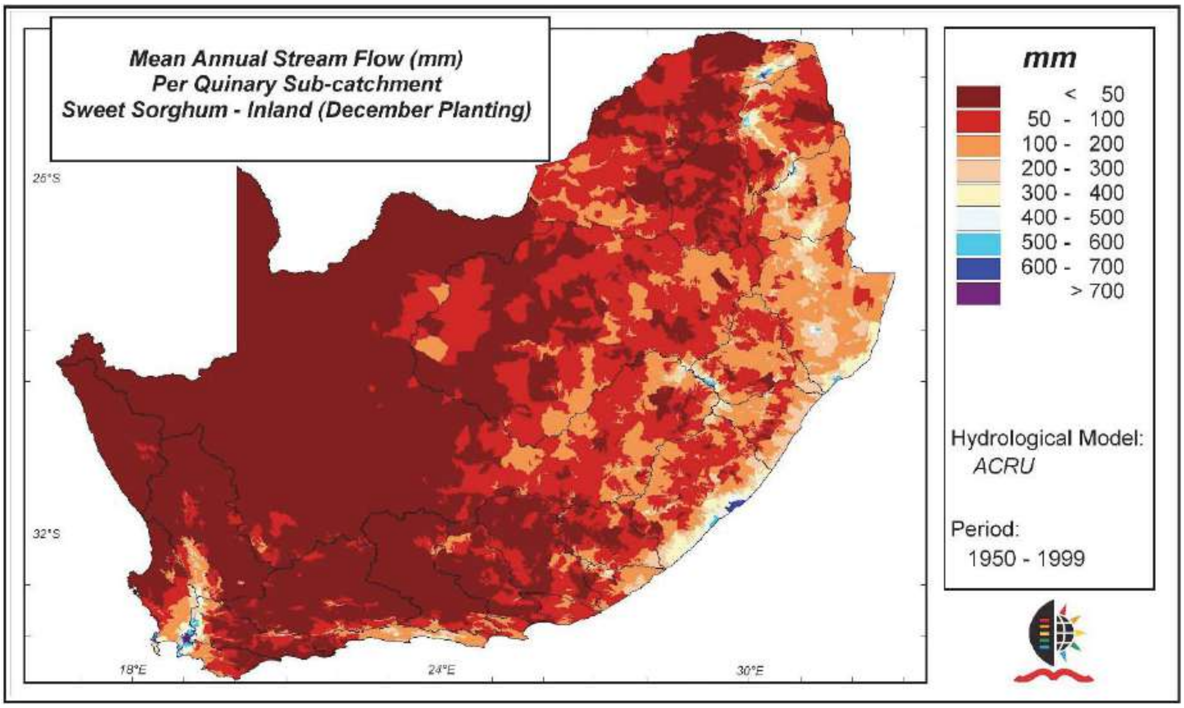
Simulated mean annual stream flow (MAR_{crop}; in mm) is shown in **Figure 7** for selected bioethanol feedstocks (with similar data for biodiesel feedstocks given in **Figure 8**). These maps were then compared to the mean annual stream flow simulated for each quinary sub-catchment for a land cover of natural vegetation (MAR_{base}; **Figure 4**). All the maps of MAR show the same trend in that generated runoff is highly influenced by rainfall magnitude.



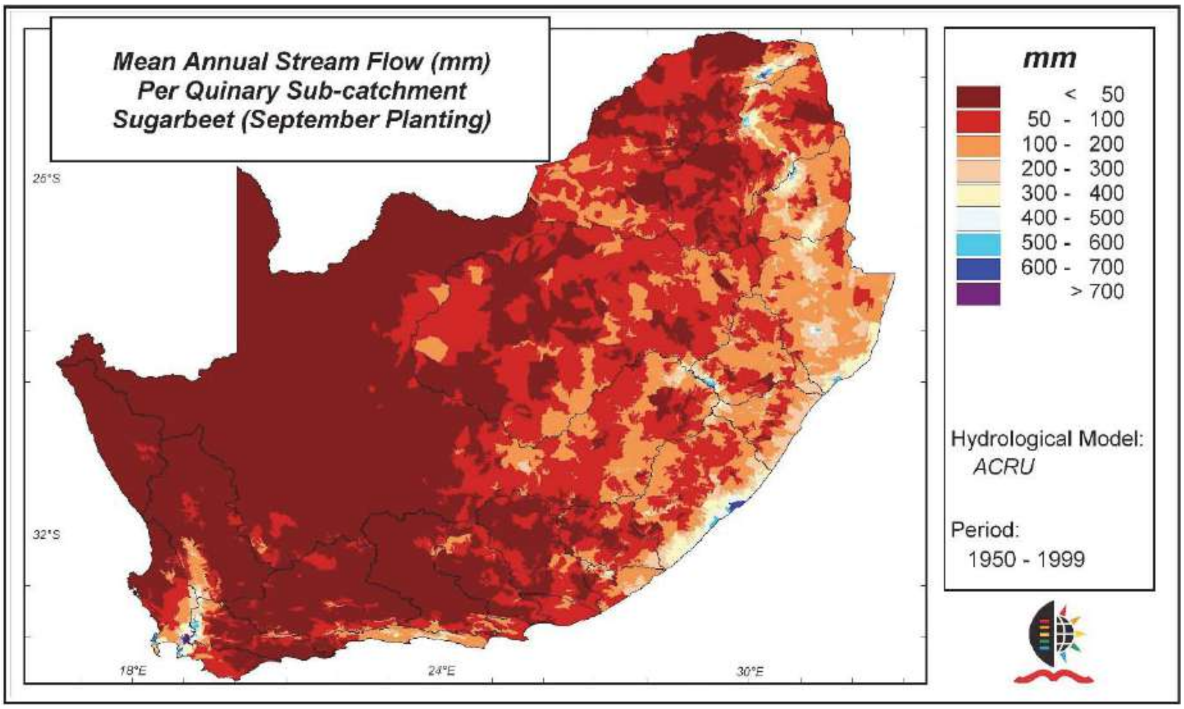
(a)


Mean Annual Stream Flow (mm)
Per Quinary Sub-catchment
Grain Sorghum (November Planting)
mm
< 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
> 700
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(b)

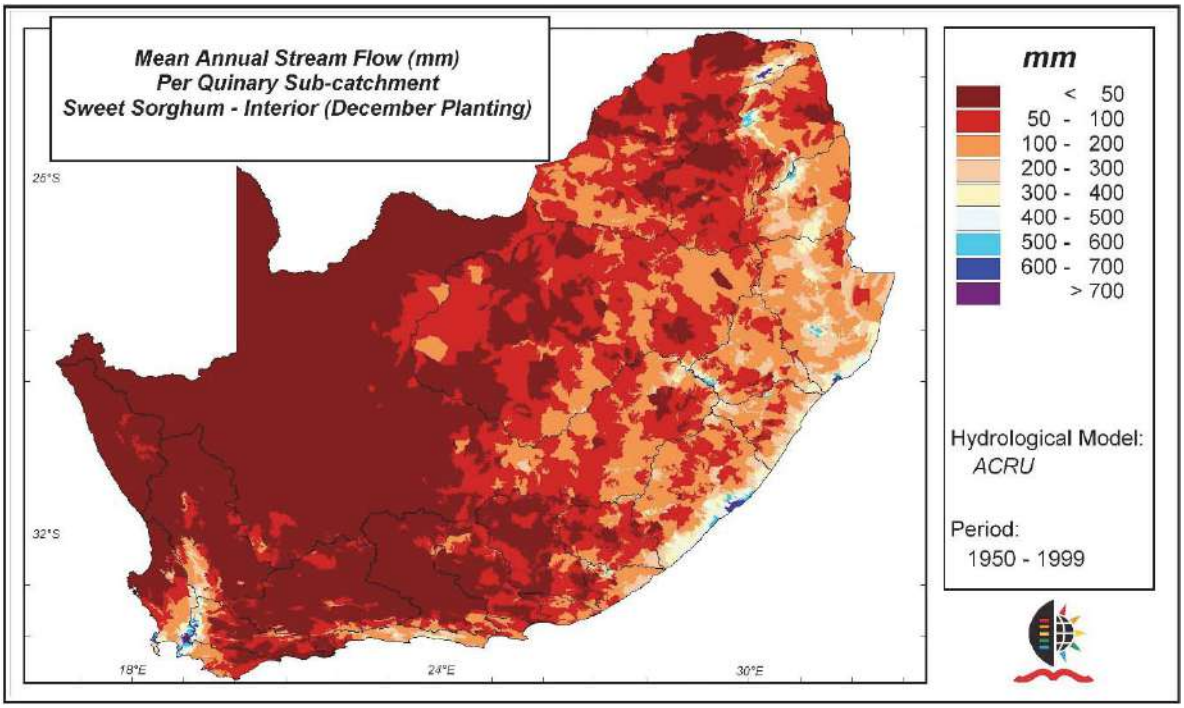

Mean Annual Stream Flow (mm)
Per Quinary Sub-catchment
Sweet Sorghum - Inland (December Planting)
mm
< 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
> 700
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(c)



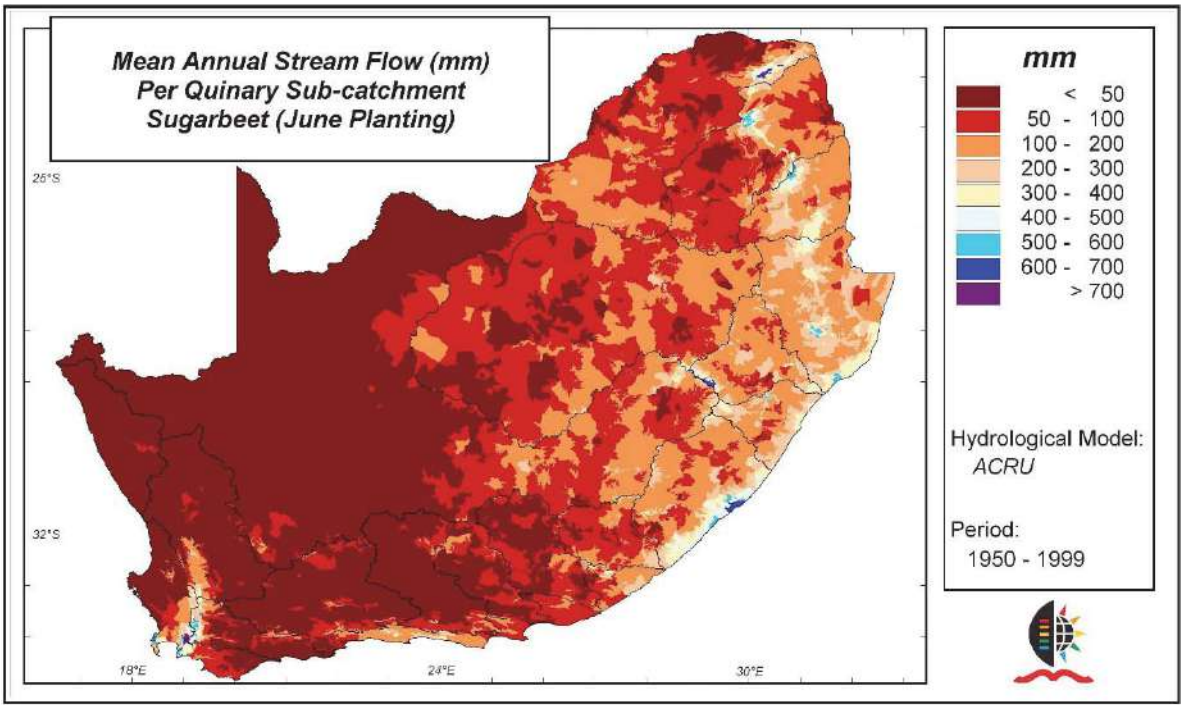
Mean Annual Stream Flow (mm)
Per Quinary Sub-catchment
Sugarbeet (September Planting)
mm
< 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
> 700
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(d)



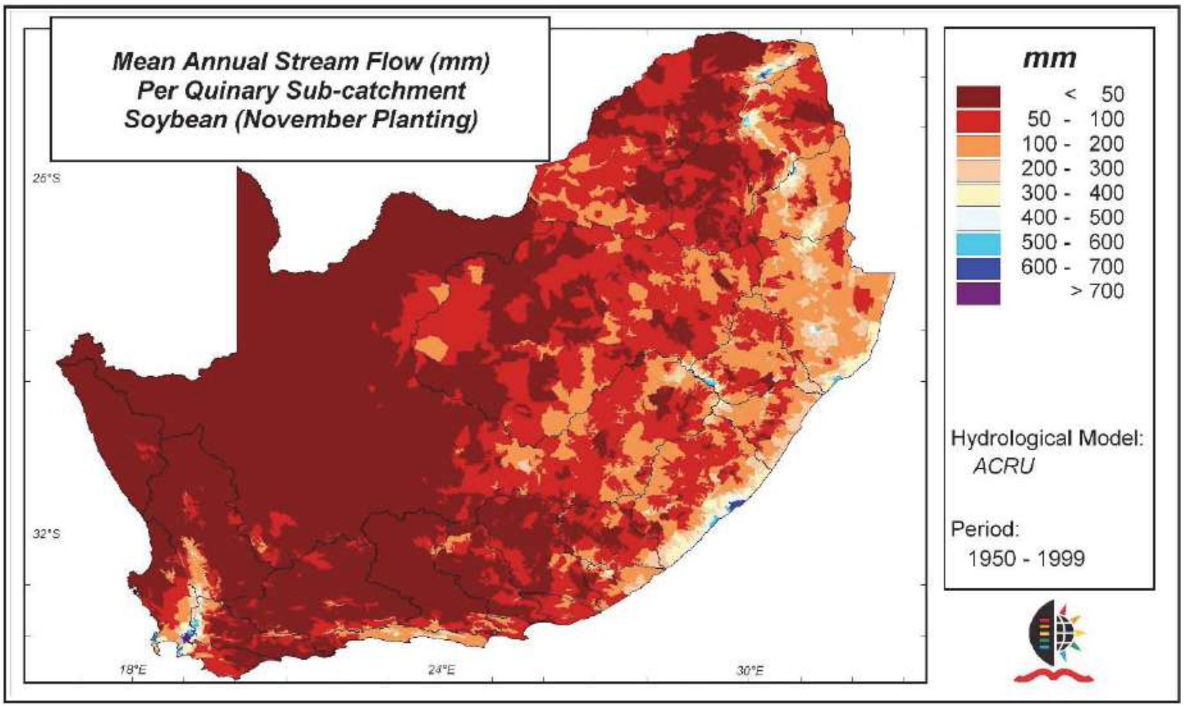
Mean Annual Stream Flow (mm)
Per Quinary Sub-catchment
Sweet Sorghum - Interior (December Planting)
mm
< 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
> 700
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(e)

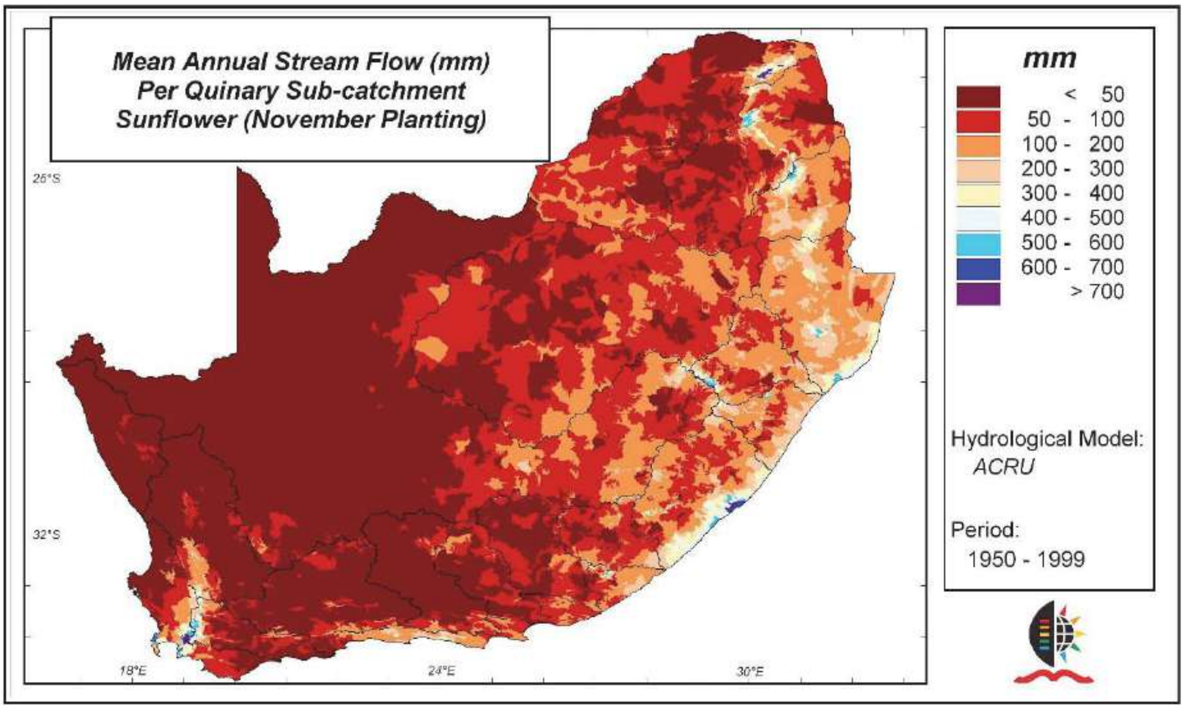


(f)

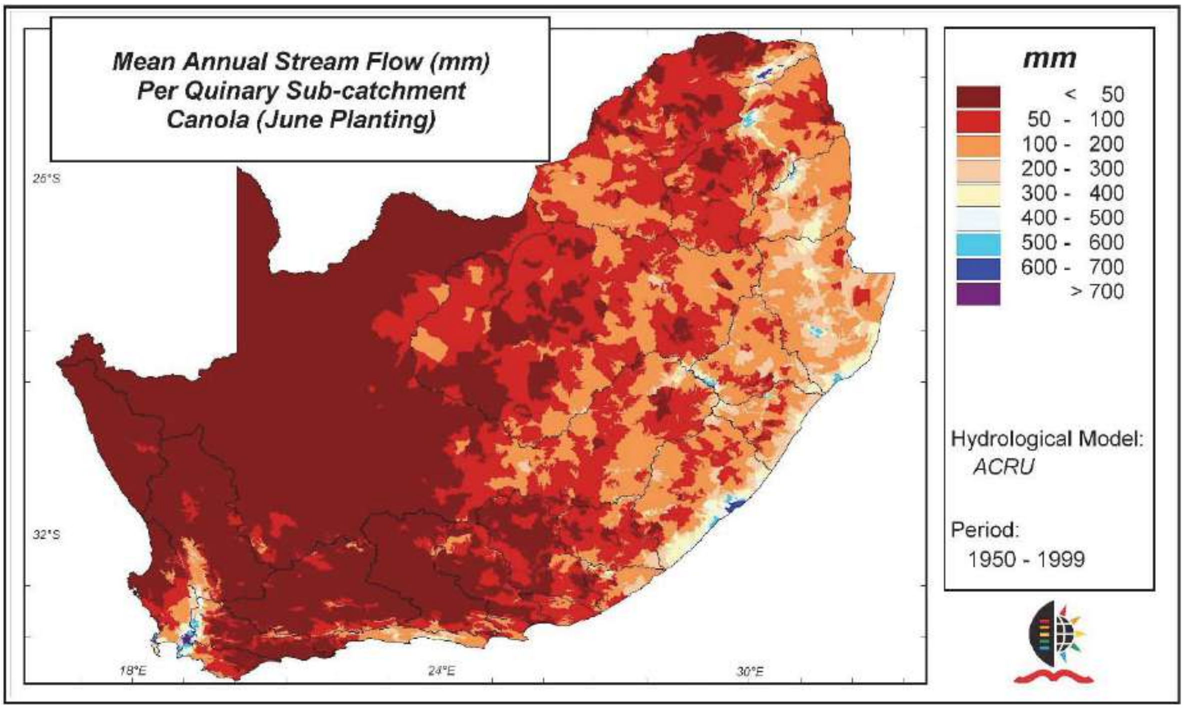
Figure 7 Mean annual stream flow (in mm) simulated using the *ACRU* model for each bioethanol feedstock (a-f)



(a)



(b)



(c)

Figure 8 Mean annual stream flow (in mm) simulated using the *ACRU* model for each biodiesel feedstock (a-c)

3.4 Stream Flow Reduction

3.4.1 Background

According to Kruger and Bosch (2002), the criteria used to assess whether a land-based activity qualifies for consideration as a SFRA includes the following:

- Dryland crop production should only be identified a SFRA when substantial scientific evidence exists for a reduction in water availability (i.e. best available scientific evidence).

- The degree to which a given land-based activity may affect water availability requires an estimate of the reduction in catchment annual runoff, calculated from the change in evapotranspiration of the activity, relative to the baseline or virgin condition (i.e. reduction in water availability).

- Based on recommendations by Jewitt *et al*. (2009b; see Figure 4.1), the reduction in runoff (relative to the baseline) is considered significant when the impact is ≥ 10% for annual runoff (i.e. extent of the impact).

- Jewitt *et al*. (2009b) also recommended that if the land-based activity's spatial extent is ≥ 10% of the catchment's area, the impact is considered significant (i.e. the extent of the impact).

However, Scott and Smith (1997) highlighted the fact that stream flow reductions during low flow periods may be proportionately greater than for total annual flows. Based on recommendations by Jewitt *et al*. (2009b; see Figure 4.1), the reduction in runoff (relative to the baseline) is considered significant when the impact is ≥ 25% for low flows.

3.4.2 Methodology

The approach followed was similar to that used in previous studies:

- Feedstock water use was calculated relative to that of natural vegetation, i.e. water use is considered the difference between stream flow generated by the proposed land use and that of Acocks veld types.

- This difference in annual runoff (*MARbase* - *MARcrop*) was then expressed as a percentage of the baseline stream flow (*MARbase*).

- If the difference was above 10%, the crop may be flagged as a possible stream flow reduction activity.

3.4.3 Results and discussion

3.4.3.1 Mean vs median statistic

The difference in annual runoff between the baseline (base) and each feedstock (crop) was expressed as a percentage relative to the baseline for each quinary. Hence, using mean annual runoff (MAR), feedstock water use is calculated as $100 \cdot (MAR_{base} - MAR_{crop})/MAR_{\mathrm{base}}$. Similarly, water use calculated from median annual runoff (MdAR) is given by 100·

($MdAR_{base}$ - $MdAR_{crop}$)/$MdAR_{base}$. Quinaries in which the reduction in runoff relative to the baseline is greater than 10% may be considered potential stream flow reduction areas.

The values presented in **Table 3** show that fewer quinaries are flagged as potential stream flow reduction areas when using the mean, rather than the median, of the annual runoff series. The most notable differences occur for feedstocks that can be planted in winter (e.g. sugarbeet and canola). This evidence highlights the difference in impact when the mean and median statistics are used to assess stream flow production potential.

Table 3 Number of quinary sub-catchments in which the reduction in annual runoff (relative to the baseline) is 10% or larger

Feedstock	No. of quinaries where annual stream flow reduction ≥ 10%	
	Median	Mean
Sugarcane	3 691	3 187
Grain sorghum	2 779	2 423
Sweet sorghum - inland	1 841	1 263
Sweet sorghum - Interior	530	228
Sugarbeet - summer	1 360	561
Sugarbeet - winter	171	27
Soybean	1 855	1 348
Sunflower	812	298
Canola - winter	287	80

Schulze *et al*. (2007b) recommended the median should be preferred to the mean statistic, particularly for annual time series of runoff. However, calculating the difference between two median values is not mathematically sound (Morris, 2015). The mean of monthly differences in runoff response that may result from a land cover change to sugarcane (in quinary 4 689) is shown in **Table 4** as 2.14 mm. This equates to a 17.3% reduction relative to the mean monthly runoff for baseline conditions (i.e. 100*2.14/12.32). The same relative reduction is obtained when the mean annual statistic is used. However, very different results are obtained with the median statistic is used as shown in the table below. Furthermore, the assessment using median monthly runoff shows no stream flow reduction potential, in contrast to the result derived from using the median annual values. Finally, the median annual approach produces a much higher impact than compared to that based on the mean annual statistic (as highlighted above in **Table 3**).

Table 4 Assessment of stream flow reduction potential in quinary sub-catchment no. 4689, assuming a land cover change to 100% sugarcane

Time series	Runoff response		Difference in runoff	
	Baseline (mm)	Sugarcane (mm)	Absolute (mm)	Relative (%)
Mean monthly	12.32	10.19	2.14	17.3
Mean annual	147.89	122.25	25.64	17.3
Median monthly	3.77	3.82	-0.04	-1.2
Median annual	116.74	83.62	33.12	28.4

In sub-catchments where the median annual runoff is very low (or even zero) for the baseline, the calculation of the relative impact cannot be made. Based on the argument presented above, **the mean runoff statistic (and not the median) must be used to assess the impact of feedstock production on downstream water availability**. Hence, the results presented in this volume are based on an analysis of mean annual and mean monthly flows.

3.4.3.2 Original *vs*. revised quinary climate database

Using the original quinary sub-catchment climate database derived by Schulze *et al*. (2011), the mean annual runoff was determined using *ACRU* variables for each sugarcane growing region (i.e. Inland, South Coast & North Coast). The results showed that 23.1% of the 134 quinaries exhibited a reduction in runoff (relative to the baseline) of 10% or more (**Table 5**).

Table 5 Analysis of simulated runoff based on preliminary *ACRU* runs (i.e. original quinary climate database), for sub-catchments which contain 10% or more of the sugarcane mill supply areas

Location of quinaries	**Percentage of 134 quinaries with a reduction in mean annual runoff ≥ 10%**			
	Inland parameters	S. Coast parameters	N. Coast parameters	Averaged parameters
Inland	23.13			26.12
South Coast		0.00		0.00
North Coast			0.00	0.00
Total	**23.13**	**0.00**	**0.00**	**26.12**

A very similar result (26.1%) was obtained using the mean annual runoff derived from the averaged crop-related variables. **Table 5** also shows that the quinaries where sugarcane production may be declared a SFRA are located in the inland growing region only (i.e. KZN Midlands). In other words, no quinaries located along the South or North Coast of KwaZulu-Natal are deemed SFRA areas. This trend was also observed in the original SFRA project undertaken by Jewitt *et al*. (2009b). Thus, the use of averaged parameters increased the number of quinaries flagged as potential SFRAs from 31 to 35 (out of 47) in the inland region. The similarity in results indicates that the decision to use averaged variables for sugarcane is well justified.

The above exercise was repeated using the revised quinary sub-catchment database. As noted earlier, the revised A-pan equivalent evaporation estimates are much higher than the original values, which means that less runoff is generated. The results presented in **Table 6** show the same trends as those derived using the original quinary climate database (**Table 5**). The use of averaged parameters increased the number of quinaries flagged as potential SFRAs from 17 to 24 (out of 47) in the inland region.

However, the increase in evaporative demand resulted in fewer quinaries for which a reduction in stream flow of 10% or more was estimated. In other words, the number of inland quinaries decreased from 35 to 24 (out of 47) based on mean annual runoff determined using averaged crop parameters (and from 31 to 17 using runoff estimates derived with inland parameters).

Table 6 Analysis of simulated runoff based on finalised *ACRU* runs (i.e. revised quinary climate database), for sub-catchments which contain 10% or more of the sugarcane mill supply areas

Location of quinaries	**Percentage of 134 quinaries with a reduction in mean annual runoff ≥ 10%**			
	Inland parameters	S. Coast parameters	N. Coast parameters	Averaged parameters
Inland	12.69			17.91
South Coast		0.00		0.00
North Coast			0.00	0.00
Total	**12.69**	**0.00**	**0.00**	**17.91**

3.4.3.3 Threshold to assess SFRAs

It must be noted that the 10% reduction in MAR threshold, which is used to flag a potential SFRA, was suggested by Jewitt *et al*. (2009b) and based on the original (1972) Afforestation Permit System (APS). For the impact on low flows, a threshold of 25% was suggested by Jewitt *et al*. (2009b). The APS considered up to a 10% reduction in mean annual runoff from whole or part of primary catchments where afforestation was being considered. However, this threshold is not stated in the Water Act (Act No. 36 of 1998). It is also important to note that a 10% (or larger) relative reduction in annual runoff is assumed to be “significant”. The problem with this assumption is that it probably lies within the confidence limits of the modelling approach and perhaps, needs to be reviewed.

For South Africa, MAR estimated using *ACRU* for the baseline ranges from 0 (quinary 2544) to 1 822 mm (quinary 2911). Hence, a 10% reduction in MAR is equivalent a range of 0 to 182.2 mm, which highlights a shortcoming of this approach. In other words, a difference of just 1 mm in mean annual runoff (MAR_{base} - MAR_{crop}) is equivalent to reductions ranging from 100 to 0.05% for MAR_{base} of 1 to 1 822 mm respectively. Thus, the 10% threshold is very sensitive to low baseline MARs. This is highlighted in quinary 2589 where the MAR may be reduced from 0.02 to 0.00 mm (i.e. 100% reduction) when the land cover is changed to sugarcane. Thus, a high relative reduction can occur in sub-catchments with little to no runoff response, which can be misleading. Furthermore, a 10% (or larger) stream flow reduction in areas with a high runoff ratio (i.e. MAR/MAP) exhibits a greater impact than a similar reduction in drier areas (i.e. low runoff ratio). On average, only 9% of the country’s rainfall is converted into stream flow (DWA, 1986).

3.4.3.4 Reduction in mean annual runoff

Simulated mean annual stream flow (MAR_{crop}) for each feedstock was then compared to the MAR simulated for each quinary sub-catchment for a land cover of natural vegetation (MAR_{base}). The absolute difference (i.e. MAR_{base} - MAR_{crop}) in mm is given for bioethanol and biodiesel crops in **Figure 72** and **Figure 73** (in **APPENDIX A**) respectively.

This difference in MAR between the baseline (base) and each feedstock (crop) was then expressed as a percentage relative to the baseline for each quinary, i.e. $100 \cdot (MAR_{base} - MAR_{crop})/MAR_{\mathrm{base}}$. Thus, **Figure 10** highlights the relative reduction in runoff that may result from a land cover change from natural vegetation to selected bioethanol crops (with **Figure 11** showing the relative reduction in runoff for selected biodiesel crops).

Figure 9 shows for each feedstock, the portion of quinary sub-catchments in which no reduction in MAR (i.e. MAR ≤ 0%) as well as a positive reduction in MAR (i.e. MAR > 0%) was simulated using the *ACRU* model. To re-cap, the MAR for each feedstock is compared to that generated for the baseline (i.e. land cover of natural vegetation).

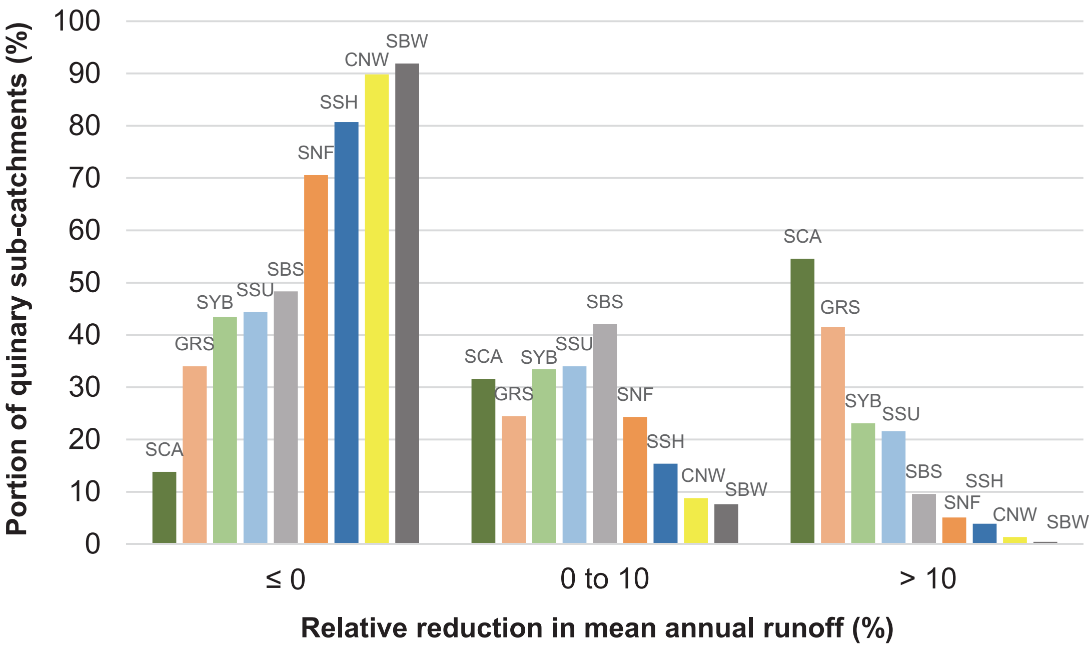
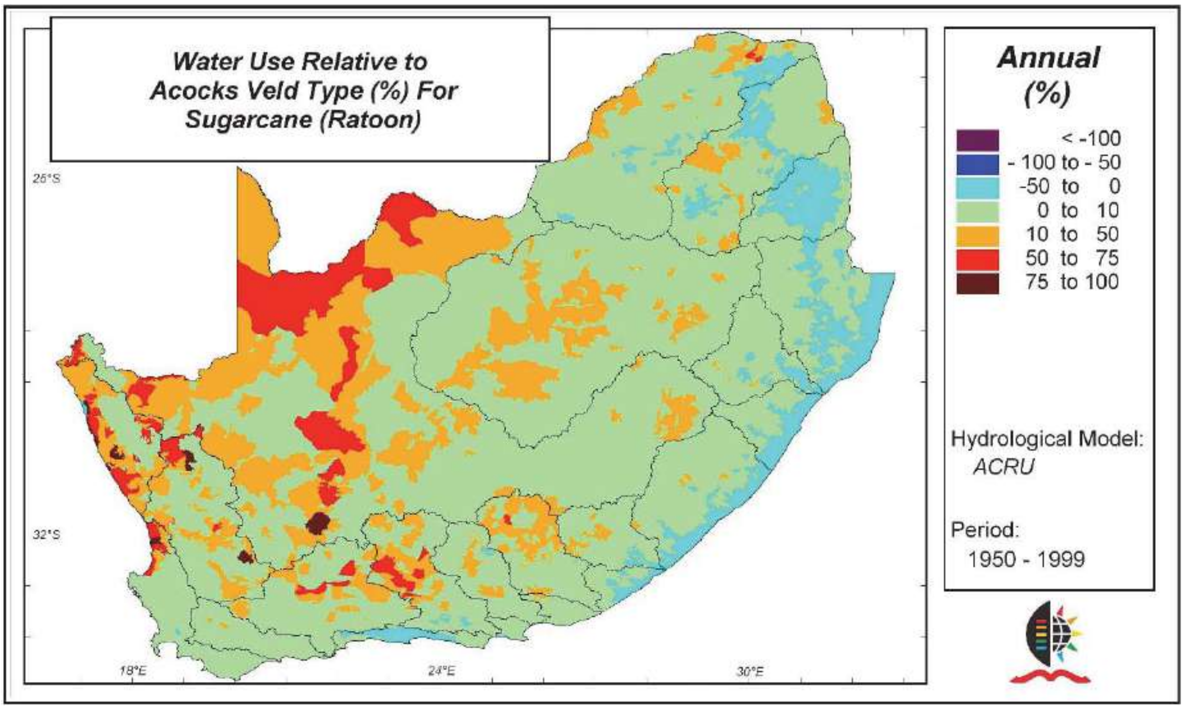


Figure 9 Reduction in mean annual runoff relative to the baseline (expressed as a percentage) for selected biofuel feedstocks

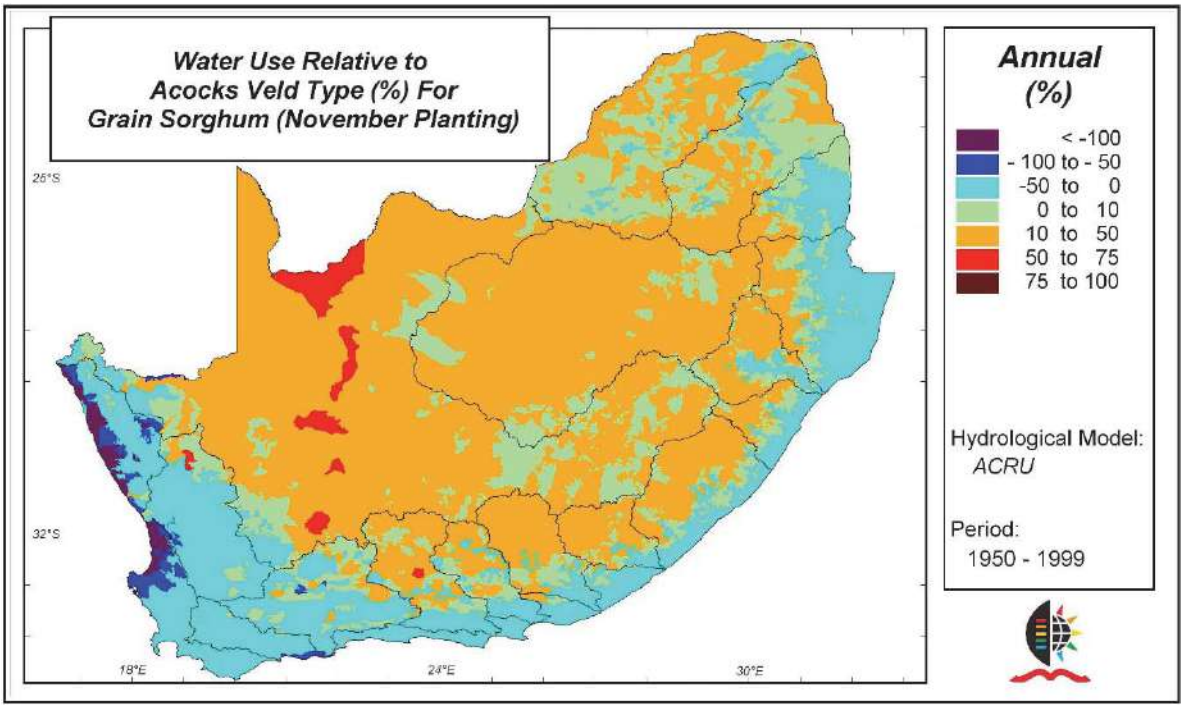
Using the 10% threshold considered as a significant reduction in MAR, the feedstocks can be ranked in terms of their potential to reduce water availability to downstream users as follows:

1. Sugarcane (SCA; highest potential)
2. Grain sorghum (GRS)
3. Soybean (SYB)
4. Sweet sorghum - inland (SSU)
5. Sugarbeet - summer (SBS)
6. Sunflower (SNF)
7. Sweet sorghum - interior (SSH)
8. Canola (CNW)
9. Sugarbeet - winter (SBW; least potential)

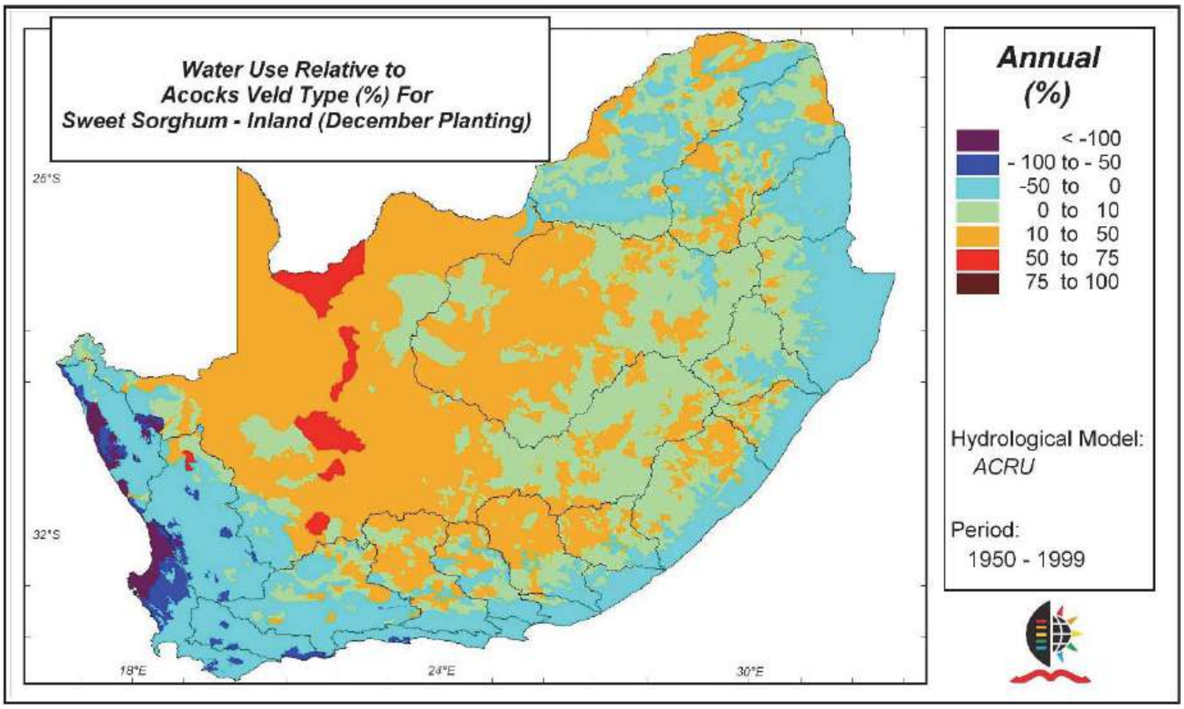
These results concur with the findings of the scoping study (Jewitt *et al*., 2009a) which concluded that sugarcane exhibits the most potential to utilise more water than the dominant Acocks Veld Type it replaces, based on a comparison of mean annual runoff. The scoping study also highlighted sweet sorghum production as a potential SFRA. However, the results presented in this study show that grain sorghum's potential to reduce runoff production is similar to that of sugarcane.


Water Use Relative to
Acocks Veld Type (%) For
Sugarcane (Ratoon)
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

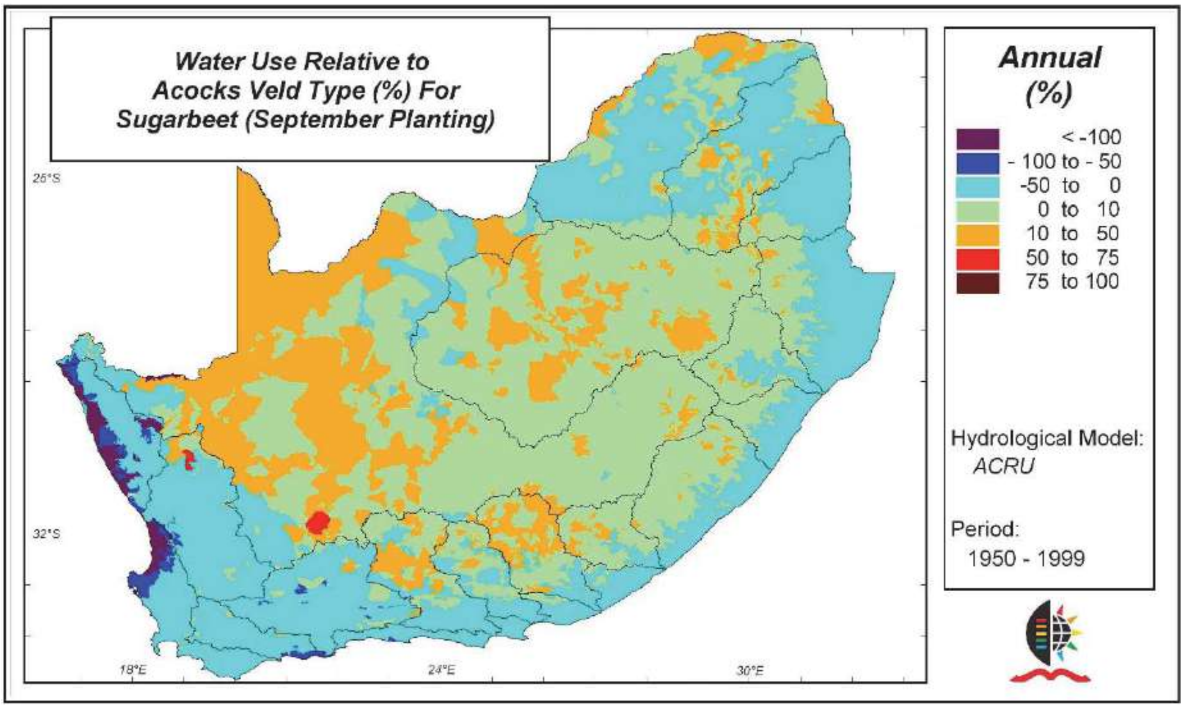
(a)


Water Use Relative to
Acocks Veld Type (%) For
Grain Sorghum (November Planting)
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

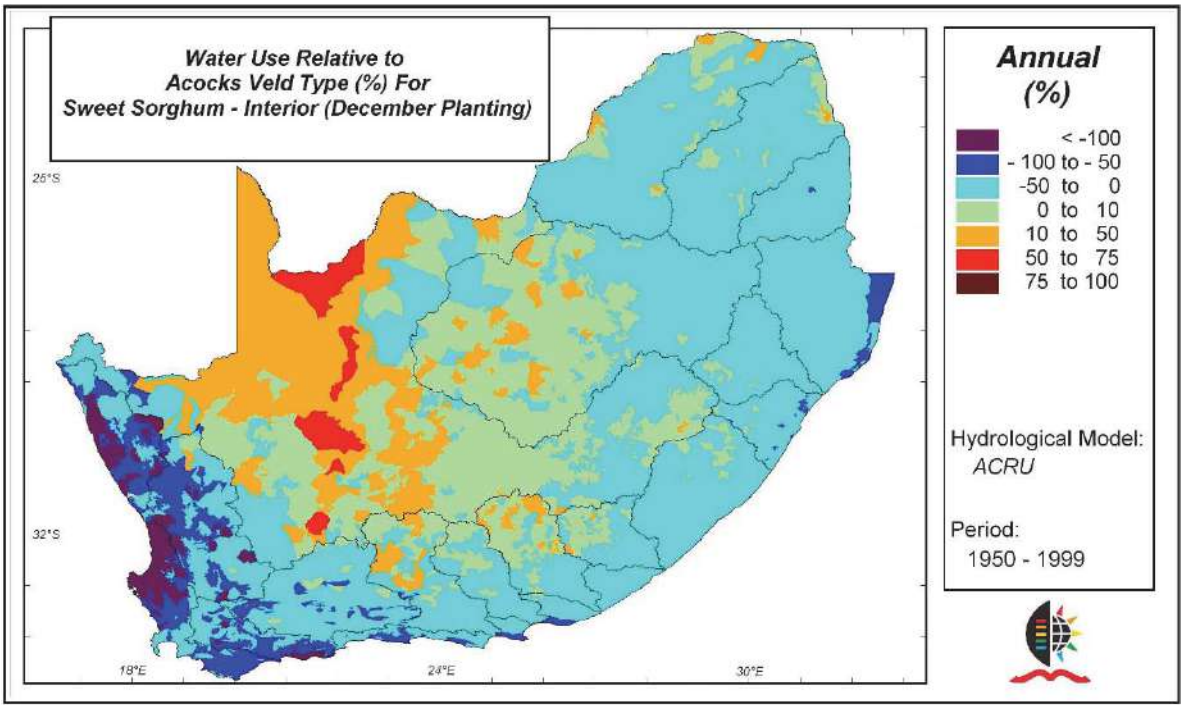
(b)


Water Use Relative to
Acocks Veld Type (%) For
Sweet Sorghum - Inland (December Planting)
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

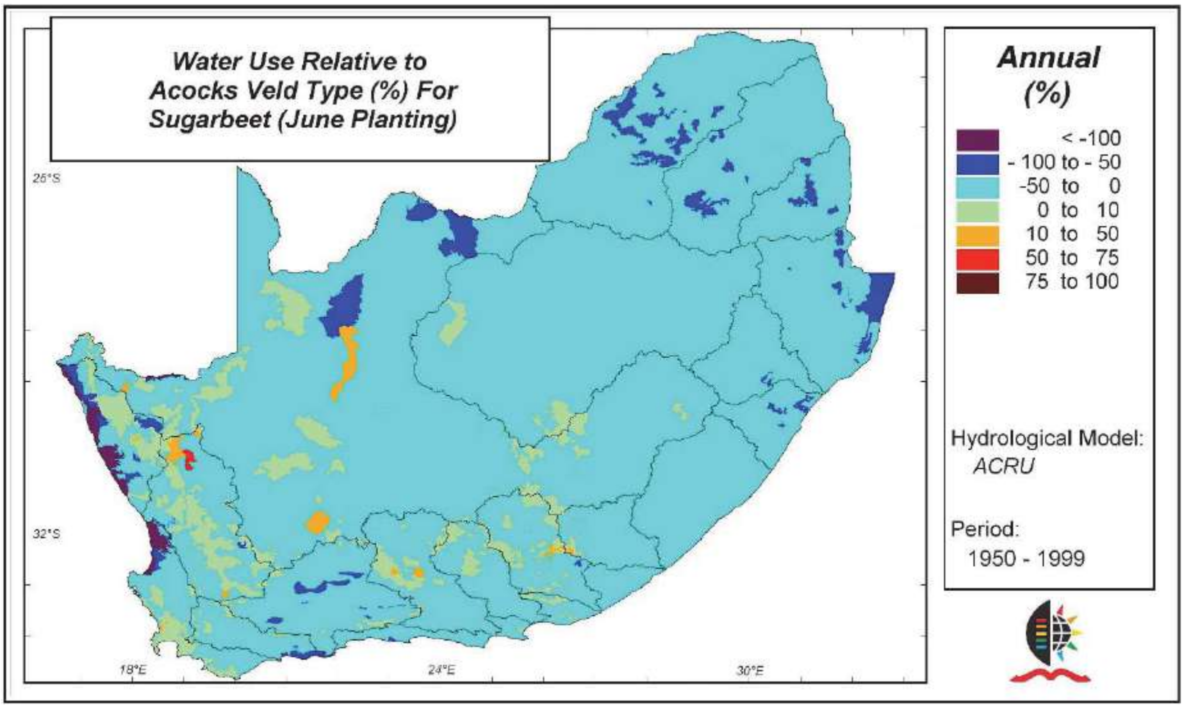
(c)


Water Use Relative to
Acocks Veld Type (%) For
Sugarbeet (September Planting)
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(d)

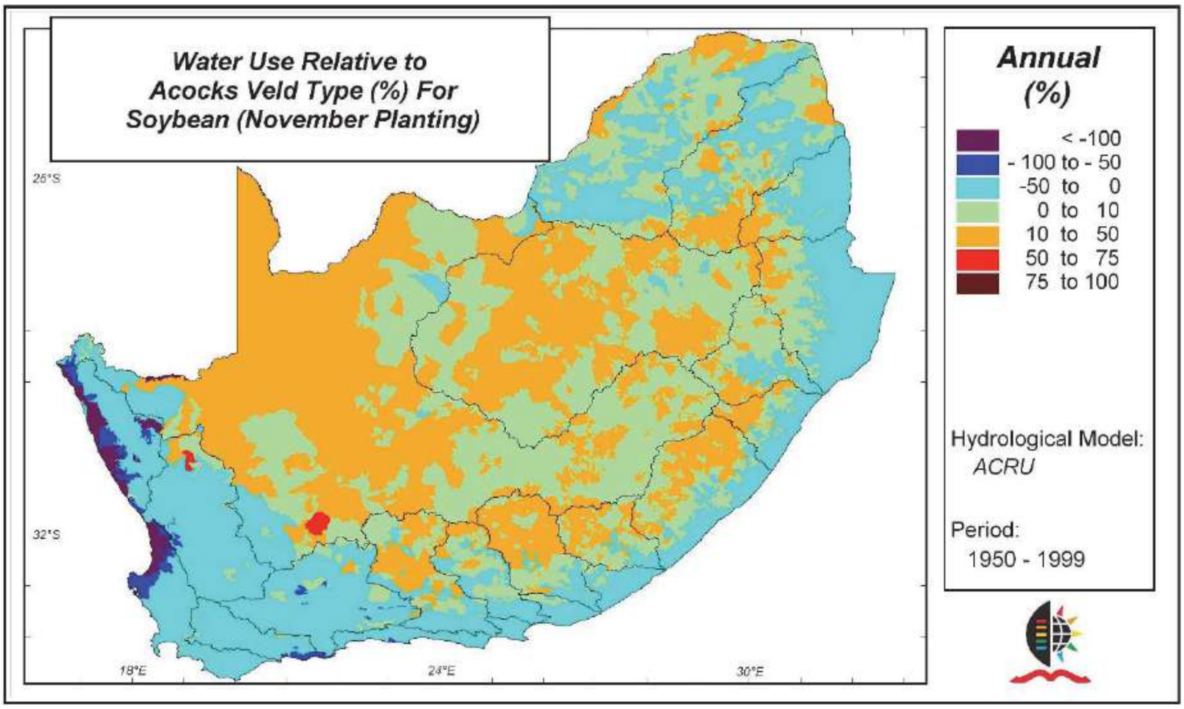


(e)

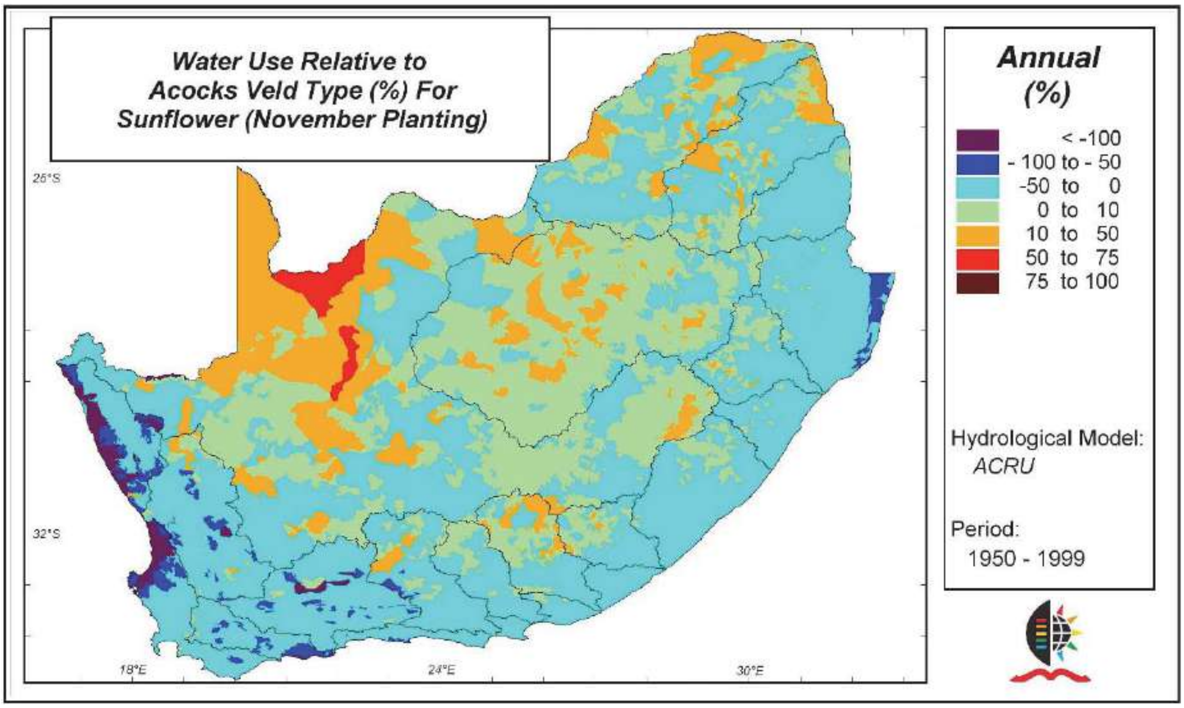


(f)

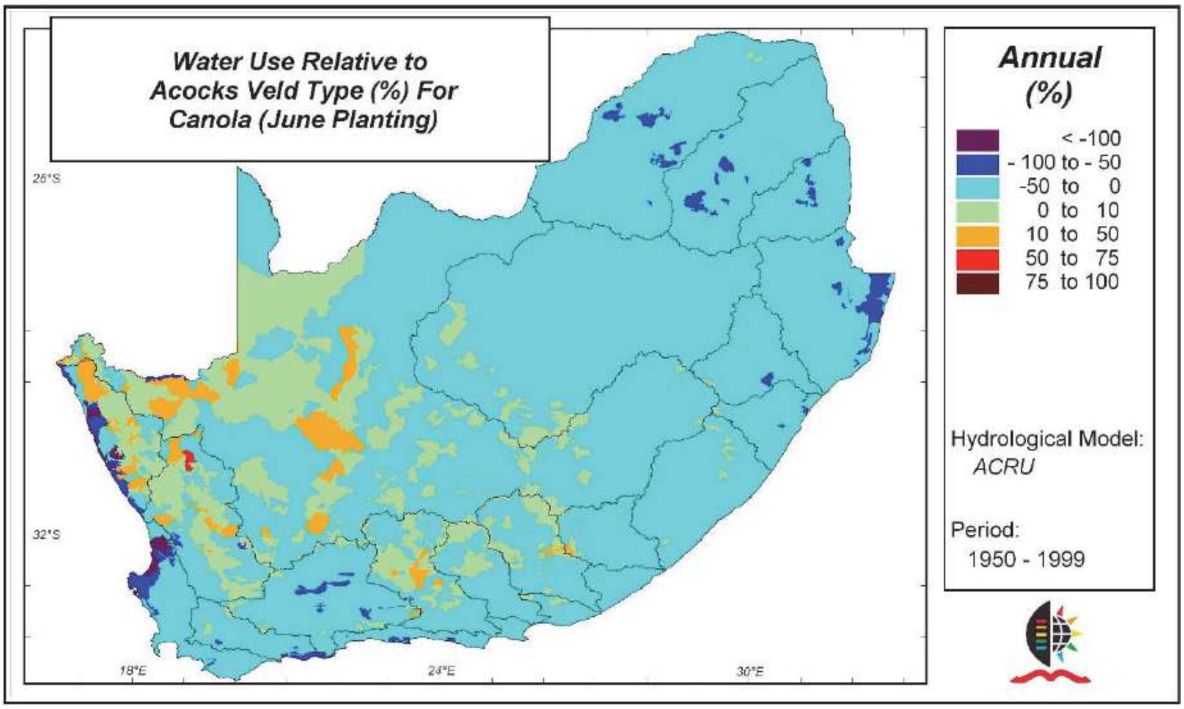
Figure 10 Water use of selected bioethanol feedstocks (a-f) expressed as a relative percentage of the baseline


Water Use Relative to
Acocks Veld Type (%) For
Soybean (November Planting)
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(a)


Water Use Relative to
Acocks Veld Type (%) For
Sunflower (November Planting)
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(b)



(c)

Figure 11 Water use of selected biodiesel feedstocks (a-c) expressed as a relative percentage of the baseline

3.4.3.5 Hydrological impact on low flows

Mean monthly flows were accumulated over the driest quartile (i.e. 3 months with the lowest runoff response) for the baseline as well as for each feedstock. The percentage difference (relative to the baseline) was then calculated. The reduction in low flow runoff (LFR) is considered "significant" if 25% or larger, as recommended by Jewitt *et al*. (2009b; Figure 4.1). **Figure 12** shows for each feedstock, the portion of quinary sub-catchments in which no reduction in LFR (i.e. LFR ≤ 0 %) was simulated using the *ACRU* model, as well as a positive reduction in LFR (i.e. > 0%).

Compared to **Figure 9**, the above chart shows that based on an analysis of low flows, the impact of feedstock cultivation is much less. The feedstocks were also ranked in terms of their potential to significantly reduce stream flow during the low flow period as:

1. Sugarcane (SCA; highest potential)
2. Grain sorghum (GRS)
3. Canola (CNW)
4. Soybean (SYB)
5. Sweet sorghum - inland (SSU)
6. Sugarbeet - summer (SBS)
7. Sugarbeet - winter (SBW)
8. Sunflower (SNF)
9. Sweet sorghum - interior (SSH; least potential)

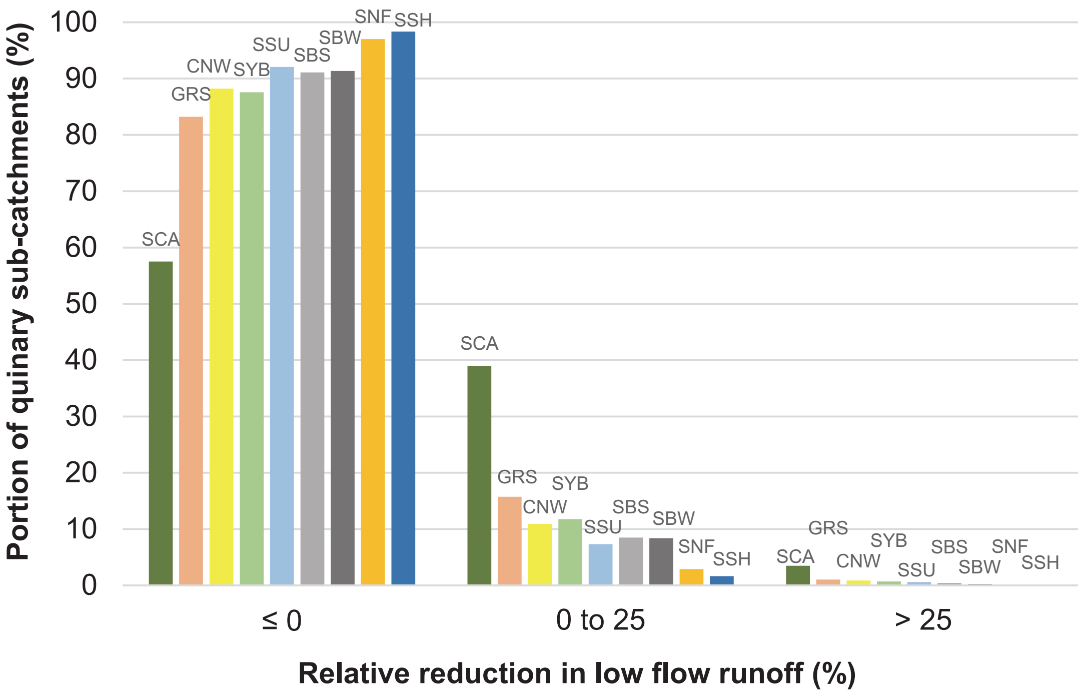
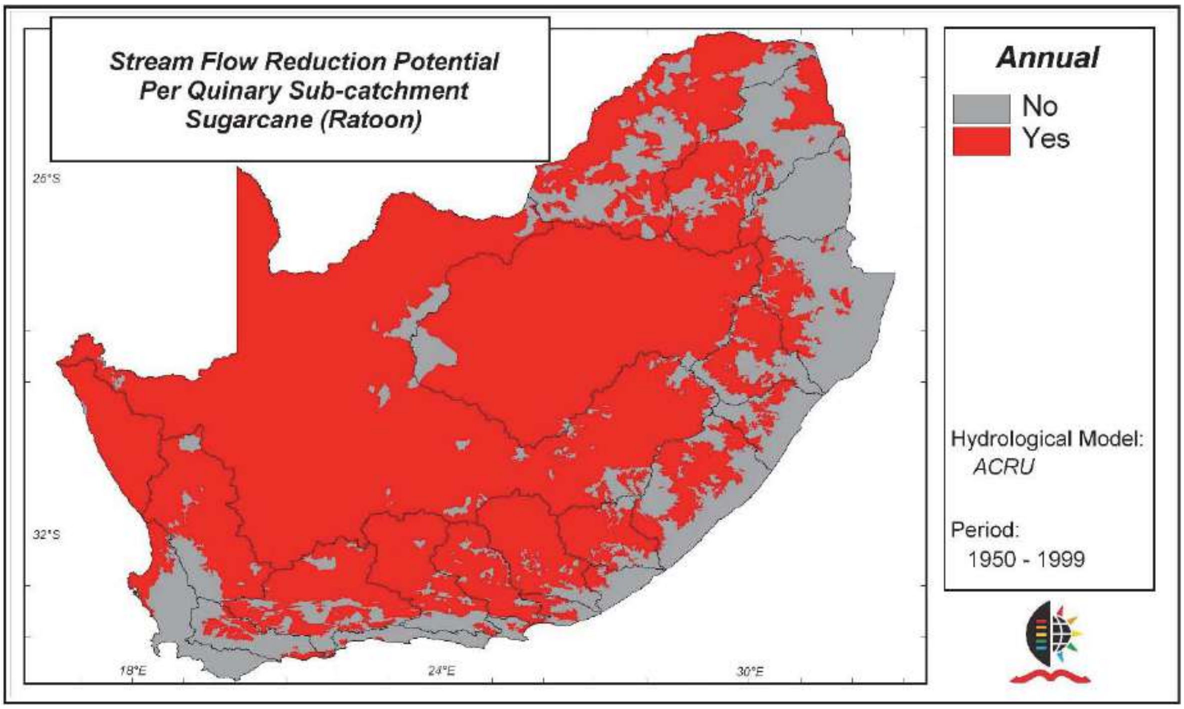


Figure 12 Reduction in low flow runoff relative to the baseline (expressed as a percentage) for selected biofuel feedstocks

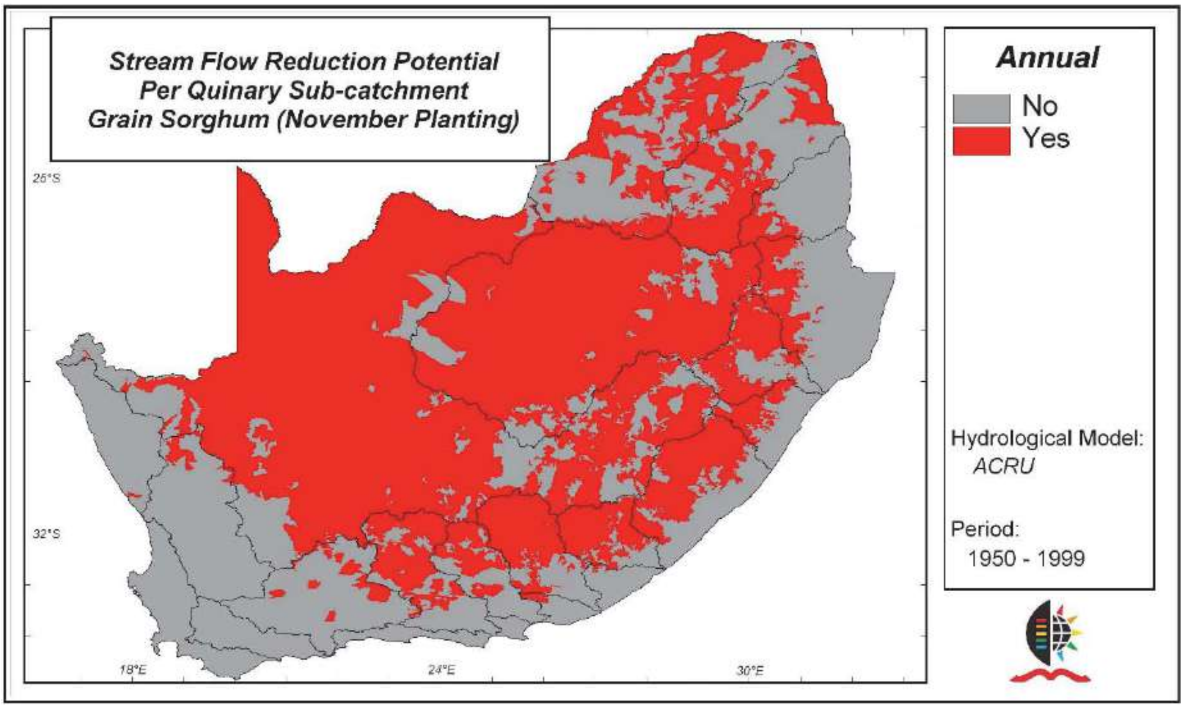
3.4.3.6 Potential SFRAs (annual runoff)

Of particular interest are quinary sub-catchments in **Figure 10** and **Figure 11** where the reduction in runoff is 10% or greater (relative to the baseline) were highlighted for bioethanol and biodiesel crops respectively. These areas are shown in **Figure 13** and **Figure 14** for bioethanol and biodiesel feedstocks respectively. The feedstocks are presented in order of most to least ability to reduce stream flow. The maps highlight the fact that all feedstocks have the potential to significantly reduce annual stream flow production. However, of all the bioethanol feedstocks considered, sugarcane exhibits the highest potential to reduce runoff in a particular quinary. Similarly, a change in land use to soybean cultivation has the highest potential of causing a significant reduction in stream flow generation, compared to the other two biodiesel feedstocks (i.e. sunflower and canola).

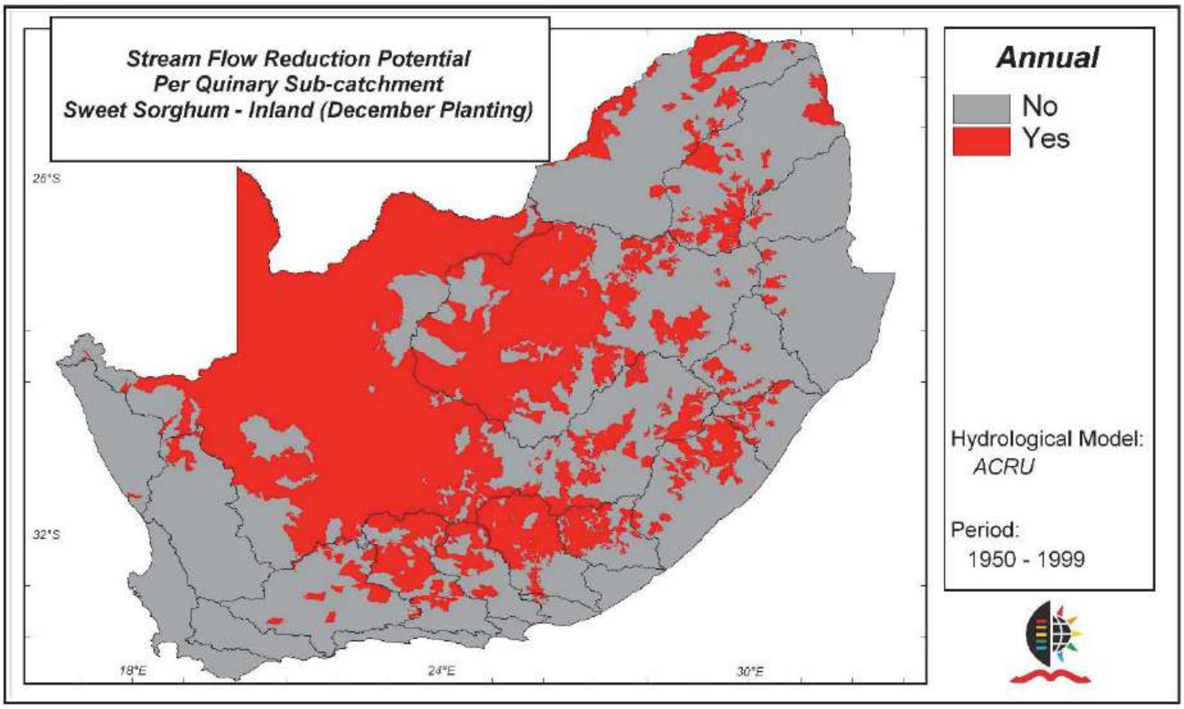
Few quinaries along the eastern and southern coastline (or just inland of the coast) are flagged as potential stream flow reduction zones. As highlighted in the SFRA project (Jewitt *et al*. 2009b), the impact on available water resources resulting from a land use change to feedstock production is negligible along the North and South Coasts (even for sugarcane). The reason for this is the dominant Acocks Veld Type along the coastline of KwaZulu-Natal is “Coastal Tropical Forest”, which is considered a tall evergreen land cover with a deep root system. Replacing this vegetation type with an annual (or perennial) crop exhibiting a shallower rooting system, will likely result in higher runoff production from the new land cover.


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sugarcane (Ratoon)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

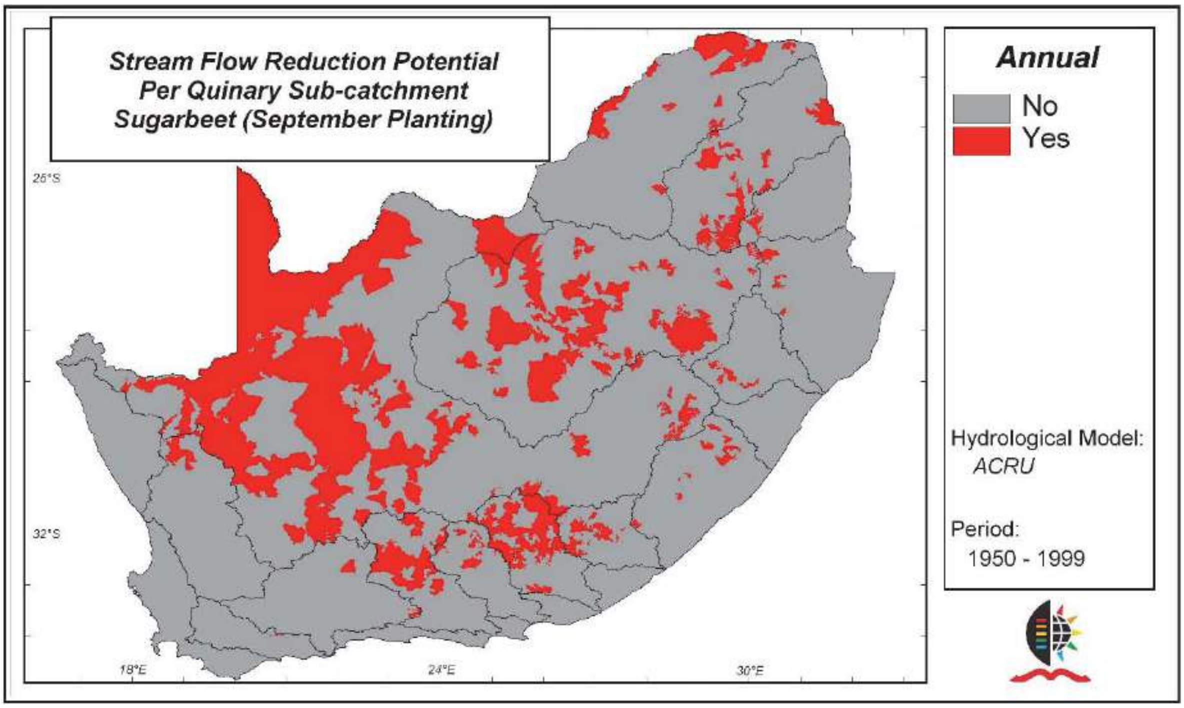
(a)


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Grain Sorghum (November Planting)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

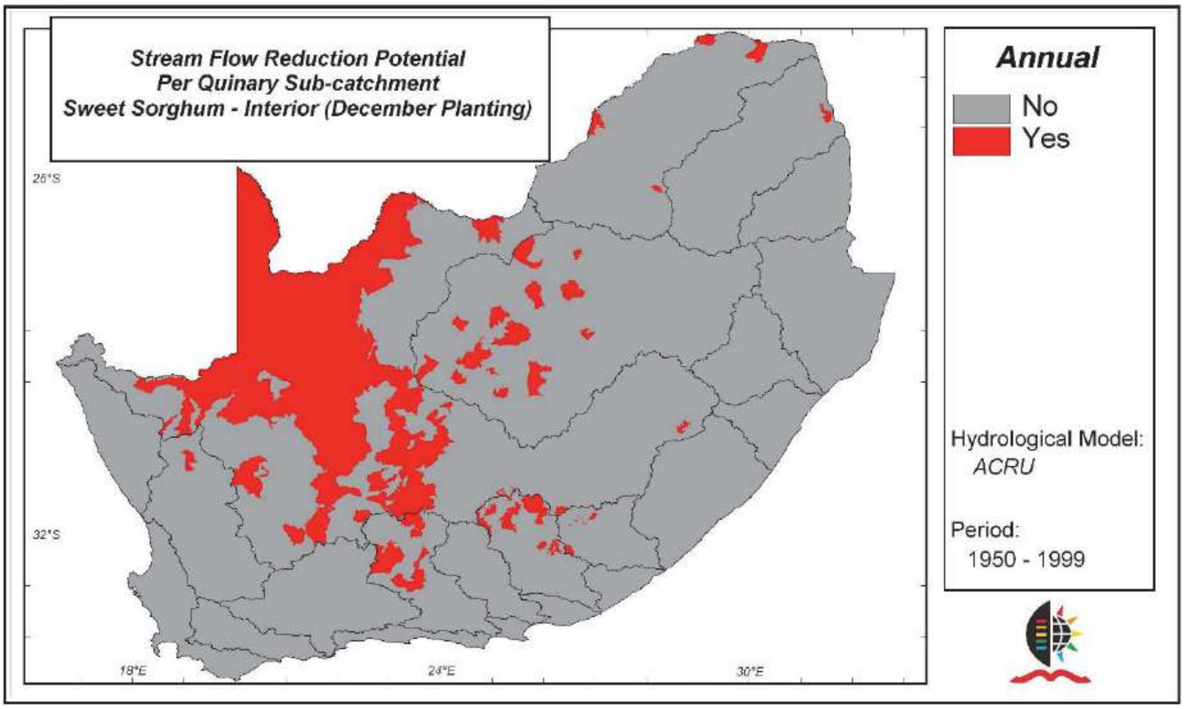
(b)


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sweet Sorghum - Inland (December Planting)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

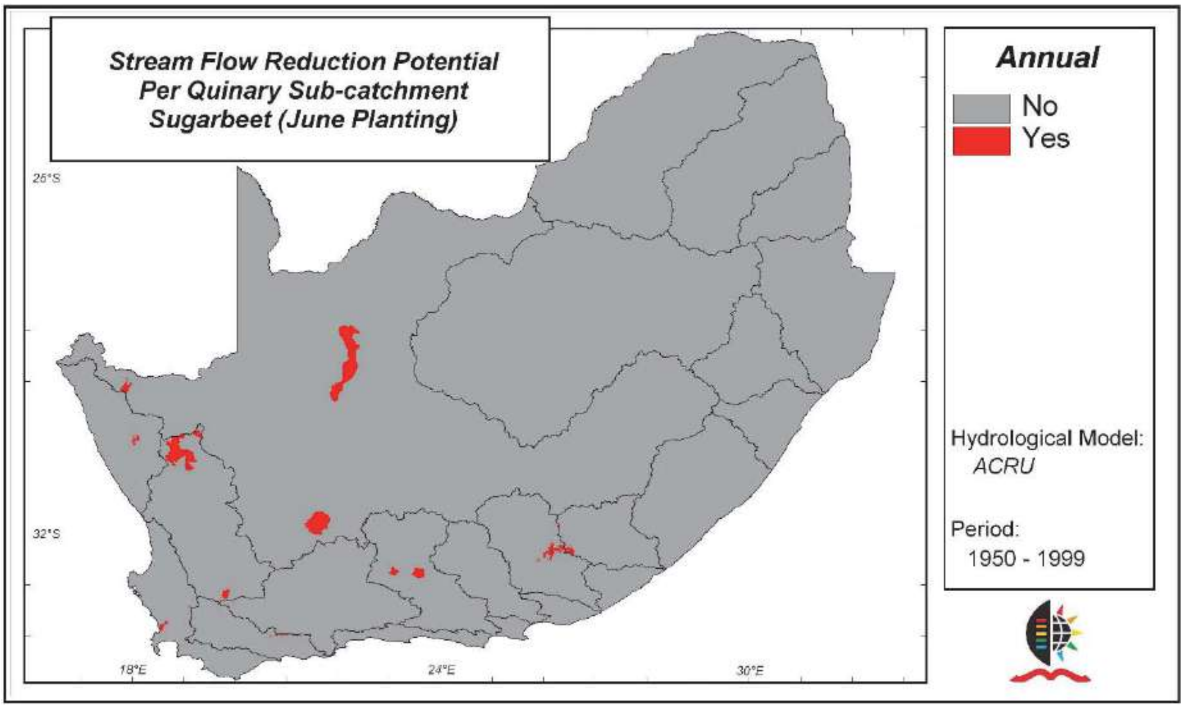
(c)


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sugarbeet (September Planting)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(d)

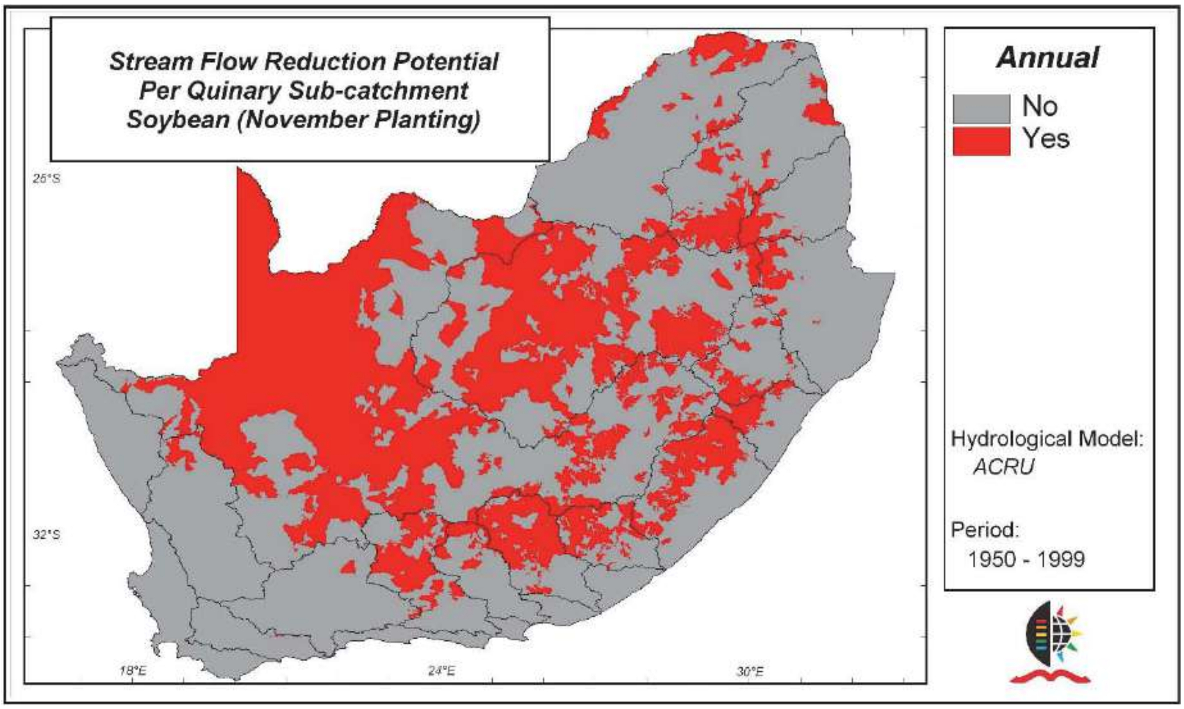


(e)

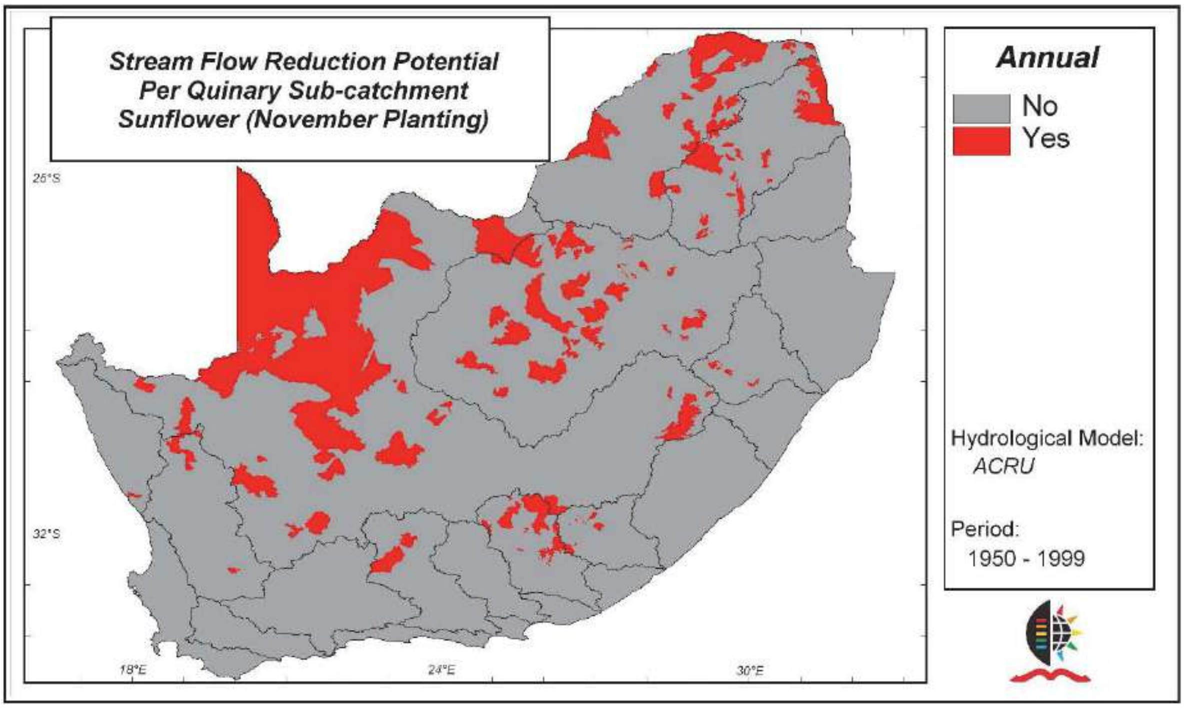


(f)

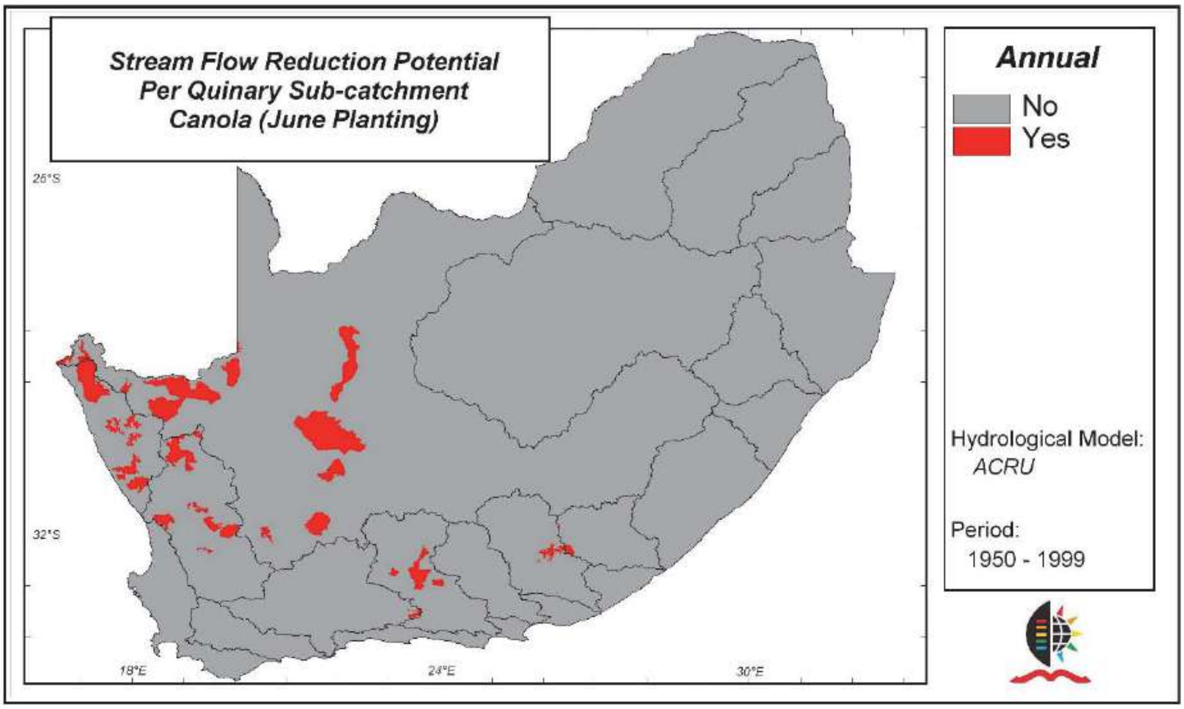
Figure 13 Sub-catchments in which the reduction in mean annual runoff resulting from a land use change from natural vegetation to a bioethanol feedstock is ≥ 10%


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Soybean (November Planting)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(a)


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sunflower (November Planting)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(b)



(c)

Figure 14 Sub-catchments in which the reduction in mean annual runoff resulting from a land use change from natural vegetation to a biodiesel feedstock is ≥ 10%

The difference between the sweet sorghum maps labelled "inland" and "interior" highlight the sensitivity of the *ACRU* model to crop coefficient inputs as well as the influence of management practice (in particular planting density) on derived crop coefficients. The "inland" and "interior" maps are based on crop coefficients derived at the Ukulinga and Hatfield research farms respectively. Instead of averaging the crop coefficients obtained at these two locations, separate national runs were done to illustrate this point. The difference also highlights the fact that crop coefficients are site-specific and need to be adapted to local growing conditions before being used in impact assessment studies. Thus, there is less confidence in the maps for canola and sunflower, which are based on international (i.e. FAO-based) crop coefficients, since no information is available locally for these two feedstocks. Finally, the importance and value of the field work component of the biofuels project needs to be emphasised.

Feedstocks planted in winter (e.g. sugarbeet and canola) are least likely to negatively impact stream flow generation. The reason for this is stream flow generation typically occurs in the summer months when rainfall is highest. However, this result can be misleading as it does not account for the supplemental irrigation that is required to establish a winter crop, especially for sugarbeet grown in the Cradock area. Similarly, canola requires at least 25 mm of rainfall/irrigation during the germination phase to ensure successful establishment. Although the maps shown in **Figure 13** and **Figure 14** highlight quinaries where feedstock production may cause a reduction in stream flow generation, they do not indicate whether or not cultivation is economically viable in that sub-catchment.

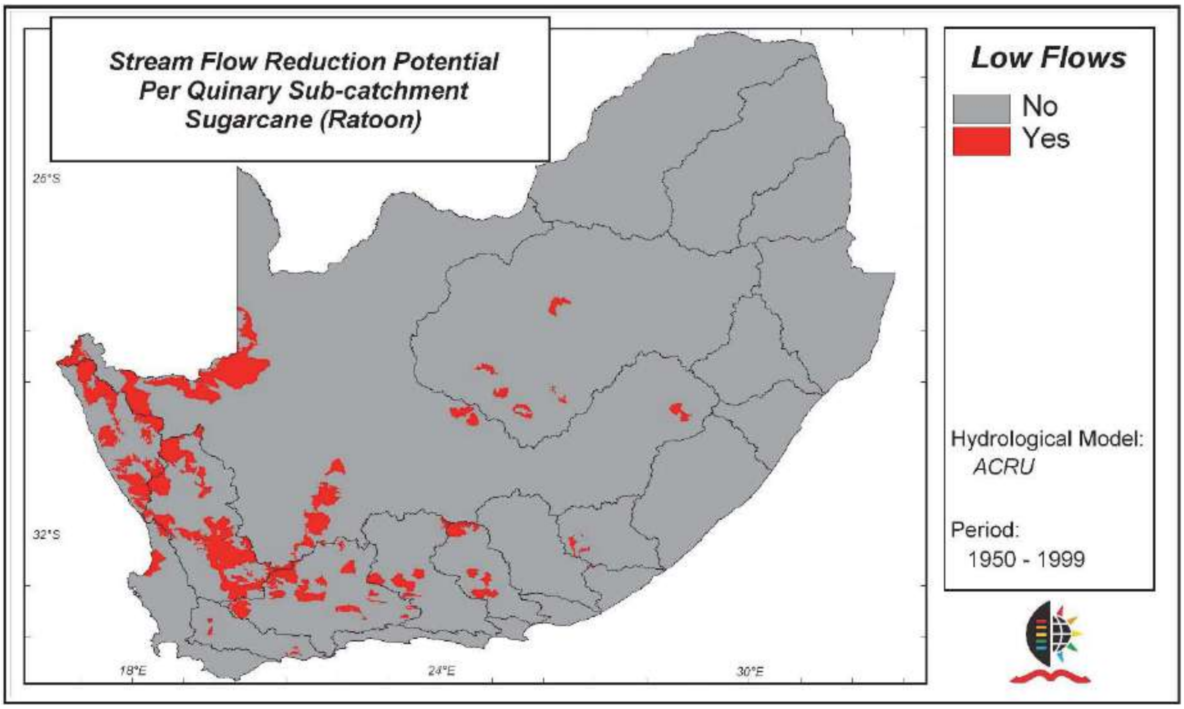
Finally, areas where dryland cultivation is deemed unfeasible (i.e. MAP < 250 mm) were not eliminated. It is not recommended that the land suitability maps (as shown in **Section 5.4.3**) are used to “filter out” quinary sub-catchments deemed unsuitable for feedstock cultivation. The reason is that the land suitability maps are not applicable at the farm level, due to the coarse spatial scale of some of the input data sets (e.g. soils data). Hence, it is likely that feedstock cultivation is possible within the majority of quinaries, except for those sub-catchments located in extremely arid areas of the country (i.e. MAP < 250 mm). In other words, crop growth is possible if the micro-climate is suitable, or irrigation is used, or a drought/heat tolerant cultivar is planted.

3.4.3.7 Potential SFRAs (low flow runoff)

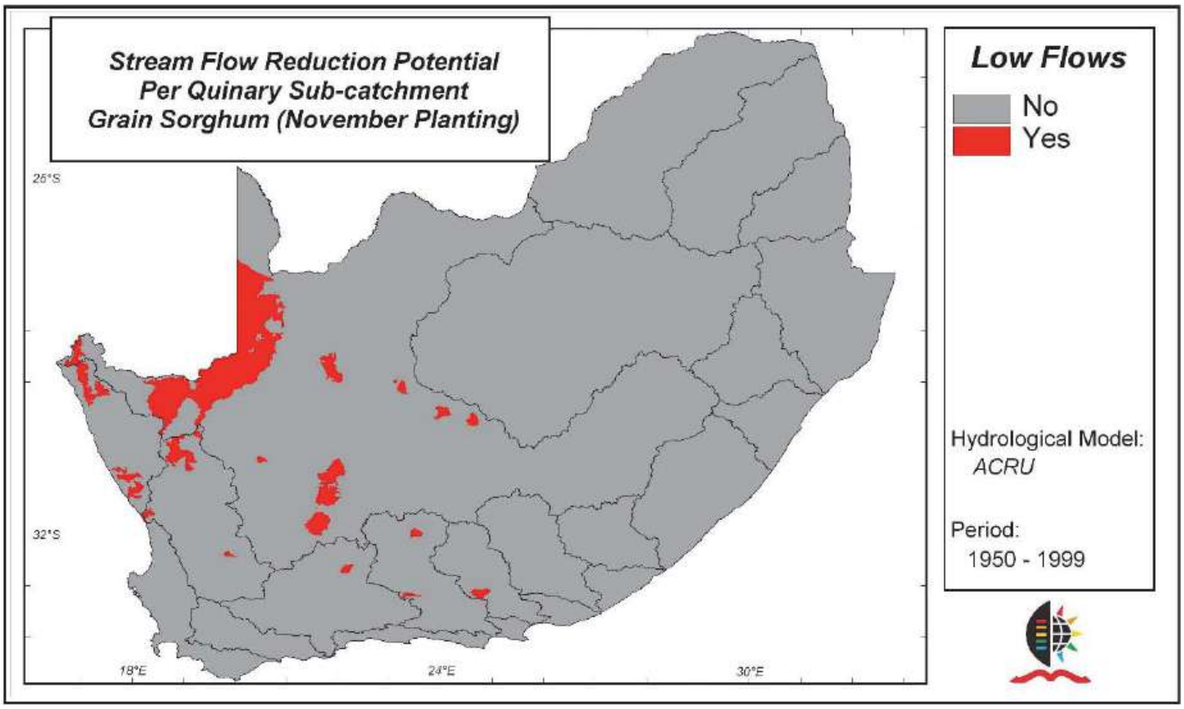
The maps presented in the previous section (c.f. **Section 3.4.3.6**) only consider the annual (and not a shorter) time scale. Hence, the impact on stream flow during an individual month in summer may be much higher for certain feedstocks.

In **Figure 15**, sub-catchments in which the reduction in mean monthly low flows is 25% or larger for bioethanol feedstocks are shown (with similar areas given in **Figure 16** for the biodiesel crops). The results indicate that, for the majority of the summer rainfall region, no feedstock should reduce the stream flow by 25% or more during the driest three months of the year (i.e. during the low flow period). The only exception is sub-catchments situated in the very late summer, winter and all-year rainfall regions (i.e. western parts of the country).

However, according to the land suitability maps given in **Section 5.4.3**, this region of the country is not suited to the growth of the key feedstocks. Finally, further investigation may be warranted to determine if the 25% threshold is too high. This recommendation is similar to that regarding the 10% threshold assumed for annual flows (c.f. **Section 3.4.3.3**).

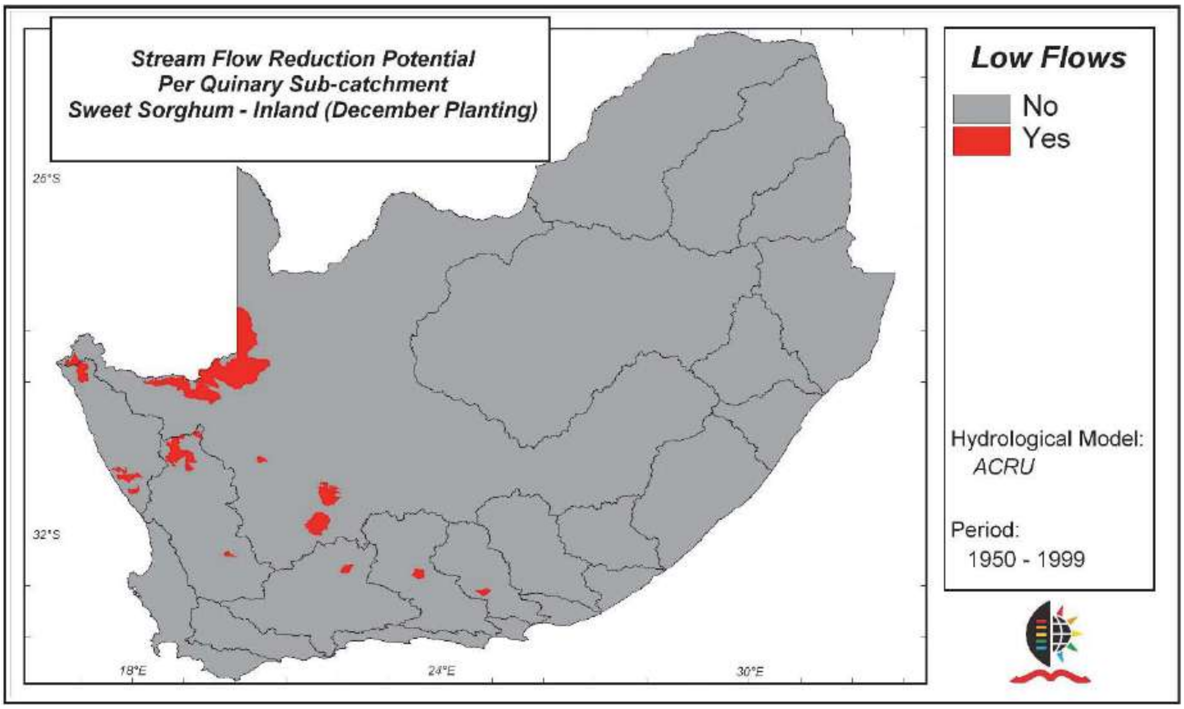


(a)



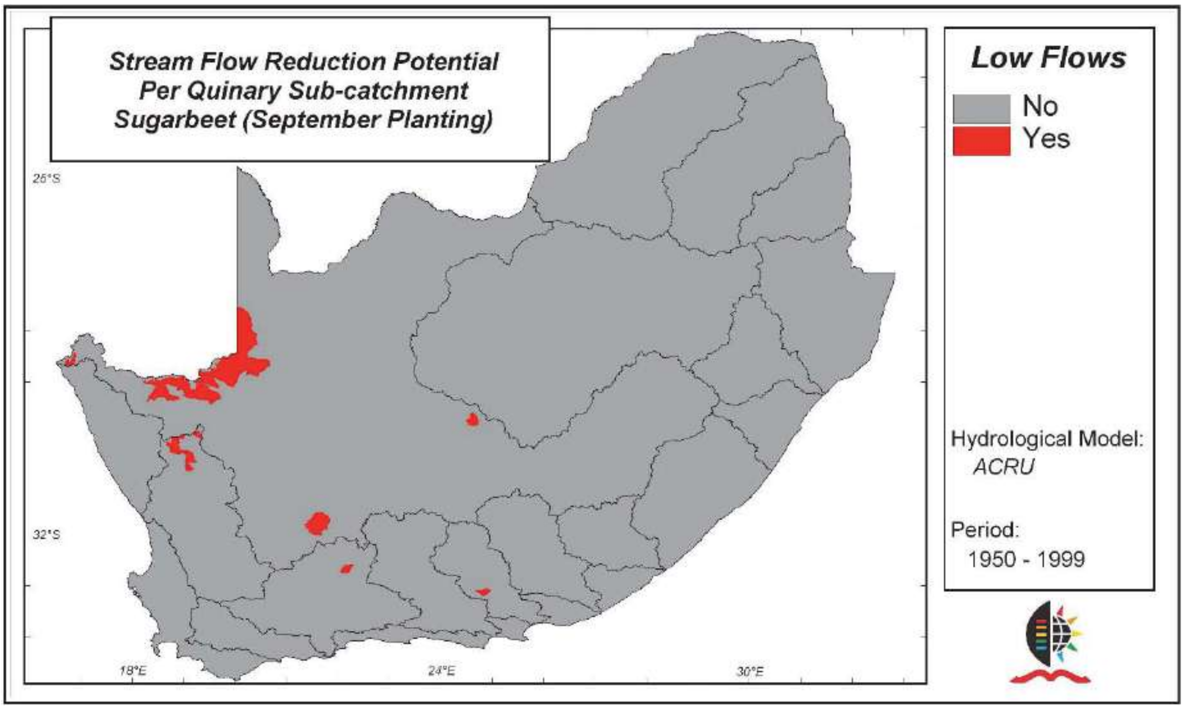
Stream Flow Reduction Potential
Per Quinary Sub-catchment
Grain Sorghum (November Planting)
Low Flows
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(b)

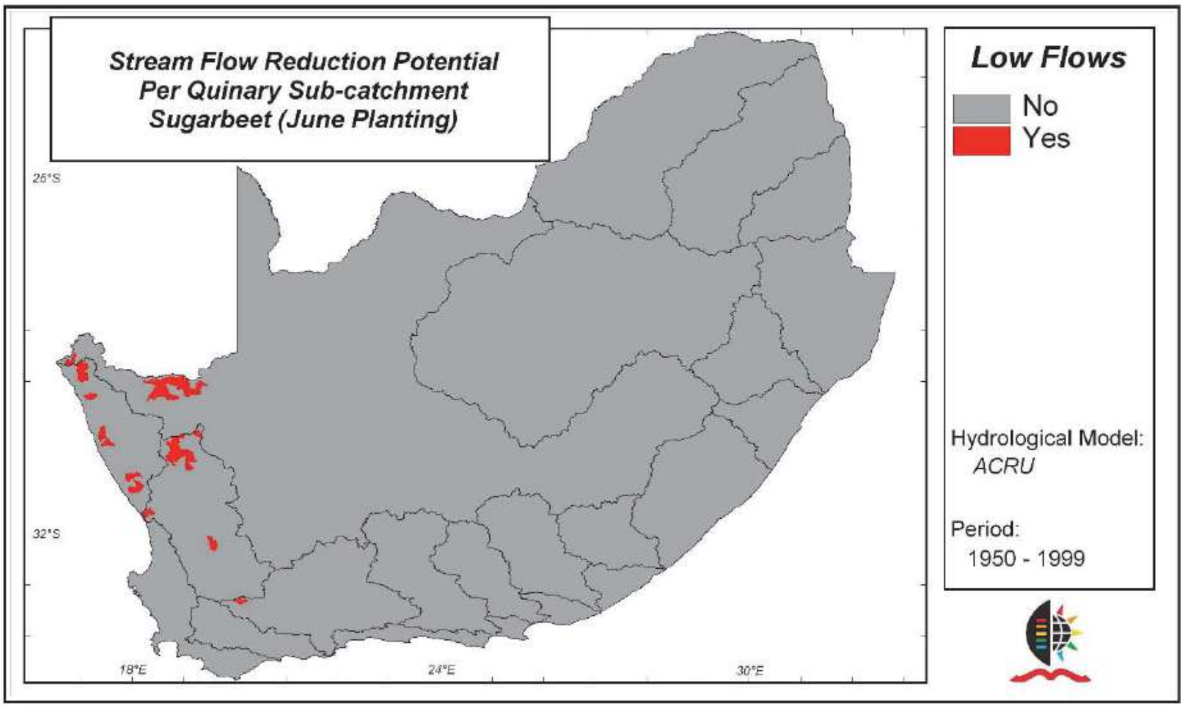


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sweet Sorghum - Inland (December Planting)
Low Flows
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

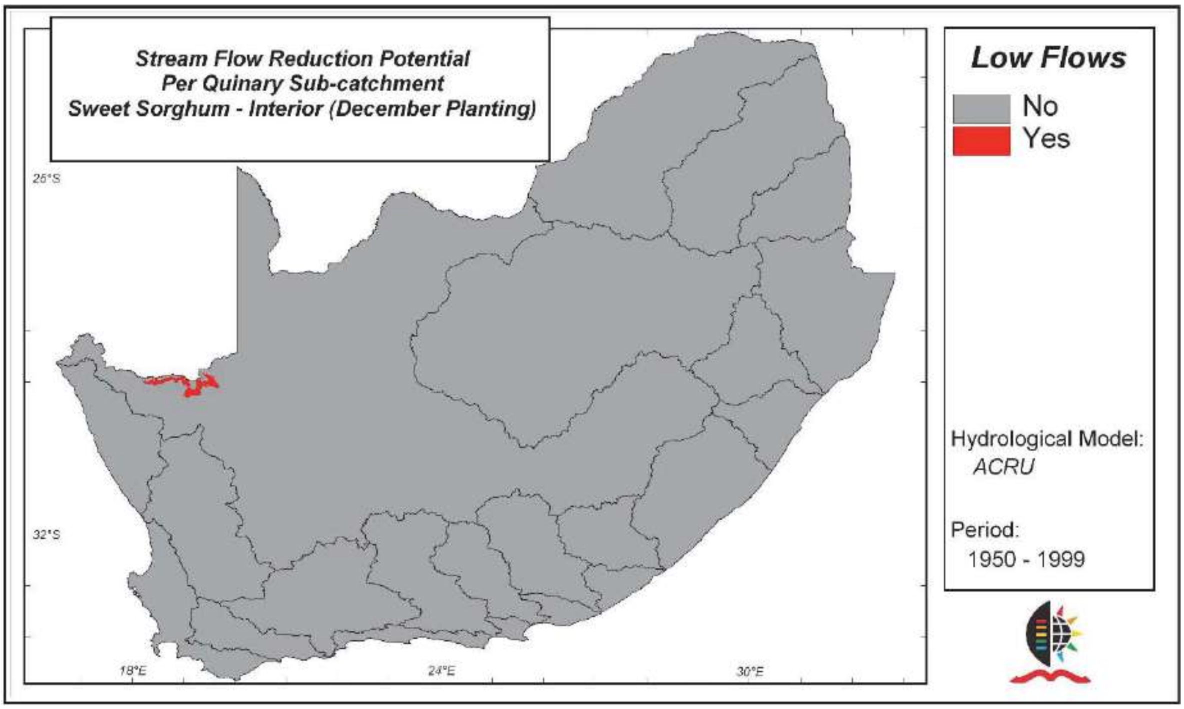
(c)


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sugarbeet (September Planting)
Low Flows
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(d)

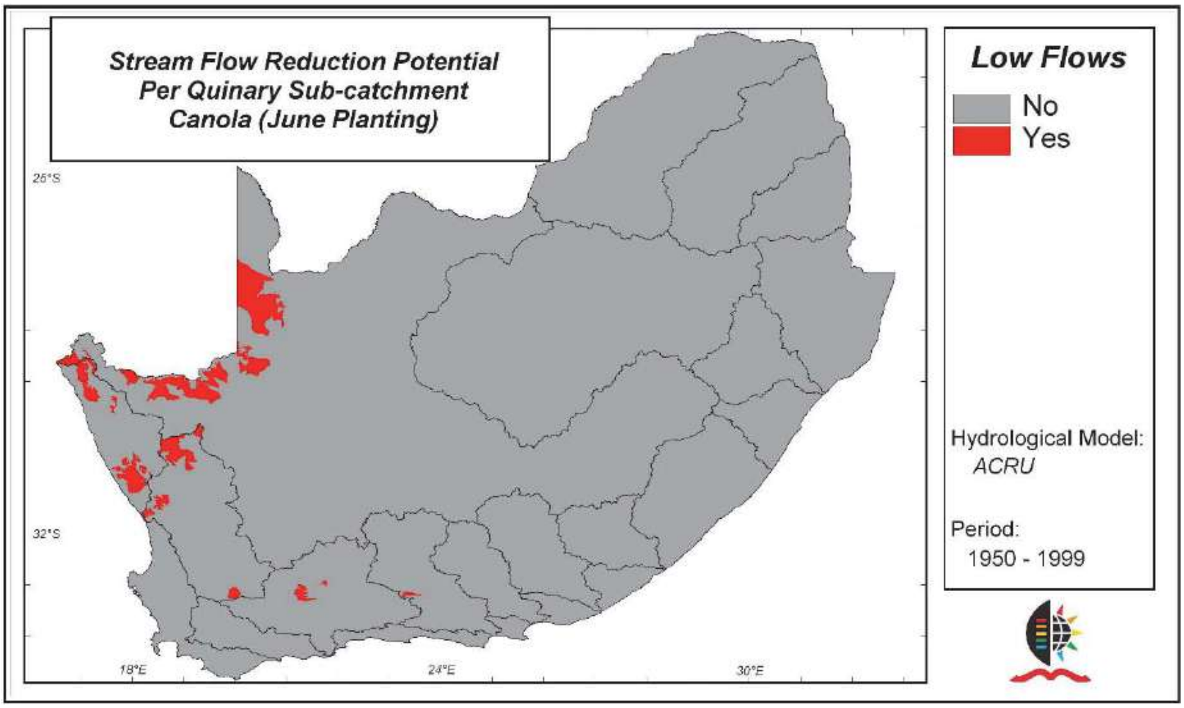

Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sugarbeet (June Planting)
Low Flows
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
26°S
32°S
18°E
24°E
30°E

(e)

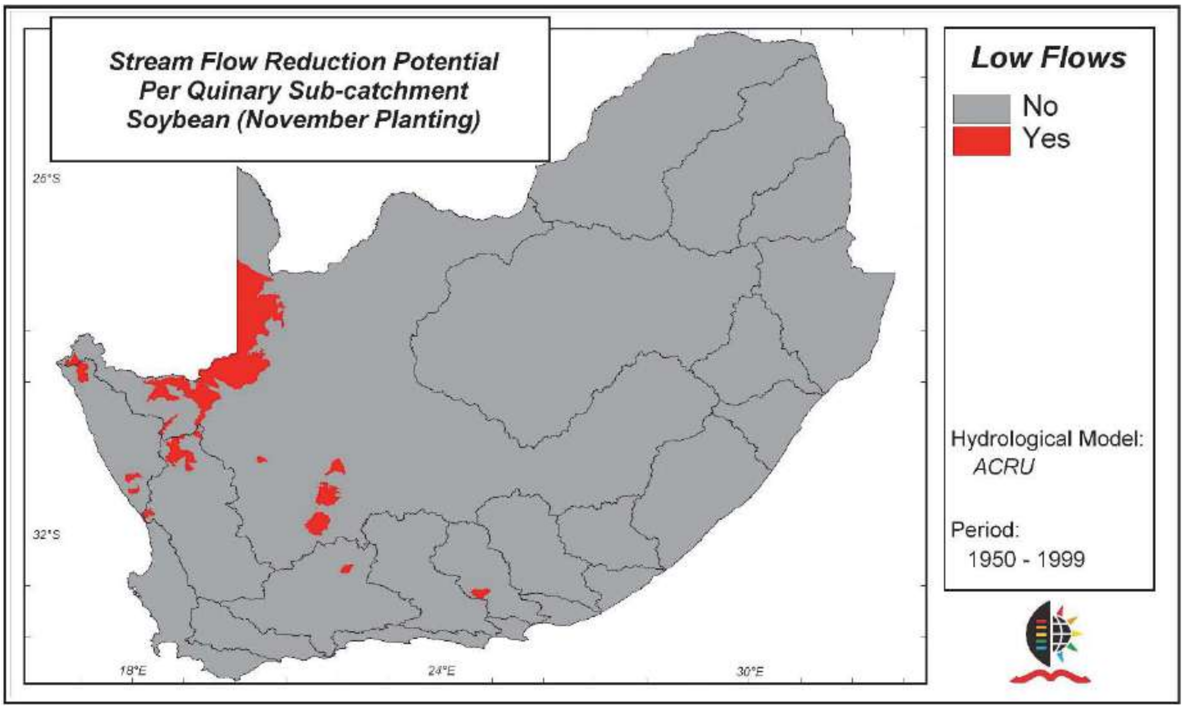


(f)

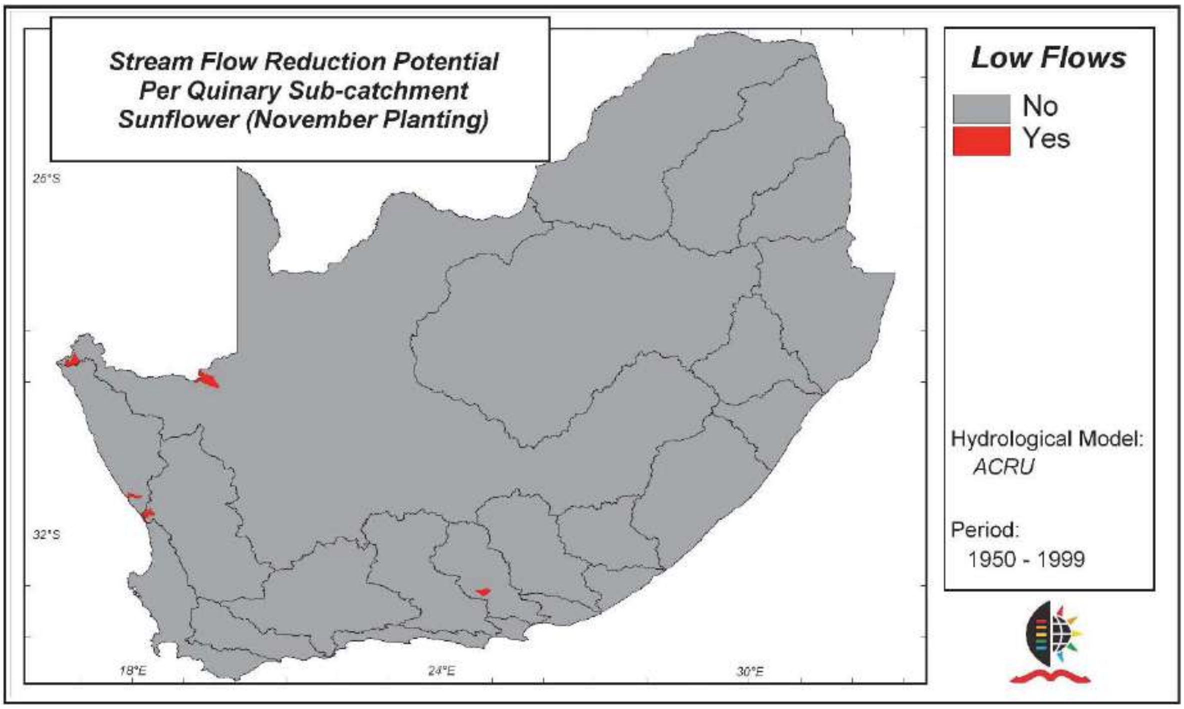
Figure 15 Sub-catchments in which the reduction in mean monthly low flows that results from a land use change from natural vegetation to a bioethanol feedstock is 25% or larger



(a)



(b)



(c)

Figure 16 Sub-catchments in which the reduction in mean monthly low flows that results from a land use change from natural vegetation to a biodiesel feedstock is 25% or larger

3.4.3.8 Shift in low flow period

In order to accumulate monthly runoff over the driest three months of the year, the start of the low flow quartile first needs to be determined. This was done using simulated mean (not median) monthly stream flows for the baseline land cover. The start month of the low flow period (i.e. driest quartile) is depicted in **Figure 17**.

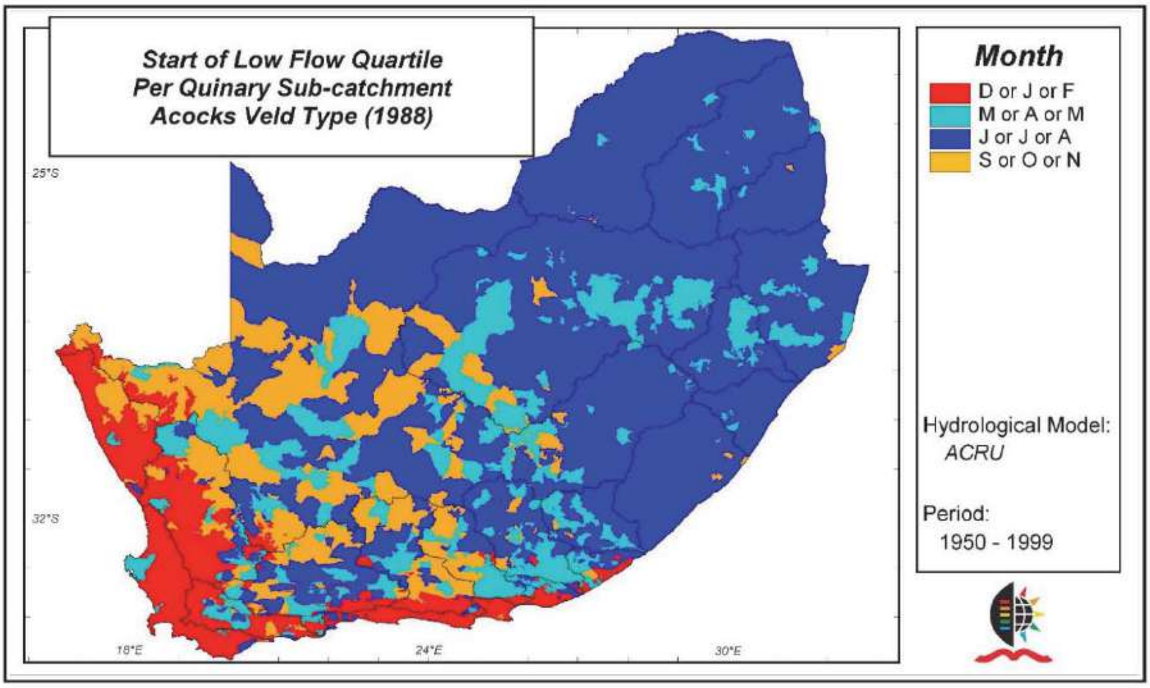


Figure 17 The first month of the low flow period, based on mean monthly stream flow simulated using the *ACRU* model for each quinary sub-catchment

For the early and mid-summer summer rainfall region (red and orange areas shown in **Figure 18**), the driest quartile typically starts in June or July or August (dark blue areas in **Figure 17**). Moving westwards across the country, the driest period starts in September or October or November. This roughly coincides with the late to very late summer rainfall region in **Figure 18**. Finally, the winter and all-year rainfall regions along the respective western and southern parts of the country largely overlap with the red areas in **Figure 17** (i.e. driest quartile starting in December or January or February).

Maps showing the first month of the low flow period for the selected bioethanol and biodiesel feedstocks are shown in **Figure 19** and **Figure 20** respectively. These maps were compared against **Figure 17** to determine if the start of the low flow quartile for the baseline, corresponded to that for each feedstock.

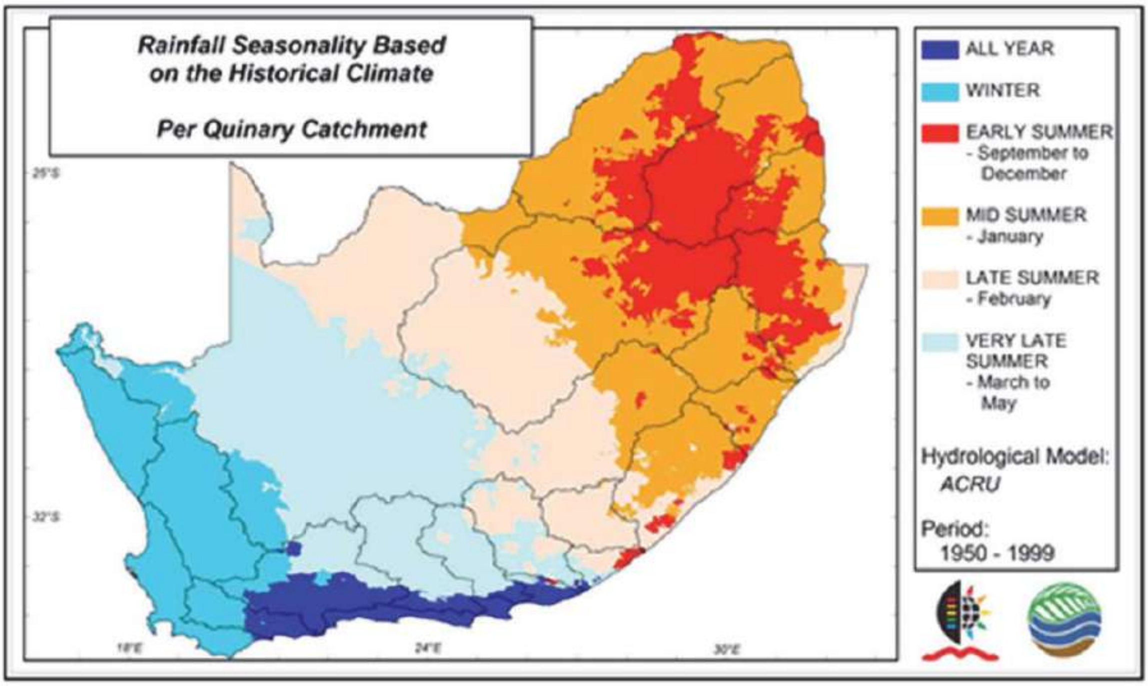
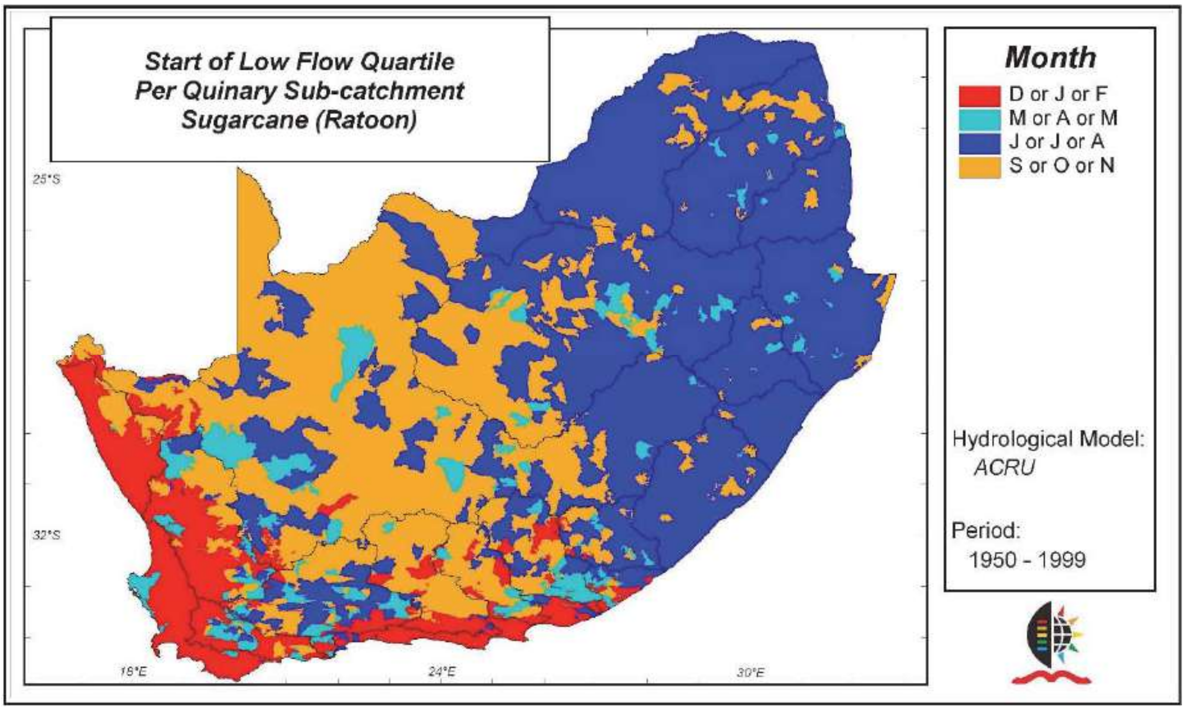
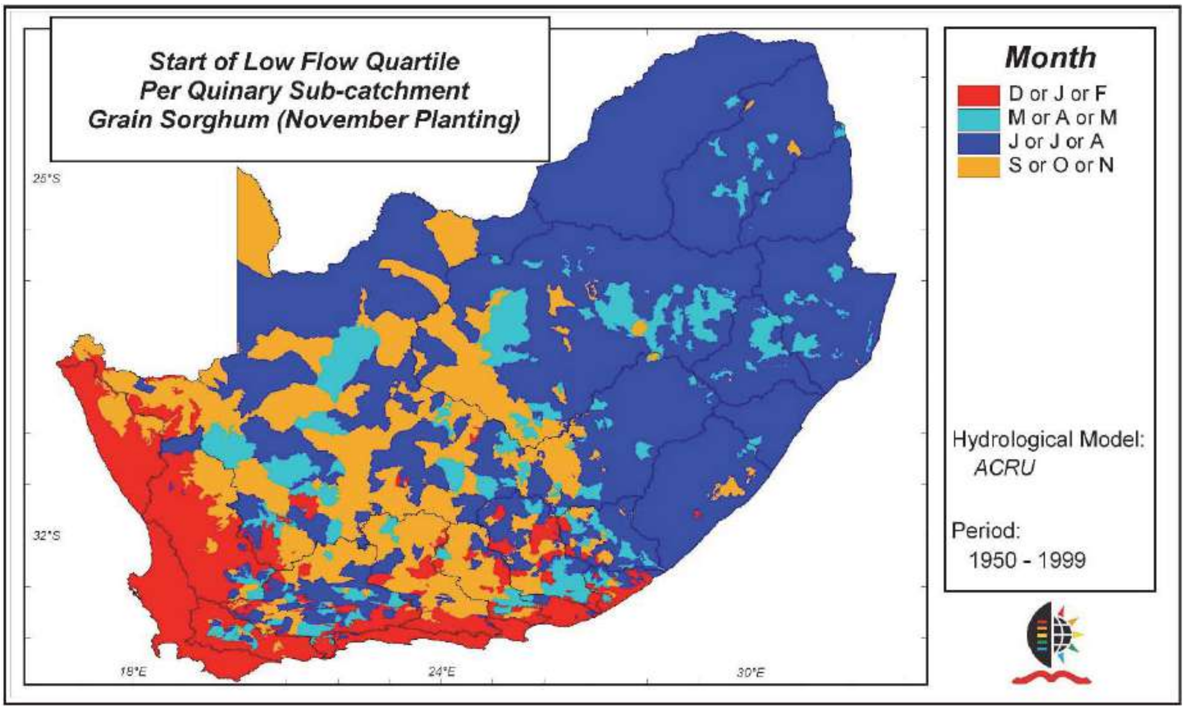


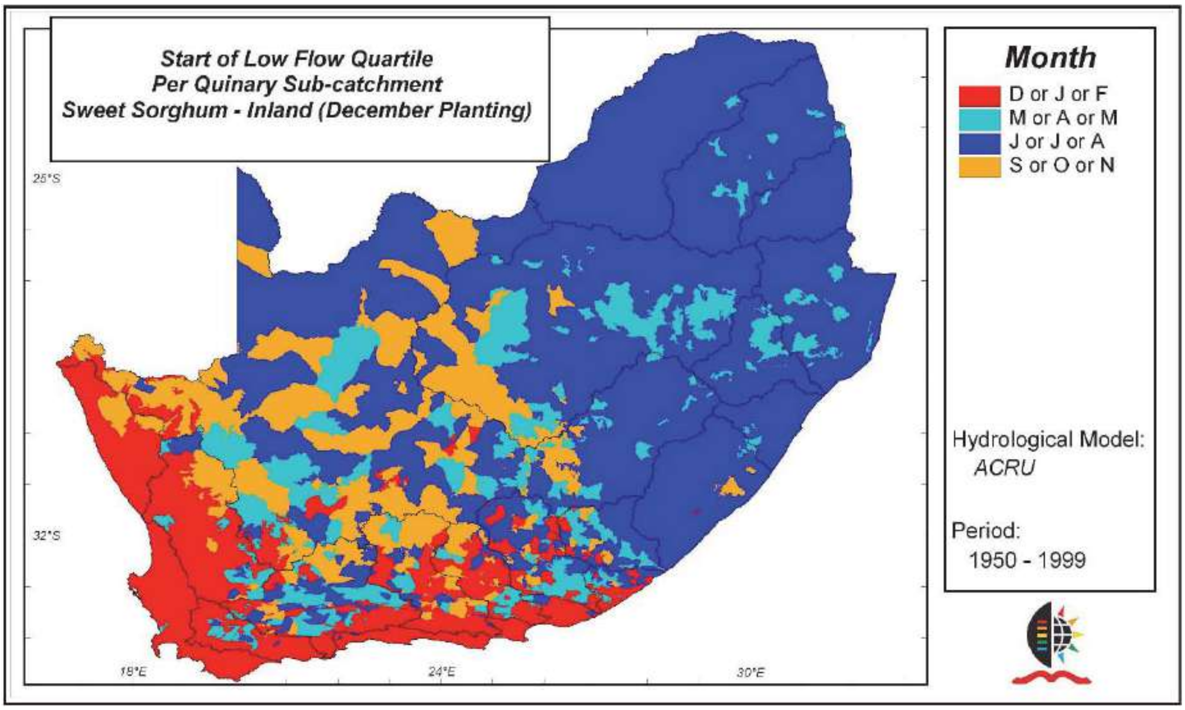
Figure 18 Rainfall seasonality classes over South Africa for the baseline (i.e. historical) climate (Schulze and Kunz, 2010a)



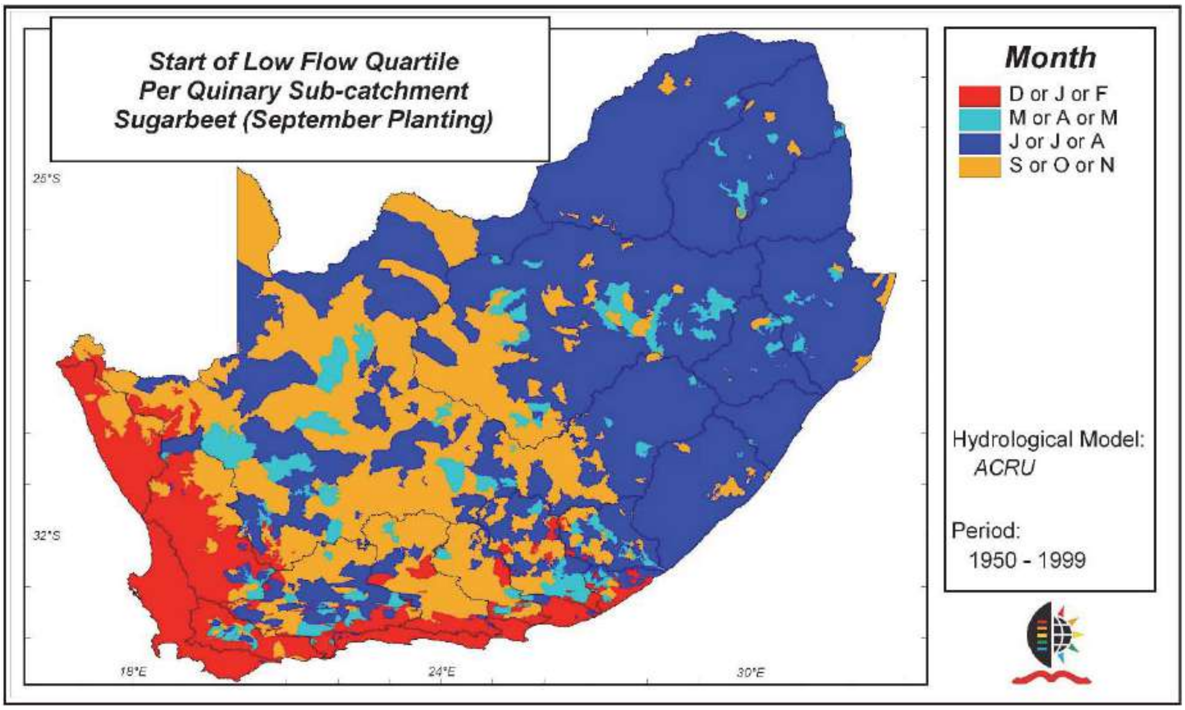
(a)


Start of Low Flow Quartile
Per Quinary Sub-catchment
Grain Sorghum (November Planting)
Month
D or J or F
M or A or M
J or J or A
S or O or N
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

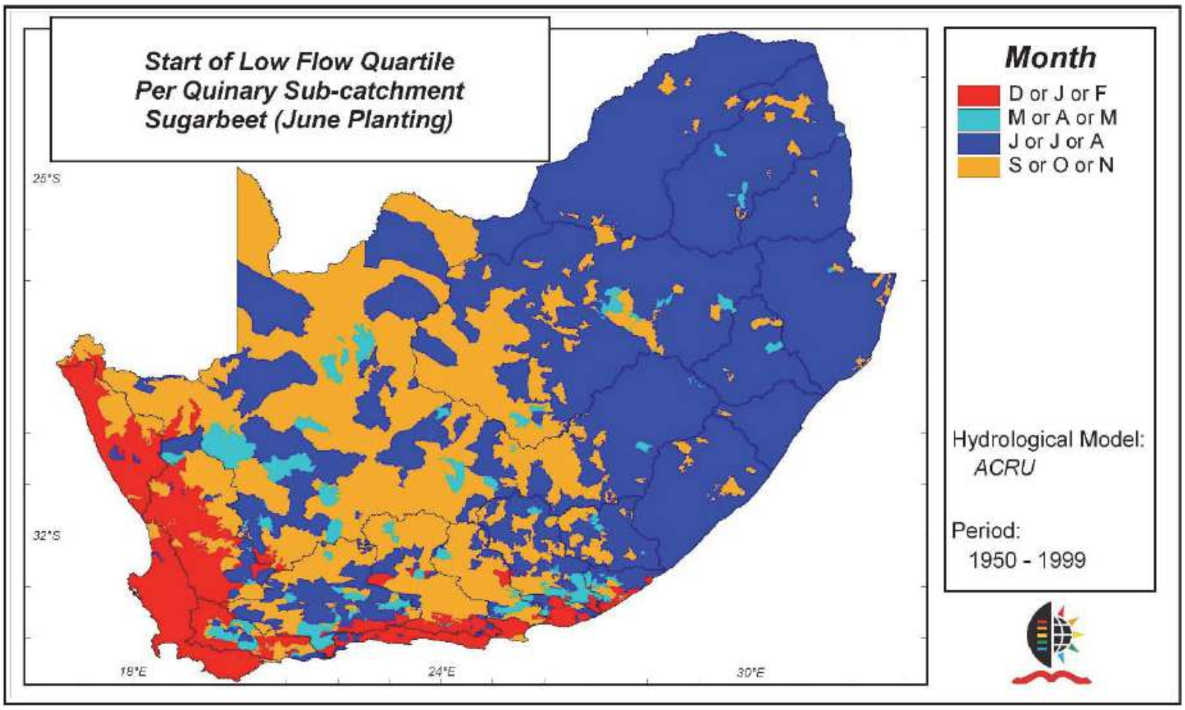
(b)


Start of Low Flow Quartile
Per Quinary Sub-catchment
Sweet Sorghum - Inland (December Planting)
Month
D or J or F
M or A or M
J or J or A
S or O or N
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

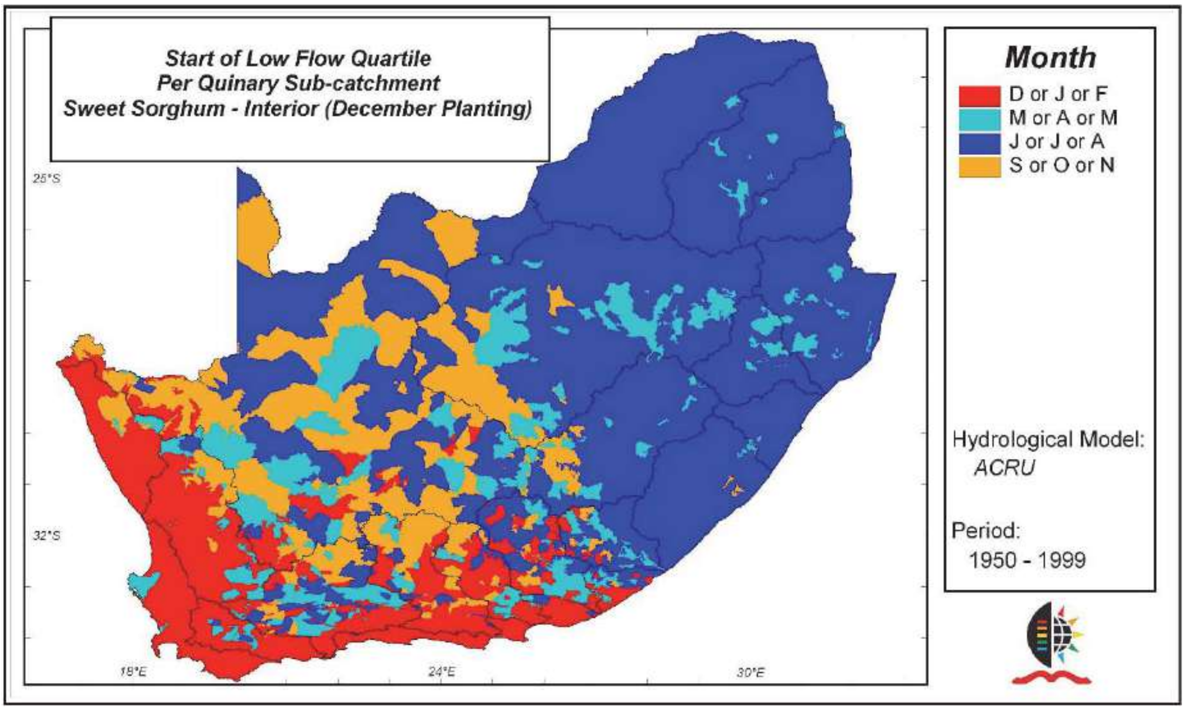
(c)


Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarbeet (September Planting)
Month
D or J or F
M or A or M
J or J or A
S or O or N
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

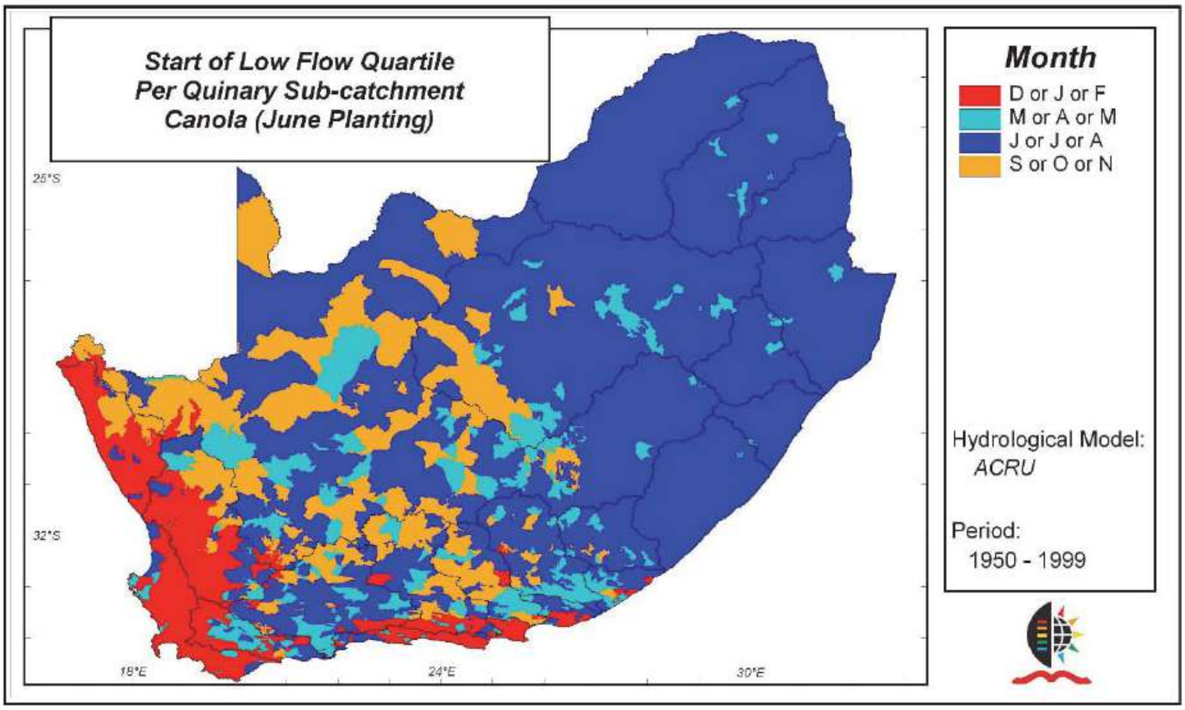

Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarbeet (June Planting)
Month
D or J or F
M or A or M
J or J or A
S or O or N
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(e)

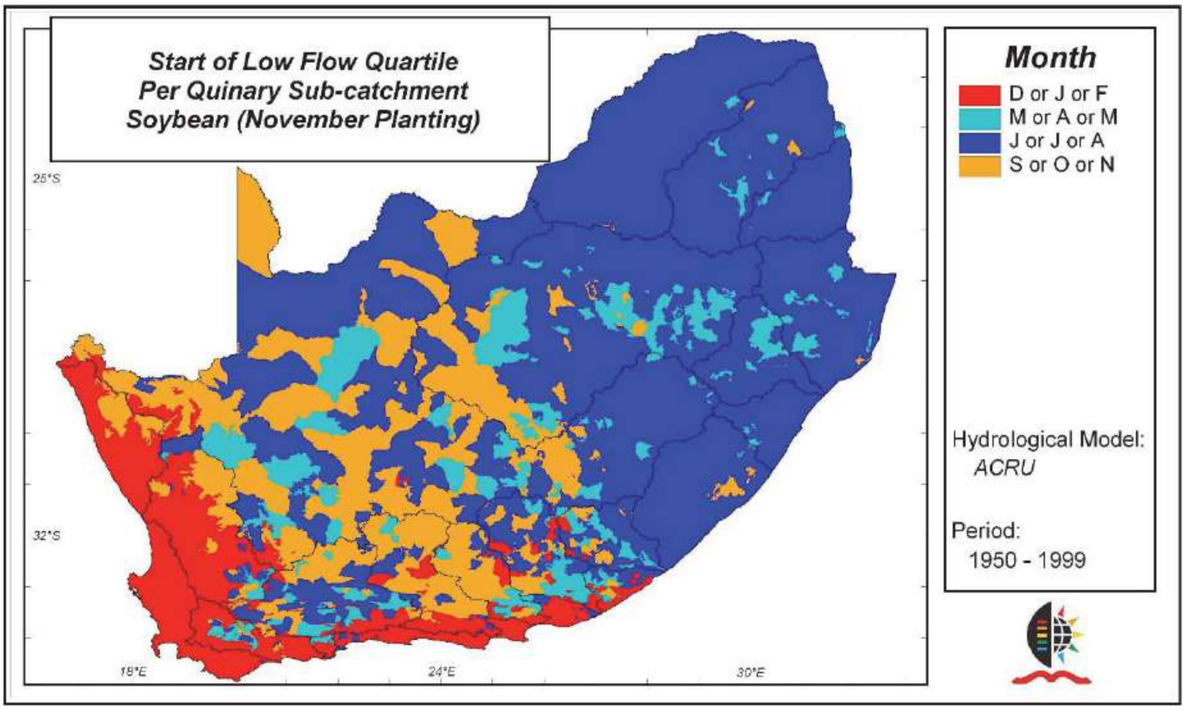


(f)

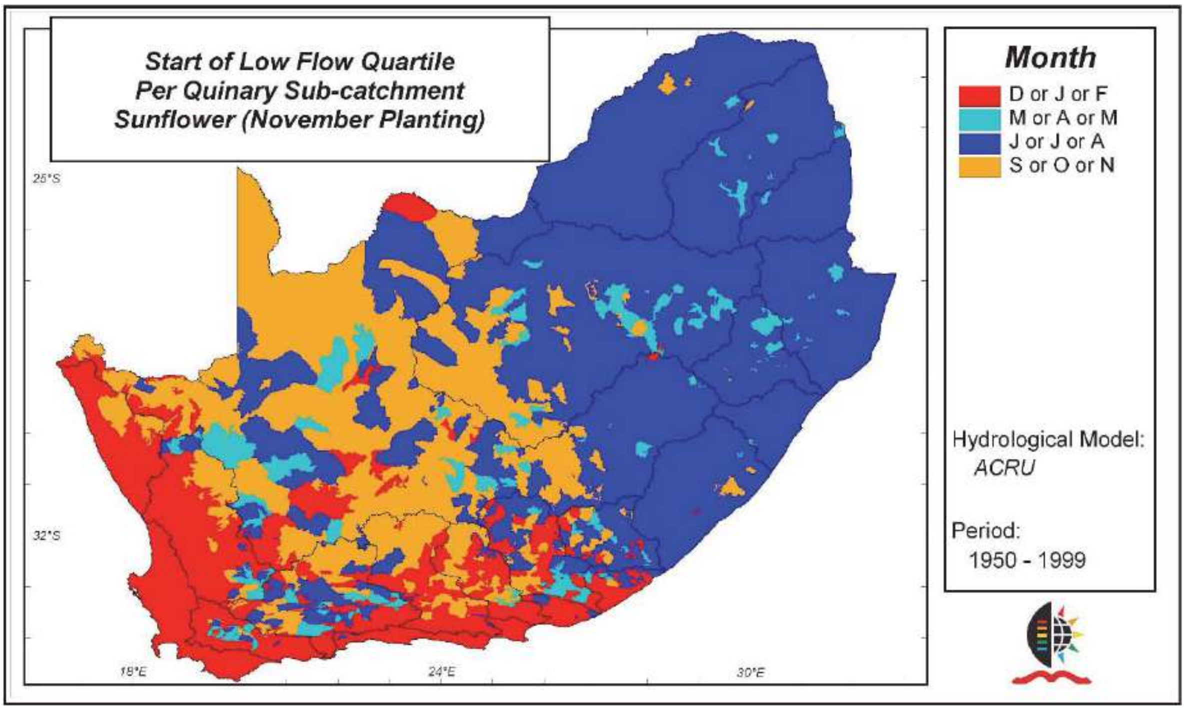
Figure 19 The first month of the low flow period for each bioethanol feedstock, based on mean monthly stream flow simulated using the *ACRU* model for each quinary sub-catchment



(a)



(b)



(c)

Figure 20 The first month of the low flow period for each biodiesel feedstock, based on mean monthly stream flow simulated using the *ACRU* model for each quinary sub-catchment

The results showed that for the majority of quinary catchments, a land use change to feedstock production should not cause a shift in the low flow period (green bars in **Figure 21**). However, it is interesting to note that, in some quinary sub-catchments and for all feedstocks considered, the start of the low flow periods does not coincide. For example, sugarcane (SCA) and winter sugarbeet (SBW) exhibit the highest potential of shifting the low flow quartile to later in the season (by up to 6 months). On the other hand, grain sorghum (GRS) and soybean (SYB) may cause the low flow period to occur earlier (i.e. sooner) in the season (by as much as 5 months).

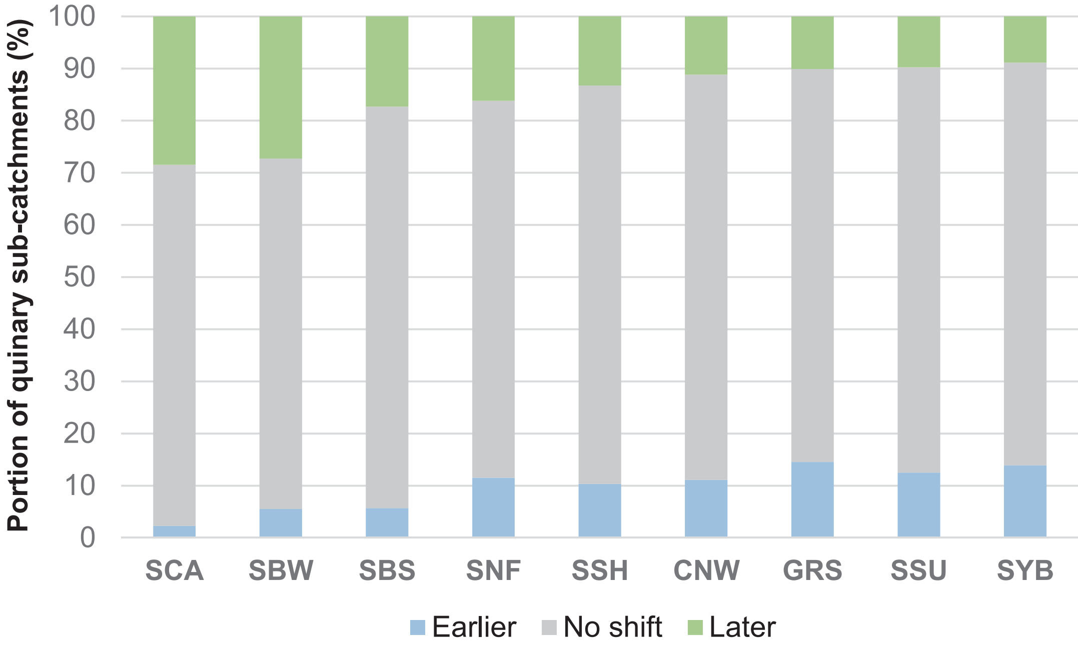
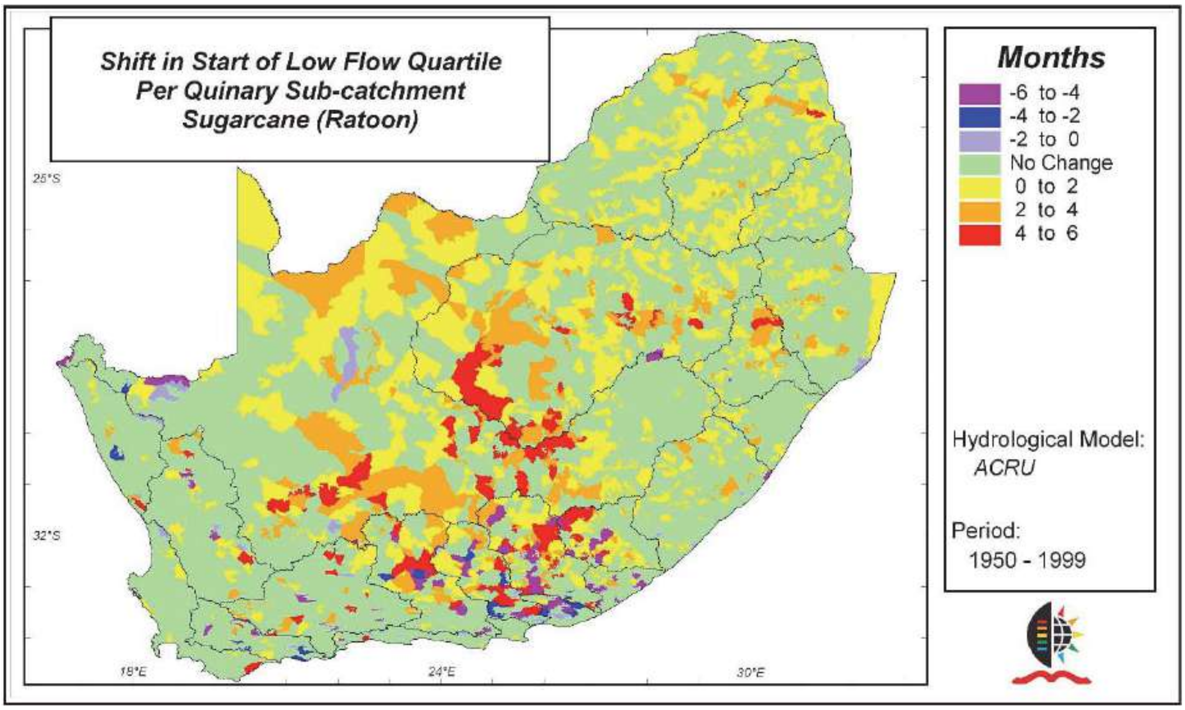


Figure 21 Possible shift in the low flow period that may result from a land use change to feedstock cultivation (SCA = sugarcane; SBW = winter sugarbeet; refer to **Table 8** for a list of all abbreviations)

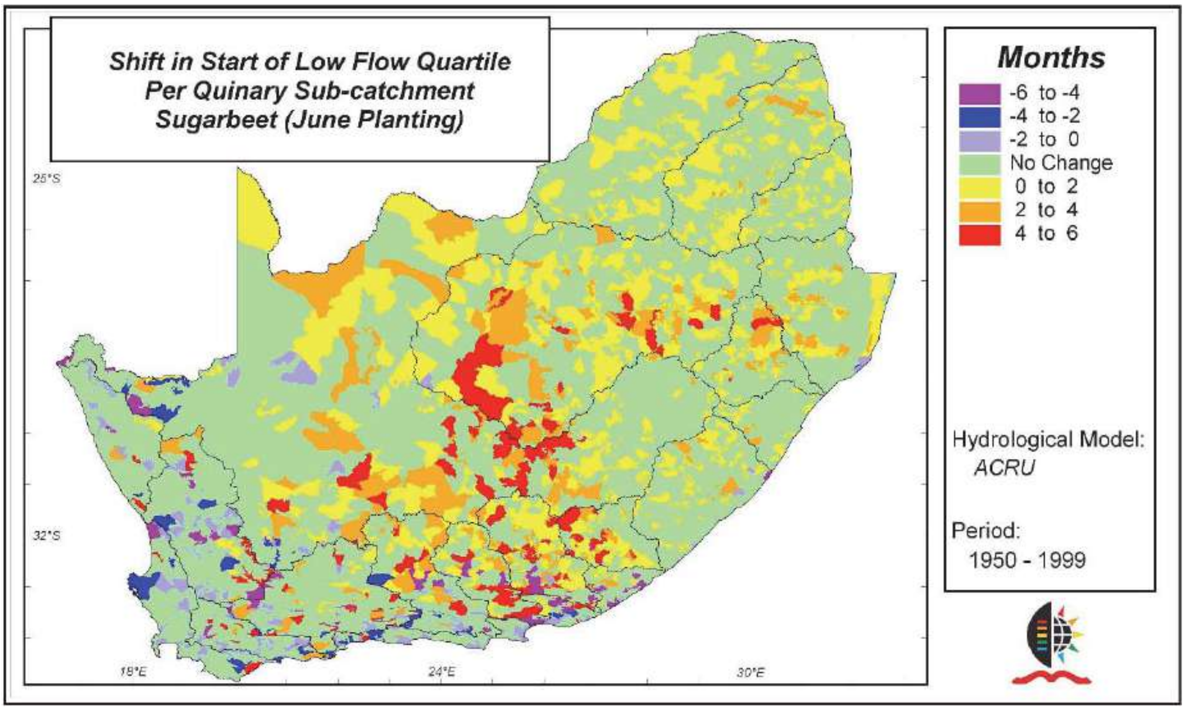
Maps showing the shift in the start of the low flow period for each feedstock (relative to the baseline) are given in **Figure 22** and **Figure 23**. The maps are presented in order of the feedstock's ability to cause a delayed shift in the start of the low flow period (as indicated in **Figure 21**). For sugarcane, a delay of up to two months was simulated for most of the early- to mid-summer rainfall region (as shown in **Figure 18**). For the majority of feedstocks, the low flow period may start up to 6 months later for sub-catchments located in the late- to very-late summer rainfall region.

The above analysis raises a question as to what constitutes the correct method of determining the 3-month low flow period. In other words, should the monthly stream flows for the baseline be used to determine the start month (i.e. **Figure 17**) or the monthly stream flows for the proposed land use (i.e. **Figure 19** or **Figure 20**)? This decision will impact the outcome of whether or not the feedstock should be declared a SFRA based on the impact on low flows.



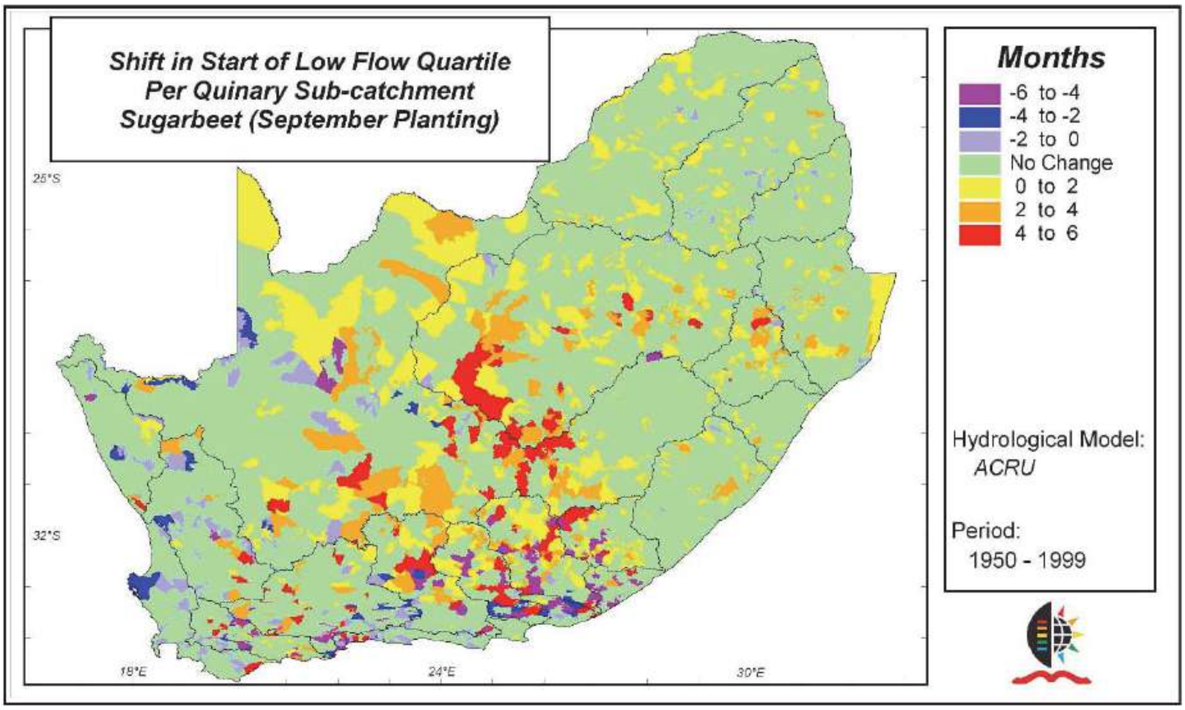
Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarcane (Ratoon)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)

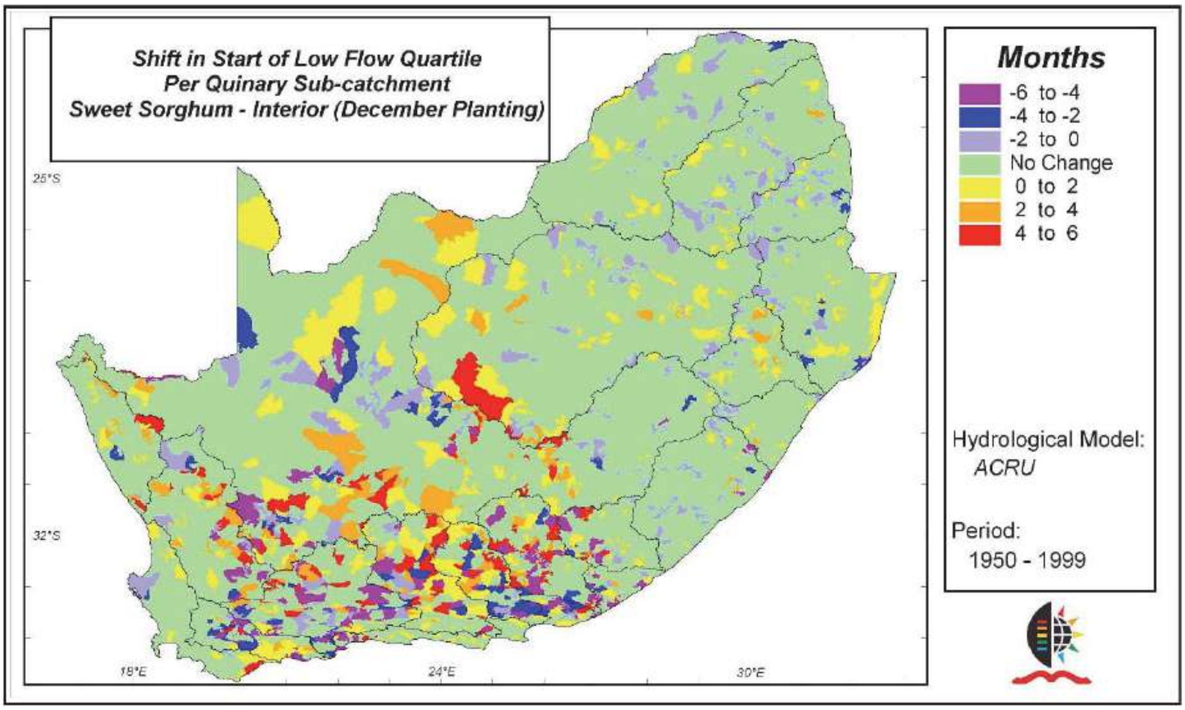


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarbeet (June Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

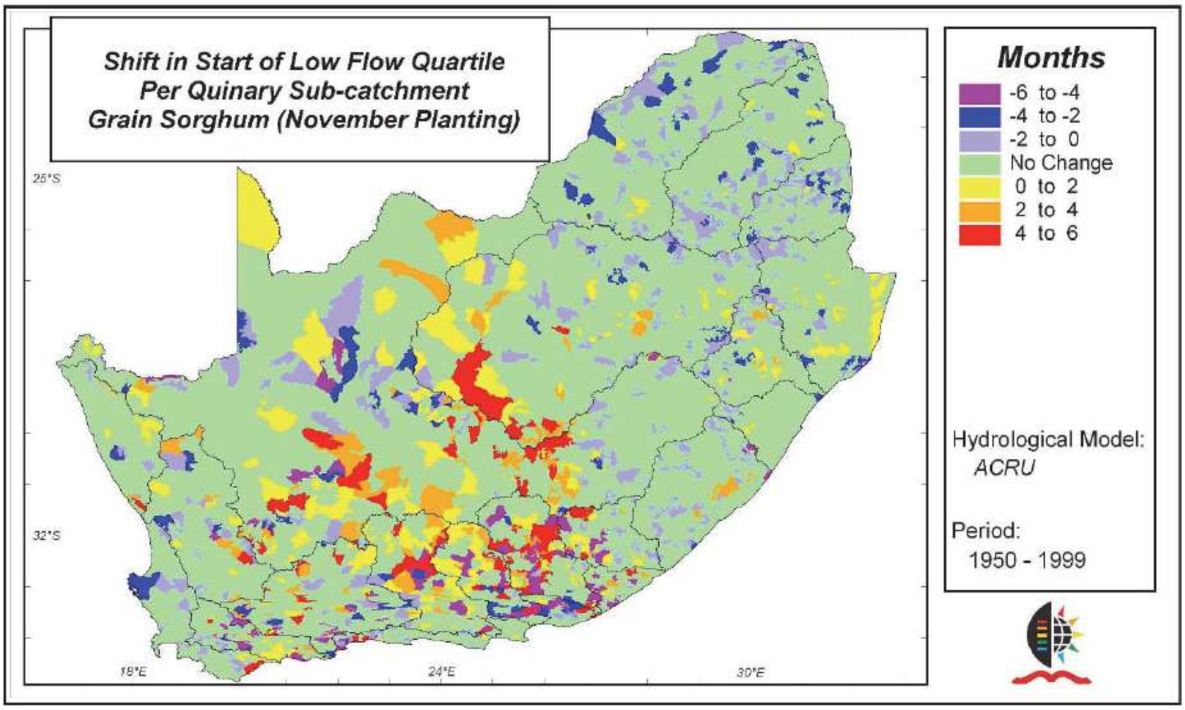
(b)


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarbeet (September Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

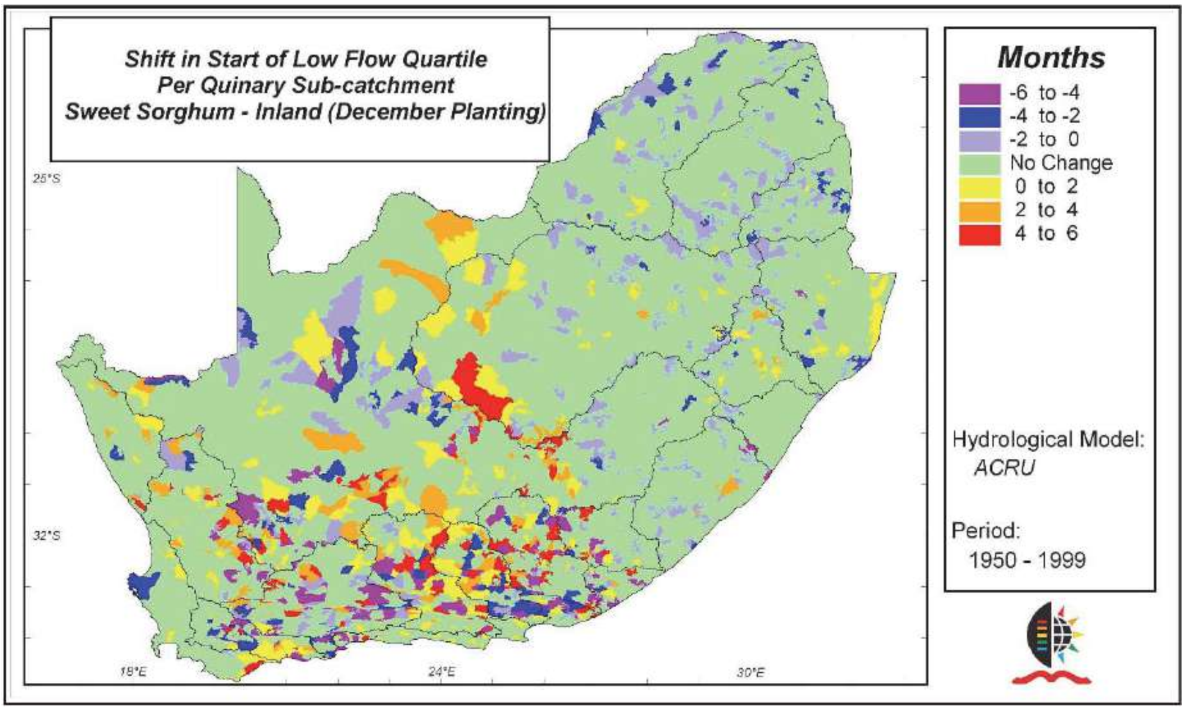
(c)


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sweet Sorghum - Interior (December Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

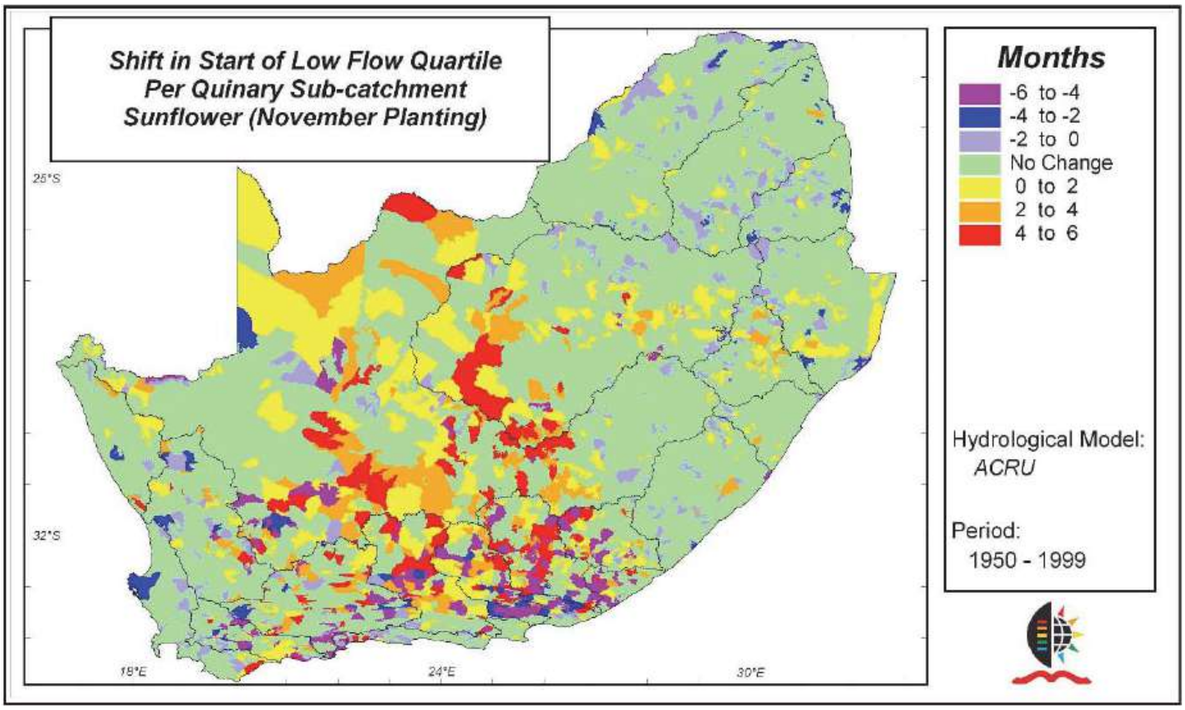


(e)

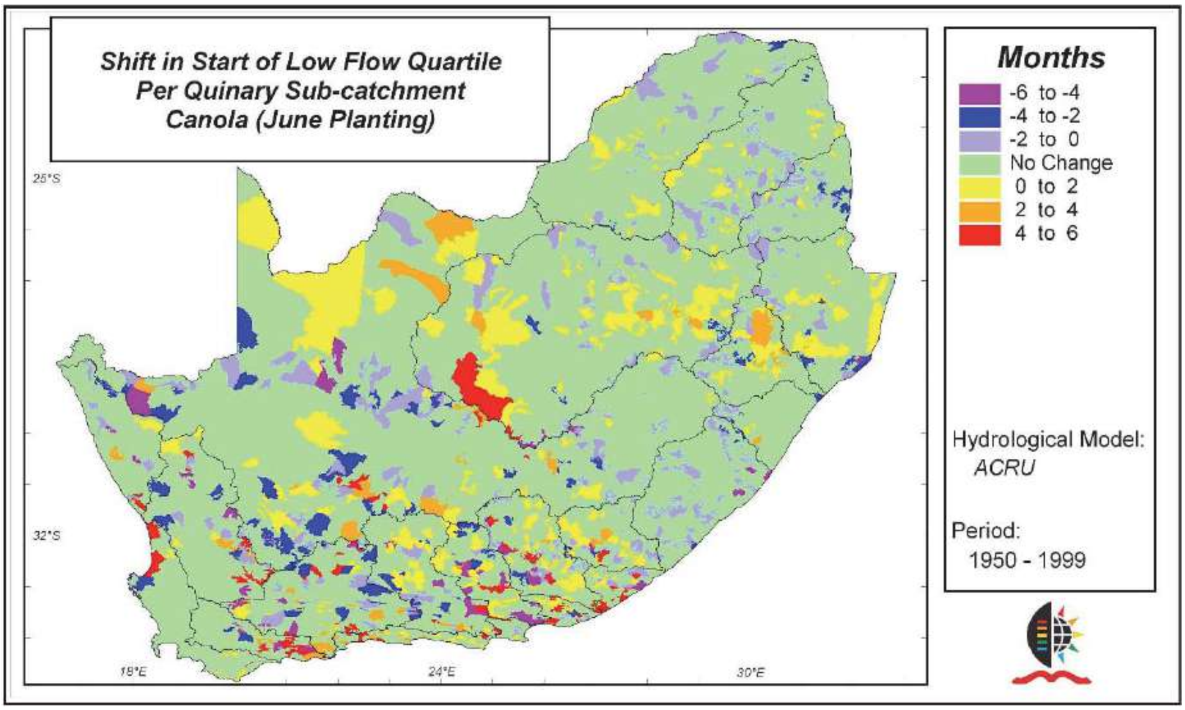


(f)

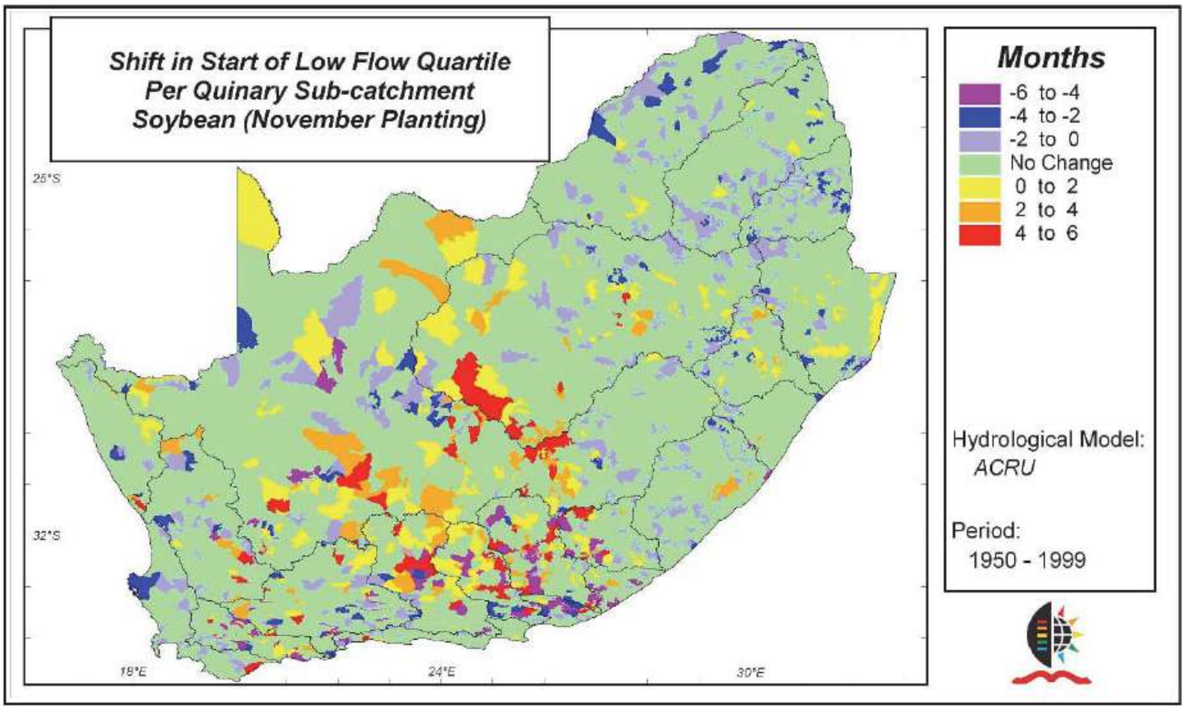
Figure 22 Possible shift in the start of the low flow period (i.e. driest three months of the year) relative to the baseline, for selected bioethanol feedstocks


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sunflower (November Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Canola (June Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



(c)

Figure 23 Possible shift in the start of the low flow period (i.e. driest three months of the year) relative to the baseline, for selected biodiesel feedstocks

3.4.3.9 Declaration of SFRAs

The previous three sections (c.f. **Section 3.4.3.6** to **Section 3.4.3.8**) indicated that a change in land use from natural vegetation to feedstock cultivation may result in the following impacts:

- a reduction in annual runoff of 10% or more, and/or
- a reduction in low flow runoff of 25% or more, and/or
- a shift in the start of the low flow period.

It must be noted that far fewer quinaries are flagged as potential stream flow reduction areas when low flows are considered. For example, a land use change to sugarcane may reduce annual runoff production by more than 10% in a total of 3 187 quinary sub-catchments (**Table 7**). Of these, only 210 also exhibit a 25% reduction in low flow runoff (LFR; i.e. driest 3 months). Hence, 2 977 sub-catchments do not experience significantly less runoff in the three driest months (**Table 7**). This may indicate that the 25% threshold used for the low flow period is somewhat conservative.

Only DWS have the authority to declare a crop a SFRA. They should base this decision on the research output from this project. The figures in the table below (**Table 8**) correspond to quinaries in which a:

- "significant" (i.e. ≥ 25%) reduction in low flow (i.e. 3-month accumulated) stream flow may occur, and
- "significant" (i.e. ≥ 10%) reduction in MAR may also occur, together with a
- possible shift in the low flow quartile.

Table 7 Portion of quinary sub-catchments in which a significant reduction in only mean annual runoff (MAR) occurs, together with a significant reduction in low flow runoff (LFR)

Feedstock	MAR ≥ 10% only		MAR ≥ 10% and LFR ≥ 25%		LFR ≥ 25% only		Total	
	No.	%	No.	%	No.	%	No.	%
Sugarcane	2 977	93.4	210	6.6	0	0.0	3 187	100.0
Grain sorghum	2 376	98.1	47	1.9	17	0.7	2 440	100.0
Soybean	1 314	97.5	34	2.5	9	0.7	1 357	100.0
Sweet sorghum - inland	1 233	97.6	30	2.4	7	0.6	1 270	100.0
Sugarbeet - summer	537	95.7	24	4.2	4	0.7	565	100.0
Sunflower	295	99.0	3	1.0	4	1.3	302	100.0
Sweet sorghum - interior	225	98.7	3	1.3	0	0.0	228	100.0
Canola	56	70.0	24	22.4	27	25.2	107	100.0
Sugarbeet - winter	23	85.2	4	9.5	15	35.7	42	100.0

Thus, the cultivation of feedstock in these quinaries should be considered carefully because there is both a reduction in generated runoff as well as a shift in the start of the low flow period. The table also highlights another issue in that a 25% (or more) runoff reduction in the low flow period does not necessarily mean that the mean annual runoff is reduced by ≥ 10%. For example, 27 (i.e. 51 - 24) quinaries show a significant reduction in the low flow period, but not in the annual runoff for winter canola. This “anomaly” can occur when the monthly runoff totals are very low, which results in a high relative difference. Thus, the 25% threshold for the low flow period should not be considered on its own to identify potential SFRAs (i.e. the MAR ≥ 10% “filter” should also be applied).

Table 8 For each feedstock, the number of quinaries where the relative reduction in low flow runoff is significant (≥ 25% only) and the mean annual runoff is reduced by more than 10%, together with a shift in the start month of the low flow period

Abbreviation	Feedstock	No. of quinaries		
		LFR ≥ 25% only	and MAR ≥ 10%	and shift
SSH	Sweet sorghum - interior	3	3	0
SNF	Sunflower	7	3	1
SBW	Sugarbeet - winter	19	4	3
CNW	Canola - winter	51	24	6
SBS	Sugarbeet - summer	28	24	9
SSU	Sweet sorghum - inland	37	30	12
SYB	Soybean	43	34	12
GRS	Grain sorghum	64	47	15
SCA	Sugarcane	210	210	46