Chapter 3
Assessing Hydrological Impacts of Tree-based Bioenergy Feedstock

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3.1 Introduction

This chapter provides a methodology for assessing the hydrological impacts of tree-based bioenergy feedstock. Based on experience gained in South Africa, it discusses the tasks required to reach an understanding of the likely water resource impacts associated with the development of a tree-based bioenergy industry, from individual tree water use rates to national-scale impacts on water resources. It is intended to be a generic methodology not just for South Africa but with more general applicability to tree-based bioenergy developments worldwide. Why is such a methodology important? Firstly, because large-scale changes in land-use (e.g. changes from existing vegetation to future bioenergy feedstock plantations) constitute a change in plant species, and consequently a change in the structure and functioning of the vegetation growing on the land. This has implications in terms of how different vegetation types use water, and how changing patterns and amounts of water-use impact the availability of water in rivers, and the resultant downstream users of that water. Secondly, there may be legal requirements specific to a particular country for determining the water resource impacts of a proposed future land-use. Finally, the growing importance of sustainable, integrated water resource management is acknowledged globally, and proven methods that strive towards this end, through the quantification of land-use driven water resources impacts, are increasingly required.

3.2 Streamflow Reductions

When considering the implications of different vegetative land-use types on water resources in general, and streamflow in particular, it is useful to refer to the concepts of 'blue' and 'green' water (Falkenmark et al. 1999). 'Green water' generally represents water supplied by rainfall that is lost from a system (e.g. a catchment area) in gaseous form (evapotranspiration), while 'blue water' represents water losses in liquid form (streamflow and groundwater recharge). One caveat is that evapotranspiration only equates to 'green water' use if no irrigation takes place. If crops or trees are irrigated then a component of 'blue water' is incorporated in evapotranspiration amounts, the use of which is dependent upon evaporative demand and the availability of adequate green water for the plant. More recently, the concepts of 'virtual water' (Allan 1998) and the 'water footprint' of a crop or nation (Hoekstra and Hung 2002) have gained popularity, accounting for all forms of water-use that contribute to the production of goods and services associated with a particular crop. Evapotranspiration of that crop is usually the single greatest contributor to its 'water footprint'. This terminology consequently emphasises the importance of evaporative (water-use) losses from land surfaces, particularly in dry countries such as South Africa, where evapotranspiration from vegetation accounts for the greatest loss of water from catchments. Accurate estimates of 'green water'-use are therefore fundamental for gaining a good understanding of the hydrological impacts of a specific plant species or vegetation type. Where large-scale changes in vegetation cover are proposed, this aspect becomes particularly important because the differences in evapotranspiration ('green water' use) between the current and the proposed vegetation ultimately translate into changes in available streamflow ('blue water') from that catchment. Stream-flow changes associated with vegetative land-use changes may consequently be calculated using a simplified water balance equation, namely:

$$Q = P - Et$$

where Q = streamflow, P = precipitation and Et = evapotranspiration. This simplified version of the equation is best applied over a suitably long time period (e.g. several years), where changes in soil water storage / ground water levels are likely to balance out, and longer term climate change impacts will not be detectable. A change in Et (caused by a change from the natural vegetation to a bioenergy feedstock plantation for example) will consequently equate to a change in stream-flow from that catchment or hydrological response unit (HRU) (Figure 3.1). Consequently, large-scale changes in land use could have significant hydrological implications if the water use of the introduced species were significantly different to that of the vegetation it would replace.

3.3 Legislative Framework

In South Africa, a robust and scientifically defendable methodology for assessing the hydrological impacts of land-use/vegetation changes is a legal requirement, established in the Water Act of 1998 (NWA 1998). Section 36 of the Act calls for a means of assessing whether an activity (in this case the establishment and growth of bioenergy feedstock) would constitute a "Streamflow Reduction Activity" (SFRA). The Act defines a SFRA as any activity "that is likely to reduce the availability of water in a watercourse to the Reserve[8], to meet international obligations, or to other water users significantly."

By means of clarification, in section 36 the Act states that: "in making a decision [about declaring an SFRA] the Minister must consider:

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[8] The "Reserve" refers to both a Basic Human Needs Reserve and an Ecological Reserve. The former requires sufficient water to be present in rivers and streams to meet basic human needs such as for drinking, food preparation, health and hygiene. The Ecological Reserve refers to the quantity and quality of the water, required to maintain the resource in an ecologically healthy condition, and needs to be determined for all or part of any significant water resource such as rivers, streams, wetlands, lakes, estuaries and groundwater.

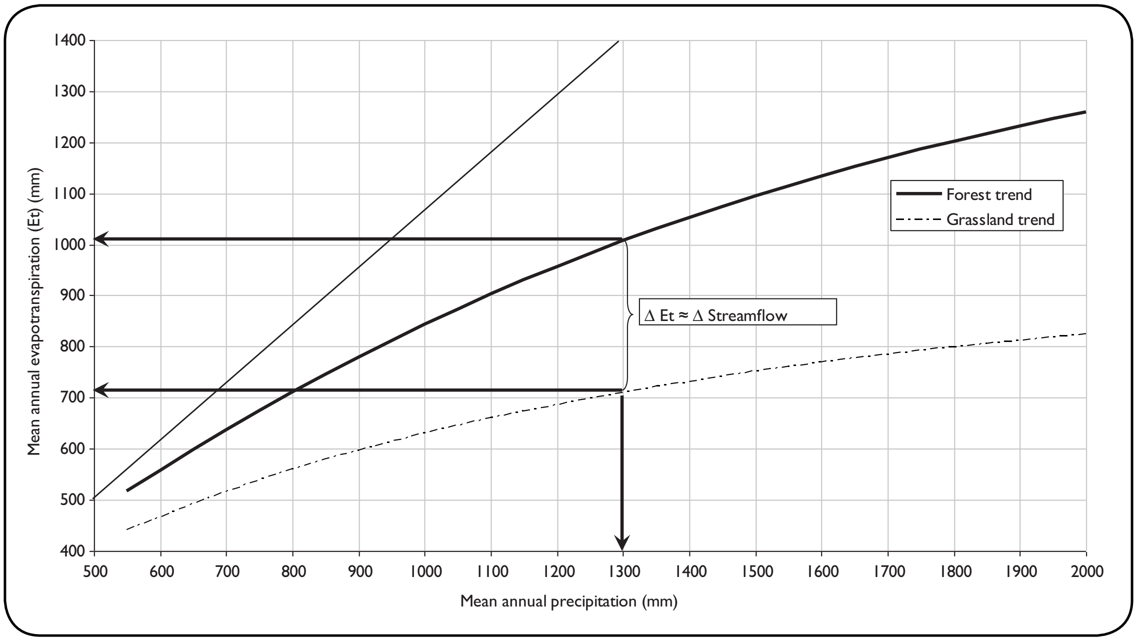


Figure 3.1: **The relationship between (MAP) mean annual precipitation and (MAE) mean annual evapotranspiration (Et) for different vegetation types. Lines indicate the global trends in mean annual evapotranspiration (MAP) from forested and grassland catchments (after Zhang et al. 1999). The effect on streamflow of differences in Et between grassland and forest sites for a given MAP are illustrated.**

a) The extent to which the activity significantly reduces the water availability in the watercourse;
b) The effect of stream flow reduction on the water resource in terms of its class and the Reserve;
c) The probable duration of the activity;
d) Any national water resource strategy;
e) Any catchment management strategy".

Implicit in the above explanation is the need to understand if a proposed activity (e.g. bioenergy plantation) will result in the consumptive use of water over and above what would be used by the "baseline" (natural) vegetation, thereby confirming it to be a streamflow reduction activity. The baseline vegetation represents the naturally occurring vegetation of the area of interest, and is used as reference against which all changes in land-use are assessed in terms of water-use impacts. The decision on whether a replacement land-use will constitute a streamflow reduction activity or not consequently requires knowledge of the water-use (evapotranspiration) of both the natural vegetation and the replacement vegetation. Importantly, the South African government (Dept. of Water Affairs) opposes irrigation of biofuel feedstock due to water and food security concerns, so water-use comparisons between rain-fed baseline vegetation types and replacement bioenergy crops (rain-fed) are valid.

This legal requirement to understand if a potential land-use change constitutes a streamflow reduction activity or not, is uniquely incorporated in South Africa's water law. This law has been lauded and acknowledged internationally for its progressive approach to environmental sustainability and equity, and other countries are increasingly identifying the need for similarly robust mechanisms of assessing the water resource impacts of potential future land-use changes. The methodology developed to meet the requirements of South Africa's water law is similarly of relevance worldwide, as it has the potential to influence future policy and the sustainable management of water in any country faced with water resource management challenges.

3.4 Methodology

Methodologies for assessing the spatial water resource impacts of potential future land-uses (e.g. tree-based bioenergy feedstock) have been developed since the new Water Act of 1998 was passed in South Africa. While approaches may differ slightly based on specific needs or preferences, they all have a fundamentally similar goal, and all require the fulfilment of a number of pre-determined steps. The means of successfully completing each step will vary depending on certain criteria (e.g. choice of plant species, availability of data, preference of model to be used, scale and time-frame), and these aspects are discussed in more detail later. Nevertheless, in terms of a broad overview of the methodology, the following tasks are suggested for a comprehensive assessment:

- Identify the geographical area of interest.
- Select an appropriate hydrological response unit (HRU) to apply the assessment at, within the area of interest.
- Identify the "baseline" vegetation for each HRU across the area of interest.
- Select an appropriate hydrological model to use.
- Gather the necessary model input data for each HRU.
- Determine the length of the simulation period.
- Decide on the most appropriate way to represent changes in vegetation parameters associated with physical plant growth.
- Run the model to simulate streamflow and evapotranspiration under baseline and future land use scenarios.
- Analyse the data to determine potential changes in evapotranspiration (and the resultant impacts on streamflow) associated with the replacement land-use.
- Draw conclusions on the likely water resource impacts of the proposed land-use.

These steps have been graphically represented by Kruger et al. (2000) for a typical South African example (Figure 3.2), and are elaborated upon in the following sections.

3.4.1 Identifying the geographical area of interest

The geographical area of interest may range in scale from farm-level plantations, to regional areas, and up to national scale assessments. For local scale development of limited extent, where an environmental impact assessment is required, the suitability of the site for cultivating the species has usually already been established as part of a business plan. However at larger scales (regional to national), the area of interest may be defined as climatically suitable areas where the proposed bioenergy species may successfully be cultivated. Determining viable production areas requires knowledge of the bio-climatic requirements of the species. These usually take the form of marginal, adequate or optimum requirements in terms of rainfall (amounts and seasonality), temperature, relative humidity, soils, frost days, solar radiation, slope and aspect, amongst others. The availability of adequate (i.e. high temporal and spatial resolution) data on climatic conditions across the potential land area being assessed are thus an important requirement. This enables the bio-climatic requirements of the species to be matched with the actual bio-climatic

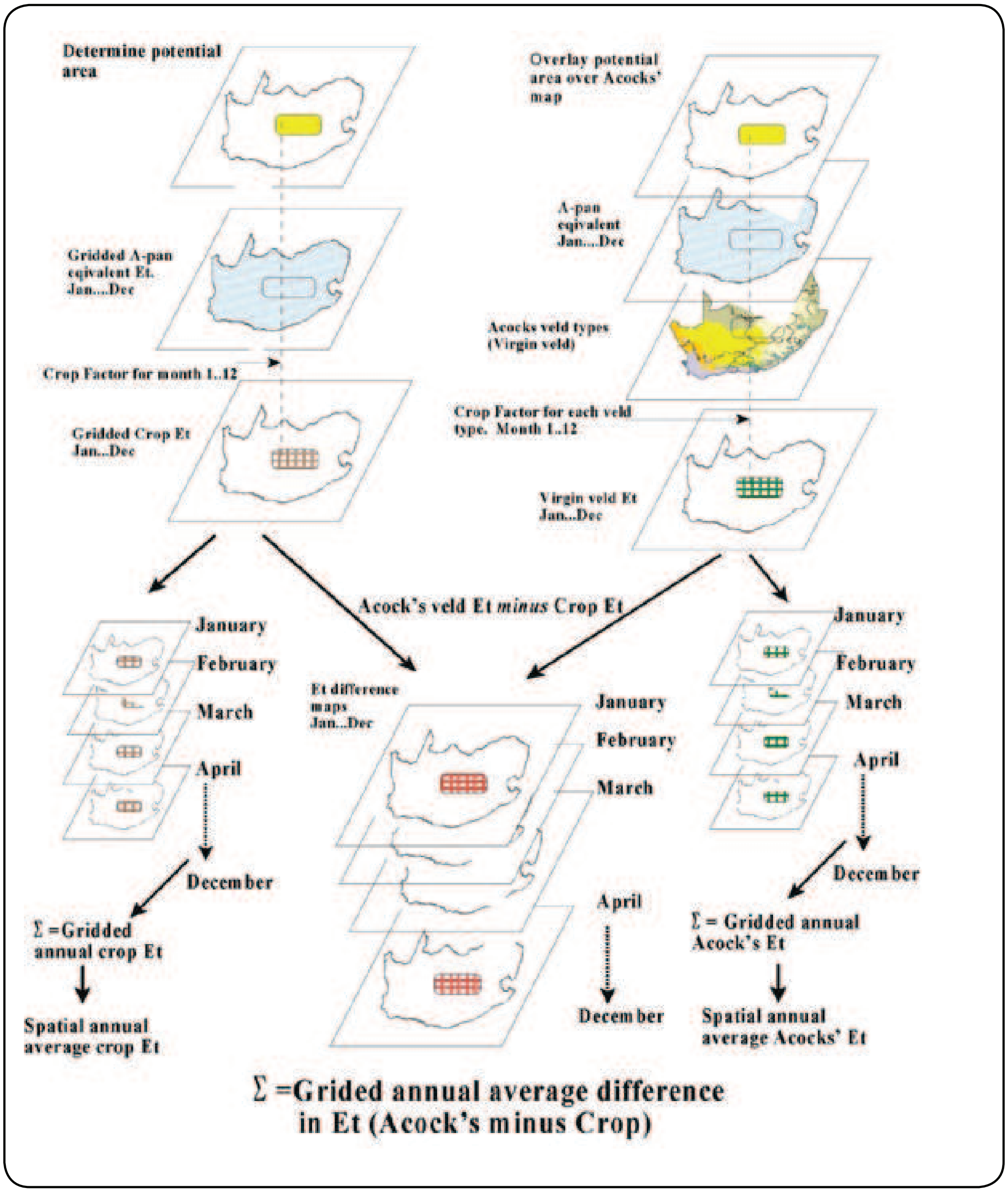


Figure 3.2: **Steps in the assessment of the potential water resource impacts of a proposed land-use by means of changes in evapotranspiration attributed to conversion of the "baseline" vegetation to a given crop across a geographical area of interest (after Kruger et al. 2000).**

conditions across the land, and areas suitable for cultivation may then be mapped. Consequently, the area of interest may initially be for the whole country (to ascertain where the species may successfully be cultivated), but is typically narrowed down to climatically (economically) viable areas only, using pre-determined cut-off values of the above bio-climatic variables. In terms of site quality, the sub-set of selected areas may then be classified as marginal, average or optimal growth areas, which also influence subsequent yield estimates.

3.4.2 Selecting an appropriate hydrological response unit

The scale at which hydrological impacts will be assessed (e.g. small scale / plantation size, or large-scale regional / national size) will determine the choice of an appropriate HRU. The more detailed the catchment and climate data available, the more detailed the water resource assessment that is possible (i.e. potential for using smaller HRUs). However the tradeoff between assessment detail (i.e. HRU scale) and computing / data analysis complexity needs to be borne in mind. Specific applications will have appropriate levels of detail. For national assessments, for example, the use of the Quaternary, and more recently the Quinary Catchment scale has been popular in South Africa, providing an adequate level of detail without undue complexity. Southern Africa has been delineated into 22 so-called Primary catchments (watersheds), and then subdivided into Secondary, Tertiary, Quaternary and now Quinary (Schulze and Horan 2007) sub-catchments. For each of these HRUs representative time-series of climatic variables (e.g. daily rainfall, reference potential evaporation, maximum and minimum temperature data), catchment attributes (e.g. area, mean altitude, MAP, latitude and longitude), soils attributes (e.g. type, texture and quality) and land cover attributes (e.g. vegetation characteristics) exist.

The development of these databases requires long-term investment and considerable research and extrapolation from observed data, but their existence greatly facilitates large-scale hydrological assessments. Southern African hydro-climatic databases have been developed/refined to the extent that wide-ranging and innovative agro-hydrological and water resources studies can now be undertaken (Schulze 2007). More regional or local-scale assessments may apply HRUs of smaller sizes, either relying on the existence of adequate observed data within each HRU or simply deriving the necessary data by means of downscaling from quinary catchment databases. Examples of the assessment of national scale hydrological impacts of commercial afforestation in South Africa are available at Quaternary (Gush et al. 2002) and Quinary (Jewitt et al. 2009) scales.

3.4.3 Identifying the baseline vegetation

The baseline vegetation type associated with each HRU represents the indigenous/ native vegetation that would have occurred in each HRU should the vegetation not have been anthropomorphically altered in any way. The determination of this baseline vegetation is critical for the assessment of streamflow impacts as it provides a platform for assessing any potential future land-use change. A number of aspects need to be considered when determining the baseline vegetation, such as which vegetation classification system is to be applied and whether data on the necessary input variables to represent the associated vegetation types are available. Assigning appropriate model input parameter values to vegetation types linked to a particular classification system is a significant task. Realistically it is only accomplished through a dedicated project, and is likely to be reliant on expert opinion; as observed vegetation parameters for all vegetation types represented in a particular classification system are unlikely to be available. Furthermore, verification studies of the resultant water-use rates are only likely to be available for a limited number of vegetation types. As vegetation classification systems are updated and become more spatially detailed so the challenge of assigning appropriate parameters to all vegetation types increases. The vegetation classification system that has been most extensively utilised in South Africa for hydrological modelling purposes is Acocks (1988), and representative model parameter values exist for all the vegetation types in this system. More recently, an updated and more detailed vegetation classification system for South Africa was produced by Mucina and Rutherford

(2006). However, vegetation characteristics appropriate for hydrological modelling purposes are not available for all the vegetation types in this latest classification system, so the earlier system of Acocks (1988) is generally utilised (Figure 3.3).

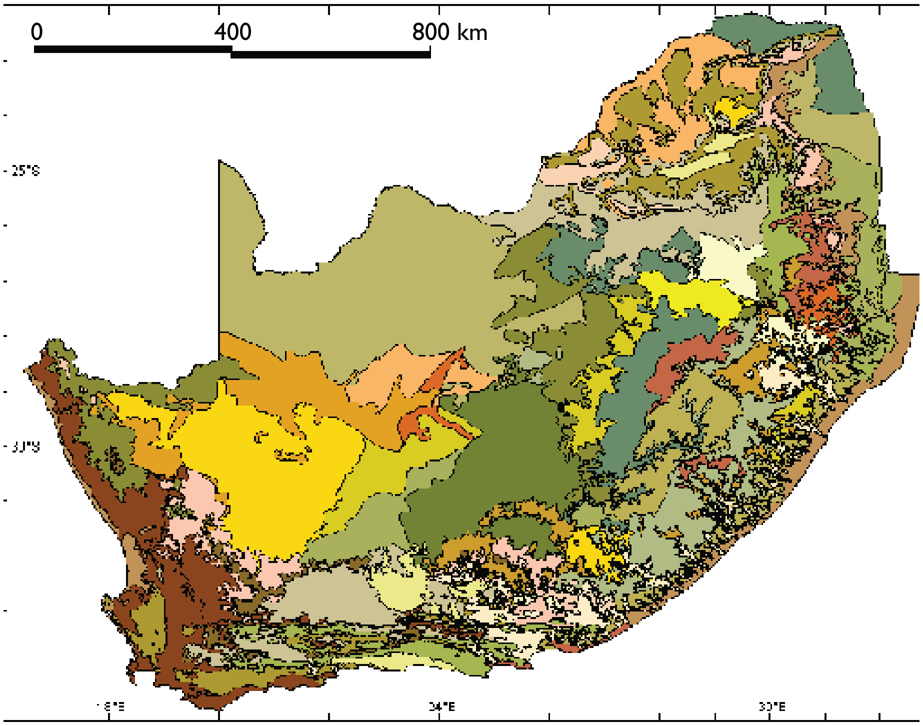
There is usually considerable uncertainty in the representativeness of the baseline vegetation type assigned to a particular HRU. This is a particular challenge when needing to assign a single spatially-representative type to large (e.g. quaternary catchment scale) HRUs. Inevitably, a pragmatic approach to the application of the baseline vegetation concept requires a certain degree of generalisation. An alternative approach, more suited to small scale assessments, is to utilise observed water-use (evapotranspiration) data for the predominant natural vegetation cover in the HRU, where such data is available. Examples of South African projects aimed at improving the prediction of evapotranspiration rates from natural vegetation types include Jarmain et al. (2004) and Dye et al. (2008). Either way, it is important that consensus be reached amongst stakeholders (see Chapter 2 for gaining stakeholder consensus in planning for sustainability) that the chosen vegetation types (and their associated model input data, and resultant water-use) are the best approximation/representation of the naturally occurring vegetation types within the HRU. The water-use of this vegetation is the basis by which the water resource impacts of future land-uses will be assessed.

3.4.4 Choice of model

The choice of an appropriate model to be used for the simulation of evapotranspiration and streamflow under baseline and future land-use scenarios is the next consideration. The choice of a particular model will depend upon a number of factors including: model availability, proven scientific credibility and application in hydrological assessments of vegetative land-use change studies, good documentation, a balance between simplicity and realism, applicability to a wide range of vegetation types, the availability of input data required by the model, the level of spatial representativeness required at the HRU level (e.g. lumped large-scale vs. spatially explicit fine-scale) and the time-scale required to operate at (e.g. daily vs. monthly). The chosen model may be locally or internationally developed, with strengths and weaknesses inherent in both options. A principal advantage of using a locally developed model is that its routines are customised to local conditions and locally available data. There is always a need to parameterise the chosen model for the location where it is being applied, and for locally developed models there is usually a history of aligned projects, such as determining suitably representative input parameter values and routines. This greatly facilitates the data collection exercise. For "off the shelf" internationally developed models, there may be a need to adjust existing local input data, or collect additional input data, in order to parameterise the model.

In South Africa, locally developed models that have been widely used for hydrological assessments include ACRU (Schulze 1995) and the Pitman model (Pitman 1973). There are numerous other hydrological models developed internationally, which have also been applied in South Africa, including SWAT (Arnold et al. 1999), FAO56 (Allen et al. 2004) and WAVES (Dawes and Short 1993). These models all require certain input data, usually comprising climate data, soils information and vegetation descriptors for the site under investigation. Vegetative land-use changes affect hydrological responses through canopy and litter interception, infiltration of rainfall into the soil and the rates of evaporation and transpiration of water from the soil. Consequently, the provision of appropriate input data required

Veld Types of South Africa
by J.P.H. Acocks



Vegetation map of South Africa
Mucina & Rutherford (eds.), 2006

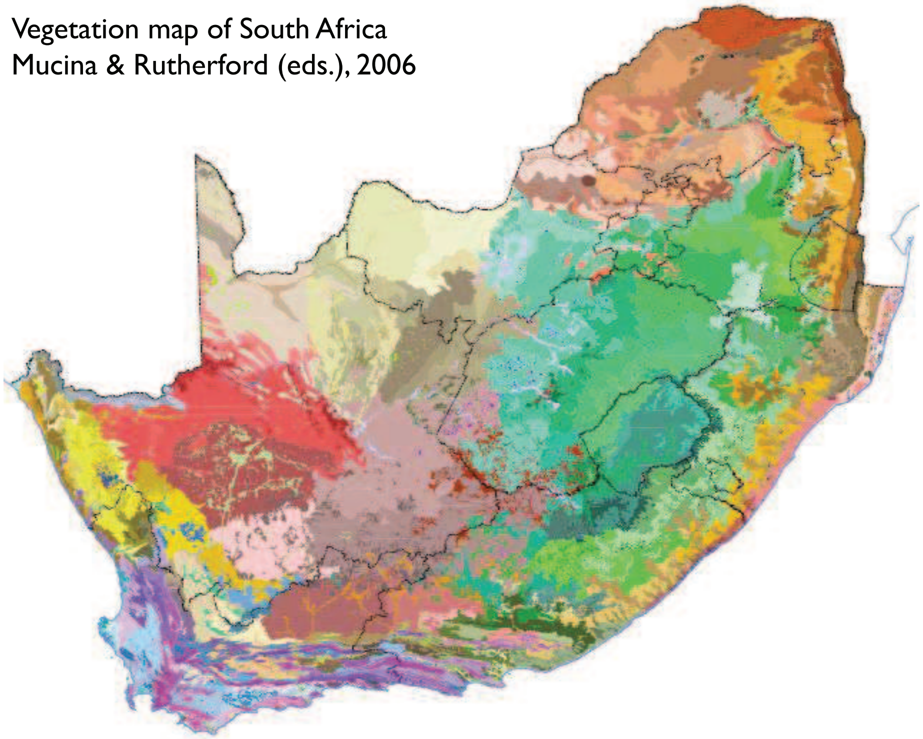


Figure 3.3: **Comparison of the vegetation classification systems of Acocks (1988), top, and Mucina and Rutherford (eds) (2006)**

by the chosen model is critical. Minimum data requirements to represent the spatial and temporal variation in vegetation vary depending upon the model, but usually include some or all of the following: monthly values of leaf area index (LAI), crop factors or coefficients, rainfall interception rates and rooting depths or root colonisation patterns. Verification studies are essential to promote confidence in the ability of the chosen model to replicate observed data. These may take the form of testing certain routines within the model (e.g. evapotranspiration), or may consist of more generalised verification of the primary model output of interest, namely streamflow.

As a local-scale alternative to using complex hydrological models, more easily measured surrogate variables (e.g. plant age or LAI), which are broadly linked to the water-use of plants, may be used to estimate plant transpiration / evapotranspiration. However, this is dependent upon the availability of observed data to verify these simple relationships. Their advantage is that they do provide an indication of changes in water-use over time (Figure 3.4).

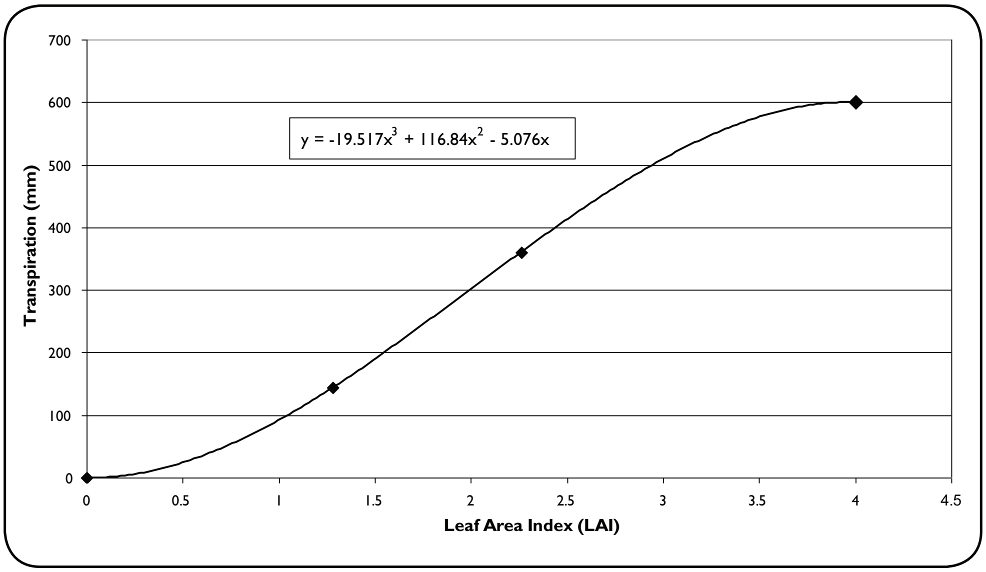


Figure 3.4: **Relationship between annual transpiration totals and maximum (mid-summer) Leaf Area Index values for different sizes of *Jatropha curcas* trees (Gush and Moodley 2007).**

3.4.5 Gathering the necessary data for each HRU

Data required for each HRU represented in the broad area of interest will depend upon the choice of model to be used, and its associated input data requirements. The minimum information required usually includes a daily rainfall record of adequate length (see next section), monthly means of maximum and minimum temperatures, monthly means of reference potential evaporation (e.g. A-Pan or Et_o), HRU physical attributes (e.g. delineated area, size, mean altitude, latitude and longitude), soils attributes (e.g. soil type and texture, horizon thicknesses, soil water contents) and land cover attributes required by the model (i.e. data to describe the vegetation within each HRU).

The importance of existing databases of climate, soils and land-use information can not be over-emphasised and obviously greatly facilitates the model parameterisation process. Ideally, these should be pre-determined, patched, quality-checked and respected databases, relevant to the country of interest. In certain instances, some or all of this data may not be available, or existing data may need to be modified to suit specific model input requirements. The degree to which scientifically credible data (required as input data into the model) is (un)available will affect the confidence that end-users have in the final product. As this is usually the case (i.e. all required model input data is rarely available), there is commonly a need to provide a justifiable method of deriving the input data that is not available. This may take the form of extrapolation of existing data sets to unmeasured areas (e.g. interpolation of climate data), the use of certain assumptions regarding parameter values (e.g. drawing on expert opinion to derive monthly leaf area, root depth and rainfall interception estimates for a broad range of vegetation types) or making allowances for generalisation or averaging of certain variables (e.g. use of the modal soil type or vegetation type in a HRU). These assumptions need to be shown to be necessary and should be backed by scientifically credible approaches to addressing them.

3.4.6 Determining the length of the simulation period

The time-period of the simulation should be a suitably representative period that is likely to incorporate typical climatic variation (dry, wet and average years) in the area of interest. The period selected should be as long as possible but obviously requires adequate input data in terms of the climatic variables required by the chosen model. The most important input variable required by most hydrological models is daily rainfall. Consequently, it is imperative that a continuous and quality-checked daily rainfall record be available for each HRU in the area of interest. The length of this record usually determines the simulation period, as monthly means of temperature and evaporation are generally acceptable to use in conjunction with a detailed daily rainfall record. Apart from being representative of the long-term climate of a particular HRU, the record length is also important in terms of statistical analysis.

3.4.7 Representing changes in plant growth over time

A single representative parameter set for the dominant (e.g. modal) vegetation type in each HRU may be used to represent the "baseline" vegetation for each HRU being assessed in the model. This parameter set needs to account for typical seasonal variation in certain parameters (e.g. by incorporating monthly changes in LAI, rooting depths and rainfall interception rates) thereby influencing the resultant monthly evapotranspiration patterns. The baseline vegetation within each HRU is usually assumed to be in a stable, climax stage of development with little year-to-year variation. However for the proposed replacement vegetation (e.g. monoculture bioenergy plantations) it may be necessary to account for the entire life-cycle or rotation period of the feedstock, with the associated variation in vegetation characteristics over time. For the hydrological assessment of small scale bioenergy developments over the typical life-span of the feedstock it may consequently be necessary to "grow" the species over time, by means of changing vegetation parameter values. This would obviously require data or assumptions on how aspects such as leaf area, rooting depth and rainfall interception rates change over the life-span of the feedstock species. Observed data on these aspects is the ideal source of information. If this data is not available, temporal changes in the species need to be modelled or estimated in some way, accounting for management activities such as pruning and thinning of trees (Figure 3.5).

For the assessment of long-term (i.e. longer than one rotation length), large-scale (e.g. quaternary/quinary catchment scale) bioenergy developments, the need to represent changing vegetation parameters over

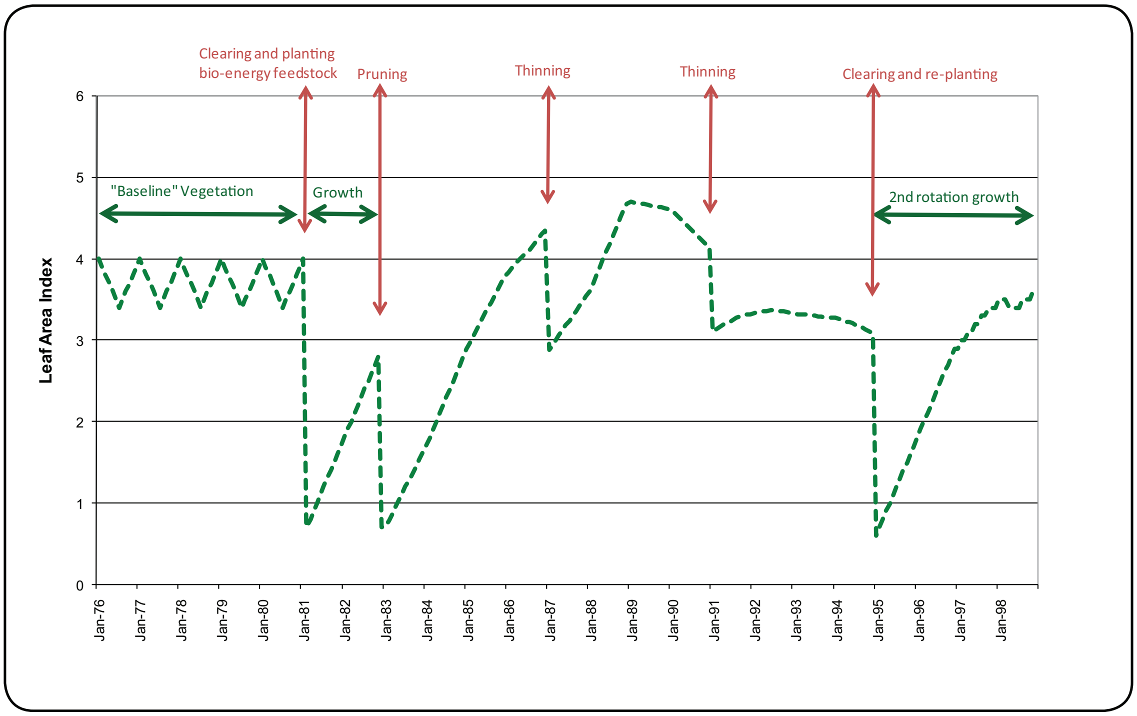


Figure 3.5: **Hypothetical changes over time in leaf area index of natural "baseline" vegetation and replacement bioenergy feedstock. Plantation management interventions and their resultant effects on LAI are illustrated.**

time may not be necessary. In this case it may be acceptable to assume that, while individual trees go through a growth cycle, bioenergy plantations at larger spatial scales would consist of a mosaic of tree ages representing all stages of the feedstock life-span as a result of variable planting dates and life-spans. Consequently, a normalized single representative age of tree may therefore be assumed to, mimic the average situation over the HRU. This representative age of the feedstock species (with its associated model input parameter values) may be utilised for each HRU. Representative parameter values may be determined by utilising age-specific vegetation parameter values to simulate the growth and resultant streamflow reductions for every year in the life-span of the feedstock. The tree age resulting in a streamflow reduction closest to the median streamflow reduction over the entire life-span may then be considered to be representative of the entire life-span of the feedstock. The relevant vegetation parameter values for that age may then be used in the model.

3.4.8 Running the model

Hydrological simulations at the desired time-step (e.g. daily) need to be run for each HRU within the area of interest, over the pre-determined simulation period. Depending upon the number of HRUs to be assessed this may require the model to be operated in 'batch' mode, whereby unique information relevant to each HRU is automatically selected from an input database and read into the model, generating outputs for each HRU respectively. Numerous potential scenarios may be modelled, however for hydrological impact assessments the minimum requirement is for simulations under the baseline vegetation, as well as under the proposed replacement land-use (e.g. bioenergy feedstock). While the climate, soils and physical catchment information remains consistent, unique input parameter values representing the respective vegetation types are utilised in the model to distinguish between the different land cover scenarios. Once the model has been run, time-series of relevant model outputs (e.g. daily streamflow (Q) and evapotranspiration (Et) information) from the respective land-use scenarios are stored for each HRU, and aggregated into time-series of monthly and annual totals for further analysis. Additional statistical outputs that may be generated for relevant variables include maximum, minimum, mean, median, percentile and coefficient of variation values.

3.4.9 Analysing the data

At Quaternary or Quinary Catchment scales, mean monthly, and mean annual, streamflow and evapotranspiration values, for each land-use scenario and each HRU, are the most important outputs with which to assess hydrological impacts of the proposed land-use. Using this information within the simplified water balance equation (streamflow = precipitation minus evapotranspiration), it is possible to calculate mean monthly and mean annual stream-flow reduction estimates for each HRU. Where the natural vegetation uses less water (on average) than the replacement vegetation, its Et will be lower and Q will be higher, indicating that the bioenergy feedstock species will (on average) result in a streamflow reduction. The converse is also possible, where the replacement vegetation may have a lower Et and higher Q than the natural vegetation, thereby resulting in a streamflow increase. The analysis of mean monthly outputs are important in terms of quantifying seasonal impacts on streamflow of the proposed future land-use. For example, water resource impacts during so-called "low flow" periods (dry months) are often more critical than during wet months, and monthly information is required to assess this. Where these kind of results are produced for numerous HRUs within the area of interest, it is possible to display them in the form of tables or maps representing spatial variation in streamflow reduction estimates (Figure 3.6).

The analysis is different for small-scale (plantation size) assessments, where streamflow reduction impacts over the life-cycle of a proposed bioenergy feedstock are to be evaluated. As assessments at this scale generally simulate streamflow changes over the entire rotation, compared to the baseline vegetation, it is better to compare accumulated streamflow under the respective land-use scenarios, over a typical bioenergy feedstock rotation. Divergence in the accumulated streamflow totals reflect differences in Et rates between the two scenarios, and the resultant impacts on streamflow attributable to the replacement land-use may be assessed at any time after planting (Figure 3.7).

3.5 Conclusions

An overview of the tasks required for the hydrological assessment of proposed land-use changes (e.g. tree-based bioenergy feedstock) have been presented in this chapter. It is clear that the approach to conducting such assessments differs depending on the scale of assessment required. However, in all modelling assessments it is important that verification studies are conducted wherever possible, in order to lend credibility to the model results and eventual extrapolation over wider scales. For example, where proposed bioenergy plantations (particularly deep-rooted, evergreen, tree-based feedstock) are to be established in areas dominated by short, seasonally-dormant vegetation (e.g. grassland or shrubland), streamflow reductions as a result of the altered land-use are likely. This has been amply demonstrated in South Africa, where exotic tree plantations established in former grassland areas have

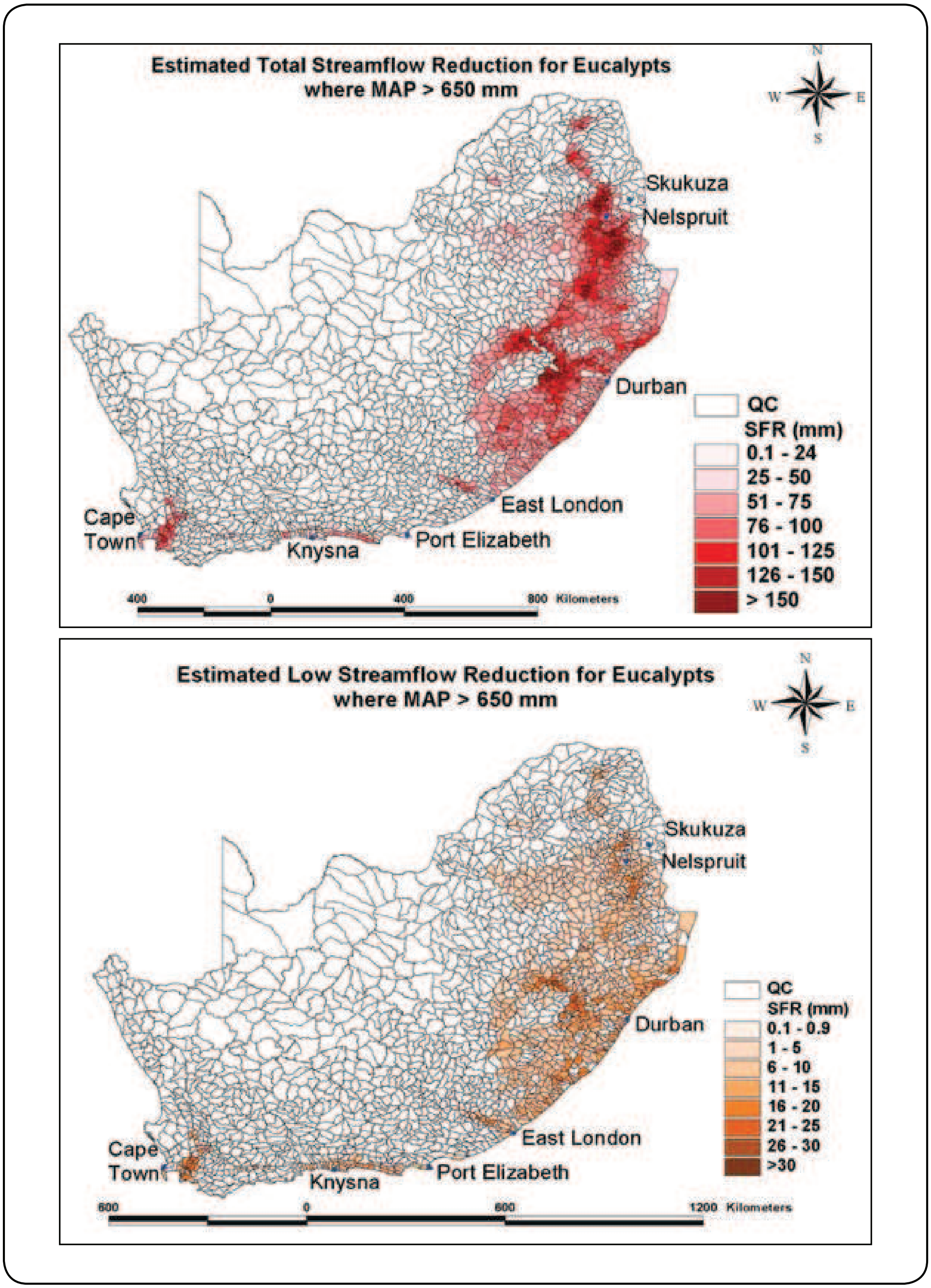


Figure 3.6: **Spatial representation of simulated streamflow reductions caused by eucalyptus plantations (total and low flows), for all South African Quaternary catchments where Mean Annual Precipitation exceeds 650mm (Gush et al. 2002).**

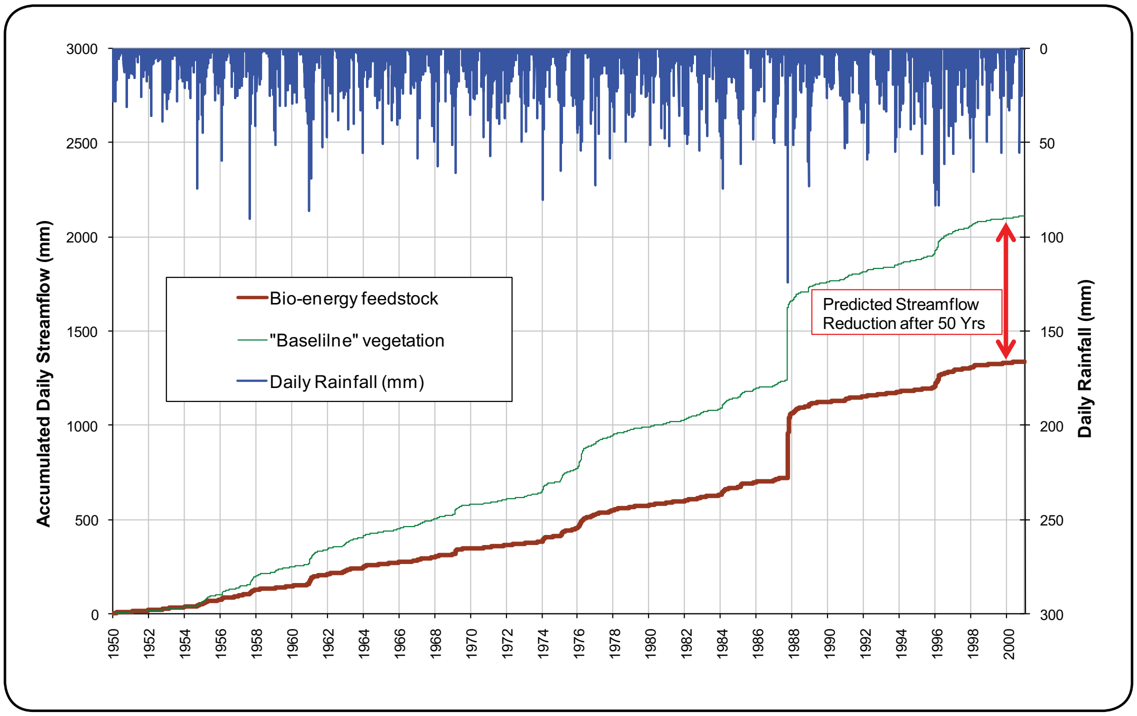


Figure 3.7: **Hypothetical example of accumulated streamflow under different land-use scenarios, simulated using a hydrological model, to predict streamflow reductions associated with potential bioenergy feedstock.**

conclusively been shown to consume more water than the baseline vegetation, reducing streamflow as a result (Bosch and Hewlett 1982; Zhang 1999; Scott et al. 2000; Brown et al. 2005; Calder 2005; Dye and Versfeld 2007; Scott and Prinsloo 2008). The expansion of exotic plantation forestry is now restricted in most areas of South Africa because of the environmental impacts (primarily in terms of water-use) of commercial plantations.

Similarly, it is imperative that bioenergy strategies being developed for any particular country consider water resource impacts together with all the other relevant social, economic and environmental considerations associated with the development of the industry. This is particularly important in those countries where there is increasing competition for water, now virtually a global phenomenon. Appropriate legislative and regulatory mechanisms may then be applied to new land use sectors (such as the bioenergy industry), if they are assessed to be streamflow reduction activities. Results of these kind of assessments therefore have the potential to influence policies governing the establishment and distribution of proposed land-use activities. Regulation, in the interests of sustainable water resource management, needs to be based on results from scientifically defendable work. The inevitable shortcomings and weaknesses associated with any methodology need to be identified and addressed in on-going research programmes.

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