Modelling Hydrological Responses to Land Use and Climate Change: A Southern African Perspective

Author(s): Roland E. Schulze
Source: AMBIO: A Journal of the Human Environment, 29(1):12-22. 2000.
Published By: Royal Swedish Academy of Sciences
DOI: http://dx.doi.org/10.1579/0044-7447-29.1.12
URL: http://www.bioone.org/doi/full/10.1579/0044-7447-29.1.12

Roland E. Schulze

Modelling Hydrological Responses to Land Use and Climate Change: A Southern African Perspective

Nine hydrological issues relating to land use and climate change are identified from a southern Africa perspective, each illustrated by an example based on field observations or simulation modelling. The nine issues are that *(i)* southern Africa's hydrological regime is already so variable that climate change will be difficult to detect; *(ii)* fluctuations in the hydrological regime are amplified by fluctuations in climate; *(iii)* hydrological responses are highly sensitive to land use changes; *(iv)* local scale abrupt land use changes may be hydrologically more significant than regional scale gradual changes; *(v)* land use change frequently exacerbates already variable flow regimes; *(vi)* detailed spatial information is vital in assessing impacts of critical land uses; *(vii)* major components of the hydrological system respond very differently to climate change; (*viii*) in developing countries inter-seasonal climate change may be more important than that at decadal time scale; and *(ix)* there is need to identify the hydrologically sensitive areas of a region.

INTRODUCTION

Land use change and climate change form a complex and interactive system by linking a human action, *viz*. the land use change, to environmental reactions which, in turn, impact again on human responses. Further complicating this system is the fact that these linkages occur at different spatial and temporal scales (1). A major environmental reaction to land use change occurs in hydrological responses such as changes in runoff components, erosion or groundwater recharge rates, with these responses being further complicated when accompanied by any changes in climate, be they short or long term.

This paper addresses issues outlined above by reviewing results from field observations and hydrological simulation modelling to a range of scenarios of land use and climate changes in a southern African context. Significant in the context of southern Africa and most of the rest of the continent is that, hydrologically, problems are perceived and experienced at a local rather than at a national to global spatial scale, and at an intra- to inter-seasonal rather than on a decadal time scale. Furthermore, the emphases in the International Geosphere-Biosphere Programme's (IGBP) core initiatives on modelling, hydrology and land use change, namely the GAIM, BAHC, GCTE and LUCC programmes, often seem far removed from the harsh realities of the lives of many Africans whose day-to-day encounter with climate and climate change often focuses on having to find enough water for the week and store it, as well as producing enough food to last through the next dry season.

The core of the paper consists of nine issues, or hypotheses, which are illustrated with examples from southern Africa. These issues are:

Issue 1. Southern Africa's hydrological regime is already so highly variable in space and time, that climate change trends may be difficult to detect.

Issue 2. Fluctuations in the hydrological regime are amplified and exacerbated by fluctuations in climate.

Issue 3. Hydrological responses are highly sensitive to, and dependent upon, land use and its change.

Issue 4. Abrupt land use changes at local scale may be hydrologically far more significant than gradual land cover changes at regional to global scale.

Issue 5. Changes in land use frequently exacerbate already variable flow regimes.

Issue 6. The detail of spatial information may be vital in assessing hydrological responses of critical land uses.

Issue 7. Between one region and the next, major components of the hydrological system often respond very differently when subjected to climate change.

Issue 8. Hydrological concerns in developing countries are currently focused more on inter-seasonal scales than on decadal scales of climate change.

Issue 9. In order to be proactive in regard to long-term climate change, there is a need to identify hydrologically sensitive areas.

A short section on terminology used and techniques applied prefaces the discussion of the nine issues.

TERMINOLOGY AND TECHNIQUES

Hydrology may be defined as the interdisciplinary geoscience which deals with the processes governing the replenishment and depletion of terrestrial water resources (2). It revolves around understanding and describing quantitatively the various physical, chemical and biological components and processes which interact and operate at a wide range of scales in time and space in an already complex land phase of the hydrological cycle, rendered even more complex by conscious and unconscious human alterations to the hydrological system, for example, by the construction of dams or changes in land use.

Land cover (Fig. 1) refers to the biophysical state of part of the earth's surface and immediate subsurface in terms of broad categories such as cropland, forest, grassland, settlements, rec-

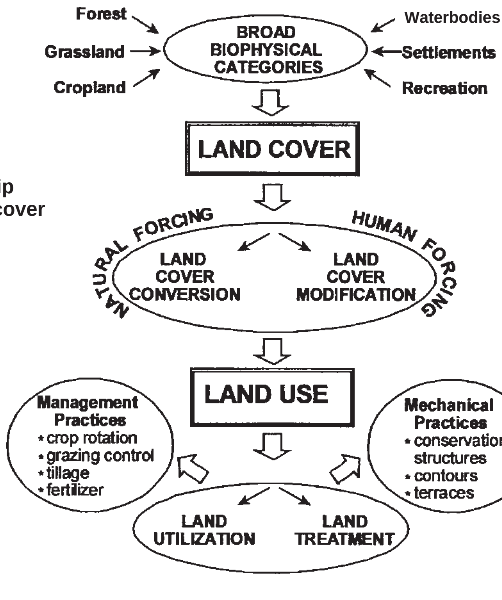


Figure 1. The relationship between land cover and land use.

reation, water bodies or mining (1). These broad landcover categories can be changed by natural factors such as long-term climate changes or climatic persistence—for example, consecutive years of drought— or naturally occurring episodic events such as fire or flooding. Overwhelmingly, however, land cover has been changed by human actions through land cover conversion and modification, primarily for purposes of agricultural production and settlement (1). These conversions and modifications of land cover introduce the concept of *land use* as distinct from land cover (Fig. 1). Land use refers to the manner in which biophysical attributes of the land are manipulated, managed and exploited. Land use thus refers, *inter alia*, to the utilization, human inputs and management levels, driven by changing production and consumption dynamics, and is subject also to social, political and economic factors. Manifestations of land use and its management may have significant hydrological response impacts by either enhancing or retarding infiltration, thereby reducing or encouraging stormflow generation and its resultant changes in sediment and/or nutrient production into watercourses.

In regard to *climate change*, two forms may be distinguished (3). The first is climate change which encompasses all forms of climate inconsistency, where deviations from long-term statistics take place over an area in the knowledge that over time these inconsistencies are *reversible* and *non-permanent*; eg. the El Niño phenomenon. Climate change, thus defined, is an entirely natural phenomenon which has taken place many times in history. The second form of climate change encompasses those changes in, say, temperature and precipitation which are *irreversible*, with new and *permanent trends* in climate statistics, i.e. with signals of a distinct sign being superimposed on natural variability; e.g. change resulting from the enhanced greenhouse effect caused largely by human actions. This paper will address both forms of climate change in the context of hydrological responses in southern Africa.

Hydrological impacts of land use and climate change are often evaluated by means of simulation models. In broad concept, a *hydrological model* is a quantitative expression of observation, analysis and prediction of the interactions of the various hydrological processes which vary in time and over space, i.e. rainfall, infiltration evaporation or streamflow. Because the natural and human hydrological systems e.g. modified by land-use change, are complex ones, the models are simplifications of the behavior of hydrological responses (4, 5).

In most modelling examples illustrating this paper the *ACRU* agrohydrological simulation model has been applied. *ACRU* is a deterministic, physical-conceptual (i.e. process based, relating

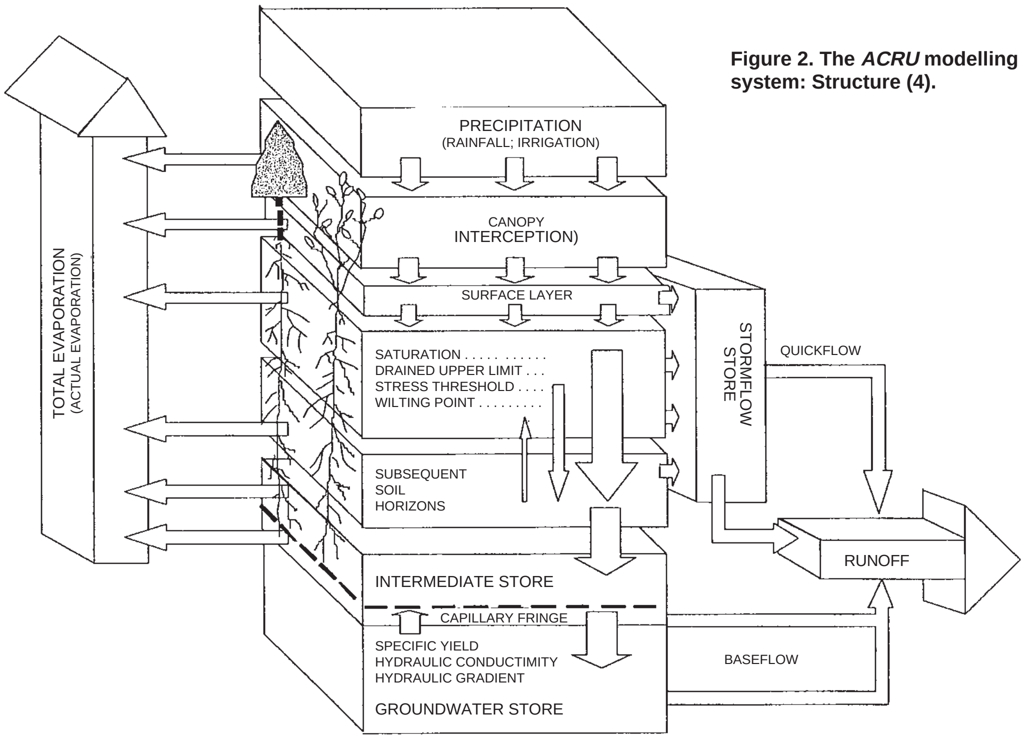


Figure 2. The *ACRU* modelling system: Structure (4).

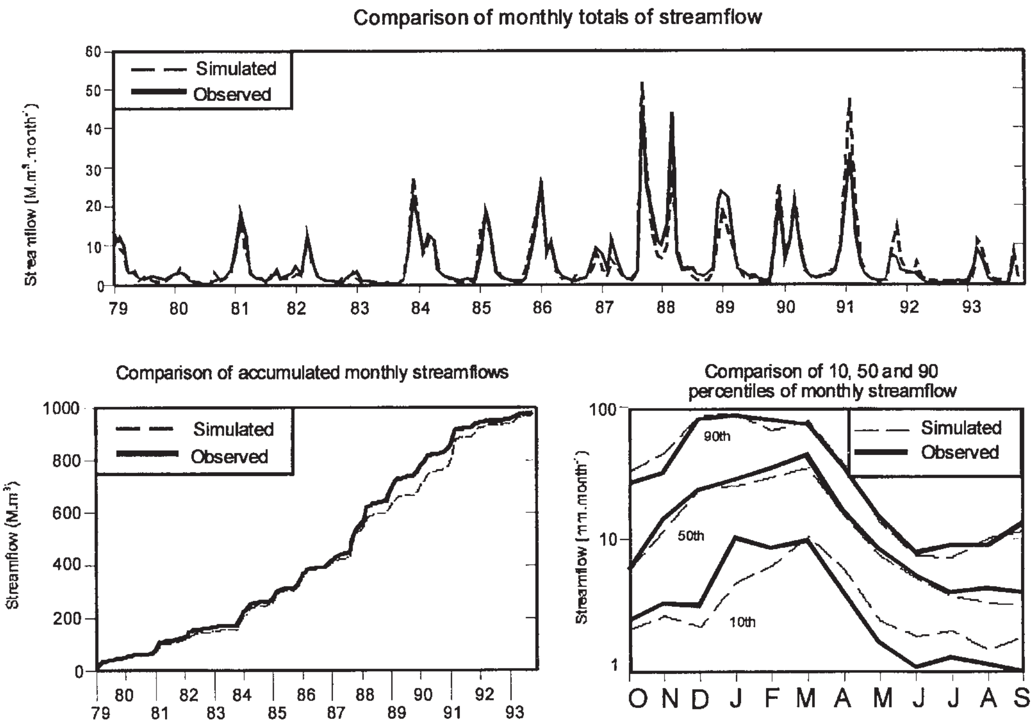


Figure 3. An example of a verification study with the *ACRU* model taken from the Lions river in the Mgeni catchment (6).

cause and effect), and integrated multipurpose modelling system (4), revolving around a daily time step multilayer soil water budget (Fig. 2). Individual internal state variables (e.g. soil moisture) as well as end-product output from the model (e.g. streamflow or sediment yield) have been widely verified in experimental field and catchment conditions under different hydrological and land use regimes in Africa, Europe and the Americas (4). One example of a verification study on an operational catchment with mixed land uses is illustrated in Figure 3, in which flows from the 362 km^2 Lions river in KwaZulu-Natal province of South Africa are simulated with *ACRU*. Not only is a good visual fit of the time trend evident, but accumulated flows and monthly flows in the wettest year in 10 (90th percentile of exceedance) and the driest year in 10 (10th percentile) are also mimicked well and the indices of model performance show a good fit for a range of critical statistics (6).

In the *ACRU* model total evaporation is partitioned into soil water evaporation and transpiration, thus rendering it sensitive to temperature change as well as accommodating a transpiration suppression function associated with increases in CO_2. In runoff generating routines, account is taken of land use/tillage induced changes in initial infiltration and soil water redistributions as well as of rainfall characteristics, while the stormflow and baseflow components of runoff are modelled separately and explicitly. Detailed descriptions of processes and options have been given elsewhere (4).

ISSUES RELATED TO LAND USE AND CLIMATE CHANGE DRIVEN RESPONSES IN HYDROLOGY

Nine issues, or hypotheses, are presented below to illustrate some of the complexities of the interactions of hydrology, land use and climate change, as experienced from a southern African perspective. Case studies, based both on field observations as well as from modelled results are taken from a range of actual catchments as well as from southern Africa viewed as a single region. Where the term *southern Africa* is used in context of this paper it implies the contiguous area comprising of South Africa plus Lesotho and Swaziland.

Issue 1. Southern Africa's hydrological regime is already so highly variable in space and time, that climate change trends may be difficult to detect.

Figure 4 (top) shows the distribution of simulated median annual runoff (that is, stormflow plus baseflow) over southern Africa. For this simulation the region was delineated into the 1946 relatively homogeneous Quaternary Catchments as identified by the South African Department of Water Affairs and Forestry. To each Quaternary Catchment a representative rainfall station with 45 years of concurrent and checked daily rainfall data (1950 - 1994) was assigned, as was information on monthly temperature and reference potential evaporation, hydrological soil properties and relevant vegetation characteristics. For this simulation a land use of grassland, taken to be under good grazing management, was assumed. All spatial attributes were geocoded onto a geographic information system (GIS) to which the model and climatic databases were linked, with the Quaternary Catchments

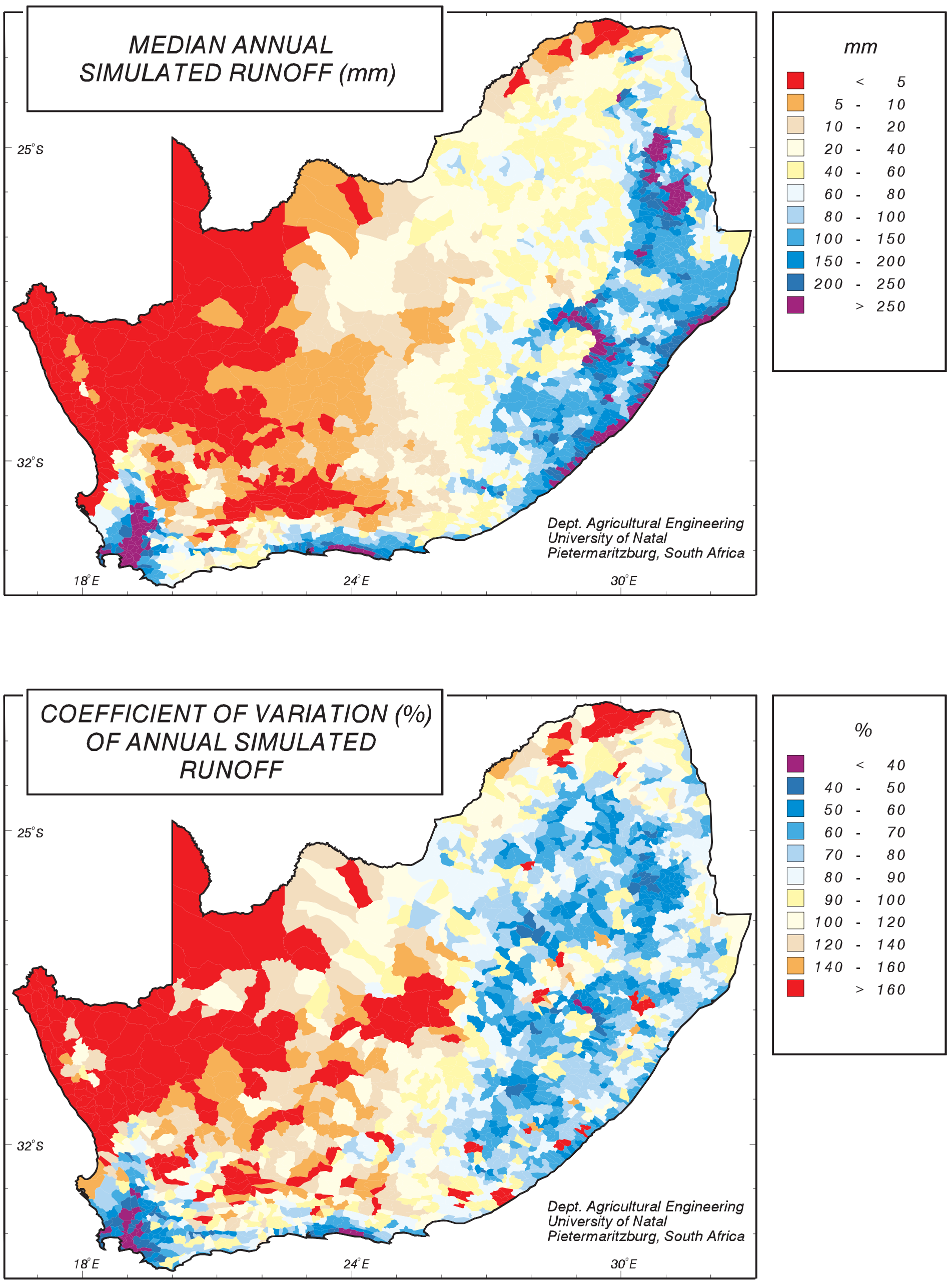


Figure 4. Distribution of median annual simulated runoff (top) and the coefficient of variation (%) of annual runoff (bottom) in southern Africa (7).

considered to be responding as individual hydrological entities.

Spatially the median annual runoff (MAR) is highly variable, ranging from < 5 mm equivalent runoff to over 250 mm. While a general decrease in MAR is evident inland of the southern and eastern coastal zones the distribution is, furthermore, spatially complex with often catchments of high and low MAR in very close proximity, usually as a result of major rainfall changes associated with physiographic discontinuities.

This high risk hydrological environment of southern Africa is highlighted even more by examination of Figure 4 (bottom), which illustrates the inter-annual coefficient of variation (CV, %) of runoff (7). Half of southern Africa has a CV of annual flows in excess of 100% and even the wetter eastern regions still have CVs around 60%. Within a year the month-by-month CVs of runoff are even higher. Such features of spatial and temporal hydrological responses under present conditions render regional water resources development very difficult and expensive.

The uncertain changes in rainfall amounts, seasonality and intensity patterns as well as rainday persistences induced by any climate change are likely to result in any meaningful trends in runoff being very difficult to actually detect by water resources planners in southern Africa because the high inter- and intra-seasonal "noise" could easily mask any "signal" in runoff change responses.

Issue 2. Fluctuations in the Hydrological Regime are Amplified and Exacerbated by Fluctuations in Climate. At the timescale of reversible climate change, southern Africa's strong seasonal climatic rhythms have been shown to be severely subjected to El Niño-related influences. In southern Africa an El Niño generally implies a regional drought. Repercussions of low rainfalls during El Niño events are usually amplified in the water sector and major water resources operators, electricity utilities who operate water-cooled power stations or irrigation boards are frequently called upon to make far-reaching and costly decisions as to when, for example, to introduce water restrictions for human, industrial or agricultural purposes or when to switch over to interbasin water transfers. Since many major southern African dams characteristically operate at only a fraction of their full supply capacity much of the time, any prognostic aid in dam-operating decisions, such as El Niño forecasts, could potentially save the subcontinent vast sums of money. Figure 5 illustrates the amplification of runoff response relative to rainfall response. In this study, daily observed rainfalls and associated simulated runoff responses were isolated for the 1982/83 hydrological year—1 October to 30 September—which represented a very strong El Niño, from each of the 1946 Quaternary Catchments for which daily hydrological simulations from 1950–1994 were being made. The rainfall as well as runoff for 1982/83 were then expressed as ratios of their respective long-term (45 year) median annual values for each catchment.

Perusal of Figure 5 (top) shows that over much of the summer rainfall regions of the eastern 2/3 of southern Africa the El Niño year's rainfall was 50–80% of the long-term median, however with sizeable areas receiving within the range of expected

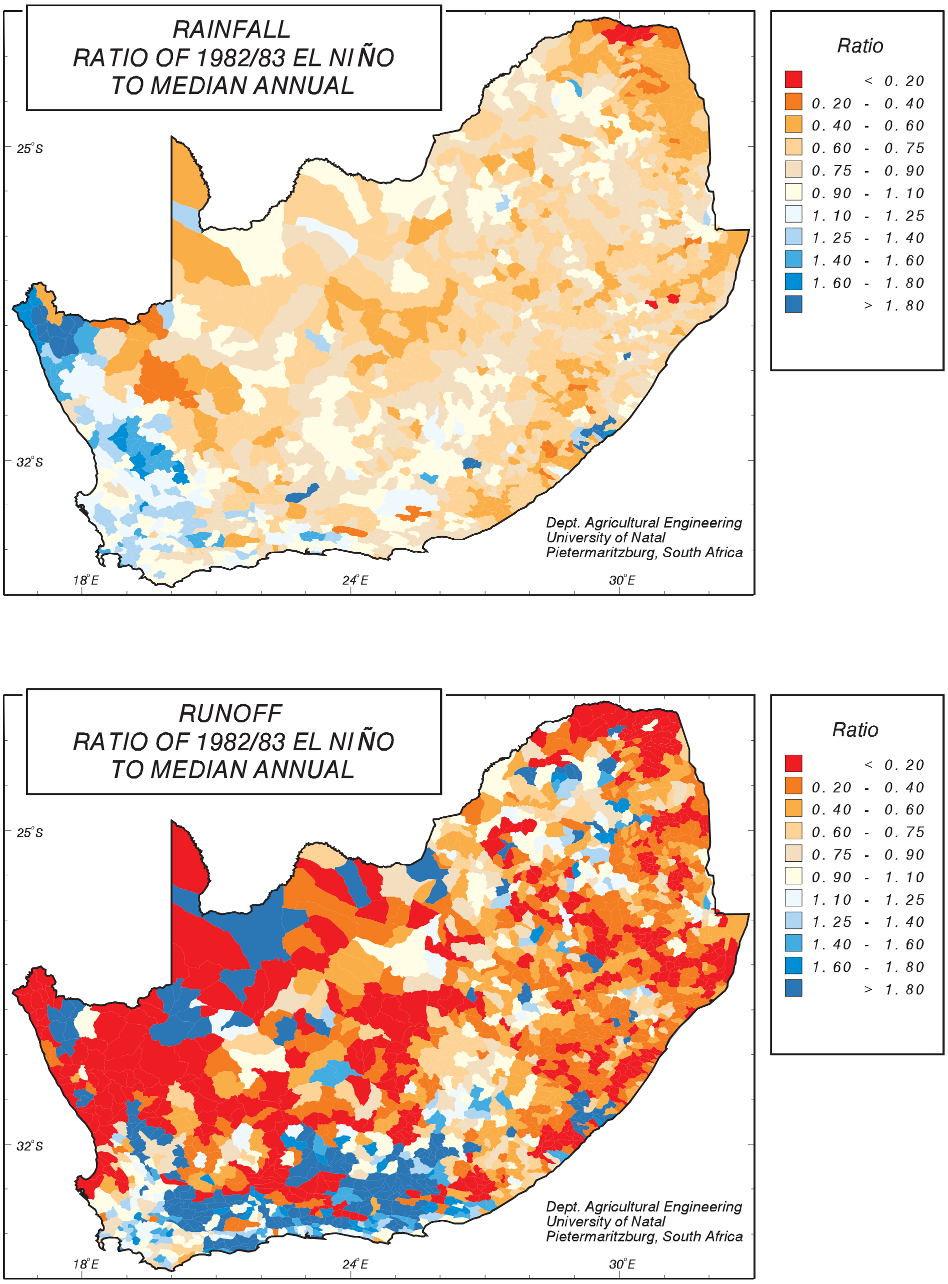


Figure 5. Ratios of observed rainfall (top) and simulated runoff (bottom) for the 1982/83 El Niño season in relation to 45 year median annual values in southern Africa (5).

rainfalls (80–120%), while a small fraction received only 20-50% of the expected precipitation. The corresponding simulated runoff responses (Figure 5, bottom) display much more complex patterns both spatially and in the range of ratios. Much of the region only yielded 20–50% of the long-term median runoff, with considerable areas generating < 20% of expected runoffs—showing clearly the intensifying effect of the hydrological cycle on rainfall perturbations. Also very evident is the patchiness of runoff responses, illustrating the high dependence of runoff on local antecedent wet or dry catchment conditions, rather than only on total amounts of rainfall.

This example has shown clearly how fluctuations in rainfall have been amplified and exacerbated in the hydrological response.

Issue 3. Hydrological responses are highly sensitive to, and dependent upon, and use and its change.

In many catchments the natural vegetation has been highly modified by a mixture of intensive crop cultivation, urbanization or overgrazing. The 4079 km^2 Mgeni catchment in KwaZulu-Natal province of South Africa is one such highly modified catchment in which natural, or pristine, vegetation represented by six of Acocks' so-called Veld Types (8) has been replaced by 21 classes making up present land uses and covers (Fig. 6, top *vs* bottom). After extensive verification studies of the *ACRU* model in the Mgeni catchment on seven catchments with a range of combinations of land uses, soils and climatic conditions (6), the influence of land uses on hydrological responses was assessed in three analyses.

In a first assessment, the runoff coefficient, i.e. the mean annual runoff (MAR) expressed as a percentage of the mean annual precipitation (MAP), was plotted against MAP for 137 subcatchments delimited within the Mgeni catchment. In Figure 7 the plot for pristine land covers shows an expected high correlation between the runoff index and MAP, while the runoff coefficient for present land covers displays no association whatsoever with MAP, illustrating clearly the sensitivity of runoff to change in the original land cover due to modification and intensification. In a second assessment, the percentage changes in median annual streamflows resulting from the modifications and conversions of pristine land covers were mapped. Figure 8 (top) illustrates how MAR reductions of up to 61% can occur, mainly in areas of intensive sugarcane and exotic forest plantations, while gains in MAR of up to 103% were simulated in areas which were urbanized or had dense populations where overstocking and associated land degradation were prevalent.

Changed hydrological responses to land use are not confined to runoff changes, however, and in a third assessment Figure 8 (bottom) illustrates the spatial patterns of the biological status of the receiving streams of the Mgeni system in a map of simulated mean annual concentrations of the pathogen *Escherichia coli (E. coli)*. In developing and verifying the model to simulate the fate of *E. coli* in a catchment, two land use variables were identified as major driving forces, namely, livestock density and the number of humans living in close proximity (< 250 m) to streams and under conditions of poor sanitation (6). The map shows simulated *E. coli* concentrations to range from un-

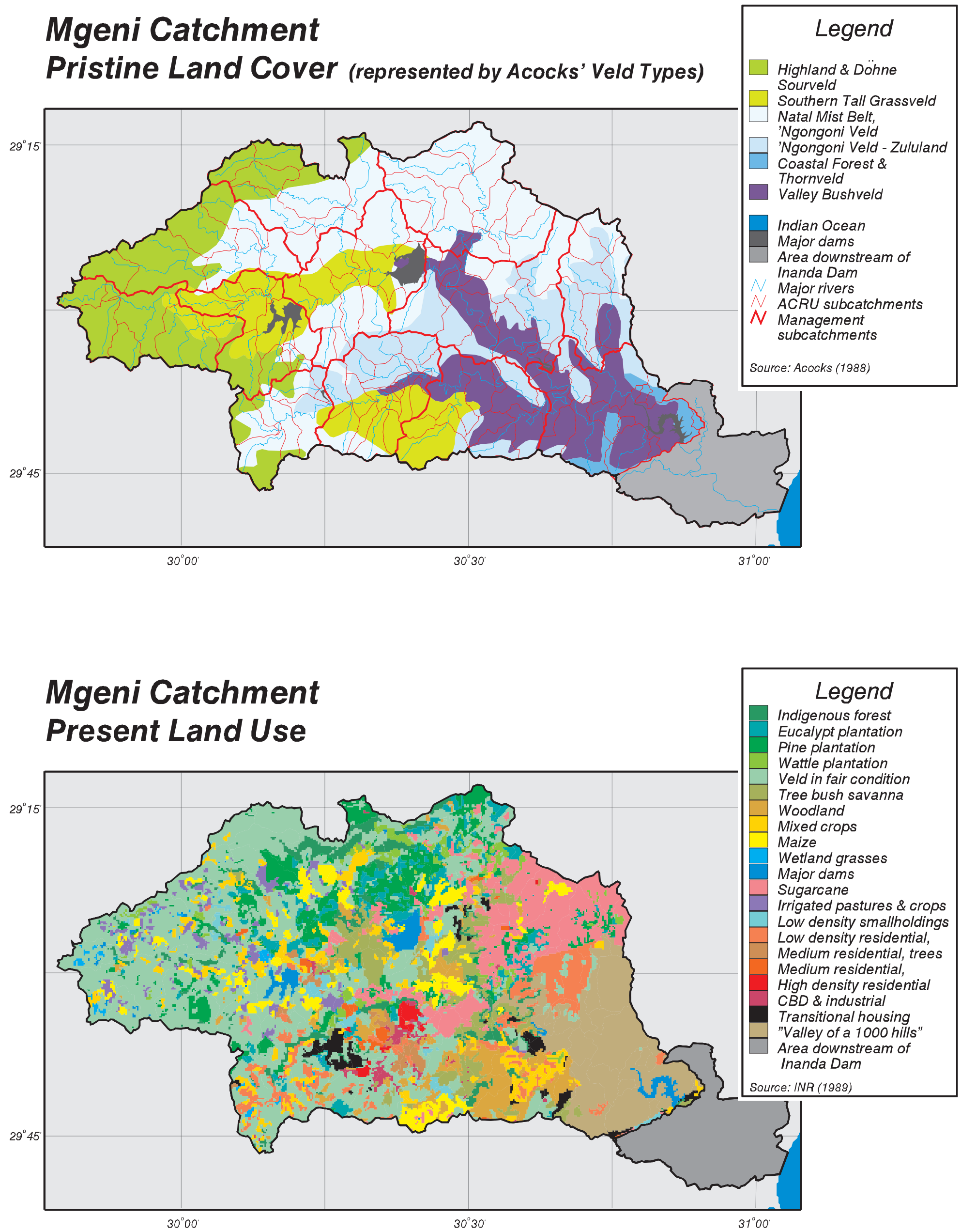


Figure 6. Distribution of pristine (top) and present (bottom) land covers in the Mgeni catchment (6).

der 250 (lowest, 30) to over 10 000 (highest, 18 200) counts per 100 ml, with areas of highest concentrations associated with informal settlements, cattle feedlots and areas of high general stocking rates.

Issue 4. Abrupt land use changes at local scale may be hydrologically far more significant than gradual land cover changes at regional to global scale.

Abrupt changes to the physical landscape can include devastating episodic events such as a fire ravaging an area. In an African context where both intentional burning and wildfires are a common feature, reported effects on hydrological behavior can be nothing short of dramatic (9), with often serious environmental and economic consequences downstream. In one such example the first rainy season's post-fire effects of the 25 August 1989 wildfire in research catchment V1H020 (area: 1.32 km^2) are assessed. This catchment was afforested partially to *Eucalyptus fastigata*, and is nested 800 m downstream of grassed research catchment V1H028 (area: 0.42 km^2) which did not burn and thus acted as a control catchment. These two catchments are part of the Ntabamhlope hydrological research station in KwaZulu-Natal, located at 29°50' S, 29°50' E and with a MAP of 980 mm.

While the high intensity wildfire only destroyed the afforested lower 26.5% of the two nested catchments, the 10 months immediately following the fire saw stormflows at V1H020 increasing by 92% from the statistically expected values and peak discharges by 1100%, while times to peak were reduced by 53% (9). Fig-

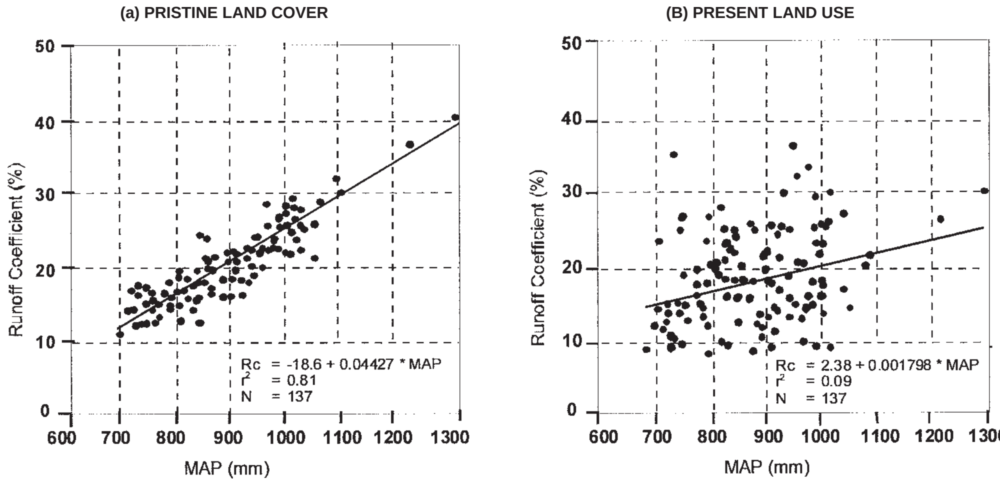


Figure 7. Associations between the runoff coefficient and MAP (mm) for 137 subcatchments of the Mgeni river system for (a) pristine and (b) present land uses.

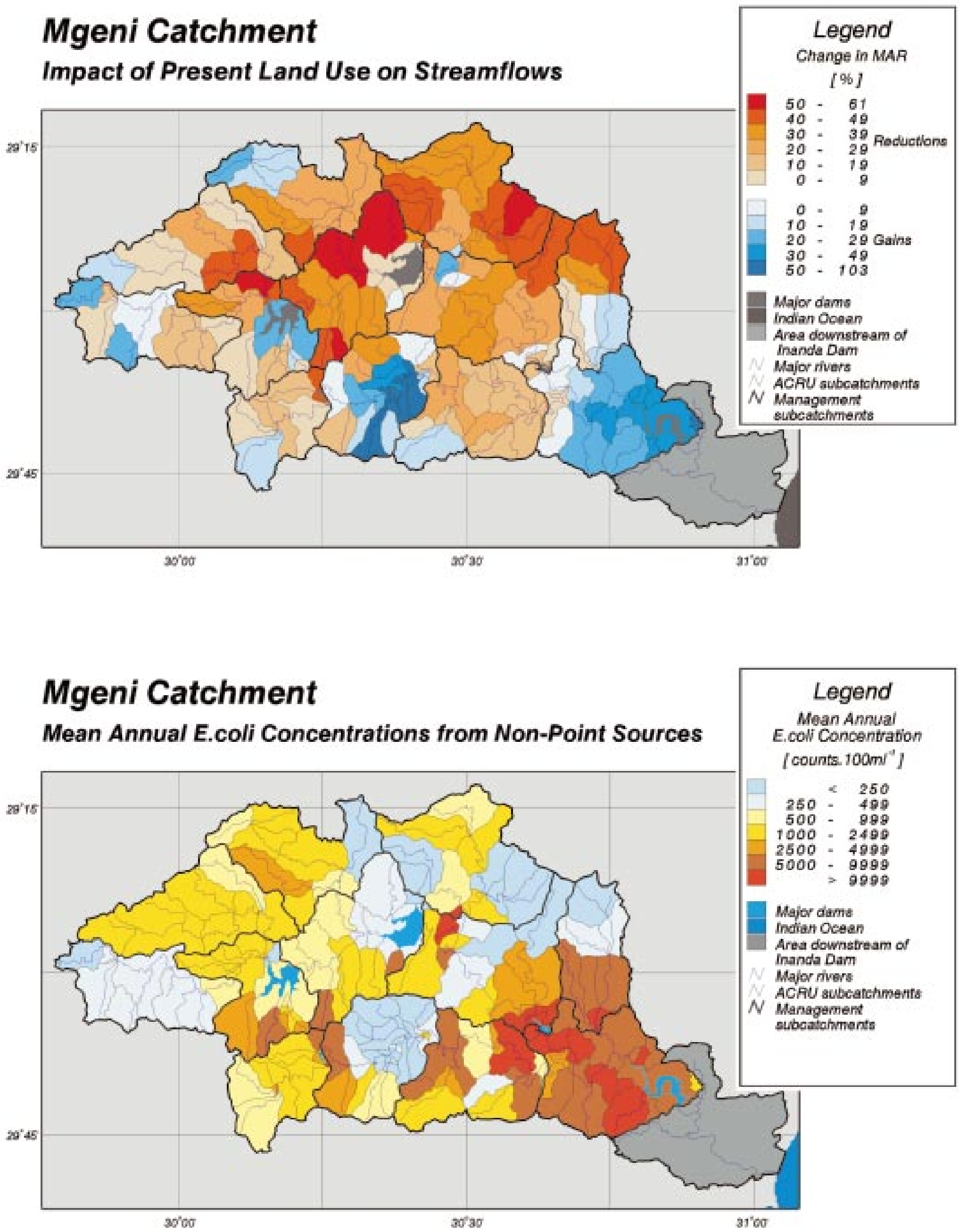


Figure 8. Percentage changes in MAR as a result of conversion from pristine land cover to present land use (top) and mean annual concentrations of *E. coli* from present land use (bottom) in the Mgeni catchment (6).

ure 9 gives examples of pre-fire and post-fire hydrograph responses for the partially burned and the control catchments (9).

It is events such as the one described above, with their immediately experienced hydrological repercussions, that are frequently the focus of local concern, within and downstream of a catchment, rather than larger scale gradual land cover changes over years or decades with imperceptible hydrological change from one year to the next.

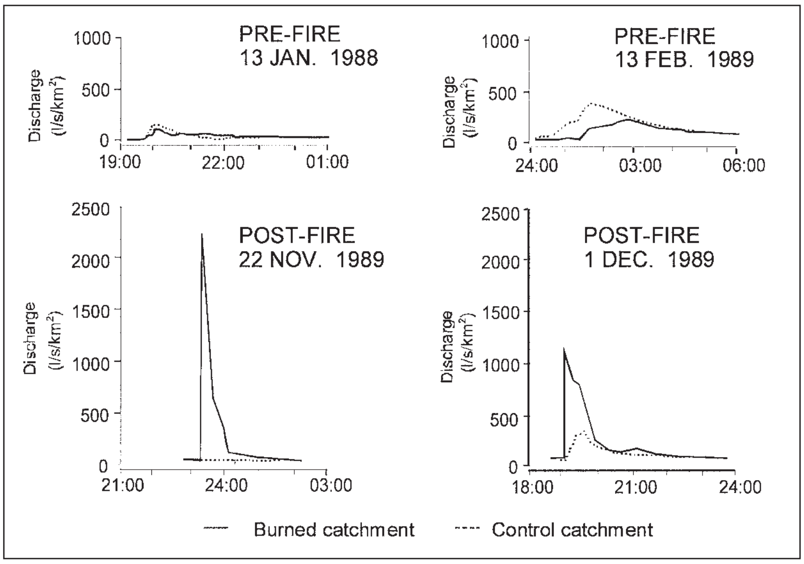


Figure 9. Examples of pre- and post-wildfire hydrograph responses at the Ntabamhlope hydrological research station on unburned and burned portions of the instrumented catchments (9).

Issue 5. Changes in land use frequently exacerbate already variable flow regimes.

Streamflow is made up of *stormflow*, which is generated at and/or near the soil surface of a catchment from a specific rainfall event and *baseflow*, which consists of water from previous rainfall events which has percolated through the various soil horizons into the groundwater zone and then contributes as a delayed flow to the streams within a catchment.

An intensification of land use from, say, an annual natural grass cover to (say) evergreen exotic forest or sugarcane plantations implies higher rainfall interception rates from both the canopy and litter/mulch layers, also enhanced infiltration rates as a consequence of tillage, higher transpiration rates as a result of increased biomass and aerodynamically rougher canopies (including year round transpiration if the plants to not senesce in the dry season—and soil water extraction from deeper soil layers as a result of deeper rooting systems. Consequently, near-surface stormflow generation may be reduced, as well as less water percolating into the groundwater zone to feed the baseflow store. Vegetation degradation, on the other hand, exposes more soil directly to rainfall, infiltrability may be reduced by crusting of the exposed soil, and trampling by livestock may further reduce initial abstractions before stormflow commences. This may lead to an increased "flashiness" of the catchment with resultant enhanced peak discharges and sediment yield, while the baseflow store is replenished to a lesser extent than with good vegetation cover.

The example selected to illustrate that land use change frequently exacerbates flow regimes is taken from the 74 km^2 Nadi catchment in KwaZulu-Natal (MAP 552 mm), in which subtropical grassland originally in good hydrological condition has, on the one hand, been degraded by severe overgrazing (10), while on the other hand parts of the catchment are currently being converted to *Eucalyptus grandis*, a fast growing evergreen exotic tree species grown for commercial purposes. By altering model input in regard to differences in intra-seasonal leaf area index, canopy interception and root distributions as well as infiltration and stormflow generating variables associated with different land uses, the respective stormflows and baseflows were simulated for grassland in good condition, in degraded condition and for an *E. grandis* plantation. While differences in median annual runoffs for the three land-use scenarios were as expected, with MAR of grassland in good condition being 61.1 mm, that of degraded grassland considerably higher at 89.6 mm and of the plantation lower at 44.7 mm, it is the increases in the variability of flows—for the different sets of reasons described above—that are illustrated clearly in Table 1 for stormflows in the case of plantations, and for both stormflows and baseflows in the case of degraded grassland and plantations.

Issue 6. The detail of spatial information may be vital in assessing hydrological responses of critical land uses.

The significance of land use change on hydrological responses has already been illustrated clearly in Figures 7 and 8. Some land uses are, however, more critical than others in their impacts on downstream users, be it because a greater overall reduction in streamflows takes place or because certain seasons' critical flows

Table 1. Coefficients of variations of 50 years' simulated stormflows and baseflows for three land use scenarios in the Nadi catchment, KwaZulu-Natal (10).

(a) Stormflows

Land use	Coefficient of Variation (%)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Grassland, good condition	140	165	107	145	374	290	501	282	392	186	151	124	126
Grassland, degraded	108	131	88	131	291	290	449	253	343	139	114	99	89
E. grandis plantation	173	194	118	181	394	275	509	275	404	223	187	148	159

(b) Baseflow

Land use	Coefficient of Variation (%)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Grassland, good condition	215	175	177	171	170	169	162	157	162	267	258	213	145
Grassland, degraded	240	195	188	189	189	189	182	179	181	301	293	247	165
E. grandis plantation	250	183	180	179	179	170	170	160	185	326	244	246	159

may be impacted more severely by such land uses. When conflicts between up- and downstream water use sectors arise in a catchment, and simulation modelling is used as a tool to resolve those conflicts and to optimize equitable allocations of water to competing sectors, then the areal extents of the critical land uses, and other associated hydrological attributes of those land uses, have to be assessed at appropriate levels of detail.

In the sub-humid areas of South Africa two such competing water use sectors are irrigation and commercial afforestation. Irrigation abstracts large volumes of water either directly from a stream or from an impoundment fed by a stream, thereby reducing the availability of water to downstream users. This reduction is likely to be more critical in low flow months. Afforestation, thereagainst, reduces amounts of rainfall reaching the soil surface by high canopy/litter interception losses, reduces stormflows by a combination of enhanced infiltration as well as transpiration losses and reduces baseflow production by soil-water extraction from a relatively deep rooting system. As in the case of irrigation, afforestation to fast-growing evergreen exotic species generally impacts low flows relatively more than high flows.

In the 1261 km^2 Bivane catchment in KwaZulu-Natal in South Africa (latitude 27°40'S, longitude 30°45'E) conflict between downstream irrigation water users and further potential reductions of upstream streamflows by proposed additional afforestation has resulted in a government moratorium being placed on any new afforestation until "afforestation *vs* irrigation" issues have been resolved—by appropriate hydrological simulation modelling. This has necessitated, *inter alia*, a detailed inventory of present day afforestation and of stored water in dams within the Bivane catchment (11).

Three approaches to assessing the areal extent of present afforestation and characteristics of dams were examined (Fig. 10). At the coarsest level, forests could be identified from the 1 km x 1 km land use grid supplied by the United States Geological Survey (Pers comm.). Figure 10 (below) shows this resolution to be clearly inadequate for, while it identifies major areas of afforestation as "evergreen", it could not pick up any of the many small dams which exist in that catchment.

Even larger discrepancies between respective percentages of critical land covers became evident when results from 1:30 000 aerial photographs, supplemented by groundtruthing in the field, were compared with those from satellite imagery using Landsat TM. Not only could the photographs distinguish between the major genera grown by commercial foresters, which is important because the genera and main species (*Eucalyptus grandis*, *Pinus patula* and *Acacia mearnsii*) have different growth rates and soil-water extraction patterns (4), but Figure 10 (middle) shows significant areas of afforestation which were identified neither by Landsat TM nor the USGS methods. In South Africa, Landsat TM imagery is frequently used by government and forestry industry as the means of identifying commercial afforestation. In this case study, the aerial photographs identified 44.8% more afforestation than was "officially" there (cf. Fig. 10 middle *vs* 10 bottom), with significant potential influences on local and downstream water resources.

In the same catchment, the study of dams revealed that Landsat TM *vs* aerial photograph dam surface areas were 39 ha *vs* 209 ha, the number of dams was 10 *vs* 59 (with the government database only containing 5 dams) while the estimated full supply capacities of the dams were 1.43 x 10^6 m^3 from Landsat TM *vs* 4.18 x 106 m^3 from aerial photographs, i.e. a difference of nearly 3 times (11).

These discrepancies illustrate clearly that the detail of land use information is vital in assessing hydrological responses, certainly

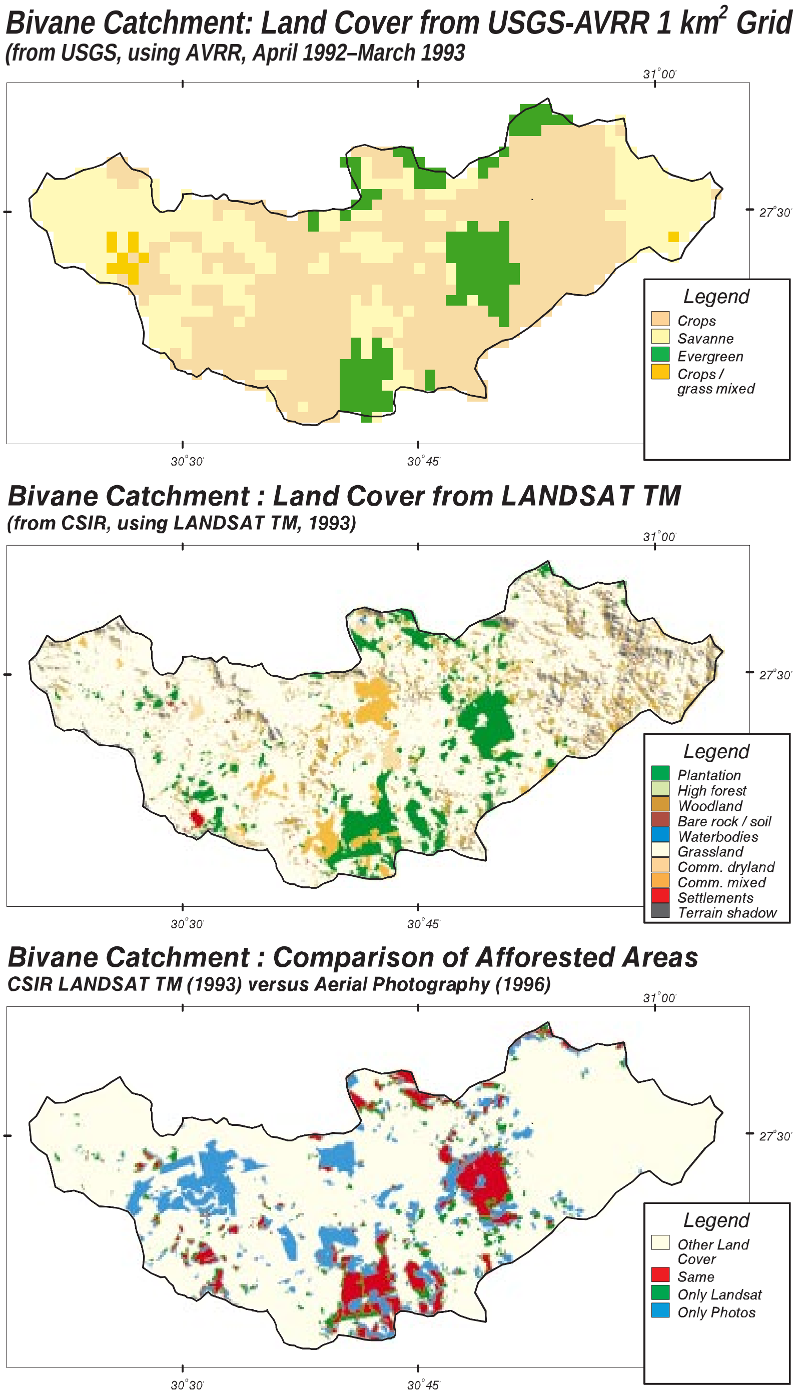


Figure 10. Identification of afforested areas in the Bivane subcatchment at different levels of detail (11).

at local scale, and certainly where critical land uses with potentially major hydrological repercussions are under scrutiny.

Issue 7. Between one region and the next, major components of the hydrological system often respond very differently when subjected to climate change.

A perception exists that under conditions of an enhanced greenhouse gas atmosphere, shifts in patterns of hydrological responses will largely mirror shifts in overall precipitation patterns. Hydrological responses are, however, subject to complex feedforward and feedback interactions in which any changes in precipitation (ΔP) on vegetated surfaces are modulated by the reductions that increased carbon dioxide levels ($+\Delta CO_2$) have on transpiration through increases in stomatal conductance, while all this may, in turn, be counteracted by positive changes in temperature ($+\Delta T$), which would increase soil water evaporation (5).

In order to illustrate that changes in, say, runoff and net irrigation demand display different spatial responses to the same changes in overall precipitation, the climate change scenario generator SCENGEN (12), which facilitates the generation of global and regional climate change scenarios using results from selected general circulation models (GSMs), was applied to southern Africa. For a simulation of monthly ΔP and ΔT between present climate and that predicted for the middle of the next century, the Hadley Centre's UKTR transient model (13) was selected to operate with the mid-range IS92a emission scenario (14) using the Intergovernmental Panel on Climate Change's (IPCC) mid-range global temperature change of 2.5°C. This model gave a warming of 1.7°C between the 1961–1990 baseline temperature and that for the decade of 2050. For spatial analytical purposes the 5° latitude/longitude grid of ΔP and ΔT values from SCENGEN was interpolated to a 1/4° grid by an inverse distance weighting procedure (15), and the interpolated values of monthly ΔP and ΔT were then used to perturb the climate databases of the 1946 Quaternary Catchments covering southern Africa. The *ACRU* model was then run for each Quaternary Catchment to produce values of various hydrological responses.

Figure 11. Simulated differences in mean annual rainfall, runoff and net irrigation requirements over southern Africa for a "future" minus present climate, using the Hadley Centre UKMO transient model in conjunction with the *ACRU* model (15).

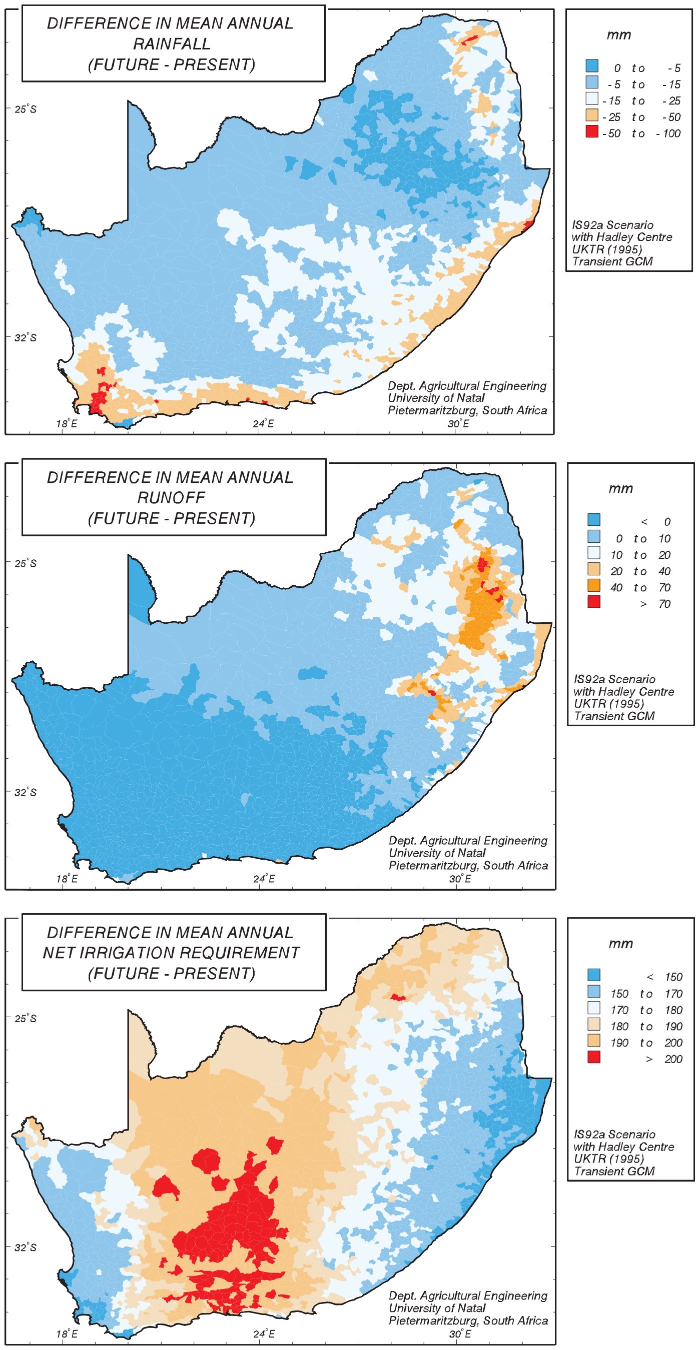
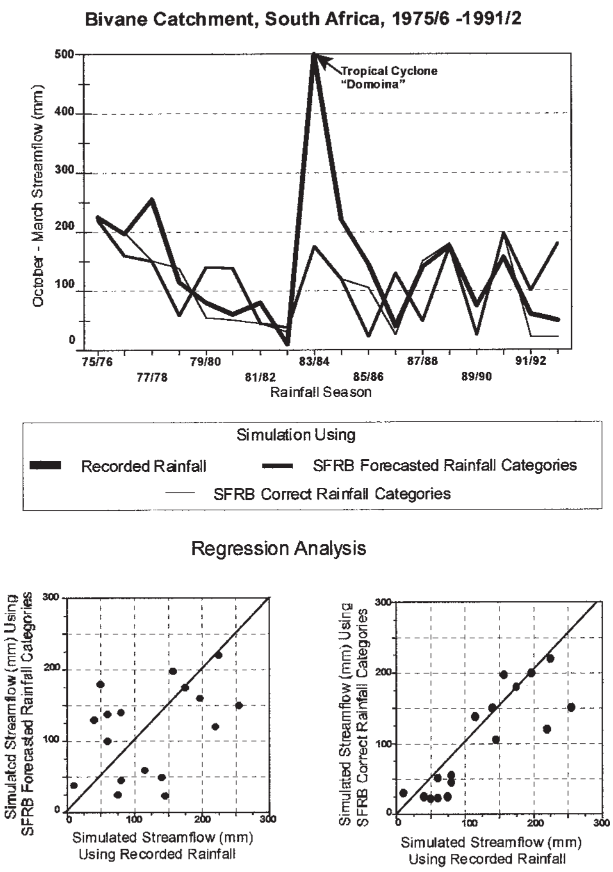


Figure 12. Comparison of seasonal streamflows in the Bivane catchment from recorded daily rainfalls, from downscaled daily rainfalls assuming correct rainfall forecast categories and those from actual forecast categories (16).



The three maps making up Figure 11 clearly support the hypothesis that different hydrological responses to global climate change do not simply mirror changes in overall precipitation patterns. The relatively large model prediction of a decrease in MAP along the south and east coasts (Fig. 11, top) does not show up in the map depicting changes in runoff (Fig. 11, middle), which changes most in a block around 27°S and 31°E. The apparently anomalous increase in runoff is in contrast to an expected decrease and is thought to be due to the *ACRU* model's overcompensating for the CO_2 effects of transpiration suppression. (This routine in the *ACRU* model has subsequently been revised). The change in net water requirements for supplementary irrigation of maize in summer (plant date 1 November; length of growing season 140 days) and wheat in winter (plant date 1 May; length of growing season 150 days) is highest in the semiarid zone from 29° to 34°S and 21° to 25°E (Fig. 11, bottom), i.e. in a totally different region to where changes in MAP and MAR occur. This illustrates clearly the different responses of components of the hydrological system in different regions in an enhanced greenhouse climate scenario.

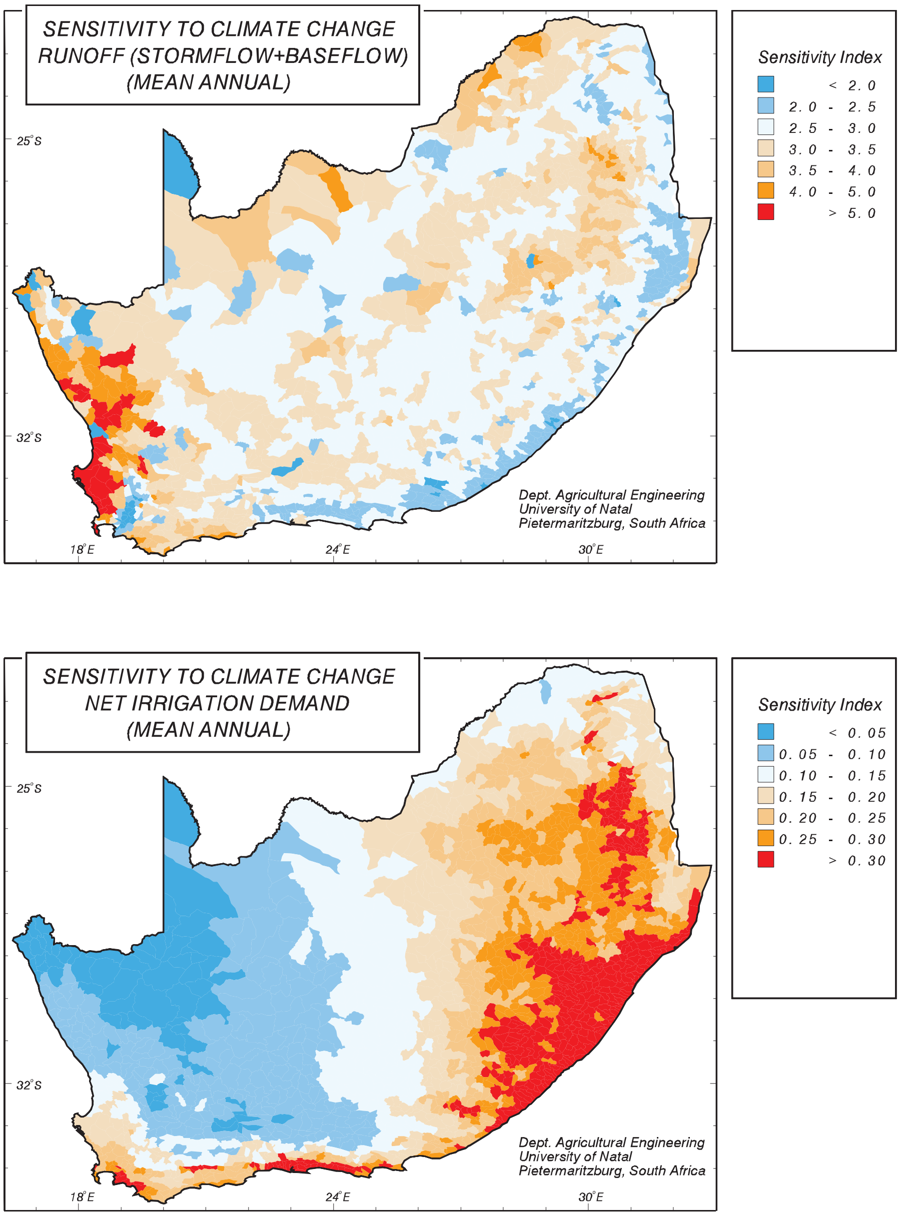


Figure 13. Sensitivity of runoff (top) and net irrigation demand (bottom) to climate change in southern Africa (15).

Issue 8. Hydrological concerns in developing countries are focused more on inter-seasonal scales than on decadal scales of climate change.

To the man in the street in rural Africa, the potential impacts of the enhanced greenhouse effect through the effective doubling of atmospheric CO_2 concentrations by (say) the year 2050 are often an incomprehensible scientific issue of no immediate concern. When, however, ordinary farmers as well as water managers start watching for Southern Oscillation Index trends and start talking of the onset of the next "Hell" Niño, these are "real" issues of the day, because food and water security are at stake to them. The correct forecasting of the onset, duration and intensity of the next El Niño, and converting this information into operational decision-making in water resources, then become scientific issues of relevance.

Two questions arise. First, if simple, but critical rainfall categories, such as above-normal, normal or below-normal could be forecast a season ahead, how well could hydrologists utilize this information? Second, how much would results improve for correct *vs* actual forecasts?

It has been shown for the Bivane catchment in KwaZulu-Natal province in South Africa (16) that *if* the categorical seasonal rainfall forecasts were correct, that by appropriate techniques of downscaling from seasonal categorical forecasts to daily rainfalls (the Seasonal Forecast Rainfall Builder, SFRB in Figure 12), a model can be used successfully to forecast rainy season streamflows (Fig. 12). However, extreme events—such as the heavy 600 mm 3-day rainfall and associated runoff coupled with cyclone Domoina in 1984—cannot yet be predicted a season ahead. Furthermore, the skill in forecasting correctly the category of a season's rainfall is still developing and if the actual forecasts which were made were to have been used in the Bivane catchment simulation, rather than assuming the rainfall forecasts to have been correct, the results are not yet as encouraging (Fig. 12, bottom left).

The example above highlights the potential application of seasonal rainfall forecasts in managing water resources by obtaining, with some confidence, an idea of the anticipated streamflows a season ahead.

Issue 9. In order to be proactive in regard to long-term climate change, there is a need to identify hydrologically sensitive areas.

In identifying regions which are more sensitive or less sensitive than others to climate change one examines the "elasticity" of a selected hydrological variable, i.e. the relative change of that variable, such as runoff or irrigation demand, to a change or combination of changes in a climatic forcing function (such as rainfall or temperature or potential evaporation). Results from a southern African spatial sensitivity study (15) are presented below. For an assumed uniform temperature increase of 2°C under x2CO_2 conditions, precipitation was initially maintained at "no change" from the present, and then perturbed by +10% and by –10% per day in the *ACRU* model for the climate databases in southern Africa. Model outputs for the three assumed precipitation regimes (ΔP of +10%, 0%, –10%) were then incorporated into a sensitivity equation such that

$$S = [(X_{+10} - X_{-10}) / X_0] / [P_{+10} - P_{-10}) / P_0]$$

in which S is the sensitivity index, X is the hydrological variable being assessed (e.g. runoff, or irrigation demand), P is the precipitation forcing function and subscripts +10, 0 and -10 refer to possible percentage perturbations of precipitation. The higher the value of S, the greater the sensitivity, i.e. the greater the relative change of the variable to a unit change in precipitation; hence the greater the nonlinear response to precipitation.

Figure 13 (top) shows that for X = runoff, the sensitivity index ranges from < 2 (moderately sensitive) to > 5 (highly sensitive). The map shows that it is not necessarily the present high rainfall or runoff areas (cf Fig. 4) that are more sensitive to relative changes of precipitation. This indicates also that more complex interactions are at play in runoff generation, for example, those related to soil properties or to antecedent wetness conditions. In the sensitivity study, where X = net supplementary irrigation demand, results of which are shown in Figure 13 (bottom), two striking differences to the runoff sensitivity map emerge. First, the highest sensitivity is, in this case, in the higher rainfall areas of the subcontinent (eastern and southern regions), where increased temperatures have a higher relative impact on supplementary irrigation water demands under different rainfall regimes than in more arid areas, where there is so little rainfall in the first instance that a +10% or –10% rainfall change has virtually no impact on an already high irrigation water demand. Secondly, it is significant to note that the values of the irrigation sensitivity index are an order of magnitude lower than those of runoff responses.

CONCLUSIONS

This paper has addressed the issue of land use, hydrology, and simulation modelling within a context of current climates as well as of climate change. Examples have been selected from experiments and modelling exercises in southern Africa and they were chosen to cross a range of spatial and temporal scales. In the final analysis, the issues presented in this paper raise some questions to the IGBP and its core programmes. These include the following:

How and when will one detect long-term climate change effects in a region where high natural variability is a dominating feature of both climate and hydrology?

Already existing, and often complex, land use patterns have significant impacts on hydrological responses. Should such studies not be pursued with the same vigor as the anticipated shifts modelled in natural vegetation belts under conditions of climate change?

Is the LUCC initiative addressing land use change and its impacts at appropriate scales for "real life" decisions to be made in, say, an African context?

Is BAHC, in its endeavors, addressing "real" issues of hydrology of, say, Africa and the modelling thereof, for actual decisions to be made for the welfare of developing populations?

Should the climate change paradigm shift from researching decadal scale prediction to seasonal scale forecasting and its operational impacts, a shift which is already evident, not be further encouraged?

In summary, are we active scientists in the IGBP programs focusing enough on actual problems of the hydrologically related environment on a continent with real, day-to-day problems of existence?

References

1. Turner, B.L., Skole, B., Sanderson, S., Fischer, G., Fresco, L. and Leemans, R. 1995. *Land-Use and Land-Cover Change: Science Research Plan*. IGBP Report, 35. IGBP, Stockholm, Sweden, 132 pp.
2. COHS. 1991. *Opportunities in the Hydrologic Sciences. National Research Council. Committee on Opportunities in the Hydrologic Sciences, Water Science and Technology Board: Commission on Geosciences, Environment and Resources*. National Academy Press, Washington DC, USA, 348 pp.
3. Nemec, J. 1995. General circulation models, climate change, scaling and hydrology. In: Kite, G. W. (ed). *Time and the River*. Water Resources Publications, Highlands Ranch, CO, USA, pp 317–356.
4. Schulze, R.E. 1995. *Hydrology and Agrohydrology*. Water Research Commission, Pretoria, RSA, 552 pp.
5. Schulze, R.E. 1997. Impacts of global climate change in a hydrologically vulnerable region: Challenges to South African hydrologists. *Progr. Phys. Geogr. 21*, 113–136.
6. Kienzle, S.W., Lorentz, S.A. and Schulze, R.E. 1997. *Hydrology and Water Quality of the Mgeni Catchment*. Water Research Commission, Pretoria, RSA, 88 pp.
7. Schulze, R.E. 1997. *South African Atlas of Agrohydrology and Climatology*. Water Research Commission, Pretoria, RSA, 276 pp.
8. Acocks, J.P.H. 1988. *Veld Types of South Africa*. Botanical Survey of South Africa, Memoirs, 57. Botanical Research Institute, Pretoria, RSA, 146 pp.
9. Scott, D.F. and Schulze, R.E. 1992. The hydrological effects of a wildfire in a eucalypt afforested catchment. *South African Forestry J. 160*, 67–78.
10. Schulze, R.E., Horan, M. and Perks, L. 1997. Water resources assessment in the Nadi catchment for community requirements at Ehlanzeni. *ACRUcons Report, 22*. University of Natal, Department of Agricultural Engineering, Pietermaritzburg, RSA, 24 pp.
11. Schulze, R.E., Taylor, V., Matthews, G. and Hughes, G.O. 1997. Hydrological impacts of land use practices in the Pongola-Bivane catchment, Phase 2: Re-assessment of land uses in the Bivane catchment and hydrological impacts thereof. *ACRUcons Report, 20*. University of Natal, Department of Agricultural Engineering, Pietermaritzburg, RSA, 22 pp.
12. Hulme, M., Jiang, T. and Wigley, T.L.M. 1996. SCENGEN, *A Climate Change Scenario Generator: User Manual*. University of East Anglia, Climatic Research Unit, Norwich, UK, 38 pp.
13. Murphy, J.M. and Mitchell, J.F.B. 1995. Transient response of the Hadley Centre coupled ocean-atmosphere model to increasing carbon dioxide. Part 2, Spatial and temporal structure of the response. *J. Climate 8*, 57–80.
14. Legget, J., Pepper, W.J. and Swart, R.J. 1992. Emissions scenarios for the IPCC: An update. In: Houghton, J.T., Callander, B.A. and Varney, S.K. (eds). *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. Cambridge University Press, Cambridge, UK, 38 pp.
15. Lowe, K.L. 1997. *Agrohydrological Sensitivity Analysis with Regard to Projected Climate Change in Southern Africa*. MSc dissertation. University of Natal, School of Environment and Development, Pietermaritzburg, RSA, 104 pp.
16. Lecler, N.L., Schulze, R.E. and Pike, A. 1996. Initial assessment of methodologies to generate agricultural and hydrological forecasts from seasonal categorical rainfall forecasts in South Africa. *Proceedings: Workshop on Reducing Climate Related Vulnerability in Southern Africa*. NOAA, Office of Global Programs, Washington DC, USA, pp 113–130.

17. Acknowledgements. The research results reported in this paper have emanated from projects funded by the Water Research Commission, the Foundation for Research Development and ESKOM, all from South Africa, as well as NOAA from the USA. Their support is acknowledged gratefully. I should also like to express my thanks to colleagues Gregory Kiker, Bradford Howe, Mark Horan and Lucille Perks for assistance with analytical/GIS work. All computations and GIS mapping were performed at the Computing Centre for Water Research at the University of Natal, and the Centre is thanked for making its facilities available.

Roland Schulze is a professor of hydrology in the School of Bioresources Engineering and Environmental Hydrology at the University of Natal in Pietermaritzburg, South Africa. His research interests are in applied hydrological modelling, climate and land use change impacts and in integrated water resources management. He is a member of the Scientific Steering Committee of IGBP-BAHC. His address: School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, P. Bag X01, 3209 Scottsville, South Africa E-mail: schulze@aqua.ccwr.ac.za