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Simulating the impacts of land-use change on streamflow time series for southern African rivers

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Abstract Two rainfall-runoff models (one daily and one monthly time-step) have been tested using catchments where the land-use changes (afforestation and clear felling) in the recent past have been well documented. In general terms, the models performed satisfactorily and the changes in parameter values required to simulate the changes were reasonably consistent across the range of catchments considered. While all the catchments used were small headwater areas, it is suggested that the same scheme of parameter value change can be applied at the larger scale. It is not really possible to determine whether the models are sensitive to differences caused by variations in planting or management practices, largely because these can be masked by errors in, or lack of representativeness of, the input rainfall and evapotranspiration data.

INTRODUCTION

The effective management of water resources in southern Africa has to consider the effects that land-use changes within catchment areas have on the availability of water downstream. This includes effects which are already present in the existing flow regimes, as well as future effects relating to expanding afforestation, clear felling or other landaus changes. Only then can effective water availability be quantified and future water resource management options be assessed. There have been a number of studies carried out in South Africa and Zimbabwe that have attempted to quantify the effects, but most of these have concentrated on estimating the changes in mean annual runoff (MAR) or other statistical summary indices of the full time series (Andrews & Bullock, 1994). There appears to have been less effort directed at assessments of incorporating the effects into time series simulation models, although the ACRU model development team at the University of Natal have worked extensively on this problem (Schulze, 1997).

This paper reports on a part of the rainfall-runoff modelling sub-programme of the first phase of the southern Africa FRIEND project which was designed to assess the applicability of daily and monthly time-step models to catchments within the region. The models chosen were the widely used Pitman monthly model (Pitman, 1973) and the daily VTI model (Hughes & Sami, 1994). The latter was chosen due to the familiarity with its application by the project team and because it has been demonstrated to simulate low flow responses quite well for catchments in the region. Apart from the general applicability of the two models, it was also decided to investigate the sensitivity of the two models to known changes in land use. The full details of the results of this study are available in Hughes (1997).

AVAILABILITY OF DATA

It was necessary to select catchments which were well gauged (in terms of rainfall and potential evapotranspiration inputs and streamflow outputs) and where the land-use changes are well documented. The only land-use impacts simulated during this project are therefore related to afforestation or clear felling on relatively small headwater catchments. Unfortunately, no data were made available to assess other typical land-use changes that are considered to potentially impact on streamflow in southern Africa (e.g. natural vegetation clearance for agriculture, overgrazing, construction of farm dams, urbanisation, etc.).

The flow data were supplied by either the Institute of Hydrology, UK, or the CSIR (South Africa) and consisted of reasonably complete records of mean daily flow. Rainfall data were obtained from the same sources as the flow data and mostly consisted of mean catchment rainfalls, rather than individual station data. These small experimental catchments are located in mountainous areas with potentially steep rainfall gradients and it is not always possible to generate suitably representative rainfall inputs. The potential evaporation data used consisted of mean monthly data from the closest possible source. Given the importance of the evaporation component of the models in assessing land-use changes, it is possible that the lack of detail (spatial and temporal) in the quantification of potential evaporation could influence the results. Details of the catchments physical characteristics have been drawn from various published reports and scientific papers. As all the catchments were established for research purposes, the general level of detail is better than most of the other catchments used in the FRIEND project. It was essential that a high level of detail about the cover characteristics was available, otherwise there would be a degree of uncertainty in any conclusions reached about the parameter value changes required to simulate different effects. It was largely this criterion that limited the number of catchments that could be used.

The catchments used

Erin catchments, North Eastern Highlands, Zimbabwe These are located in the headwaters of the Odzi River at 18°54 S and 32°53 E and consist of a gauged control area of 0.21 km^2 and a treated area of 0.76 km^2, the total area also being gauged. The catchments are relatively steep (approximately 20% slopes) and the soils (Du Toit, 1961) vary from shallow and stony sandy to sandy clay loams on the ridge tops and steep slopes to deeper sandy loams over sandy clays in the flatter areas. The bedrock consists of weathered and fractured granites, which are expected to play a major role in the catchments' baseflow response. The original vegetation consisted of relatively short montane grassland with some low shrubs and relict montane forest trees. The sequence of afforestation in the Lower catchment (0.76 km^2) began during 1980 with land clearance and there were two periods of thinning (1985 and

1992/1993). Rainfall data were available for 1975 to 1991, while flow data were available from 1977. Hydrological years 1977 and 1978 could therefore be used to calibrate the models under grassland conditions, after which the parameter values could be changed to reflect the treatment applied to the Lower catchment.

Jonkershoek catchments, Western Cape, South Africa These consist of six gauged areas draining the Jonkershoek Mountains to the Eerste River in the Western Cape, South Africa (van Wyk, 1987). In this study, three of the gauged areas have been used; Bosboukloof (200.9 ha), Lambrechtsbos B (65.5 ha) and Langrivier (245.8 ha). The area is underlain by sandstones of the Table Mountain Group, which overlie deeply weathered Cape Granites. The soils are deep sandy to silty loams with high gravel and rock content, which are friable, have high infiltration rates and become highly water repellent at depth after intense fires (Scott & van Wyk, 1990). The natural vegetation is a tall (2–3 m) open to closed shrubland, dominated by *Protea* species, with evergreen tall forests occurring along permanent streams. Rainfall data were provided from the closest stations, but rainfall gradients are very steep, varying from approximately 1300 mm over Bosboukloof to over 2200 mm for Langrivier. Estimation of rainfall inputs to the latter are particularly difficult as the only raingauge is in the lower part of the catchment.

Bosboukloof (data from 1978 to 1990) was planted (57% of area) to *Pinus radiata* in 1940, clear felled and re-planted during 1980/1982 then burned during a high intensity wildfire in 1986. The first two years of the record can therefore be used to establish parameter values for mature forest cover and the remaining period to assess the parameter value changes to account for clear felling and burning. Lambrechtsbos (data from 1972 to 1995) was planted (82%) to *Pinus radiata* in 1964/1965 and then progressively thinned over 1973/1983. As the trees had not reached maturity when the hydrological data start, there is no stable cover period that can be used to calibrate the models. The approach was therefore to compare the results of fixed parameter values for the whole period versus changing values to account for a combination of growth and thinning. Langrivier (data from 1971 to 1995) has natural Fynbos cover that was burned in a wildfire during 1987.

Mokobulaan catchments, Mpumulanga, South Africa These are situated (at 25°17 S, 30°34 E) in the Uitsoek State Forest on the Transvaal Drakensburg escarpment and full descriptions of their characteristics are provided in Nänni (1971). The area is underlain by basal shales which are semi-weathered, broken to 30 m below the surface and permeable to roots and water for much of this depth. The real soil is only a few centimetres deep and plant growth relies upon water stored within the shale bedrock. The original vegetation is a sub-climax grassland with evergreen forest in the riparian strips. There are three gauged catchments: A (26.2 ha) planted to eucalypts, B (34.6 ha) 100% planted to pines in 1971 and thinned in 1973; C (36.9 ha) kept as a grassland control. Only data for Mokobulaan B were made available to this project. The catchments are relatively steep (slopes > 20%) and experience mean annual rainfalls of 1100–1200 mm. The data made available cover the period from 1971 to 1982 after which all runoff ceased. As the data do not cover the period prior to planting, it was not possible to calibrate the models during natural conditions. The approach has therefore been to carry out a rough calibration on the first three years of data, before the trees would be expected to have a great influence and then to test the parameter value change principles developed for the other catchments for the remainder of the period.

Westfalia Estate, near Tzaneen, Northern Province, South Africa These are mountain catchments (slopes >20%) underlain by granite gneiss with friable, well drained and deep, clay loam soils. The mean annual rainfall is of the order of 1600 mm, the natural vegetation consists of scrub forest and they are situated close to 23°43 S, 30°04 E. Data were made available for the treated catchment (40 ha) from 1975 to 1991. Clearance of the natural vegetation took place during 1981/1982 followed by planting and thinning of *Eucalyptus grandis*. The first six years of data could be used for model calibration, after which the parameter values were changed to account for clearing and forest growth.

MODEL CALIBRATIONS

The calibrations were started using the Erin data, by first using the control catchment and the part of the record on the modified catchment before afforestation. The parameters of the models were then modified according to an intuitive understanding of the effects of parameter value changes in relation to the perceived impacts of afforestation, or through direct input of the area of forest (for those parameters which are estimated from physical catchment characteristics). The parameters changed are therefore mainly those that relate to interception, vegetation water demand and rooting depth. However, it was also perceived that the increased cover in relatively mature forest would influence the infiltration characteristics of the soil surface, largely by reducing effective rainfall intensity and through increased litter. Once the intuitive parameter value changes were revised for the Erin, the models were applied to the other catchments to determine if the same basic principles could be used.

Both models allow "time-slices" of varying parameter values to be established. Periods within the total simulation can be defined so that parameter values either increase or decrease linearly over the time-slice, or are raised or dropped instantaneously at the start of the time-slice. The procedure for simulating new afforestation is therefore to gradually increase or decrease the relevant parameter values to simulate growth. The instantaneous change option is used for clear felling or thinning. It was accepted that there may be several stages of growth with different rates and that several separate time-slices may be required to simulate the situation from initial planting to maturity, with some intermittent thinning. The same principle would apply for a managed plantation under different harvesting and re-planting (rotation) practices.

Pitman model results: Erin catchments

Table 1 lists some of the parameter values and the initial phase of afforestation (first 2–3 years after clearing) has been simulated with no forest cover, but a return to characteristics similar to summer grassland but with more effective

Table 1 Some Pitman model parameters, Erin catchments.

	Control (21 ha)	Afforested (76 ha): Before November 1980	November 1980 for 1 month	February 1981 for 43 months	October 1984 for 36 months
Min. absorption rate (mm)	320.0	320.0	320.0	320.0	350.0
Max. absorption rate (mm)	950.0	950.0	950.0	950.0	950.0
Summer grass interception (mm)	1.5	1.5	1.0	1.5	1.5
Winter grass interception (mm)	1.2	1.2	1.0	1.5	1.5
Forest interception (mm)	4.0	4.0	4.0	4.0	4.0
Evap-storage coeff (mm)	0.5	0.5	0.75	0.4	0.1
Forest area (%)	0.0	0.0	0.0	0.0	92.1
Forest/grass PE ratio	1.5	1.5	1.5	1.5	1.5

Table 2 Simulation results, Pitman model, Erin catchments (the values in parenthesis for the mean and SD of monthly flows are the simulated values).

Catchment	Period	Mean (Ml)	SD (Ml)	Mean % error	R^2	CE
Control 21 ha	1977–1991 Obs (Sim)	5.0 (5.8)	4.7 (5.0)	16.0	0.88	0.80
Total 97 ha (Fixed grass parameters for 76 ha)	1977–1982 Obs (Sim)	49.3 (42.5)	44.7 (34.7)	−13.7	0.94	0.88
	1982–1987 Obs (Sim)	29.3 (33.4)	27.5 (27.4)	14.0	0.72	0.68
	1987–1991 Obs (Sim)	21.5 (33.1)	17.1 (21.2)	53.9	0.88	0.32
Total 97 ha (Time-sliced parameters for 76 ha)	1977–1982 Obs (Sim)	49.3 (43.0)	44.7 (34.7)	−12.8	0.94	0.89
	1982–1987 Obs (Sim)	29.3 (29.8)	27.5 (25.2)	1.8	0.76	0.75
	1987–1991 Obs (Sim)	21.5 (21.3)	17.1 (15.9)	0.9	0.89	0.89

evapotranspiration. The following time-slice of three years then introduces the main impacts, which have been assumed to remain stable for the remainder of the period to September 1991. Table 2 lists some statistics for the simulation results divided into three periods. The afforested catchment results are presented for the simulations with fixed grass parameters (derived from the calibration period; 1977–1979) and for the parameters that were used to simulate the land-use changes. The same calibration period was used for the control catchment and it is apparent that some revision of the parameter values would be appropriate to achieve better overall simulations. The time-sliced parameters produce better simulations over the second two periods than the fixed grassland parameters (Fig. 1) and suggest that the runoff volume was reduced by some 13% during the first 5 years and 42% during the 4-year period after 1987.

Pitman model results: Other catchments

There is not space in this paper to report on all the results in detail so this section is confined to a brief summary. The results demonstrate that, in general terms, the model is able to simulate the impacts of afforestation with either pine or eucalypt trees and clearfelling of pine trees. There is a reasonably high degree of stability in the nature of the parameter value changes that are necessary to achieve this. The model did not seem to be very sensitive to the effects of wildfires on two of the catchments and the results were not examined in sufficient detail to determine whether or not the model is capable of correctly simulating the shorter term effects during different stages of growth. It is very difficult to make firm conclusions about the model's abilities in this regard as it involves assessing the simulation results for individual years, when other factors (rainfall and PE input accuracy, for example) also influence the results. Figure 2 illustrates the simulation results for time-sliced

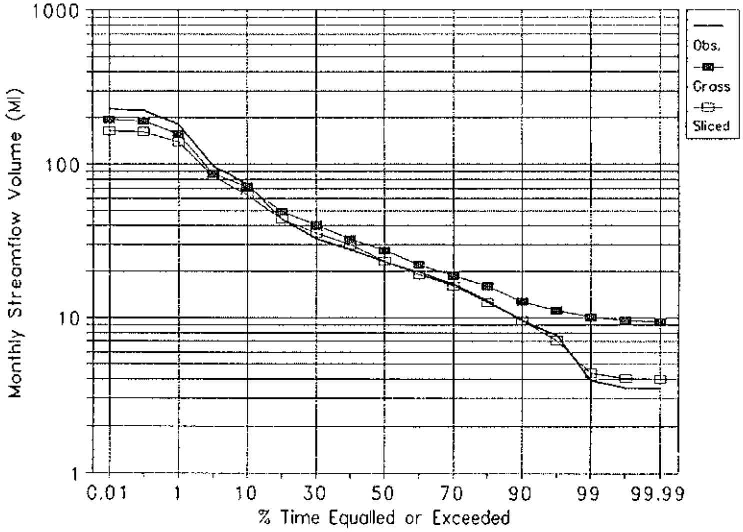

Fig. 1 Erin total catchment (97 ha, 70 ha afforested), monthly flow duration curves for observed and simulated (using fixed grassland and sliced parameter values) based on data from October 1977 to September 1991.

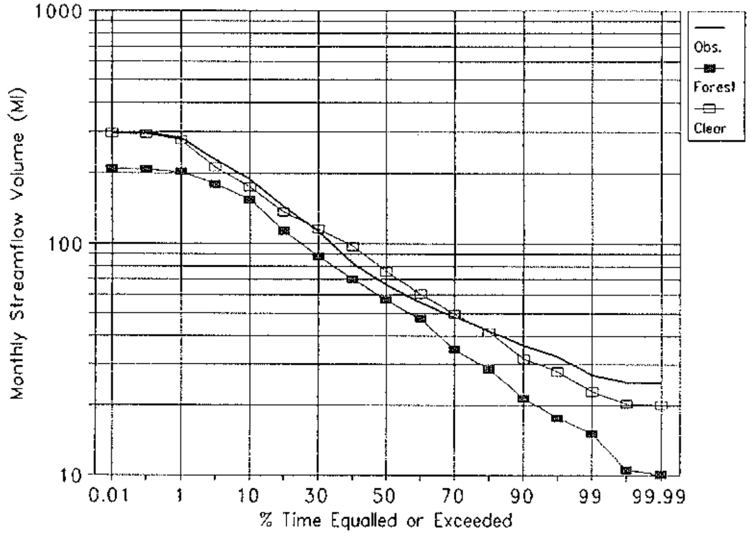

Fig. 2 Bosboukloof catchment (200.9 ha, 111 ha afforested), monthly flow duration curves for observed and simulated (using fixed forest and sliced parameter values for clearance and wildfire) based on data from January 1981 to December 1991.

clearance of the Bosboukloof catchment versus fixed forest parameters. The mean percentage error in simulated monthly volume changed from -36% to -8% after the introduction of the modified parameters. The most dramatic effect of afforestation can be seen in the Mokobulaan catchment (Fig. 3) where the simulations with fixed grassland parameters gave 79% and 530% errors for the periods 4-8 and 8-11 years after planting, respectively. The time-sliced forestry parameters changed these errors to -4.5% and 39%.

VTI model results: Erin catchments

Table 3 lists the values of the model parameters (see Hughes & Sami, 1994) for explanations of their meaning) that were changed to simulate the afforestation effect, while Table 4 presents some comparative statistics (based on daily data) between observed and simulated flows. It is clear that the results are comparable to those obtained using the monthly model, but given that these are based on daily data, the implication is that the VTI model has performed somewhat better.

VTI model results: other catchments

In general terms the application of the model to the other areas was successful; the model is sensitive to most of the land-use changes considered and the parameter value modifications used to generate the effects are reasonably consistent. Where relevant, these changes can also be predicted using the standard set of estimation procedures associated with this model. As with the Pitman model, the wildfire effects were not very straightforward to simulate and it is difficult to confirm whether or not the parameters used to simulate the effects of thinning are really appropriate.

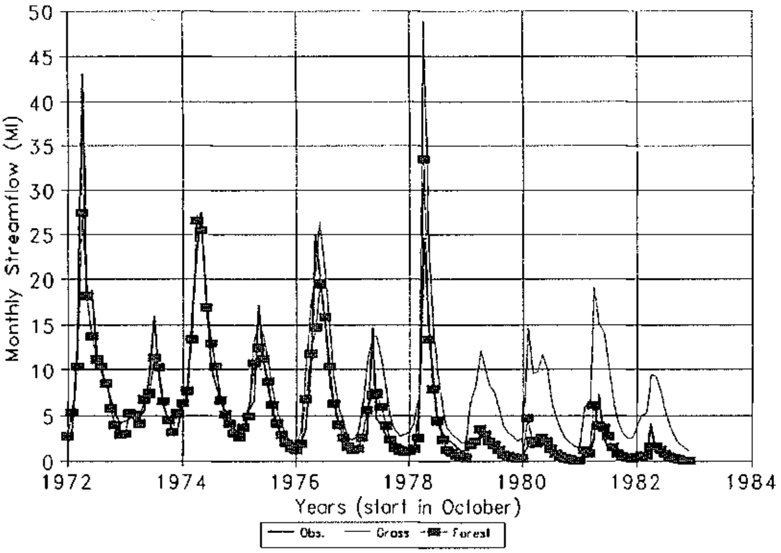

Fig. 3 Time series of observed and simulated (using grass and modified parameter values) monthly flows for Mokobulaan.

GENERAL CONCLUSIONS ABOUT THE MODEL RESULTS

The main report (Hughes, 1997) summarises the parameter value changes for the two models that have been used to simulate the land-use effects represented by the limited data set that was made available. The report integrates the results for all the catchments and provides approximate guidelines for future use of the models in similar situations. Caution should be exercised in applying these guidelines too literally as they are developed on the basis of a small sample of small sized catchments.

The models certainly seem to be capable of simulating the general response of catchments to afforestation and clear felling, but it is not clear to what extent the models are suitable for simulating the effects of thinning and the responses at certain stages of growth. The implication is that the experience of the models is not sufficient to allow their application to simulating the different responses brought about by different planting and management practices. The fact that the models have been able to reproduce the responses during the growth of a plantation forest, without even really attempting to relate the parameters to actual stages of growth, suggests that there is some potential for applying both models to more detailed studies. However, the likely success (or failure) of such an exercise cannot be concluded from the results of the present study.

With respect to a comparison of the volumes of the different components of the two models it is interesting to note what proportions are lost from canopy

Table 3 VTI model parameters, Erin catchments.

		Afforested (76 ha):			
	Control (21 ha)	Before November 1980	November 1980 for 1 month	February 1981 for 43 months	October 1984 for 36 months
Crop factor	0.8	0.8	0.6	0.8	1.4
Proportion veg. cover	0.36	0.36	0.26	0.40	0.85
Leaf Area Index	1.3	1.3	0.9	1.3	4.2
Canopy capacity (mm)	0.33	0.33	0.16	0.33	1.85
Infil. curve k parameter	0.63	0.63	0.63	0.63	0.63
Infil. curve C parameter	175.0	175.0	175.0	175.0	200.0
St. dev. soil moist. distr.	0.11	0.16	0.16	0.16	0.14

Table 4 Simulation results, VTI model, Erin catchments (the values in parenthesis for the mean and SD of daily flows are the simulated values).

Catchment	Period	Mean (l s^{-1})	SD (l s^{-1})	Mean % error	R^2	CE
Control 21 ha	1977–1991 Obs (Sim)	2.0 (1.9)	2.2 (2.1)	5.0	0.79	0.78
Total 97 ha (Fixed grass parameters for 76 ha)	1977–1982 Obs (Sim)	18.6 (17.8)	19.8 (14.5)	–4.3	0.89	0.89
	1982–1987 Obs (Sim)	11.0 (13.2)	11.3 (12.2)	20.0	0.71	0.58
	1987–1991 Obs (Sim)	8.2 (13.7)	7.2 (10.0)	67.0	0.86	0.27
Total 97 ha (Time-sliced parameters for 76 ha)	1977–1982 Obs (Sim)	18.6 (18.4)	19.8 (15.8)	–1.1	0.90	0.89
	1982–1987 Obs (Sim)	11.0 (12.0)	11.3 (11.2)	9.1	0.80	0.76
	1987–1991 Obs (Sim)	8.2 (9.4)	7.2 (7.2)	14.6	0.86	0.81

evaporation and soil or ground water evapotranspiration. For the Erin catchment under grassland conditions, the Pitman model suggests 16% and 84% for losses from the canopy and soil, respectively. Under forest conditions the overall evaporative losses increase by 31% and the distribution changes to 35% (canopy) and 65% (soil). The grassland figures for the VTI model are similar, except that 4% is simulated as being lost from ground water. For the forested condition (26% increase in total losses), 29% is lost as canopy evaporation, 67% from the soil and 4% from ground water. The other catchments indicate broadly similar trends, given the differences in the land-use changes and the parameter values used to represent them. Apart from the additional ground water component, the two models give broadly similar results using the Pitman model parameters recommended by the study.

APPLICATION TO OTHER CATCHMENTS

There are many gauged catchments in South Africa that have quite extensive areas of afforestation. However, in a large number of cases, either the plantations were established prior to accurate gauging, the extent of coverage is not well defined or the proportion of the catchment covered is relatively small. These factors make it difficult to assess the application of the parameter value change recommendations to larger catchments and longer time series. However, the same parameter value principles have been applied during extensive use of the two models for simulating historical runoff from catchments within South Africa and other parts of the subcontinent. The results have always been generally favourable and the estimates of the runoff reductions caused by afforestation (estimated by operating the model with parameters applicable to afforested and natural conditions) are comparable with other approaches (Gorgens & Lee, 1992; Scott & Smith, 1997).

The same conclusions in general can be applied to other land-use changes. Both models are capable of simulating the impacts of irrigation, assuming that the amounts and patterns of abstraction, application and return flow can be defined. This applies equally to whether the water is obtained through a direct, run-of-river scheme, or from a series of dams. With respect to other rural land-use changes, the main problem lies in defining the different water uses for the original versus the changed cover. If these are well documented, it is considered by the authors that such effects can be incorporated into the models without too much difficulty. However, there are many cases where this is not the case and an example is the conversion of indigenous forest to managed pine forests. While the water use of the plantations is reasonably well documented, the water use dynamics of indigenous forest in a southern African context is not. Neither of the models has been adequately tested in catchments subject to urbanisation and therefore no conclusions can be reached about their applicability to such land-use changes.

Hughes & Smakhtin (1997) developed a relatively simple daily model (requiring no rainfall data and very little calibration) that can be used to patch and extend flow time series based on the characteristics of duration curves and a spatial interpolation approach. One of the issues related to the application of the model is that the source and destination sites of the spatial interpolation procedure should have the same stationarity characteristics (i.e. they should both be stationary, or both affected by the same impacts). However, the model could have wider application if the effects of various land-use changes could be interpreted into effects on flow duration curves. One possible method of determining these effects is to run a series of simulations for different climate zones and land-use effects using the VTI model.

CONCLUSIONS

While there are existing techniques that allow the reduction in total or low flow runoff from afforested catchments to be estimated (e.g. Scott & Smith, 1997), less attention has been given to techniques that are relatively simple to apply and that can generate time series of natural and impacted streamflow under a variety of scenarios. Such time series are frequently necessary for detailed catchment yield analyses (whether based on direct abstractions or reservoirs) and studies designed to assess and recommend environmental instream flow requirements. In these situations the mean flow conditions are of less importance than quantifying the intra-seasonal variations and the extreme low flows that occur during drought periods. It is therefore useful to have a broad range of tools that can estimate flow reductions (or increases) with changes in land use and that are all reasonably compatible with each other in terms of the results that they produce.

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