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# The effects of afforestation and deforestation on water yields

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**Abstract**

The exploitation of land and water resources to sustain an ever-increasing population inevitably involves the utilisation for both urban and agricultural development of rural areas and the natural landscape. This process can result in profound changes to the flow regime of river basins that are so affected, the scope and magnitude of which have been investigated by means of experimental catchment studies. The extensive data base that has resulted from such activities has provided a basis for developing a series of generalised relationships which can be used by water resources planners to anticipate the changes in water yield that can result from alterations to the predominant vegetative cover of a catchment. The application of fuzzy linear regression analysis to data from 145 experiments has shown that, for a 10% reduction in cover, the yield from conifer-type forest increased by some 20–25 mm, whereas that for eucalyptus-type forest increased by only 6 mm. Both values were somewhat lower than those previously published, as was the 5 mm decrease in yield associated with a 10% afforestation of scrub. A 10% reduction in the cover of deciduous hardwood gave a 17–19 mm increase in yield, broadly in line with earlier estimates.

## 1. Introduction

To all those involved in hydrology and water resources, land-use change is the problem which will not go away. Such changes disrupt the hydrological cycle of a drainage basin, altering both the balance between rainfall and evaporation and the runoff response of the area. In semi-arid areas with fragile ecosystems, vegetation removal by overgrazing and firewood collection reduces evaporation and may initiate a feedback mechanism that results in lower rainfall (Savenije and Hall, 1993; Savenije,

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1995). In contrast, the changes in surface composition and the introduction of man-made drainage systems that accompany urbanisation cause a series of wide-ranging effects that can increase flood volumes and peak flow rates, reduce low flows and even intensify local storm activity (Hall, 1984).

The precise mechanisms by which the water balance of an area changes in response to alterations in land use can also be controversial, as demonstrated by the debate on whether catchments draining to reservoirs should be predominantly forest or grassland, which has only been resolved by detailed studies of the physical processes involved (Calder, 1990). Indeed, the traditional approach to evaluating the effects of land-use changes has involved the use of experimental catchments, either singly or in pairs (McCulloch and Robinson, 1993). In the former case, following an initial calibration period with one land use, changes are made and measurements are continued over a comparable period. In the latter case, either two catchments that are similar in all characteristics except vegetal cover are monitored simultaneously, or one of the pair is subjected to a land-use change following an initial calibration period and the other remains in its original condition as a control over the subsequent measurement period. These approaches have been applied for more than a century, and a considerable literature has been generated. The major review by Bosch and Hewlett (1982) summarised 94 such experiments, and activities have continued apparently undiminished in intensity during the last 12 years, with particular attention being paid to tropical rainforest (Bruijnzeel, 1990) and eucalyptus forest (Ruprecht and Schofield, 1989).

Although the results obtained from experimental catchment studies can only be explained satisfactorily in terms of the hydrological processes that are affected by the land-use changes that have been implemented, there remains a need for broad guidelines which can be applied in water resources planning studies to anticipate how flow characteristics, such as catchment water yields, might respond to such changes. The development of such guidelines could be based upon a generalisation of the results already published in summary form. In this paper, this possibility is explored using both classical techniques of multiple linear regression analysis (MLRA) and fuzzy linear regression analysis (FLRA). The following section therefore describes the data base developed for this purpose, building upon and updating the information presented by Bosch and Hewlett (1982). The application of MLRA is then outlined, but the unsatisfactory results obtained prompted the exploration of FLRA, an alternative technique founded in the theory of fuzzy sets (Bardossy et al., 1990). Based upon the results obtained by FLRA, some preliminary guidance is presented on the effects on water yield of the removal of different cover types.

## 2. The data base

The starting point for compiling the data base was the comprehensive tabulation of 94 catchment experiments provided by Bosch and Hewlett (1982, Table 1). Further useful summaries have subsequently been provided of deforestation of eucalyptus in Australia (Ruprecht and Schofield, 1989, Table 2), deforestation of tropical rainforest

(Bruijnzeel, 1990, Table 4), and of the impact of forest treatments in the North-eastern USA (Hornbeck et al., 1993). The effects of regrowth after fire have been reported by Scott (1993) and Lavabre et al. (1993), and further useful data were extracted from Troende and King (1987), Borg et al. (1988), Samaraj et al. (1988), Robinson et al. (1991), Ruprecht et al. (1991), Blackie (1993), Cornish (1993), Robinson (1993) and Stoneman (1993). For the convenience of other users, the additional information collected has been summarised in the Appendix. The forms in which results have been presented vary widely between researchers, and in compiling these data, some interpretation has inevitably been required.

The updated compilation of data contained the details of 145 catchment experiments relating to the deforestation and afforestation of many different species of vegetal cover. The available information was therefore classified into the following seven different cover types describing the condition of the catchments before treatment:

hardwood: catchments with hardwood, oak, aspen, juniper and beech, which cover a high proportion of the ground and do not have a continuous layer of grass beneath the canopy, were included in this group;

conifer: drainage areas with perennials such as conifer, pine, spruce and fir were allocated to this group;

hardwood–conifer: a mixed cover of species in the first two categories;

eucalyptus: native vegetation in Australia, also investigated in India;

rainforest: dense cover found in high-rainfall areas of the tropics;

scrub: catchments with stunted trees and bushes, particularly characteristic of arid areas, were included in this group along with maquis and chaparral;

grassland: areas with short, dense cover and few trees were allocated to this classification.

For all catchments, those characteristics that might be related to a change in the annual volume of runoff or water yield were collected and entered in the data base. Where possible, information was extracted on mean annual rainfall, mean annual potential evaporation, mean annual runoff, catchment area, elevation, percentage of area treated, soil type and basin orientation. Where the details were provided, the changes in yield were the averages over a period of up to 5 years subsequent to treatment. Unfortunately, not all experiments were reported in the same format, and values of some variables (including catchment area in some instances) were not quoted at all. However, adopting the above classification of cover types yielded sufficient data to explore the possible relationships of the change in annual yield with selected independent variables.

## 3. Linear regression analysis

Bosch and Hewlett (1982) provided a graphical summary of their data, using three cover types (conifer, deciduous hardwood and scrub) and assuming that the maximum decreases in yield following afforestation of grassland or scrub were equivalent to the first-year increase after clearcutting. Although the regression of annual streamflow increases on percentage reductions in cover yielded three distinct relationships, the reported explained variances ranged from only 12 to 42%, with the conifer data yielding the best equation, albeit with substantial scatter of points about the line. The question therefore arises of whether the availability of more data might improve the estimates of the regression coefficients and the inclusion of additional independent variables might reduce the amount of residual variance.

First, correlation matrices were constructed for each of the seven cover types defined above. Following Bosch and Hewlett (1982), annual yield change was taken as the dependent variable. (Consideration was given to using the quotient of yield change and mean annual runoff, but lack of information on the latter parameter was considered to make the sample sizes too small.) From these matrices, five independent variables were identified, values of which were available for as many catchments as possible. These variables included mean annual precipitation (MAP), mean elevation above sea-level (ELEV), mean annual potential evaporation (MAE), catchment area (AREA) and percentage of catchment over which cover was altered (PTR). Unfortunately, not all variables were reported for all experiments, resulting in reduction of sample sizes to single figures in the case of hardwood–conifer and eucalyptus forest-types, although 40 data were available for hardwood forest-type and the remaining cover types provided between 12 and 16 sets.

Second, each of the data sets was subjected to a stepwise linear regression analysis both with and without logarithmic transformation. Results were evaluated on the basis of the percentage of variance explained by the independent variables and the null hypothesis that all true partial regression coefficients were equal to zero was examined by means of an $F$-test. Although the explained variance with all five independent variables (three for the eucalyptus forest-type) only dropped below 80% in three cases, the null hypothesis of zero partial regression coefficients was rejected only for hardwood, conifer and grassland cover types. Moreover, the order in which the independent variables entered into the regression varied between data sets, with MAP chosen first in five cases and second in one, and PTR selected second in two cases and third in one.

The lack of consistency in the form of equation and the absence of statistically significant relationships for four cover types was considered to arise largely from the small sample sizes available and the general heterogeneity of the data set. In these circumstances, there are several alternatives to conventional least-squares regression that could be explored, such as robust regression, which assists in identifying outliers in the data set (Rousseeuw and Leroy, 1987; Sprent, 1993), or the application of bounded influence estimators, which attempt to reduce the effects of individual suspect data (Rousseeuw and Leroy, 1987). Yet another alternative applicable to the same situation is that of fuzzy linear regression analysis (FLRA), a comprehensive description of which has been provided by Bardossy et al. (1990).

In FLRA, both the dependent variable and the regression coefficients may be treated as fuzzy numbers, i.e. numbers that belong to a given range of values with a certain degree of membership. The particular advantage of this approach is the ability to define the outer limits to the derived relationships, as represented by the zero membership levels, as an integral part of the procedure. Bearing in mind the limited extent to which fuzzy concepts have been applied to hydrological problems, an exploratory study using FLRA was conducted of the extended data set relating to changes in water yield following afforestation and deforestation.

## 4. Fuzzy linear regression analysis

As proposed by Tanaka et al. (1982), FLRA provides the means by which the 'goodness' of a relationship between two variables, $y$ and $x$, may be evaluated on the basis of a small sample size. In this approach, the regression coefficients are assumed to be fuzzy numbers, i.e. numbers that belong to a given set with a certain degree of membership. By definition, a fuzzy set, $A$ (say), is a collection of objects without clear boundaries. The grade of membership of an element $x$ to this set is described by a membership function, $m(x)$ say, which is limited to values between one ($x$ clearly belongs to $A$) and zero ($x$ does not belong to $A$). Membership levels of zero and one are said to denote 'crisp' sets. The value of $m(x)$ therefore reflects the level of belief (or vagueness) that $x$ fulfills the condition of belonging to $A$. More formally, the $H$-level set, $0 < H < 1$, of the fuzzy set $A$ is denoted by $\{x, m(x) > H\}$.

In applying FLRA, particular attention is paid to a special class of fuzzy numbers, known as $L$–$R$ fuzzy number, for which

$$\begin{aligned} L(x) = R(x) &= 1, \quad x < 0 \\ L(x) = R(x) &= 0, \quad x > 0 \end{aligned} \tag{1}$$

and $L(x)$, $R(x)$ are strictly decreasing functions on the interval [0,1]. More specifically,

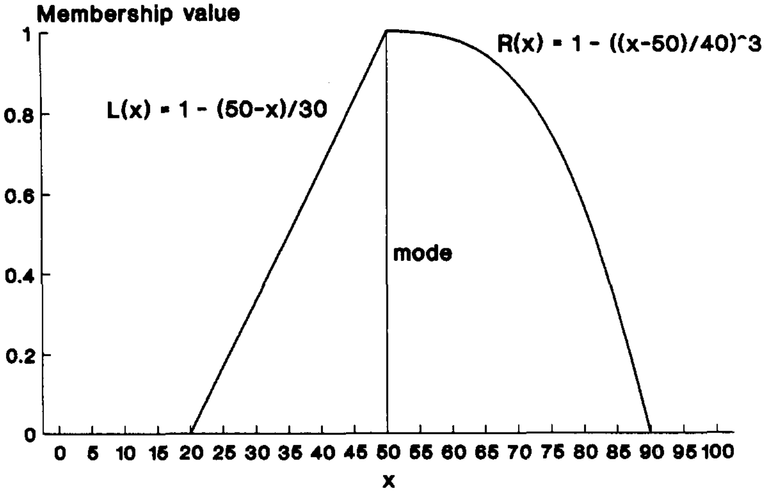


Fig. 1. Typical membership functions for a fuzzy variable having a mode of 50 and left and right scaling factors of 30 and 40, respectively.

a fuzzy number, $M$, is an $L$–$R$ fuzzy number if

$$\begin{aligned} m(x) &= L\left(\frac{m-x}{b}\right), \quad x \leqslant m, \ b > 0 \\ m(x) &= R\left(\frac{x-m}{c}\right), \quad x > m, \ c > 0 \end{aligned} \tag{2}$$

$M$ may therefore be denoted by $(m, b, c)_{LR}$, where $m$ is the modal value, and $b$ and $c$ are the scaling factors of the membership function. $L$–$R$ fuzzy numbers may have different $L$- and $R$-functions, and by way of illustration, Fig. 1 shows an example in which $L(x)$ has the form $(1-x)$, and $R(x)$ the form $(1-x)^3$.

FLRA differs from ordinary least-squares regression in having no simple measure of goodness-of-fit, such as the minimum sum of squares, but only a level of belief (or vagueness) in the fitting of the postulated function to the data. The $y_i^*$ for each measured $x_i$ are fuzzy numbers with a specified membership function, and the degree of belief, $H$, is chosen so as to reflect the quality of the data and the existence of the proposed relationship. The regression coefficients, $a^*$ and $b^*$, of the expression

$$y_i^* = f(x_i) = a^* + b^* x_i \tag{3}$$

are then fuzzy numbers to be estimated such that the $H$-level sub-set of the regression, $f_H(x)$, contains the $H$-level sub-set of the measurements, $y_{iH}$. Perhaps more simply, for each data point, $y_i$, corresponding to $x_i$, $H$ indicates the degree of belief that the point approaches the regression line. As many fuzzy functions may satisfy this requirement, that which is chosen should be the crispest among the available alternatives. Identification of the parameters of Eq. (3) may therefore be treated as a constrained optimisation problem in which the crispness of the fuzzy linear function is maximised (or alternatively, its vagueness is minimised) such that each measurement point fits the linear function with a membership level equalling or exceeding $H$. Of course, solutions will differ according to the measure of crispness (or vagueness) that is adopted and the level of $H$ that is selected.

Given $n$ data points, $(x_i, y_i)$, and supposing for the purposes of this exercise that the $y_i$ are crisp, the fuzzy function may be defined as

$$f^*(x_i) = a^* + b^*(x_i - x_r) \tag{4}$$

where $a^* = (A, b_1, c_1)_{LR}$ and $b^* = (B, b_2, c_2)_{LR}$ are the $L$–$R$ representations of the unknown parameters of Eq. (4), and $x_r$ is a reference point for the $x_i$ that should be chosen to be the value at which the proposed relationship is regarded as being at its strongest. The condition that the $H$-level sets of $y^*$ are contained within the $H$-level sets of $f^*(x_i)$ have been derived by Bardossy (1990) as

$$\begin{aligned} y_i &\geqslant A - b_1(1-H) + [B - b_2(1-H)](x_i - x_r), \quad x_i \geqslant x_r \\ y_i &\leqslant A + c_1(1-H) + [B + c_2(1-H)](x_i - x_r), \quad x_i \geqslant x_r \\ y_i &\geqslant A - b_1(1-H) + [B + c_2(1-H)](x_i - x_r), \quad x_i < x_r \\ y_i &\leqslant A + c_1(1-H) + [B - b_2(1-H)](x_i - x_r), \quad x_i < x_r \end{aligned} \tag{5}$$

Eqs. (5) are linear with respect to the unknown parameters, $A$, $B$ and $b_i$, $c_i$ $(i = 1, 2)$, and, for any given $L$, $R$, $x$ and $y$, form the constraints for the optimal estimation of the parameters. The solution also requires a suitable measure of crispness to be maximised or vagueness to be minimised, typical forms of which include the 'average vagueness' of the parameters,

$$b_1 + c_1 + b_2 + c_2 \tag{6}$$

as proposed by Tanaka et al. (1982), or the 'prediction vagueness', introduced by Bardossy (1990) to represent the vagueness of the fuzzy regression function defined on the domain of the independent variables:

$$c_1 R^* + b_1 L^* + \left[\frac{0.5(d^2 + e^2)}{d + e}\right](c_2 R^* + b_2 L^*) \tag{7}$$

where $d = x_r - x^-$, $e = x_r - x^+$, $R^*$ and $L^*$ are the integrals of the chosen $R$- and $L$-functions between the limits of zero and one, and $x^+$ and $x^-$ are the maximum and minimum values of the $x_i$. Both Eqs. (6) and (7) are linear with respect to the unknown parameters, thereby allowing the optimisation problem to be solved by means of linear programming.

## 5. Application of fuzzy linear regression analysis

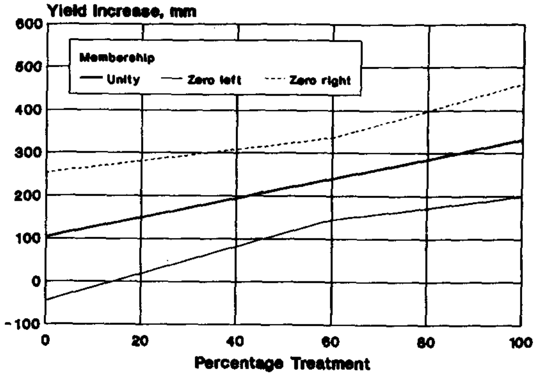
In applying FLRA, the annual change in yield, $YC$ (mm), was employed as the dependent variable, with all values assumed to be crisp. In effect, this assumption reduces the procedure to the identification of the minimum scaling factors for the membership functions. A simple fuzzy function of the form of Eq. (4) was assumed, with percentage treatment, PTR, as the independent variable. The application of FLRA depends upon the selection of the following: (1) the level of credibility associated with the analyst's belief in the chosen form of relationship and the worth of the data; (2) the form of membership function representing the regression parameters; (3) the criterion of vagueness to be minimised; (4) the reference point for the regression.

As noted by Bardossy et al. (1990), the level of credibility is generally chosen so that $0.5 < H < 0.7$. At the lower end of this range, the predicted values of the dependent variable are fuzzy and relatively imprecise, but as $H$ increases they become increasingly crisp. In the following analyses, a value of 0.7 was assumed, applied uniformly to all data points.

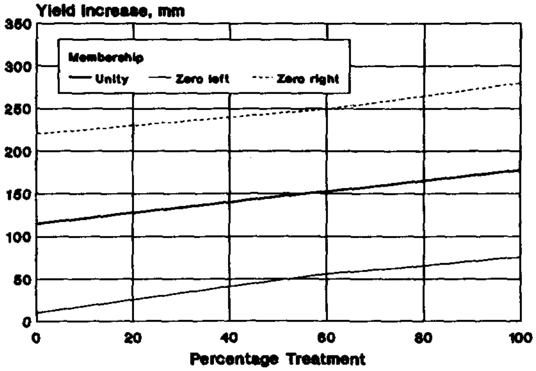
With regard to (2) above, the membership functions for the regression parameters are usually assumed to take the general form $(1 - x^k)$, where $k$ increases with the degree of belief in the modal value (or degree of suspicion about values away from the mode). In addition, the membership functions themselves can be assumed either asymmetrical or symmetrical ($b_i = c_i$, $i = 1, 2$). However, preliminary trials undertaken on the conifer-type forest data set indicated that symmetrical functions with $k > 1$ yielded smaller membership widths, and so a value of $k = 3$ was finally adopted.

As indicated in the previous section, different measures of vagueness may be adopted in solving for the fuzzy regression parameters. According to Bardossy et al.

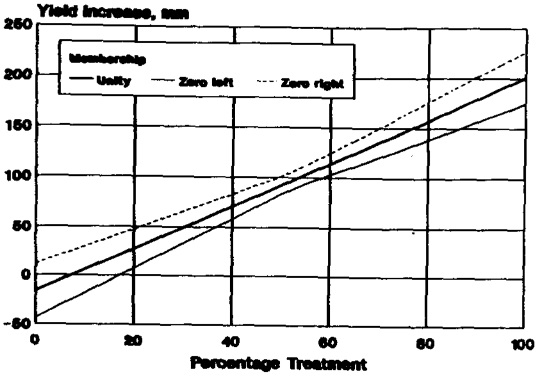
(a) Conifer-type Forest



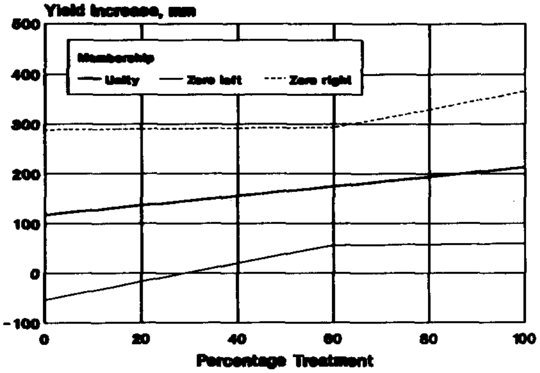
(b) Eucalyptus-type Forest



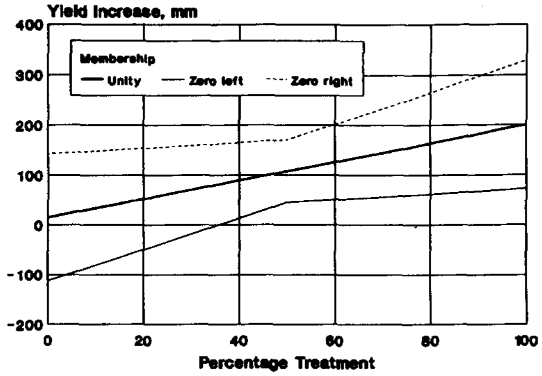
(c) Hardwood/Conifer-type Forest



(d) Rainforest



(e) Hardwood-type Forest MAP<1500mm



(f) Hardwood-type Forest MAP>1500mm

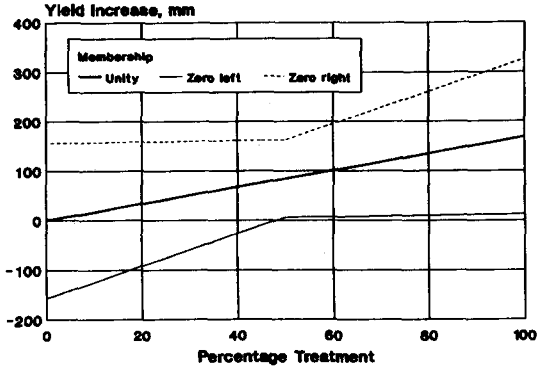
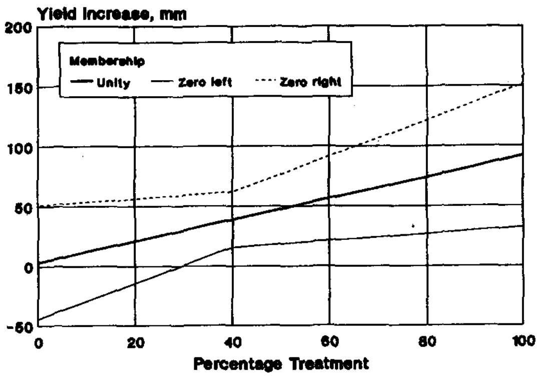
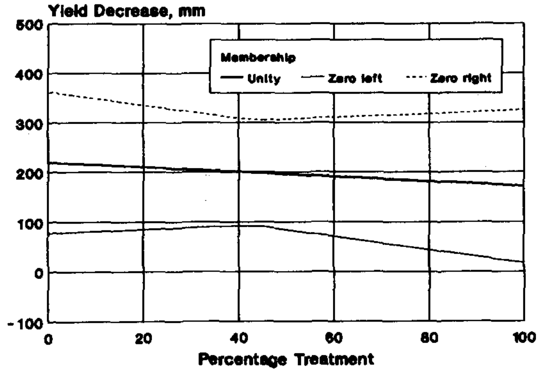


Fig. 2. Relationships between increases in annual catchment yield (mm) and percentage of the catchment cleared for six forest types.



(a) Scrub-type (clearing)



(b) Scrub-type (planting)

Fig. 3. Relationships between changes in annual catchment yield and percentage of the catchment treated for both clearing and planting of scrub-type vegetation.

(1990), prediction vagueness is robust in relation to selection of the reference point for the regression. The latter (item (4) above) should be selected at the point where the regression is believed to be the crispest and most accurate. Typically, the average or the mid-range is selected as $x_r$, but the maximum or the minimum may also be appropriate, depending on the context of the problem. Once again, preliminary trials with the conifer-type forest data set were undertaken, the results of which indicated that the mid-range reference point was to be preferred, but that average and prediction vagueness criteria gave similar regression parameters.

On the basis of the above-mentioned assumptions, the analysis was extended to the other six cover types. Unfortunately, the grassland data set did not yield a solution for the regression parameters that did not lie on one of the constraints. In all other cases, satisfactory values were obtained for the modal values and membership widths. The former may then be inserted in Eq. (4) to give the relationship between $YC$ and PTR corresponding to minimum vagueness. In addition, these values along with the membership widths may be inserted into Eqs. (5) to give the limits to the relationship corresponding to a given level of credibility, $H$. For the purposes of presentation, the absolute upper and lower limits, corresponding to $H = 0$, provide a useful visual check of the utility of the derived relationships. As noted by Bardossy et al. (1990), the spacing of these uncertainty bands should be as narrow as possible, and the width of the band should vary as little as possible over the range of the independent variable.

With all six data sets that provided an optimal solution for the regression parameters, the widths of the uncertainty bands were found to be rather large, with the widths of the membership functions of a similar order of magnitude to the modal values. In such cases, the lines corresponding to zero membership also diverge noticeably as the independent variable moves away from the reference point. Although the extension of Eqs. (4) and (5) to the multivariate case is straightforward (see Bardossy (1990)), the preferred approach in this study was to reclassify the larger data sets according to the values of a second independent variable. The experience obtained with the application of MLRA summarised above had indicated the importance of mean annual rainfall, and the hardwood-type data set was therefore divided into 'low' and 'high' rainfall groups at an MAP value of 1500 mm. In addition, the scrub-type cover data set was divided into a two parts according to whether the change involved afforestation or clearing of vegetation. The remaining data sets were also screened for obvious outliers, which were reviewed and removed where such action was deemed appropriate.

The results obtained are summarised in Fig. 2 for the conifer, eucalyptus, hardwood–conifer, rainforest and hardwood-type data sets, and in Fig. 3 for the scrub-type cover. These results demonstrate that the derived relationships are somewhat variable in their utility, but they at least provide some improvement over the ordinary MLRA approach. The principal features to examine are the proximity to the origin of the fitted relationship for zero percentage treatment, the spacing of the limits to membership and the amount of divergence of the limits away from the reference point.

Although the assumption of a linear relationship between annual yield change and percentage treatment, as given by Eq. (4), is somewhat restrictive, the results displayed in Figs. 2 and 3, which show that in four of the eight cover categories the yield change for zero treatment is less than ±16 mm, are encouraging. However, the corresponding figures for conifer, eucalyptus and rainforest cover-types all exceed 100 mm, and that for the afforestation of scrub reaches 171 mm, thereby confirming the disquiet expressed by Bosch and Hewlett (1982) over the sparse but highly variable results from experiments involving changes in cover of less than 20%.

A further measure of the utility of the derived relationships is the width of the band denoting zero membership. Taking as an example the widths at 100% treatment, the figures range from ±93% of the ordinate predicted by the fitted relationship for hardwood (MAP > 1500 mm) forest-type to ±13% for hardwood–conifer forest-type (see Table 1). Apart from conifer forest-type at ±40%, all other results are in the range 57–72%. The narrowest bands were therefore obtained with the largest, and apparently most homogeneous data set.

The overall results show that, for 100% deforestation, by far the largest increase

Table 1
Summary of results from the application of FLRA

| Cover type | Yield change for 100% treatment (mm) | Yield change per 10% cover change (mm) | Membership width for 100% treatment; mm (%) |
|---|---|---|---|
| Conifer | 330 | 23 | 131 (40) |
| Eucalyptus | 178 | 6 | 102 (57) |
| Hardwood–conifer | 201 | 22 | 26 (13) |
| Rainforest | 213 | 10 | 153 (72) |
| Hardwood (MAP < 1500 mm) | 201 | 19 | 128 (64) |
| Hardwood (MAP > 1500 mm) | 169 | 17 | 157 (93) |
| Scrub (clearing) | 92 | 9 | 60 (65) |
| Scrub (planting) | −220 | −5 | 142 (65) |

(330 mm) was obtained for a conifer forest-type (see Table 1). Hardwood–conifer, rainforest and hardwood (MAP < 1500 mm) forest-types all show an increase of 200–215 mm, similar to the yield reduction obtained for the afforestation of scrub. Eucalyptus and hardwood (MAP > 1500 mm) forest-types both show increases of 170–180 mm, and only the clearing of scrub shows an increase of less than 100 mm for a 100% cover change.

A further ranking of the results is obtained by considering the gradients of the derived relationships. Table 1 shows that four of the eight cases have slopes in the range 17–23 mm per 10% change in cover, whereas the other four gave figures between 5 and 10 mm per 10% change in cover. However, bearing in mind the previous remarks about the nearness of the fitted relationships to the origin, perhaps the clearest indication to be drawn from these figures is the similarity in the gradients of the hardwood–conifer and the hardwood (both ranges of MAP) forest-types at 17–22 mm per 10% change in cover, about double that of the clearing of scrub.

## 6. Concluding remarks

The data base compiled by Bosch and Hewlett (1982) and extended in this study is clearly heterogeneous, with the majority of results being obtained from experiments involving drainage areas of no more than a few hectares. The arguments in favour of the use of small catchments for such studies, in terms of accuracy of measuring streamflow outputs and rainfall inputs, are obvious. However, the question inevitably arises of whether the results from such experiments can be transferred to larger areas (see, e.g. Pilgrim et al. (1982)). Such differences can and are being explained by a more thorough evaluation of hydrological processes on a catchment-by-catchment basis (e.g. Ruprecht and Schofield, 1989; Bruijnzeel, 1990). Nevertheless, the need remains for broad-brush estimates of the order of magnitude of the yield changes that result from alterations to the vegetal cover of a catchment as an aid to decision-making. The results obtained from this study indicate that FLRA may provide an appropriate approach to constructing the required relationships.

Despite the ability of FLRA to handle small, heterogeneous data sets, relationships for a single independent variable along with membership limits were derived in only eight cases. No solution was found for data relating to the afforestation of grassland, possibly because the associated changes in evaporation are not as immediate as those brought about by the clearing of forest cover. Some difficulties were also experienced because of the absence of certain key statistics from the reported results of many experiments, a deficiency that future authors of such reports could perhaps bear in mind.

Acknowledging the constraints on data availability, Figs. 2 and 3 may be employed to provide preliminary estimates of yield changes, provided that the proportion of the catchment treated exceeds 0.2–0.25 and is preferably greater than 0.4. The estimates of yield changes for 100% afforestation or deforestation presented in Table 1 provide a convenient ranking for the magnitudes of the changes associated with different initial cover types. The largest yield increases appear to be those associated with the removal of conifer forest-type, whereas the increases associated with hardwood–conifer, hardwood (all MAP values), rainforest and eucalyptus cover-types are between 50% and 60% of the conifer value. The clearing of scrub produces an increase of some 5% of the conifer cover-type increase. However, as illustrated by Figs. 2 and 3, the variances of these estimates, as exemplified by the bandwidths of zero membership, remain high, except in the case of hardwood–conifer forest-type. The possibilities that better relationships might be developed from sub-sets identified on the basis of alternative criteria, by treating the dependent variable as fuzzy along with the regression coefficients, or by the application of multiple FLRA (Bardossy, 1990), remain to be explored. The utility of these approaches might also be usefully compared with that of robust regression and other alternatives to conventional MLRA.

## Appendix: Data summary

| Experiment no. | Country | Catchment | Area (ha) | Elevation (m) | Cover type | Soil type | Treatment year |
|---|---|---|---|---|---|---|---|
| 1 | France | Rimbaud | 140 | 570 | Scrub | Rock | 1990 |
| 2 | India | Nilgiri | 31.8 | 2166 | Grassland | Sandy loam | 1972 |
| 3 | Germany | C. FM-S | 3.0 | 530 | Grassland | Clay loam | 1962 |
| 4 | Germany | C. FM-N | 3.0 | 530 | Grassland | Clay loam | 1969 |
| 5 | Germany | C. KM | 32.0 | 530 | Grassland | Clay loam | 1960 |
| 6 | USA | D. Creek | 270.0 | 3208 | Conifer |  | 1978–84 |
| 7 | USA | N. Fork | 41.0 | 3208 | Conifer |  | 1978–84 |
| 8 | USA | Unit 8 | 41.0 | 3208 | Conifer |  | 1980–81 |
| 9 | S. Africa | Bosbouk. | 200.9 | 543 | Scrub | Sandstone | 1986 |
| 10 | S. Africa | V1H020 | 132.0 |  | Grassland | Clay loam | 1976–77 |
| 11 | S. Africa | Swartbos. | 180.0 |  | Scrub | Sandstone | 1987 |
| 12 | USA | WS2 L.R. | 43.0 | 360 | Hardwood | Silt loam | 1976–77 |
| 13 | USA | WS4 H.B. | 36.0 | 606 | Hardwood | Sandy loam | 1970 |
| 14 | USA | WS2 L.R. | 43.0 | 360 | Hardwood | Silt loam | 1971–72 |
| 15 | USA | WS2 L.R. | 43.0 | 360 | Hardwood | Silt loam | 1975–76 |
| 16 | USA | Marcell 4 | 34.0 | 433 | Hardwood | Peat | 1970–71 |
| 17 | Australia | Wights | 94.0 |  | Eucalyptus | Sandy loam | 1976–86 |
| 18 | Australia | Yarrug.4L | 126.0 |  | Eucalyptus | Gravel | 1983 |
| 19 | Australia | Lemon |  |  | Eucalyptus |  | 1976–83 |
| 20 | Australia | Dons |  |  | Eucalyptus |  | 1976–83 |
| 21 | Australia | March Rd. |  |  | Eucalyptus |  | 1982–85 |
| 22 | Australia | April Rd. |  |  | Eucalyptus |  | 1982–85 |
| 23 | Australia | L. South |  |  | Eucalyptus |  | 1982–85 |
| 24 | Australia | Yerrami. S |  |  | Eucalyptus |  | 1982–85 |
| 25 | Australia | Wellbucket |  |  | Eucalyptus |  | 1977–81 |
| 26 | Australia | Hansen | 80.0 |  | Eucalyptus | Gravel | 1985–86 |
| 27 | Australia | Thomson | 196.4 |  | Agriculture | Sandy loam | 1977–83 |
| 28 | Australia | Kokota | 97.4 | 695 | Eucalyptus | Rock | 1983 |
| 29 | Australia | Coachwood | 37.5 | 695 | Eucalyptus | Rock | 1983 |
| 30 | Australia | Corkwood | 41.1 | 695 | Eucalyptus | Rock | 1983 |
| 31 | Australia | Jackwood | 12.5 | 695 | Eucalyptus | Rock | 1983 |
| 32 | Australia | Barratta | 36.4 | 695 | Eucalyptus | Rock | 1983 |
| 33 | Australia | Bollygum | 15.1 | 695 | Eucalyptus | Rock | 1983 |
| 34 | UK | Coalburn | 150.0 | 300 | Grassland | Clay loam | 1972–73 |

| MAP (mm) | MAR (mm) | Treatment area (%) | Treatment | Yield change (mm) | References | Observations |
|---|---|---|---|---|---|---|
| 1164 | 626 | 85 | Burned | 148 | Lavabre et al. (1993) | |
| 1535 | 550 | 59 | Eucalyptus | −87 | Samaraj et al. (1988) | |
| 1410 | 430 | 100 | Afforested | −280 | Robinson et al. (1991) | |
| 1410 | 475 | 100 | Afforested | −235 | Robinson et al. (1991) | |
| 1410 | 945 | 100 | Agriculture | 235 | Robinson et al. (1991) | Drained for agriculture |
| | | 10 | Deforested | 18 | Troende and King (1987) | |
| | 27 | 36 | Deforested | 60 | Troende and King (1987) | |
| | | 40 | Deforested | 48 | Troende and King (1987) | |
| 1296 | 593 | 80 | Afforested | 140 | Scott (1993) | Planted with pine |
| 838 | 140 | 27 | Eucalyptus | −31 | Scott (1993) | |
| 2270 | 1060 | 100 | Burned | 79 | Scott (1993) | Prescribed burn |
| 1060 | 440 | 43 | Clearcut | 97 | Hornbeck et al. (1993) | |
| 1340 | 860 | 33 | Deforested | 350 | Hornbeck et al. (1993) | |
| 1060 | 440 | 27 | Deforested | 61 | Hornbeck et al. (1993) | 6 years average increase |
| 1060 | 440 | 40 | Deforested | 83 | Hornbeck et al. (1993) | 10 years average increase |
| 760 | 110 | 100 | Deforested | 30 | Hornbeck et al. (1993) | 21 years average increase |
| 1200 | 88 | 100 | Agriculture | 239 | Ruprecht and Schofield (1989) | Maximum increase was 359 mm |
| 1120 | 6 | 80 | Deforested | 17 | Stoneman (1993) | |
| 800 | 6 | 54 | Agriculture | 17 | Ruprecht and Schofield (1989) | Maximum increase was 38 mm |
| 800 | 4 | 38 | Agriculture | 11 | Ruprecht and Schofield (1989) | Maximum increase was 38 mm |
| 1070 | 82 | 100 | Regrowth | 121 | Ruprecht and Schofield (1989) | Maximum increase was 196 mm |
| 1070 | 62 | 100 | Regrowth | 104 | Ruprecht and Schofield (1989) | Maximum increase was 155 mm |
| 1220 | 143 | 70 | Regrowth | 116 | Ruprecht and Schofield (1989) | Maximum increase was 178 mm |
| 850 | 24 | 60 | Regrowth | 20 | Ruprecht and Schofield (1989) | Maximum increase was 38 mm |
| 700 | 2 | 23 | Regrowth | 2 | Ruprecht and Schofield (1989) | Maximum increase was 3 mm |
| 1200 | 232 | 75 | Deforested | 166 | Ruprecht et al. (1991) | |
| 950 | 150 | 70 | Eucalyptus | −83 | Borg et al. (1988) | In 1950s, 45% area was clearcut |
| 1669 | 531 | 29 | Regrowth | 188 | Cornish (1993) | |
| 1549 | 362 | 61 | Regrowth | 120 | Cornish (1993) | |
| 1758 | 505 | 40 | Regrowth | 195 | Cornish (1993) | |
| 1485 | 311 | 79 | Deforested | 215 | Cornish (1993) | |
| 1705 | 590 | 25 | Regrowth | 64 | Cornish (1993) | |
| 1617 | 505 | 32 | Regrowth | 244 | Cornish (1993) | |
| 1266 | 824 | 90 | Conifer | 167 | Robinson (1993) | Increase after drainage |

| Experiment no. | Country | Catchment | Area (ha) | Elevation (m) | Cover type | Soil type | Treatment year |
|---|---|---|---|---|---|---|---|
| 35 | UK | B. Kirkton | 685.0 | 547 | Forest | Peat | 1986 |
| 36 | Kenya | Sambret | 700.0 | 2200 | Forest | Rock | 1957–64 |
| 37 | Kenya | Kimakia | 36.4 | 2440 | Bamboo forest | Rock | 1958 |
| 38 | UK | B. Monac. | 770.0 | 601 | Grassland | Peat | 1986 |
| 39 | Malaysia | B. Berem | 13.3 | 235 | Rainforest | Rock | 1979 |
| 40 | Malaysia | B. Berem. | 30.8 | 235 | Rainforest | Rock | 1979 |
| 41 | Australia | Babinda | 18.3 | 105 | Forest | Rock | 1973 |
| 42 | Costa Rica | La Selva | | 165 | Rainforest | Rock | |
| 43 | Malaysia | S. TekamA | 37.7 | 70 | Rainforest | Rock | 1982 |
| 44 | Malaysia | S. TekamB | 59.2 | 70 | Rainforest | Rock | 1980 |
| 45 | Nigeria | IITA | 44.0 | | Forest | Clay loam | 1978–79 |
| 46 | Taiwan | L. Hua-Chi | | | Conifer | Silt loam | 1975 |
| 47 | Zambia | Luano | 120.0 | 1300 | Forest | | 1964 |
| 48 | Philippines | Left Fork | 1.0 | 225 | Grassland | Clay loam | 1973 |
| 49 | India | Dehra Dun | 1.5 | 520 | Scrub | Clay loam | 1961 |
| 50 | Madagascar | Manankazo | 3.2 | 1550 | Grassland | Rock | 1962 |
| 51 | Madagascar | Manankazo | 3.9 | 1150 | Grassland | Rock | 1962 |

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| MAP (mm) | MAR (mm) | Treatment area (%) | Treatment | Yield change (mm) | References | Observations |
|---|---|---|---|---|---|---|
| 2354 | 1931 | 20 | Deforested | 193 | Blackie (1993) | |
| 2130 | 793 | 54 | Tea | 220 | Bruijnzeel (1990) | |
| 2307 | 1151 | 100 | Conifer | 125 | Bruijnzeel (1990) | |
| 2770 | 2149 | 14 | Afforested | −43 | Blackie (1993) | |
| 1900 | 235 | 40 | Deforested | 165 | Bruijnzeel (1990) | First year after treatment |
| 1900 | 230 | 33 | Deforested | 85 | Bruijnzeel (1990) | First year after treatment |
| 4037 | 3786 | 67 | Regrowth | 265 | Bruijnzeel (1990) | |
| 4000 | 1443 | | Regrowth | 375 | Bruijnzeel (1990) | Manual clearing |
| 1880 | 94 | 100 | Deforested | 110 | Bruijnzeel (1990) | First year after treatment |
| 1880 | 170 | 60 | Deforested | 145 | Bruijnzeel (1990) | |
| 1450 | | 100 | Agriculture | 305 | Bruijnzeel (1990) | |
| 2100 | 776 | 80 | Regrowth | 450 | Bruijnzeel (1990) | 2 years average increase |
| 1400 | 348 | 100 | Grassland | 195 | Bruijnzeel (1990) | Area range 95–143 ha |
| 3170 | 1263 | 100 | Grassland | 120 | Bruijnzeel (1990) | Grassland to fire-protected grassland |
| 1430 | 54 | 100 | Eucalyptus | −15 | Bruijnzeel (1990) | |
| 1715 | | 100 | Agriculture | −75 | Bruijnzeel (1990) | 11 years average decrease |
| 1715 | | 100 | Conifer | −80 | Bruijnzeel (1990) | 11 years average decrease |

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