Methods of Determining Reforestation Area and Distribution for Salinity Control

by N. J. Schofield

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Water Authority
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ABSTRACT

Two predictive methods and one field method of estimating reforestation areas for salinity control are described.

The first method, based on a simple water balance model, shows promise for practical use because model parameters are easily determined and the sensitivity of prediction is readily assessed. Further measurements of some model parameters are necessary to improve the reliability and applicability of the model.

The second method is based on a regression of observations of water table reduction below experimental plantations on area reforested. The regression had a high correlation coefficient (r^2=0.98) and was statistically significant at the 0.1% level. It was thus regarded as a useful predictor of area of reforestation required to lower the water table at a given rate. Application of the regression should be limited to the range of conditions sampled.

The third method of estimating reforestation requirements is a field approach. This method requires field testing and evaluation before it can be considered a useful approach.

One means of determining the optimum reforestation distribution on a catchment is described. The approach is based on a groundwater model. The model was found to have extensive data requirements and generally involved assuming values for some key model parameters. However, the model was useful for designing reforestation layouts for a specified reforestation area. Tree layouts prescribed by the model should always be checked in the field.

The best approach to reforestation design to date is to use the water balance model or the experimental regression to predict area of reforestation required, and then to use the groundwater model to design the optimum reforestation layout.

1. INTRODUCTION

Land and stream salinisation affects several arid and semi-arid regions of the world. Increasing salinity of irrigated soil is a problem going back at least 4,500 years to Mesopotamian times (Jacobsen and Adams 1958) and today affects about one-third of the irrigated land around the world (Reeve and Fireman 1967). In Australia some 123,000 ha of irrigated cropland are affected by soil salinity (Peck et al. 1983). Over the last 100 years salinity problems have occurred in non-irrigated areas, particularly in regions of North America and Australia which have been developed for agriculture. This 'dryland salinity' affects some 810,000 ha of the northern Great Plains of the United States and Canada (Brown et al. 1983) and 426,000 ha of Australia (Peck et al. 1983).

Agricultural development in south-west Western Australia has had a dramatic impact on stream salinity and land salinisation. Stream salinities of this region have increased to the extent that only 48% of the divertible surface water resources remain fresh (less than 500 mgl^{-1} TSS). By 1984 some 255 000 ha or 1.6% of agricultural land was severely salt-affected (Western Australian Bureau of Statistics, pers. comm. 1988).

A large part of the world's dryland salinity occurs as an indirect result of the reduction of the quantity of water evaporated by vegetation. In south-west Western Australia the main cause has been the replacement of native perennial vegetation (mainly forest and woodlands) with annual agricultural plants. A number of measures to reclaim salt-affected areas have been investigated, including pumping of groundwater, surface and subsurface drainage, changes in agronomic practices, and planting trees and shrubs. The use of trees and other perennial plants to control salinity has been a subject of interest for some years (Greenwood 1978, Morris and Thomson 1983, Malcolm 1986). In particular phreatophytes and halophytes have been suggested as being appropriate for the reduction of groundwater recharge and discharge and hence salinity control (Greenwood 1986). Reforestation of salt-affected catchments may require replanting significant areas of land previously converted to agriculture. This in turn may involve governments in expensive land purchases. The conflict of reforestation with agriculture and the ability of tree plantations to control or eliminate land and stream salinity both depend on the area of reforestation.

A number of simple analytical models (Peck 1976, Morris and Thomson 1983, Stewart 1984), regressions based on experimental reforestation data (Bell et al. 1988), a field technique (Greenwood 1986) and a numerical groundwater model (Hookey and Loh 1985 a,b,c) have been developed for the purpose of designing or assessing revegetation strategies for salinity control. Most of these techniques were developed with reforestation in mind, but some of the techniques developed for reforestation could also be applied to agronomic options. The essential premise of all the reforestation techniques is that revegetated areas will evaporate more water per unit area than the original forest, and so only part of the cleared area will need to be reforested to restore the hydrologic balance.

This paper reviews the simple analytical models and presents a new model, describes other methods of determining reforestation areas required for salinity control, and discusses a method of designing reforestation layouts.

2. SIMPLE ANALYTICAL MODELS

2.1 Development of Models

Near-identical formulations of a simple analytical method of estimating the required area of reforestation for salinity control have been reported by Peck (1976), Morris and Thomson (1983) and Stewart (1984). The model was extended by Stewart (1984) to consider not only the area of reforestation required to utilise excessive groundwater recharge, but also to lower the water table.

MODEL 1

The above authors envisaged application of the model to slightly different vegetation strategies. For simplicity one strategy is considered here. It is taken that the native forest (Fig. 1 (a)) was totally cleared and that some decades later has been partially reforested on the lower slopes (Fig. 1 (b)). With this strategy phreatophytes can be planted on the lower slopes to access groundwater beneath the stands. The lower slope vegetation will also intercept groundwater moving downslope from the cleared areas above.

The evaporation rate of the native forest is taken to be E_f mm yr^{-1} and the area of native forest is taken to be unity. The evaporation rates of the reforestation and agricultural areas are taken to be E_r and E_c respectively. If the area of reforestation is A_r then the area of agriculture, A_c, is $(1-A_r)$. For the total evapotranspiration from the reforested and agriculture area to equal that of the native forest we require.

$$E_r A_r + E_c(1 - A_r) = E_f \quad . \qquad (1)$$

This equation can be simply re-arranged to give the required proportion of the area for reforestation:

$$A_r = \frac{E_f - E_c}{E_r - E_c} \quad . \qquad (2)$$

Equation (2) is equivalent to that of Peck (1976, equation (2)), although Peck substitutes $\Delta G = E_f - E_c$, where ΔG is the increase in groundwater recharge due to converting native forest to agriculture. Equation (2) is also equivalent to that of Stewart (1984, equation (b)), except that Stewart substitutes $W = E_f - E_c$, where W is the rate of rise in the water table. Morris and Thomson (1983, Appendix example 3) substitute R for $(E_f - E_c)$, where R is the recharge rate following clearing; and P for E_r, where P is potential evaporation. The form of equation (2) is preferred here because the variables E_f, E_c and E_r are directly measurable, whereas recharge and potential evaporation are generally more difficult to quantify.

MODEL 2

Stewart (1984) took into account the need to lower groundwater tables in order to ameliorate land and stream salinisation. His analysis is slightly modified here.

The analysis assumes that the water table is horizontal and would be lowered uniformly across the whole catchment. If it is required to reduce the water table at a rate of Z mm yr^{-1}, and the change in volumetric water content from saturation to 'field capacity' is θ^* ($m^3 m^{-3}$), the required water balance equation is now:

$$E_r A_r + E_c (1 - A_r) = E_f + \theta^* Z \qquad (3)$$

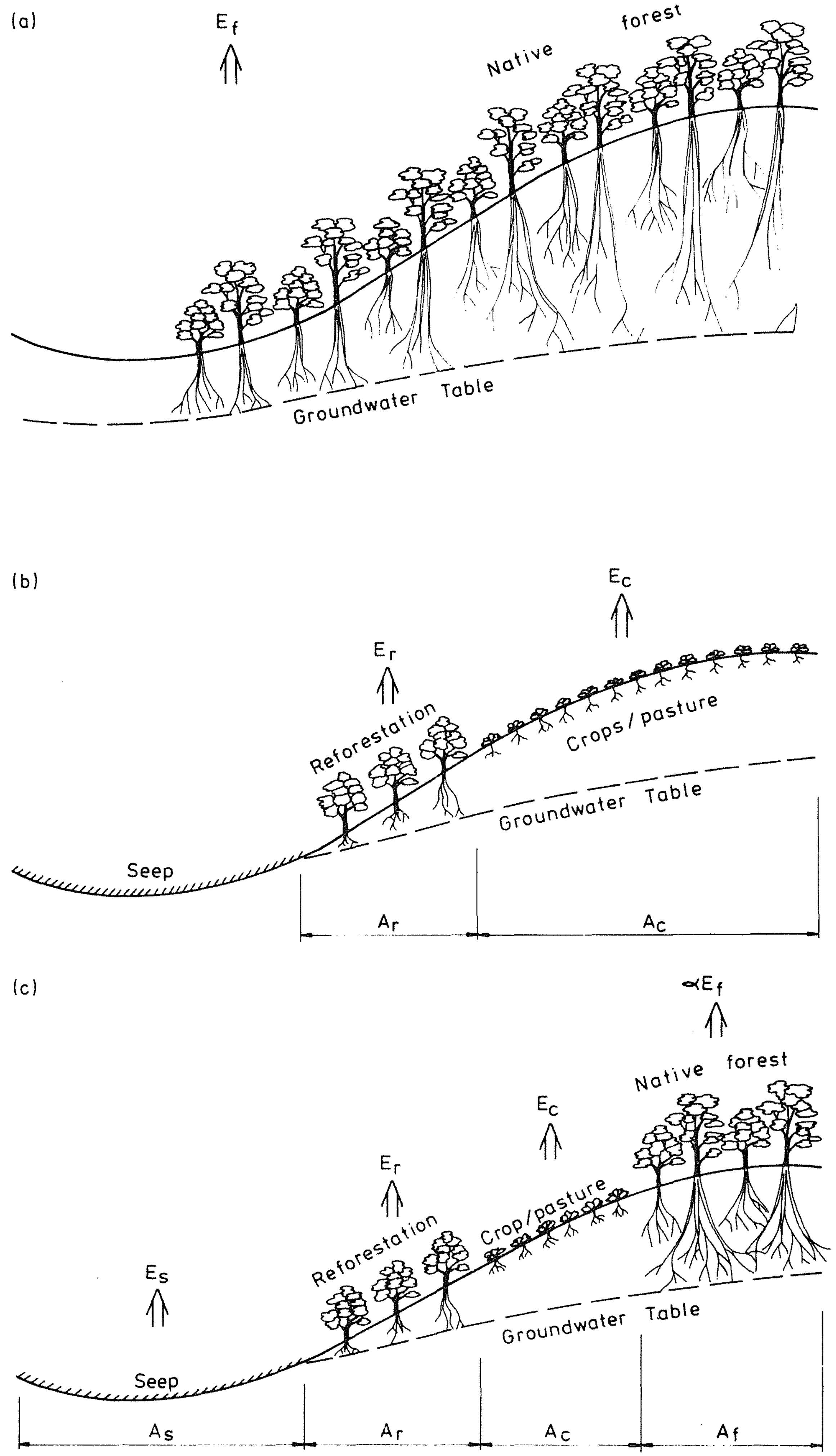

Figure 1. Conceptual illustrations for water balance models

Re-arranging this equation gives

$$A_r = \frac{E_f - E_c + \theta^* Z}{E_r - E_c} \qquad (4)$$

Equation (4) is of the same form as Stewart (1984, equation 7) except account is taken here of the change in water content following desaturation.

MODEL 3

A more common situation that is encountered in the water resource catchments of south-west Western Australia is the retention of some native forest, usually on the upslope areas and ridges. It is assumed that evaporation from the retained native forest is α times that of undisturbed native forest. The seep areas themselves can occupy significant portions of agricultural catchments and should be taken into account in the water balance (Fig. 1 (c)). If the evaporation rates from remnant native forest and seeps are taken as αE_f and E_s respectively, and their areas as A_f and A_s respectively, then for the total evaporation to equal that of undisturbed forest we require:

$$E_s A_s + E_r A_r + E_c(1-A_s-A_r-A_f) + \alpha E_f A_f = E_f \qquad (5)$$

which on re-arrangement gives

$$A_r = \frac{E_f(1-\alpha A_f) + A_s(E_c-E_s) - E_c(1-A_f)}{E_r - E_c} \qquad (6)$$

MODEL 4

If it is required to lower the water table at a rate of Z mm yr^{-1}, equation (6) becomes

$$A_r = \frac{E_f(1-\alpha A_f) + A_s(E_c - E_s) - E_c\ (1-A_f) + \theta * Z}{E_r - E_c} \qquad (7)$$

MODEL 5

Peck (1976) considered the problem of the spacing of vegetation strips for a strip planting strategy. He proposed that an analogy to tile drainage theory could be used. The assumptions of the theory are that the soil profile is uniform and overlies a horizontal, impermeable basement; and that movement of water to roots is similar to the groundwater flow to a drainage ditch. Under these assumptions the spacing (D in metres) between parallel rows of phreatophytic vegetation necessary to maintain the water table constant is given by (Van Schilfgaarde, 1957):

$$D = 2[(H^2 - h^2)\ K/R]^{1/2} \qquad (8)$$

where H and h are the heights (in metres) of the water table above the impermeable basement midway between the strips and beneath the strips respectively, K is the saturated hydraulic conductivity of the soil in m day^{-1} and R is the average rate of recharge of water beneath the pasture or crop in m day^{-1}.

Substituting typical values for the Darling Range, Peck (1976) estimated that the spacing between vegetation strips (D) would range from 80 to 350 m, the larger value representing lower rainfall, lower recharge areas.

In this model it is assumed that trees behave hydrologically like drains. At the scale of the individual tree that is clearly not the case because, unlike drains: it is increasingly difficult for trees to extract water with increasing depth; roots of most trees do not function beneath the water table; tree roots are distributed with highest density near the surface; and the volume of soil occupied by roots expands over time for growing trees. However, at the scale at which a strip of trees can be regarded as a line sink for groundwater (albeit a time-varying sink), application of drainage theory may be possible.

2.2 Application of Models to Western Australian Conditions

Application of Models 1-4 in the previous section, represented by equations (2), (4), (6) and (7) require knowledge of the following variables: E_f, E_c, E_r, θ^*, α, A_c, A_f, A_s and E_s. The variable Z can be specified arbitrarily. All these equations attempt to predict the area of reforestation required for specified conditions and can be compared.

Data for the above variables have been determined for a high rainfall area (1200 mm yr^{-1}) and a low rainfall area (750 mm yr^{-1}). The sources of the data are discussed below and the values summarised in Table 1. The locations referred to in this section are shown in Fig. 2.

Values of native forest evaporation (E_f) have been obtained by subtracting mean annual streamflow from rainfall. These differences have been calculated for 30 catchments in the jarrah forest and grouped and averaged for the high rainfall zone (>1100 mm yr^{-1}), intermediate rainfall zone (900-1100 mm yr^{-1}) and low rainfall zone (600-900 mm yr^{-1}). The averaged values are plotted in Fig. 3. Values of E_f were extracted for 750 mm yr^{-1} and 1200 mm yr^{-1} as indicated in the figure.

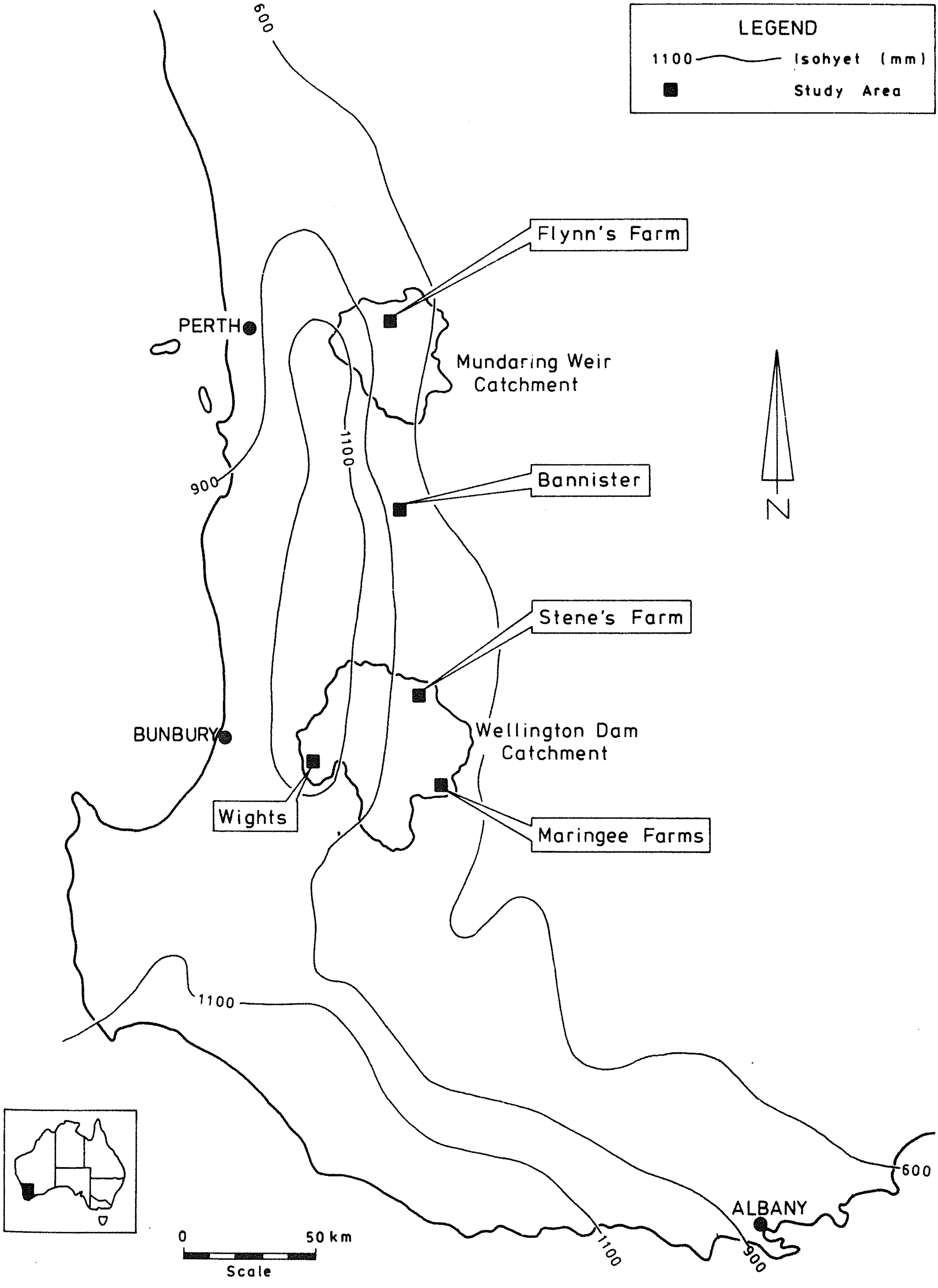

Figure 2. Location of study areas

Table 1 Data for model comparisons

Variable	High Rainfall	Low Rainfall	Units
E_f	1032	734	mm yr^{-1}
E_c	714	390	mm yr^{-1}
E_r	1870	1870	mm yr^{-1}
θ*	0.25	0.25	$m^3 m^{-3}$
α	1	1	-
A_f	0.44	0.34	$m^2 m^{-2}$
A_s	0.18	0.16	$m^2 m^{-2}$
E_s	150	150	mm yr^{-1}
Z	200	200	mm yr^{-1}

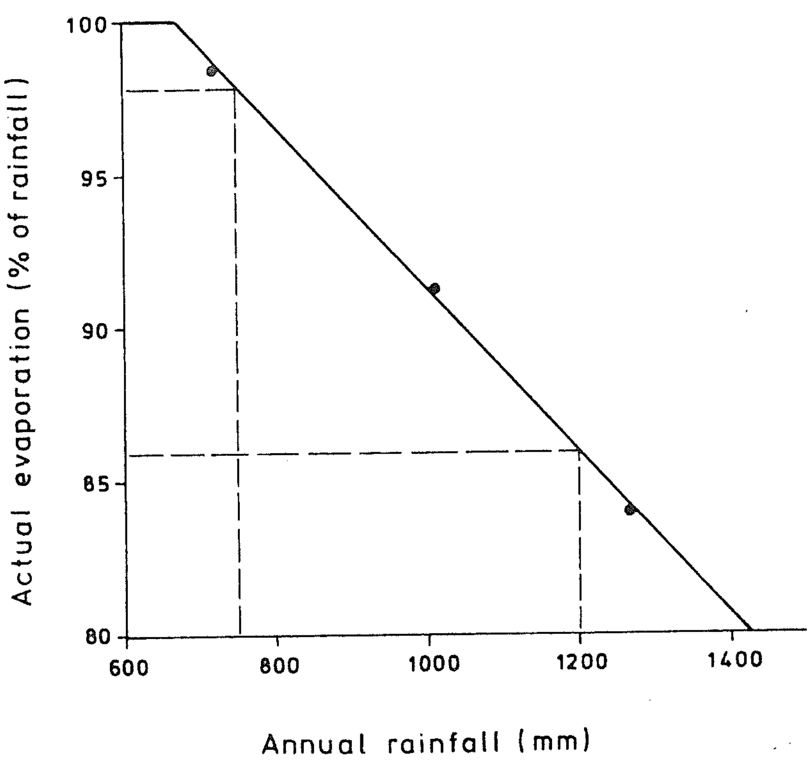

Figure 3 Actual evaporation as a function of annual rainfall

The value of evaporation from land under agricultural use (E_c) for the high rainfall area was determined by subtracting the observed mean annual streamflow from Wights catchment (Fig. 3) for the period 1983-86 from the rainfall for that period. The low rainfall value of E_c was taken as the value measured for pasture by Greenwood et al. (1985) in an area which recorded 680 mm annual rainfall in one particular year of measurement.

The value of evaporation from the reforested area (E_r) was taken as the average of values reported by Greenwood et al. (1985) for midslope plantations of E.globulus (2200 mm yr^{-1}), E.wandoo (1600 mm yr^{-1}) and E.leucoxylon (1800 mm yr^{-1}). Although these measurements were taken at a site of 850 mm yr^{-1} rainfall, the value calculated for E_r was assumed to apply to both high and low rainfall areas because of a lack of other data.

The value of θ^* was obtained from data reported by Ruprecht and Schofield (1988) by taking the difference between porosity values and unsaturated water contents in spring averaged for one 6 m deep profile at a high rainfall jarrah forest site.

The multiplicative factor α for the remnant native forest evaporation cannot at this time be determined from field measurements. The conservative assumption is to take $\alpha = 1$, implying no enhanced transpiration, which may not be too unreasonable when the remnant vegetation is located on upslope areas of the catchment.

The areas of remnant forest (A_f) in the high and low rainfall zone were taken from Schofield (in press, Table 2).

The groundwater seepage area (A_s) for the high rainfall zone was taken as that determined by Ruprecht and Schofield (in press) for Wights catchment as at 1986. For the low rainfall zone, area A_s was taken as the value predicted by groundwater simulations for Maringee Farms catchment (Fig. 3) at 1988 (Hookey 1985a).

The rate of evaporation from the seep area (E_s) depends on the extent and success of revegetation. The conservative assumption is that these areas are not revegetated. A measurement of evaporation rate from bare soil in a salt seep 200 km east of Perth was reported by Greenwood and Beresford (1980). Although the measurement was taken during summer, the daily rate (0.4 mm day^{-1}) was well below winter pan evaporation rates, and so the measured daily rate has been extrapolated here to an annual rate.

The rate of decrease of water table depth (Z) was set at a value which would lead to a significant impact on land and stream salinity within 10 years of reforestation. A lowering of the saline water table by two metres over 10 years would take it below the critical depth of 1.5-1.8 m above which agricultural production is affected (Nulsen 1981).

The four models represented by equations (2), (4), (6) and (7) are compared for high (1200 mm yr^{-1}) and low (750 mm yr^{-1}) rainfalls in Table 2. For the data in Table 1, the predictions of Models 1-4 were reasonably similar at a particular rainfall. For all models the predicted reforestation areas decreased with rainfall. Greater areas of reforestation are required when the water balance includes a continuous lowering of the water table (compare Models 2 and 4 to 1 and 3 respectively), and lower areas are required when some native vegetation is left on the catchment (compare Models 3 and 4 to 1 and 2 respectively).

Table 2 Model predictions of areas required for reforestation

Model	Equation	High rainfall ($1200\ mm\ yr^{-1}$) A_r (%)	$A_r/(1-A_f)$ (%)	Low rainfall ($750\ mm\ yr^{-1}$) A_r (%)	$A_r/(1-A_f)$ (%)
1	(2)	28	-	23	-
2	(4)	32	-	27	-
3	(6)	24	43	18	27
4	(7)	29	51	21	32

2.3 Model 4 Response to Parameter Variation

Model 4 (equation 7) is the most general form of Models 1-4 and is therefore potentially the most useful in field application. The response of Model 4 predictions to variation of its parameters is described in this section. Some useful limiting cases are also presented.

The prediction of Model 4 is discussed with respect to variation of E_r, E_f, E_c, E_s, A_f, A_s and Z in turn. The values taken by these variables, except when being tested, are those in Table 1 under low rainfall.

Variation of A_r with E_r

The variation of A_r with E_r over the range 0-3000 mm yr^{-1} is shown in Fig. 4a. The seepage area (A_s) and the area under native forest (A_f) together cover 50% of the catchment area. The required area of reforestation (A_r) varies non-linearly from about 13% at E_r = 3000 mm yr^{-1} to 50% at E_r = 1021 mm yr^{-1}. The limiting value of E_r when A_r = $1 - A_s - A_f$ is of interest. This is the minimum value required of evaporation from reforestation when all the area available for reforestation is planted. If we call this limiting value $E_{r\ min}$, then from equation (7) it can be shown that:

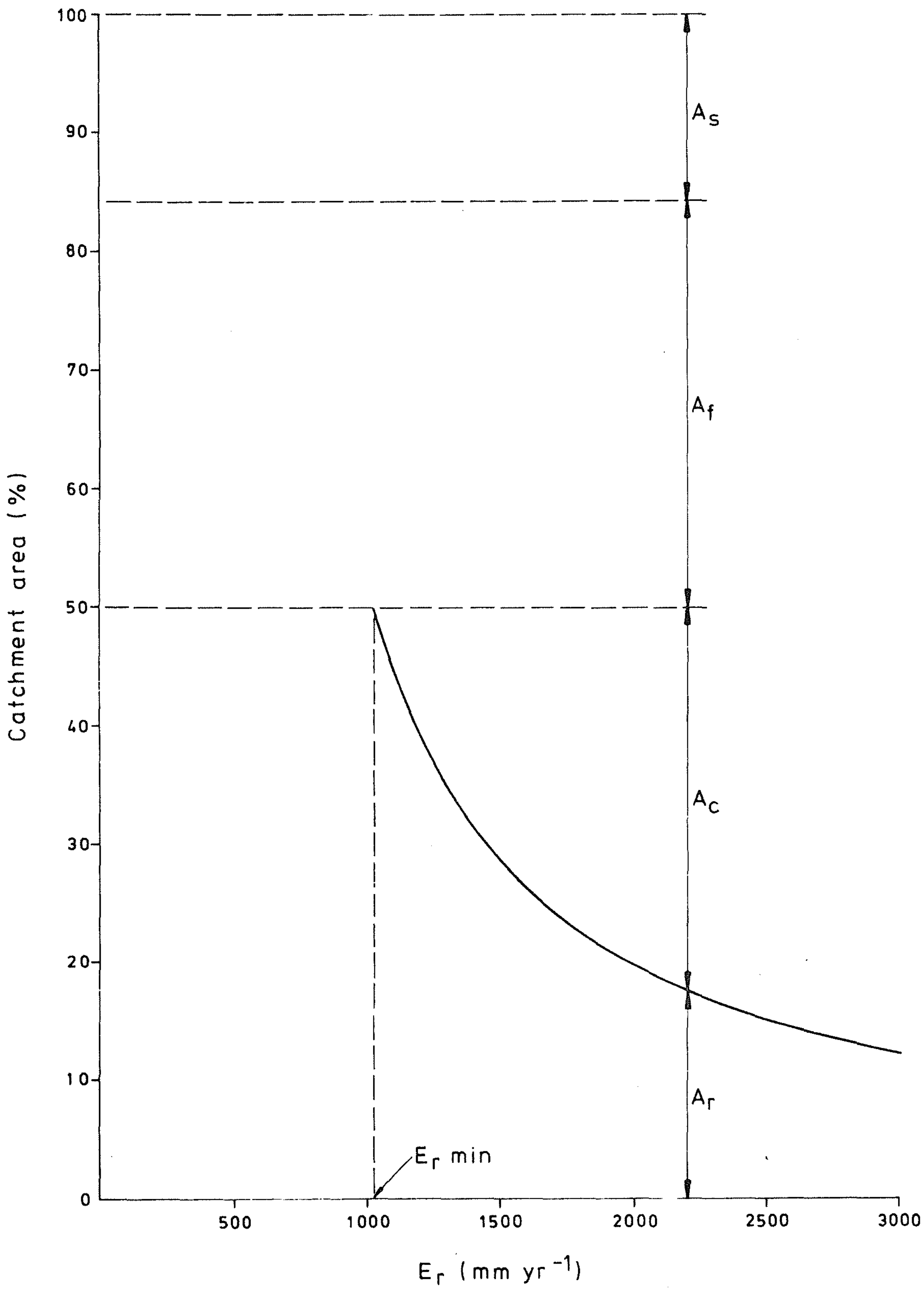

Figure 4a. Variation of A_r with E_r

$$E_{r\ min} = \frac{E_f\ (1 - \alpha A_f) - A_s E_s + \Theta^* Z}{1 - A_f - A_s} \quad (9)$$

In the present example $E_{r\ min}$ = 1021 mm yr^{-1}.

Variation of A_r with E_f

The variation of A_r with E_f over the range 500-1600 mm yr^{-1} is shown in Fig. 4b. The figure shows that the required area of reforestation increases rapidly with increasing E_f. Note E_f here is assumed to be constant for a given rainfall, and variation in E_f implies a variation in rainfall. Increasing A_r with E_f is a result of an increased rainfall input which has to be evaporated by the reforested area. It should also be noted that E_c is likely to increase with increasing rainfall (e.g. Table 1) due to greater water availability to crops and pastures, and E_r could decrease with decreasing rainfall due to less water availability and increasing soil and groundwater salinity. These factors would tend to lower the rate of increase of A_r with E_f indicated by Fig. 4b. At this time there are inadequate data on E_r and E_c to simultaneously vary these quantities with E_f (i.e. with rainfall).

Under the assumptions of Fig. 4b, it is apparent that there is a maximum value of E_f, say $E_{f\ max}$, at which all the cleared area would need to be reforested to maintain the water balance. Substitution of the condition $A_r = 1-A_f-A_s$ into equation (7) gives

$$E_{f\ max} = \frac{E_r(1-A_s-A_f) + A_s E_s + \Theta^* Z}{(1-\alpha A_f)} \quad (10)$$

In the present example $E_{f\ max}$ = 1529 mm yr^{-1}.

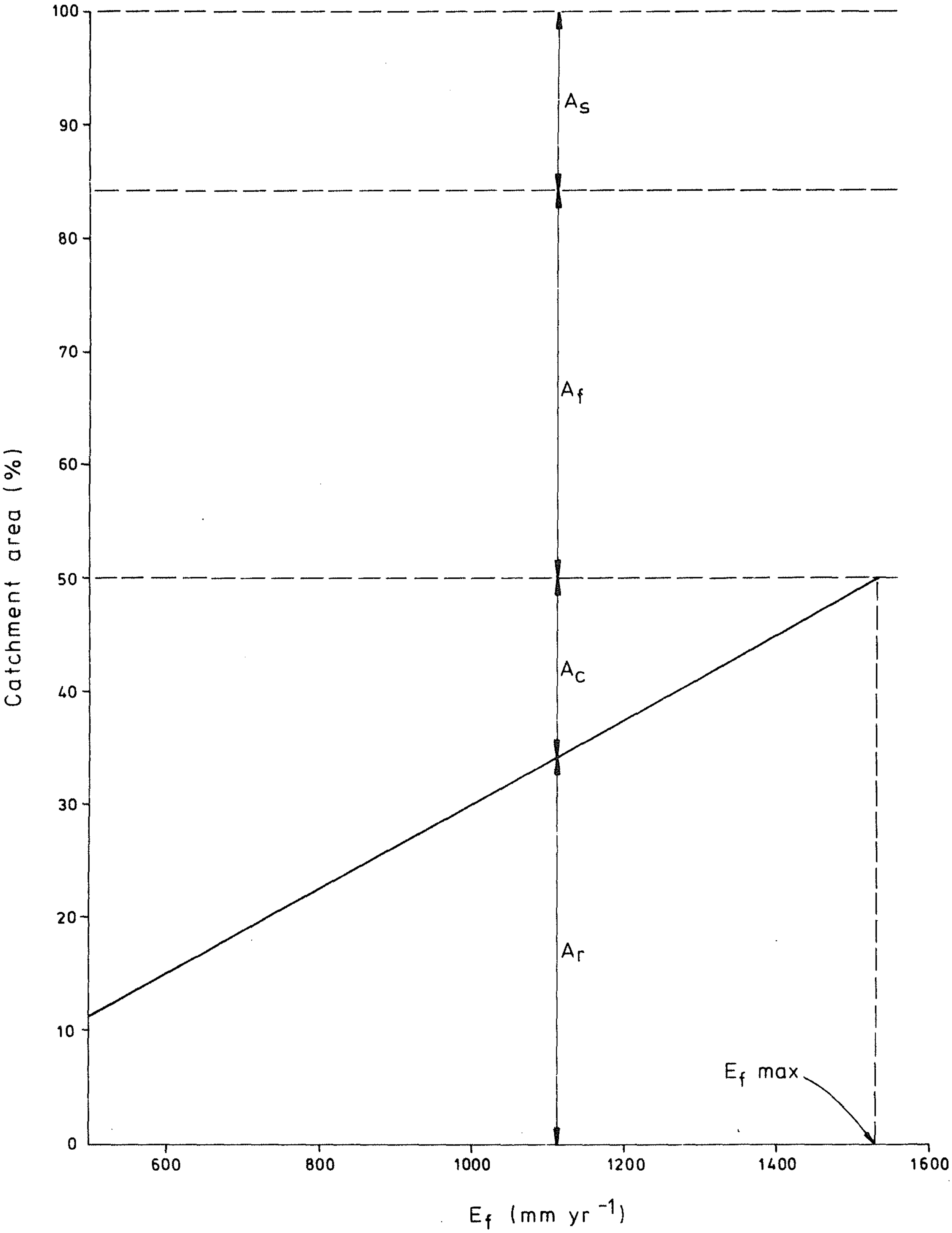

Figure 4b. Variation of A_r with E_f

Variation of A_r with E_c

Model 4 prediction of A_r in response to variation in E_c over the range 0-1200 mm yr^{-1} is shown in Fig. 4c. As crop and/or pasture evaporation increases, the area of required reforestation decreases non-linearly. A limiting case of interest here is the value of E_c such that $A_r = 0$, i.e. the magnitude of agricultural evaporation ($E_{c\ max}$) at which no reforestation is required. Substitution for this condition into to equation (7) gives, $E_{c\ max} = E_{r\ min}$.

Variation of A_r with E_s

In the formulation of Model 4 the seep area has been treated separately. Revegetation of seep areas for both salinity control and cropping has been actively pursued for several years, with increasing success (Malcolm 1986, Ritson and Pettit 1988). Therefore it is of value to determine the response of Model 4 to variation in E_s. This is shown in Fig. 4d for E_s in the range 0-2200 mm yr^{-1}. The proportion of area required for reforestation (A_r) decreases linearly with increasing E_s. A limiting case of interest is the value of E_s (= $E_{s\ max}$) required such that no reforestation would be required ($A_r = 0$). Substitution into equation (7) gives:

$$E_{s\ max} = \frac{E_f(1-\alpha\ A_f) - E_c(1-A_s-A_f)+\theta*Z}{A_s} \qquad (11)$$

For this example $E_{s\ max}$ = 2122 mm yr^{-1}.

Variation of A_r with A_f

The variation of A_r with A_f over the range 0-100% is shown in Fig. 4e. Clearly, in this example, A_f cannot reach 100% because part of the catchment is occupied by reforestation and the seep area. A limiting case of interest is when $A_c = 0$,

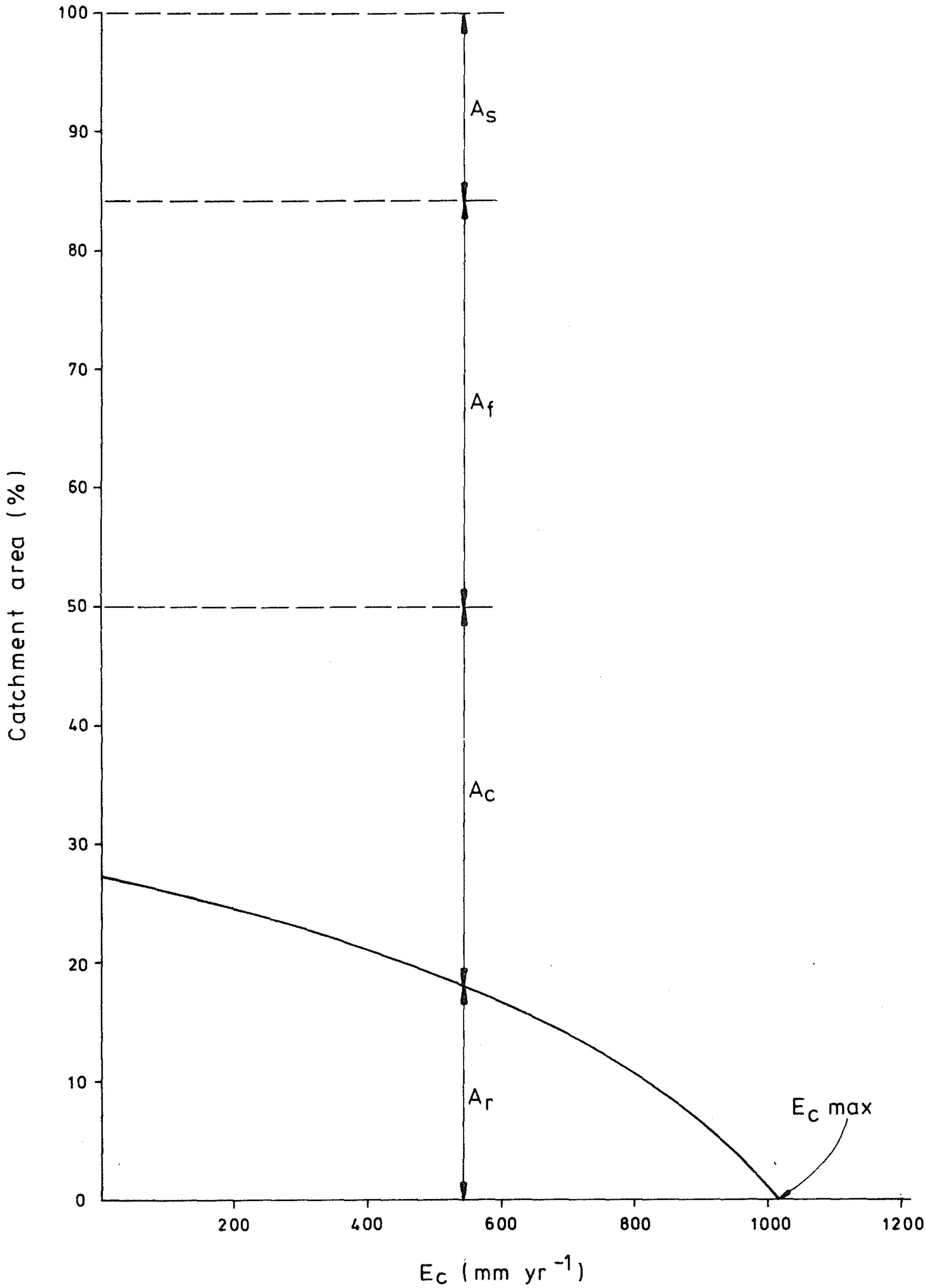

Figure 4c. Variation of A_r with E_c

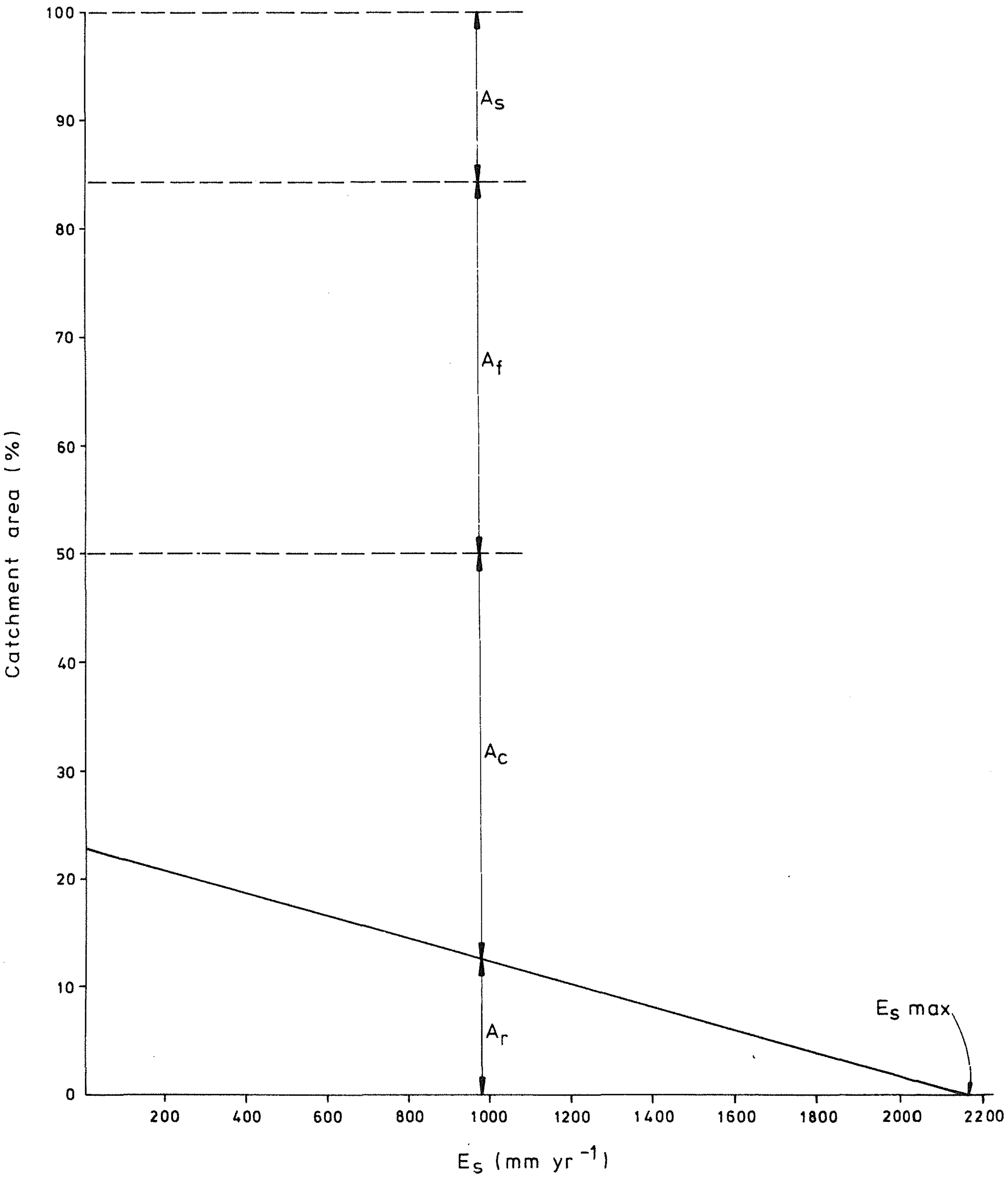

Figure 4d. Variation of A_r with E_s

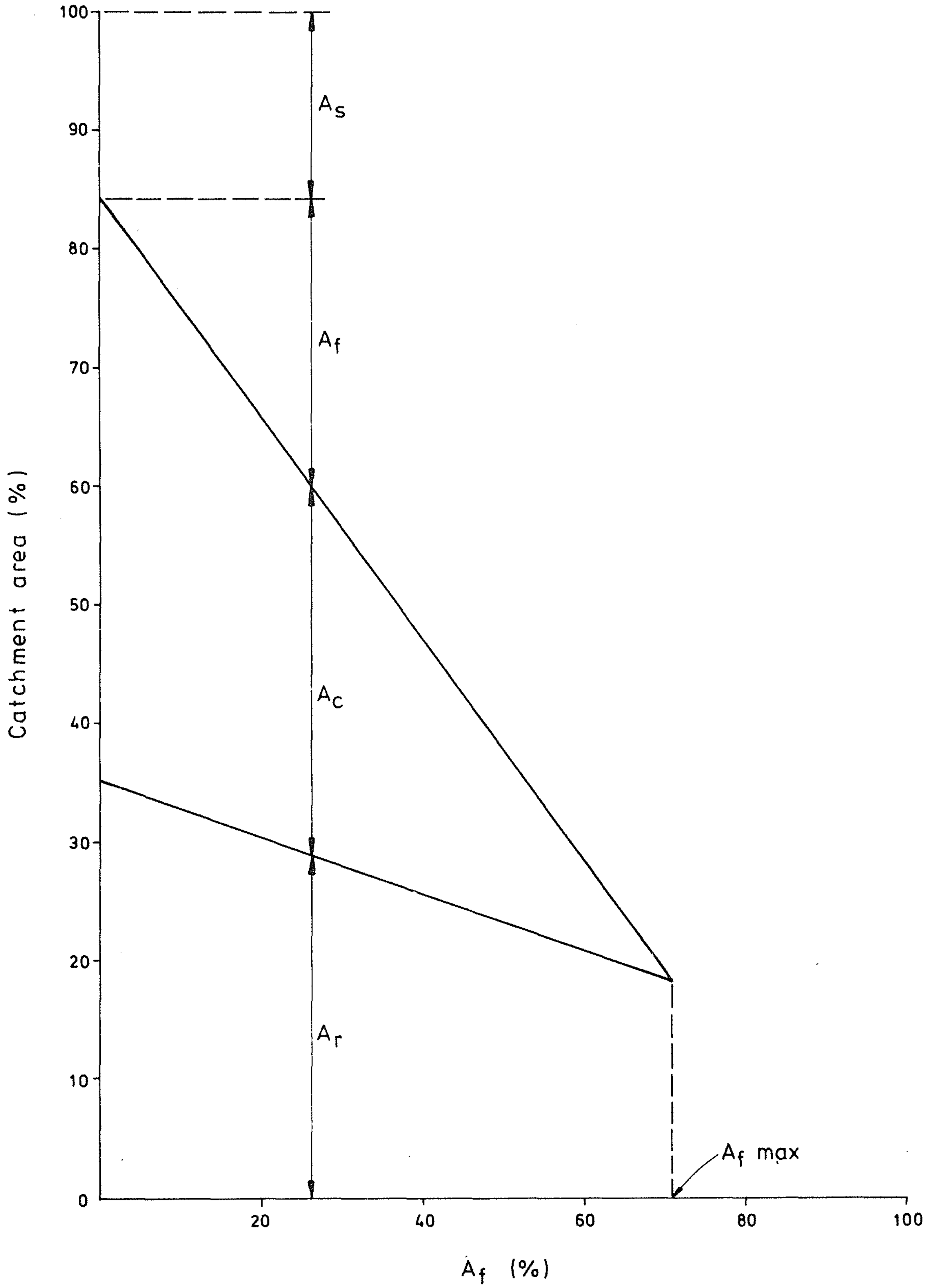

Figure 4e. Variation of A_r with A_f

i.e. when all the catchment is occupied by either native forest, reforestation or seep area. If the value of native forest area at this limit is $A_{f\ max}$, then from equation (7):

$$A_{f\ max} = \frac{E_r - E_f - A_s (E_r - E_s) - \theta * Z}{E_r - \alpha E_f} \qquad (12)$$

This case implies that, for values of A_f beyond $A_{f\ max}$, the required water balance is not achievable.

In this example $A_{f\ max}$ is 71%.

Variation of A_r with A_s

Model 4 predictions for A_r with variation in the seepage area A_s over the range 0-50% are shown in Fig. 4f. As the seep area increases the area required for reforestation increases linearly. As these two areas increase the area of land available for reforestation decreases. A limiting case of interest is when $A_c = 0$, i.e. there is no more land available for reforestation. If the area of the seep at this stage is $A_{s\ max}$, then substitution of the limiting conditions into equation (7) gives:

$$A_{s\ max} = \frac{E_r - E_f - A_f (E_r - \alpha E_f) - \theta * Z}{E_r - E_s} \qquad (13)$$

Thus for seepage areas larger than $A_{s\ max}$ it would not be possible to restore the water balance to that of undisturbed forest. In this example $A_{s\ max}$ is 41% of the catchment area.

Variation of Z

Z is the specified required rate of water table depletion across the catchment. The predicted reforested area requirements for Z over the range 0-2000 mm yr^{-1} are shown in Fig. 4g. With other variables being constant, A_r increases

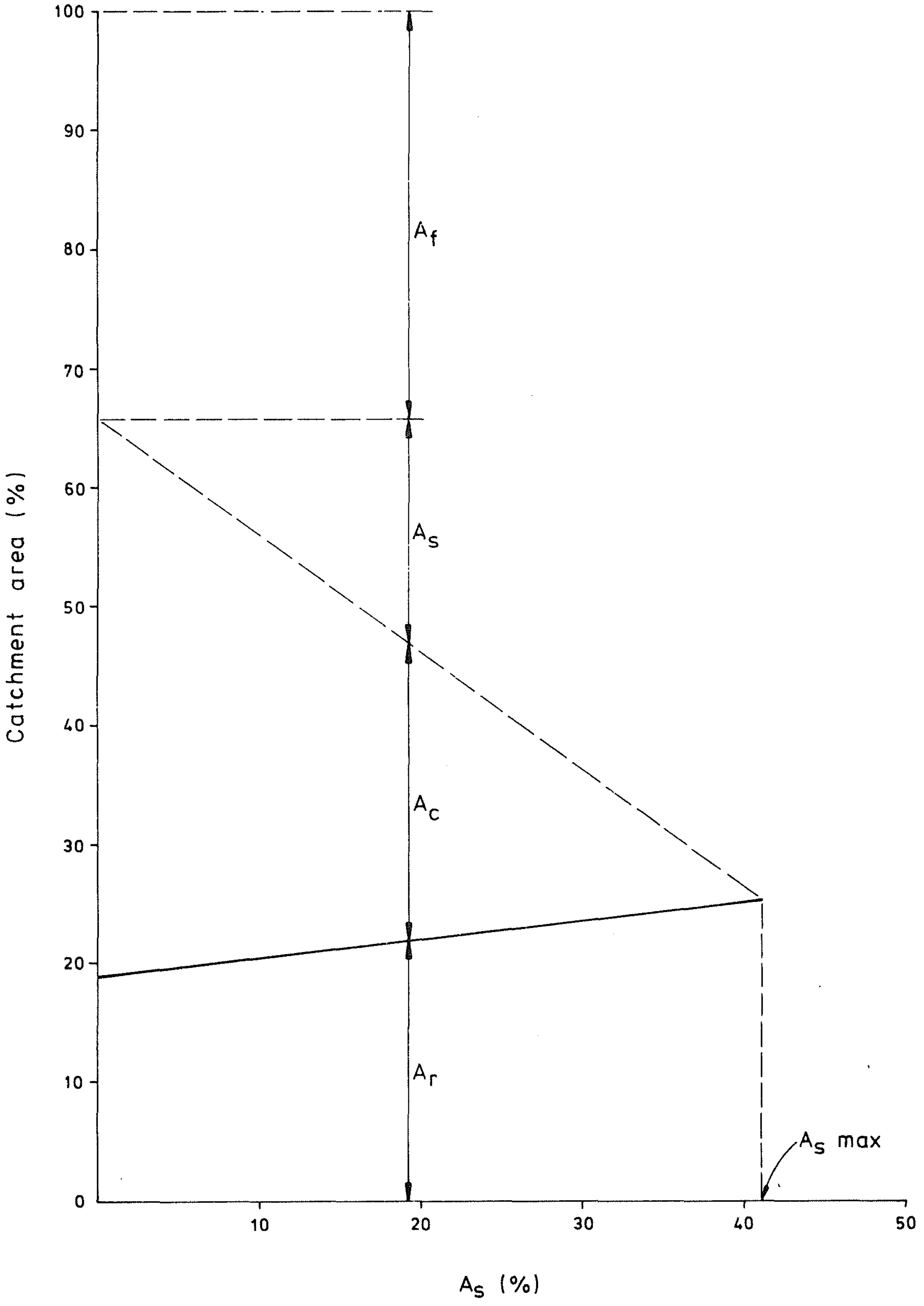

Figure 4f. Variation of A_r with A_s

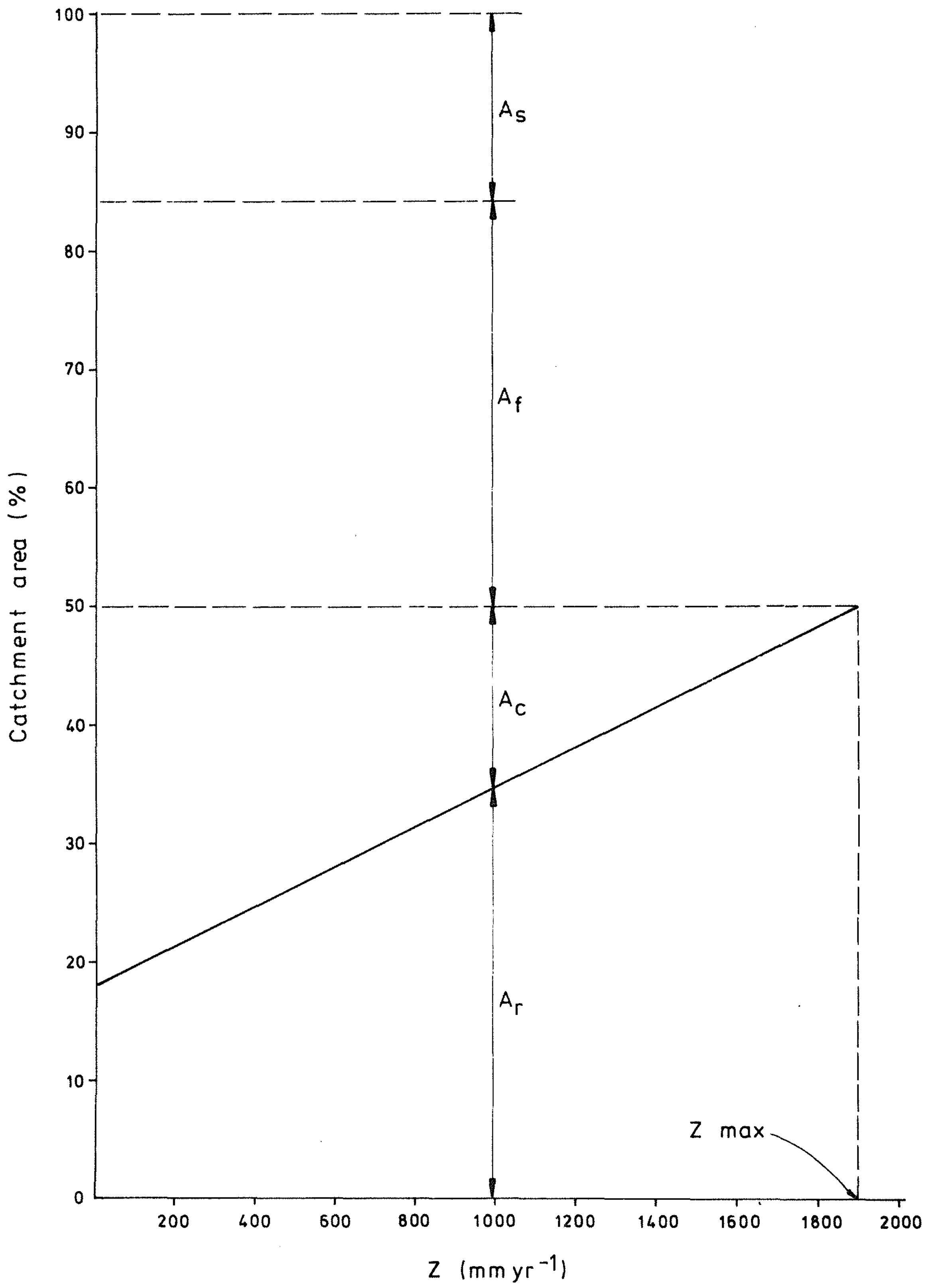

Figure 4g. Variation of A_r with Z

linearly with increasing Z. The limiting case of interest is the value of Z (= Z_{max}) when all the available area is reforested ($A_c = 0$). Under these conditions, equation (7) gives:

$$Z_{max} = \frac{E_r - E_f - A_s\,(E_r - E_s) - A_f(E_r - \alpha E_f)}{\theta^*} \qquad (14)$$

In this example Z_{max} is 1898 mm yr^{-1}.

3. EXPERIMENTAL REGRESSIONS

A number of experimental sites were established in the late 1970s in the Mundaring, Hotham and Wellington catchments (Fig. 2) to test different reforestation strategies for salinity control. The characteristics of these sites are summarised in Table 3. One of the main objectives was to determine whether partial reforestation of salt-affected agricultural catchments could lower water tables and consequently eliminate groundwater and solute discharge to streams. Groundwater levels have been monitored at all sites over the period 1979-86. The groundwater behaviour at the five sites associated with Flynn's Farm and Stene's Farm (Fig. 3) have been analysed by Bell et al. (1988). Groundwater responses at the Bannister site were reported by Biddiscombe et al. (1985) and have been updated by Greenwood (pers. comm. 1988).

The characteristics listed in Table 3 show that the sites are similar only in respect of rainfall and vary significantly in initial groundwater depth and groundwater salinity. A range of reforestation strategies were employed. Regressions between vegetation cover as at December 1987 and rates of groundwater level change averaged over the period 1979-86 have been sought. Vegetation cover was measured by an instrument similar to that proposed by Montana and Ezcurra (1980). Averaged rates of groundwater level change over the 1979-86 period were used rather than rates of groundwater level change at 1986 because groundwater levels were sensitive to variation in annual rainfall. Thus no account was taken of the growth of the plantations over the period of measurement. It should also be noted that the rainfall for the period was 10% less than the 1926-81 average.

Only regressions involving rates of water table change beneath reforestation have been considered. The rates of groundwater level change were calculated as the difference between the

Table 3 Characteristics of experimental reforestation sites

Site name	Annual rainfall (mm)	Year Planted	Area uncleared A_f (%)	Area reforested A_r (%)	Seep area A_s (%)	Plantation crown cover at 1987 (%)	Initial * groundwater depth (m)	Initial groundwater salinity (mg l^{-1} TSS)
Flynn's Farm								
Site 1	725	1978	0	60	25	29	3.3	7400
Site 2	725	1978	20	13	10	43	2.1	4800
Site 3	725	1978	70	26	0	14	4.4	2400
Stene's Farm								
Site 1	725	1976-8	70	4	8	47	2.7	7500
Site 2	725	1979	70	9	0	41	6.3	5500
Site 3	725	1979	70	21	3	39	7.1	5500
Bannister	850	1976-77	16	12	4	?	5-8	2000-5500

* Initial depth to annual minimum groundwater level below reforested areas, taken as the average of bores.

minimum groundwater level in 1979 and the minimum level in 1986, divided by the period.

Two linear regressions have been calculated. The first is a regression of rate of water table change (Z) beneath reforestation on proportion of area reforested. The regression is shown in Fig. 5a. Flynn's Farm site 3 was deliberately excluded from this regression because it was an agroforestry plantation which consequently had very low crown cover. The regression has a high r^2 (= 0.98) and a high statistical significance ($p<0.001$). The regression indicates that an area greater than 13% of the area cleared must be replanted if a lowering of the water table is to occur within 7 years of planting. Since the annual rainfall during the measurement period was some 10% below the long term mean, the minimum area of planting to achieve water table lowering under normal rainfall conditions would probably be greater. It is also clear that the greater the proportion of cleared area replanted the greater the rate of water table reduction.

In the second regression the rate of water table change (Z) was regressed on the product of crown cover and the proportion of cleared area reforested. This approach was first presented by Bell *et al*. (1988). The regression (Fig. 5b) again has high r^2 (= 0.86) and high significance ($p \sim 0.01$). This result indicates that a minimum cover x proportion of cleared area replanted of 5% was required to lower the water table within 7 years of planting. The relationship also suggests that the rate of water table reduction is not sensitive to the method of tree planting, i.e. as to whether the plantations are wide-spaced or close-spaced.

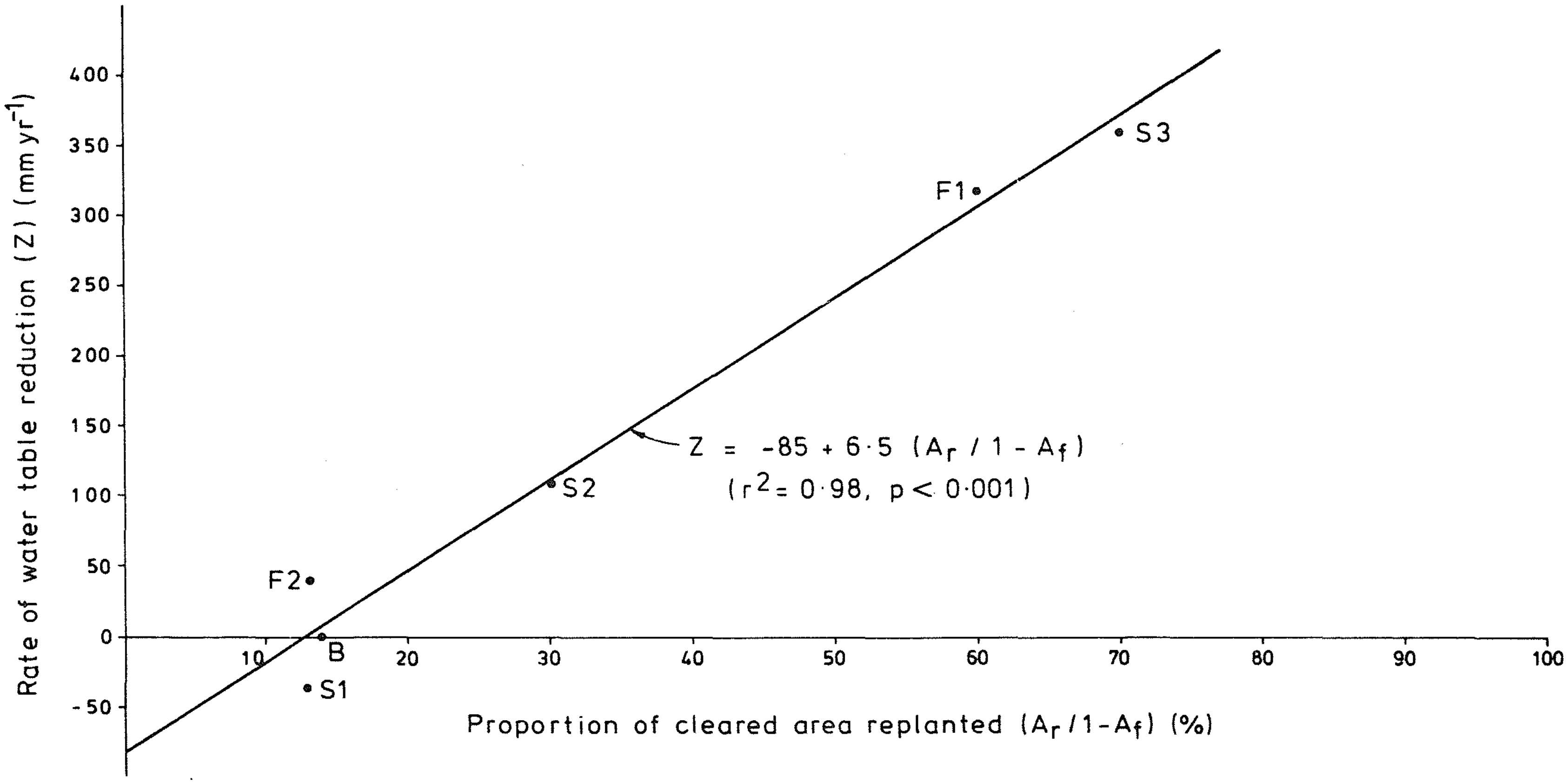

Figure 5a. Dependence of rate of water table reduction on proportion of cleared area replanted

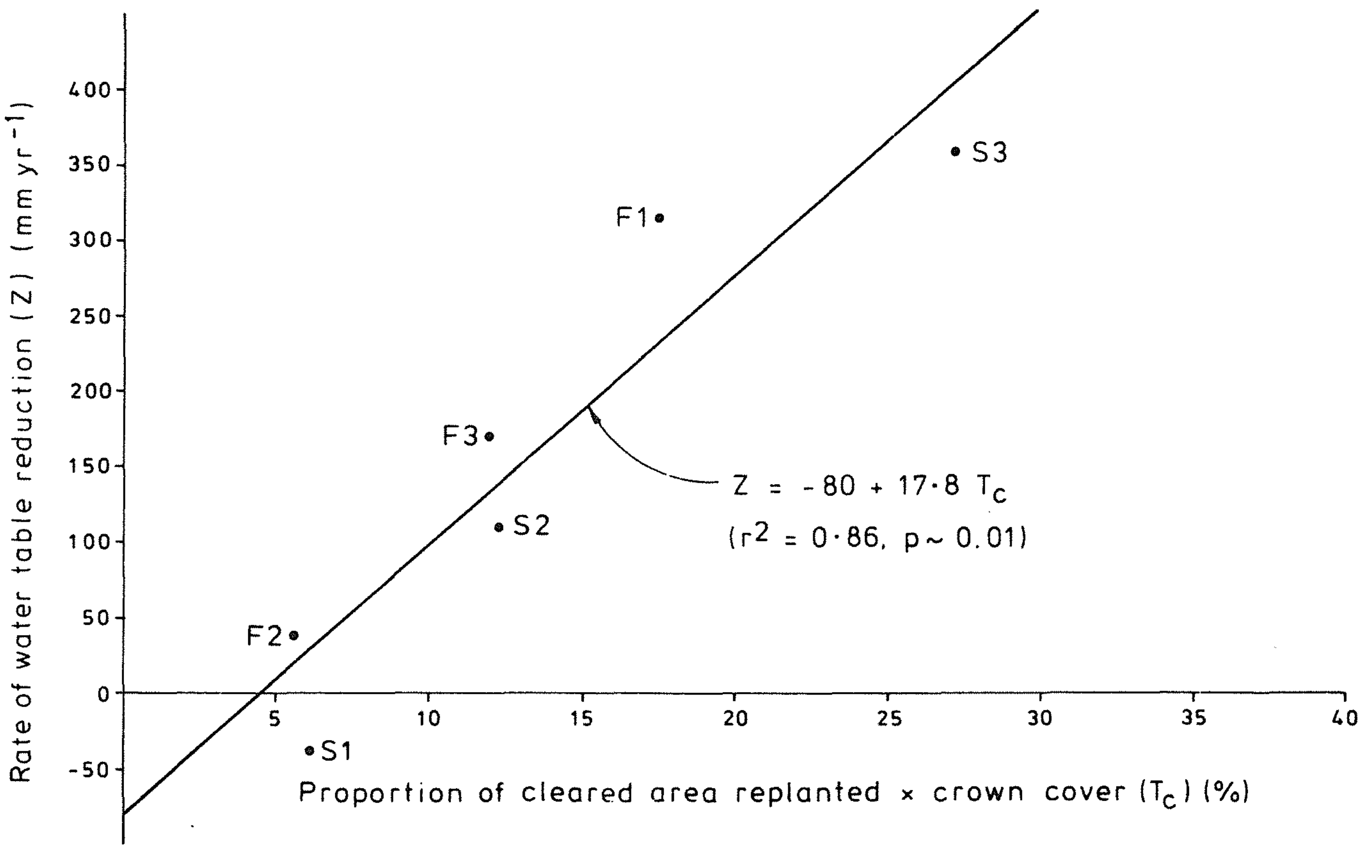

Figure 5b. Relationship between rate of water table reduction and product of proportion of cleared area planted and crown cover

4. A FIELD APPROACH TO REFORESTATION

A field approach to reforestation for salinity control was discussed by Greenwood (1986). His main concern was that partial revegetation of a salt-affected catchment could be totally ineffective if the flow rate of the groundwater aquifer was too great for the planted vegetation to discharge. He thus suggested that basic groundwater data should be obtained before the vegetation strategy is considered. His plan of action basically consisted of the following steps:

(a) use semi-quantitative, workable methods of assessing groundwater flow rate and aquifer yield per unit change in water table elevation at a few key sites in the landscape;

(b) calculate the annual value of transpiration which must be attained by vegetation to lower the water table by the desired amount;

(c) if the required value of transpiration needed to lower the water table exceeds any found in the literature for appropriate vegetation, abandon the project;

(d) if the prospects seem good, adopt a vegetation strategy which optimises transpiration;

(e) estimate how long it will take for optimum transpiration to develop and for the water table to be lowered to the required depth.

Little information was given by Greenwood for the practical solution of steps (a) and (b), although he briefly alluded to bore pump tests. Most of his useful discussion was given to factors affecting transpiration rate and methods of measurement of water use in the field. For optimizing transpiration (step (d)) he noted the following considerations: the total amount of water taken up from the unsaturated zone increases with the rooting depth of the plant; phreatophytes transpire more than non-phreatophytes; water uptake from the saturated zone declines with increasing depth to the water table and with increasing groundwater salinity; in saline soils halophytes transpire more than non-halophytes; and transpiration increases with leaf area index. Greenwood offered no method of determining how long it will take to develop optimum transpiration and for the water table to be lowered to the required depth.

5. GROUNDWATER MODELLING APPROACH TO REFORESTATION DISTRIBUTION

The realisation that vegetation strategies exert salinity control by limiting input to, or extracting water from the groundwater system led to the approach of groundwater modelling for reforestation design. It was also appreciated that the groundwater discharge response to a particular vegetation layout would depend to some extent on aquifer properties such as saturated hydraulic conductivity and storage coefficient, and bedrock topography. It was envisaged that groundwater modelling could lead to more effective vegetation layouts and also determine the groundwater response times for specific cases.

The groundwater model used was essentially that described by Prickett and Lonnquist (1971). Applications of the model to clearing and reforestation have been reported by Hookey and Loh (1985 a,b,c) and Hookey (1987). The partial differential equation solved is

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = S_t\frac{\partial h}{\partial t} + Q \qquad (15)$$

where T = aquifer transmissivity
h = water table elevation
t = time
S_t = aquifer storage coefficient
Q = net groundwater withdrawal or recharge rate per unit area
x,y = rectangular co-ordinates.

This equation describes nonsteady, two-dimensional groundwater flow in the x and y directions for an unconfined, nonhomogeneous and isotropic aquifer. The two-dimensional model implies horizontal groundwater flow and negligible vertical flow. The numerical solution of equation (15) employs a finite difference method. An x-y grid is superimposed over the catchment and may be of variable spacing. The change in groundwater level, or hydraulic head, in each grid cell is the summation of groundwater flow rates to or from adjoining cells plus vertical recharge through the unsaturated zone or discharge via transpiration. When groundwater levels rise above the ground surface they are considered to be discharging as a seep. In this way the model can simulate the seepage area and seepage rate in a catchment.

Application of the model requires knowledge of the saturated hydraulic conductivity and storage coefficient of the aquifer, the initial groundwater level in relation to bedrock and the soil surface, and groundwater recharge and discharge rates. Each of these variables must be specified for each grid cell. Surface topography data can be adequately procured from 1:10 000 scale maps with 2 m contours. Bedrock topography is somewhat more difficult to obtain for the deep (~30 m) lateritic profiles, requiring either seismic surveys or intensive drilling. Saturated hydraulic conductivity (or transmissivity) and storage coefficient can be obtained from pump tests or bore slug tests. Saturated hydraulic conductivity is known to be highly variable in the saprolite aquifers of south-west Western Australia (Peck 1983).

Agricultural clearing has been clearly shown to increase groundwater recharge. Grid cells on which forest has been cleared were assumed to undergo continuous, constant groundwater recharge. Recharge rates may be determined from analysis of the variation of piezometric levels (Peck and Williamson 1987) or analysis of soil profile chloride distributions (Johnston 1987).

In areas which had been reforested with phreatophytes, groundwater would be continuously extracted. It was assumed that the rate of groundwater extraction (G) decreased with depth according to the function:

$$G = G_{max} \qquad z < z_1 \qquad (16)$$
$$G = G_{max} (z_2 - z) / (z_2 - z_1) \qquad z > z_1$$
$$G = 0 \qquad z > z_2$$

where G_{max} = maximum rate of extraction
z_1 = depth to which maximum rate of extraction occurs
z_2 = depth at which extraction becomes zero.

The maximum rate of groundwater extraction itself (G_{max}) was increased linearly from zero at the time of planting to G_{max} after 10 years of growth. Over the same period the groundwater recharge was decreased linearly to zero. G_{max} was specified as that amount of groundwater extraction by reforestation necessary to consume the groundwater recharge (R) beneath cleared areas (Hookey 1985 a). This groundwater balance implies:

$$G_{max} A_r = R A_c$$

$$\text{or} \quad G_{max} = \frac{A_c}{A_r} R \qquad (17)$$

where A_c is the area cleared. Thus it is assumed that the area to be planted (A_r) has been previously specified. The model can then be used to determine the time response of the groundwater system to various reforestation layouts and so determine the optimum layout. Predictions can also be made of decreases in seepage area and groundwater discharge over time.

6. DISCUSSION

Four approaches to determining the area and distribution of reforestation required for salinity control have been described.

The simple water balance models described in section 2 appear to be a promising practical approach at this stage. Of the models described, Model 4 is the most comprehensive. Determination of the model parameters is relatively straightforward. A_s and A_f can be easily determined from aerial photographs. The required rate of decrease of groundwater (Z) can be arbitrarily specified. Where significant stands of native vegetation remain, it is probably reasonable to assume $\alpha=1$. For small or non-continuous stands, increased water availability and increased advection may lead to α being greater than unity. Field transpiration measurements could determine this. The evaporation rates from reforested stands, agricultural plants and seep areas again rely on field measurement. A number of these measurements are already available but additional measurements would improve the reliability of the estimates and applicability of the model over a range of conditions. Model 4 is also amenable to sensitivity testing and some limiting cases are easily assessed.

The calculated regressions between rate of water table reduction and proportion of cleared area reforested, or proportion of cleared area reforested x crown cover, from observed data at experimental sites appears to be a useful approach for local conditions. The regressions, however, are based on data from sites with similar rainfall conditions and cannot therefore be reliably used in other locations. Also no account has been taken of the effects of increasing transpiration of the reforestation stands with age. This is mainly because year-to-year groundwater levels are significantly influenced by rainfall. The regression of the product of crown cover and proportion of cleared area planted on rate of water table reduction is not as useful as the regression involving area of planting for determining plantation specifications because crown cover is not determinable prior to planting.

The field approach described by Greenwood (1986) lacks field testing and evaluation. In particular the initial key steps involving groundwater assessment and calculation of required transpiration require further appraisal. Obtaining quantitative estimates of groundwater flow rates and aquifer yields at a number of key sites would involve drilling, bore installation and pump testing, all of which are expensive. Moreover the saturated hydraulic conductivities of groundwater aquifers have a high spatial variability.

The groundwater modelling approach described in section 3 has concentrated on designing optimum layouts for salinity control for a specified area of reforestation, and determining time responses of the system. Besides the limitations of the model itself (e.g. 2-dimensional horizontal flow assumed), the data requirements are difficult to satisfy. For each grid cell the following are required : saturated hydraulic conductivity, storage coefficient, bedrock depth, initial water table depth, and groundwater recharge and discharge rates. As mentioned above, determination of reliable values for aquifer parameters is difficult and expensive. Surface topography requires detailed mapping from aerial photography and bedrock topography requires drilling or seismic work. The groundwater system can also be strongly affected by intruding dykes which are known to be of low permeability and are common in the region (Engel et al. 1987). As a general tool for determining required areas of reforestation this approach would be too expensive, unless uniform characteristics are assumed to apply over significantly larger areas than those tested. To date the model has been used in this way and, despite the limitations, the resultant simulations have been useful in identifying potential groundwater discharge areas and in determining the most effective distribution of reforestation. The predicted reforestation layouts should, however, be checked by an experienced person in the field to ensure that the areas to be reforested are sensibly placed with respect to observed seeps.

7. CONCLUSIONS

Simple water balance models, experimental regressions and groundwater modelling appear to be the best current approaches to determining appropriate areas and distribution of reforestation for salinity control.

Parameters for the water balance model are relatively easy to determine. The variables to which the model is most sensitive are annual evaporation rates from reforestation stands and agricultural plants. Additional measurements of these variables will improve the reliability and applicability of the model predictions. The models are easy to use and their prediction sensitivity is readily determined for any specified field conditions.

A good regression of rate of water table change with reforestation area was obtained from experimental field data. This regression was considered to be a useful predictor of reforestation requirements for the local conditions sampled. Extrapolation to other conditions would be inadvisable. A limitation of the regression was not taking into account the variation of reforested stand transpiration with age.

A proposed field approach to determining reforestation areas requires further field testing and evaluation.

A groundwater modelling approach to designing reforestation layouts required data that is somewhat more difficult and expensive to obtain. The data requirements included aquifer parameters, surface and bedrock topography and groundwater recharge and extraction rates. The model has been usefully employed for determining optimum vegetation layouts by utilising readily available parameter data and by assuming values for parameters which are difficult or expensive to obtain. Predicted reforestation layouts should be checked in the field. Groundwater modelling has also been used to determine changes in discharge area and discharge rate over time.

A combination of the simple water balance or experimental regression method for predicting reforestation area with groundwater modelling and field inspection for locating reforestation in the landscape would represent the best available approach.

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