Institute of Hydrology

Natural Environment Research Council

A guide to the estimation of the water use from upland catchments in the U.K.

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1. Introduction

Studies worldwide have shown that a changing land use can have a profound effect on the hydrology, and in particular the water use, of catchments. Perhaps the most dramatic change of land use is the establishment, or felling, of forestry. Generally an increase in forest area leads to an increased water use and hence a decrease in river flow. Water use in this context is defined as the loss of water from an area by the processes of evaporation and transpiration. This worldwide picture was corroborated with the results of the paired catchment experiment at Plynlimon, mid- Wales, where the forested area appears to have twice the water use of the adjacent grassland area. Process studies have indicated that this difference is due to the interception by and subsequent evaporation of rainfall from the forest canopy. It is thus likely to be most pronounced in areas of high rainfall such as the upland regions of the north and west of the UK. Subsequent studies in Scotland, in the Balquhidder catchments and elsewhere, have shown that there can be large differences of water use between upland grassland at differerent altitudes and other upland vegetation types such as heather. This fact has complicated the fairly straightforward picture of the effect of afforestation on water use found from the Plynlimon catchments. Mathematical models have been developed to explain and predict the observed water use patterns and thus provide a means to extrapolate the observations to other catchments and other land use mixes.

This guide is intended to provide a means of estimating the water use of upland catchments with a mix of vegetation covers. The procedure can be used both to estimate water use with the current land use and to estimate the possible effects of changes of land use. It provides estimates of the long-term annual water use; an extension of the procedure is provided to estimate the water use in dry and wet years. As is indicated above, the method is based on the catchment and process study results obtained in Scotland and elsewhere over the last two decades. The derivation of the procedure is not discussed in detail. For the detail of the work on which the equations are based the reader is referred to the series of papers and reports listed in the Bibliography.

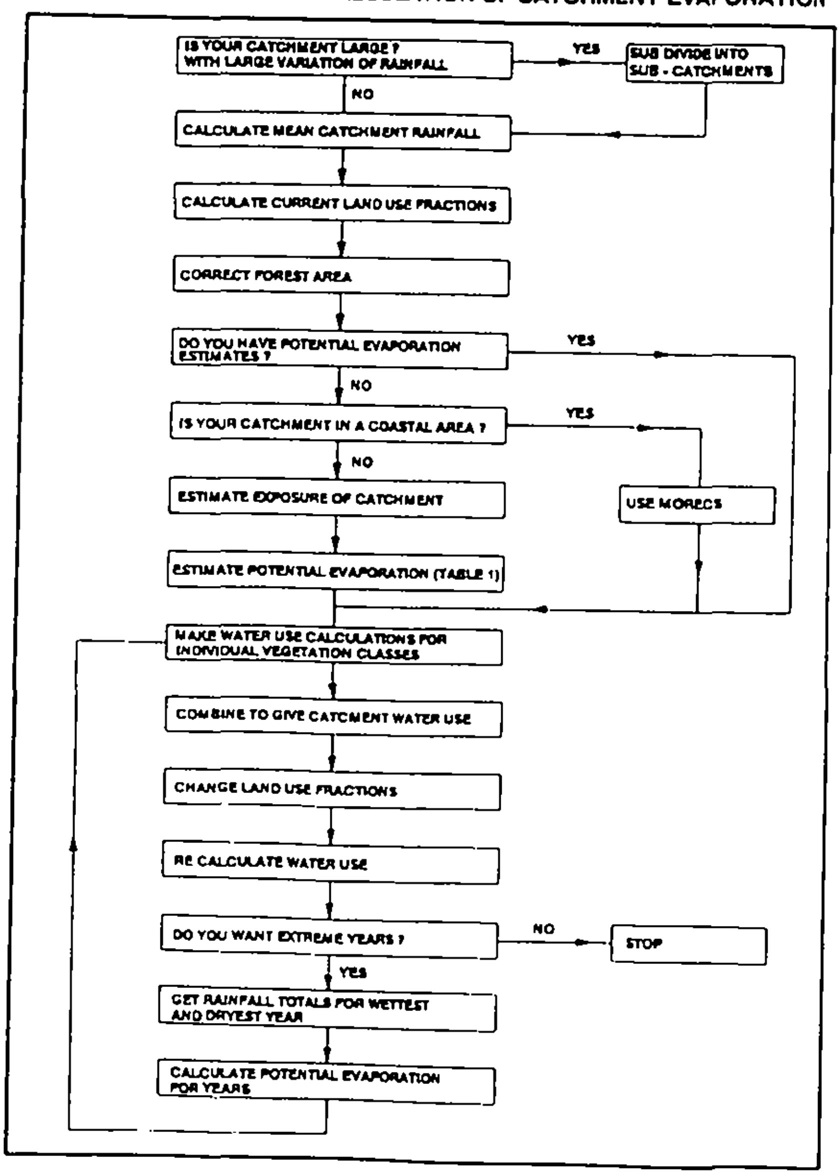
This simple procedure can be used with confidence only in the high rainfall regions for which it was developed. In drier areas (with a rainfall of less than 1200 mm) significant soil water stress will develop in most years. This is a complex process which is not taken into account in the equations used here.

The guide provides an estimate of the total annual actual water use from a catchment - as defined above. The method makes extensive use of 'potential evaporation' E_T. This concept was originally developed to estimate from meteorological data the evaporation from short grass, freely supplied with water in lowland areas of the UK. While the potential evaporation is not directly applicable to upland Scotland it has proved useful as an index from which to calculate the water use of the vegetation types present.

The main guide is divided into three sections. In the first the equations required to estimate the water use from different vegetation types and to combine these into a catchment water use figure are presented. These equations are very simple and can be used directly with a calculator or a micro-computer. However, simple diagrams are also given to estimate the water use from different vegetation types. The use of these simplify the calculations with only a small loss of precision. In the second section the data requirements of the method are discussed. It is assumed that the user knows the current land use of his catchments and the rainfall totals (although some guidance on the classification of vegetation types is given in section 3). In the case of large catchments it is a good idea to subdivide the catchment. The estimation of the potential evaporation applicable to a catchment is a more difficult problem and some guidance is given. Finally the third section presents some refinements which can be made to the procedure, such as estimation in extreme dry and wet years.

Figure 1 Presents a flow diagram of the main procedure.

FLOW DIAGRAM FOR THE CALCULATION OF CATCHMENT EVAPORATION



2. Water use calculations

2.1 THE INVIDUAL LAND USE TYPES

The procedure to calculate the water use requires as input the mean annual rainfall, R, and the mean annual potential evaporation, E_t. The quantities (E_F, E_H, E_{GL}, E_{GM}, E_{GH} and E_O) are the mean annual water use values from the individual vegetation classes. All above quantities are in units of mm per annum.

CONIFEROUS FOREST, E_F.

$$E_F = 0.3 R + (1 - D) E_t$$

D is the fraction of time the canopy is wet, this calculated from the annual rainfall (in mm) using the method described by Calder and Newson (1979). Their expression reduces to:

$$D = 0.0001223 R.$$

MEDIUM HEIGHT VEGETATION (heather, bilberry and bracken), E_H.

$$E_H = 0.2 R + 0.6 (1 - D) E_t$$

LOWLAND GRASSLAND, E_{GL}

For areas below an altitude of 200m.

$$E_{GL} = E_t$$

MID-ALTITUDE GRASSLAND, E_{GM}

For areas between altitudes of 200m and 700m.

$$E_{GM} = 0.75 E_t.$$

HIGH ALTITUDE GRASSLAND, E_{GH}

For areas above 700m.

$$E_{GH} = 0.6 E_t$$

OPEN WATER, E_O

If direct calculations of open water evaporation, E_O, are available these should be used. If not an estimate can be made from E_t:

$$E_O = 1.2\, E_t$$

Thus the water use of a variety of upland vegetation types can be calculated from the rainfall and potential evaporation only. Figures 2 a to g give the water use for the different vegetation classes as a function of rainfall for a number of potential evaporation totals.

2.2 CALCULATION OF CATCHMENT WATER USE, E_C

The water uses of the individual vegetation classes are combined in the proportion of their percentage cover on the catchment.

$$E_C = E_F f_F + E_H f_H + E_{GL} f_{GL} + E_{GM} f_{GM} + E_{GH} f_{GH} + E_O f_O$$

where f_F, f_H, f_{GL}, f_{GM}, f_{GH} and f_O are the fractional areas of the different land use classes. In the case of grassland catchments it is acceptable to make an estimate of the mean altitude and relate this to the evaporation estimate.

In the case of the forest area there is a complication. A forest area is rarely completely covered; there are always forest rides, road and clearings and often areas of immature or cleared forest. It is suggested that the area of forest is reduced to 75% of its mapped value and the area of grassland is correspondingly increased. If, from local knowledge, there are large areas of immature forest, or perhaps gaps following felling or wind damage, it is suggested that the figure of 75% be modified after a field survey.

Thus the percentage of forest canopy, f_F, is calculated from the mapped value, f_{Fm}:

$$f_F = 0.75\, f_{Fm},$$

and the area of grassland adjusted:

$$f_G = f_{Gm} + 0.25\, f_{Fm}$$

A further refinement is required if the catchment is large and contains a large spatial variation of rainfall and potential evaporation. This is particularly important if, as is likely, these are correlated with different vegetation types. (It is likely, for example, that forestry will occur in the lower part of the catchment, where the rainfall is lower.) In these cases it is suggested that the catchment is subdivided into either altitude ranges or subcatchments.

figure 2a

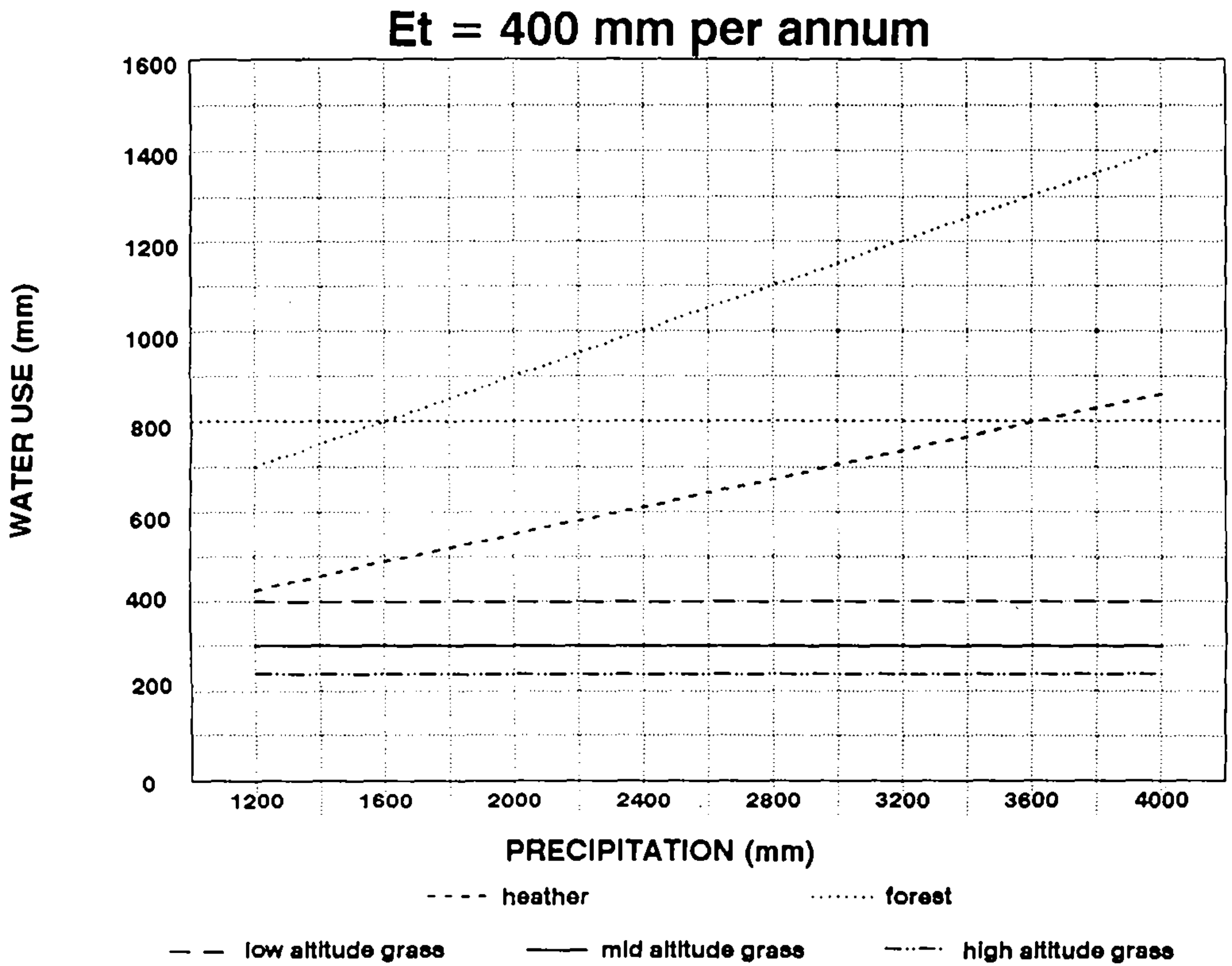
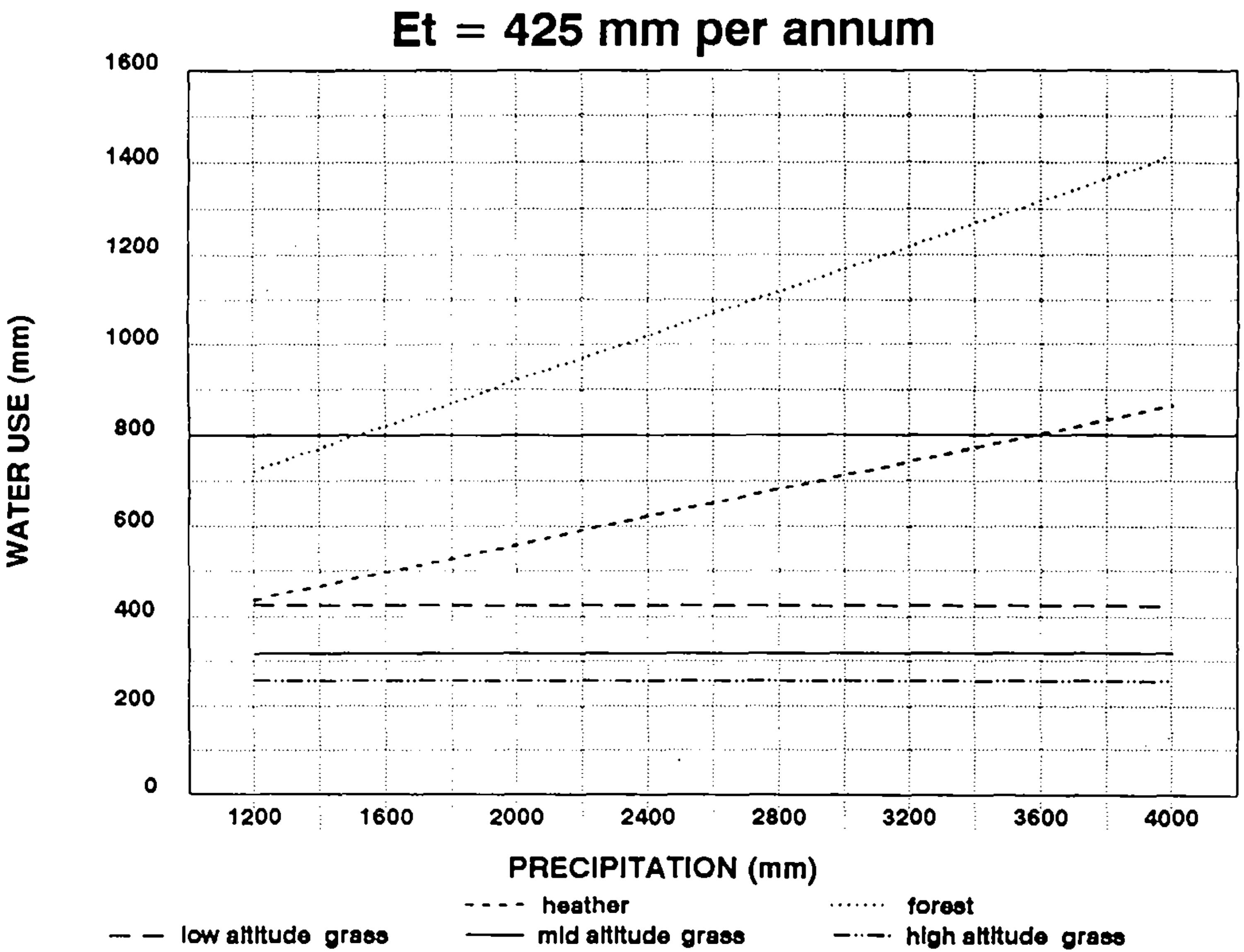

Et = 400 mm per annum
1600
1400
1200
1000
800
600
400
200
0
WATER USE (mm)
1200
1600
2000
2400
2800
3200
3600
4000
PRECIPITATION (mm)
heather
forest
low altitude grass
mid altitude grass
high altitude grass

figure 2b



Et = 425 mm per annum
1600
1400
1200
1000
800
600
400
200
0
WATER USE (mm)
1200
1600
2000
2400
2800
3200
3600
4000
PRECIPITATION (mm)
heather
forest
low altitude grass
mid altitude grass
high altitude grass

figure 2c

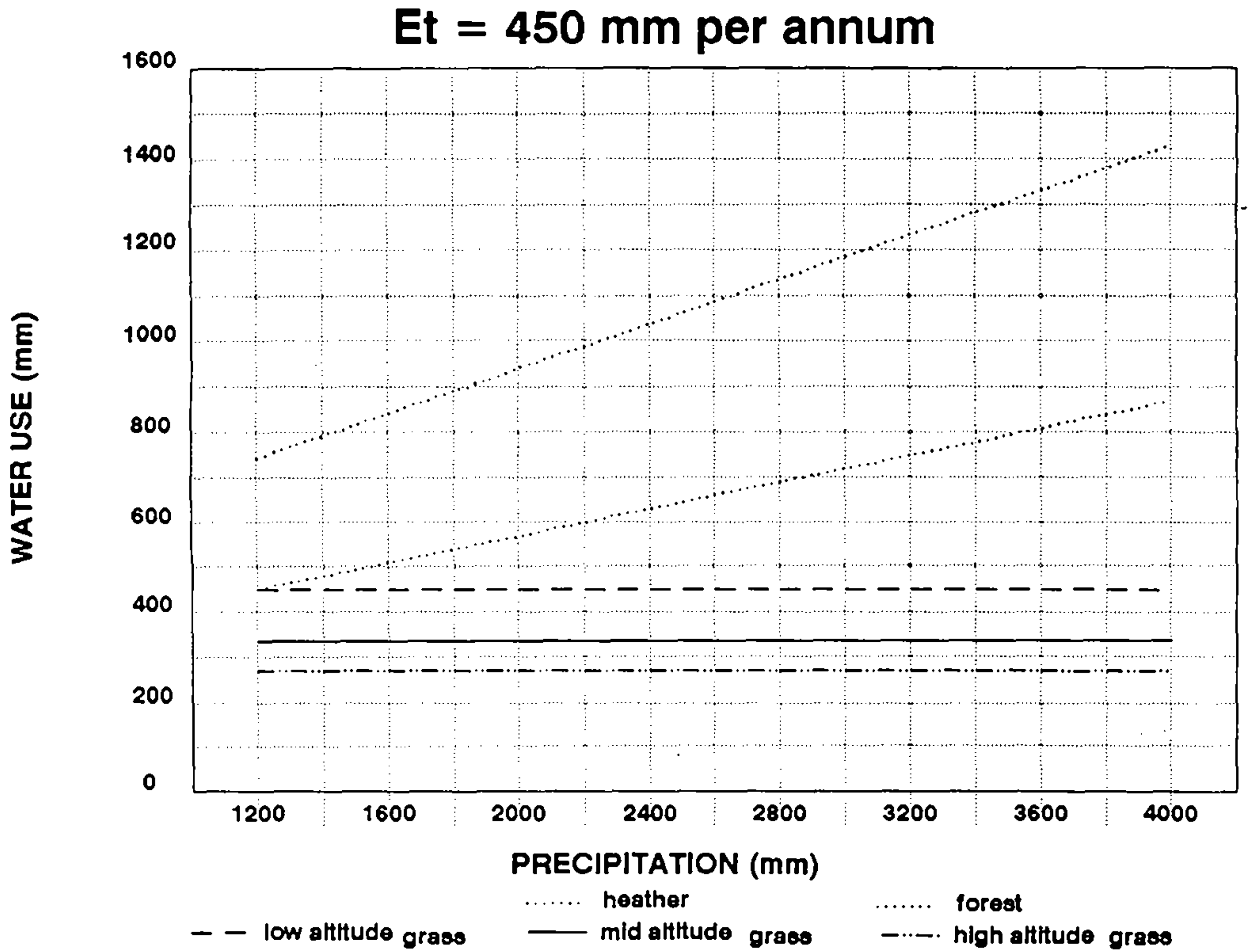
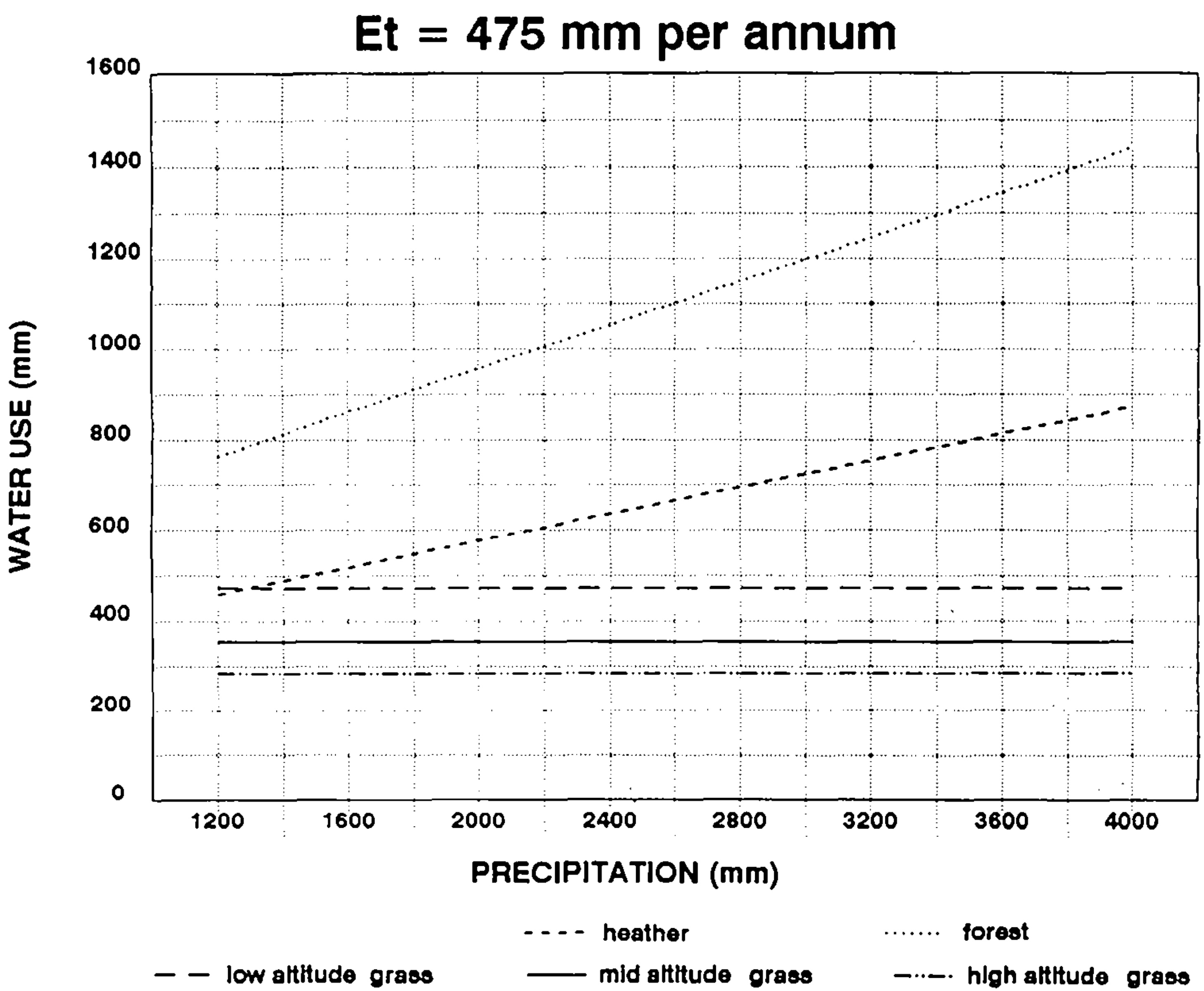
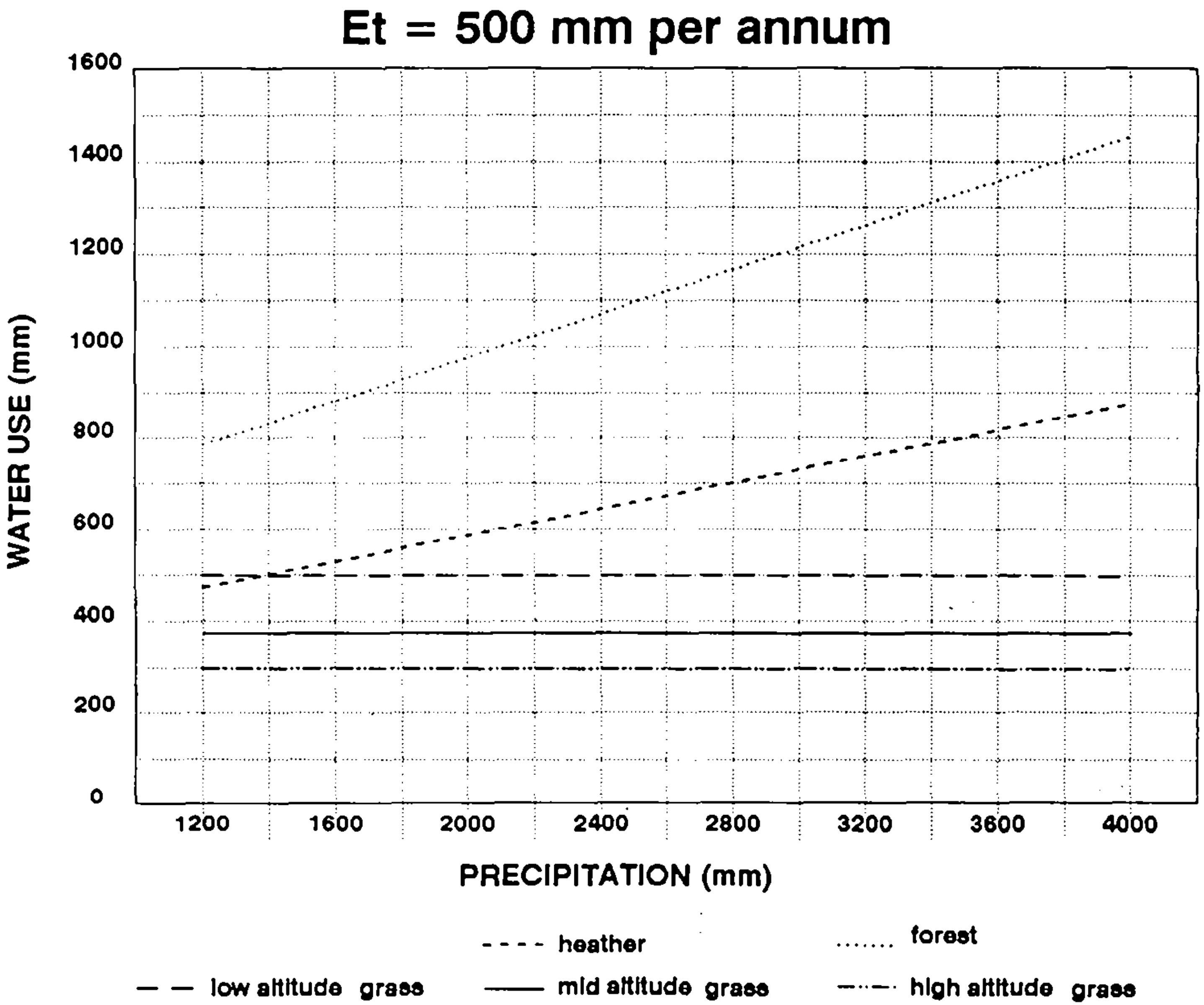

Et = 450 mm per annum
WATER USE (mm)
0
200
400
600
800
1000
1200
1400
1600
1200
1600
2000
2400
2800
3200
3600
4000
PRECIPITATION (mm)
heather
forest
low altitude grass
mid altitude grass
high altitude grass

figure 2d



Et = 475 mm per annum
1600
1400
1200
1000
800
600
400
200
0
WATER USE (mm)
1200
1600
2000
2400
2800
3200
3600
4000
PRECIPITATION (mm)
heather
forest
low altitude grass
mid altitude grass
high altitude grass

figure 2e



Et = 500 mm per annum
WATER USE (mm)
1600
1400
1200
1000
800
600
400
200
0
1200
1600
2000
2400
2800
3200
3600
4000
PRECIPITATION (mm)
heather
forest
low altitude grass
mid altitude grass
high altitude grass

figure 2f

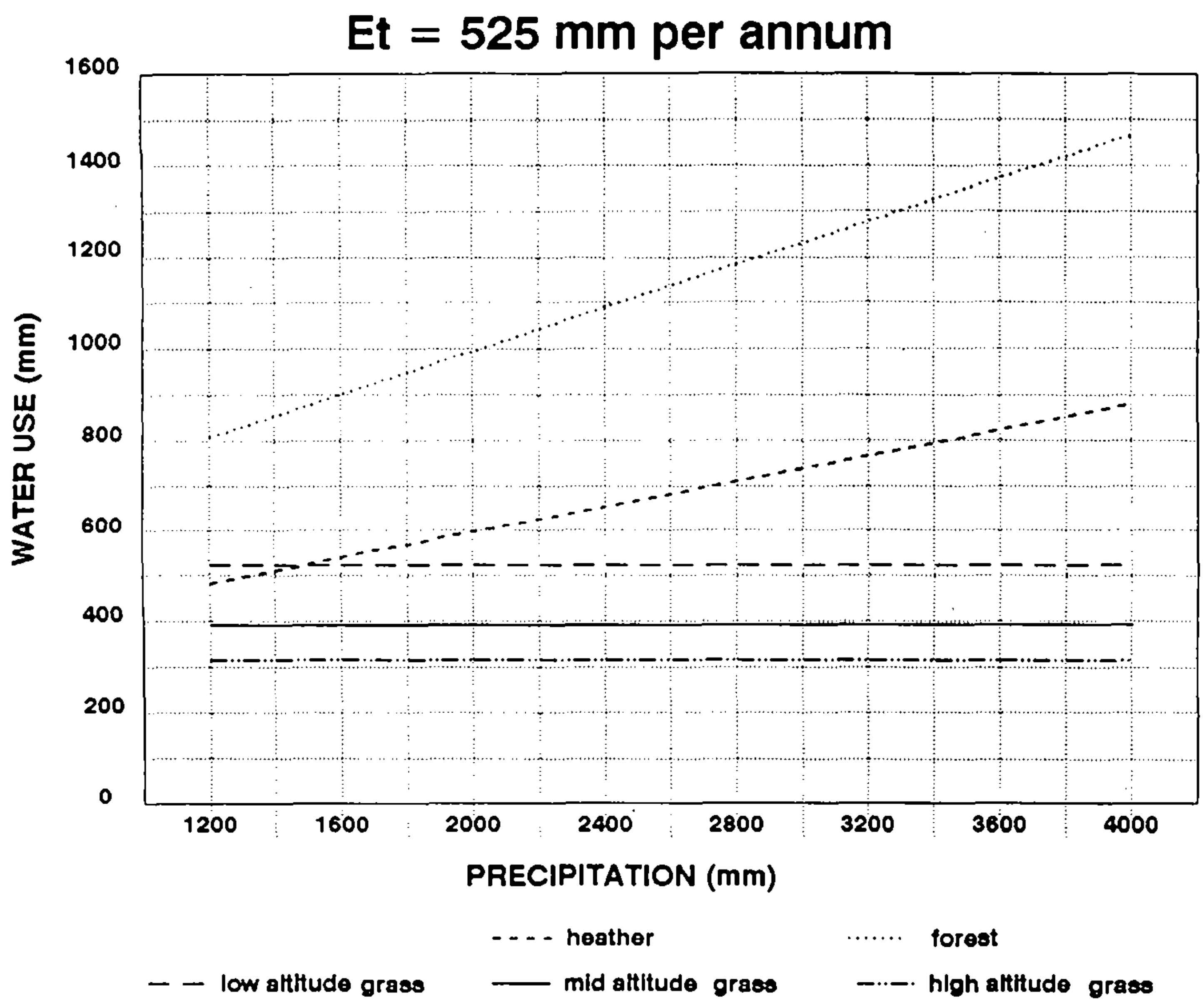
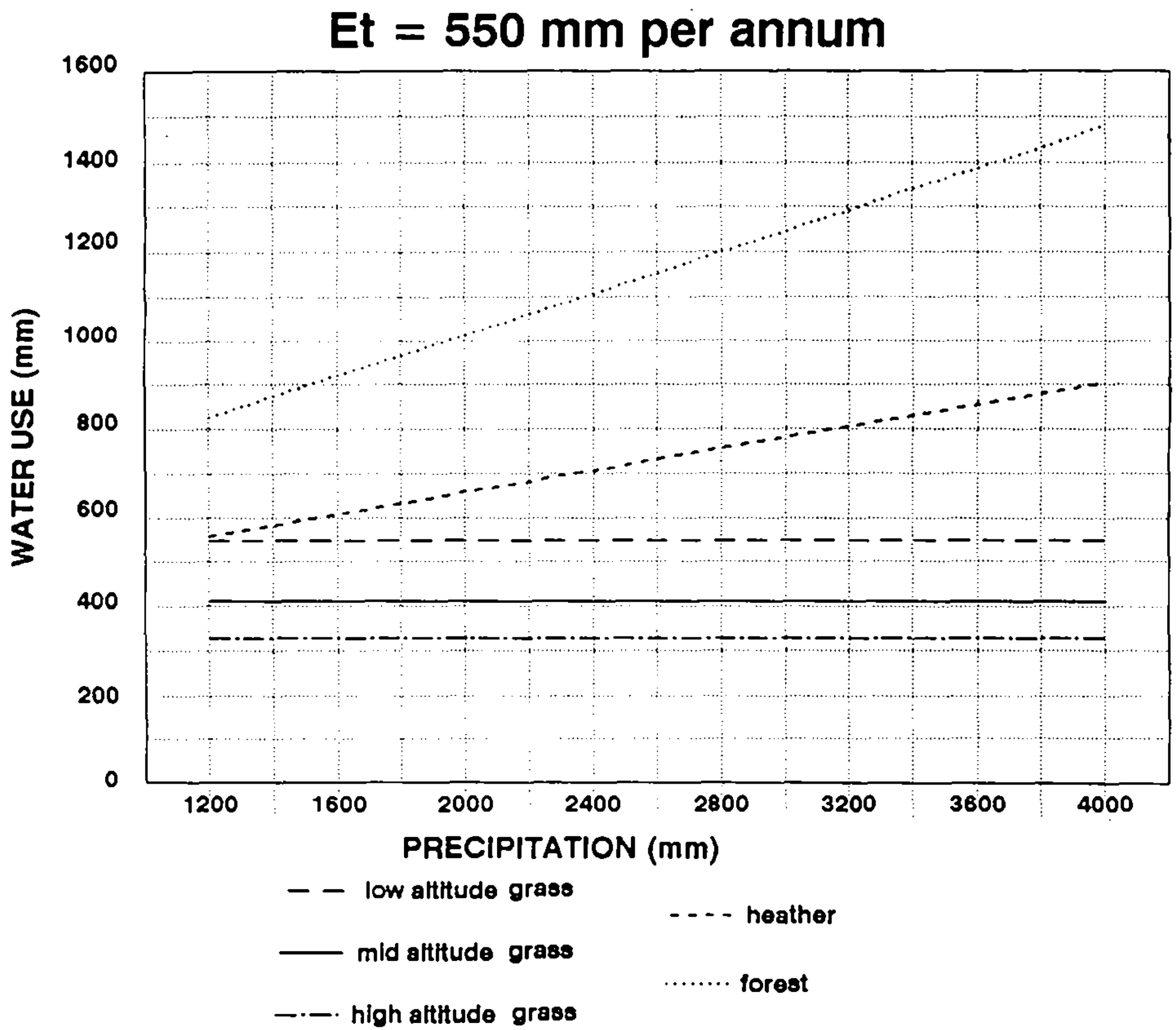

Et = 525 mm per annum
1600
1400
1200
1000
800
600
400
200
0
WATER USE (mm)
1200
1600
2000
2400
2800
3200
3600
4000
PRECIPITATION (mm)
heather
forest
low altitude grass
mid altitude grass
high altitude grass

figure 2g


Et = 550 mm per annum
1600
1400
1200
1000
800
600
400
200
0
WATER USE (mm)
1200
1600
2000
2400
2800
3200
3600
4000
PRECIPITATION (mm)
low altitude grass
heather
mid altitude grass
forest
high altitude grass

3. Data requirements

3.1 VEGETATION AREAS

Forest areas should be available from maps from the Forestry Commisssion (supplemented with ground surveys to check on canopy coverage within the forest areas). Equally areas of open water (lakes and reservoirs) can be estimated from maps.

The identification of areas of Heather and Grassland is difficult. It can be attempted from ground surveys. Areas of medium height vegetation, such as Bracken and Bilberry, should be included with the Heather. Areas of Mosses and Marsh should be included as grassland.

Remote sensing techniques can be used to define the areas of the vegetation types. Images from the SPOT satellite have been successfully used at the Institute of Hydrology to map the vegetation cover of two small research catchments in the central Highlands. If the demand is there this work could be extended to other regions in Scotland.

3.2 PRECIPITATION

It is assumed that the user has a map of the mean annual precipitation of the catchment. No distinction should be made between rain and snow, this causes a small but at present unavoidable error. As discussed above, if there is large variation of rainfall across the catchment it should be subdivided.

3.3 POTENTIAL EVAPORATION

The potential evaporation used in this method is that first described by Penman (1948) for lowland grassland. It is calculated from daily measurements of temperature, humidity, wind speed and solar radiation (or sunshine). Its estimation for upland catchments in Scotland presents a major problem. Apart from in a small number of research catchments very few measurements exist at high altitude. Ideally measurements from the catchment in question should be used. These are unlikely to be available and published measurements may have to be used (see below).

There are two published sources of potential evaporation data for Scotland: MAFF Technical Bulletin No. 16 (1967) and the more recent MORECS system published by the Meteorological Office. Both these estimation schemes suffer from a paucity of measurements at high altitude in Scotland. The measurements from the Balquhidder catchments have shown that the altitudinal corrections suggested in the MAFF Bulletin are wrong for the Scottish Highlands and should not be used for land over 300m. Equally the MORECS scheme in Scotland is heavily biased to coastal and low altitude stations and should again be used with great care in inland highland Scotland. In the absence of other estimates or measurements the following scheme is suggested. This scheme is based on the high altitude measurements from the Balquhidder research catchments and the MORECS estimates:

1. For coastal, lowland areas the MORECS scheme can be used.

2. For inland and upland areas the mean values in Table 1 should be used with adjustment for the exposure of the catchment.

Table 1 Mean values of Potentials evaporation for inland Highland Scotland

Sheltered areas	425 mm per annum
Moderately exposed areas	450 mm per annum
Highly exposed areas	500 mm per annum
For very high altitude areas (above 800 m AMSL)	350 mm per annum

The estimation of exposure of a catchment, or part of a catchment, is obviously subjective; as a guide incised valleys are generally sheltered (especially if they run perpendicular to the prevailing wind), summits and open plateaus are generally highly exposed and shallow valleys and valleys running parallel to the prevailing wind are moderately exposed.

It should be emphasised that this procedure will give only a rough estimate. However, it can be seen from figures 2 a to g that the water use estimates are not strongly dependent on the estimate of potential evaporation.

4. Extreme wet and dry years

It is of some interest to estimate the effect of land use changes in extreme years. To make this estimate the rainfall and potential evaporation totals are required in these years. It is assumed that the user knows the rainfall total for his catchment for a range of years. An estimate of the potential evaporation for individual years can be calculated from the mean annual potential evaporation from the catchment (estimated above) and the deviation from the mean presented for each year in Table 2. Thus:

$$E_t \text{ (year)} = E_t \text{ (mean)} \,.\, DEV$$

were DEV is the deviation of an individual year from the mean (Table 2).

Table 2 Mean annual totals of E_t for upland Scotland for individual years and the deviation from the mean (DEV)

Year	E_t(mm)	DEV	Year	E_t(mm)	DEV
1961	416	0.99	1976	437	1.04
1962	427	1.01	1977	450	1.07
1963	435	1.03	1978	403	0.95
1964	418	0.99	1979	423	1.00
1965	371	0.88	1980	441	1.04
1966	384	0.91	1981	437	1.04
1967	397	0.94	1982	441	1.04
1968	371	0.88	1983	432	1.02
1969	395	0.94	1984	472	1.12
1970	401	0.95	1985	405	0.96
1971	416	0.99	1986	431	1.02
1972	364	0.86	1987	397	0.94
1973	409	0.97	1988	430	1.02
1974	459	1.09	1989	492	1.17
1975	441	1.05	1990	465	1.10

5. Case studies

5.1 MONACHYLE CATCHMENT

AREA: 7.70 km^2

MEAN RAINFALL: 2770 mm

LAND USE: Grass 49%
Heather 51%

EXPOSURE: The lower third of the catchment is a valley bottom with N-S orientation, but wind funnels along the valley, therefore moderate exposure. Upper two thirds highly exposed.

POTENTIAL EVAPORATION:

Lower two thirds moderate exposure - E_t = 450 mm
Upper third highly exposed - E_t = 500 mm

Catchment E_t = 0.33x450 + 0.67x500 = 483 mm

VEGETATION WATER USE:

Mid-altitude grass, E_{GM} = 0.75 x 483 = 363 mm

Heather, E_H, (Figure 2.d and 2.e) = 714 mm

CATCHMENT WATER USE:

E_C = 0.49 x E_{GH} + 0.51 x E_H

= 0.49 x 363 + 0.51 x 714

= <u>542 mm</u>

5.2 KIRKTON CATCHMENT

AREA: 6.85 km^2

MEAN RAINFALL: 2370 mm

LAND USE:

forest: 39% (f_F = $0.75xf_{fm}$ = 0.29)

grass: 61% (f_G = f_{Gm} + $0.25xf_{Fm}$ = 0.71)

EXPOSURE:

N - S orientation
lower third of catchment (forested part) is well sheltered.
Upper part (grass) is highly exposed.

POTENTIAL EVAPORATION:

E_t = 0.33x425 + 0.67x500 = 475 mm.

VEGETATION WATER USE:

forest, E_F = 1040 mm (figure 2c)

grass, E_G = 0.7 E_t = 324 mm

(assumed to be two thirds mid-altitude and one third high altitude.)

CATCHMENT WATER USE:

$$E_C = 0.29x1040 + 0.71x329 = \underline{535\ mm}$$

5.3 ALT UAINE CATCHMENT

AREA: 3.13 km^2

LAND USE: grass 100%

ALTITUDE RANGE: 330 m to 884 m

EXPOSURE:

N - S orientation
Steep sided valleys : mixture of sheltered and moderately exposed.
Highly exposed on ridges.
Assume on averge moderate exposure.

POTENTIAL EVAPORATION:

average exposure, E_t = 450 mm

VEGETATION AND CATCHMENT WATER USE:

altitude range suggests between E_{GM} and E_{GH} i.e.

$$E_C = 0.75x0.5x450 + 0.6x0.5x450$$

$$= \underline{303\ mm}$$

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