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V. SOIL MOISTURE CHARACTERISTICS AND EVAPOTRANSPIRATION

By A. B. Costin,* D. J. Wimbush,* and R. N. Cromer*

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Summary

Soil moisture characteristics and evapotranspiration from natural and disclimax communities in meadow, forest, snow gum–snow grass, and alpine herbfield areas were examined at Kosciusko during 1956–58.

The most important soils of these communities—transitional alpine humus soils at 4500–5000 ft and alpine humus soils above 5000 ft—are deep, friable, and rich in organic matter, have high infiltration capacities, are permeable to saturated flow but have low unsaturated permeabilities, and are generally well supplied with available moisture.

Gypsum block measurements from 3 in. down to 6 ft indicate similar rates of evapotranspiration between different groups of communities, except on severely depleted sites where water use was reduced by 10% in one of the forest areas and 6% in one of the snow gum–snow grass areas.

In the snow gum–snow grass areas, where the soils were never far from field capacity, there was good agreement between measured and calculated evapotranspiration values. In the lower forest areas where greater drying out of the soils occurred, the actual losses of moisture were considerably less than the calculated values, apparently because the rate of evapotranspiration began to fall below the potential rate even at fairly high soil moisture contents.

The dominance of meteorological control over evapotranspiration at higher levels in the Snowy Mountains leaves little scope for modifying water yield by ordinary methods of vegetation management such as thinning, development of shallower-rooted communities, or replacement of climax by disclimax vegetation. The hydrological merit of the alternative plant communities at present available should therefore be assessed on other grounds. These include infiltration and protection from soil erosion, accumulation and persistence of snow, and moisture increment from rain, cloud, and fog, as discussed in the preceding papers of this series.

I. Introduction

In this series of catchment studies the hydrological efficiency of the main soil and vegetation types in the Australian Alps is being evaluated. Earlier papers described trends in soils and vegetation, surface run-off and soil loss characteristics, accumulation and persistence of snow, and interception of rain, cloud, and fog (Costin and Wimbush 1961; Costin, Wimbush, and Kerr 1960; Costin *et al.* 1959, 1961). The present study investigates other important groups of hydrological properties, namely, soil moisture characteristics and evapotranspiration in relation to water yield. Other considerations being equal, the plant communities which consume least water are the most desirable in catchments used primarily for water supply. Conversely, in flood control catchments, high water use may be desired.

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The specific objectives of the present study are, therefore:

(1) To characterize the soils in terms of absorption, detention, and retention of moisture.

(2) To characterize the plant communities in terms of water use.

Given this information and standard meteorological data, reasonable predictions of catchment behaviour can be made. With the development of catchments for hydroelectric power, irrigation water, and flood control, the ability to make such predictions is becoming increasingly important.

II. Soil Moisture Characteristics of the Experimental Areas

The areas chosen for the soil moisture studies were the same as those used in determining soil loss and surface run-off (Costin, Wimbush, and Kerr 1960). They contained representative examples of the main natural, near-natural, and disclimax vegetation found between 4000 and 7000 ft.

The Sawpit area (*c.* 4000 ft) is a typical wet meadow environment with meadow soils (wiesenboden) and tall wet tussock grassland vegetation, in places modified by grazing to a short turf. The profile shows about 1–2 ft of dark brownish black crumb- to cloddy-structured clay, underlain by a single-grained, tenacious, mottled gravelly clay subsoil in which there is a permanent water-table (Costin 1954).

The Waterfall (*c.* 4400 ft) and Wilson's Valley (*c.* 5100 ft) areas contain typical examples of upper montane sclerophyll forest, dense regrowth forest, and disclimax heath and grassland. The soils are mainly transitional alpine humus soils (Costin 1954) in places approaching brown podzolics. From top to bottom of the profile there is a gradual transition from a relatively organo-mineral topsoil (typically sandy loam, *c.* 5% organic matter) to subsoil horizons which are essentially decomposing parent material, without strong development of illuvial horizons of sesquioxides or clay. Unlike the Sawpit soils, drainage is free throughout.

The Crackenback (*c.* 5200 ft), Rennix Gap (*c.* 5200 ft), Hotel Kosciusko (*c.* 5000 ft), Daner's Creek (*c.* 5200 ft), Prussian Creek (*c.* 5500 ft), Lower Smiggins (*c.* 5600 ft), and Upper Smiggins (*c.* 5700 ft) areas are all within the subalpine tract of snow gum woodland with snow grass. The main communities represented are natural snow gum woodland, dense regrowth snow gum scrub, disclimax heath, natural snow grass grassland, short-grazed pasture, and depleted areas characterized by various amounts of bare ground. The soils belong to the alpine humus group, in which the organo-mineral horizon is the dominant feature (Costin 1954). A typical profile shows a more or less humified A_0 horizon of dark grey to dark brown colour, merging gradually into brownish black to greyish black organo-mineral A horizon (sandy loam texture, *c.* 10% organic matter) of excellent crumb structure, porosity, and friability; the subsoil is essentially an AC horizon which becomes gradually less organic, more compact and stony, and yellowish in colour towards the underlying rock, without the development of illuvial horizons of sesquioxides or clay. Drainage is free throughout.

The Boggy Plains area (*c.* 5000 ft) is also in the subalpine tract and generally similar to those above, except that it occupies a low-lying situation transitional to

Sphagnum bog. The alpine humus soils are thus subject to seasonal waterlogging, and consequent development of gleying in the subsoil. The adjacent *Sphagnum* bog areas, which are peaty and permanently wet, were made the subject of a separate study (results in preparation) on account of the special problems of moisture measurement which they present.

The Carruthers area (*c.* 6800 ft), in the alpine tract above the tree-line, contains examples of natural alpine herbfield and the depleted vegetation derived from it. The alpine humus soils happen to be relatively shallow—bed-rock is only 4–5 ft below the surface, compared with more than 6 ft in most of the other areas studied.

From Sawpit to Carruthers, a horizontal distance of about 18 miles, there is a steady fall in mean annual temperature from about 45 to 35°F, and a rapid increase in precipitation from about 30 in. to more than 100 in. of which progressively more occurs as snow. In the montane areas below winter snowline (i.e. Sawpit, Waterfall, Wilson's Valley), annual P/E ratios are estimated to range from 1 to 2 (Costin 1954) and the monthly values exceed or approach 1 for about 5–6 months of the winter–spring period. In the subalpine tract the annual ratio varies from 2 to 4 and the monthly values are not less than 1 for 9–12 months of the year. The annual value in the alpine tract is about 4 to 5 and all months have values of 1 or more. Considered in conjunction with the considerable depth and moisture storage of the soils, these meteorological data suggest that the alpine humus soils of the alpine and subalpine tracts should be well supplied with moisture throughout the year, and that the transitional alpine humus soils of the montane tract should be well supplied for at least several months. The meadow soils should also be well supplied for a few months, and possibly throughout the year if the summer–autumn water-table remains within the range of plant roots. These expected soil moisture conditions will be examined further in the light of actual soil moisture determinations.

The most important soil properties in the present study are those affecting the ability of the soils to absorb, retain, detain, and transmit moisture. Such properties include infiltration capacity of the surface, the field capacity and wilting point moisture contents of the various horizons (providing an approximation to retention storage and available moisture), macroporosity (providing an estimate of detention storage and permeability), and soil depth and volume weight (cf. Lassen, Lull, and Frank 1952).

It has been shown that infiltration capacities are high and that depending on the condition of the soil surface as much as 90–100% of the total precipitation enters the surface soil (Costin, Wimbush, and Kerr 1960). Thus, in view of the high precipitations of these areas, differences in infiltration capacity are not likely to cause major differences in soil moisture content.

Approximations to field capacity and permanent wilting percentage are provided by the soil water contents at tensions of 100 cm and 15 atm respectively. The water held in the soil between these two moisture contents is normally regarded as representing the soil water which is available for plant growth. At tensions less than 100 cm, permeabilities of soil to water flow are usually high (except in clays) and gravitational drainage in the soil normally removes excess water fairly rapidly so that it is available for plant use for only a short time. As tensions increase above

100 cm, the unsaturated permeability of the soil decreases rapidly so that gravitational drainage can remove only a small fraction of the soil water, but the tension gradients developed between the water in the roots of the transpiring plants and the surrounding soil water are sufficient to allow some moisture movement to the plant. The extent to which this water movement can satisfy the transpiration demand of the plant depends on the magnitude of the demand, the tensions developed in the plant, and the unsaturated permeability of the soil. Below a moisture content corresponding to a tension of about 15 atm, the unsaturated permeabilities of soils have normally

TABLE 1

MOISTURE CHARACTERISTICS OF MEADOW, TRANSITIONAL ALPINE HUMUS, AND ALPINE HUMUS SOILS AT KOSCIUSKO

Soil	Depth (ft)	Volume Weight (g/cm³)	Water Content (g/g soil) at Tension of		Available Water	
			100 cm*	15 atm	(g/g soil)	(in./ft soil)
Meadow	0–1	0·95	0·253	0·137	0·116	1·3
	1–2	1·64	0·250	0·115	0·135	2·7
	2–3	1·89	0·242	0·095	0·147	3·3
	3–4	1·74	0·232	0·080	0·152	3·2
	4–5	1·58	0·225	0·075	0·150	2·8
Transitional alpine humus	0–1	0·83	0·233	0·105	0·128	1·3
	1–2	1·18	0·220	0·090	0·130	1·8
	2–3	1·40	0·214	0·084	0·130	2·2
	3–4	1·44	0·210	0·090	0·120	2·1
	4–5	1·50	0·210	0·110	0·100	1·8
Alpine humus	0–1	0·85	0·475	0·201	0·274	2·8
	1–2	1·30	0·420	0·145	0·275	4·2
	2–3	1·50	0·360	0·097	0·263	4·7
	3–4	1·52	0·305	0·095	0·210	3·8
	4–5	1·55	0·253	0·094	0·159	3·0

* The use of the soil moisture content at 100 cm tension may give high estimates for field capacity for the alpine humus soils and other sandy soils which are rich in organic matter.

decreased to such an extent that movement through the soil to the roots of plants is very slow. The consequence is that plants tend to wilt as this moisture content is approached and water extraction by the plant becomes very small. Plants may also wilt at higher soil moisture contents if the transpiration demand exceeds the rate at which the soil can supply water.

Average values of available water in the widespread transitional alpine humus (4500–5000 ft) and alpine humus soils (above 5000 ft) and the more local meadow soils (below 5000 ft) are given in Table 1; in shallower stonier soils the available water would be less. The last column of Table 1 also permits estimates to be made of the water available to plants and plant communities of which the effective root depths are known, down to a maximum depth of 5 ft. For example, in the alpine humus soils minor herbs with most of their root system in the surface foot would have access to a maximum of about 2·8 in. of water, perennial grasses, shrubs, and trees with effective root systems down to 2 ft about 7·0 in., and deeper-rooting species at least 10 in. Under field conditions the water relations of the surface foot are likely to be of most importance since most of the roots, even under forest, are found to occur there. Measurements in forest areas at Waterfall showed that although root penetration occurred at least to depths of 8 ft, 70–90% of the roots were concentrated within the top 2 ft, mostly near the surface.

The permeability of the soil to water is important for both plant growth and water yield (cf. Marshall 1959). In the case of plant growth, water movement in the unsaturated condition is usually more significant; estimates of microporosity* are valuable in this regard. In the case of water yield, movement under saturated conditions, and hence information on macroporosity†, are more useful. In the alpine humus and transitional alpine humus soils total porosities in the surface are as high as 70% and decrease progressively to about 40% at depths of 5 ft; the corresponding microporosities vary from about 35% down to 10%. In the meadow soils total porosities are only slightly lower (60% in the surface down to 30% at 5 ft) but the pore-size distribution is very different. Apart from the surface foot, where microporosity and macroporosity are about equal, the capillary pores account for almost all of the pore space, the non-capillary porosity being less than 5%; such soils are almost impermeable to roots (Lassen, Lull, and Frank 1952).

These estimates suggest why the meadow soils can support a hygrophilous grassland but are unsuitable for deeper-rooting trees, and indicate that whilst retention (capillary) storage is high, detention (non-capillary) storage is very low. The widespread alpine humus and transitional alpine humus soils, on the other hand, have high saturated permeabilities and detention storage capacities which will help sustain stream flow. Actual measurements of changes in soil water content during and following the spring thaw have confirmed these estimates for alpine humus soils. At Smiggins Holes in the Kosciusko area in 1956, the water content in a 6 ft profile decreased from 33% during active snow-melt to 14% two days after the completion of the thaw. However, unsaturated permeabilities will be relatively low, implying that local soil moisture stresses might develop in the immediate vicinity of plant roots although the soil in the root zone as a whole may not be much drier than field capacity.

Summation of the detention storage capacities of successive foot-depths of soil indicates values of up to 10, 12, and 13 in. of water for soils 3, 4, and 5 ft deep respectively. Thus, in catchments with an average depth of about 4 ft of soil mantle the detention storage capacity will be about a foot of water. Application of these data to actual catchments in the Snowy Mountains area indicates that Guthega catchment‡ has a detention storage capacity of more than 35,000 ac ft compared with an active capacity of 1000 ac ft for Guthega pond, Tantangara catchment‡ more than

* Capillary porosity: pore space due to soil aggregates of diameter less than approx. 0·5 mm.

† Non-capillary porosity: pore space due to soil aggregates of diameter greater than approx. 0·5 mm.

‡ Natural catchment plus area tapped by aqueducts and tunnels.

125,000 ac ft compared with 193,000 ac ft for Tantangara dam, and Eucumbene catchment* about 1,000,000 ac ft compared with 3,500,000 ac ft for Lake Eucumbene itself.

These estimates of detention storage capacity are probably conservative, since they do not take into account the often considerable depths of deeply weathered rock (Moye 1955). They do, however, focus attention on the importance of the deep alpine humus and transitional alpine humus soils of the Snowy Mountains in regulating and sustaining stream flow, and help to explain why some of the streams (e.g. the Snowy River) are virtually permanent rivers at their very headwaters. The alpine torrent regime of steeper mountains, characterized by spring thaw floods which rapidly dwindle to no flow at all, does not occur (cf. Costin 1955; Dortignac 1956; Interior and Insular Affairs Committee 1952).

III. Soil Moisture in Relation to Cover Type

Few aspects of hydrological research have received more attention in recent years than the relations between water yield and vegetation. Five main methods of study have been employed:

(1) The physiological approach, which attempts to predict the effects of different plant communities on the amount of water yield, on the basis of measured differences in transpiration rates, stomatal closure, root depth, etc., between different species (cf. Croft 1948, 1950; Dortignac 1956; Grieve 1955, 1956; Henrici 1940, 1946*a*, 1946*b*, 1947; Lassen, Lull, and Frank 1952; Laurie 1957; White 1934).

(2) The water budget approach, which endeavours to measure or estimate for different plant communities all of the main components of the water budget, namely, precipitation, interception, surface run-off, seepage, and changes in soil storage (cf. Brookes 1950; Burgy and Pomeroy 1958; Colman 1953; Croft and Monniger 1953; Cunningham 1960; Gray 1958; Hopkins 1958; McDonald 1955; Ovington 1957; Rowe 1948, 1956; Rutter 1958; Specht 1957; Veihmeyer 1953; Wilm and Dunford 1948).

(3) The hydrometric approach, which endeavours to evaluate water yield characteristics of different cover types by measuring the input of water as precipitation into experimental catchments and the proportion recovered as stream flow (cf. Colman 1953; Davenport 1944; Davis 1956; Hoover 1944; Penman 1948, 1963; Rowe and Colman 1951; West 1933).

(4, 5) The climatological and meteorological approaches, which estimate evapotranspiration from data such as solar radiation, temperature, wind speed, and vapour pressure gradients, which on a large catchment scale are mostly independent of the type of plant cover. In the climatological approach relatively simple weather data are used and simplifying assumptions have to be made (e.g. Closs 1956; Pelton, King, and Tanner 1960; Penman 1950*a*, 1950*b*, 1955, 1963; Rickard 1957; Slatyer 1960; Thornthwaite and Mather 1955). In the strictly meteorological approach all of the important components used in the estimation of evapotranspiration are actually measured (e.g. Slatyer and McIlroy 1961; Tanner 1960).

* Natural catchment plus area tapped by aqueducts and tunnels.

In view of the fact that the experiment was to be conducted over a large area under conditions where access was not always possible and where delicate equipment could not be operated unattended, the choice of methods lay between the hydrometric and water budget approaches. The disadvantage of the hydrometric approach was the high cost of the stream-flow recorders which would have been required in several groups of catchment areas, and the long duration (5–10 yr) of this kind of experiment. Thus the water budget method was finally chosen.

Practical and economic considerations led to the selection of the gypsum block method to measure changes in soil moisture under the various plant communities, despite the expectation that for a considerable period during the colder months the soils would probably be wetter than field capacity and consequently beyond the sensitive range of gypsum blocks. This was not expected to be a great disadvantage, however, since any significant differences in evapotranspiration which might exist between different plant communities would be most likely to occur during the relatively warm and dry summer–autumn seasons when transpiration would be greater and the soils dry enough to lie within the sensitive range of gypsum blocks. During this period errors due to deep seepage, which was not measured, would be minimal.

The 57 plots used in the experiment to measure surface run-off and soil loss (Costin, Wimbush, and Kerr 1960) were installed with gypsum blocks at depths of 3, 6, 12, 24, 36, 48, and 72 in., together with a sufficient number of thermistors to measure soil temperatures. These installations provided the following experimental conditions:

Wet meadow (Sawpit):

- Natural wet tussock grassland (2 plots)
- Short-grazed pasture (2 plots)

Wet sclerophyll forest (Waterfall and Wilson's Valley):

- Natural forest with largely herbaceous understorey (5)
- Forest with regrowth scrub (3)
- Forest with largely bare ground (2)
- Disclimax heath and grassland (3)

Snow gum–snow grass (Crackenback, Rennix Gap, Kosciusko, Daner's Creek, Prussian Creek, Lower Smiggins, Upper Smiggins):

- Natural snow gum woodland with herbaceous understorey (4)
- Dense regrowth snow gum scrub (4)
- Disclimax heath (2)
- Snow grass (10)
- Short-grazed pasture (4)
- Depleted grassland with bare areas (7)

Snow grass–wet heath (Boggy Plains):

- Three areas

Alpine herbfield (Carruthers Peak):

- Natural herbfield (2)
- Depleted herbfield with bare ground (4).

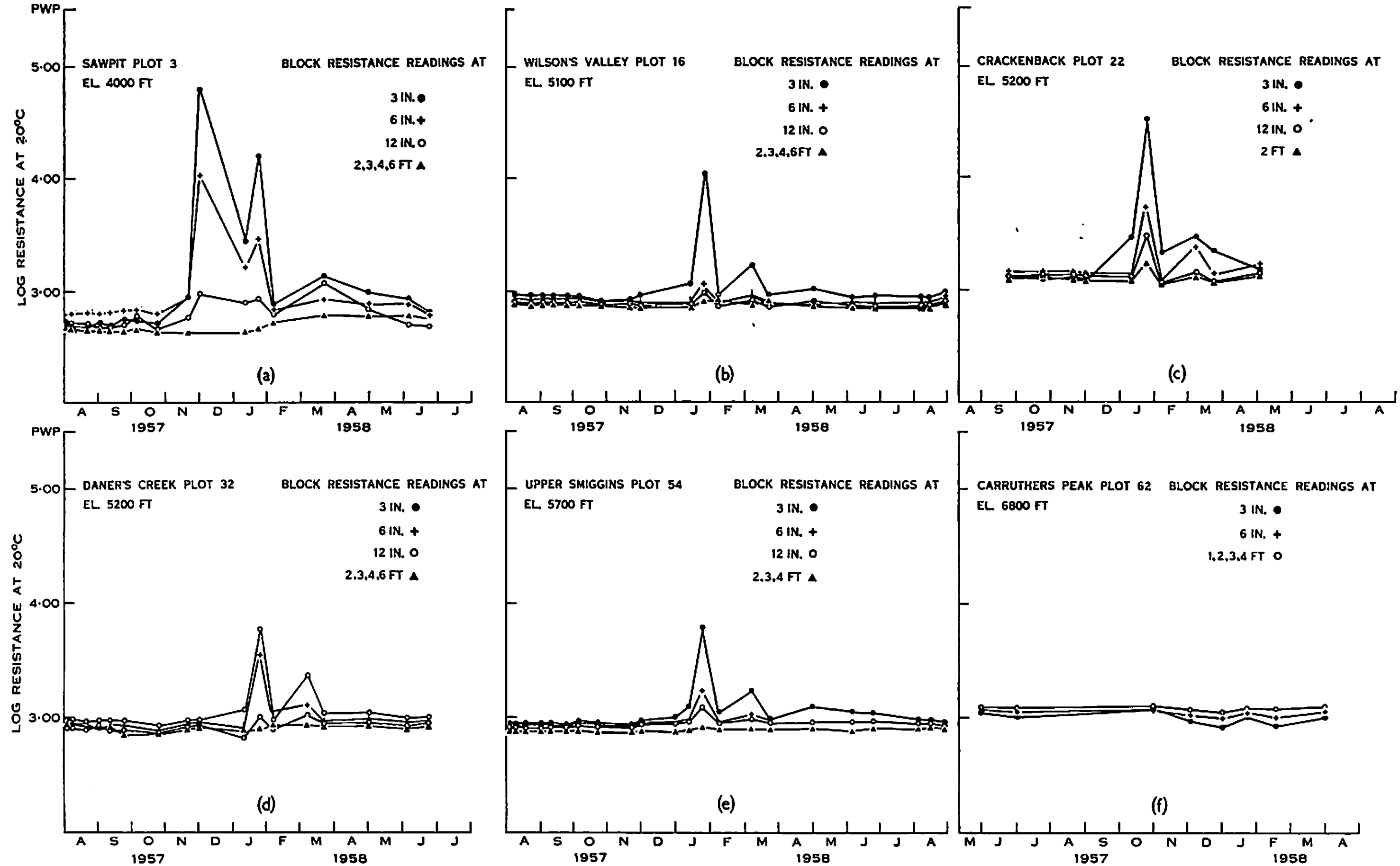

Fig. 1.—Changes in soil moisture in meadow (*a*), forest (*b*), snow gum–snow grass (*c*, *d*, *e*); and alpine herbfield (*f*) areas, Kosciusko, 1957–58. *PWP*, permanent wilting percentage.

Measurements were commenced in the summer of 1956–57 and continued until spring 1958. By this time several of the blocks, especially in the wetter areas at Boggy Plains and Sawpit, had ceased to function because of excessive corrosion, whilst measurements on a few other plots had to be abandoned because of damage to the gypsum block and thermistor leads by sheep and birds. Although the experimental period was thus of necessity rather short, the 1957–58 growing season was not unusually wet, so that any differences in evapotranspiration which might exist between the various cover types should have shown up.

Soil moisture contents expressed as the logarithm of the block resistance values* were progressively plotted for each of the 57 plots. Typical results for meadow, forest, snow gum–snow grass, and alpine herbfield areas are shown in Figure 1.

It will be seen that at all sites drying out of the soil was confined to summer and to a less extent to the autumn months. The degree of drying decreased with increasing elevation, until at the highest site (Carruthers Peak, 6800 ft) there was no perceptible drying. The soil moisture contents at depths of 3 in. and below were never reduced to the permanent wilting percentage (PWP), although this may have occurred superficially on a few occasions. Even at the lowest site (Sawpit, 4000 ft), drying out was largely confined to the surface foot.

To facilitate statistical comparison of evapotranspiration from similar groups of plots, the corrected log resistance readings at successive depths in each plot were converted to inches of water and summed to give the water content of the profile as a whole. Water balance sheets were then drawn up for six measurement periods (of about 30 days' duration) within the main period of measurement (September 1957–May 1958), in terms of change in soil moisture, and precipitation received by and surface run-off lost from each plot. The values for precipitation and surface run-off were those obtained in a concurrent experiment (Costin, Wimbush, and Kerr 1960). Evapotranspiration was obtained by subtracting the values for surface run-off and change in soil moisture from precipitation during each measurement period. Average rates of evapotranspiration in hundredths of an inch per day were then calculated.

It will be seen from Table 2 that, although evapotranspiration in the forest and snow gum sites showed considerable variation when the individual measurement periods (of about 30 days) were taken, rather similar values were obtained (0·10–0·12 in. per day) when the calculations were based on the whole of the 1957–58 season (of 218 days). This similarity seems surprising in view of the fact that the sites cover an altitudinal range of about 1300 ft, over which there is a steady decrease in the rate of free-water evaporation.

Evapotranspiration from the different cover types at each site was also rather similar, although at some sites a general relation with the amount of plant cover can be observed, especially at the lower altitudes.

* Laboratory calibrations showed that the relationship between log resistance and moisture tension (measured as pF) was linear over the range of log resistance values from 2·8 to 4·0.

TABLE 2
MEAN DAILY EVAPOTRANSPIRATION (1/100 IN.), 1957–58

Locality	Plot	Type	Period						
			24.ix.57–24.x.57	24.x.57–20.xi.57	20.xi.57–12.i.58	12.i.58–6.ii.58	6.ii.58–21.iii.58	21.iii.58–30.iv.58	Total
Wet meadow areas									
Sawpit,	1	Short pasture	7·7	15·6	14·7	10·0	5·4	—	10·7
4000 ft	2	Tall grass	6·9	12·5	14·0	14·0	11·1	—	11·7
	3	Short pasture	7·7	12·2	14·4	7·0	9·0	—	10·1
	4	Tall grass	7·8	14·1	11·8	12·4	9·8	—	11·2
Forest areas									
Waterfall,	5	Regrowth: trees + scrub	5·7	13·1	10·8	9·8	8·7	10·1	10·0
4400 ft	6	Regrowth: trees + scrub	4·7	12·9	9·8	8·8	7·7	9·1	9·0
	7	Depleted: trees + bare ground	5·7	8·7	8·2	7·9	6·1	6·6	7·4
	8	Depleted: trees + bare ground	5·2	12·7	7·4	9·9	5·5	9·2	7·7
	9	Natural: trees + grass	5·3	11·4	8·0	10·9	5·7	6·5	7·1
	10	Natural: trees + grass	5·6	11·9	8·2	10·0	6·7	6·9	8·2
Wilson's Valley,	11	Depleted: shrubs + bare ground	—	13·9	11·1	13·0	8·4	7·2	10·6
5100 ft	12	Natural: trees + shrubs + grass	10·7	13·9	14·6	15·2	11·3	11·4	14·9
	13	Natural: trees + shrubs + grass	8·9	15·4	13·1	12·6	9·2	10·0	11·9
	14	Natural: trees + shrubs + grass	10·3	15·1	13·9	8·3	9·3	5·9	10·9
	15	Regrowth shrubs	8·2	14·8	11·9	11·6	9·4	6·6	10·6
	16	Depleted: short grass + bare ground	8·3	14·7	11·8	12·8	8·0	6·8	10·6
	17	Regrowth scrub	8·2	14·4	11·2	14·1	8·3	7·6	10·7

Snow gum–snow grass areas									
Crackenback, 5200 ft	21	Depleted: snow grass + bare ground	7·6	8·6	16·5	11·2	7·7	6·5	10·1
	22	Regrowth shrubs	8·7	8·8	16·5	11·9	7·3	5·6	10·0
	24	Regrowth scrub	8·4	8·5	16·3	11·9	7·7	6·2	10·1
Rennix Gap, 5200 ft	25	Short pasture	14·1	8·5	15·9	11·3	8·5	8·1	11·1
	26	Short pasture	13·3	13·1	16·1	12·0	6·1	6·6	11·1
	28	Snow grass	15·6	11·2	17·2	10·9	6·8	5·9	11·2
Daner's Creek, 5200 ft	32	Snow grass	18·1	17·3	15·0	13·7	8·1	7·1	12·9
	33	Snow grass	—	16·3	14·6	14·7	7·6	6·7	12·5
	34	Depleted: minor herbs + bare ground	14·2	14·5	17·0	14·2	5·1	8·6	12·1
	35	Depleted: minor herbs + bare ground	—	14·2	17·2	12·9	6·3	7·6	12·3
Prussian Creek, 5500 ft	36	Natural: trees + snow grass	7·8	13·6	19·4	12·9	8·8	7·8	11·9
	37	Regrowth scrub	6·8	14·3	19·6	12·5	8·1	8·8	11·9
	38	Regrowth shrubs	7·1	13·5	19·0	12·3	8·8	8·5	11·8
	39	Depleted: snow grass + bare ground	7·5	12·4	18·1	12·0	7·6	7·8	11·0
	40	Snow grass	6·7	13·2	18·2	12·4	8·4	8·3	11·4
	41	Depleted: bare ground	7·2	12·8	18·0	11·6	8·3	7·6	11·2
Lower Smiggins, 5600 ft	48	Natural: trees + snow grass	9·8	11·0	21·4	13·5	10·1	9·1	12·7
	49	Regrowth scrub	8·4	11·0	20·2	13·9	9·1	9·9	12·2
	50	Depleted: snow grass + bare ground	9·7	9·1	20·0	13·8	8·8	10·5	12·1
	51	Snow grass	9·6	10·5	20·8	13·2	9·6	8·9	12·2
	52	Snow grass	7·3	12·2	20·5	12·9	9·7	9·4	12·2
Upper Smiggins, 5700 ft	53B	Natural: trees and snow grass	7·7	14·8	20·4	15·6	8·7	9·2	12·8
	54	Snow grass	9·9	12·0	21·0	14·1	9·0	8·3	12·5
	55	Snow grass	9·9	11·7	20·7	14·5	8·7	9·4	12·7
	56	Short pasture	9·9	11·5	20·8	14·4	9·3	8·4	12·7
	57	Regrowth scrub	9·4	12·1	20·7	14·4	9·7	9·7	12·7

Thus at Sawpit, the long grass plots lost moisture slightly faster (0·115 in. per day) than the short pasture plots (0·104 in. per day); however, the difference was not significant at the 5% level.

In the forest site at Waterfall, evapotranspiration from the regrowth plots (0·095 in. per day) was significantly greater than from the depleted plots (0·076 in.). It also exceeded evapotranspiration from the natural plots, but the difference was not significant. At the more elevated forest site at Wilson's Valley the natural and regrowth plots lost more moisture than the depleted plots, but the differences were not significant.

In the snow gum–snow grass areas, the snow gum woodland, scrub, snow grass, short pasture, and depleted plots behaved similarly, except at Prussian Creek where evapotranspiration was significantly less on the severely depleted plots (0·111 in. per day) than on the snow gum, scrub, and shrub plots (0·119 in.).

Despite the paucity of data from the Carruthers area, the similarity of the log resistance curves (e.g. Fig. 1) indicates substantially similar rates of evapotranspiration even between well-vegetated alpine herbfield and almost bare areas. The Boggy Plains plots, with different proportions of bog shrubs and snow grass, also behaved similarly.

IV. Discussion

The fact that in the forest areas the natural (rather open) and regrowth (dense) stands and disclimax heath and scrub lost similar amounts of water indicates that ordinary methods of forestry management are unlikely to affect evapotranspiration on a catchment scale. However, the lower water use of the depleted plots shows that more extreme reduction of cover (and presumably of root development) will significantly reduce evapotranspiration. The reduction in water use was about 10% compared with adjacent forest. This represents a water saving of about 2½ in. per year, but at the expense of considerable soil loss (Costin, Wimbush, and Kerr 1960). Similarly, in the snow gum–snow grass areas, only the severely depleted plots at Prussian Creek lost significantly less moisture. Here the saving was about 6%, equivalent to about 2 in. of water per year, with a value of almost £1 per acre per hydroelectric power station (cf. Costin *et al.* 1961). However, this gain is overshadowed by the other hydrological effects of poor ground cover and treelessness, namely accelerated soil erosion, loss of snow and more rapid melting, and lack of moisture increment from intercepted rain, cloud, and fog (Costin and Wimbush 1961; Costin, Wimbush, and Kerr 1960; Costin *et al.* 1961). At still higher levels no amount of cover depletion appears to reduce evapotranspiration loss effectively.

Because of the labour necessary to conduct a programme of soil moisture measurements adequate for the maintenance of a continuous water budget in catchment areas, it would be advantageous if evapotranspiration losses could be calculated from routine meteorological observations. Thus further studies were made in which the evapotranspiration losses as determined from the gypsum block measurements were compared with the losses calculated from meteorological data and soil storage characteristics (cf. Section II). The measured and calculated values for the snow gum–snow grass and forest areas at Upper Smiggins and Wilson's Valley are summarized in Tables 3 and 4.

TABLE 3

AVAILABLE SOIL MOISTURE (CALCULATED) IN SURFACE 12 IN. OF ALPINE HUMUS SOIL UNDER SNOW GUM–SNOW GRASS, UPPER SMIGGINS

(All figures in 1/100 in.)

Period	Net Precipitation	Potential Evapotranspiration*	Available Moisture in Surface 12 in. of Soil at End of Period
23.ix.57–21.x.57	275	59	280† (216 surplus)
21.x.57–29.xi.57	455	253	280 (212 surplus)
29.xi.57–10.i.58	868	435	280 (433 surplus)
10.i.58–6.ii.58	389	336	280 (53 surplus)
6.ii.58–21.iii.58	385	493	172 (no surplus)
21.iii.58–30.iv.58	363	270	265‡ (no surplus)

* Measured free-water evaporation × 0·75.

† Available moisture at field capacity (from Table 1).

‡ Sample calculation: Net precipitation−potential evapotranspiration = 93 points. At the beginning of this period the soil had a retention storage capacity of 280−172 = 108 points. Thus the 93 points of unused precipitation goes into soil storage, bringing the available moisture to 172+93 = 265 points. As this is less than field capacity (280 points), there is no surplus moisture.

TABLE 4

AVAILABLE SOIL MOISTURE (CALCULATED) IN SURFACE 12 IN. OF TRANSITIONAL ALPINE HUMUS SOIL UNDER WET SCLEROPHYLL FOREST, WILSON'S VALLEY

(All figures in 1/100 in.)

Period	Net Precipitation	Potential Evapotranspiration	Available Moisture in Surface 12 in. of Soil at End of Period
24.ix.57–24.x.57	270	110	130* (160 surplus)
24.x.57–20.xi.57	417	211	130 (206 surplus)
20.xi.57–12.i.58	622	648	104 (no surplus)
12.i.58–6.ii.58	334	356	82 (no surplus)
6.ii.58–21.iii.58	337	574	Nil (155 deficit†)
21.iii.58–30.iv.58	256	312	Nil (56 deficit‡)

* Available moisture at field capacity (from Table 1).

† This deficit could be satisfied if effective root system penetrated to 22 in.

‡ This deficit could be satisfied if effective root system penetrated to 25 in.

According to Table 3, the surface foot of the alpine humus soils of the snow gum–snow grass areas would have been close to field capacity for most of the measurement periods in 1957–58; only in summer would slight drying out have occurred. These results are therefore in general agreement with the measured values (cf. Fig. 1) and support the conclusion that ordinary methods of manipulating the vegetation such as thinning or replacing deep-rooted by shallow-rooted communities will not substantially affect water yield. The same conclusion may be drawn for the still more elevated alpine areas above the tree-line.

According to the calculations summarized in Table 4, the surface foot of soil in the sclerophyll forest areas at Wilson's Valley (and especially in the forest and meadow areas at Waterfall and Sawpit) would have undergone considerably more drying out, at times to the permanent wilting percentage. The fact that this degree of soil moisture depletion did not occur (Fig. 1) indicates that moisture was also extracted from depths greater than 1 ft and/or that the potential rate of evapotranspiration was not maintained even at low moisture tensions. Substantial extraction

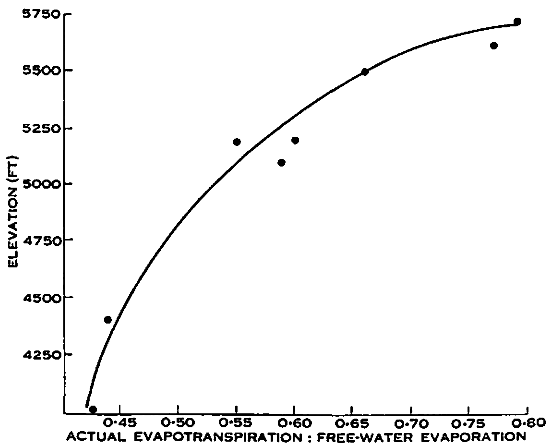

Fig. 2.—Ratio of actual evapotranspiration to free-water evaporation, Kosciusko, January 10 to April 30, 1958.

of water from depths greater than 12 in. would imply that evapotranspiration could be reduced by substituting shallow-rooted for deep-rooted vegetation. However, the measured values of soil moisture (Fig. 1) showed that deep drying out did not occur, so the effects of root depth on evapotranspiration will be limited. The alternative must therefore be accepted, that evapotranspiration begins to be restricted at quite low soil moisture tensions.

The above possibility can be examined further by plotting the ratio of actual evapotranspiration to free-water evaporation for the groups of experimental plots arranged in altitudinal sequence. As mentioned earlier, this sequence is one of rapidly decreasing temperature and increasing precipitation, and hence of decreasing soil moisture stress. These data for the period January 10, 1958 to April 30, 1958, which was the longest run of relatively settled weather, are shown in Figure 2.

The ratio of evapotranspiration to free-water evaporation (determined from standard evaporimeters operated by the Snowy Mountains Hydro-Electric Authority) is seen to increase exponentially with altitude, in inverse relation to the sequence of soil moisture stress depicted in Figure 1. It is interesting to note that the maximum values of 0·7 to 0·8 are in general agreement with Penman's findings, that potential evapotranspiration from a well-vegetated surface under conditions of active plant growth and adequate moisture supply is about 0·75 × free-water evaporation. Under these conditions, evapotranspiration from different plant communities should be essentially similar, unless they differ markedly in canopy albedo characteristics.

The lower values of about 0·6 and less in the forest areas below about 5000 ft are somewhat surprising, in view of the fact that even at times of maximum soil moisture stress there is plenty of water in the vicinity of roots below 1–2 ft (cf. Fig. 1 and Table 4). It would appear that not only are these deeper roots (about 10–20% of the total) of little significance in water yield considerations, but that the surface roots (comprising 80–90%) begin to become inefficient in extracting soil moisture at tensions not much greater than field capacity. This inefficiency would tend to minimize the moisture gains normally to be expected by replacing deep-rooted by shallow-rooted communities. The eucalypt forests and associated communities between about 4500 and 5000 ft are not, therefore, undesirable for water yield purposes, in view of their restricted water use during the summer months. Such relationships are not unexpected on soils with low unsaturated permeabilities (cf. p. 7). However, they would not necessarily apply on finer-textured soils where some movement of soil moisture to plant roots could more easily take place.

These findings suggest that, provided the moisture characteristics of the soils are known, standard meteorological data can replace actual soil moisture measurements for the purpose of calculating evapotranspiration in moister catchments of the Snowy Mountains above 5000–5500 ft. In the lower catchments, however, the calculations based on meteorological data appear to overestimate evapotranspiration, so that at the present state of knowledge they are an inadequate substitute for actual soil moisture determinations.

Figure 2 also throws light on the hydrological role of moisture intercepted by the canopy. In the snow gum–snow grass and alpine herbfield areas, where evapotranspiration is proceeding at near-potential rates, the evaporation of intercepted moisture will result in an almost similar saving in transpiration. In the lower forest areas, however, where the rate of evapotranspiration during the warmer months is only about half the potential rate, evaporation of intercepted moisture will be more rapid than transpiration. This means that differences in canopy interception between plant communities will have little effect on evapotranspiration at higher levels, but will be increasingly important lower down.

The general finding that ordinary methods of vegetation management affecting either the depth or density of root development cannot substantially affect evapotranspiration above about 4500 ft does not necessarily mean that more effective methods cannot be developed in the future. Any changes in vegetation properties which interact with important meteorological factors can be expected to influence water yield. Changes in canopy albedo, for example by the application of reflective leaf coatings, could reduce evapotranspiration. Similarly, the development of extensive uniform stands of vegetation might reduce water use by minimizing turbulence over the canopy, although the effect, if any, would probably be small, and there would be a reduction in the amount of snow (Costin *et al.* 1961). The application of substances which increase the resistance to water movement from leaf to atmosphere, by partial blocking of the stomata, might also be effective. These are problems for the future.

In conclusion, it should be pointed out that the plant relations of water of significance in hydrological studies are not necessarily the same as the water relations of plants of concern to plant physiology. The fact that evapotranspiration and water yield at higher levels may not be capable of substantial changes by vegetative management does not mean that different plant communities (e.g. wind-exposed fjaeldmark and protected alpine herbfield) do not transpire at different rates; such differences, however, are determined primarily by the external environment rather than by the plant. Similarly, although the soils may rarely be far from field capacity, and the plant community as a whole may be transpiring at near the potential rate, intense drying out of the surface inch or two of soil can occur (Costin, Wimbush, and Kerr 1960) and individual plants commonly undergo water stress. Several alpine forbs such as *Craspedia uniflora* regularly undergo temporary wilting during clear sunny weather, and trees and shrubs are frequently killed by physiological water stress during the snow-melt period when the soils are chilled to near freezing point. Such problems of transpiration and water stress are obviously important in questions of survival, competition, and distribution of high mountain plants and plant communities, but they do not affect the generalization that at the higher levels evapotranspiration is primarily the result of meteorological factors and largely independent of the type of plant cover, at least within the present range of natural and disclimax vegetation.

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