AN EVALUATION OF WATER BALANCE FOR HEATH VEGETATION USING SIMULATION

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Abstract

Water balance was simulated using 70 years rainfall data for Pinaroo using the program WATBAL. Parameters in the model reflecting soil water availability and rate of water use were varied so as to reflect all possible vegetation types. Results for representative vegetation types in the region are illustrated using mean annual patterns of soil water storage. Seasonal variability is illustrated by the 10 and 90 percentiles of soil water storage for heath. Patterns of soil water storage are dominated by the seasonal pattern of pan-evaporation but variability in rainfall and vegetation type are also predicted to have marked effects.

The effect of variability in rainfall was evaluated by graphing the isopleths of annual maximum change in soil water, the minimum 10 percentile of weekly soil water and the water surplus for all values of soil water storage and rates of water use. These relations illustrate the efficiency of usage of a given soil water volume, the likelihood of soil water being fully depleted and the likelihood of a water surplus or wastage of water respectively. With this analysis, heath is shown to have a conservative pattern of water use in that the available soil water is never fully depleted. This pattern tends to an optimum under the prevailing conditions in that water use tends to a maximum within the minimum soil volume required to avoid depletion at the given rate of water extraction. It is suggested that plants introduced with agricultural development are unlikely to achieve such a pattern of water use thereby necessitating the use of senesing or annual life forms to achieve survival during periods without available soil water.

Introduction

It is a truism that plants are adapted to their environment but the nature of the adaptation is often obscure. One approach to the problem has been to describe adaptive traits, features expressed by plants that are recognized as being adaptations to particular conditions or perturbations. Thus regrowth from lignotubers and the retention of seed in woody capsules may be seen as adaptations to fire but they are also adaptations to drought and any other perturbation which kills the aerial portions of the plant.

The problem of evaluating adaptation is simplified if, instead of subjectively considering the morphology of the plants, one investigates function. The optimum leaf form for photosynthesis has been evaluated in relation to environmental conditions (Parkhurst and Loucks, 1972). However, such studies are difficult to apply in the field because, even with water use efficiency, the optimum for a plant in isolation need not be an optimum for plants in mixtures (Cowan, 1977). Efficiency is only important in limiting situations and then only when the sparing use of a resource equates with its subsequent availability. The leaving of resource for another plant confers no direct benefit.

The objective of this study was to evaluate the efficiency of water use in heath/mallee heath communities by investigating the interaction between the rate of water use and subsequent availability of water. Rainfall is limiting in these communities and the variability is such that mean conditions do not adequately characterize the availability of water. The analysis is facilitated by the simple hydrologic characteristics of such systems (Nulsen et al., 1986) and has been simplified further by assuming that the community acts as a whole, thereby avoiding the complexity of interactions between individuals.

The soil can be regarded as a reservoir, retaining water for subsequent use by plants. Given that an optimum reservoir is one where, for minimum cost, there is neither wastage nor complete depletion of water, an optimum pattern of water use by perennial vegetation would achieve full utilization of water from a minimum soil volume without either water loss or complete soil water depletion.

Loss of water through run-off or deep drainage is an obvious inefficiency. Depletion of soil water indicates probable death of plants through drought while the requirement for a minimum volume of soil arises because of the root development required to exploit the soil volume. As plants can control both the rate of water use and the volume of soil exploited by roots, the efficiency of the vegetation can be examined by studying the consequences of changes in these factors on water loss, the maximum change in soil water storage and soil water depletion

Methods

Water balance simulations were undertaken using the WATBAL model (Keig and McAlpine 1974) with parameters selected to reflect different soil and vegetation types. In the model, the current soil water storage (S_t) is calculated from the antecedent soil water storage (S_{t-1}), rainfall (R) and actual evapotranspiration (E_a) according to the relation

$$S_t = S_t\text{-}1 + R - E_a \qquad (1)$$

The maximum soil water storage (S_{max}) is constrained to reflect the maximum volume of soil water available to plants so that if $S_t > S_{max}$ there is a water surplus (WS) where

$$WS = S_t - S_{max};\ \ S_t \text{ is then set equal to } S_{max}.$$

The time step used in computation was one week.

The determination of actual evapotranspiration was subject to a two stage approach, modulated firstly with respect to a vegetation characteristic to produce a potential evapotranspiration, E_p, and secondly with respect to the availability of soil water to produce actual evapotranspiration, E_a. Thus we have equations (2) and (3)

$$E_p = f\, E_o \qquad (2)$$

where f is a time dependent function of vegetation type and E_o is pan evaporation. The estimated time dependence of f for wheat crops grown on a research station and a production farm are given in Fig. 1. The capacity of perenial vegetation to transpire water was assumed to be constant throughout the year, thus the value of f for perennial vegetation was taken as 1.0 at all times.

The modification of evapotranspiration due to soil is given by

$$E_a = \frac{E_p \ S_a}{P \ S_{max}} \qquad (3)$$

with the proviso that $E_a = E_p$

when $\frac{S_a}{P \ S_{max}} > \text{or} = 1$

where S_a is the weekly available water (S_{t-1} + R) and P is a constant. Figure 2a illustrates the relationships of E_a/E_p, S_{max} and P. From this figure it is apparent that the value of P may be taken as equalling the value of S_a/S_{max} at which potential evapotranspiration occurs. Where f=1 and E_a/E_oresistance, the value of which is given by the reciprocal of the slope of the regression relating the ratio of actual to potential evaporation to the relative availability of soil water (Fig. 2a). The applicability and derivation of P can be illustrated by the results of Specht and Jones, 1971. In Figs. 3 and 6 they plot E_a/E_o against absolute soil water storage. If these data are replotted as E_a/E_o against normalized soil water availability (S_{max} - S_{min} normalized over the range of zero to 1) then the reciprocal of the slope of the regression is close to 2 for all regressions and this defines P.

It should be noted that we are dealing with weekly values and so in a week of high precipitation the value of S_a/S_{max} can exceed the value of 1.0. Also, high values of S_{max} associated with large values of P provide for the case where E_a never reaches E_p as can occur with sclerophyllus vegetation.

Figure 2b illustrates the time course of S_t/S_{max} under a constant value of E_o and no water input. With uniform drying conditions the decline in storage with time is linear where $(S_{t-1})/S_{max} > P$ and is exponential where the reverse applies. Values of P of 0.25, 0.5 and 0.75 produce similar results to the negative exponential functions used by others to describe the effects of sand, loam, and clay soils, respectively. However, setting P equal to 2 best simulates results for water use of heath vegetation in south east Australia (Specht and Jones, 1971).

Results

Water balance simulations were run on 70 years of rainfall observations for Pinaroo (lat. 35^0 155', long. 141^0 17'E) and Penman estimates of average weekly pan evaporation for Walpeup (lat. 35^0 8'S, long. 142^0 1'E). The annual patterns of rainfall and pan evaporation for the region are illustrated in Fig. 3 using data for Ouyen (lat. 35^0 4'S, long. 142^0 20'E). The different centres reflect availability of data but all are in close proximity and have almost identical climates.

Significant rainfall is received throughout the year but, on average, two-thirds of the rain falls in the six months of May to October. This slight seasonality in rainfall contrasts with the strongly seasonal pattern of pan-evaporation; the net outcome is a wet winter, dry summer pattern of a mediterranean climate. The seasonality in rainfall is more evident in the number of rain days per month than actual rainfall with the probability of receiving rain on a given day rising from 10% in summer to 30% in July and August. However, the main feature of the rainfall is the variability with the 90 percentile value being approximately three times the mean.

Soils in the region are mainly sands (calcareous sands, leached sand (Great Soil Groups, after Stace et al. 1968); Uc1.12, Uc2.21 (after Northcote, 1971)) or calcareous desert soils; Gc1.12 but there are significant areas of clayey soils (solonized brown soils, grey clays ; Gc2.12, Ug3.2) and saline soils (Solonchak ; Uf6.51). These soils have markedly different water holding properties and, together with variations in depth, this results in a range of conditions of water availability. The associations between soils and vegetation and their distribution in the region are given by Tunstall and Reece, 1989.

Two series of simulations were carried out. In the first, the values of f and P were set to reflect native grassland, wheat, heath and halophytic samphire vegetation; for the perennial heath and samphire vegetation f was set to 1 to reflect a lack of seasonal change in vegetation. The results for heath (Fig. 4a) show that the seasonal patterns of soil water storage are dominated by the potential evaporation but that variability in rainfall also has a pronounced effect.

Soil water storage is not predicted to become zero during the year with the perennial vegetation but it is with grasses (Fig. 4b). With wheat, the availability of water was a limiting factor at the beginning and end of the growing season for both the 'research' and 'farm' crops. This was mainly due to low rainfall at the beginning of the season in autumn and decreasing rainfall coupled with full crop development and high evaporative demand at the end of the season in early summer. However, it should be noted that in the model there is assumed to be no interaction between water availability and crop development. The levels of f given in Fig. 1 are based on the assumption that growth, and hence the potential to transpire water, is unaffected by lack of water.

In the second series of simulations f was kept constant at 1.0 to reflect perennial vegetation. Potential evaporation (E_p) was therefore always equal to the pan evaporation (E_o). The factors S_{max} and P were then varied independently for values of 60, 120, 180, 240, 300, 360 and 480 for S_{max} and 0.25, 0.5, 0.75, 1.0, 1.5, 2.0. 3.0 and 4.0 for P. The maximum soil water storage, S_{max}, depends on the rooting characteristics of the plants as well as various soil properties. The resistance to evapotranspiration, P, is less well defined. It is introduced as a plant dependent function related to plant physiology, leaf characteristics, root characteristics and plant density but, as some of these factors interact with the soil, it also depends on the water absorption and release characteristics of the soil.

The program WATBAL provides a statistical summary of the weekly levels of the soil water storage, S_t, and the annual accumulation of water surplus, WS, which is a water loss that can occur through surface runoff or deep drainage. The levels of these factors were examined for each of the above combinations of P and S_{max}. The results from the model are output as means, medians, quartiles, and deciles that define each week independently. Only through assuming independence between weekly events can they be used to deduce the probability of a specific temporal sequence.

If we define the maximum range in soil water storage, S_r, as the .Ydifference between the maximum weekly value of the 90 percentile and the minimum weekly value of the 10 percentile of S_t, then this can be used to evaluate the efficiency of utilization of the soil water store. An optimum for vegetation occurs where the volume of soil to be exploited by roots is minimal and this is indicated by a minimum in the difference between S_{max} and S_r. Fig. 5 shows the isopleths of S_r for all combinations of P and S_{max}. This suggests that the minimum volume of soil required occurs when P is around 2 for all levels of S_r. This optimum for the efficiency of utilization of stored soil water is further illustrated in Fig. 6 where S_r is plotted against P for values of S_{max} of most relevance to plant growth.

If we define S_{min} as the minimum weekly value of the 10 percentile ñYof S_t, i.e. the lower limit used to calculate S_r, then we can identify P and S_{max} combinations that will result in complete soil water depletion. The isopleths of S_{min} for all combinations of P and S_{max} are plotted in Fig. 7. The isopleth for $S_{min} = 0$ probably indicates the combinations of P and S_{max} below which perennial vegetation cannot be supported because of the depletion of soil water.

The simple definition of soil water store used in equation 1 means that water surpluses are generated only when S_t exceeds S_{max}. Fig. 8 plots the isopleths of the median annual value of water surplus for all values of P and S_{max}. The value of WS equals zero represents a 50% probability that in one week of the year S_t reaches S_{max}.

An optimum pattern of water use by perennial vegetation would achieve maximum utilization of available water from a minimum volume of soil without complete soil water depletion or loss of water through runoff or drainage. With these results, this condition is represented by minima for both S_{max} and the difference between S_r and S_{max}, zero surplus water and a minimum soil water store greater than zero. The optimum condition is therefore the minimum S_{max} at a level of P around 2 occurring above the zero contour for minimum change in soil water store and close to the zero contour for surplus water. The results given in Figs. 5, 6, 7 have been combined in Fig. 9 to illustrate these constraints. Results from field measurement of water use for heath communities (Specht and Jones 1971) indicate that these communities function close to indicated optimum with regard to this analysis (Fig. 9). The mature heath community uses more water than the regenerating community but the mean annual difference in water usage (approximately 10 mm) is considerably less than the difference in maximum soil water storages (approximately 28 mm).

Discussion

The WATBAL model is simple but has been useful in Australia in representing water use by vegetation, particularly in arid and semi-arid regions. One reason is that it partitions water between defined limits; it is therefore never greatly in error and tends to be self correcting. The averaging over a reasonably long time period (weeks) enhances these features. The other reason is that, in Australia, rainfall rarely exceeds potential evaporation over weekly intervals so that the results are dominated by the potential evaporation and variability in rainfall. Its application to heath has the additional advantage that a weakness in the model, the lack of attention to redistribution of water through surface flow and seepage, is of little consequence (Nulsen et al., 1986).

The 'validation' of water use models is usually done by comparing measured and predicted temporal sequences. With perennial vegetation this has the limitation that the period of measurement is short compared with the longevity of the dominant plants in the community;

the measurements usually only cover a subset of the possible circumstances with regard to both weather and vegetation. The approach taken here was to use a simple, robust model to predict the range of possible responses when vegetation is subject to the variations in weather that would be experienced over the life span of the plants and then relate the performance measured over a short period to these predictions. This allows evaluation of vegetation response in a general context and displays the differences and similarities between vegetation types.

Conclusions drawn from this analysis are that the annual pattern of soil water storage at Pinaroo is mainly determined by the high potential evaporation in summer and the low potential evaporation coupled with reliable rainfall during winter but that there are major differences in water storage patterns related to vegetation and soils. Heath has a conservative pattern of water use in that the available soil water tends never to be fully depleted and this pattern represents an optimum under the prevailing conditions.

While the water use characteristics for heath at Frankston and Dark Island (Specht and Jones, 1971) support this conclusion the comparisons require some qualification. The rainfalls at Frankston and Dark Island are 650 and 450 mm respectively compared with 340 mm at Pinaroo. Moreover, the measurements at Dark Island probably resulted in a small underestimate of S_{max}. However, the values of P for the two locations were virtually identical, indicating similar rates of water use relative to water availability (The suggestion by Specht and Jones (1971) that they are different is based on their use of absolute rather than relative levels of soil water storage. Relating these values of P to the respective soil water storages (Fig. 9) indicates that, while neither community is likely to fully deplete the available water, there is a remote possibility that this may occur with the Black Island heath. Conversely, the Frankston heath could have double the rate of water use without fully depleting the available water whereas a slight increase in water use of the Dark Island heath would result in depletion of the available water at some time.

The use of P = 2 requires some comment as the values normally used in WATBAL range between 0.5 and 1. P = 2 indicates that, over weekly intervals, the maximum E_a is one half E_o. Thus, a value of P = 2 alone suggests a conservative pattern of water use. However, the significance of the value of P depends on the relationship between E_o and the amount, seasonal distribution and variability of rainfall. A value of P = 1 would be conservative where rainfall always exceeded E_0.

Given the limited field data further comment on the results would be largely speculative but some discussion is warranted. Considering that grasses and introduced species are unlikely to exploit a greater soil volume than the Black Island heath, then the area of Fig. 9 of interest for agriculture lies below P = 2 and S_{max} = 140. As grass species have higher rates of water use than heath with values of P normally in the range of 0.5 to 1, then such vegetation will have to survive without water for some period. This indicates that senescing or annual life forms are appropriate and illustrates the difficulties in maintaining adequate pasture cover throughout the year in this region.

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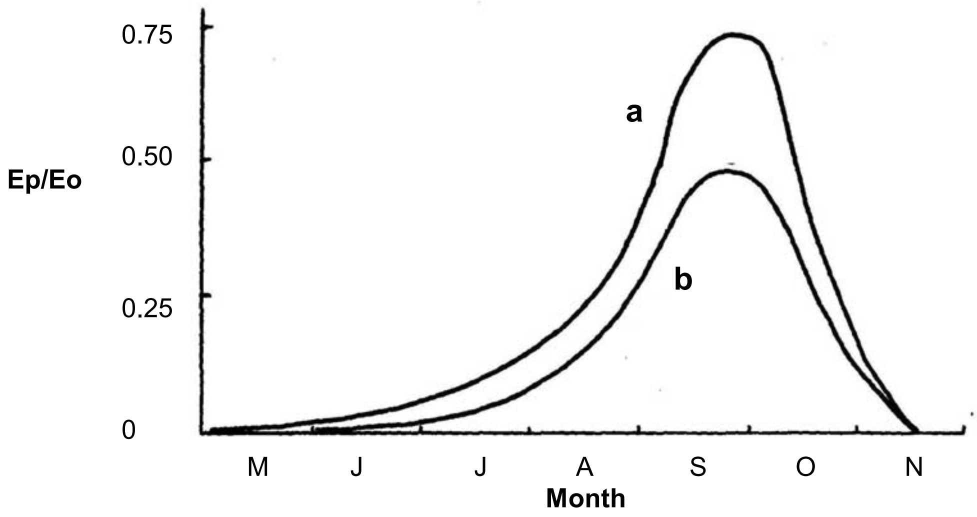

Fig. 1. The cycle of crop coefficient f = E_p/E_o used to estimate potential evapotranspiration, E_p, for wheat

a. grown on a research station

b. grown on a production farm.

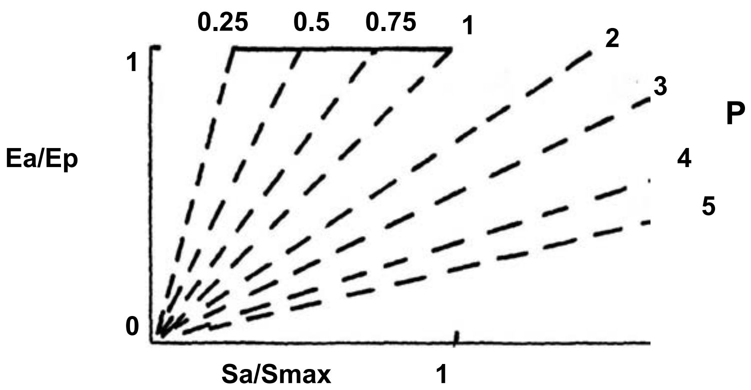

Fig. 2a. Relationships between rate of water use and weekly available soil water for a range of values of P.

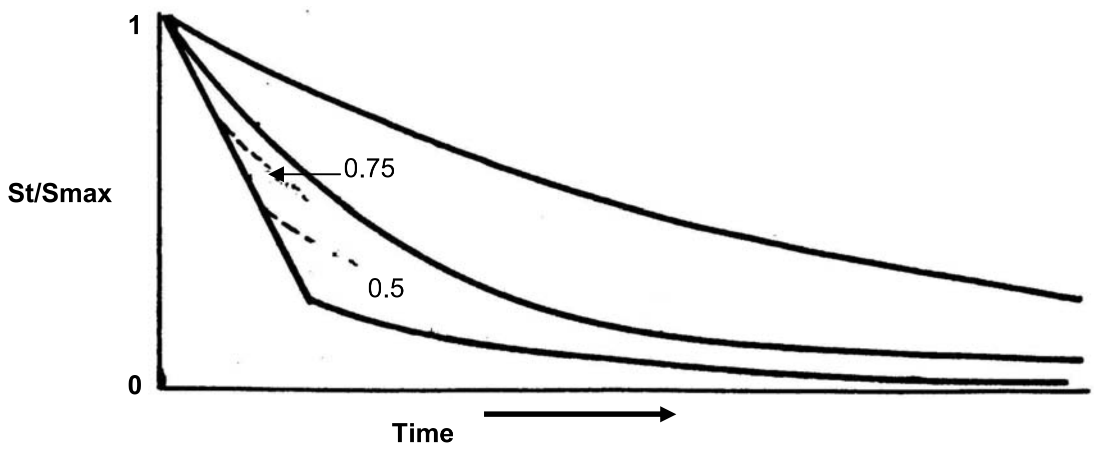

Fig. 2b. Temporal change in soil water store for some values of P calculated assuming E_o = constant and no water input.

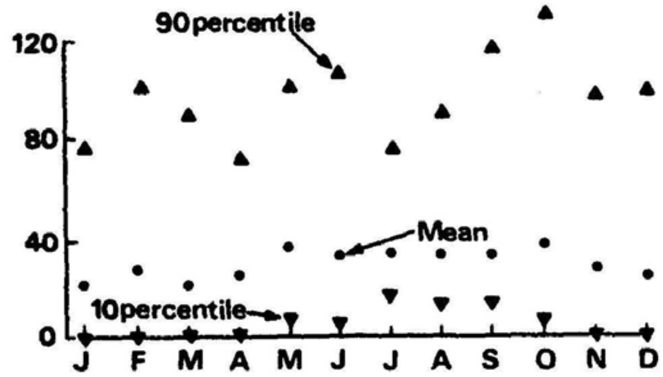

Fig. 3a. Monthly rainfall for Ouyen

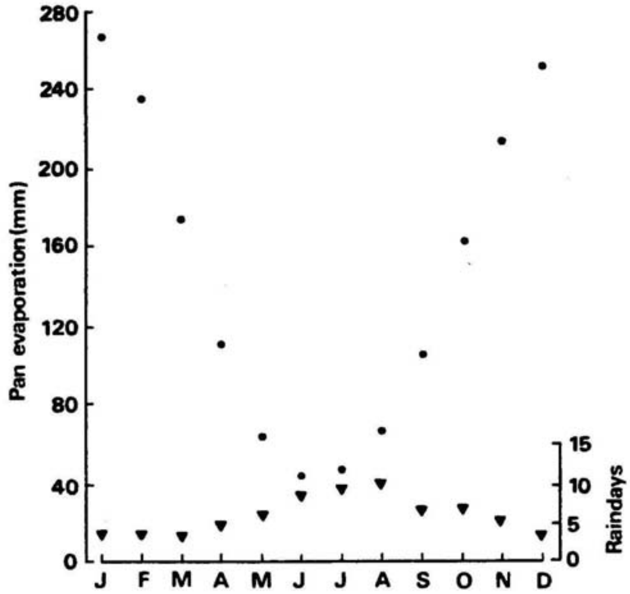

Fig. 3b. Mean monthly pan evaporation and average rain days per month for Ouyen.

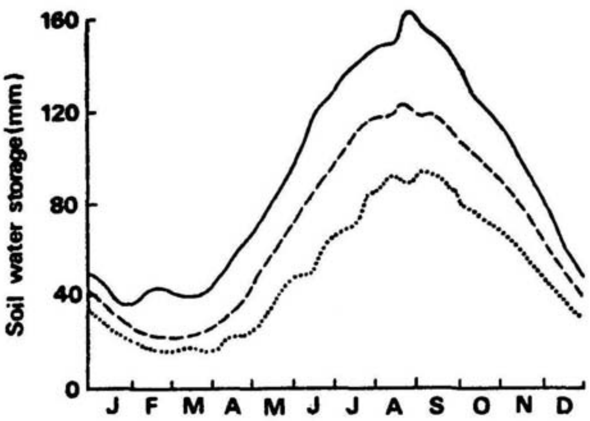

Fig. 4a. Median and upper and lower quartiles of soil water storage simulated for mallee/heath vegetation (S_{max} = 180 mm and P = 2).

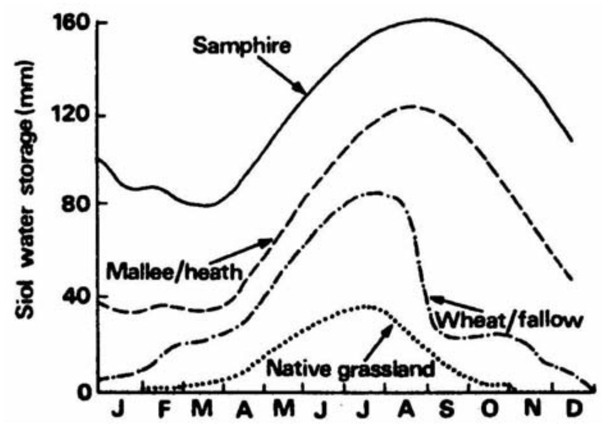

Fig. 4b. Mean soil water storages simulated as for Fig. 4a but to reflect different vegetation types

c.	samphire	S_{max} = 180 mm P = 4
d.	mallee/heath	S_{max} = 180 mm P = 2
e.	wheat/fallow	S_{max} = 120 mm P = 1

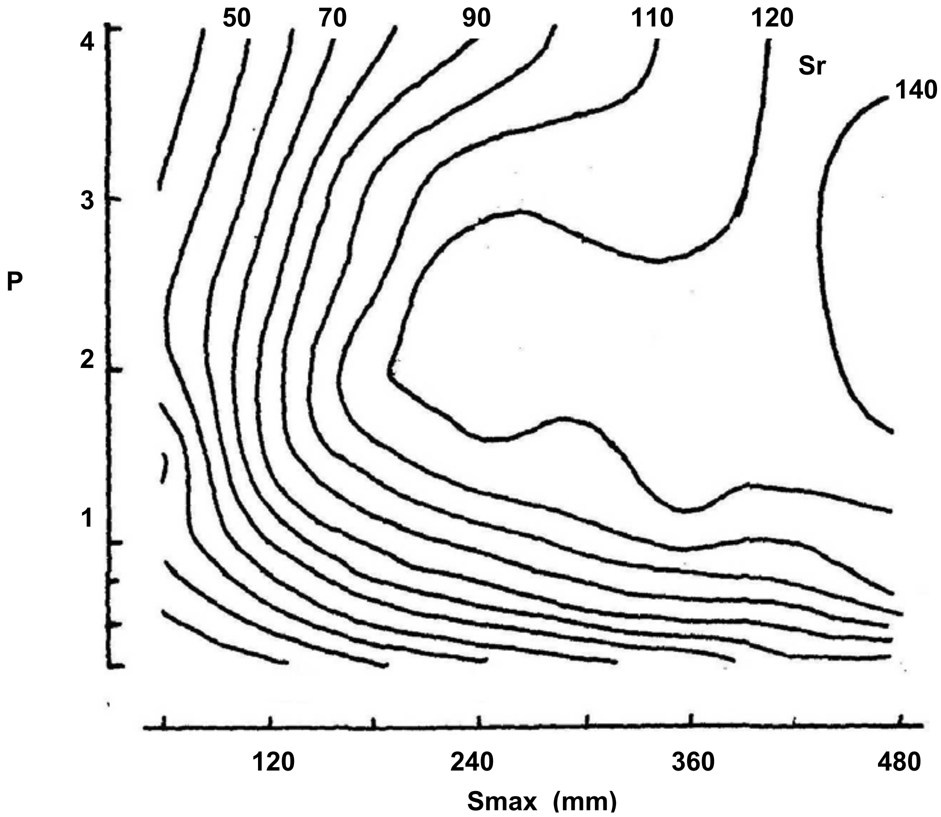

Fig. 5 Isopleths of the maximum change in soil water, S_r, in relation to soil water store, S_{max}, and rate of water use, P.

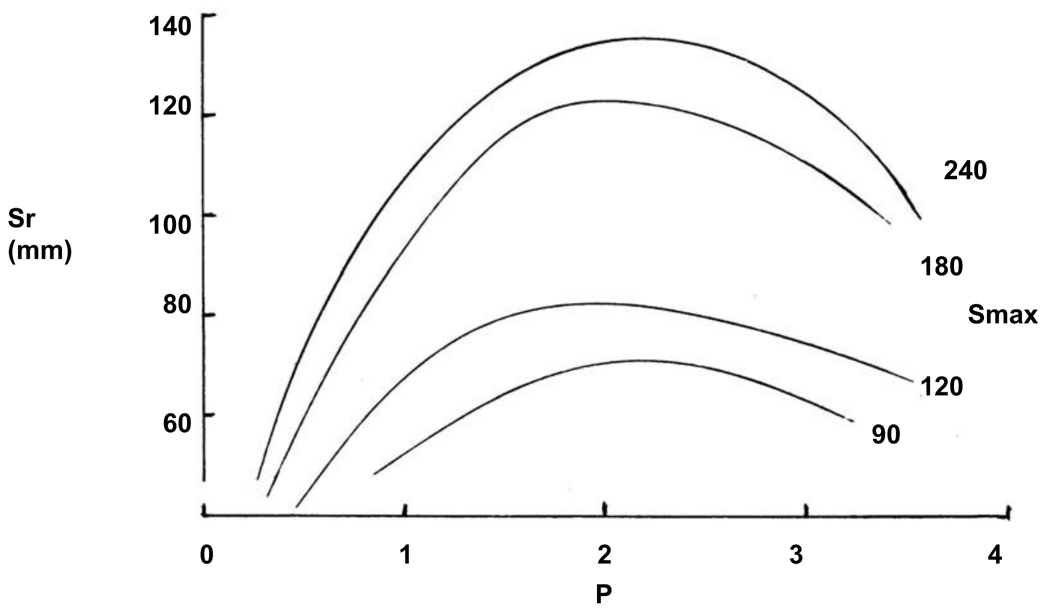

Fig. 6 Maximum change in soil water (S_r) in relation to the rate of water use (P) for four values of maximum soil water store (S_{max}).

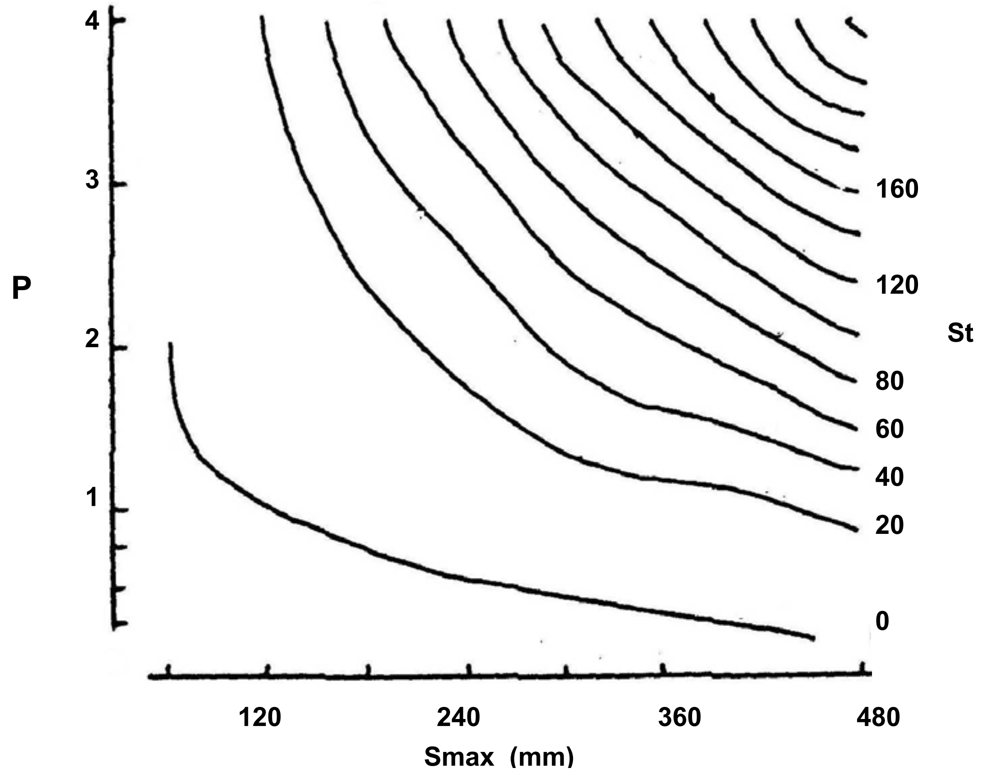

Fig. 7 Isopleths of the minimum weekly value of the 10 percentile of weekly soil water store, S_t, in relation to soil water store, S_{max}, and rate of water use, P.

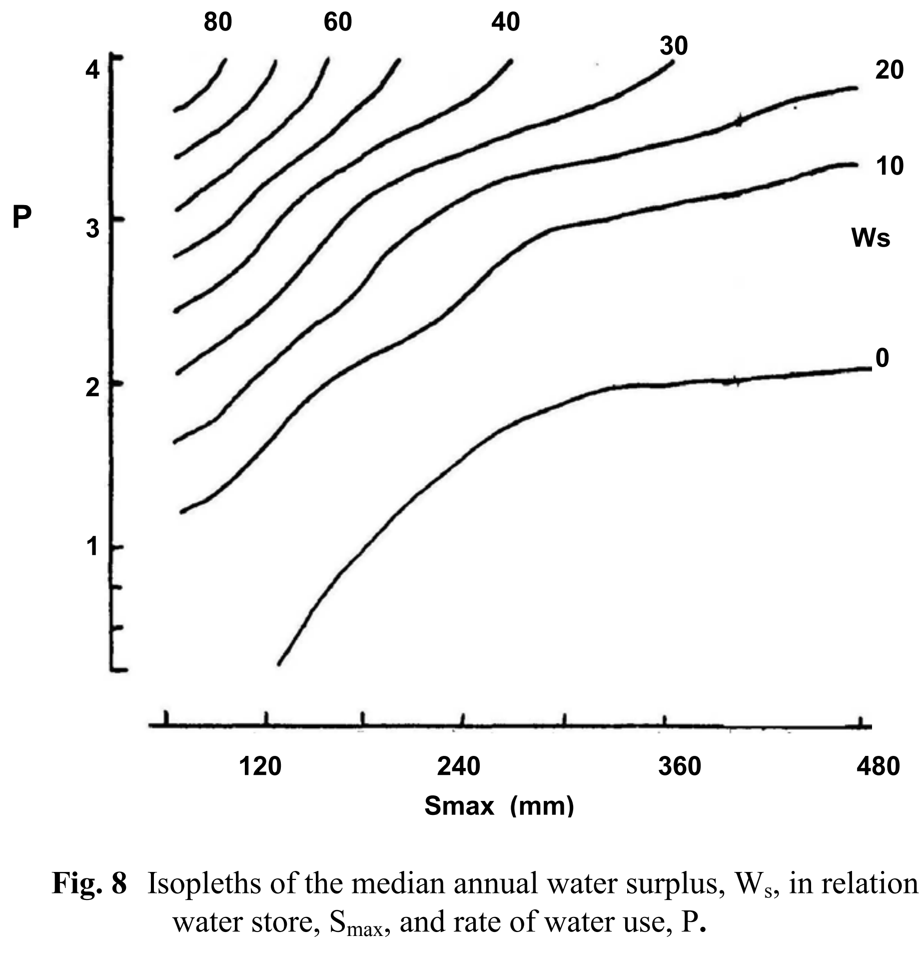

Fig. 8 Isopleths of the median annual water surplus, W_s, in relation to soil water store, S_{max}, and rate of water use, P**.**

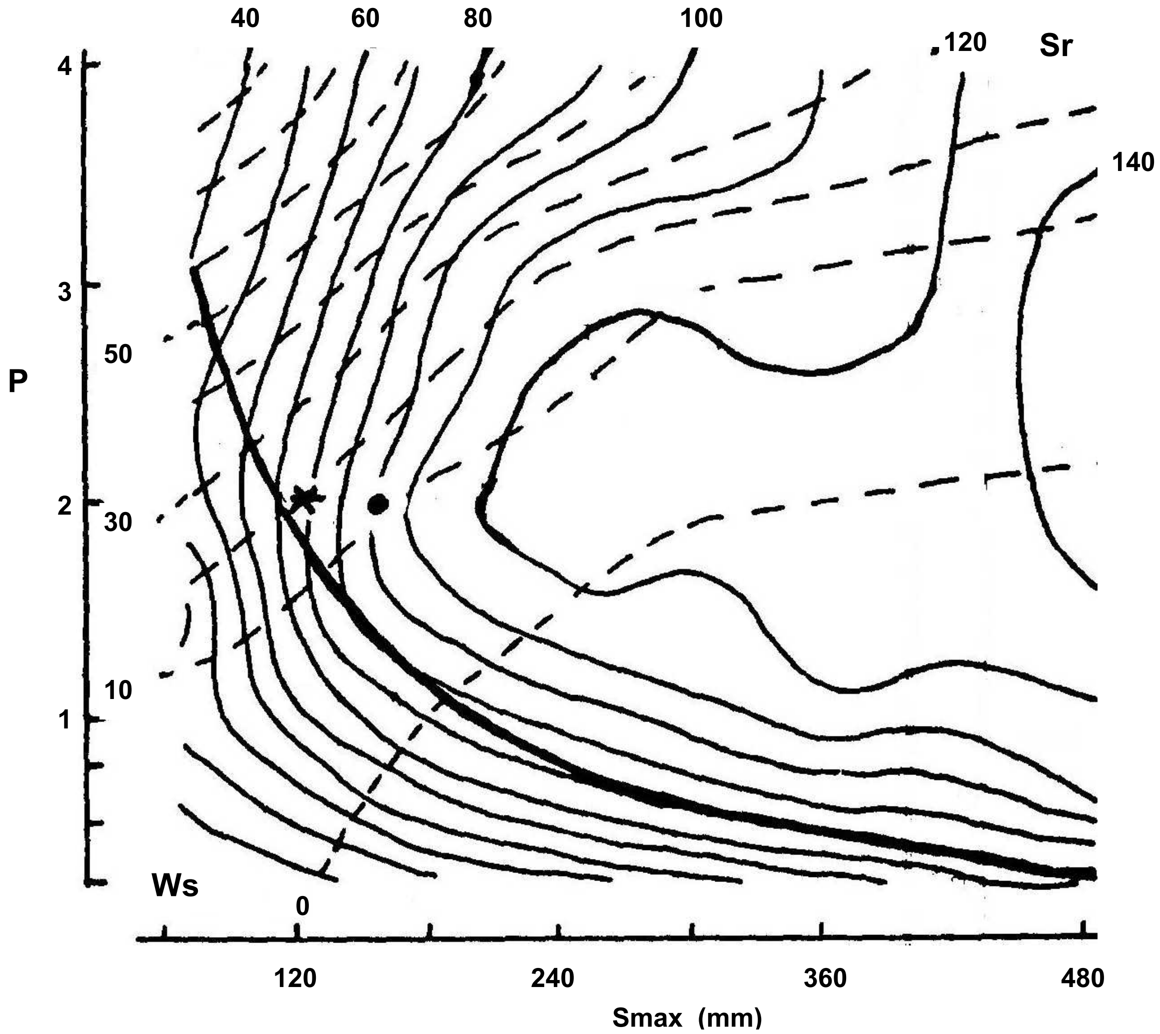

Fig. 9. Isopleths for surplus water, W_s, and the zero isopleth for the minimum weekly value of the 10 percentile of soil water store, s_t, superimposed on the isopleths for annual maximum change in soil water, S_r (Figs. 5, 6, and part of 7 combined).

---------- Median water surplus

S_r

10 percentile of $S_t = 0$

● Measured value for Frankston heath

* Measured value for Dark Island heath.