DEPARTMENT OF WATER AFFAIRS

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FACTORS CONTROLLING THE PRECIPITATION/WATER YIELD RELATIONSHIP

by

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FACTORS CONTROLLING THE PRECIPITATION/WATER YIELD RELATIONSHIP

1. HYDROLOGICAL EQUILIBRIUM

The equation of hydrological equilibrium implies that the water input into a hydrological system such as a catchment must in the long term be balanced by the water output and any change in the water stored within the system, that is

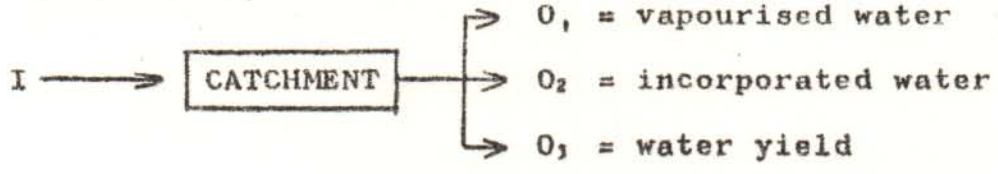
$$I - O = \Delta S$$

where I = water entering the catchment
O = water leaving the catchment
S = change in storage within the catchment

The input (I) comprises
- precipitation falling on the catchment,
- surface inflow,
- subsurface inflow
- imported water.

The output (O) comprises
- O_3, being the surface and subsurface outflow and exported water,
- O_2, being water incorporated in products leaving the catchment,
- O_1, water vapourised by evaporation and transpiration

Schematically



that is -

$$\begin{aligned} I &= O + \Delta S \\ &= O_1 + O_2 + O_3 + \Delta S \\ &= (e + t + i) + O_2 + (s + g) + \Delta S \end{aligned}$$

where
I = input
O = output
O_1 = vapourised water
e = evaporation
t = transpiration
i = net interception loss
O_2 = water incorporated in products leaving the catchment
O_3 = total water yield
s = surface water yield
g = ground-water yield
ΔS = change in storage within the catchment.

O_3, representing what is commonly denoted as "water yield" or "water resources", together with O_2 (generally much smaller), can be regarded as potentially productive water, in contrast to O which is regarded as water "loss".

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To maintain the hydrological equilibrium, a change in any term(s) must effect a compensating change in one or more of the other terms. While equal but opposite in absolute value, this compensating effect may be very different in the relative sense, due to the wide disparity in the quantities of water represented by the various terms.

It follows that water yield (O_3) can be influenced by
- a change in input, especially precipitation, and/or by
- such changes in the system (that is, on the catchment) through which the input is routed, as can alter the partioning of the output between the "loss" and the "yield" terms.

In a stable catchment with a more or less fixed relation= ship between O_1 and O_3, both are largely predictable in terms of I. But should the character of the catchment through which the input is routed alter radically - for example, by the conversion of short, shallow-rooted grassland to tree plantations - then a quasi-permanent change in the relationship between the water "loss" and "yield" terms will likely ensue, as well as a change in the time distribution and even the quality of the water yield.

In general, the longer water is retained on the catchment the greater is the opportunity for vapour losses, which proceed at the expense of water yield. A seemingly negligible change in a major component of the cycle can induce a far greater relative compensating change in a smaller component. For example, assume the mean annual rainfall over a catchment to be 500 mm of which 45 mm runs off, and that a change in land use reduces run-off by 15 mm. The increase in retention is a mere 3% whereas run-off is reduced by 33%.

The following sections concern the major process governing the precipitation/water yield relationship.

2. INTERCEPTION

2.1 The process: Interception by vegetation interrupts the free fall of rain and partitions it into
- throughfall, drip and stemflow, which reach the ground, and
- water retained on the foliage, which evaporates and constitutes the gross interception loss.

2.2 Controlling variables:

2.2.1 The storage capacity of the vegetation

Interception loss is mainly a function of the capacity of a plant to retain water temporarily, which depends on
- the point reached between the pioneer and climax stages of ecological succession,

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- the species composition,
- the plant volume per unit of land surface area (alternatively the biomass, or density of the stand)
- morphological characteristics such as the size, shape, positioning and inclination of the leaves,
- the length of time that the plant is in leaf,
- the age of the plant, that is, its size and stage of development,
- the surface tension relations between the leaf surface and water,
- management practices (e.g. thinning of trees, clearing undergrowth, veld grazing).

Because of their large leaf area/ground area ratio , grasses, shrubs and crop plants can intercept surprisingly large quantities of water at maturity (sometimes comparable to that of forest) but their growing season is generally short.

Conifers are said to intercept more water than deciduous trees of comparable size in full leaf.

The leaf litter beneath trees may intercept more water than the trees themselves.

2.2.2 Wetting cycles

When rain begins some time is required to saturate the foliage. Initially only scattered drops penetrate the plant canopy and reach the ground, but these gradually increase, and once the volume of water retained equals the storage capacity of the plant, the plant will shed rain as fast as it falls (except for some loss by evaporation). As interception is greatest at the start of a shower, it follows that the greater the number of precipitation events (individual showers, rain-days) the greater will be the total interception loss over a season or a year. Thus, other factors being equal, the combined interception loss from three showers of 5 mm each will exceed that from a single shower of 15 mm. Trees intercept 25 - 100% of showers less than 10 mm, and 10 - 40 percent of showers over 10 mm.

2.2.3 Evaporation

Once the storage capacity of the vegetation has been satisfied, the amount of precipitation ceases to affect the interception loss which then reduces to the replenishment of evaporation loss during the shower, and thus becomes time dependent. Evaporation opportunity, and hence interception loss, will be greater during intermittent than continuous rain. Interception loss will be a function of all those meteorological factors affecting evaporation rate, such as

- radiant and advective energy
- ambient temperature
- relative humidity
- wind

Evaporation and hence interception loss increases with

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wind speed during light wind. High winds increase drip by shaking water off the leaves. The impact of large drops has the same effect - hence interception loss is also affected by rainfall intensity, and hence by seasonal and regional differences in the incidence of precipitation.

2.3 Interactions:

Interception loss is water that would otherwise have reached the soil surface and then run off, infiltrated or evaporated. The rainfall reaching the ground is commonly assumed to be the same as that recorded in a raingauge at an unobstructed site, but in fact both the point and time distribution of the rain reaching ground level may be modified considerably by interception. Thus run-off is affected not only by the reduction in the quantity of precipitation reaching the ground but also by the change in intensity and distribution characteristics.

Throughfall beneath trees tends towards greater uniformity, small raindrops collecting on the leaves and coalescing into drip, while large raindrops are broken into smaller droplets on striking the foliage.

Indirectly interception reduces the drain on soil moisture, for transpiration is reduced while intercepted water evaporates. Nevertheless, despite this compensating factor, there is generally still some net interception loss - occasioned, for example, by the evaporation of intercepted water at night when most plants cease transpiring.

In certain circumstances interception can increase the supply of available water if plants intercept water (termed occult precipitation) from ground fog or low scud, or collect dew.

2.4 Formulae:

The general form of most interception equations is

$$I = C + ET$$

where I = the interception loss during a storm
C = storage capacity of the vegetation
E = evaporation rate during the storm
T = duration of the storm

Formulae of this type are applicable only to falls of rain exceeding the storage capacity of the vegetation.

3. INFILTRATION

3.1 The process:

Various definitions of infiltration have been proposed. In the present context it relates to the entry of water into the soil through the surface layer, the term percolation referring to the further downward movement and distribution of that moisture through the unsaturated zone. Clearly, however, infiltration is closely related to percolation, having two components, namely

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- a diffusion component, being the process whereby water gradually fills the pore spaces in the soil from the surface downwards, at a diminishing rate, and
- a transmission component which represents the unimpeded flow of water through the soil and is therefore constant.

These components are embodied in the infiltration equation

$$I = T + D.t^{-1/2}$$

where I = infiltration rate of any instant
T = transmission constant of the soil
D = diffusion constant of the soil
t = time elapsed since the rain began

In the present context infiltration capacity denotes the maximum rate at which soil in a given condition can absorb water, the term infiltration rate referring to the actual rate at which water penetrates the soil, this often being lower than the infiltration capacity.

3.2 Controlling variables:

The variability of infiltration, both areally and with time, can be marked. The main governing factors are the following:

3.2.1 Rainfall intensity

If the rainfall intensity exceeds the infiltration capacity of the soil, the excess water will first collect in depressions on the surface and then evaporate or run off as overland flow to the river channels, even though the soil has been only partly wetted. The situation is aggravated by various adverse effects on the absorptive capacity of the soil surface, resulting from the impact of large drops falling at high intensity. (see 3.2.2.2)

3.2.2 Soil surface

3.2.2.1 Texture: A well-aggregated, coarse-textured or broken, well-aerated soil surface containing a large proportion of non-capillary (macro) pores has a high infiltration capacity. A high proportion of clay in the surface soil not only reduces the size and number of macro-pores but causes the soil to swell and form a waterproof layer when wet.

3.2.2.2 Compaction: This is a major influence. Compaction by the force with which large drops falling at high intensity strike the ground is more pronounced on exposed clay soils than on sandy soil. Compaction by tractors and other heavy vehicles and by trampling by grazing animals reduces especially the non-capillary component of total porosity, particularly when the soil is wet. One pass of a tractor has been known to reduce macro-pore space by half and infiltration rate by 80%.

3.2.2.3 Clogging: Loose dust washed into the soil, and fine particles dislodged from soil aggregates by raindrop impact or by slaking during prolonged wet periods, can drastically lower the infiltration rate by sealing the pores in the soil surface.

3.2.2.4 Cracking: Shrinkage of clay soils in particular on drying causes cracks to develop which subsequently increase the initial infiltration rate until the wetted soil swells and the cracks close.

3.2.2.5 Slope: Run-off and throughflow increase with slope, at the expense of infiltration.

3.2.2.6 Cover: By interrupting the free fall of drops, vegetation and plant litter absorb their kinetic energy, protect the soil from the direct impact of large drops, break them into smaller droplets and retard the rate at which water reaches and flows over the soil, thus enchancing absorption. The mat of roots near the soil surface increases the permeability and hence the infiltration capacity of the soil, while the organic matter affects both the stability and size of soil aggregates and hence the pore size distribution spectrum.

At the other extreme are the solid structures and paved surfaces in urban areas, whose infiltration capacity is near to zero.

3.2.3 Transmission properties of the soil

From the foregoing it is clear that no matter how good the drainage of the soil, it will remain undercharged with water if compaction or sealing of the surface inhibits infiltration. The converse also holds, namely that however high the infiltration capacity at the surface may be, water cannot continue to be absorbed faster than it can be transmitted downward through the soil. Thus an improvement in surface conditions will not have the desired effect unless the transmission capability of the soil, notably that of the least permeable layer, is adequate.

3.2.3.1 Non-capillary porosity: The number of macro-pores, rather than total porosity, is one of the main factors governing infiltration capacity, and depends not only on soil texture (the infiltration capacity of sand being far in excess of that of a clay soil) but on soil structure, notably the size and stability of soil aggregates. The tendency for aggregates to disintegrate or swell generally results from the presence of certain clay minerals. Channels left by decayed roots, earthworms and by burrowing insects and animals all enchance the infiltration capacity of the soil.

3.2.3.2 Soil profile: Soil tends to stratify into horizons whose permeability often, although not invariably, decreases with depth.

In addition, minerals and fine particles leached from the surface soil may accumulate lower down to form a "hardpan" of low permeability, which can cause waterlogging above it. On worked land a compacted "plough sole" may develop below the depth of cultivation, which likewise impedes drainage of water through the soil.

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The thickness of soil above a horizon of low permeability determines how much water can infiltrate and the time that will elapse before the available storage capacity of the soil is depleted and infiltration rate declines to a constant minimum.

3.2.3.3 Moisture content: Infiltration rate tends to diminish as the soil moisture content increases. This is associated with

- the gradual filling of the pore spaces, which reduces the capacity of the soil to absorb more water,
- the strong capillary forces created when the surface of dry soil is wetted, which augment the force of gravity in drawing water into the soil,
- the swelling of colloids, which reduces pore size and shrinks cracks.

3.2.3.4 Properties of the infiltrating water: Theoretically the temperature of water will affect its viscosity and hence the infiltration rate, but is of ~~minor~~ significance.

Both the physical and chemical quality of the infiltrating water are important. Water rendered turbid by dust, clay and silt particles in suspension blocks soil pores and causes puddling. Especially in alkaline soils dissolved salts may affect the viscosity and hence the rate of advance of the infiltrating water, and form complexes with the colloids which affect their rate of swelling.

The deeper the water on the surface, the greater is the hydraulic head, but if the depth is less than about 12 mm its effect on infiltration rate is negligible.

3.2.4 Summary

Infiltration rate is generally highest during the first part of a storm, being governed mainly by the size, number and continuity of super-capillary or macro-pores in the soil through which water can easily move. Thereafter the infiltration rate decreases rapidly and then more slowly to a constant minimum rate (corresponding to the transmissibility of the least permeable layer), due to the filling of the pores with water, the diminishing storage capacity (the latter being determined initially by the thickness and porosity of the soil, and the antecedent moisture content), the decreasing hydraulic gradient as the water penetrates deeper, changes in the soil caused by compaction, surface sealing and puddling, the latter resulting from drop impact and disintegration of soil aggregates, and to swelling of colloids and closure of macro-pores and cracks. The difference between the initial maximum and ultimate minimum infiltration capacity during prolonged rain varies considerably both with the type of soil and its condition. The difference is negligible (and the rate consistently high - of the order of 25 mm/hour or more) in the case of porous sandy soil and increases as the soil texture become finer.

3.3 Interactions:

Infiltration is a key process in the dynamics of a hydro=

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logical system, being that water which is stored temporarily in the soil and thereupon carries nutrients to and through the plant and supplies the large quantities of water used by plants in transpiration, or else evaporates or accrues to ground-water. It also determines the residual volume of overland flow (the main contributor of flood flow and sediment) and of throughflow (the main source of perminal and base flow of rivers) and also influences streamflow patterns.

Assuming the rainfall intensity to remain constant during a given storm, surface run-off and thus streamflow will increase progressively as the infiltration rate declines. Should the same total fall of rain occur in the form of sporadic showers, the draining and partial drying of the soil during the intervening periods will cause the infiltration capacity of the soil to recover, so that the total infiltration will be higher, and run-off less, than in the case of a continuous storm.

Hitherto infiltration has been assessed mainly as the difference between measured rainfall and run-off, but warrants more direct methods of study and an upgrading in research priority.

4. EVAPOTRANSPIRATION

4.1 The process:

Evapotranspiration is an omnibus term embracing the processes whereby water moves from the soil to the atmosphere, involving a change from the liquid to the vapour state. Also known as "consumptive use", "total evaporation" or "vapour loss", evapotranspiration (ET) includes

- transpiration, i.e. the movement of water from the soil through the plant to the atmosphere, and
- evaporation of water from the adjacent soil.

The physics of evaporation and transpiration are basically the same - in fact, transpiration is sometimes known as "physiological evaporation". Evapotranspiration is a major component of the water budget, upwards of 80% of the mean annual rainfall of South Africa as a whole being returned to the atmosphere by this process.

A simplifying concept is that of "potential evapotranspiration" (PET) which refers to the water used by a short, dense, green plant cover continuously supplied with adequate water. It is of practical use firstly because it sets an upper limit to the combined loss by evaporation and transpiration and hence to plant vater requirements (this information being basic to irrigation scheduling) and also because PET is essentially a function of climatic variables alone, in contrast to ET (i.e. actual, or non-protential evapotranspiration) which is also influenced by soil and plant factors.

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4.2 Controlling variables:

4.2.1. Evaporation from soil

Evaporation from a wet, irregular soil surface may equal and even exceed that from free water since the total area of soil exposed to evaporation is greater than that of a plane water surface with the same projectional area. Evaporation will remain high if the soil is saturated or if there is continual upward capillary movement from a free water table, but in unsaturated soil the evaporation rate diminishes rapidly once the surface layer dries. Thus the main loss by evaporation occurs from the top few centimetres of soil although its influence can be detected in normal soil to depths of 30 cm or more. During prolonged dry seasons moisture may move upwards from depth in the vapour phase against the temperature gradient, condense near the surface and then evaporate.

Because of the high initial rate of evaporation from a wet surface, it follows that total evaporation loss over a season is largely a function of the number of occasions on which the soil is wetted anew, rather than on the amount of rain.

Evaporation rate is generally higher from compact than from loose soils, from granular than from aggregated soils, and from dark than from light soils.

4.2.2 Transpiration

Physically the process is the same as that of evaporation. The difference lies in the nature of the surface, for whereas evaporation takes place from a free water surface, transpiration loss occurs from leaves composed of thin walled, moist cells (mesophyll) covered by a layer of cells (the epidermis) which are relatively impervious to moisture and gases, but which include small elongated pores (stomata) through which moisture that collects in the intercellular spaces in the mesophyll escapes as vapour. Opening and closure of each stoma is effected by changes in the turgor of two adjacent guard cells, in reaction not only to the internal supply of water to the leaves but to changes in light intensity, temperature, humidity, etc. In response to these external stimuli, generally upwards of 95% of the transpiration loss occurs during the daytime. When the stomata are open, transpiration is governed by the same factors that control evaporation - hence transpiration exhibits much the same diurnal and seasonal trend as insolation and temperature.

The water extracted by a plant from the soil plays an essential rôle in the uptake of nutrients, in photosynthesis and in the transport of substances through the plant, but the quantity of water so used is very small relative to the vast quantity of water transpired.

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Transpiration would therefore seem to be largely a passive process forced by the evaporative power of the air, not proportionately related to growth, and largely unavoidable and uncontrollable - hence the importance of seeking to attain the maximum crop return from this major water loss.

Of the weather variables controlling the evaporative power of the air, solar radiation (insolation) is the ultimate source of energy which furnishes the latent heat required to vapourise water, whether by evaporation or transpiration. It also plays a vital rôle in photosynthesis.

Temperature, being a function of the intensity and duration of insolation as well as of heat exchange, is a useful criterion of plant growth potential, and combines with relative humidity and wind speed to govern the rate of vapourization of water.

Evaporation, being the net transfer of water molecules into the air, can occur only if there is a vapour pressure gradient between the evaporating surface and the air, and is therefore also a function of the relative humidity of the air.

By removing water vapour that has been evaporated or transpired, and by renewing the supply of unsaturated air to the evaporating/transpiring surface, wind speed also effects evaporation rate although its influence is generally secondary to that of insolation.

Transpiration depends not only on the evaporative power of the air but also on the availability of moisture in the soil. This depends on the field capacity and wilting point of the soil, and on the rooting habit of the plant, for the deeper and more ramified the root system, the greater the store of water that can be reached by the plant.

4.2.3 Potential evapotranspiration (PET)

If the moisture content of soil is maintained at or near field capacity (the maximum quantity of water the soil can hold against gravity), then the evapotranspiration rate for all short dense crop covers of more or less the same colour and reflectance (albedo) will be approximately the same irrespective of the type of soil or plant - and will be determined by prevailing weather conditions, notably the total available energy. It provides an estimate of maximum crop water requirements and hence is particularly useful as a basis for calculating water quotas and scheduling irrigation.

In no part of South Africa does the mean monthly rainfall exceed mean monthly PET throughout the year although there are seasonal surpluses.

4.3 Formulae

Of the many formulae that have been developed - mainly to calculate PET - some are based on the aerodynamic (mass transfer) method, some on the energy budget method, some

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are combinations of the two approaches, while others are empirical. Amongst the most popular are those of Lowry-Johnson, Dlaney-Criddle, Hargreaves, Thornthwaits and Penman.

4.4 Interrelationships

It is the loss of water from the leaves in response to the evaporative "pull" of the atmosphere that initiates the series of processes whereby water is abstracted from the soil through the root hairs and pulled through the stems to the leaves to replenish the transpiration loss. The plant thus contains a continuous column of water that is moved upward through the xylem, a hydraulic conductor of low resistance, at rates of up to many cubic metres a day and to heights of up to 100 m or more. One of the theories to account for this is that it is accomplished by the considerable tension that can be transmitted up the thin xylem capillary tube by the cohesion of the water molecules.

In effect, transpiration is the cause, and not the result, of the movement of water through a plant.

It is also important to recognize that transpiration is not a measure of growth. A plant whose growth is stayed by lack of nutrients continues to transpire, as does an annual whose growth stops on reaching maturity. Conversely, growth is not a measure of transpiration, as is evident from the fact that a well fertilized crop will heavily outyield an unfertilized stand grown under the same rainfall conditions and therefore transpiring substantially the same quantity of water.

As the soil moisture section increases from ± 0,1 bar at field capacity to ± 15 bar at the permanent wilting point of the soil, the energy required to extract a given quantity of water from the soil increases as the soil dries. Some contend that transpiration and the growth of plants must likewise decrease as the soil dries. However, as has already be mentioned, growth and transpiration are not necessarily proportional to each other. Furthermore it has been calculated that in the case of a tree 10 m high transpiring in air at 30°C and relative humidity 40%, the total energy required to extract water from the soil at permanent wilting point is only 0,07% more than that required when the soil is saturated, and that as this is such a negligible difference water can be regarded as being equally readily available to the plant between field capacity and the wilting point. As the adherents of both viewpoints can adduce substantiating evidence, other influences have to be considered to resolve these seeming inconsistencies, such as the prevailing temperature and humidity of the air, and the moisture transmissibility of the soil.

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5. CATCHMENT MANAGEMENT

Even a slight change in the quantity of water retained on the expanse of a catchment will have a greatly amplified effect on the generally much smaller quantity that runs off and is then confined within a river channel.

Land management changes integrate the effect on water yield of the "loss" process already dealt with, namely interception and evapotranspiration. Wicht has incorporated general conclusions on the influence of vegetation on stream discharge, in the following well-formulated, tenable hypothesis:

> "The hydrological influences of vegetation, all other factors being constant, are correlated with the degree to which it utilises the site*. Dense, fully-stocked forest will, owing to the considerable vapour losses caused by precipitation, interception and transpiration, as well as the increased lag of impeded surface flow and freer infiltration, reduce flood peaks and the rate of spate-discharge generally. Dense forest will also decrease the total water yield, and in long dry seasons, it will cause more rapid baseflow recession so that the water supplies towards the end of a dry period will be restricted. The transpiration of phreatophytes and the substitution of evergreen for dormant vegetation, will increase the vapour losses. Reduced density of plant cover even to the extreme "cement paving" condition, will increase the peaks of spates, the rates of discharge generally and the total discharge from catchments because infiltration will be restricted and the water movement will be less impeded, immediate and rapid. Streams from denuded catchments will soon dry up during dry periods".
>
> (*The degree of utilization might be indicated by the density of aerial and underground vegetal parts or the total amount of living plant material above and below the ground, i.e. the phytomass).

Many analyses of trends in run-off per unit of rainfall have been made over the years, using covariance and other statistical techniques. These have recently been updated and consolidated in a study involving the analysis of the hydrographic records of 50 long term river gauging stations in South Africa. In general, the higher the mean annual rainfall (that is, in general, the greater the intensification of forming) the greater has been the reduction in run-off. As there is no evidence of any consistent diminution in rainfall, the trend is almost certainly the result of intensified land use associated with South Africa's explosive economic growth. This feed-back effect whereby the factors that force up water demands also tend to diminish the effective supply, is shortening the time still available in which to seek means of meeting therising demands for water once they

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outstrip the supply available from conventional sources. The results of this study highlight the need to examine all run-off records for trends and then to adjust them accordingly so as to arrive at realistic estimates of current mean annual run-off.

Only in the case of afforestation has the effect of land management on catchment water yield been studied in depth. Even less research has been done on the extent to which the water yield of catchments could be increased by judicious land use systems and management practices without detriment to yield or to soil stability. Some wor has been done on the effect on stream flow of phreatic vegetation and its removal, but very little is known about the hydrological effects of, say, bush encroachment, various systems of veld management, alternative cropping practices, and the like. Practices which could increase water yield include: reduction in interception and evapotranspiration by management practices (judicious gazing, burning and mowing) that keep pasture short except at seeding time, eradiction of broad-leaf, deep rooted weeds, combating bush encroachment, selection of crops that are short, shallow-rooted and have a narrow leaf rather than those that are fall, dense, deep-rooted and broad leafed, possible use of anti-transpirants and defoliants, measures for reducing evaporation from soil, and the practice of "water harvesting" from treated surfaces.

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